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GRAVITY THICKENING OF ACTIVATED SLUDGE

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Stephen W. Buckley

Peter Kos

Tsuan Hua Feng

Report for Division of Water Pollution Control
Massachusetts Water Resources Commission

Contract Number 73-07(3)



ENVIRONMENTAL ENGINEERING
DEPARTMENT OF CIVIL ENGINEERING
UNIVERSITY OF MASSACHUSETTS
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PREFACE

This report is to present the application of a mathematical model for continuous gravity thickening of sludge developed by Peter Kos to the thickening of activated sludge.

Mr. Peter Kos was a Graduate Research Assistant in the Department of Civil Engineering at the University of Massachusetts/Amherst and is currently employed by Dorr-Oliver, Incorporated, Stamford, Connecticut as a Research Engineer. Under the direction of Dr. Donald D. Adrian, Professor of Civil Engineering at the University of Massachusetts/Amherst, he developed a mathematical model describing the gravity thickening of flocculent suspensions being a fluid regime of channelling and compression similar to a filtration process through a deformable porous medium.

The experiments reported herein were performed by Mr. William L. Donovan and Mr. Stephen W. Buckley to fulfill a requirement for their respective Master of Science degrees in the Department of Civil Engineering at the University of Massachusetts/Amherst. Currently Mr. Donovan is a contact engineer with the Paramine Technical Division of Exxon Chemical, USA and Mr. Buckley a consulting engineer with S.E.A. Consultants, Incorporated, Boston, Massachusetts.

In their tenure as graduate students at the University, Mr. Kos was supported by an EPA Research Fellowship, No. U-910012 and both William L. Donovan and Stephen W. Buckley were supported by

an EPA Training Grant, No. T900179. All three also received supplementary financial aid from the Massachusetts Division of Water Pollution Control research grant, No. 73-07(3), for which Mr. John R. Elwood, Supervising Sanitary Engineer of the Division, served as the project officer.

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ABSTRACT

Continuous gravity thickening was examined for activated sludge samples, taken from the wastewater treatment pilot plant of the University of Massachusetts/Amherst. Data obtained from this study were evaluated using the mathematical model for continuous gravity thickening developed by Kos [11]. His model takes into account the thickening (consolidation) zone as well as the clarification zone.

Curves for the evaluation of the thickening capacity of the secondary sedimentation tanks (handling activated sludge from extended aeration process) were developed.

The effect of temperature on thickening performance was also determined. For winter conditions, 5°C, thickening area requirements were found to be 30 percent greater than those necessary for summer operation, 20.5°C. It is recommended that the design of secondary clarifiers be based on winter conditions.

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SECTION I - INTRODUCTION

The significant amount of water contained in sludges produced in the treatment of water, wastewater, and industrial wastes is of great concern today. With the increasing stringency of environmental quality standards, it would prove most practical and economical to be able to concentrate sludge prior to subsequent dewatering processes.

One process that concentrates or thickens sludge is known as gravity thickening. Gravity thickening of sludge is defined as a process by which particles, or aggregates of particles of dilute sludge, due to their greater specific gravity, settle through water and concentrate.

Besides reducing subsequent chemical and volumetric requirements in dewatering processes, gravity thickening is also an important consideration in the design of secondary clarifiers. Presently, the area requirements of secondary clarifiers are based on a surface loading rate of approximately 800 gal/ft²/day. This, however, is not enough for sufficient thickening of mixed liquor having sludge volume index in the range of 200-500 ml/gm. Thus, the calculations of area requirements should not be based solely on clarification data.

It seems obvious in the design of secondary clarifiers that their thickening function be evaluated in conjunction with their clarification ability. The surface loading rate is capable of evaluating the clarification process and its impact on the effluent quality. Area requirements for the accumulation of solids and the underflow concentration can only be evaluated on the basis of sludge consolidation.

I-1 Objectives

The objectives of this investigation were three-fold:

- 1) to apply Kos' mathematical model for continuous gravity thickening of sludge to activated sludge, and to compare results with those obtained by Kos [10] for water treatment sludge.
- 2) to develop curves for the evaluation of thickening of activated sludge.
- 3) to show the effect that temperature has on the performance of a continuous gravity thickener and secondary Sedimentation basins.

I-2 Gravity Thickening

Gravity thickening is a process which increases the concentration of solids by gravitational forces. There are basically two types of gravity thickening processes: batch settling and continuous settling.

Settling velocities are primarily examined in the process of batch thickening. Columns of various depths and diameters are employed but only columns of 1.5 - 7 ft. in height have proved representative. This process however enables only sedimentation or clarification properties to be evaluated.

Continuous gravity settling simulates a thickening chamber and is thus much more representative of the real operation. In studying the process of thickening, two types of continuous thickeners may be used: Laboratory columns varying from 0.5 - 2 ft. in diameter, and pilot plant thickeners, usually with diameters greater than 5 ft. Both types attempt to portray the real operation and therefore should have the same height as standard tanks.

I-3 Thickening of Non-flocculent Suspension

Evaluation of the depth of the thickening zone and the area

requirements are essential in the design of thickeners. Early studies were primarily concerned with the determination of area requirements. Coe and Clevenger [3] introduced the use of solids handling capacity and the concept that each concentration layer of a suspension has a certain capacity to transmit solids by:

$$C = \frac{u_i}{\frac{1}{c_i} - \frac{1}{c_u}} \quad (1)$$

where

C = the capacity of a suspension at concentration c_i , to transmit solids

u_i = the zone settling velocity of a suspension having concentration c_i , obtained from the linear portion at the beginning of the sedimentation curve

c_u = underflow concentration

The function $u_i = f(c)$ was attained by Coe and Clevenger from a series of settling tests using various initial solids concentrations. Various solids handling capacities may be obtained for a series of combinations of c_i and c_u . Critical in the design of the thickener area is the minimum solids handling capacity.

Work done by Kynch [12] was quite important as it was the basis of many further studies of thickening evaluation. Kynch carried out a theoretical analysis of concentration changes which can occur during sedimentation in a monodisperse suspension of rigid particles. From this he was able to demonstrate that the thickening process could be thought of as a propagation of density or concentration changes upward due to the downward movement of the solids. Depending on the continuity of the concentration gradient, the density or

concentration changes may be either finite or infinitesimal.

Talmadge and Fitch [18] employed the Kynch analysis of the movement of planes of constant concentration. From one batch settling curve (as opposed to multiple batch settling tests) they demonstrated that the settling velocity, which is a function of concentration, $u = f(c)$, determined from either multiple batch settling tests or the Talmadge-Fitch single batch settling test, the required thickening area can be obtained by using equation (1), or the graphical method developed by Yoshioka [20].

Richardson and Zaki [16], in a study of non-flocculent suspensions found for sedimentation properties that:

$$\frac{u}{u_0} = E^m \quad (2)$$

where

u = zone settling velocity of concentration, c

u_0 = settling velocity of a single particle

E = volume fraction of liquid

m = constant

was the best relationship between settling velocity and concentration. Rearranging equation (2), we obtain

$$u = u_0 (1 - sc)^m \quad (3)$$

where

c = concentration of suspended solids

s = reciprocal of density of solids

I-4 Thickening of Flocculent Suspensions and Real Sludges

In the treatment of water, wastewater, and industrial wastes, real sludges or slurries are encountered and their behavior varies greatly from suspensions of monodisperse particles. Many articles discussed these differences, for example, [4], [5], [6], [7], [8], and [13].

Figure 1 shows the difference in behavior between non-flocculent and flocculent suspensions. The basic difference lies in the fact that for higher concentrations, flocculent suspensions enter into a state of channelling and compression, while this does not apply to the non-flocculent suspension. Nomenclature for these flocculent suspensions has been inconsistent (see [5] [7] and [8]). Channelling and compression have sometimes been used interchangeably. Generally accepted is that the lowest range of compression is referred to as channelling.

The distribution of concentrations in the continuous thickener was published in references [4], [7], [8]. Flocculent suspensions of sludge form two separate zones. The top zone is the sedimentation zone. The lower zone is the thickening zone.

It is the zone of thickening that must be evaluated for the determination of thickener area. Thus, it is more important to study the channelling and compression characteristics as opposed to the sedimentation characteristics in the continuous thickener.

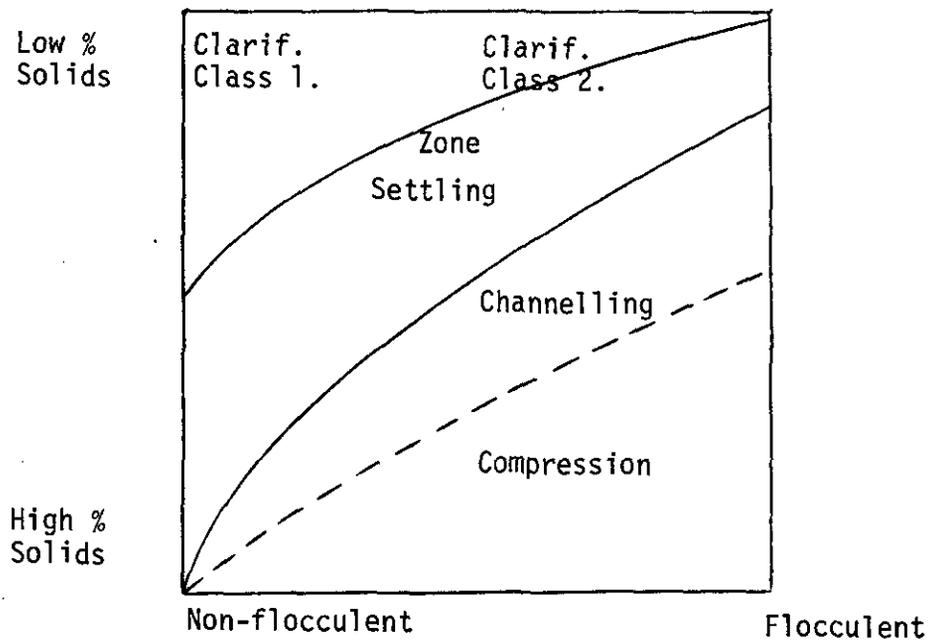


FIGURE 1. DIFFERENT BEHAVIOUR OF NON-FLOCCULENT AND FLOCCULENT SUSPENSIONS.

I-5 Channelling and Compression

Many equations have been developed to describe the phenomena of compression during the thickening process. An equation by Roberts [17] shows that:

$$dD/dt = k' (D - D_{\infty}) \quad (4)$$

or

$$D - D_{\infty} = (D_c - D_{\infty})e^{-k't} \quad (5)$$

where

D = dilution (mass ratio of fluid to solids)

D_c = dilution at point of compression

D_{∞} = dilution at final point

t = time

k' = constant of proportionality

Expanding upon equation [5], Tory and Shannon [19] published the Deer-Roberts-Yoshioka equation in the form:

$$\frac{dz}{dt} = (\bar{k}/c_i z_i) (z - z_{\infty}) \quad (6)$$

or in the form

$$z/c_i z_i - z_{\infty}/c_i z_i = (z_c/c_i z_i - z_{\infty}/c_i z_i)e^{-\bar{k}(t-t_c)/c_i z_i} \quad (7)$$

where

z = height of the sludge - liquid interface at time t

t = time

\bar{k} = constant of proportionality

c = solids concentration

subscripts

i = initial

∞ = final value

c = value at point of compression

Several authors have presented comparisons between these equations and the drop of the sludge - liquid interface during the tests of batch and continuous thickeners. Larian and Forest (see Behn [1] [2]) developed a method for calculating the depth at the compression part of the thickening zone based on a batch test. Assuming the volume of the compression zone, divided by the area calculated by the Talmadge-Fitch method, they determined the depth of the compression zone.

These equations have not proved adequate. Due to assumptions and simplifications the interface curves cannot describe the thickening process and the effects due to pressure and slow stirring. Konicek et al [9] have shown that the velocities of relative motion of solids and liquids in the channelling and compression stages during continuous thickening are functions of concentration and pressure from the upper layer of sludges.

I-6 Model Describing Thickening as Consolidation

Kos [11] has recently developed a mathematical model describing the gravity thickening process of flocculent suspensions being in channelling and compression. Using general equations developed by Raats [14] for porous media, he viewed the thickening process as a filtration process through a deformable porous medium. The basic concept on which the model depends is the nature of solid

particles. The solid particles in the flocculent suspension are not separate in nature but rather form an agglomeration of particles due to their large surface area and attractive forces.

In the continuous gravity thickening process, the sludge is fed into the top of the thickener. Upon entering this sedimentation zone, the solid particles create flocs and settle down to the top of the thickening zone. As the flocs build up at the top of the thickening zone, they lose their individual characteristics and form a porous solids matrix. As sludge continues to build, a pressure, due to their weight is transmitted through the matrix to the bottom of the thickening zone. Pressure transmitted through this interparticle contact is termed effective pressure, σ . As the matrix of solids is compressed downwards, the water is squeezed or forced upward through the solids matrix.

The model developed by Kos is applicable to both batch and continuous thickening. However, the theory discussed herein will focus on the steady-state continuous thickening process.

In the steady-state operation of the gravity thickening process, the following parameters are held constant: L_s , the suspended solids loading; and Q_u , the rate of underflow. Striking mass balances for the solid and liquid phases, respectively, it is found that

$$G_s = \rho_s v_s = \text{constant} \quad (8)$$

$$G_l = \rho_l v_l = \text{constant} \quad (9)$$

where

G_s = mass flux of solid phase

G_l = mass flux of liquid phase

v_s = velocity of solids

v_l = velocity of liquid

ρ_s = bulk mass density of solids

ρ_l = bulk mass density of liquid

Equations (8) and (9) can be expressed in terms of flows and concentrations as follows:

$$G_s = \frac{Q_u C_u}{A} \quad (10)$$

$$G_l = \frac{Q_u C_u}{A} \left[\frac{1}{C_u} - \frac{1}{d_s} \right] d_l \quad (11)$$

where

A = tank area

d_l = density of liquid

d_s = density of solids

Q_u = rate of underflow

The velocities of both the solid phase and the liquid phase, v_s and v_l , respectively may be related to flow rate and concentration. The superficial velocity, $(v_s - v_l)n$, which is equivalent to the zone settling velocity, now has the form:

$$(v_s - v_l)n = \frac{Q_u C_u}{A} \left[\frac{1}{C_i} - \frac{1}{C_u} \right] = G_s \left[\frac{1}{C_i} - \frac{1}{C_u} \right] \quad (12)$$

where

n = porosity

Using this equation, the superficial velocity may now be

determined for any concentration c_i within the thickening zone.

Utilizing momentum balances on both the solid and liquid phases, the pressure distributions throughout the thickening zone may be developed. The force balance for the liquid phases, after neglecting the force due to inertia, may be expressed as a variation of Darcy's law:

$$dp/dx = d_l g_x + \frac{\mu}{k} (v_s - v_l)n \quad (13)$$

where

d_l = density of liquid

g_x = gravitational acceleration

μ = dynamic viscosity

$(v_s - v_l)n$ = superficial velocity

k = Intrinsic conductivity

Considering now the force balances for the solid phase and the liquid phase, the following relationship between effective and liquid pressure, within the sludge layer, to that of total pressure can be developed:

$$\frac{d\sigma}{dx} + \frac{dp}{dx} = g_x (\rho_l + \rho_s) \quad (14)$$

or

$$\sigma(x) + p(x) = g_x \int_0^x (\rho_l + \rho_s) dx \quad (15)$$

i.e. effective liquid total
pressure + pressure = pressure

It was found convenient to measure and express the quantity $\bar{\sigma}_T$,

as the difference between total and hydrostatic pressure, and \bar{p} , as the difference between liquid (piezometric) and hydrostatic pressure. Thus, the true, effective pressure transmitted by the solids matrix is determined by:

$$\sigma(x) = \bar{\sigma}_T(x) - \bar{p}(x) \quad (16)$$

The mathematical model developed by Kos requires the definition of a constitutive equation of the solid phase. For the effective pressure distributions throughout the thickening zone the non-linear relationship between stress and strain was determined to be quite satisfactory. The modulus of linear compressibility, a , may be expressed by:

$$a = d\rho_S/d\sigma \quad (17)$$

Due to the nonlinearity of the $\sigma - \rho_S$ relationship the modulus of linear compressibility is a function of the concentration of the solid phase, ρ_S . Thus:

$$a = a(\rho_S) \quad (18)$$

Together, Equations 13, 14, 12, and 18 completely describe steady-state continuous gravity thickening. With the aid of a computer and numerical analysis the steady-state continuous gravity thickening equations can be solved, and the desired information can be generated for continuous thickening.

I-7 Summary

Using the Kos model, concentration and pressure distributions with respect to depth of the thickening zone of a continuous thickener can be calculated. In order to accomplish this, two physical characteristics of sludge must be determined. They include:

- a) the intrinsic or hydraulic conductivity which is a function of local concentration of solid phase, $k = k(\rho_s)$ or $k = k(c)$
- b) the modulus of linear compressibility which is also a function of concentration of solid phase, $a = a(\rho_s)$ or $a = a(c)$

The intrinsic conductivity characterizes the filtration properties of porous medium (filtration properties of sludge in our case), and the modulus of linear compressibility characterizes the consolidative properties of the matrix of solids. These two properties will be specific for each particular sludge. After determining these characteristics, the pressure and concentration distributions within the thickening zone can be simulated for any set of operating conditions.

SECTION II - MATERIALS AND EQUIPMENT

The activated sludge used in this study was taken from the University of Massachusetts/Amherst wastewater treatment pilot plant in Amherst, Massachusetts. A general description of the pilot plant system, the sludge characteristics, and the equipment used for analysis follows.

II-1 Pilot Plant Facility

The activated sludge process of the University of Massachusetts wastewater treatment pilot plant is an extended aeration system. The aeration basin and settling tank have the following characteristics:

a) Aeration Basin	Length	17'4"
	Width	6'
	Height	9'
	Volume	935 cu ft 7000 gallons
b) Settling Tank	Depth	8'3"
	Diameter	6'
	Surface Area	28.3 sq ft
	Capacity	1783 gallons
	Surface Loading	247 gal/sq ft/day

The daily flow averaged 7000 GPD, or 4.86 GPM.

II-2 Sludge Characteristics

The characteristics of the studied sludge were predetermined by the performance of the activated process which is summarized in the Table 1. Based on the average BOD loading of 7.5 lb/day the food-to-microorganism ratio (F/M ratio) was found to be 0.057. Literature shows that for the 24 hour extended aeration system F/M ratio

TABLE 1
PERFORMANCE OF EXTENDED AERATION UNIT*

	<u>Influent</u>	<u>Tank</u>	<u>Effluent</u>
Temperature		22 ⁰ C	
MLSS		2740 mg/l	
MLVSS		2270 mg/l	
Flowrate	5 GPM		
pH	7.4		
Settleability (30 min)		80 ml/l	
SVI (30 min)		110 ml/gm	
Dissolved Oxygen		4.7 mg/l	
Turbidity	35 JTU		10 JTU
Phosphorous	4.2 mg/l		4.2 mg/l
NH ₃	18.1 mg/l		2.0 mg/l
Alkalinity	140.5 mg/l CaCO ₃		3.5 mg/l CaCO ₃
BOD	125 mg/l		16 mg/l
Density of Solids(d _s)		1.4764 g/ml	

*Average Values

values range from 0.05 - 0.20. Thus, this system is near the lower end of the range.

The sludge used for the thickening experiments was drawn directly from the aeration basin. The average value of the concentration of MLVSS was 2270 mg/l. This concentration was adjusted as to our needs throughout the period of experimentation. This simply required either dilution with effluent or concentration by settling with subsequent withdrawal of supernatant.

In order to use the mathematical model developed by Kos, the parameter, density of solids, d_s , had to be experimentally determined. Utilizing a pycnometer and gravimetric analysis, Figure 2 shows a straight line relationship between density and suspended solids concentration. The best fit line was determined by the linear regression method. Having this straight line relationship, the density of solids, d_s , can be determined from:

$$d_s = \frac{c_i d_1}{c_i + d_1 - (d_{s1})_i} \quad (19)$$

where

d_s = density of solids

c_i = suspended solids concentration

d_{s1} = density of sludge having concentration c_i

d_1 = density of water

For this particular sludge, the density of solids, d_s was found to be 1.4764 g/ml (See Appendix II-II(f) for calculation).

II-3 Equipment

Batch settling tests were studied in columns of 2, 1.5, 1.0,

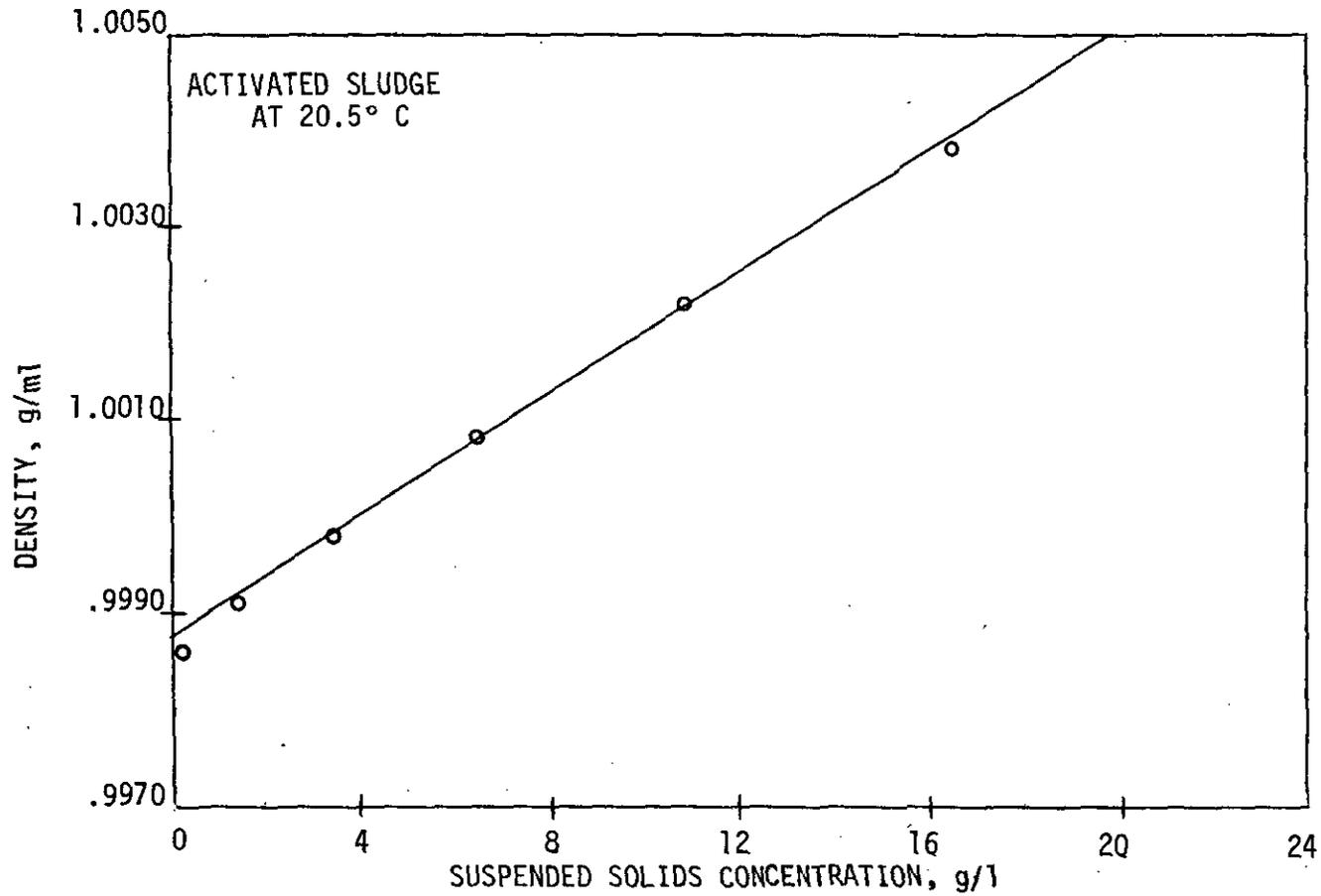


FIGURE 2. DENSITY OF SLUDGE AS A FUNCTION OF SUSPENDED SOLIDS CONCENTRATION

0.75, and 0.5 meters in height. The inside diameter for these columns was 13.8 cm (5-7/16 inches). Figure 3 displays these five columns.

Continuous thickening was examined in a thickener designed by Kos [10] [11] for his study of the thickening process. Figure 4 is a schematic diagram of the unit used.

The plexiglass column, Figure 5, has an inside diameter of 29 cm (11.5 inches) and a total height of 253 cm (8.5 ft). Sampling ports, used in determining the concentration profile, were placed at 10 cm intervals.

The piezometric and the total pressure distribution could, theoretically, be measured by a series of piezometer columns. Such a simple arrangement would not, however, be capable of measuring the minute values of effective pressure (by difference) within the sludge layer. In order to measure the small pressures of interest, the pressures were electronically amplified by a "Statham Low Pressure Accessory" (SLPA) which is capable of pressure measures in the range zero to 0.1 psi. So that the SLPA measured \bar{p} and $\bar{\sigma}_T$, pressures (i.e. eliminated the "masking effect" of hydrostatic pressure), it was placed a few millimeters below the water level of the laboratory thickener. Thus the datum of pressure measurement was then level of the SLPA and only the portion of pressures above this datum was measured.

In order to obtain pressure distributions with respect to thickener depth, the SLPA was connected by tygon tubing to a series of ports, spaced 10 cm (vertical distance) apart along the length of the column.

As there is a solid phase in the column and its intrusion into the tubing would cause erroneous measurements, "separation cells" were placed between ports and tubing (see Figure 7 for "separation cell" details).

The feed tank was a 55 gallon drum, which, with the use of an electric stirrer, maintained a constant inflow concentration.

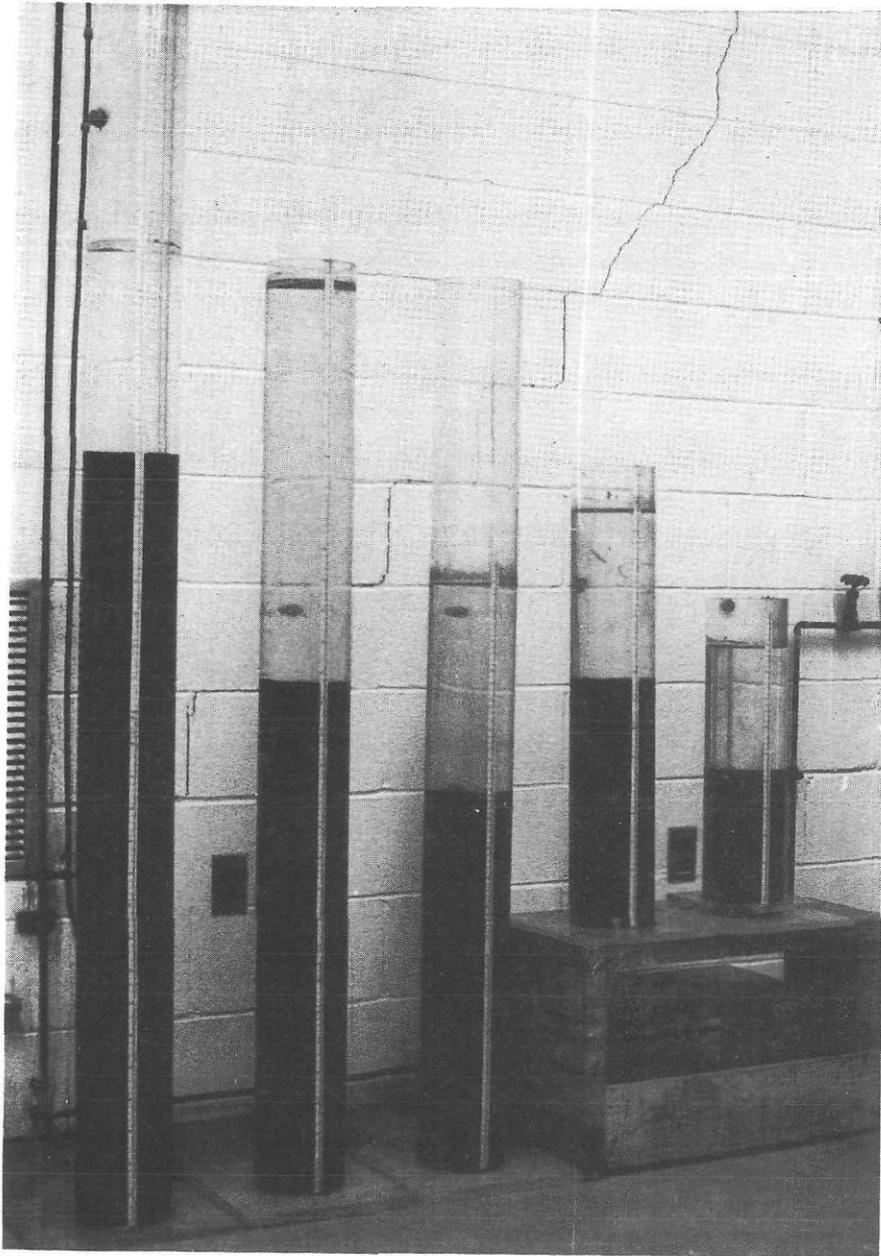
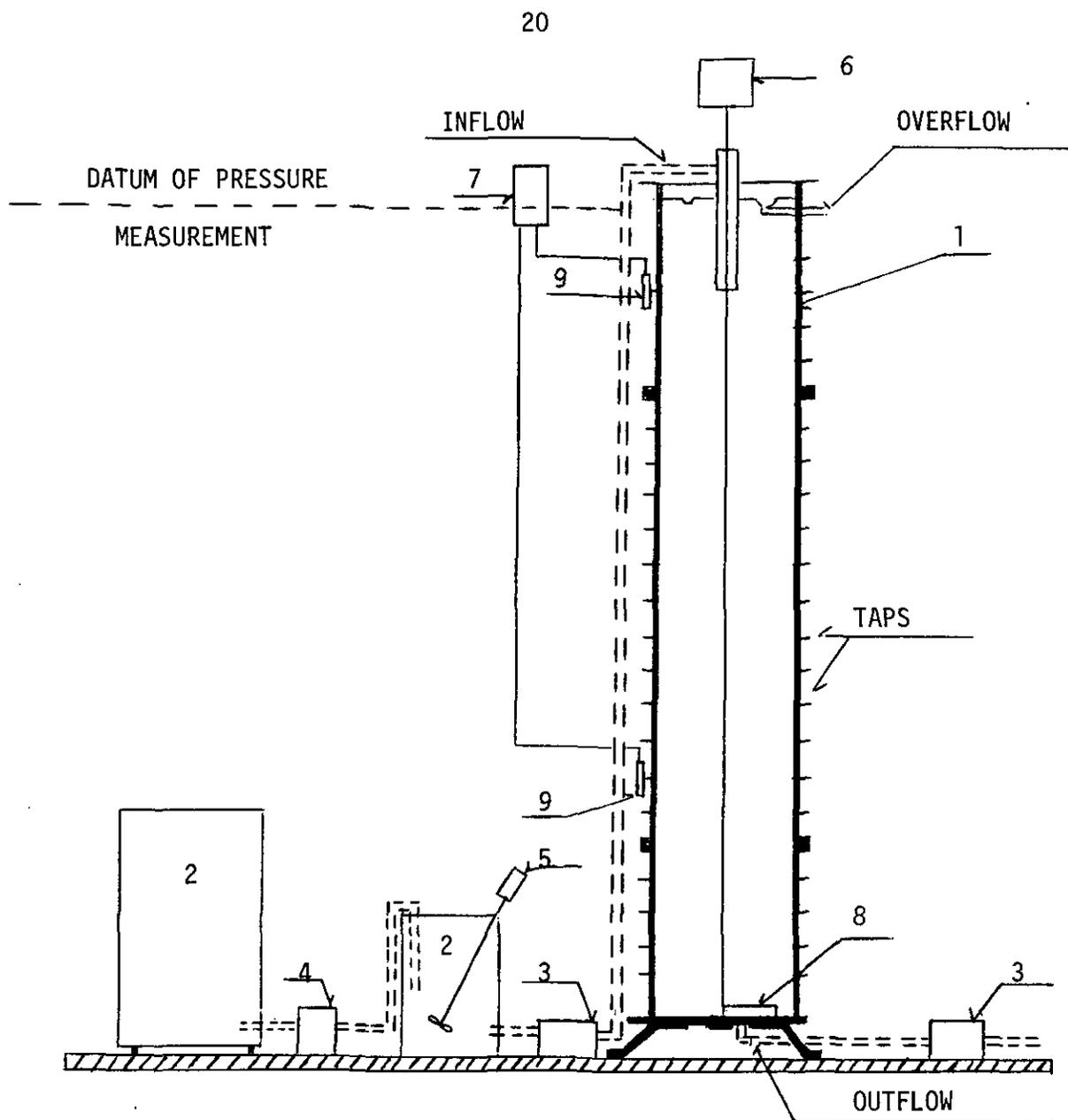


FIGURE 3. BATCH SETTLING COLUMNS



- 1 COLUMN ID = 11 1/2 in, LENGTH 8 1/2 ft
- 2 STORAGE TANKS
- 3 DOSING PUMPS
- 4 TRANSPORT PUMP
- 5 STIRRING IN TANK
- 6 DRIVE OF THE RAKE
- 7 MEASUREMENT OF THE PIEZOMETRIC AND THE TOTAL PRESSURES BY MEAN OF "STATHAM LOW PRESSURE ACCESSORY"
- 8 RAKE
- 9 SEPARATION CELL

FIGURE 4. LABORATORY CONTINUOUS THICKENER - SCHEMATIC DIAGRAM.

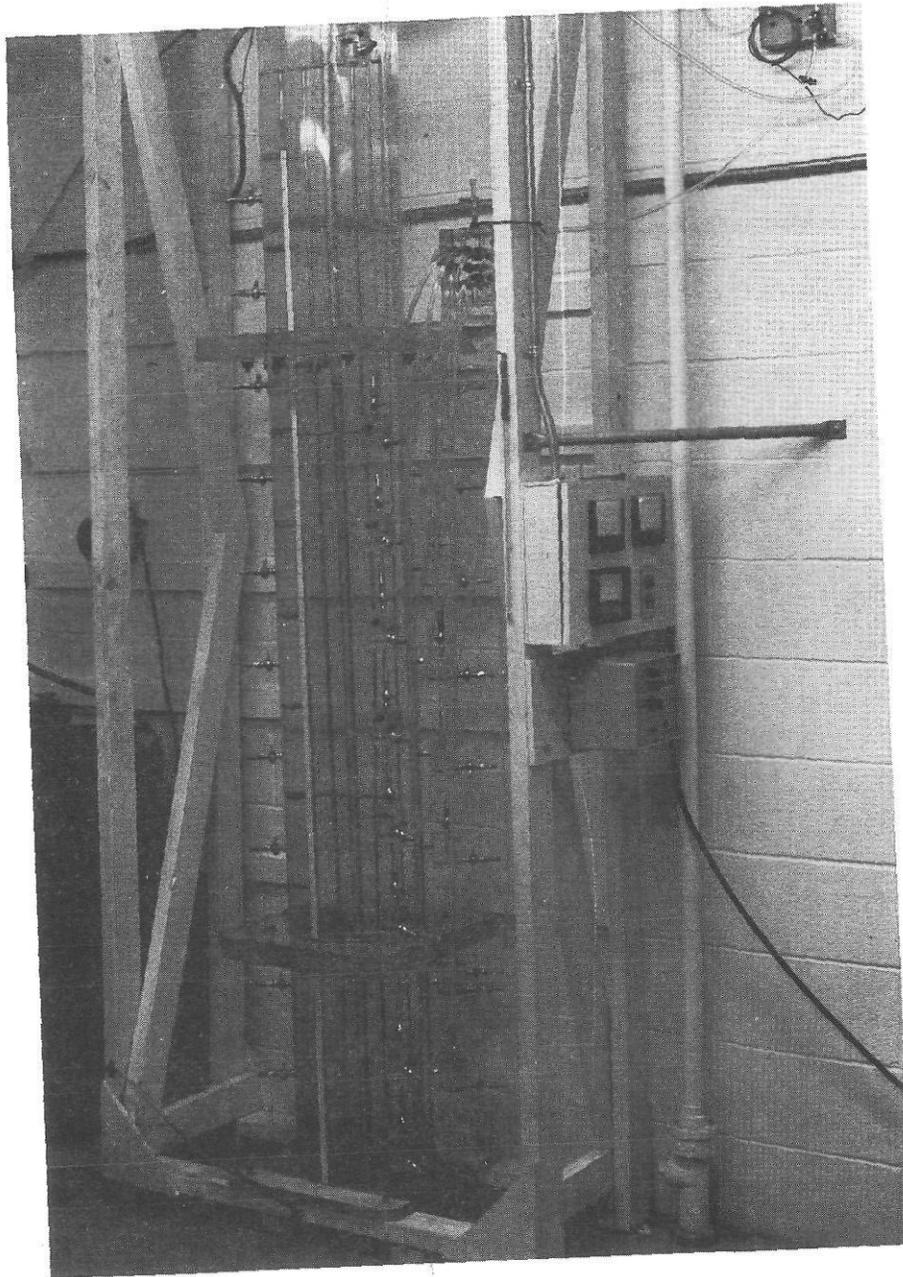


FIGURE 5. LABORATORY CONTINUOUS THICKENER

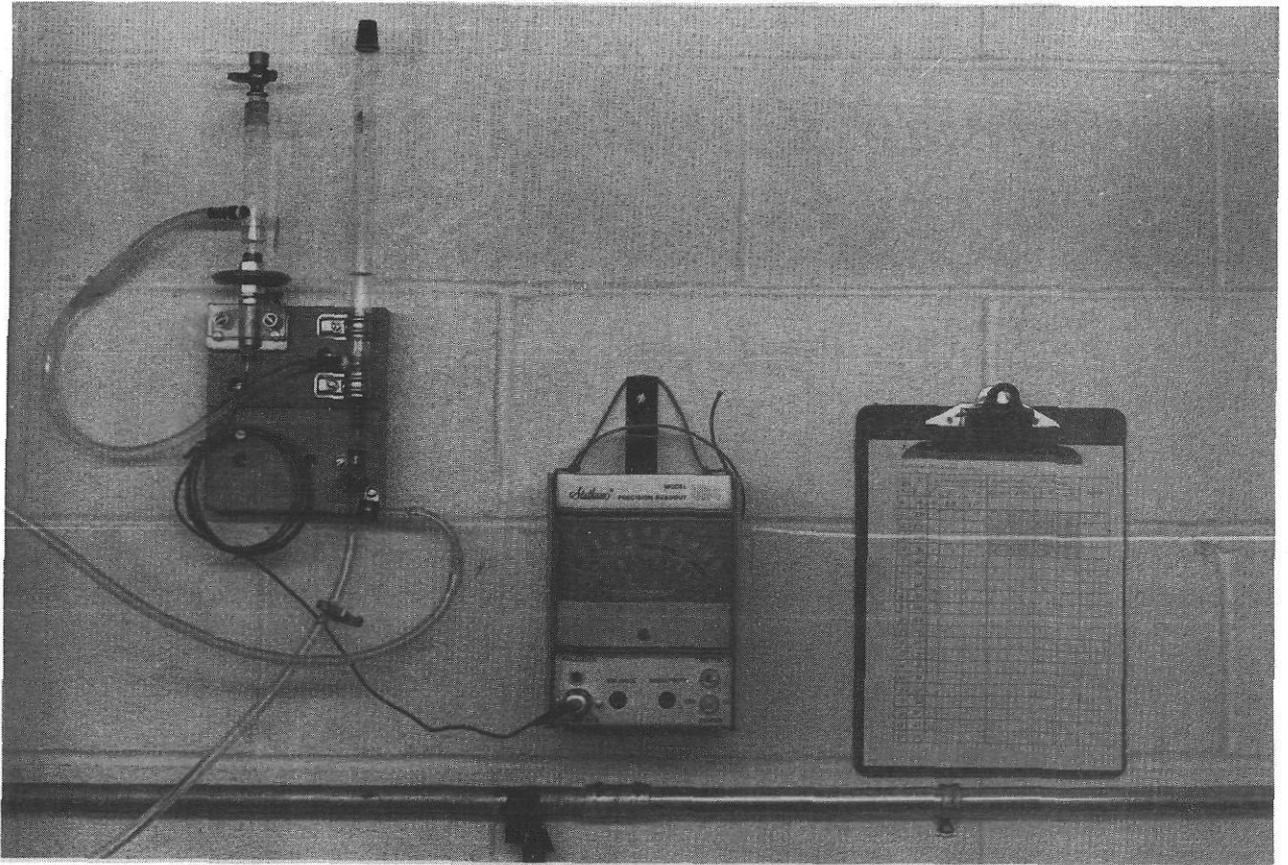


FIGURE 6. STATHAM LOW PRESSURE ACCESSORY WITH READOUT.

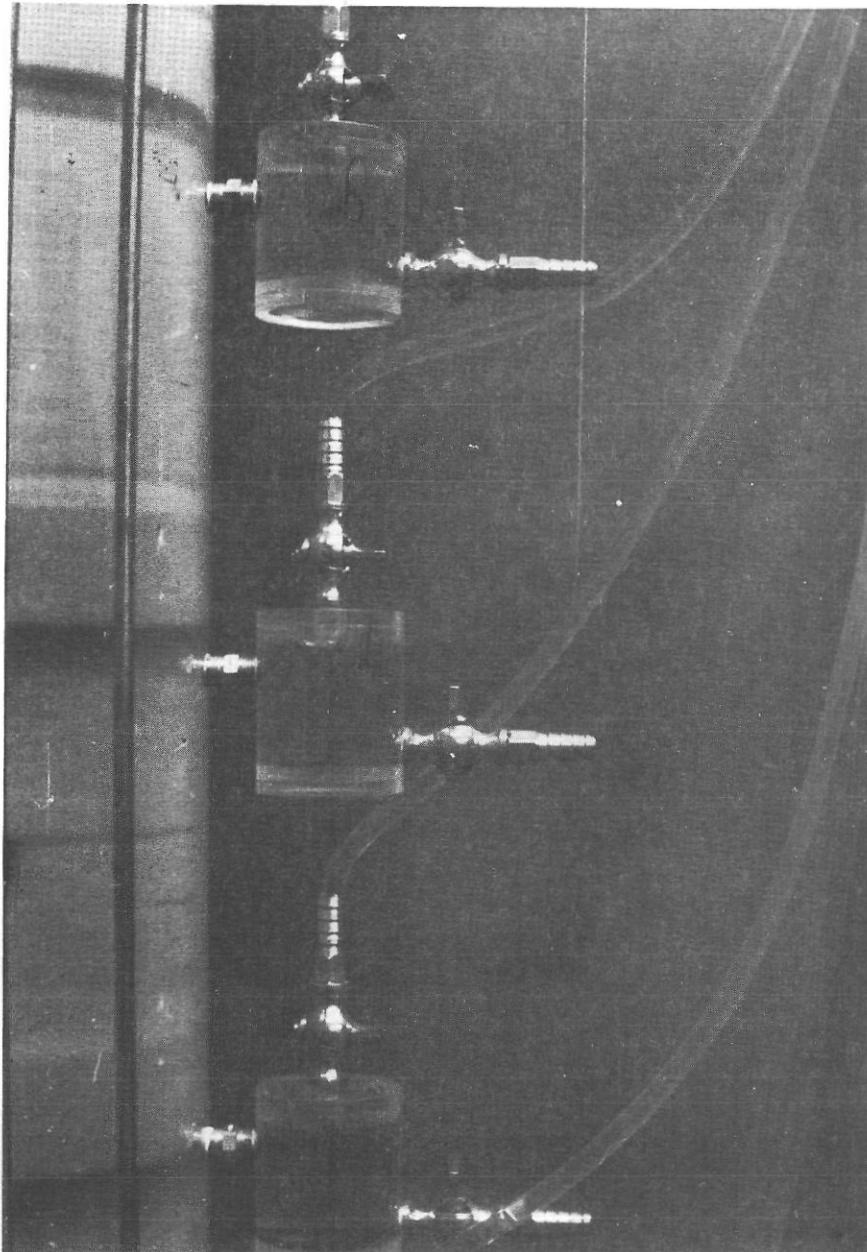


FIGURE 7. SEPARATION CELLS.

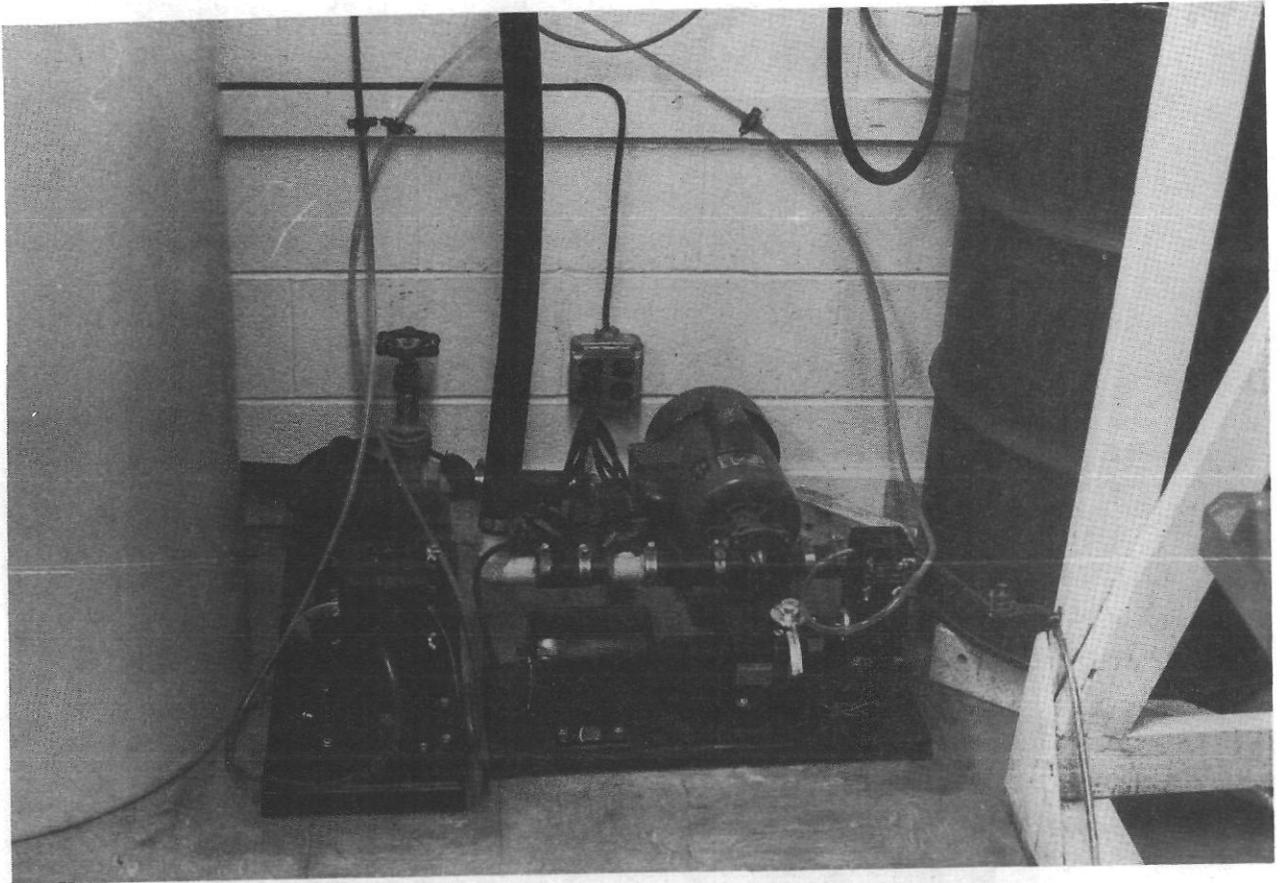


FIGURE 8. SIGAMOTOR PUMPS

The apparatus was equipped with inflow, overflow, and underflow lines. The rates of inflow and underflow were controlled with Sigamotor pumps, as pictures in Figure 8.

The material cost of the equipment was approximately \$6000. An additional sum of \$5000-\$6000 was required to install and assemble the apparatus. Mulcahy et al [14] described the construction of the apparatus in detail.

SECTION III - EXPERIMENTAL PROGRAM

III-1 Experimental Procedure

III-1.1 Batch Thickening

The settling characteristics of the activated sludges having suspended solids concentrations ranging from 3.0 to 10.6 g/l were observed in batch thickeners. As the sludge was settling, the time and the height of the solids - liquid interface were recorded. For lower initial solids concentrations (those from the zone settling concentration range), the increasing height of the compacted solids was noted. It was later that channelling occurred as some of the suspended solids concentration reached 8.5 g/l or higher.

The total and suspended solids concentrations were determined by gravimetric analysis. The temperature during the experiment was also noted.

III-1.2 Continuous Thickener

Operation of the laboratory continuous thickener consisted of feeding a sludge of known concentration of suspended solids (c_{in}) into the thickener at a chosen solids loading rate, (L_s), and drawing an underflow at a chosen concentration, (c_u).

The overall mass balance was found to be:

$$Q_{in}c_{in} = Q_u c_u + Q_o c_o \quad (20)$$

where

c_{in} = inflow suspended solids concentration

Q_{in} = rate of inflow

c_u = underflow suspended solids concentration

Q_u = rate of underflow

c_o = overflow suspended solids concentration

Q_o = rate of overflow

Assuming the overflow concentration, c_o , to be negligible, the rate of underflow can be determined from:

$$Q_{in}c_{in} = Q_u c_u \quad (21)$$

Similarly, by striking a mass balance, the solids loading rate, L_s , was determined as:

$$L_s = Q_{in}c_{in} \quad (22)$$

where

L_s = chosen loading rate of suspended solids

c_{in} = suspended solids concentrations of feed

Q_{in} = flowrate of feed

Given the solids loading, the concentration of the feed and the underflow concentration, the rate of the underflow can then be determined, from equation 21. Since the estimation of L_s and c_u requires an experience, the procedure for the specific startup procedure and the method for estimating initial values of L_s and c_u recommended by Mulcahy et al [14] was followed.

The continuous thickening process was conducted and the height of the solid-liquid interface was observed until it leveled off

and held constant. For lower solids loading rates, it generally took 2 to 3 days to reach a steady-state condition. When the system was at a steady-state condition, profiles of the total pressure, (σ_T), piezometric pressure (\bar{p}), and suspended solids concentration were taken. A mass balance of suspended solids will show whether or not the system has reached equilibrium. It is recommended that one keep the system at equilibrium and obtain the profiles in duplicate. For specific procedures in attaining the profiles see Mulcahy et al [14].

The continuous thickener was operated for the period of six weeks. During this period four different steady state conditions were established and measured. Much more steady states conditions could be obtained during that period, but problems connected with the operation of the activated sludge unit disturbed a few times the measurement.

III - 2 Analysis of Data

III - 2.1 Batch Thickening

For each concentration studied a plot of interfacial height (cm) versus the time (min) was constructed for each of the five columns. For each column the zone settling velocity maximum slope is graphically determined (See Figure 9). Then the average zone settling velocity, the average of the settling velocities of a sludge sample in various columns, for each suspended solids concentration is determined. Should erroneous results occur from the shorter columns, they may be omitted.

A plot of the average zone settling velocity versus suspended solids concentration is constructed. The best fit line through these points was determined to be:

$$u = u_0 \left(1 - \frac{c}{d_s}\right)^m \quad (23)$$

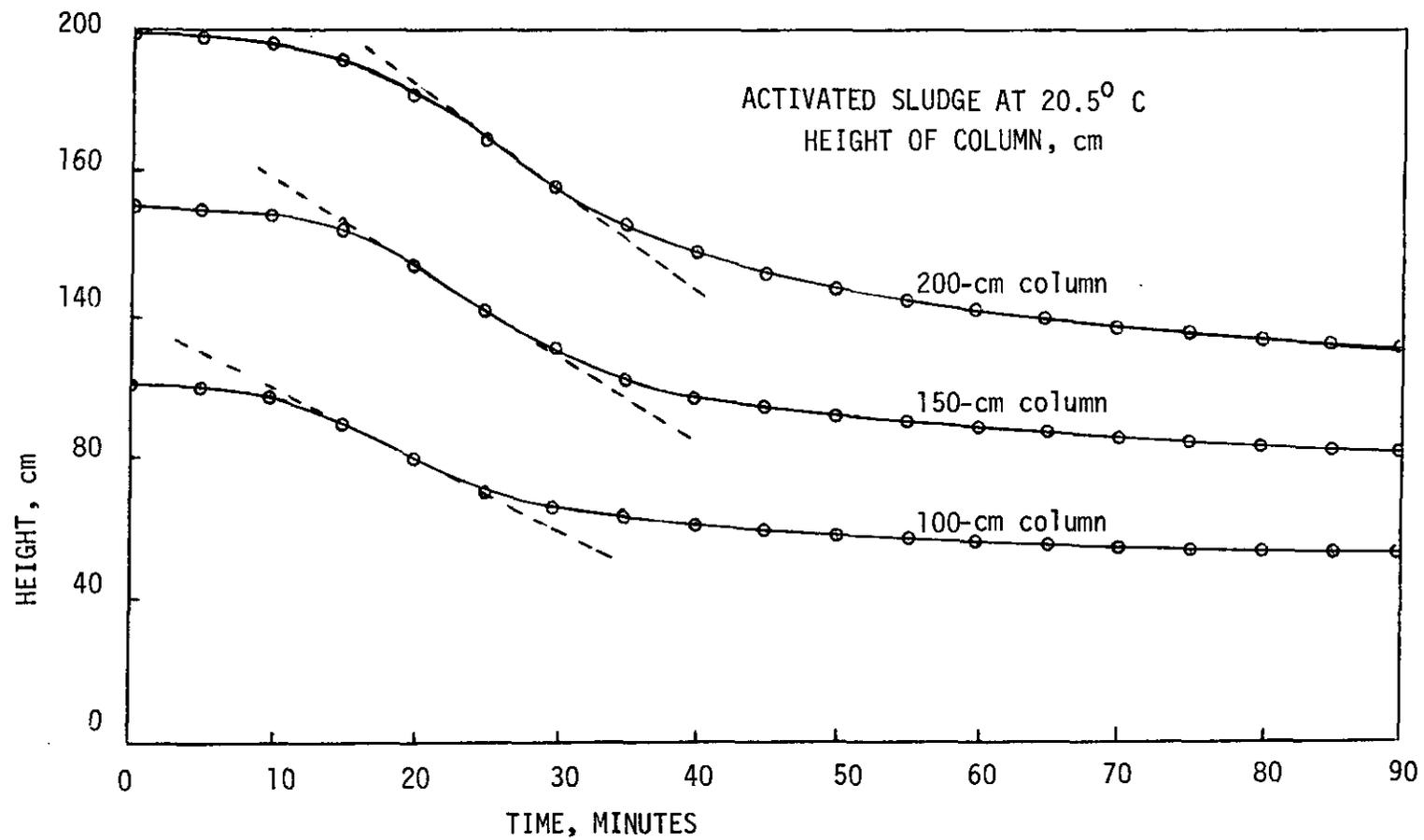


FIGURE 9. HEIGHT OF SOLID - LIQUID INTERFACE AS A FUNCTION OF TIME

where

u = zone settling velocity of concentration, c

u_0 = zone settling velocity of a single particle

c = suspended solids concentration

d_s = density of solids, 1.476 g/ml

m = constant

Figure 10 shows the average settling velocities versus suspended solids concentrations and the resulting best fit line.

From Figure 10, the fitted curve will generate values of u , zone settling velocity, for a specified suspended solids concentration. The plot of the product ($u \cdot c$) or the solids flux, G_s , versus suspended solids concentration, can now be developed (see Figure 11). Since the zone settling is limited for the concentration range from ~ 2 g/l up to 8.5 g/l the curves in Figure 10 and Figure 11 are not valid beyond the concentration 8.5 g/l. Figure 11, solids flux versus suspended solids concentration, is used in the conventional method, based on batch settling curves, for the analysis of the thickening process.

III - 2.2 Continuous Thickening

The mathematical model developed for channeling and compression by Kos describes gravity thickening from the consolidation point of view. This requires the measurement of parameters other than those commonly considered important. These are the distribution of piezometric pressure, effective (inter-particle) pressure, and concentration distribution with depth of the thickened sludge. The measurement of these parameters enables filtration and consolidation characteristics of a particular sludge to be established. Utilizing the mathematical model, it is possible to evaluate the performance of continuous gravity thickeners and the thickening ability of secondary settling tanks.

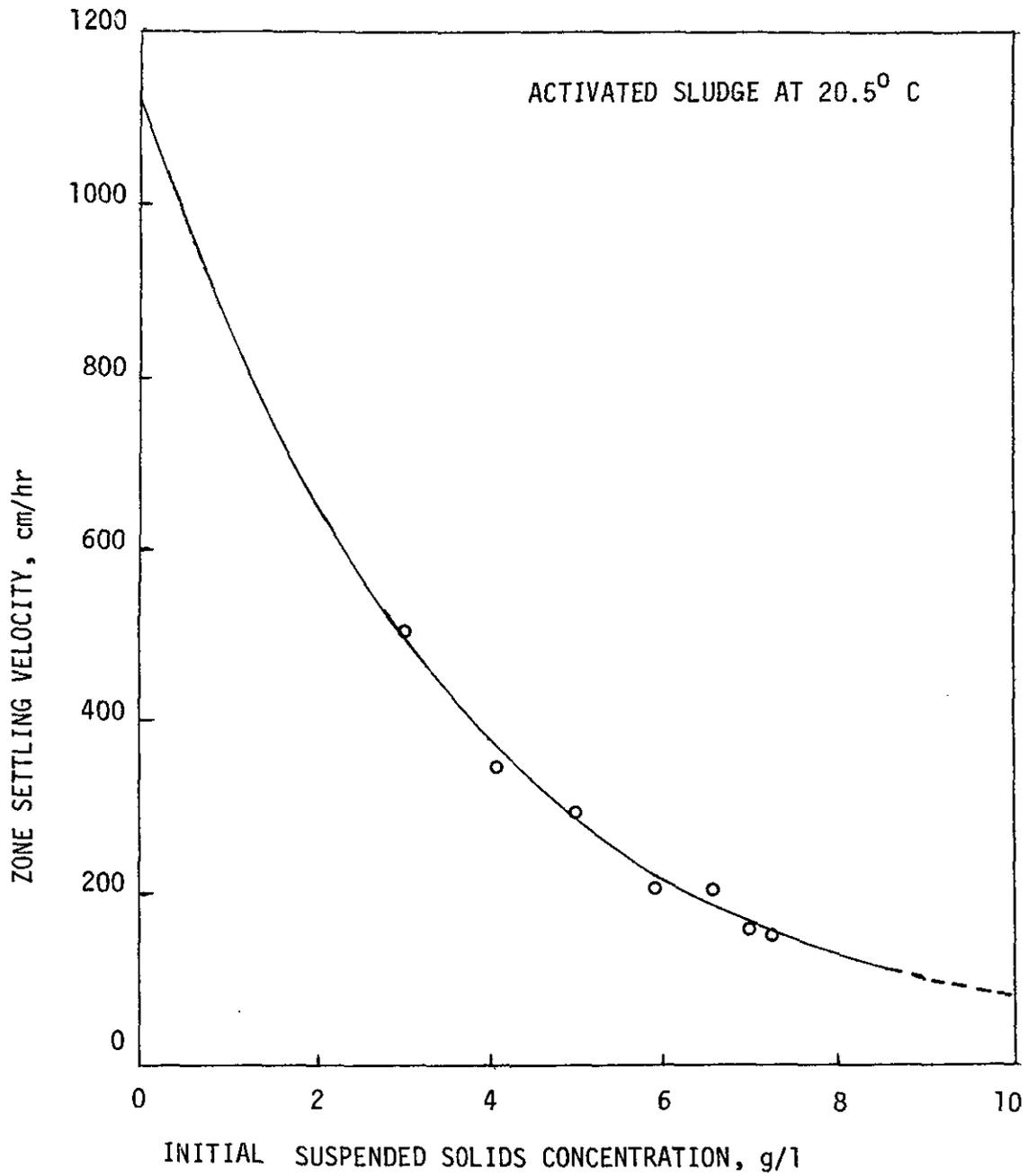


FIGURE 10. ZONE SETTLING VELOCITY AS A FUNCTION OF SUSPENDED SOLIDS CONCENTRATION

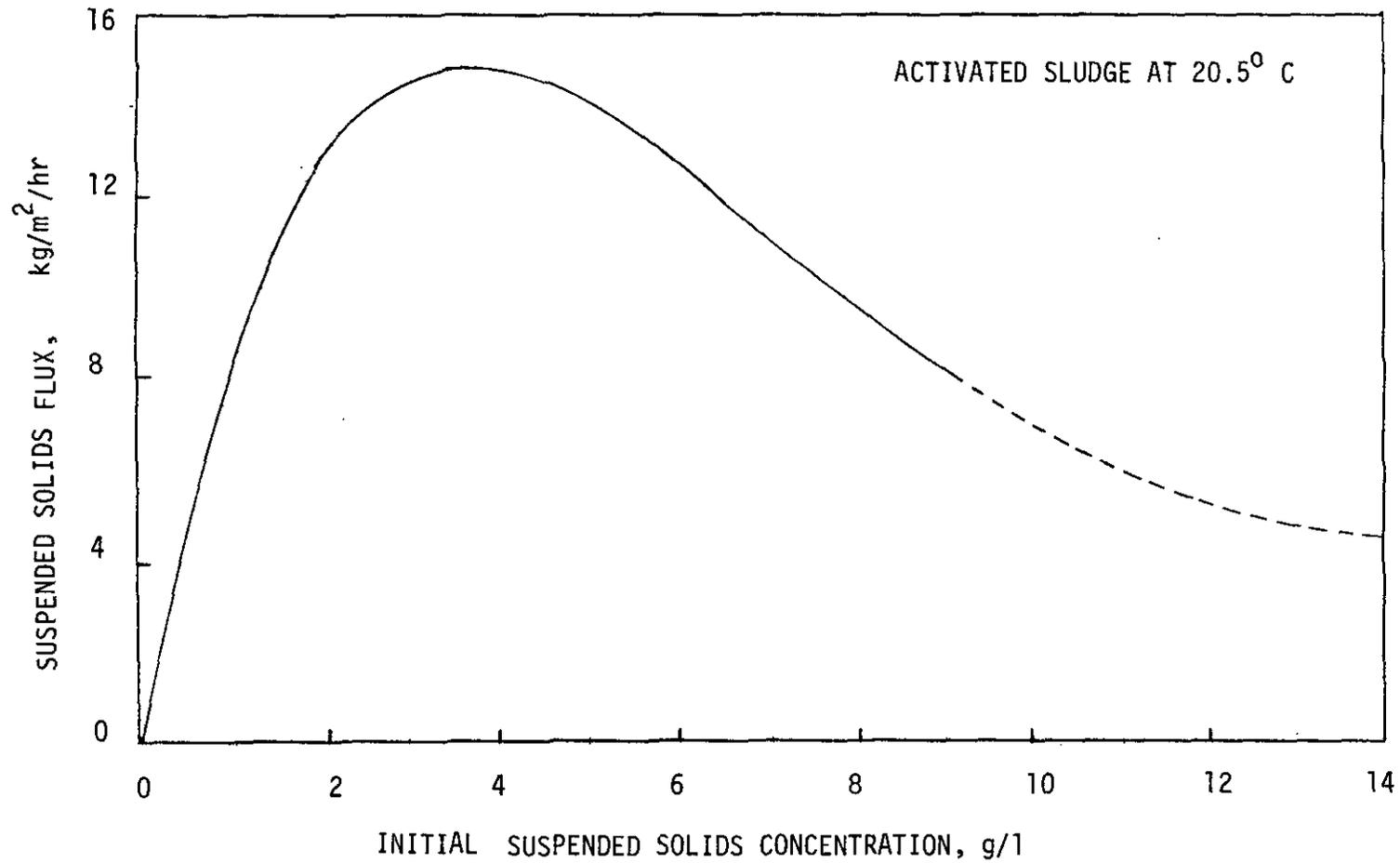


FIGURE 11. SUSPENDED SOLIDS FLUX AS A FUNCTION OF SUSPENDED SOLIDS CONCENTRATION.

Raw data include total and piezometric pressure distributions with respect to column height, and concentration profiles. The following procedure may be followed for analysis of these data:

The determination of filtration characteristics is involved with the description of the resistance to flow up through the porous media. To do this the relationship between superficial velocity and the piezometric pressure drop must be described for each concentration. Kos has found that these relationships are not linear and can be approximately expressed in form:

$$(v_s - v_l) n = A' (\overline{dp}/dx)^{B'} \quad (24)$$

where

n = porosity

v_s = velocity of solid matrix at point x

v_l = velocity of liquid at point x

$(v_s - v_l)n$ = superficial velocity

A', B' = constants depending on concentration

\overline{dp}/dx = change of piezometric pressure per change in height through the solids layer

- a) To generate these values, simultaneous plots of the height of the sampling port versus suspended solids concentration, and height of the port versus \overline{p} - pressure and $\overline{\sigma}_T$ - pressure are generated. Figure 12 is an example. A specified concentration sets a height in the sludge layer and at that height the change of piezometric pressure per change of height, \overline{dp}/dx , can graphically be determined. The \overline{dp}/dx is determined

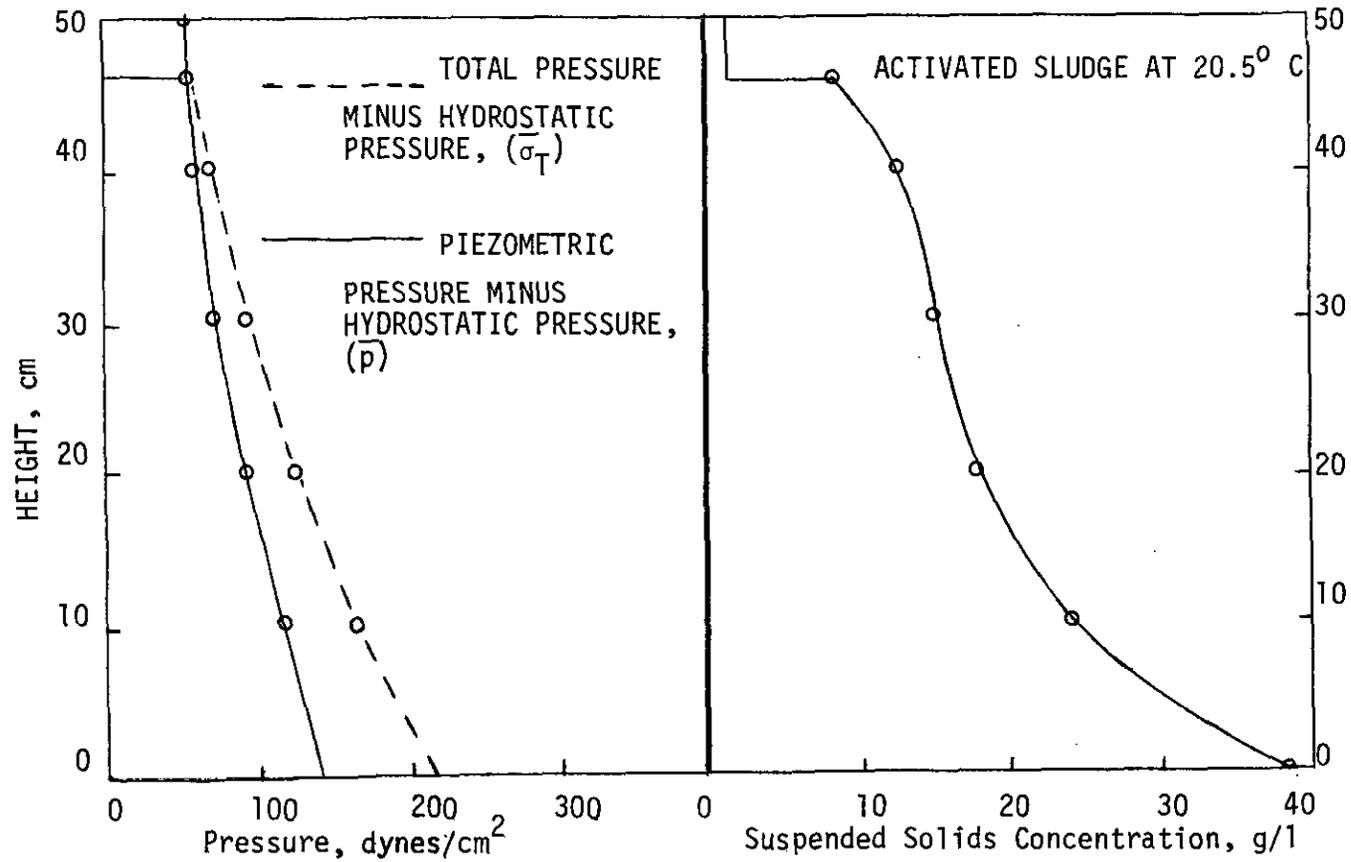


FIGURE 12. PRESSURE AND SUSPENDED SOLIDS CONCENTRATION DISTRIBUTION IN THE THICKENING ZONE.

for each profile and for the concentrations between c_b and c_u . (c_b is the concentration of sludge at the boundary between zone settling and channelling and for tested sludge $c_b = 8.79$ g/l.)

- b) An overall mass balance is necessary for each of the profiles taken. Specifically required for the model is the rate of underflow, Q_u , and the underflow concentration, c_u . Table 2 shows a typical mass balance.

Given the parameters Q_u , c_u , the superficial velocity can be calculated for any concentration between c_b and c_u (using Equation 12). Since it is necessary to calculate many values of the superficial velocities a computer program (See Mulcahy et al [14]) which generates incremental values of concentration and their corresponding superficial velocities $(v_s - v_l)n$ was used.

The expression of the filtration properties by the relationship between superficial velocity and the piezometric pressure drop (Equation 24) has two disadvantages. It is necessary to have a lot of results to define it for each concentration and it cannot be used for a prediction of the effect of temperature changes on thickening of sludge. Kos suggested and verified a different form of expressing the filtration properties of sludge during consolidation. This is based on an understanding that flow through a porous media (such as sludge) can accurately be modelled as flow through closely bunched capillary tubes whose diameter varies with flow conditions. The diameter of an imaginary capillary tube, δ , is:

$$\delta = \frac{32k}{n} \quad (25)$$

where

n = porosity

$k = [(v_s - v_l)n] / \overline{dp/dx}$

μ = dynamic viscosity

TABLE 2

MASS BALANCE OF SUSPENDED SOLIDS

Depth of Thickening Zone		46.0 cm
Feed		
Rate of Flow	Q_{in}	82.5 ml/min
Concentration (SS)	c_{in}	12.856 g/l
	$Q_{in} \cdot c_{in}$	1.0606 g/min
Underflow		
Rate of Flow	Q_u	24.5 ml/min
Concentration (SS)	c_u	38.69 g/l
	$Q_u \cdot c_u$	0.9479 g/min
Overflow		
Rate of Flow	Q_o	58 ml/min
Concentration (SS)	c_o	0.539 g/l
	$Q_o \cdot c_o$	0.0312 g/min
	$\frac{(Q_{in} \cdot c_{in} - Q_o c_o) + Q_u c_u}{2}$	= 0.988865 g/min
Suspended Solids Loading		0.89806
Corrected Rate of Underflow, Q_u		25.55 ml/min

The shear stress τ , on the walls of an imaginary tube is given by:

$$\tau = \frac{-8\mu(v_s - v_l)n}{\delta n} \quad (26)$$

where

$$\tau = \text{shear stress in dynes/cm}^2$$

The diameter of an imaginary capillary tube changes with the change of flow conditions, it is with the change of the shear stress on its wall. These changes are about linear, which make it possible to predict the filtration properties with less data. Furthermore the δ - τ relationship make possible evaluation of the temperature effect upon the thickening of sludges.

Because of these facts this second form of filtration properties description was used.

- c) For each profile, the values for concentration, \overline{dp}/dx , and superficial velocities are now available.

Given this information the program CPLRY (See Mulcahy et al [14]) calculates the values of the effective diameter and the shear stress on the wall of a capillary tube (through which the liquid passes in the thickening process). Figure 13 is a plot of capillary diameter δ , versus shear stress, τ . The three points for each concentration, correspond to the three steady-state profiles obtained.

Determining the best fit line with so few points would have proven troublesome. From experimental results obtained by Kos on water treatment sludge, an average slope of 0.35 was found. It was with this slope that the experimental points were fitted and the intercept, δ_0 , determined.

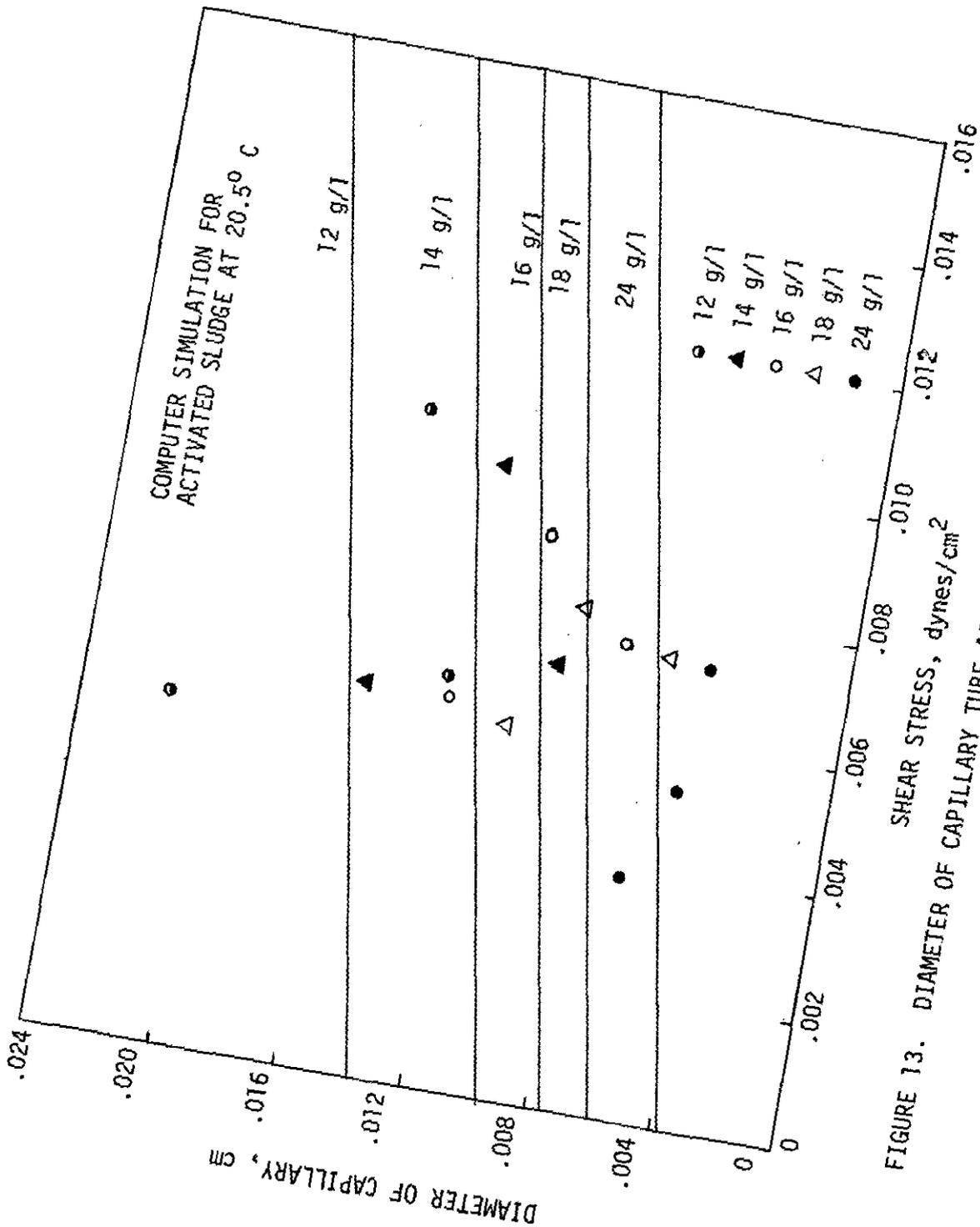


FIGURE 13. DIAMETER OF CAPILLARY TUBE AS A FUNCTION OF SHEAR STRESS

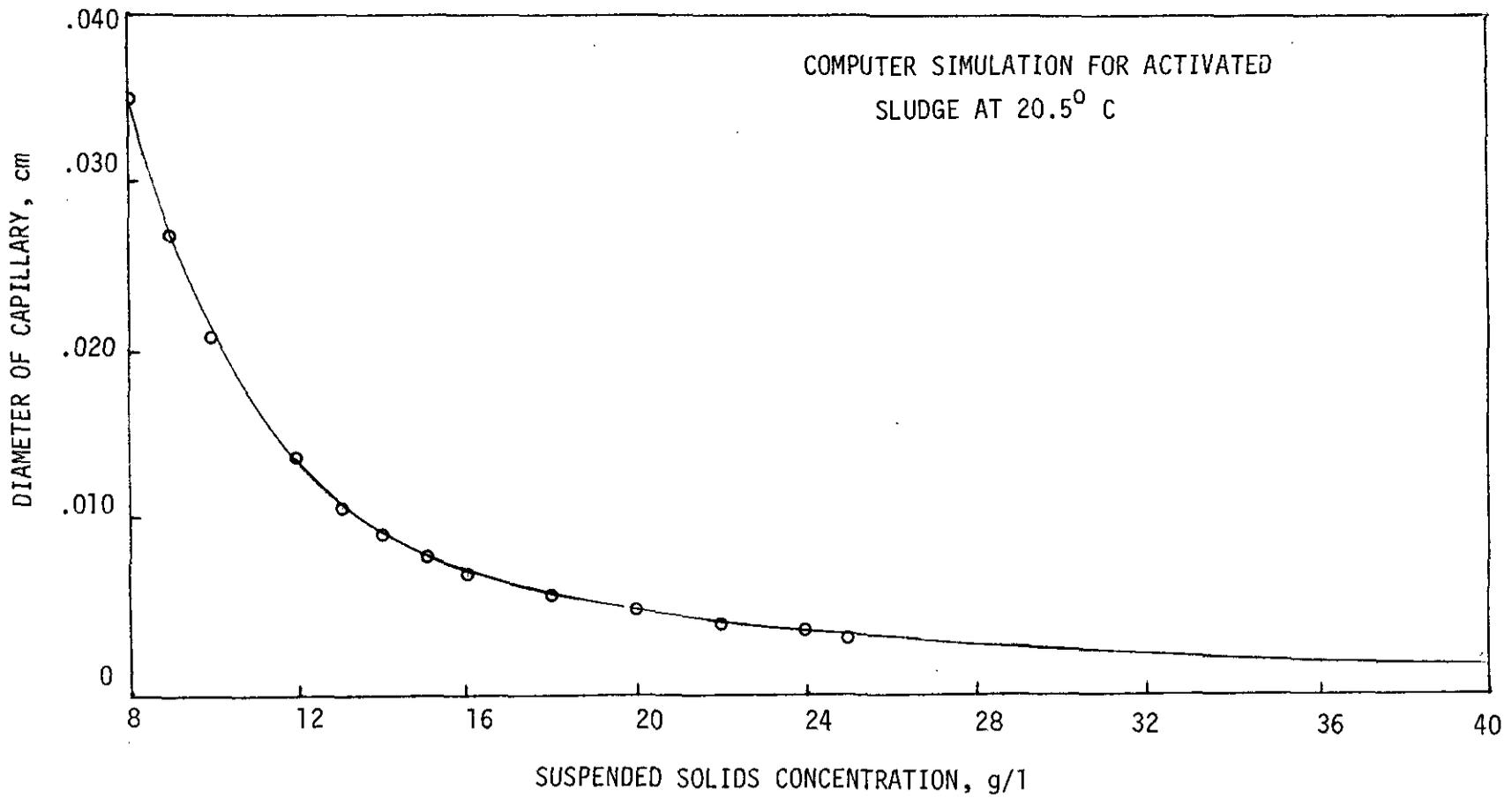


FIGURE 14. DIAMETER OF CAPILLARY TUBE AT THE ZERO SHEAR STRESS, δ_0 , AS A FUNCTION OF SUSPENDED SOLIDS CONCENTRATION

- d) The δ_0 constant, or intercept, was corrected for possible error. From Figure 13, and the best fit line for each concentration, the value for δ_0 is plotted versus concentration, (See Figure 14). Again a smooth curve is constructed. Adjusted values for δ_0 and the slope .35, from Figure 13, was used for the description of the filtration properties of measured sludge.

In determining consolidation characteristics of the sludge, it is necessary to describe compression of the solids matrix. Pressure exerted by the solids matrix is termed effective pressure σ , which can easily be related as a function of $\bar{\sigma}_T$ and \bar{p} by:

$$\sigma(x) = \bar{\sigma}_T(x) - \bar{p}(x) \quad (27)$$

where

$\sigma(x)$ = effective pressure

$\bar{\sigma}_T(x)$ = total pressure minus hydrostatic pressure

$\bar{p}(x)$ = piezometric pressure minus hydrostatic pressure

- e) From Figure 12, a specified concentration will set a height and at that height the corresponding $\bar{\sigma}_T$ - pressure and \bar{p} - pressure can be determined. The difference between these two yields the desired effective pressure. Figure 15 shows the results for measured activated sludge and so demonstrates the relationship between effective pressure and concentration. Kos has shown this relationship for water treatment sludge to be non-linear, as described by:

$$c = c_b + \bar{A}\sigma^{\bar{B}} \quad (28)$$

where

\bar{A} and \bar{B} are constants

Since the relationship between effective pressure and concentration (Figure 15) is close to the straight line, a straight line was fitted to

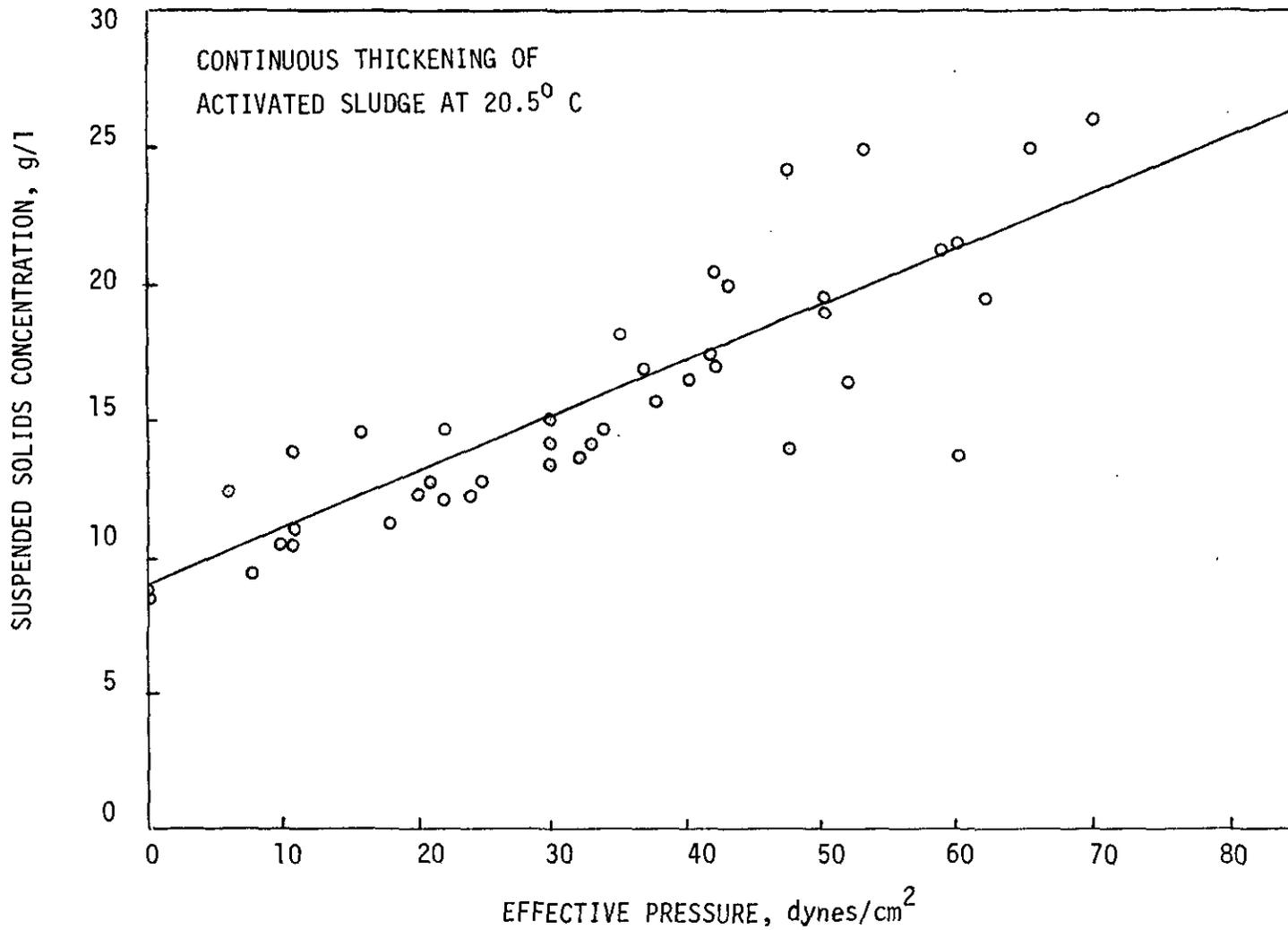


FIGURE 15. SUSPENDED SOLIDS CONCENTRATION AS A FUNCTION OF THE EFFECTIVE PRESSURE

to the data using the minimum sum square deviation criterion. The resultant form of that relationship is

$$c = 8.79 + 0.1974\sigma \quad (29)$$

Having this equation, the consolidation behavior of the sludge layer may be predicted with given pressure information.

- f) The density of solids, d_s , must also be determined for the mathematical model. The procedure is discussed in Section II.
- g) The temperature at which this study took place was 20.5°C. The Kos model using δ - τ relationship allows for the consideration of other temperatures. The mathematical model requires the viscosity of water for the desired temperature in order to yield the filtration characteristics at that particular temperature.

The information required for Kos' mathematical model is now available. The computer program DEPTH (See Mulcahy et al [14]) is capable of simulating thickening zone information for any given operating conditions. Output includes the depth of the thickening zone, the distribution of the suspended solids concentration with depth, and the piezometric, effective and total pressure distribution in the thickening zone.

In Figure 16 is the comparison of the measured concentration profile with the computer simulated result. As it can be seen, the simulated profile is in good agreement with that obtained experimentally.

The most significant results are obtained by using the program DEPTH and determining the required depth of thickening zone for any combination of solids loading and underflow concentration. Figures 17-20 (Section IV) are plots of thickening zone depth versus underflow concentration for various loadings and four specific temperatures. The use of these curves is explained in the following section.

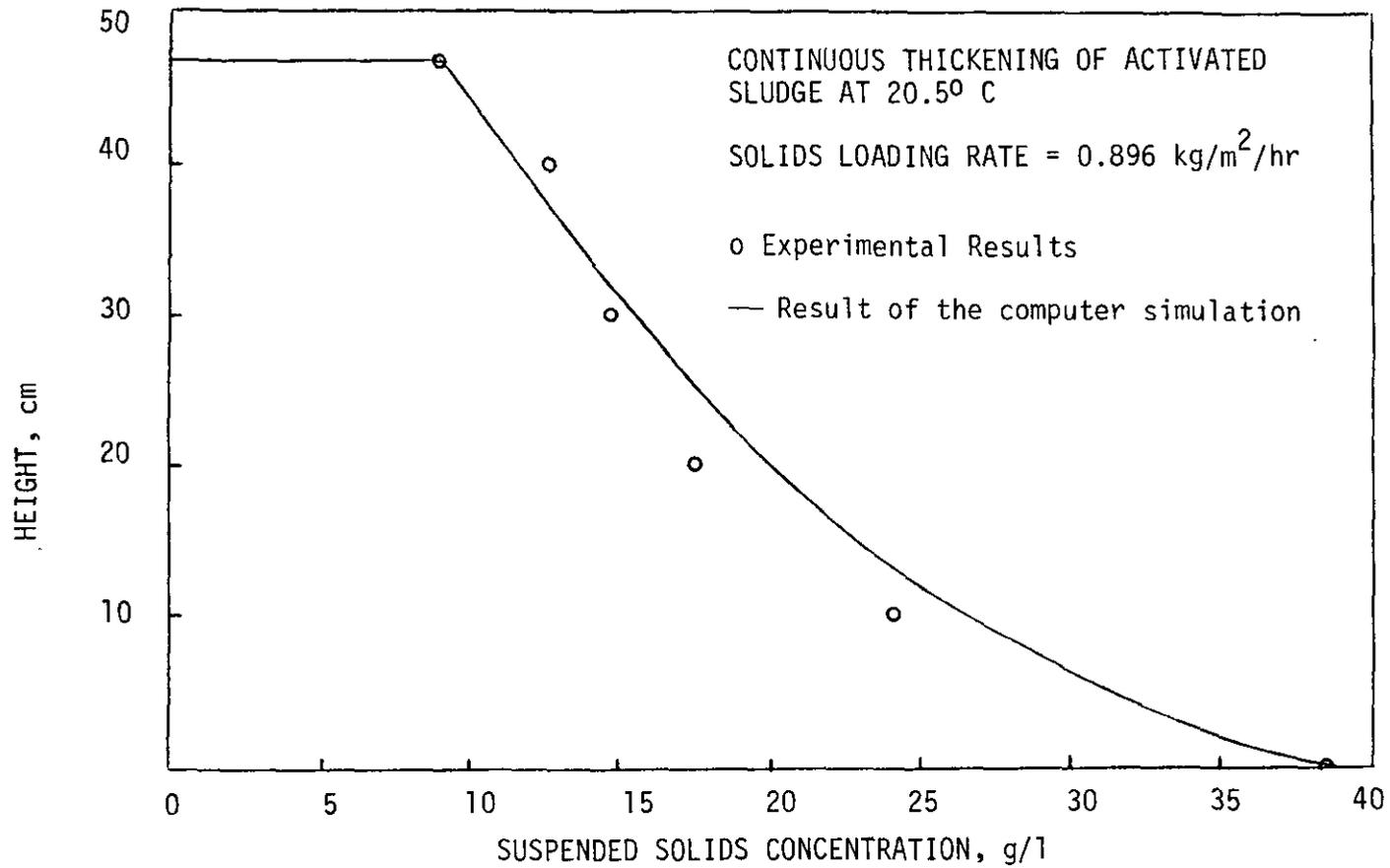


FIGURE 16. COMPARISON OF THE MEASURED CONCENTRATION DISTRIBUTION WITHIN THE LABORATORY THICKENER WITH THE DISTRIBUTION SIMULATED BY COMPUTER.

From the information supplied by Figures 17-20 (Section IV), it can be seen that no significant increase in underflow concentration is obtained with an increase of depth of thickening zone beyond about 150 cm, for solids loading rates greater than $3 \text{ kg/m}^2/\text{hr}$. Thus, for economical reasons it would be inappropriate to design thickening zone above this level.

For the case where the depth of the thickening zone is considered to be 150 cm or less, the maximum suspended solids loading as a function of underflow concentration is plotted for various temperature in Figure 21. These curves were generated from Figures 17-20 (Section IV) and also portray the effect that temperature has on the thickening process.

Figure 22 (Section IV) demonstrates results obtained by the conventional method of analysis and results from the new theory of evaluation. Discrepancies can clearly be seen.

SECTION IV - USE OF CURVES IN DESIGN AND THE EFFECT OF TEMPERATURE

For the evaluation of the thickening capacity of the secondary sedimentation basins the final five curves, Figures 17 to 21 inclusive, will be used.

Figures 17-20 are plots of depth of the thickening zone versus concentration, for several different loadings and temperatures of 20.5, 15, 10, and 5°C, respectively. It can be seen that as the loading, ($\text{kg}/\text{m}^2/\text{hr}$) decreases, the depth of the thickening zone for a desired underflow concentration also decreases. From Figure 17, for example, it can be seen that if an underflow concentration of 28 g/l or 2.8 percent solids is desired, a thickening zone of 1.55 meters would be required for a loading of $3.0 \text{ kg}/\text{m}^2/\text{hr}$, whereas only 0.775 meters are required for a loading of $2.5 \text{ kg}/\text{m}^2/\text{hr}$.

Of greater importance, however, is the sensitivity of a specific solids loading to underflow change. For example, a loading of $5 \text{ kg}/\text{m}^2/\text{hr}$ is being used. For an underflow concentration of 1.8 percent solids, a depth of approximately 60 cm is required for the thickening zone. However, if either intentionally or unintentionally the underflow is decreased the underflow concentration will be increased very little, say, to 2.0 percent solids, it can be seen that over 2.75 meters would be required, and very possibly the tank would overflow.

In conclusion, the loading will depend primarily upon the desired underflow concentration and the range of flexibility that is desired.

Figure 21 is a derivation from the previous figures, height versus underflow concentration. Setting the height of the thickening zone at 1.5 meters, a reasonable and economical height, the concentration

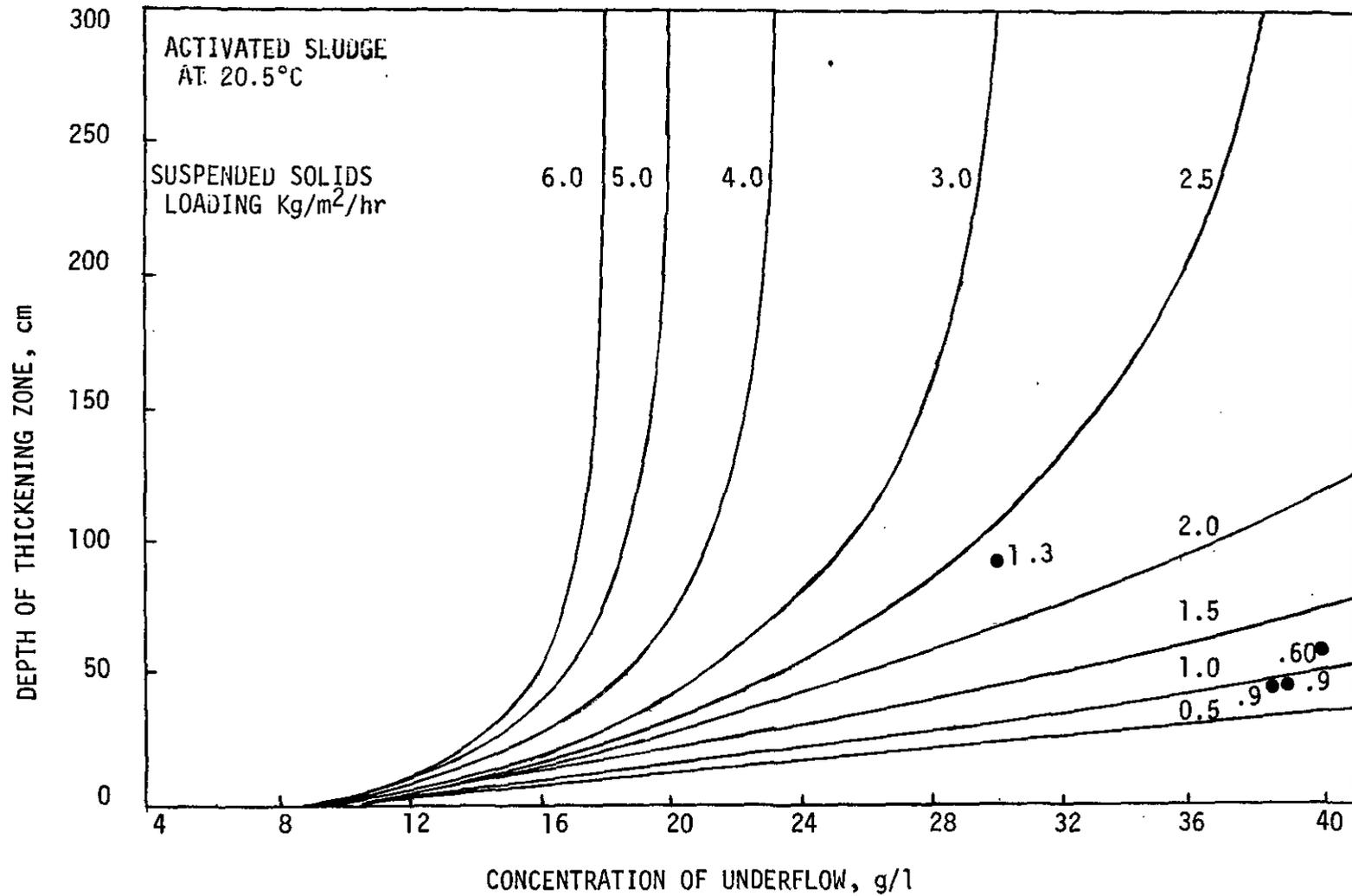


FIGURE 17. DEPTH OF THICKENING ZONE AS A FUNCTION OF UNDERFLOW CONCENTRATION AND SUSPENDED SOLIDS LOADING AT 20.5°C.

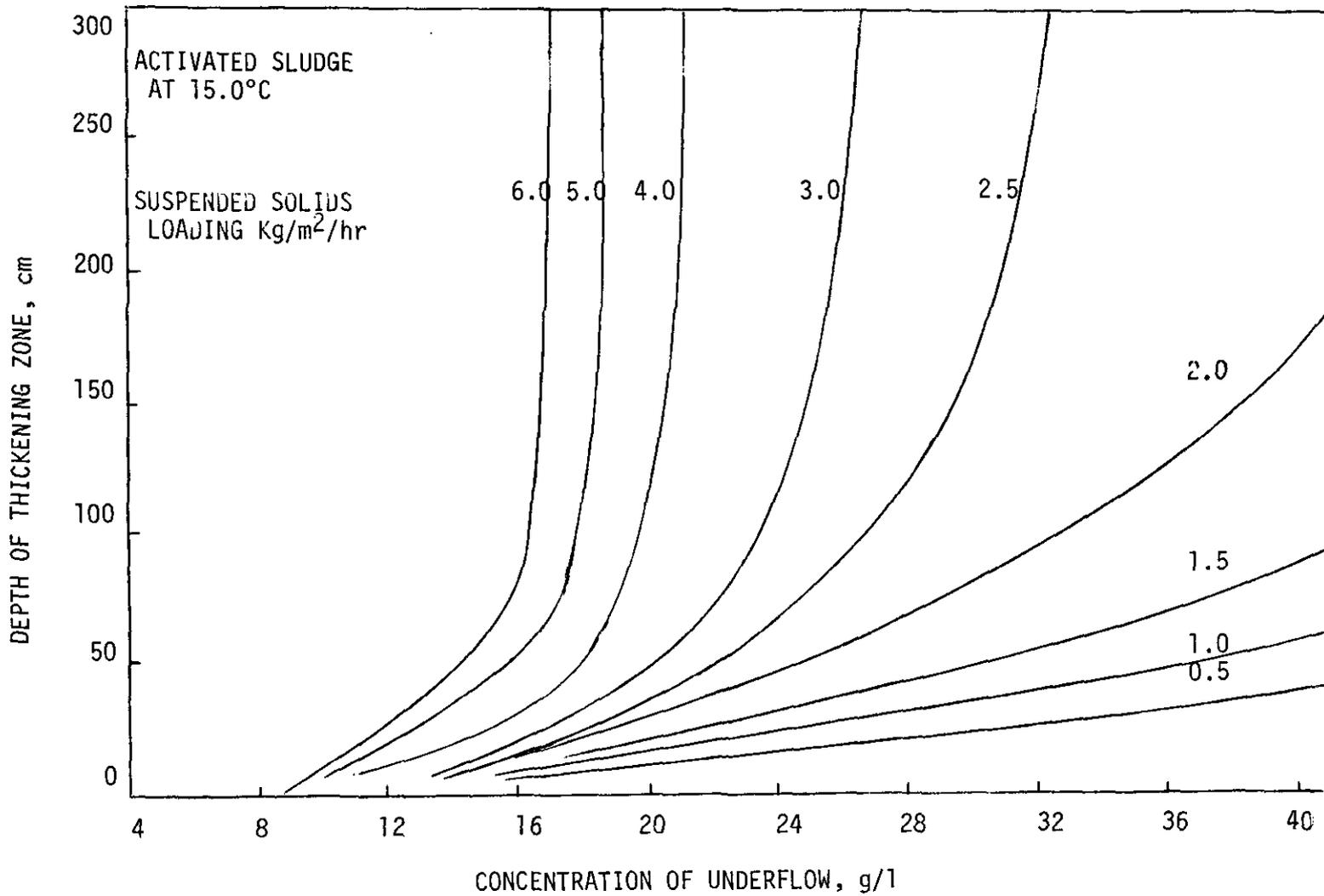


FIGURE 18. DEPTH OF THICKENING ZONE AS A FUNCTION OF UNDERFLOW CONCENTRATION AND SUSPENDED SOLIDS LOADING AT 15.0°C.

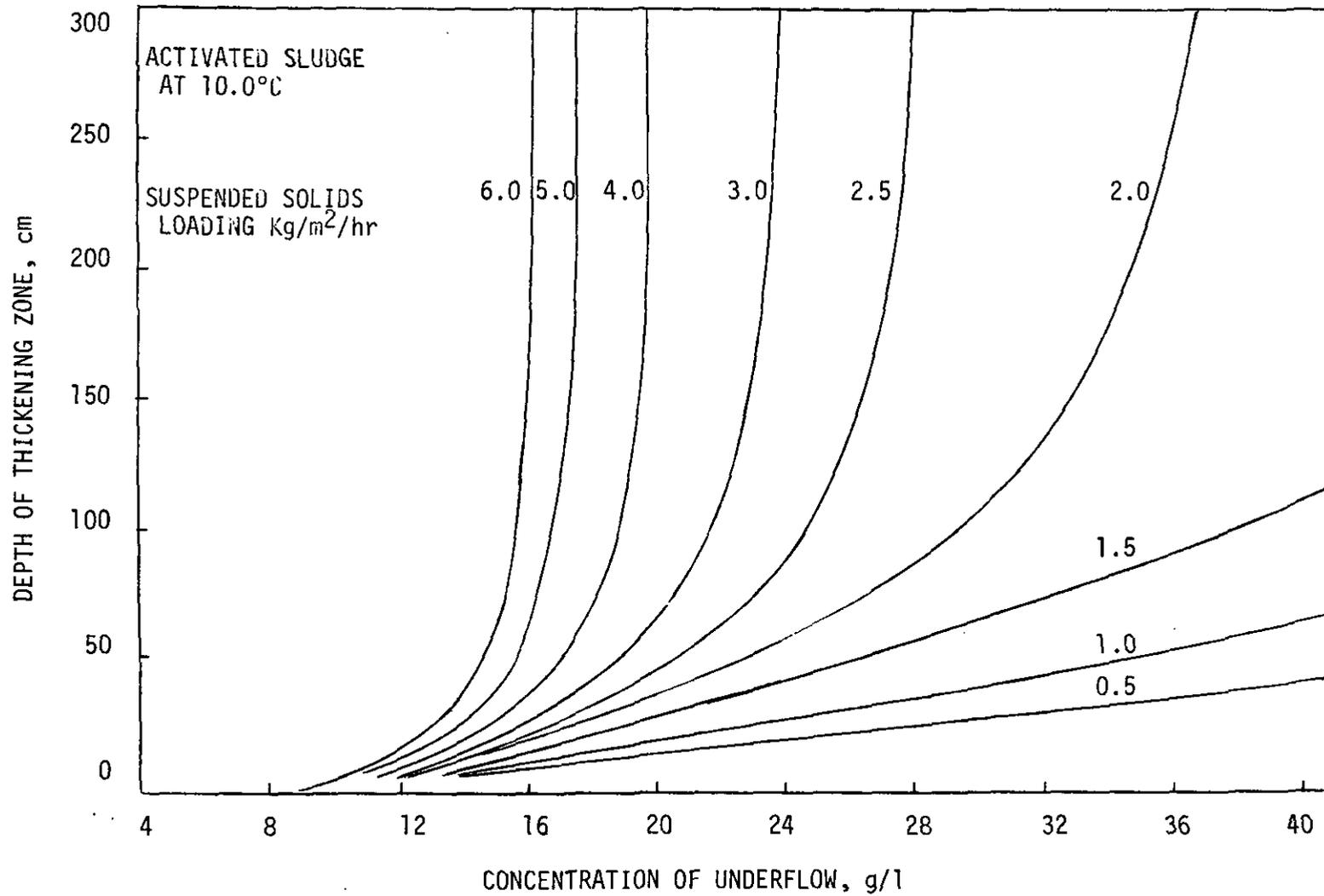


FIGURE 19. DEPTH OF THICKENING ZONE AS A FUNCTION OF UNDERFLOW CONCENTRATION AND SUSPENDED SOLIDS LOADING AT 10.0°C.

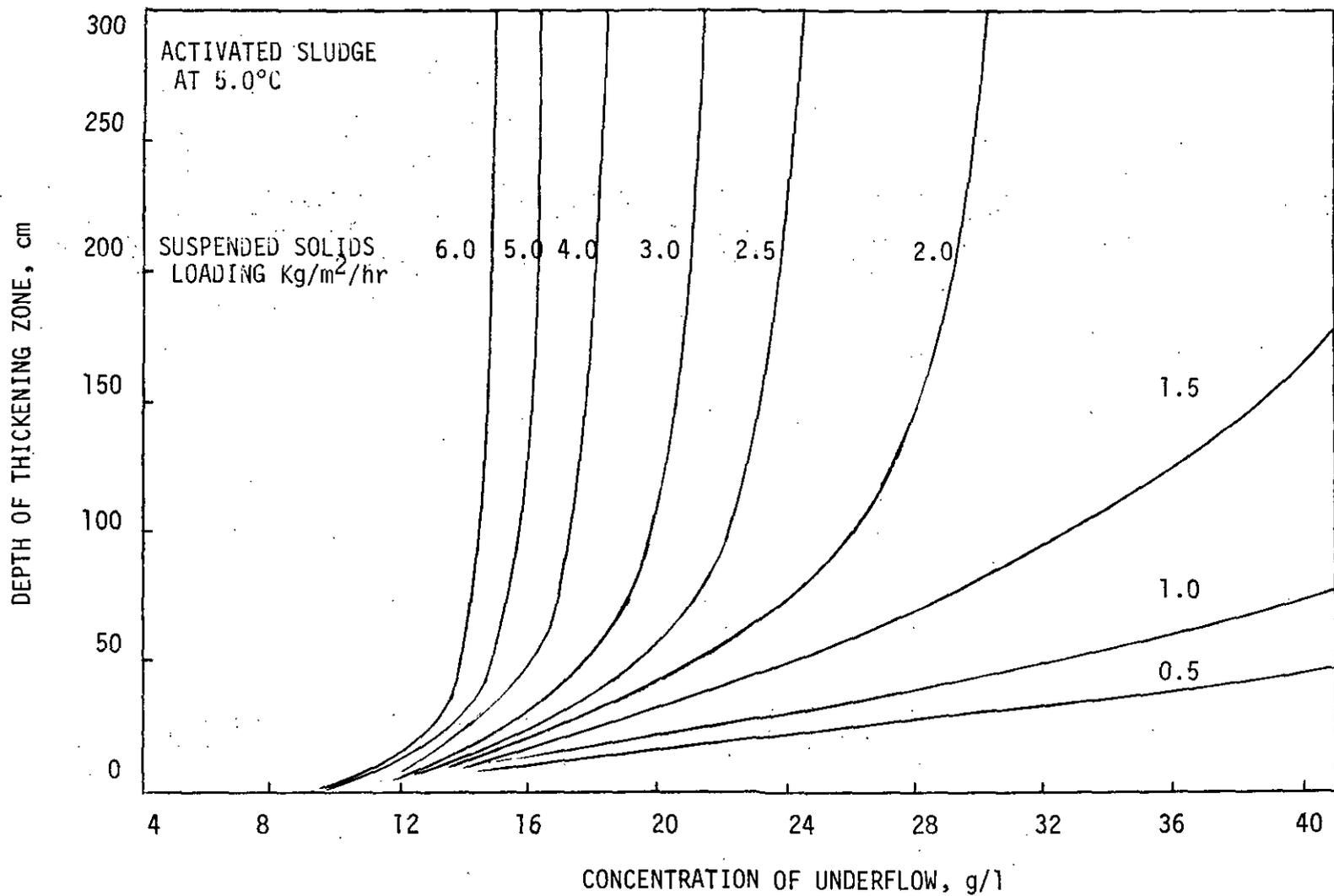


FIGURE 20. DEPTH OF THICKENING ZONE AS A FUNCTION OF UNDERFLOW CONCENTRATION AND SUSPENDED SOLIDS LOADING AT 5.0°C.

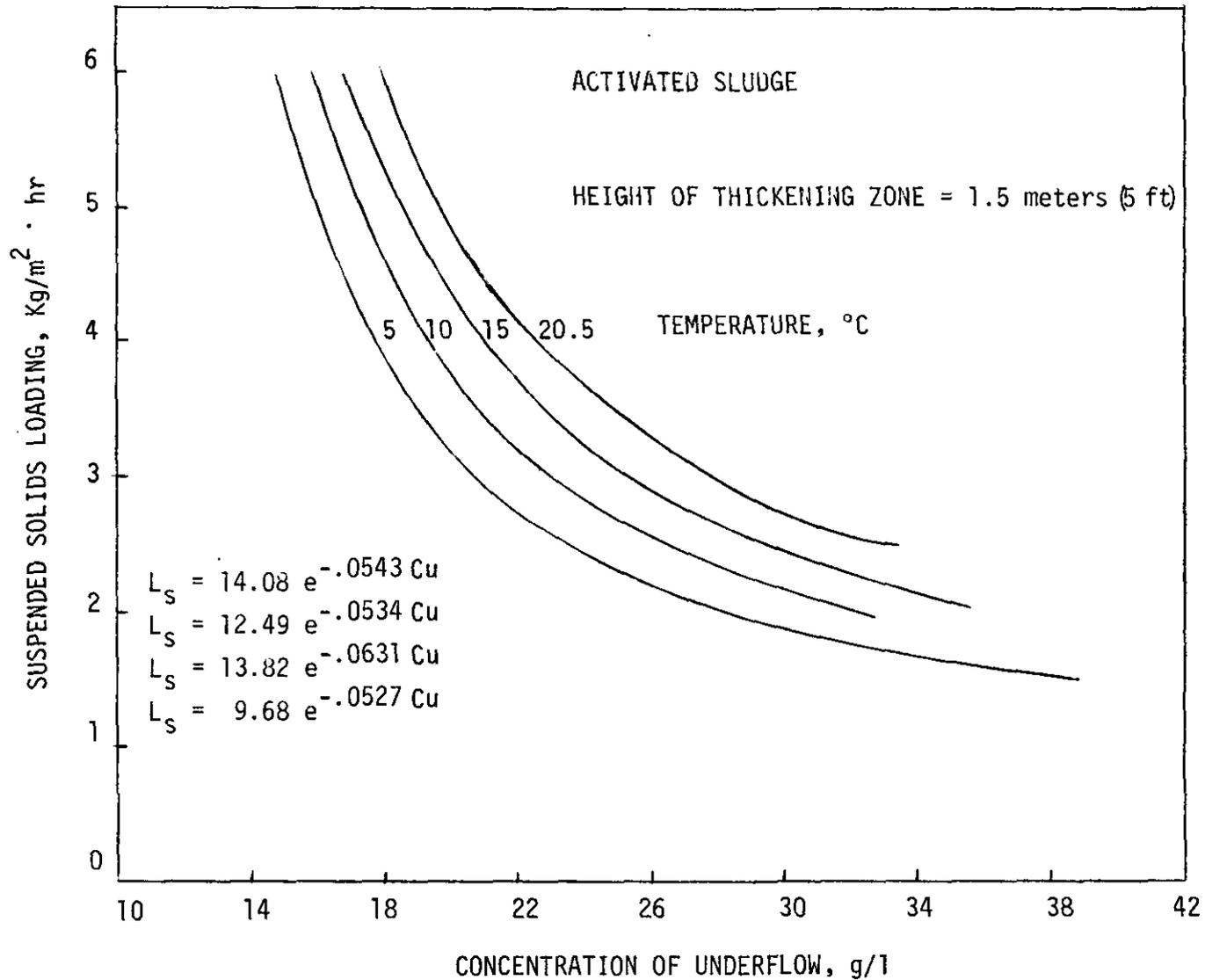


FIGURE 21. MAXIMUM SUSPENDED SOLIDS LOADING OF THE THICKENING ZONE AS A FUNCTION OF UNDERFLOW CONCENTRATION AND TEMPERATURE.

for each loading is recorded and plotted. Figure 21 represents the solids loading rate versus underflow concentration. This was done for four temperatures: 20.5, 15, 10, and 5°C, and as can be seen, smooth curves were formed.

At a constant loading of $5 \text{ kg/m}^2/\text{hr}$ (which is about the average loading of secondary sedimentation tanks) and for 20.5°C, an underflow concentration of about 1.9 percent solids will be yielded. If the temperature were to drop to 10°C or 5°C, and the loading were held constant at $5 \text{ kg/m}^2/\text{hr}$, then the underflow concentration would decrease to 1.73 or 1.6 percent solids, respectively. This decrease is not as significant at higher loading rates as it is at lower ones. For instance, for a loading of $2.5 \text{ kg/m}^2/\text{hr}$, and the temperatures of 20.5°C and 10°C, underflow concentrations change from 33.5 g/l to 26.5 g/l, respectively.

More practically, however, one would be interested in maintaining a constant underflow concentration i.e. 2.0 percent solids. At a temperature of 20.5°C, it would be necessary to have a loading rate of about $4.75 \text{ kg/m}^2/\text{hr}$. However, in order to insure the same underflow concentration, 2.0 percent solids, at 10°C, a loading rate of only $3.75 \text{ kg/m}^2/\text{hr}$ is necessary.

Curves generated for 20.5°C and 5°C represent summer and winter conditions, respectively. Examining these two together, we find that area requirements consistently vary by about 30 percent. Thus, it is imperative that design of secondary clarifiers be done for winter conditions, thus insuring that area requirements are met. Also, it is essential that the relationship between depth of thickening zone and underflow concentration be completely understood by both designers and operators.

SECTION V - LIMITATIONS OF RESULTS

One should note that the results obtained in this study are not general and can only be applied to a very specific sludge. As previously mentioned, the sludge was the activated sludge taken from the extended aeration unit at the University of Massachusetts wastewater treatment pilot plant in Amherst.

In order to insure that these results are applicable to another source of activated sludge the reader is referred to Section III, which describes physical characteristics of the activated sludge studied. Several laboratory tests can be performed on a different source of activated sludge in order to see how closely it resembles the sludge previously examined. The tests include:

- 1) Total and suspended solids determination
- 2) Sludge volume Index (SVI) (see Table 1)
- 3) Density versus suspended solids concentration (See Figure 2)
- 4) Settling velocity versus suspended solids concentration (See Figure 9)

If after completing these tests it can be concluded that the sludge is approximately similar to the one previously studied, the previously developed curves may be used as a design basis.

With further research, it is hoped that an entire range of activated sludges will be studied and their corresponding curves generated. With this information one could then perform the laboratory bench scale tests on a specific source of sludge for which a secondary

sedimentation tank is to be designed. The design curves for the sludge that it most closely resembles may be selected and used for the design.

SECTION VI - CONCLUSIONS AND RECOMMENDATIONS

The purpose of the investigation was three-fold:

- 1) to apply Kos' mathematical model for continuous gravity thickening evaluation to activated sludge, and to compare results with those obtained by Kos for water treatment sludge.
- 2) to develop curves for the evaluation of thickening of activated sludge.
- 3) To show the effect that temperature has on the performance of secondary sedimentation basins.

Results obtained in this investigation of activated sludge are analogous to those obtained by Kos [10] for water treatment sludge. Figure 22 is a comparison of resultant design parameters based on the conventional method of batch settling curves and on a new theory of evaluating continuous gravity thickening data developed by Kos [11]. The suspended solids loading as a function of underflow concentration was plotted for both procedures. The conventional-method curve was obtained from batch settling tests upon utilization of Yoshioka's [20] graphical method. The more representative continuous thickening curve was derived from the mathematical model developed by Kos [11]. The discrepancies between these two models can clearly be seen.

Figures 17-20 in Section IV show the required depth of thickening zone as a function of underflow concentration for various loadings. These figures represent respectively the specific temperatures of 20.5, 15, 10, and 5°C. From these curves, the solids loading rate that will yield a desired underflow concentration can be chosen.

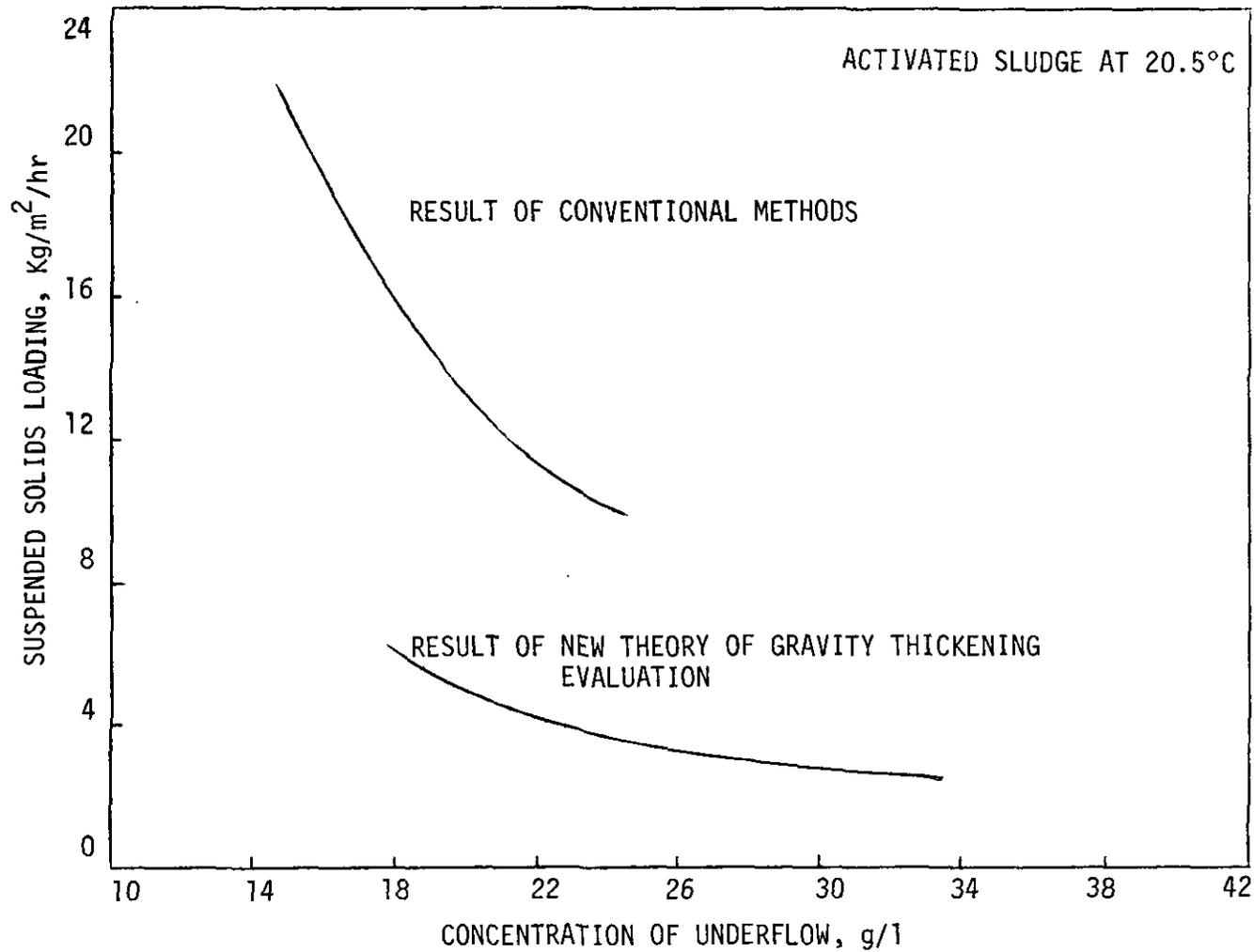


FIGURE 22. COMPARISON OF THE MAXIMUM SUSPENDED SOLIDS LOADINGS OF THE CONTINUOUS GRAVITY THICKENER OBTAINED BY THE NEW METHOD WITH THOSE OBTAINED BY CONVENTIONAL METHODS.

From this information, the necessary depth of the thickening zone can be determined. It is recommended that a loading rate be chosen that is not susceptible to great change in thickening height with a slight change of underflow concentration.

Figure 21 (Section IV) is a comparison of the design curves at the four different temperatures. Assuming the maximum depth of the thickening zone of 1.5 meters, a very reasonable and economical one, the maximum solids loading rate as a function of underflow concentration is plotted.

The four curves were fitted to the exponential equation:

$$L_s = \bar{a}e^{\bar{b}c_n} \quad (30)$$

The constants for the four curves were found to be:

Temperature, °C	\bar{a}	\bar{b}
20.5	14.08	-.0543
15	12.49	-.0534
10	13.82	-.0631
5	9.68	-.0527

The effect of temperature can be seen from the graph. If a solids loading of 5 kg/m²/hr is being operated at a temperature of 20.5°C, an underflow concentration of approximately 19.5 g/l will be obtained. If the temperature should drop to 10°C, and the same loading rate is maintained, then the underflow concentration will drop to 17.2 g/l. Much more significant changes are observed at lower solid loading rates.

From the operational point of view, it can be seen that at 20.5°C and a desired underflow concentration of 20 g/l or 2.0 percent

solids, a solids loading rate of approximately $5.80 \text{ kg/m}^2/\text{hr}$ is allowed. If the temperature now drops to 10° C , and the same underflow concentration is desired, then the allowable solids loading is reduced to $3.75 \text{ kg/m}^2/\text{hr}$.

Thickening capabilities were simulated for summer and winter conditions, or 20.5° and 5° C , respectively. It was found, from Figure 21, that solids loading rates, and thus thickening area requirements, vary by 30 percent. It is thus recommended that design of secondary clarifiers be based on winter conditions.

These results exemplify the importance of a working knowledge of these curves in both the design and operation of thickening units.

Further examination of this method for evaluating continuous thickening is highly recommended. The activated sludge examined in this study was one of specific characteristics. If five or six similar studies could be performed on activated sludges with varying characteristics, then curves would be readily available for the thickening design of any activated sludge. Due to the extensive time required for the development of these design curves, it would be more advantageous to perform simple bench scale tests on the sludge in question. The design curves for the sludge that it most closely characterizes may be used in the thickener design.

The study of activated sludge proved to have more operational problems than the water treatment sludge studied by Kos [10]. Three problem areas are as follows:

- 1) Unlike the water treatment sludge, activated sludge samples must be obtained each day. Over the long period of examination the physical characteristics of activated sludge may change due to operational procedures at the treatment plant.
- 2) Due to the fact that the inflow concentration had to be closely estimated (in order to determine the solids loading rate) to operate the continuous flow column, samples were prepared prior to their use. This leads one to question the exact quality of the sludge when it was finally used.
- 3) Continuous operation of the column proved difficult due to the nature of the activated sludge. Unless the column was continuously observed, feed lines, overflow lines and underflow lines were subject to particle build-up, resulting in altered flow rates. When an altered flow rate went unnoticed for a period of time, the approach to equilibrium was highly hindered.

Appendix I - List of Symbols

The following symbols are used in this paper:

Symbol		Dimensions
A	Area	L^2
\bar{A}	Constant from Equation 28	$L^{-2}T^2$
A'	Constant from Equation 24	$M^{-1}L^2T^2$
a	Modulus of linear compressibility ($a=dp_s/d\sigma$)	$L^{-2}T^2$
\bar{a}	Constant from equation 30	$ML^{-2}T^{-1}$
\bar{B}	Constant from Equation 28	----
B'	Constant from Equation 24	----
\bar{b}	Constant from equation 30	$M^{-1}L^3$
c	Concentration of suspended solids	ML^{-3}
c_b	Concentration of sludge at the boundary between zone settling and channeling	ML^{-3}
c_u	Concentration of underflow	ML^{-3}
c_{in}	Concentration of inflow	ML^{-3}
c_o	Concentration of overflow	ML^{-3}
C	Solids handling capacity	$ML^{-2}T^{-1}$
D	Dilution	----
D_c	Dilution at point of compression	----
D_∞	Final value of dilution	----
d_s	Density of solid particles	ML^{-3}
d_l	Density of liquid	ML^{-3}
d_{sl}	Density of sludge	M
E	Fraction void of liquid	----

L	Suspended Solids Loading	$ML^{-2}T^{-1}$
G_s	Mass flux of the solid phase	$ML^{-2}T^{-1}$
G_l	Mass flux of the liquid phase	$ML^{-2}T^{-1}$
g	Acceleration of gravity	LT^{-2}
g_x	Acceleration of gravity in the x direction	LT^{-2}
k	Intrinsic conductivity	L^2
k'	Constant of proportionality from Equations 4,5	T^{-1}
\bar{k}	Constant of proportionality from Equations 6,7	$ML^{-2}T^{-1}$
m	Constant in Equations 2, 3, 23	----
n	Porosity ($n = \rho_l/d_l$)	----
p	Liquid phase pressure	$ML^{-1}T$
\bar{p}	Piezometric pressure minus the hydrostatic pressure	$ML^{-1}T^{-2}$
Q	Flow rate	L^3T^{-1}
Q_{in}	Inflow	L^3T^{-1}
Q_u	Underflow	L^3T^{-1}
Q_o	Overflow	L^3T^{-1}
s	Reciprocal of density of solids	$M^{-1}L^3$
t	Time	T
u	Zone settling velocity	LT^{-1}
u_o	Zone settling velocity of single particle	LT^{-1}
v_s	Velocity of solid matrix at point x	LT^{-1}
v_l	Velocity of liquid at point x	LT^{-1}
$(v_s - v_l) \cdot n$	Superficial velocity	LT^{-1}
x	The spatial or Eulerian coordinates	L
z	Height of the sludge-liquid interface	L
δ_o	Diameter of the capillary at zero shear stress	L

δ	Diameter of the capillary	L
ρ_s	Bulk mass density of solids	ML^{-3}
ρ_l	Bulk mass density of liquid	ML^{-3}
μ	Dynamic viscosity	$ML^{-1}T^{-1}$
σ	Effective (interparticle) pressure	$ML^{-1}T^{-2}$
σ_T	Total pressure	$ML^{-1}T^{-2}$
$\bar{\sigma}_T$	Total pressure minus the hydrostatic pressure	$ML^{-1}T^{-2}$
τ	Shear stress	$ML^{-1}T^{-2}$

Appendix II - Sample Calculations

I Batch Analysis

- A. Determine suspended solids concentration, by gravimetric analysis which was 5.893 grams/liter.
- B. Graphically determine settling velocity for each column. (max slope) See Figure 9.

Column Height (cm)	Settling Velocity (cm/hr)
200	205.98
150	214.38
100	210.97
75	209.69
50	187.89

- C. Determine average settling velocity which was 205.78 cm/hr.
- D. A plot of average settling velocity versus suspended solids concentration was constructed. See Figure 10.

For this study the following data were obtained:

SS Concentration (g/l)	Average Settling Velocity (cm/hr)
4.005	345.9
3.085	497.3
4.940	291.0
5.893	205.8
6.530	202.3
6.950	157.1
7.284	151.4

- E. The best fit line through these points was determined to be:

$$u = u_0 \left(1 - \frac{c}{d_s}\right)^m$$

and
$$u = 1105.6 \left(1 - \frac{c}{1.476}\right)^{403.91} \quad d_s = 1.476 \text{ g/ml}$$

F. With the equation above, a given concentration specifies a settling velocity. The product of the two ($v \cdot c$) was plotted, Figure 11, as a function of suspended solids concentration.

Suspended Solids Concentration g/l	Settling Velocity cm/hr	Solids Flux ($v \cdot c$) kg/m ² /hr
0	1105	0
1	840	8.40
2	640	12.80
3	486	14.58
4	369	14.76
5	280	14.00
6	213	12.78
7	162	11.34
8	123	9.84
9	93.3	8.39
10	70.8	7.08

II Continuous Thickener Analysis

Raw Data:

Height of Sludge Layer (cm)	Total Pressure ($\bar{\sigma}_T$ - dynes/cm ²)	Piezometric Pressure (\bar{p} - dynes/cm ²)	Suspended solids (g/l)
0 (underflow)	-	-	38.69
10	166.25	118.51	24.2
20	124.10	89.82	17.8
30	89.82	68.69	14.7
40	68.69	61.58	12.6
46 (height of thickening zone)	-	-	8.5
60	52.84	-	0.75

a) Simultaneous plots of the height of the sampling port versus suspended solids concentration, $\bar{\sigma}_T$ - and \bar{p} - pressure were generated - See Figure 12. The $d\bar{p}/dx$ was determined graphically. The following example calculation included only every other concentration.

Concentration (g/l)	Height (cm)	$\Delta \bar{p}$	Δx	$\frac{\Delta \bar{p}}{\Delta x} = d\bar{p}/dx$
11	43.5	85	112.0	0.7589
13	38.5	115	80.0	1.4375
15	28.0	126	70.5	1.7872
17	22.0	132	65.0	2.0307
19	17.5	137	60.5	2.2644
21	14.0	139	58.0	2.3965
23	11.8	140	56.5	2.4779
25	9.9	141	55.5	2.5405

b) Overall mass balance was necessary. See Table 2.

Example: Height of sludge layer = 46 cm.

$$\begin{aligned} Q_{in}c_{in} - Q_o c_o &= Q_u c_u \quad (\text{From Table 2}) \\ (1.0606 \text{ g/min}) - (0.0312 \text{ g/min}) &\approx 0.9479 \text{ g/min} \\ 1.0294 \text{ g/min} &\approx 0.9479 \text{ g/min} \end{aligned}$$

Average of 1.0294 and 0.9479 = 0.98865 g/min

Loading (using average value):

$$\begin{aligned} L_s &= 0.908375 \times 10^{-3} (Q_{in} \cdot c_{in}) \\ &= 0.908375 \times 10^{-3} (0.98865) \\ L_s &= 0.89806 \text{ kg/m}^2/\text{hr} \end{aligned}$$

Corrected Rate of Underflow

$$\begin{aligned} Q_u &= \frac{L_s}{(0.908375 \times 10^{-3}) (c_u)} \quad (c_u = 38.69 - \text{See Table 2}) \\ Q_u &= \frac{0.89806}{(0.908375 \times 10^{-3}) (38.69)} \\ Q_u &= 25.55 \text{ ml/min} \end{aligned}$$

Having determined Q_u and c_u , we were able to specify a concentration, c_i , and determine the corresponding superficial velocity, $(v_s - v_1)n$, by applying equation 12. A computer program, CONTH, was written to eliminate repetitive calculations.

This program uses equation 12 to generate the values of superficial velocity [in both meters /hr and cm/sec] that correspond to incremental concentrations [c_i] over the range c_b to c_u .

Input variables that must be specified are the rate of underflow, Q_u (ml/min) and underflow suspended solids concentration c_u (g/l).

A Program CONTH and an example of output is given in [14].

- c) For each profile, values for concentrations and the corresponding values for \overline{dp}/dx and superficial velocities were then available. Given concentration, \overline{dp}/dx , and the superficial velocity $(v_s - v_l)n$, computer program CPLRY calculates values of effective diameter and the corresponding shear stress on the capillary tube. The listing of a program CPLRY and an example [14] show results for concentrations of 13, 15, 17 and 19 g/l.

This procedure was followed for each steady state profile that was taken. Thus, three profiles were obtained; there were three data points for each concentration.

Figure 13 is a plot of capillary diameter δ , versus shear stress τ . The three points for each concentration represent the three steady state profiles. A straight line fit by linear regression yielded the required δ_0 .

- d) The intercept, δ_0 , was corrected for possible error. Figure 13 is a plot of all the δ_0 intercepts. A best fit line is drawn through these points and the corrected values of δ_0 recorded.
- e) The effective pressure, the difference between total and piezometric was determined for corresponding suspended solid concentrations.

Example - See part A of Appendix

Effective Pressure dynes/cm ²	Concentration g/l
47.74	24.2
34.28	17.8
21.13	14.7
7.11	12.6

Figure 15 is a plot of all data points obtained from all steady state profiles. The equation that describes best fit line was found to be:

$$c = 8.79 + 0.1974 (\sigma)$$

This equation was required in the final computer program, DEPTH [14].

- f) The density of solids, d_s must be determined. See Figure 2, Equation 19.

For 20 g/l = 0.020 g/ml, density = 1.0051213 g/ml

density of water = 0.9986493 g/ml

$$d_s = \frac{(0.020)\text{g/ml} \times (0.9986493) \text{ g/ml}}{(0.020)\text{g/ml} + (0.9986493) \text{ g/ml} - (1.0051213) \text{ g/ml}}$$

$$d_s = \frac{.0199729}{.0135280}$$

$$d_s = 1.476418 \text{ g/ml}$$

- g) To consider the effect of temperature, the Kos model requires only the specification of the viscosity of water at the desired temperature. This was input into the program DEPTH at line 80, AM = the values of viscosity.

Temperature	Viscosity
20.5 ⁰ C	0.010216
15.0 ⁰ C	0.011452
10.0 ⁰ C	0.013097
5.0 ⁰ C	0.015201

The information required for Kos' mathematical model was then available. The computer program DEPTH is capable of simulating thickening zone information for any given operating conditions. Output included the depth of the thickening zone, the suspended solids concentration at that depth and the piezometric, effective, and total pressure distribution in the continuous gravity thickener. Figure 16 was the result of the computer output when a solids loading rate of 0.89806 kg/m²/hr and an underflow concentration of

38.69 g/l were specified as the operating conditions. Results are shown. It must be noted that the depth of the thickening zone was measured from the top to the bottom. Program DEPTH can be used to determine the relationship between the aforementioned input and output variably over a specified range. For each solids loading rate, the underflow concentration that corresponded to 150 cm was plotted. Since, there were four temperatures considered, Figure 21 yields four curves, showing the effect of the temperature.

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