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The study of activated sludge settleability using the solids-flux analysis

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ABSTRACT

The Study of Activated Sludge Settleability Using the Solids-Flux Analysis

by
Churng-Cherng Lin

The activated sludge was cultivated in two pilot-scale activated sludge systems under three ratios of BOD to N, equal to 20:1, 70:1 and 300:1 in the influent wastewater. The aeration tank of the activated sludge system was constructed in two different configurations: one without compartments in the tank, the other consisting of six compartments. The activated sludge withdrawn from the last compartment of each system was tested in a one-liter graduate cylinder to measure its zone settling velocity. The solids-flux method was employed to analyze the sludge settling characteristic as a function of solids concentration. The results show that the activated sludge grown under the nitrogen-sufficient condition and cultivated in a compartmentalized aeration tank under the nitrogen-deficient condition were excellent in settleability. In contrast, the poor settling sludge was found in the severely limited nitrogen system and in the nitrogen-deficient system without compartments in the aeration tank. This study indicates that sufficient nitrogen in the wastewater is necessary for successful treatment of wastewater, and the compartmentalization of the aeration tank could improve the efficiency of the secondary sedimentation tank.

THE STUDY OF ACTIVATED SLUDGE SETTLEABILITY USING THE SOLIDS-FLUX ANALYSIS

by
Churng-Cherng Lin

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APPROVAL PAGE

The Study of Activated Sludge Settleability Using the Solids-Flux Analysis

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This thesis is dedicated to
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CHAPTER 1

INTRODUCTION

At most wastewater treatment plants, the effluent of the secondary settling tank represents the quality of treatment achieved prior to its discharge into the receiving waters. Therefore the secondary settling tank has been considered the most important unit process in a secondary waste treatment system. The secondary settling tanks always follow the aeration tanks to perform these two functions: (1) separation of the mixed-liquor suspended solids from the treated wastewater, which results in a clarified effluent, and (2) thickening of the activated sludge, which is returned to the aeration tanks to maintain a given-solids level.

Since secondary settling tanks act as both settling tanks and thickeners, it make senses to design for both of these processes. However, Dick [1] has pointed out that it is likely that thickening, in fact, is often the most critical of the two processes and that both the settling and thickening requirements must, therefore, be considered. Basically, there are two methods of designing a secondary settling tank, one is based on the experience of previous designers by using their design criteria, the other is the utilization of laboratory data directly derived from the settling tests. Obviously, the latter is the better way to design a proper settling tank which can handle the characteristics of specific wastewater. If using previous design criteria, it is important to caution that these design values are believed to be acceptable for existing settling tanks, and cannot be used without considering the peculiarities of each individual sludge and plant.

Perhaps the most widely used batch thickening test is the sludge volume index (SVI), which was developed originally to aid the treatment plant operator in monitoring the quality of the activated sludge. Unfortunately, this has been used as a research tool to aid thickener design [2]. As useful as this test is, its limitation must also be recognized.

Actually the SVI is highly dependent on the initial suspended- solids concentration. Vesilind has pointed out that the SVI has the maximum value for any solids concentration according to definition and its value is always below 150 when suspended-solids concentration is greater than 7,000 mg/l. Thus it is misleading to speak of the SVI of a sludge at greater than 7,000 or 8,000 mg/l of solids. Furthermore, two kinds of sludge could be equal in SVI, though they have totally different settling curves [3].

On the basis of data derived from column-settling tests, two design approaches can be used for the settling/thickening tanks. In the first approach, only a single settling test is performed to derive the data. The theory of this approach was proposed by Kynch, who assumes that during a settling test layers of increased concentration rise up from the bottom and eventually intersect the slurry liquid interface [4]. The introduction of this approach seems to be good news for design engineers who are always seeking to avoid laboratory work. Unfortunately, experiments have proven that it does not apply to highly compressible materials such as activated sludge and other wastewater sludge [5]. The second approach, known as solids-flux method, concerns conducting a series of settling tests at various solids concentrations. But the strength of solids flux analysis for secondary settling tank design is widely recognized in current literature.

In the solids-flux method, there are two ways to determine the limiting solid-flux which is the critical design criterion for the settling tanks. One is to plot the total solids-flux against the solids concentration, then to find the lowest point of the total solids-flux curve. That point is exactly the limiting solids-flux. The other way is to conduct the mathematical differentiations to find the minimum value of the total solids-flux curve.

In this study, the solids-flux method, including plotting and differentiations, will be used to analyze the settling characteristics of three kinds of wastewater which has the specific ratio of BOD to Nitrogen (N). Moreover, the same method is also used to investigate whether the compartmentalization of the aeration tanks can effectively increase the sludge settleability, and whether the greater the number of compartments in the aeration tanks can result in the better settling properties for the activated sludge.

CHAPTER 2

MATERIALS AND METHODS

2.1 Experimental Apparatus

Two pilot-scale activated sludge systems were installed in the laboratory. A schematic flow diagram for the system is shown in Figure 1. Each pilot unit consisted of a feed pump, an aeration tank, a secondary settling tank, and a sludge recirculating pump, which was connected to a mechanical timer. Both the biological reactor and the secondary settling tank were constructed of Plexiglass; their physical structures were as specified in Table 1.

Generally, the reactor in system 1 (S-1) was similar to the conventional completely-mixed reactor, whereas the other reactor in the system 2 (S-2) was divided into six compartments. This aiteration reduced the dispersion number and made the reactor more similar to a plug-flow reactor.

During the entire period of this study, the influent wastewater and the return sludge were pumped to the head of the first compartment of the aeration tanks by a flux pump. The hydraulic retention time of both activated sludge systems was regulated at nearly 24 hr, and the experimental temperature was maintained at 21^{o}C. Air was provided for aeration and mixing. Air stone diffusers were placed along one side of the aeration tanks. The amount of air introduced to the reactor in S-1 was identical to that

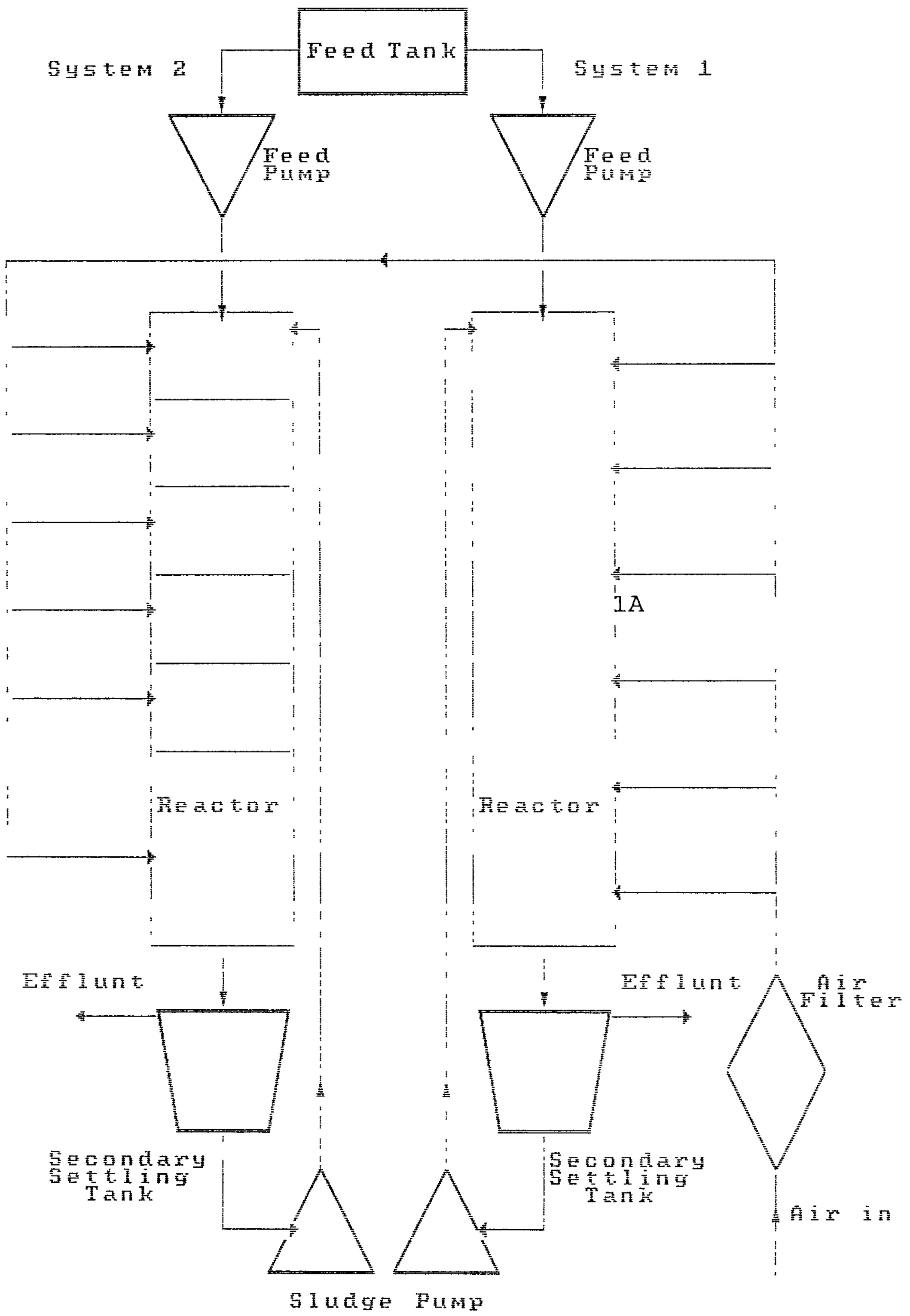

Figure 1 Schematic Flow Diagram for Pilot Plant

applied for S-2 by using an air-pressure regulator and six airflow meters with control valves. Before the air was mixed with the mixed liquor suspended solids, it was passed through a cotton filter for removal of impurities.

Table 1 Pilot Plant Specifications

		Dimension			
System	Component	Length (cm)	Width (cm)	Depth (cm)	Volume (l)
S-1	Aeration tank	151.5	31.0	39.5	160.0
S-2	Aeration tank		Compartment 1-5		
		20.0	31.0	39.5	21.4
			Compartment 6		
		51.0	31.0	39.5	53.5
S-1 & S-2	Secondary settling tank	60.0 5.5	60.0[a] 5.5[b]	100.0	132.0

a : Top area

b : Bottom area

In the secondary settling tank, there was a settling chamber that was used to collect the effluent of the aeration. After the sludge had settled to the bottom of the settling tank, it was recycled back to the aeration tank by a positive displacement pump. The sludge was recycled at a rate of approximately 25% of the influent waste flow for 15 minutes each hour, which meant that the recycle ratio of sludge was 0.25.

2.2 Wastewater Composition

The chemical composition of the wastewater used for this study is shown in Table 2. Glucose provided the carbon and energy source. The amount of ammonia nitrogen, the source of nitrogen in this study, was prepared to achieve three ratios of BOD to N, 20:1, 70:1 and 300:1. Two kinds of phosphates were used as sources of phosphorus and buffer solution. Other salts and tap water provided the necessary trace elements for growth. The feed solution was prepared daily in order to minimize the effect of bacterial degradation.

Table 2 Chemical Composition of Synthetic Wastewater

Constituent	Concentration (mg/l)
Glucose as COD	450.0
NH_4Cl as N	varied
$MgSO_4.7H_2O$	100.0
$FeCl_3.6H_2O$	7.5
NaCl	40.0
$CaCl_2.2H_2O$	8.5
KH_2PO_4	33.0
K_2HPO_4	64.0
$NaHCO_3$	200.0
KCl	7.0
Tap water	to one liter volume

2.3 Samples Collection and Analysis

The organic loading, food-microorganism ratio, in the first compartment of aeration tank for system 1 and system 2 were controlled within the range of 1.25 to 1.65 g BOD/g MLSS/day and 0.92 to 1.25 g BOD/g MLSS/day, respectively. The samples were collected from the last compartment of the aeration tanks and then analyzed to measure the mixed-liquor suspended solids (MLSS) and sludge zone settling velocity (ZSV). Both tests were carried out in accordance with "Standard Method", and will be explained briefly in next two sections.

Regular microscopic observation of the developed activated sludge cultures were made to examine the composition of the activated sludge floc. The identification of filamentous microorganisms was performed in accordance with the method suggested by Eikelboom [20].

2.3.1 The Measurement of Mixed-Liquor Suspended Solids

The sample is filtrated through a weighed standard glass-fiber filter(with a nominal pore size of about 1.2 micrometers), and the residue retained on the filter is dried to a constant weight at 103°C to 105°C. The increase in weight of the filter represents the total suspended solids. MLSS is then obtained by dividing the value of the total suspended solids by the volume of the sample, and is usually expressed as "mg/l" [17].

2.3.2 Zone Settling Velocity Derived from Column-Settling Tests

The ZSV is obtained from the "column-settling tests," which in the laboratory is conducted in a transparent graduate cylinder filled with sludge and mixed to distribute the solids evenly. At time zero the mixing is stopped, and the solids are allowed to settle. If the solids concentration is sufficiently high, the solids will settle as a blanket without any interpartical movement and, therefore, all individual particle settle at the same velocity. This creates a distinct solid-liquid interface, the height of which can be measured with time. The slope of the straight-line portion of this curve is exactly the zone-settling velocity of the sludge at that solids concentration. Actually, the zone settling velocity of the sludge depends on its solids concentration, and will decrease due to the higher concentration of solids, as seen in Figure 2.

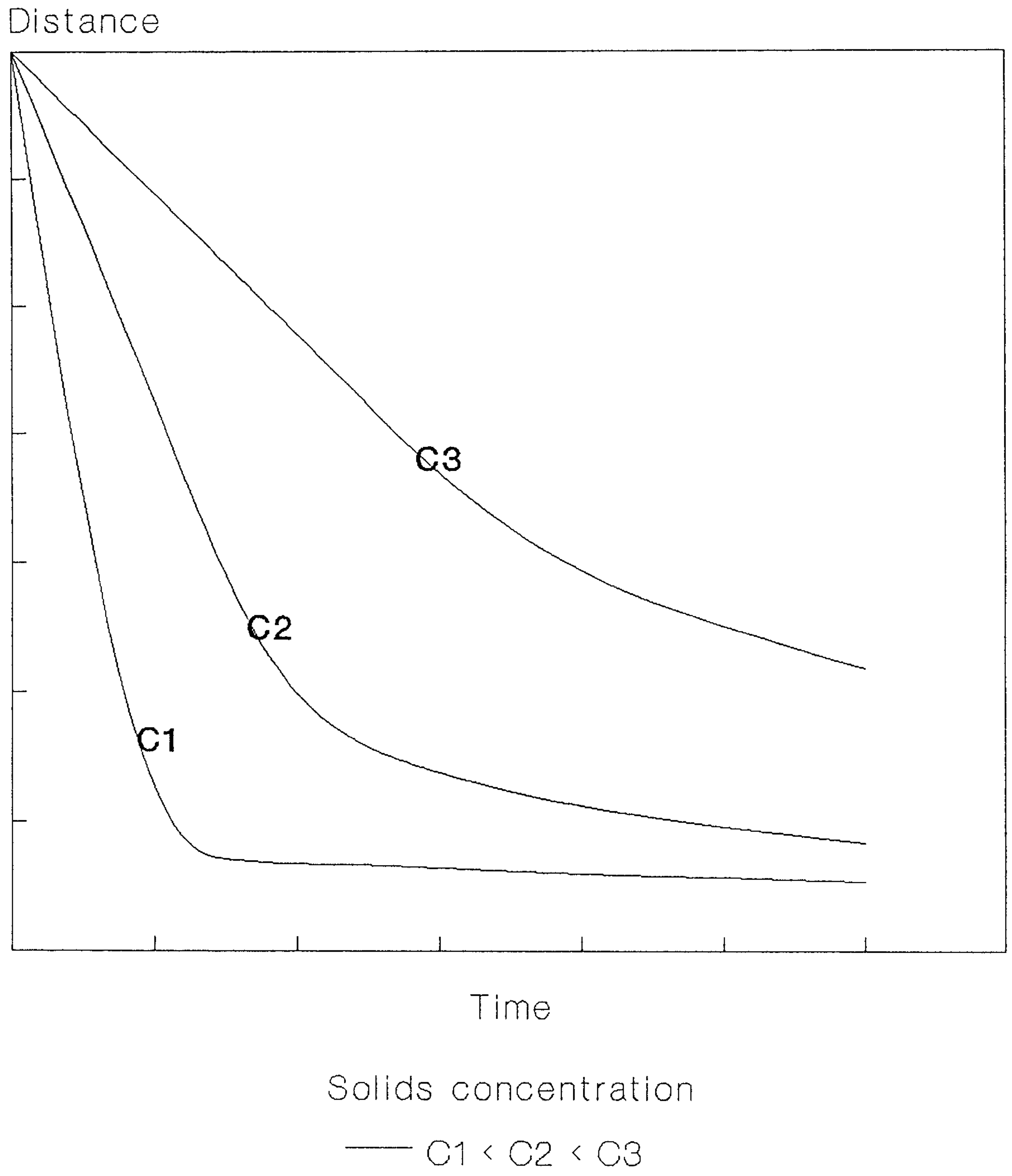

Figure 2 - Zone Settling Velocity
Derived from Column-Settling Tests

CHAPTER 3

THE SOLIDS-FLUX ANALYSIS

The solids-flux, which consists of the mass of solids movement in a settling tank divided by the area of the tank per unit time, is defined by multiplying the initial settling velocity by the solids concentration. There are two ways that the solids move toward the bottom of the tank. The first one is due to the gravity settling of solids within the tank. If the solids did not settle, no thickening would take place. The second one is the bulk downward movement due to the underflow being pumped out and recycled. The continuous movement of solids out the bottom, as sludge underflow, creates a velocity within the thickener that is independent of the solids settling rate. At some level , i , the total solids flux is therefore equal to the sum of the flux due to the gravity settling flux and the underflow movement flux. The equation can be expressed as:

$$G_i = v_iC_i + uC_i \qquad (1)$$

where

G_i = total solids flux at level i, mass/area/time

C_i = solids concentration at level i, mass/volume

v_i = zone settling velocity of sludge at C_i, length/time

u = underflow velocity, length/time

3.1 Graphical Method

The flux of solids due to gravity settling depends on the solids concentration and the settling characteristics of the solids at that concentration. At low concentration, the movement of solids due to gravity is small because the settling velocity of the solids is more or less independent of concentration. If the velocity remains essentially the same as the solids concentration increase, the total solids-flux due to gravity starts to increase as the solids concentration starts to increase. At a very high solids concentration, the zone settling velocity approaches zero, and the total solids-flux due to gravity again becomes extremely low. Thus it can be concluded that the solids flux due to gravity must pass through a maximum value as the concentration is increased, which is shown in Figure 3.

The solids flux due to bulk transport is a linear function of the concentration with slope equal to the underflow velocity. The total flux, which is the sum of the gravity and the underflow flux, is also shown in Figure 3.

As shown in Figure 3, if a horizontal line is drawn tangent to the low point on the total flux curve, its intersection with the vertical axis represents the limiting solids flux that can be processed in the settling tank [6].

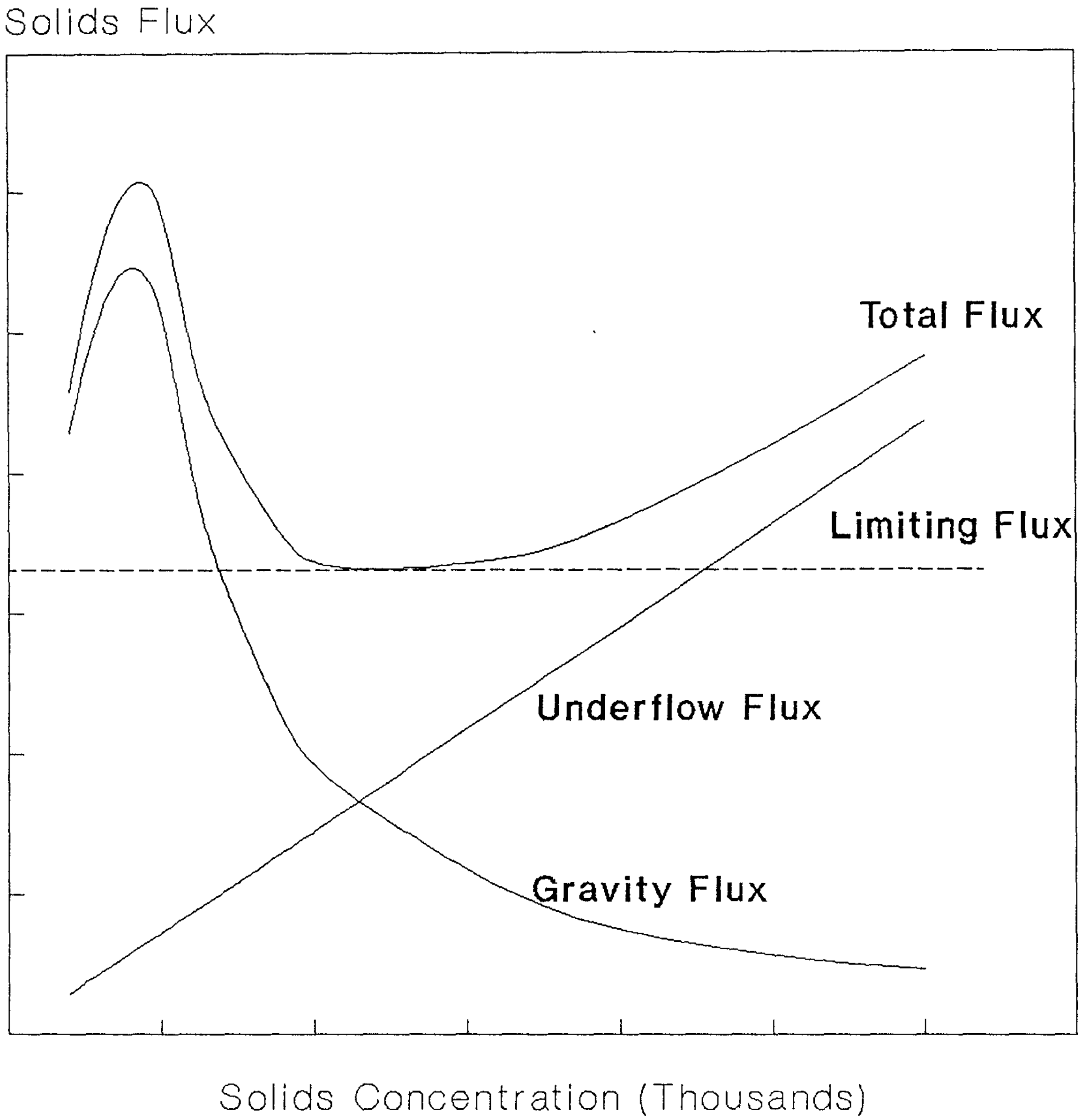

Figure 3 Definition Sketch for
the Solids-Flux Analysis

The limiting solids flux defines the maximum rate at which solids may be added to the tank and still maintain equilibrium at a given underflow rate. If the quantity of solids fed to the settling tank is greater than the limiting solids-flux value, the solids will build up in the settling tank and, if adequate storage capacity is not provided, ultimately overflow at the top. Thus the design of a secondary settling tank is reduced to determining this critical point.

The other application of the limiting solids flux is its relationship with the settling characteristics of the sludge. If the sludge are settled in the same settling tank and the other conditions are the same, the larger value of the limiting solids flux represents the better settling characteristic.

3.2 Mathematical Model

In addition to the plot procedure as mentioned, the solids flux analysis may be performed mathematically. Mathematical expression of secondary settling tank performance requires description of solids transport due to gravity and solids transport due to underflow. The latter effect readily can be expressed in the form of an equation, but the former is not so easy. This is because the amount of solids flux due to gravity is established by the experimentally determined relationship between suspended solids concentration and zone settling velocity. To permit mathematical description of the secondary settling tank performance, the concentration-velocity relationship must be expressed as an equation. In this study, it is expressed as:

$$v_i = mC_i^{-n} \qquad (2)$$

Taking logarithm on both sides, we get

$$\text{Log } v_i = \text{Log } m - n\ (\text{Log } C_i)$$

Therefore, the coefficient of m and n are , respectively, the intercept and the slope of the linear portion of a logarithmic plot of zone settling velocity against solids concentration.

If this relationship is substituted into the equation 1 for the total solids flux, we obtain the following:

$$G_i = G_i m V_i^{-n} + uC_i$$

or

$$G_i = mC_i^{(1-n)} + uC_i$$

then

$$\frac{dG_i}{dC_i} = m(1-n)C_i^{-n} + u$$

The limiting solids flux is the value of Gi when

$$\frac{dG_i}{dC_i} = 0$$

Solving for C_i and calling this the limiting concentration C_L at the limiting flux,

$$C_L = [m(n-1)/u]^{1/n}$$

For this to be true minimum,

$$\frac{d^2G_i}{dC_i^2}$$

must be greater than 1.

$$\frac{d^2G_i}{dC_i^2} = \frac{mn(n-1)}{C_i^{(1+n)}}$$

and the expression is positive if m is positive and n is greater than 1.

The limiting flux is, therefore,

$$G_L = [m(n-1)]^{1/n}[n/(n-1)]u^{(n-1)/n} \qquad (3)$$

It is to be cautioned that this equation is valid only when the absolute value of n is greater than 1.0 and the plot of logarithmic solids concentration against logarithmic zone settling velocity is linear. Nonlinearity of these data would necessitate development and use of a different equation to substitute for Equation 2 [7].

Both methods, plot and differentiations, which could determine the limiting solids flux, will be used to analyze the activated sludge settling data derived from the column-settling tests in this study.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 The Effect of Nitrogen in the Wastewater on Sludge Settleability

Three different ratios of BOD to N in the wastewater were investigated. The ratio of 20:1 represents the nitrogen-sufficient condition; the ratio of 70:1 indicates a deficiency of nitrogen; and the ratio of 300:1 specifies the condition of extremely low nitrogen. The studies conducted under various BOD to N ratios were used to determine the effect of wastewater properties on activated sludge composition and settleability. The results of these three ratios will be expressed and discussed below:

4.1.1 BOD:N = 20:1

For System 1, the aeration tank without compartments, the zone settling velocity varied between 8.2 cm/min and 2.5 cm/min when mixed liquor solids concentration fell from 1,500 mg/l to 3300 mg/l. Using the graphical method of solids-flux discussed previously, we could find that the limiting solids flux was about 8.5 Kg/m^{2}hr, as seen in Figure 4.

For System 2, the reactor with six compartments, the ZSV varied between 12.2 cm/min and 3.0 cm/min, while the MLSS fell from 2,050 mg/l to 4,100 mg/l. The limiting solids flux is about 12.0 Kg/m^{2}hr, which is shown in

Figure 5. Obviously, the sludge settleability in System 2 is better than that in System 1, which had no compartments in the aeration tank.

4.1.2 BOD:N = 70:1

For System 1, the ZSV never exceeded 0.25 cm/min. This meant that the settleability of the activated sludge was poor in this system. Compared to the system with the same type aeration tank, but under the condition of BOD to N ratio of 20:1, the poor settling of the activated sludge in this system could result from the lower concentration of nitrogen in the wastewater.

For System 2, the ZSV varied between 9.7 cm/min and 2.8 cm/min while the MLSS fell from 1,600 mg/l to 3,300 mg/l. The limiting solids flux was about 10.5 Kg/m^2hr, as shown in Figure 6. Compared to System 1, which was under the condition of the same ratio of BOD to N, this system obviously produced the better settling activated sludge in the tank. Therefore, the compartmentalization of the aeration tank in this system seemed to improve the settleability of the activated sludge in the settling tank.

4.1.3 BOD:N = 300:1

In this condition, neither System 1 or System 2 could tolerate the degree of nitrogen limitation, because the

ZSV was reduced to 0.05 cm/min. Actually with such a small value of ZSV, there was almost no settling in the tank. Most of the solids flux came from the underflow which was pumped out and recycled in the bottom of the settling tank.

The system under the condition of a BOD to N ratio of 20:1 in the wastewater and with compartments in the aeration tank has the maximum value of limiting solids-flux. Both the systems, a BOD to N of 70:1 in the wastewater and with compartments in the aeration tank, and a BOD to N of 20:1 in the wastewater and without compartments in the aeration tank, have a satisfactory value of limiting solids-flux. For the other three systems, a BOD to N of 70:1 in the wastewater and without compartments in the aeration tank, and a BOD to N of 300:1 in the wastewater and with or without compartments in the aeration tank, the limiting solids-flux could not even be found in the plots, as seen in Figure 7.

4.2 Sludge Settling Problem

Obviously, some problems in sludge settlement had occurred in the last three systems. So microscopic observations were performed to investigate the morphological structure of the activated sludge withdrawn from the tanks. It is clearly seen that the activated sludge produced from the non-compartmentalized system,

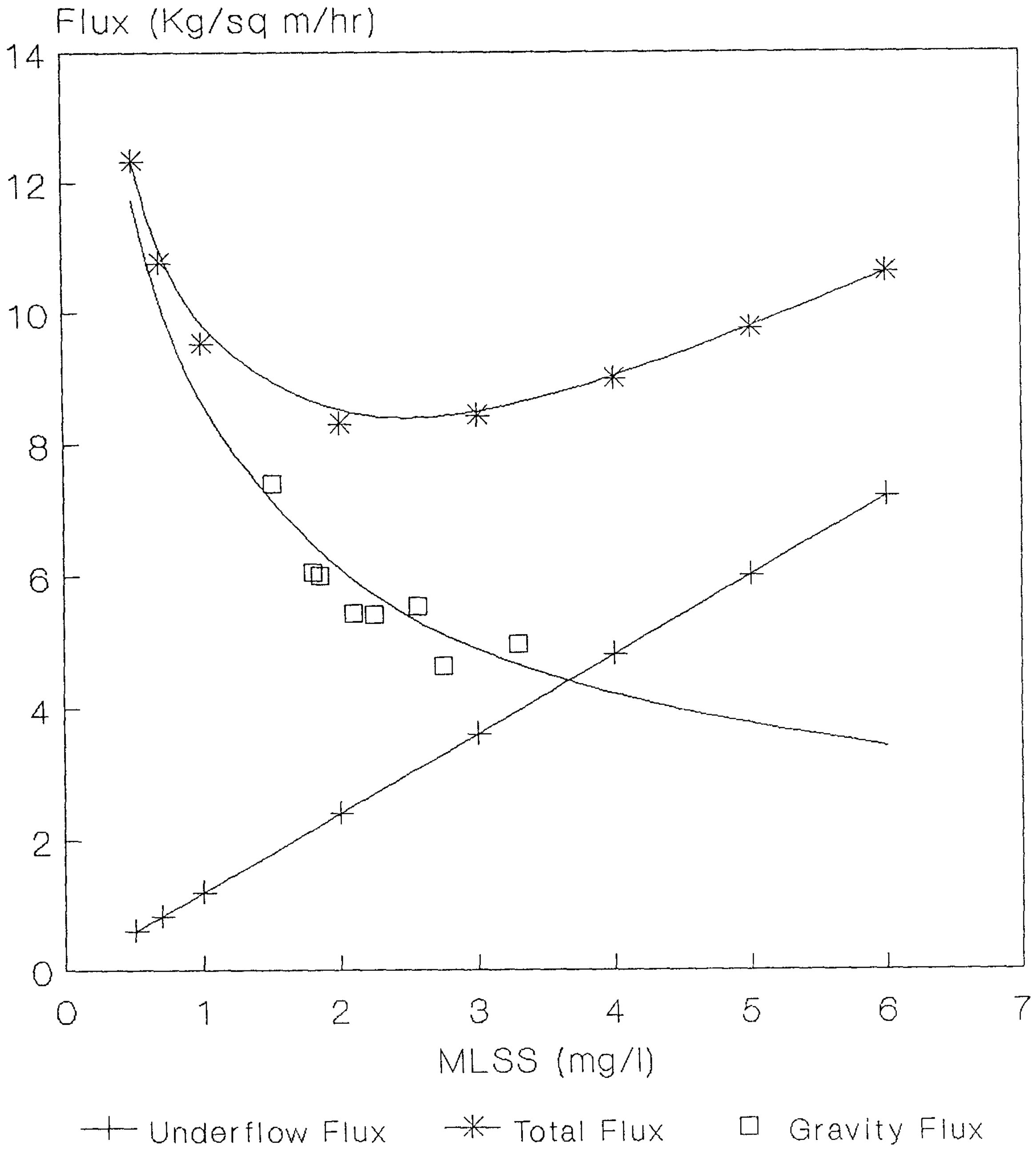

Figure 4 Solids-Flux Curves for
BOD:N = 20 in Wastewater and
Reactor without Compartments

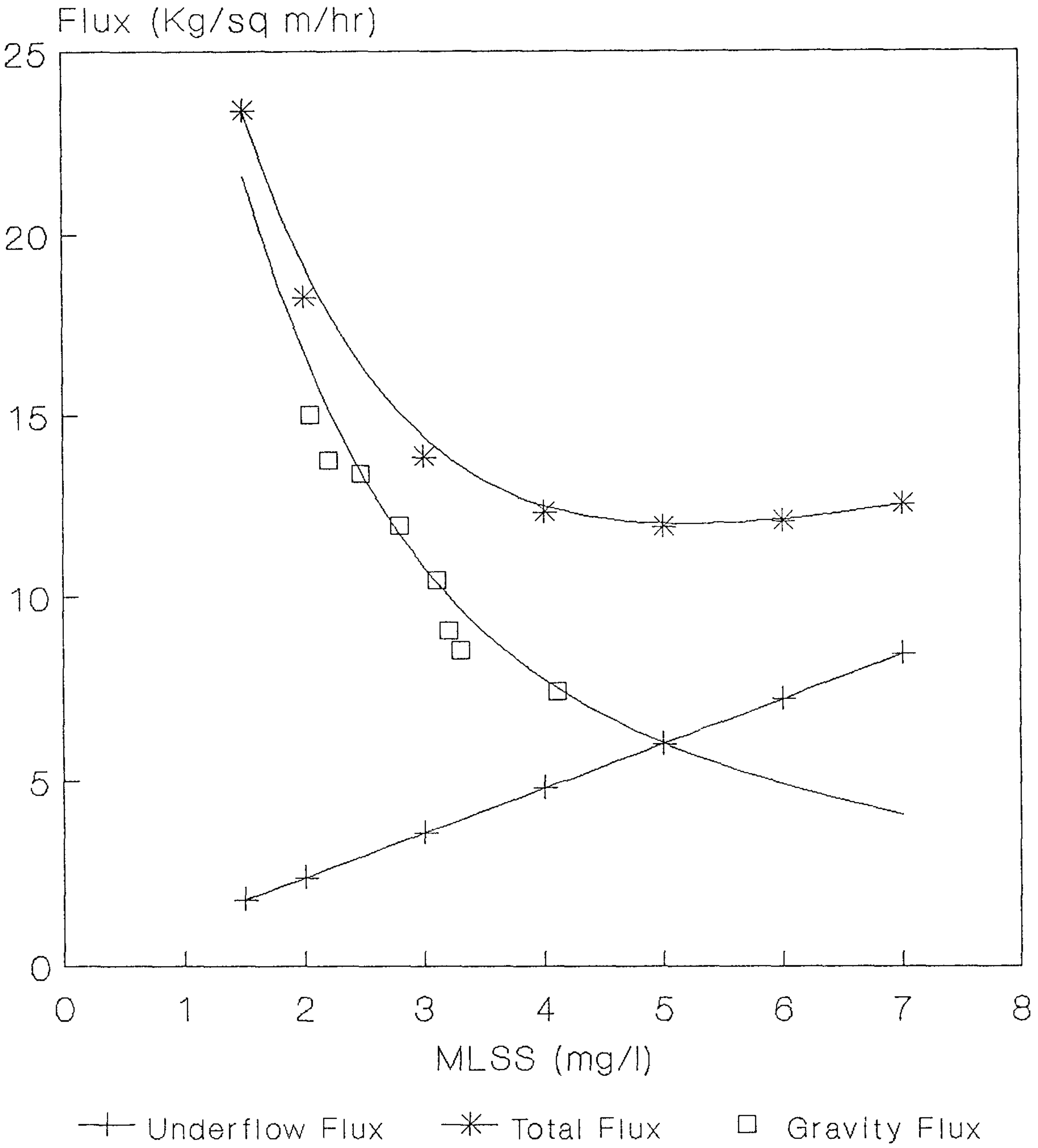

Figure 5 Solids-Flux Curves for
BOD:N = 20 in Wastewater and
Reactor with Compartments

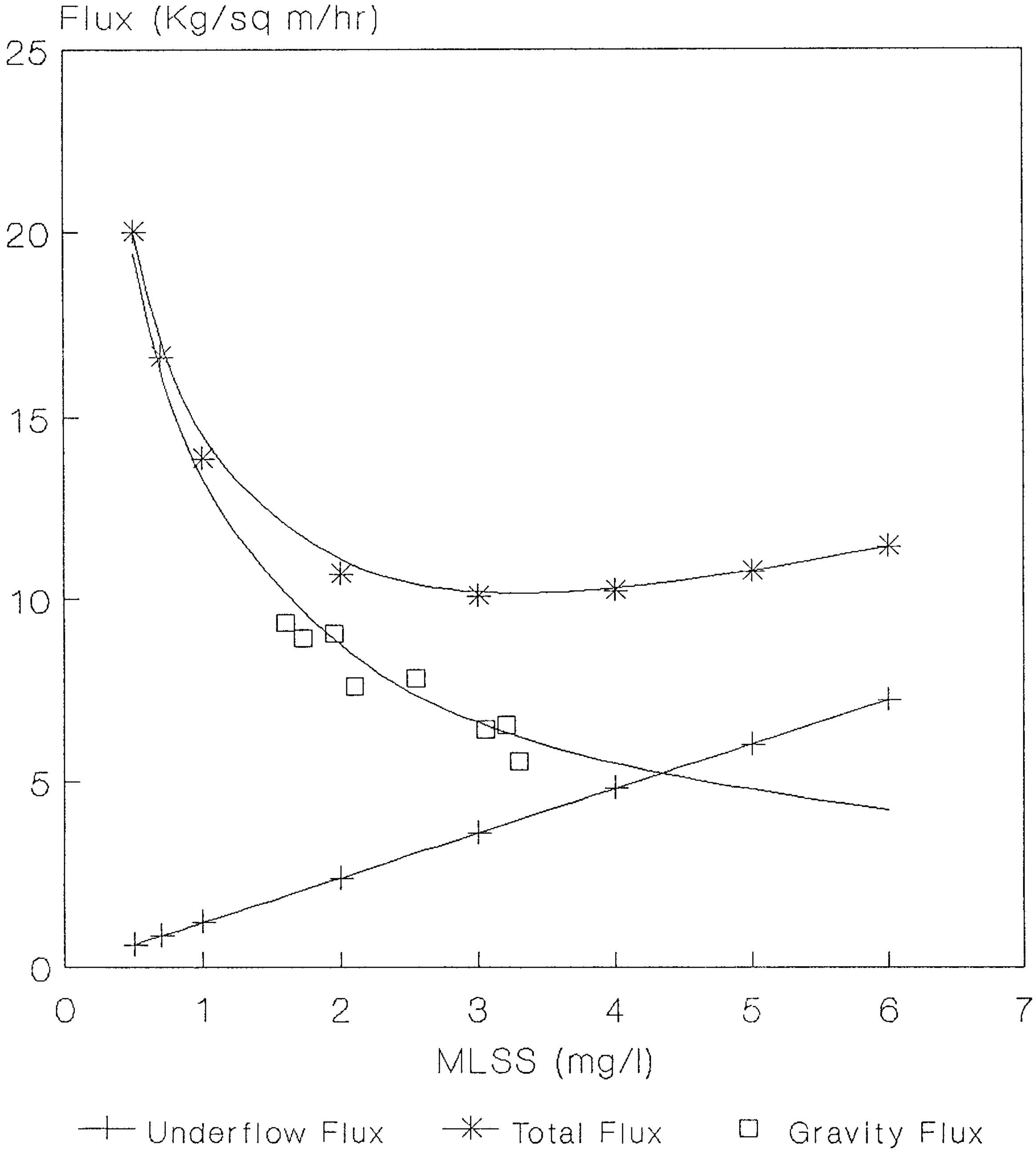

Figure 6 Solids-Flux Curves for BOD:N = 70 in Wastewater and Reactor with Compartments

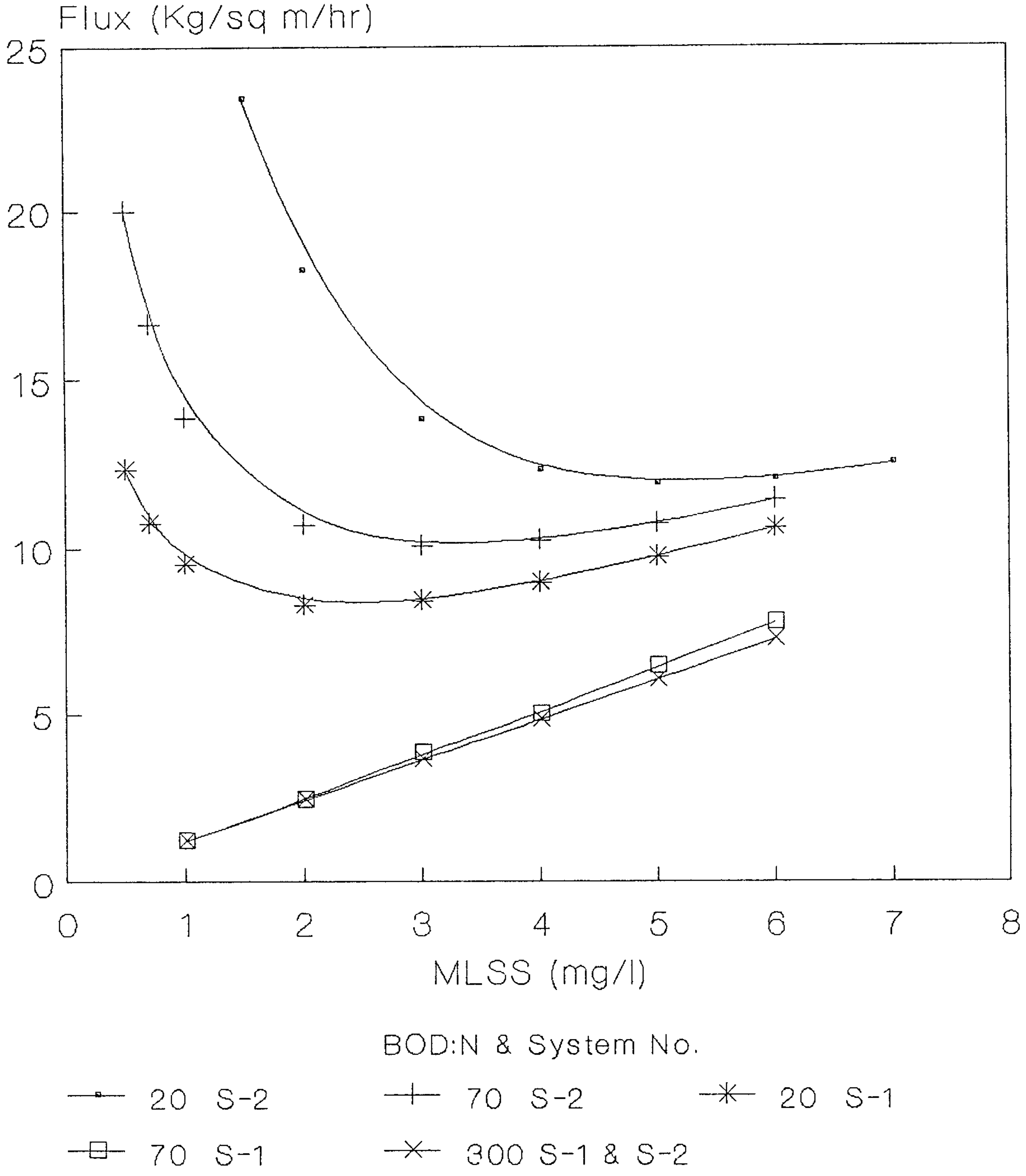

Figure 7 Total Solids-Flux Curves

with a BOD to N ratio of 70:1 in the wastewater, was outgrown by long-length attached filaments. More accurate assessments of filamentous development can be made by the measurement of total filament length [8]. Either of these methods will give the evidence of sludge bulking, in which filamentous organisms extend from the flocs into the bulk solution, interfering with settlement and subsequent compaction of the activated sludge.

On the contrary, only a few filaments were found in the activated sludge produced from the system of which wastewater source is extremely deficient in nitrogen, the BOD:N ratio is 300:1 in this study, therefore it is not a bulking problem due to the overgrowth of filamentous organisms. Indeed, it is caused from the deflocculation or dispersed bacteria failing to aggregate into flocs. This situation can be proved by the turbid effluent.

4.3 The Effect of Compartmentalization on Sludge Settleability

To understand how the settleability of activated sludge responds to the degree of compartmentalization of the biological reactor, the other experiment was carried out. The system 1 was changed so that it was divided into four compartments, and the system 2 still kept six compartments. Both systems were under a constant BOD:N ratio equal to 100:1 in the influent wastewater. The procedure to determine the limiting solids flux is the same as the previous one. The results are shown in Figure 8 and 9.

The results of this experiment indicate that the compartmentalization in the aeration tank could achieve the better sludge settleability in the settling tank. Indeed, changing the mixing pattern in completely mixed aeration tanks to a more plug-flow type, which is reducing the degree of dispersion, produces better settling characteristics [9]. This alteration reduces the competitive advantage that filaments have over floc-forming bacteria due to their higher surface area to volume ratio, which makes them more efficient in obtaining nutrients in conditions of low-nutrient and low-dissolved oxygen concentration [10].

This study also shows that the larger number of the compartments or the lower the dispersion number used, the greater difference in the substrate concentration gradient along the reactor and the better sludge settleability could be [11].

4.4 The Limiting Solids-Flux Derived from Calculation of Mathematical Model

The first step to determine the limiting solids flux by using the mathematical model is to find the relationship between solids concentration (MLSS) and zone

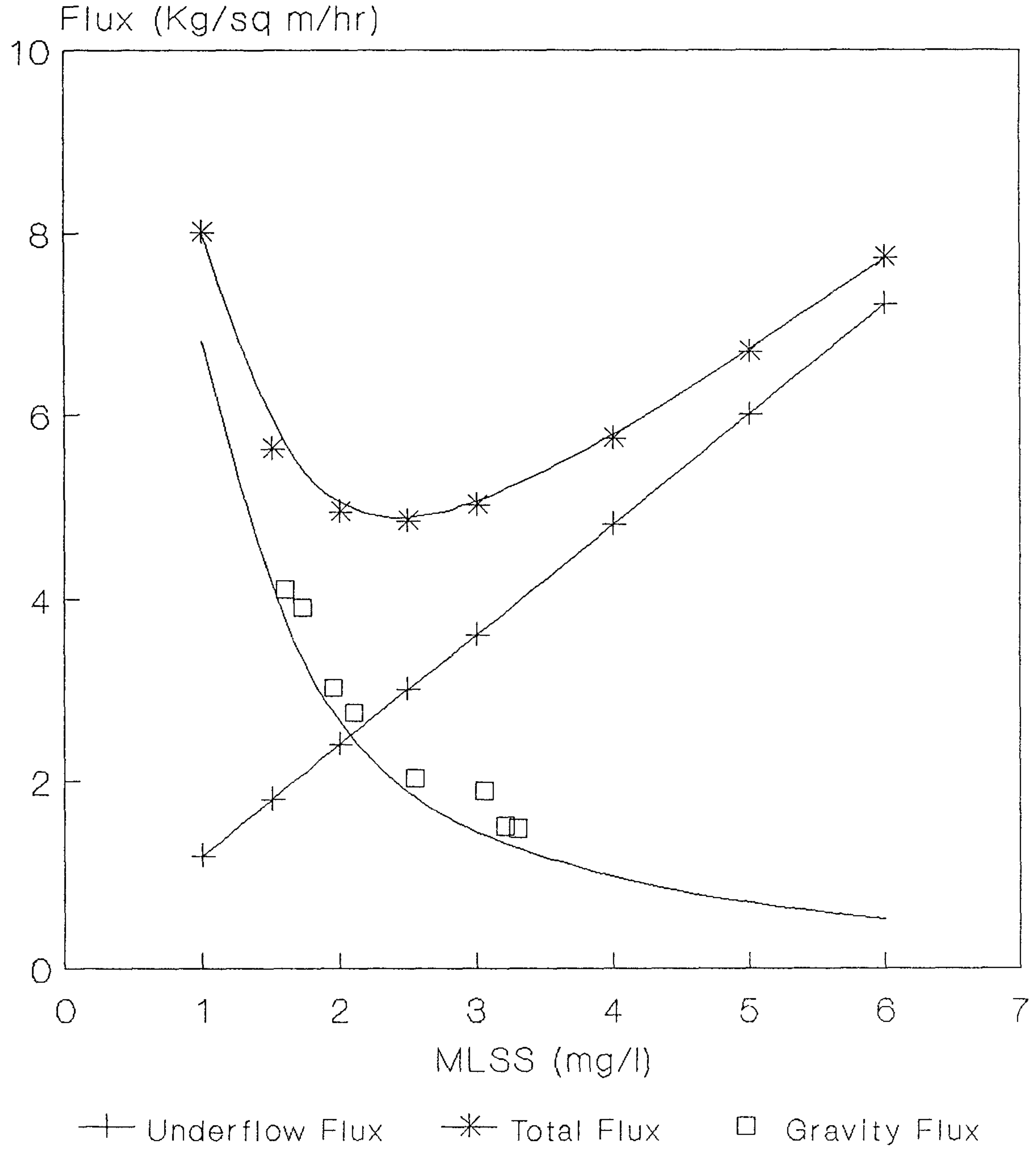

Figure 8 Solids-Flux Curves for
BOD:N = 100 in Wastewater and
Reactor with 4 Compartments

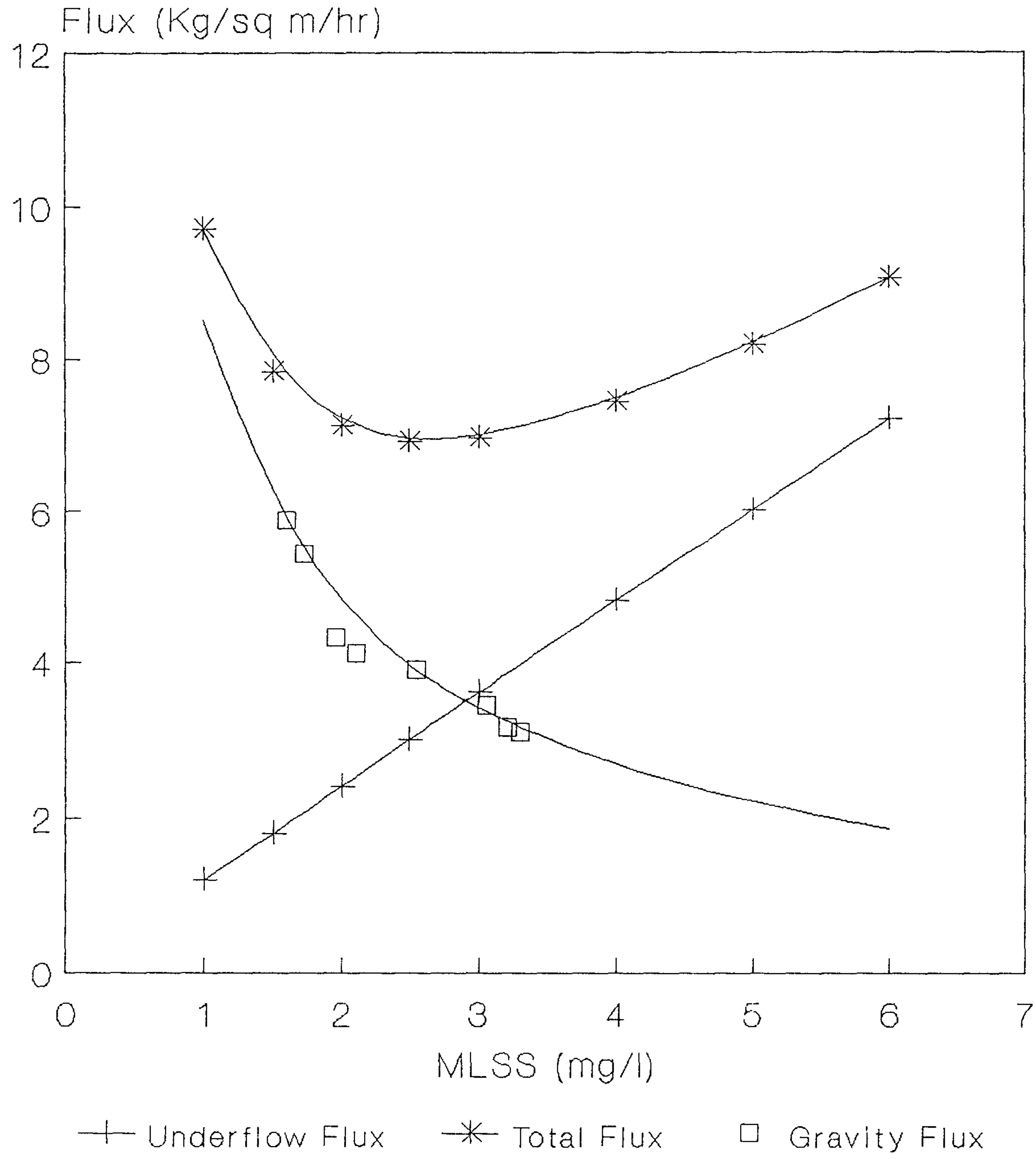

Figure 9 Solids-Flux Curves for
BOD:N = 100 in Wastewater and
Reactor with 6 Compartments

settling velocity (ZSV), which is shown in Figure 10, then a linear portion of a plot of natural logarithm of MLSS against natural logarithm of ZSV is conducted to determine the coefficient m and n, as seen in Figure 11. This method has been discussed previously.

Using the data of m and n, and the underflow velocity, which can be calculated by incorporating a solids mass balance through the secondary settling tank and equals to 2.0 cm/min in this study, we can calculate the corresponding value of the limiting solids-flux for various conditions based on Equation 3, which is shown in Chapter 3.

Table 3 The Results Derived from Mathematical model

				Limiting flux (Kg/m^2hr)	
Condition	Ln(m)	m	n	Mathematics	Plot
BOD:N = 20 Reactor without compartments	13.0	429348	1.50	8.1	8.5
BOD:N = 20 Reactor with compartments	18.4	95677577	2.08	11.8	12.0
BOD:N = 70 Reactor with compartments	14.2	1458250	1.61	10.2	10.5

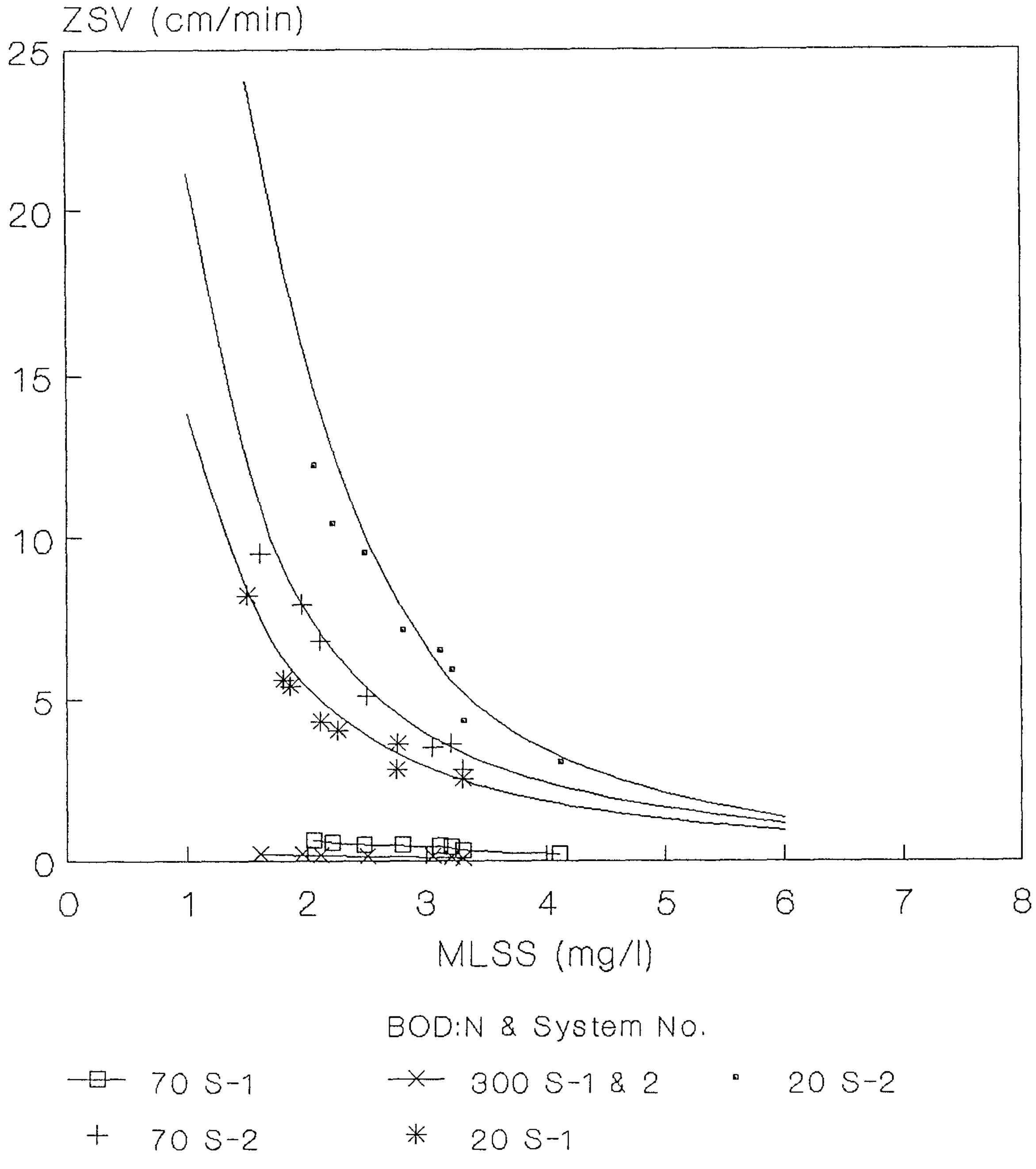

Figure 10 Zone Settling Velocity at Various Solids oncentration

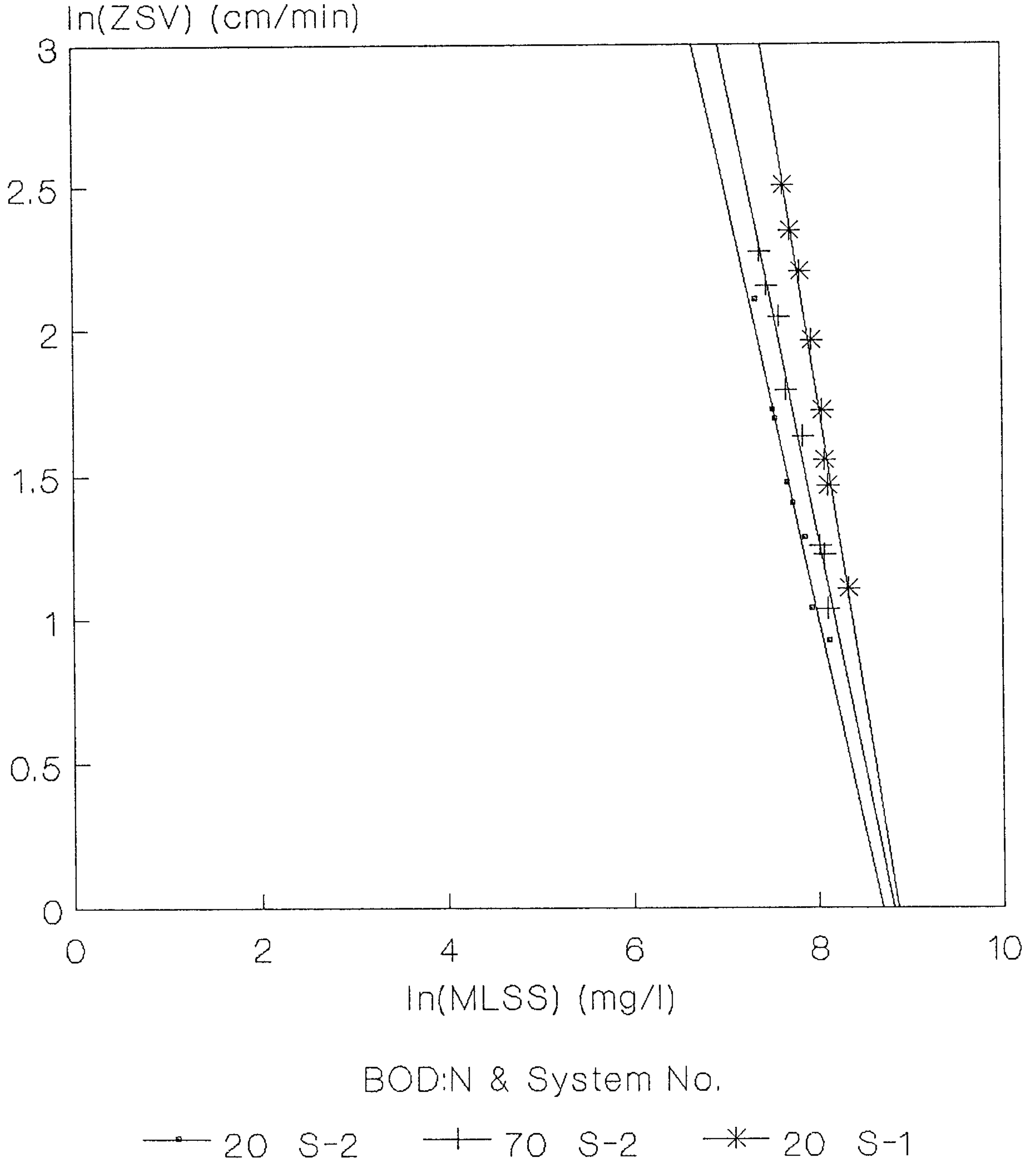

Figure 11 Natural Logarithmic Plot of ZSV vs MLSS

When using Equation 3, we must multiply this equation by unit constant, which is 0.0006 in this case when the unit of MLSS, ZSV and flux is, respectively, mg/l, cm/min and $Kg/m^2/hr$.

The results are shown in Table 3. Compared to the value derived from the plot procedure, the mathematical results are acceptable. The value of m and n can determine the limiting solids flux, therefore they also influence the shape of the total solids flux. Values of m shift the curve up or down. Higher n values yield steep total solids-flux curves while lower values generate flatter broad curves [12].

CHAPTER 5

CONCLUSIONS AND SUGGESTIONS

It was found in this study that well-flocculated good settling sludge was obtained in the nitrogen-rich system (BOD:N = 20:1), and also in the nitrogen-deficient system (BOD:N = 70:1) with the aeration tank divided into six compartments. In contrast, the poor settling sludge was found under the severe nitrogen limiting growth condition (BOD:N = 300:1), and also in the nitrogen-deficient system (BOD:N = 70:1) without any compartments in the aeration tank. The results indicate that the composition and settling characteristics of the activated sludge are a function of the wastewater condition and the aeration tank configuration.

In order to achieve good settleability for the activated sludge in the secondary sedimentation tank, the wastewater must contain sufficient quantities of degradable source of nitrogen. Normal domestic wastewater has nitrogen in excess, while certain industrial wastewater may well be nitrogen deficient (e.g. pharmaceutical, chemical, sugar beet processing). A BOD:N ratio of 100:5 is recommended to prevent bulking [13], which had also been proved in this study.

So it seems possible to improve the sludge settleability by using an aeration tank consisting of many compartments. Each compartment has its own aeration system and can be operated as a number of separate completely-mixed aeration tanks or in series to produce a plug flow configuration. However, alteration of the aeration tank configuration may be expensive, and for that reason it should be considered the final remedial action attempted in the control of bulking.

Finally, it is possible to develop a mathematical model to calculate the limiting solids flux of any activated sludge as long as the relationship between zone settling velocity and solids concentration can be found and expressed as an equation. The parameters in this equation can be determined experimentally and exactly represent the unique settling properties of specific activated sludge.

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