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A GENERALIZED COMPUTER MODEL FOR STEADY-STATE PERFORMANCE OF THE ACTIVATED SLUDGE PROCESS

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A GENERALIZED COMPUTER MODEL

FOR

STEADY-STATE PERFORMANCE OF THE ACTIVATED SLUDGE PROCESS

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INTRODUCTION

Mathematical models used to represent the activated sludge process in the past have covered a bewilderingly wide range of forms. The different forms correspond to differing sets of assumptions concerning the hydraulic and biological relationships believed to be significant in the particular biological system under study.

Because of the problems of measurement and the difficulty of fitting data to complex models, researchers often use simplified models which either omit or make some plausible assumption concerning the role of various factors in the process.

In this way a multiplicity of models many of which are basically different have been proposed and used in correlating measurements made on the activated sludge process.

The purpose of this report is to examine the whole range of models which have been used in the past and to investigate by means of analysis and computation the differences and similarities between them. Particular attention will be given to graphical or computational methods which can be used to evaluate the characteristic parameters of the process from the experimental data.

For this purpose two digital computer programs have been developed. The first (CSSAS)* is a steady state model of the conventional activated sludge process which is flexible enough to simulate any of the models proposed. The second digital program (FADAS)** attempts to simulate the biological activity in a fill and draw bench experiment in which activated sludge is mixed with substrate in any proportions.

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* Continuous Steady State Activated Sludge
** Fill and Draw Activated Sludge

The researcher who wishes to select a mathematical model for the activated sludge process has many choices. An almost unlimited number of models can be synthesized by making selections from the various ideas presented in the literature relating to each of the following basic questions.

1. What mixing model best represents the flow regime in the aerator?

2. What is the form of the equation expressing the time rate of synthesis of substrate into new cells?

3. What factors control the yield coefficient, the death rate of cells, the basal metabolism requirements, and the return to solution of lysed cells? To what extent are non-biodegradable metabolic end products produced?

4. What is the fate of colloidal and particulate biodegradable matter in the aerator? How can the accumulation of non-biodegradable particle in the system be expressed?

5. What factors control the nitrifying bacteria which convert ammonia to nitrates?

6. How can the oxygen requirements of the system be computed?

7. How can the performance of the final settler be expressed in terms of the efficiency for removing particulate from the liquid phase and in terms of the sludge compaction characteristics?

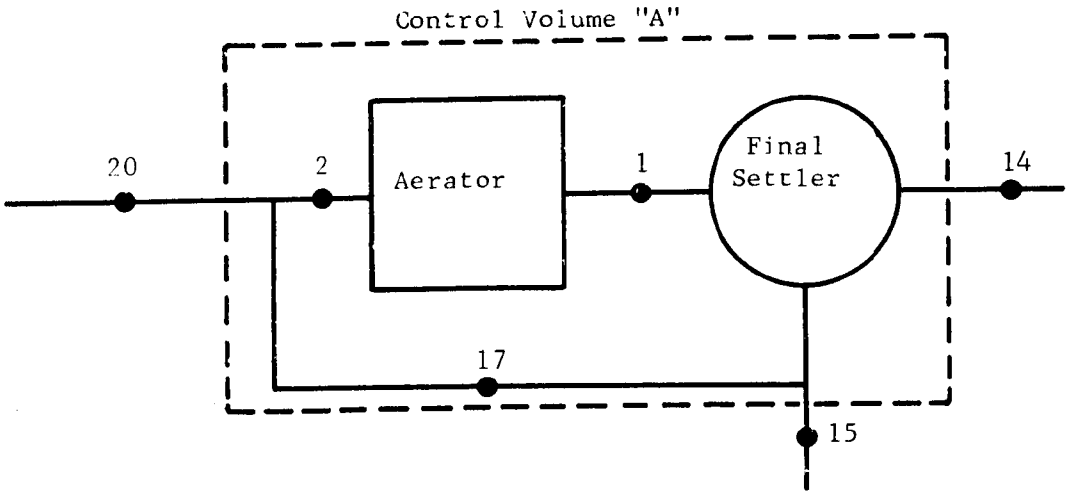
8. What is the effect of secondary parameters such as water temperature, dissolved oxygen concentration, pH, toxic substances, etc.?

The answers to these questions can be determined only by an objective study of available data. The data in most instances is inadequate to give satisfactory answers. These questions, however, should be considered, at least, in developing models for the activated sludge process. The digital computer programs (CSSAS and FADAS) described in this report

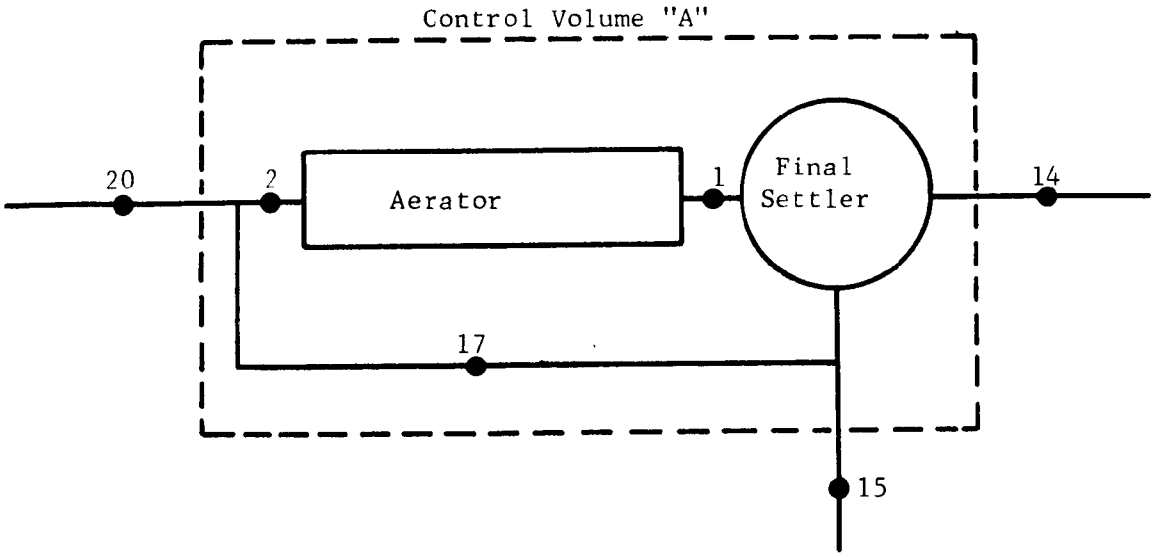
were designed to investigate the consequence of alternative assumptions for the above questions and to act as a tool for analysis of measurements made on the activated sludge process. A discussion of each question listed on the previous page will be given first. Next, available graphical techniques are discussed. Finally, both programs will be described fully and computed results together with measurements from several bench scale and full-sized processes will be presented.

1. WHAT MIXING MODEL BEST REPRESENTS THE FLOW REGIME OF THE AERATOR?

The first place where dissimilarities develop in models for the activated sludge process is in the hydraulic (mixing) assumptions. The two limiting conditions for a single tank are completely mixed (Figure 1a) and plug flow (Figure 1b). The completely mixed assumption is equivalent to assuming that each element of wastewater which enters the tank is immediately dispersed uniformly throughout the volume of the tank. The plug flow condition can be understood by visualizing the tank as being made up of a number of completely mixed sub-volumes in series and then allowing the number of sub-volumes to increase without limit. The mixing regime which fits any particular process can then, hopefully, be found somewhere between these two limits by assuming that the aerator behaves like some number of completely mixed tanks in series. It has been found that ten tanks are almost sufficient to adequately represent the plug flow condition. The digital computer program (CSSAS) provides for setting the number of tanks in series to any number between one and ten. Various other more complicated mixing models including such ideas as "stagnant zones" or "short-circuiting" have been proposed but other massive uncertainties surrounding the activated sludge process make it very unlikely



a. Completely Mixed Reactor with Recycle



b. Plug Flow Reactor with Recycle

Figure 1

that anything more complex than some intermediate point between these two limiting mixing models will be justified in models for the activated sludge process. This intermediate point can hopefully be represented by some number between one and ten of equal volume completely mixed sub-aerators.

2. WHAT IS THE FORM OF THE RATE EQUATION EXPRESSING THE TIME RATE OF SYNTHESIS OF BIODEGRADABLE MATTER INTO NEW CELLS?

All mathematical representations for the activated sludge process are expressed in terms of mass balances with the emphasis on mass balances around the aerator. For example, using Figure 1a, representing a single completely mixed aerator, we can write the following mass balance around the aerator for active cells.

$$V \frac{dX_1}{dt} = Q_2(X_2 - X_1) + G - D_e \qquad (1)$$

G = growth of cells in the aerator per unit time, (lb/day)/8.33
D_e = death of cells in the aerator per unit time, (lb/day)/8.33

Since X_1 and X_2 are related through the recycle stream (17); the first term on the right of equation (1) can be rewritten in a more convenient form. Assuming that no significant amount of biological activity occurs in the settler (shown by Reid[2]) the following mass balance relationships can be written.

$$X_1 Q_1 = Q_{14}X_{14} + Q_{15}X_{15} + Q_{17}X_{17}$$

Also, by assuming that stream (20) contains no significant amount of active cells the following relationship follows:

$$X_2Q_2 = Q_{17}X_{17}$$

Subtracting these two equations:

$$Q_2(X_2 - X_1) = -(Q_{14}X_{14} + Q_{15}X_{15})$$

Equation (1) can, therefore, be rewritten as equation (2) below. This is equivalent to writing the mass balance for active cells around control volume "A".

$$V \frac{dX_1}{dt} = G - D_e - (Q_{14}X_{14} + Q_{15}X_{15}) \qquad (2)$$

A similar mass balance can be written about the aerator for substrate as follows.

$$V \frac{dS_1}{dt} = Q_2(S_2 - S_1) - G/Y \qquad (3)$$

Y = yield coefficient, lb cells synthesized/lb substrate utilized

If we assume the substrate in stream (1) to be dissolved, S_2 can be related to S_1 in the following way.

$$Q_2S_2 = Q_{20}S_{20} + Q_{17}S_1$$

$$Q_1S_1 = (Q_{14} + Q_{15} + Q_{17})S_1$$

therefore,

$$Q_2(S_2 - S_1) = Q_{20}S_{20} - (Q_{14} + Q_{15})S_1$$

Again, writing a mass balance about the aerator is equivalent to writing a mass balance about control volume "A".

An important consequence of this transformation is elimination of the need for consideration of the recycle stream No. 17. Some authors such as Ramanathan and Gaudy[3] and Reynolds and Yang[4] appear to believe that the volume of the recycle stream is a significant parameter in controlling the operation of the completely mixed activated sludge process. This point will be reexamined later where it will be shown that Q_{17} must be considered when more than two sub-aerators are used.

Noting that the sum of Q_{14} and Q_{15} equals Q_{20} and the substrate at stations (1) and (14) has been assumed to be dissolved, equation (3) can be rewritten as follows.

$$V \frac{dS_1}{dt} = Q_{20}(S_{20} - S_{14}) - G/Y \tag{4}$$

The steady state solutions to equations (2) and (4) are easily obtained by setting the left-hand term equal to zero. The following expression for substrate removal in the activated sludge process is obtained from the steady state solution of equation (4).

$$S_{14} = S_{20} - G/Y/Q_{20} \tag{5}$$

This relationship can be used to effectively correlate data if the form of G is known and the assumption that substrate is wholly dissolved at station (1) is justified. With some notable exceptions, the growth (G) and death (D) of microorganisms per unit of time is generally agreed to be directly proportional to the number of microorganisms present, that is, to the product of the aerator volume (V) and the concentration (X) of microorganisms (expressed as dry weight per unit volume). Garrett and Sawyer[5] showed this to be true through experimentation with mixed cultures and a synthetic dissolved substrate prepared to simulate natural sewage. It is, therefore, more convenient to discuss the growth of microorganisms in terms of the growth per pound of microorganisms present expressed as $G^* = G/(VX)$. The units of G^* are (lb/day)/lb or $days^{-1}$. Similarly, it is reasonable to express the death of microorganism as $K_e = D_e/VX$. Most of the discussion found in the literature is concerned with finding the form of the relationship between G^* and the concentration of substrate (S) or other growth limiting nutrient surrounding the bacteria. G^* is known to

have a value of zero when (S) falls below some limiting value; usually taken as zero concentration. It is also known that G* has some maximum asymptotic value which is approached as the concentration of limiting nutrient becomes very large. Various relationships have been proposed in the literature to express these ideas quantitatively.

Penfold and Norris[6] were among the first to observe that the doubling time, T_d, for bacteria (B. typhosis) varies inversely with the concentration of limiting nutrient. This can be expressed as follows. k_1 and k_2 are constants.

$$T_d = k_1(1/S) + k_2 \tag{5a}$$

If we assume the concentration of limiting nutrient (S) to be fixed; the growth of bacteria can be expressed as follows.

$$G^* = \text{a constant}$$

$$G = G^*(VX) = d(VX)/dt$$

$$dX/X = G^* \cdot dt$$

$$\ln(X/X_o) = G^* \cdot \Delta t$$

The time, Δt, for the weight of bacteria to double is then given as follows.

$$T_d = \ln(2)/G^* \tag{6}$$

Substituting this into equation 5a we obtain the following:

$$1/G^* = k_3(1/S) + k_4 \quad \text{Where } k_3 = k_1\ln(2) \text{ and } k_4 = k_2\ln(2) \tag{7}$$

Monod[7] found that G* could be related to the concentration of growth limiting nutrient in the following way.

$$G^* = \frac{K_r S}{K_s + S} \tag{8}$$

Taking the inverse of both sides of this equation we obtain the following.

$$1/G^* = \frac{K_s}{K_r}\frac{1}{S} + \frac{1}{K_r} \tag{9}$$

Notice the similarity between equations (7) and (9). Relationships proposed by Penfold and Norris and Monod are essentially the same. Schulze[8], working with Eschericia coli in a continuous flow reactor found that measured values fit the following type of equation. This form had apparently been suggested previously by Teissier[9].

$$G^* = K_r(1 - e^{-aS}) \tag{10}$$

K_r = maximum growth rate, day^{-1}

a = a constant

It will be shown later that this form is almost equivalent to the Monod relationship.

Garrett and Sawyer[5] and Eckenfelder and McCabe[10] have proposed a two phase discontinuous relationship between G* and S as follows:

$$G^* = K_{r1}S \qquad \text{for } S < S^* \tag{11}$$

$$G^* = K_{r2} \qquad \text{for } S > S^* \tag{12}$$

Garrett and Sawyer noted that the disagreement between measurements and this discontinuous function was greatest at the point of discontinuity. Garrett and Sawyer also stated the opinion that this type of function fit the measurements made by Monod better than the relationship proposed by Monod (equation 8).

Rao, Gaudy, and Ramanathan[11] investigated the form of the relationship between G* and substrate concentration (S) using a synthetic substrate containing a carbon source of 1000 mg/l of glucose. They found the Monod relationship allowed a better fit of the data than either the Schulze or the following expression suggested by Moser[12].

$$G^* = K_r/(1 + K_s^{\ x} S^{-x}) \qquad (13)$$

Rao Gaudy and Ramanathan also found the relationship between G* and S to depend on the detention time (V/Q). The rate of growth was generally greater for the short detention time (3 hr.) and least for the longer detention times up to 24 hr. Finally, McKinney[13] and Smith[14], unlike most other investigators, do not accept the hypothesis that the growth of microorganisms in the aerator (G, lb/day) is directly proportional to the amount of microorganisms present. Indeed, Smith asserts that the active solids can range from 6-2500 mg/l without affecting the growth rate G. Since it was found by Frazier[15] that active solids represented about 27% of the mixed liquor suspended solids, this corresponds to a range of 22-9250 mg/l for mixed liquor suspended solids. McKinney's findings can be summarized as follows:

$$G = k_4 S \quad \text{for food/microorganism} < 2.1 \qquad (14a)$$

$$G = k_5 X \quad \text{for food/microorganism} > 2.1 \qquad (14b)$$

Food is measured in terms of ultimate oxygen demand (mg/l) and microorganisms as dry weight of microorganisms per liter. Clearly, equation (14a) applies to most practicable wastewater treatment applications.

Typical values for process constants taken from the literature are given below for domestic sewage and pure substrates at 20°C. Downing and Wheatland[16] suggested the following values for use with the Monod relationship for cell growth.

$K_r = 4.8\ \text{day}^{-1}$

$K_s = 150$ mg/l (5-day BOD)

$Y = 0.50$ lb volatile suspended solids/lb 5-day BOD

The Monod relationship using these values is shown in Figure 2.

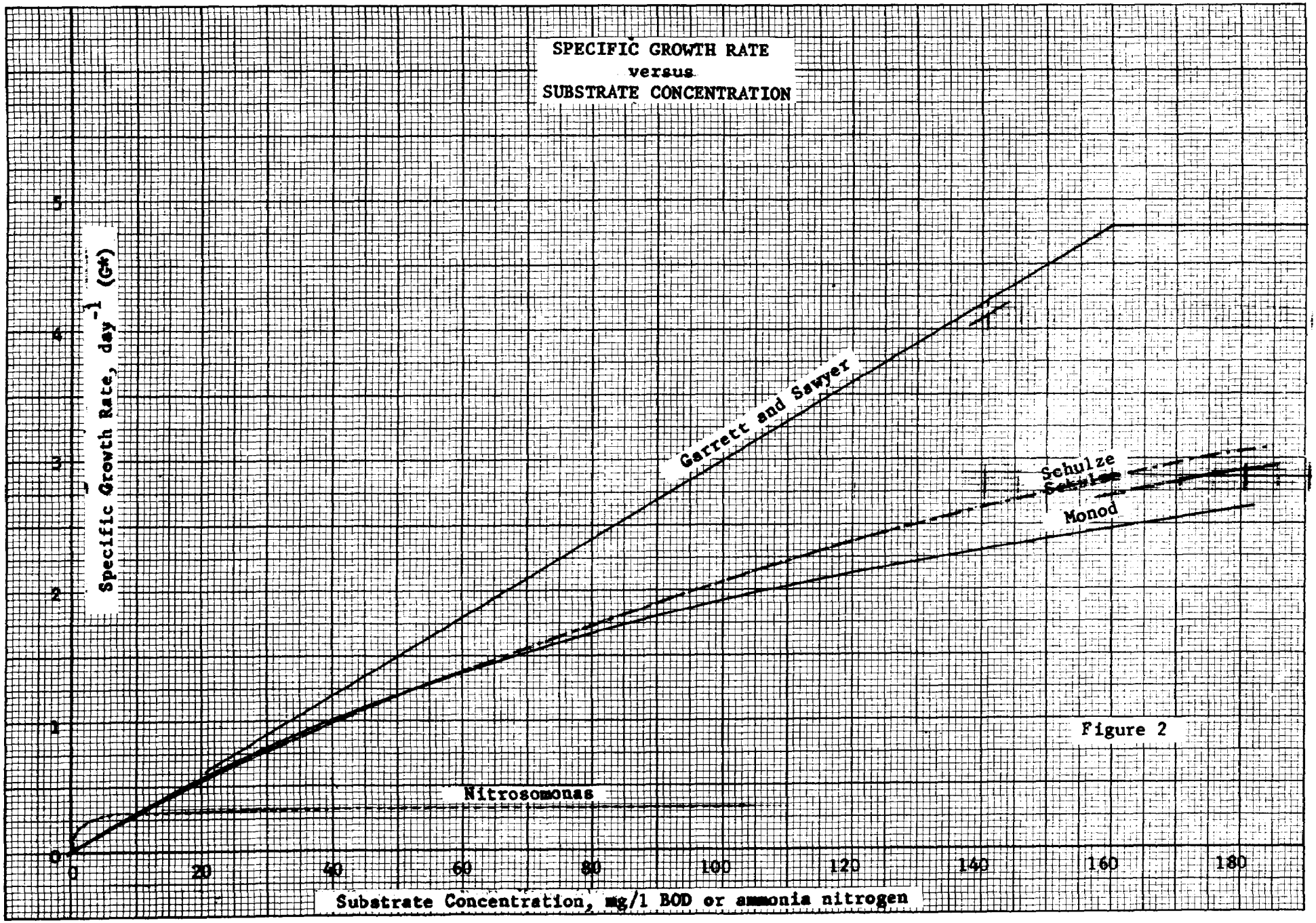

SPECIFIC GROWTH RATE
versus
SUBSTRATE CONCENTRATION
Specific Growth Rate, day^{-1} (G*)
Garrett and Sawyer
Schulze
Monod
Nitrosomonas
0
20
40
60
80
100
120
140
160
180
Substrate Concentration, mg/l BOD or ammonia nitrogen

Figure 2

Garrett and Sawyer[5] found the break point for the two phase discontinuous relationship (11) and (12) to occur at about 160 mg/l (5-day BOD). Garrett and Sawyer also found the maximum value for G* to be 1.92 day^{-1} at 10°C, 4.8 day^{-1} at 20°C and 7.2 day^{-1} at 30°C. Garrett and Sawyer used a dissolved synthetic sewage. The Garrett and Sawyer relationship for 20°C is shown in Figure 2.

Schulze[8], using a pure culture of Escherichia coli, found a maximum value for G* of 18.2 day^{-1} and a value for the constant (a) of (0.014). An equation of the form suggested by Schulze can be shown to (Figure 2) fall very close to the Monod relationship if the following constants are used.

$$G^* = 4.6(1 - e^{-.006S}) \tag{16}$$

Some of the best work with pure substrate and mixed cultures has been reported by Gaudy, Ramanathan, and Rao[11]. They found a range of values from 9.35 day^{-1} to 13.1 day^{-1} for K_r in the Monod relationship. Values found for K_s in the Monod relationship ranged from 35-138 mg/l glucose. The reactor temperature was 25°C. As mentioned previously, they found a strong dependence of both K_r and K_s on detention time. Much additional work has been performed using pure cultures and pure substrates but these experimental values are of little usefulness in estimating the constants for domestic sewage.

When the flow regime for the aerator is assumed to be <u>plug flow</u> as shown in Figure 1b the computed aerator performance differs significantly from the completely mixed case. The most important difference is greatly increased synthesis for the same detention time using the plug flow aerator. Recycle ratio (Q_{17}/Q_{20}) also has an effect on performance in the

plug flow aerator system. Recycle is determined, in part, by the compaction ratio (URSS = (X_{17}/X_1)). It should be emphasized that consideration of the plug flow aerator is only of academic interest since most real aerators more closely approximate one or two completely mixed tanks. The performance of the plug flow aerator system shown in Figure 1b can be solved in closed form if we make the following simplifying assumptions.

1. Endogenous respiration rate equals zero
2. Substrate completely dissolved
3. No loss of active cells from the system at station 14

From assumption (1) above, the following relationship between substrate and heterotrophs across the aerator can be written.

$$X_1 - X_2 = Y(S_2 - S_1) \tag{17}$$

By combining (17) with the Monod expression for growth shown in equation (8) a differential equation is found which when integrated takes the following form.

$$(H + 1)\log_e(X_2/X_1) - H\cdot\log_e(S_2/S_1) = -K_rT \tag{18}$$

where

$$H = K_sY/(X_1 + YS_1)$$

$$T = V/Q_1 = V/(Q_{20}(1 + p))$$

$$p = Q_{17}/Q_{20}$$

If we take X_1 and S_1 as independent parameters, the following expressions for p, (X_1/X_2) and (S_2/S_1) can be computed from the following mass balance expressions which relate to Figure 1b.

$$p = \frac{1 - Y\left[S_{20} - S_1\right]X_1}{URSS - 1} \tag{19}$$

$$\frac{X_2}{X_1} = \frac{p \cdot URSS}{1 + p} \tag{20}$$

$$\frac{S_2}{S_1} = \frac{S_{20}/S_1 + p}{1 + p} \tag{21}$$

Some sample computations have been made using equations (18), (19), (20), and (21). The following values were used for the constants.

S_{20} = 130 mg/l 5-day BOD

K_r = 4.8 days^{-1}

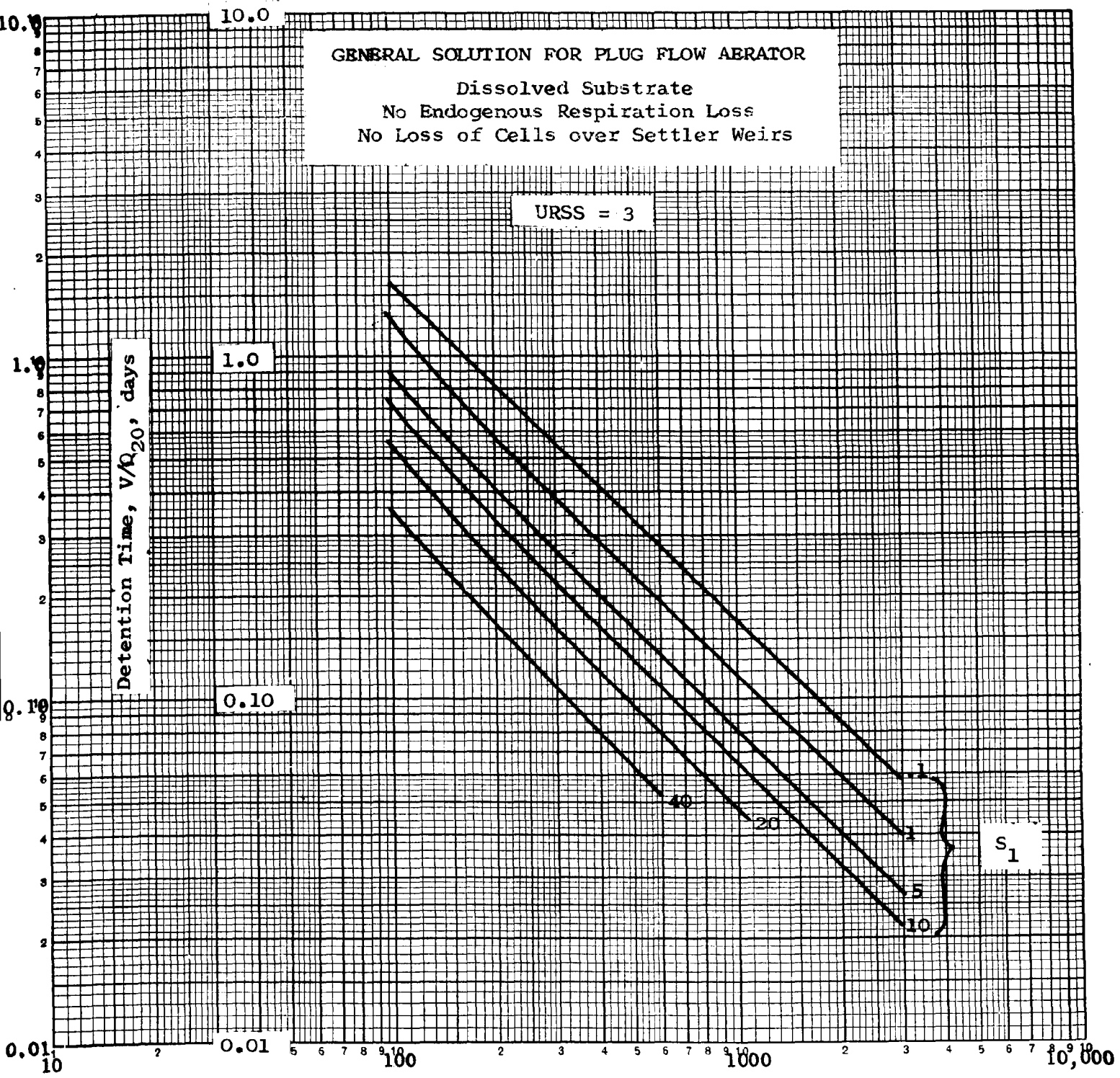
K_s = 150 mg/l 5-day BOD

URSS = 5.0, 3.0, 2.0

Detention time is defined as the volume of the aerator divided by the volume flow at station (20). The computed detention time (days) for combinations of X_1 and S_1 are shown in Figure 3. A value of (3.0) for URSS was used in computing the data shown in Figure 3. The effect of different values for URSS is shown in Figure 4. Changing the value of URSS from (5.0) to (2.0) increases the required detention time about 20%. This is not a major effect and since plug flow is not realizable in the real world, it is probably more correct to say that performance is independent of recycle than to consider recycle as a primary parameter.

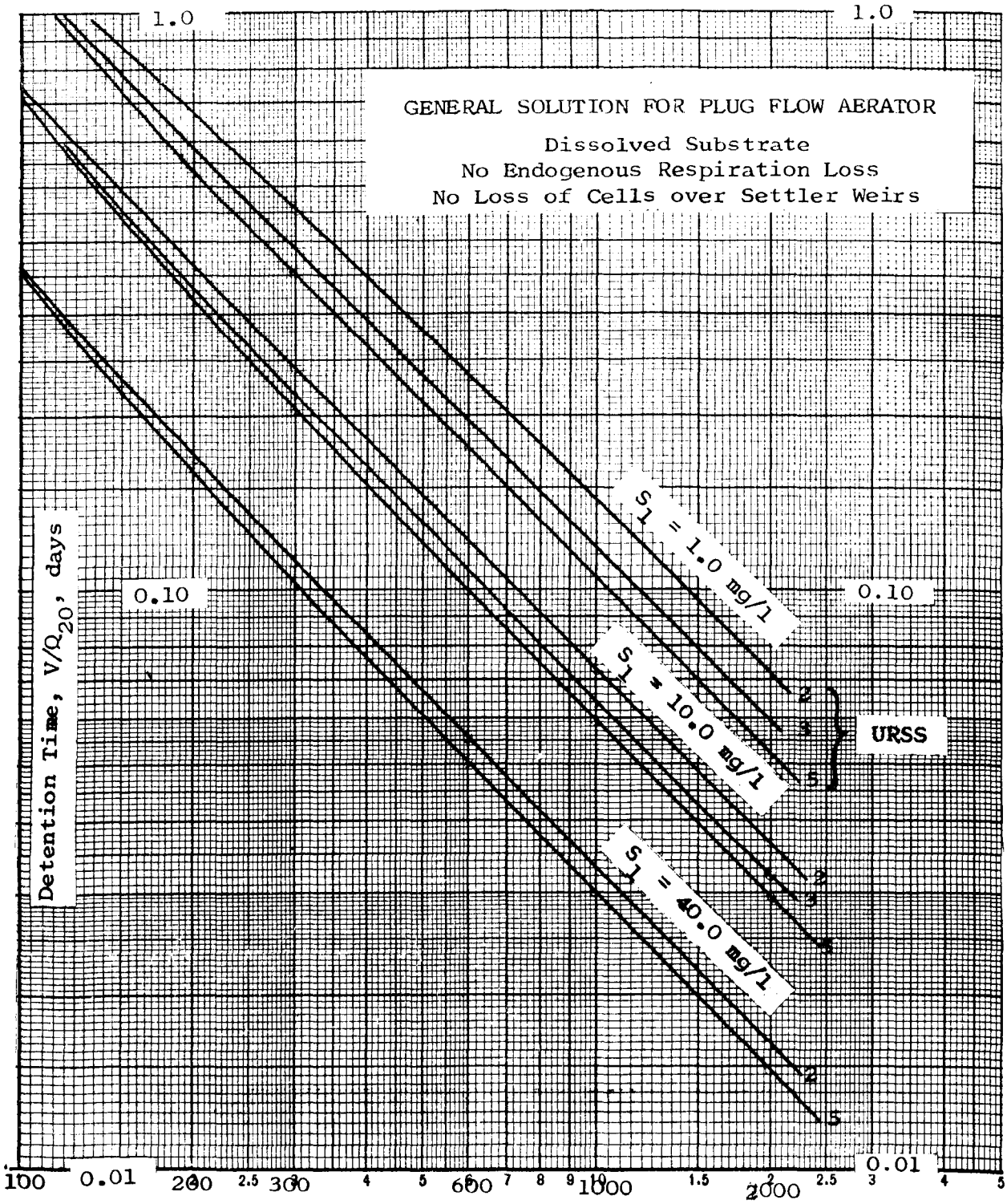
3. <u>WHAT FACTORS CONTROL THE YIELD COEFFICIENT, THE DEATH RATE OF CELLS, THE BASAL METABOLISM REQUIREMENTS, AND THE RETURN TO SOLUTION OF LYSED CELLS? TO WHAT EXTENT ARE NON-BIODEGRADABLE METABOLIC END PRODUCTS PRODUCED?</u>

The stoichiometric factors to be considered in selecting a model for the activated sludge process are illustrated in Figure 5. Substrate (5-day BOD or ammonia nitrogen) is combined with dissolved oxygen to produce new



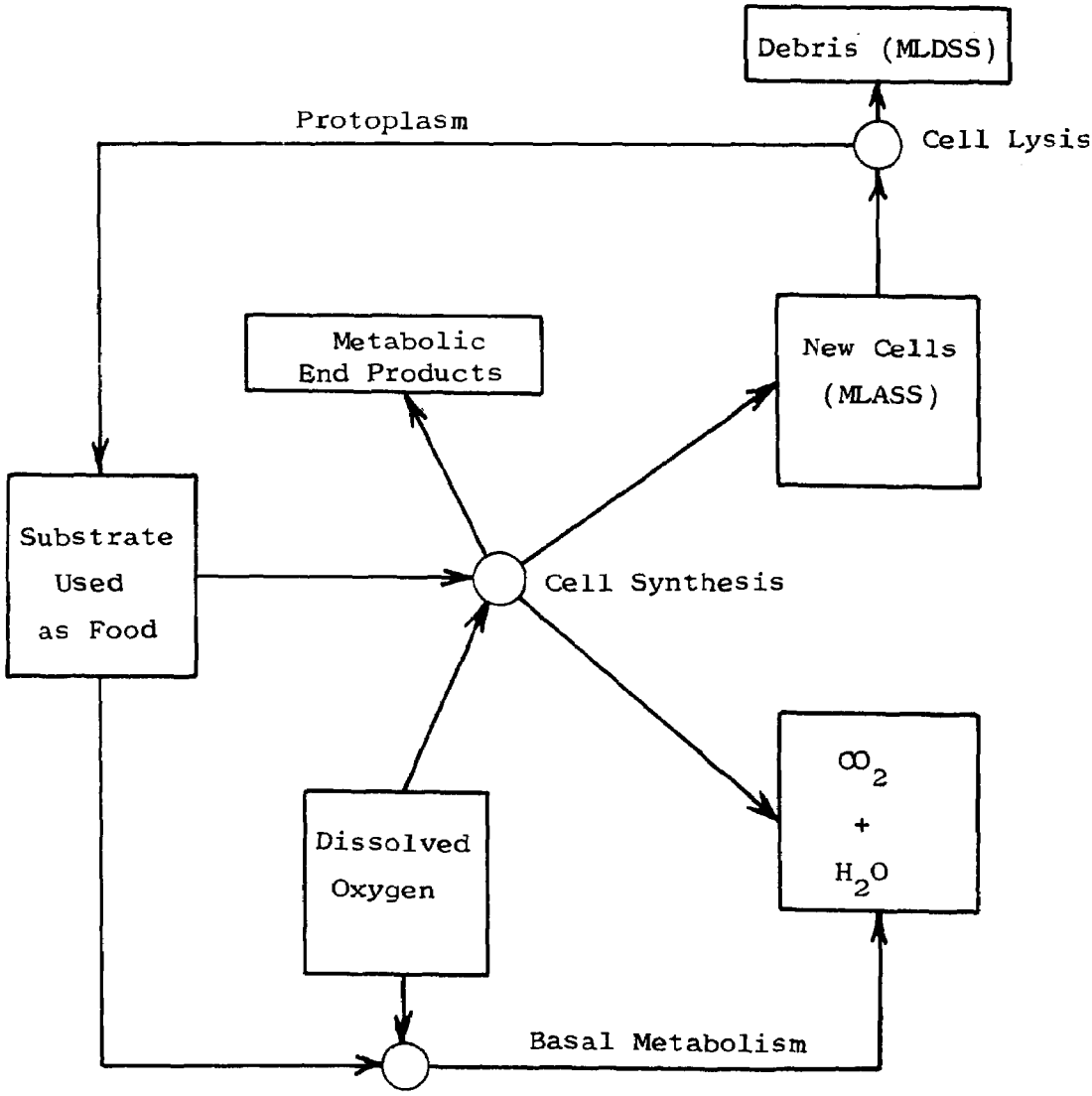
Concentration of Heterotrophs at Station No. 1, mg/l

FIGURE 3



Concentration of Heterotrophs at Station No. 1, mg/l

FIGURE 4



STOICHIOMETRIC PATHWAYS FOR
ACTIVATED SLUDGE

FIGURE 5

cells, carbon dioxide and water, and non-biodegradable end products. About ½ lb of heterotrophs are produced per lb of 5-day BOD utilized while only about 5/100 lb of Nitrosomonas are produced per lb of ammonia nitrogen utilized. The viable cells in the aerator use substrate and dissolved oxygen for vital cellular activity, respiration, and locomotion. This is referred to as basal metabolism or endogenous respiration. Dissolved non-biodegradable end products are difficult to distinguish from dissolved non-biodegradable organics entering the system in the feed stream. Jenkins and Garrison[17] estimate the dissolved non-biodegradable organics in a well operated activated sludge process as 30-40 mg/l COD. Eckhoff and Jenkins[18] measured the metabolic end products in a bench scale process using synthetic substrate as 5.56% of the influent COD.

It is generally recognized that a certain portion of the viable bacteria die and lyse each day and that a portion of the cell protoplasm returns to solution as substrate while a portion becomes particulate non-biodegradable material. The substrate requirement for endogenous respiration can be related to the oxygen used over and above oxygen requirements for synthesis. This is found to be about equal to the substrate released to solution as a result of cell lysis. Bhatla, Stack and Weston[19] in fill and draw experiments with activated sludge and natural substrates found that a kind of equilibrium is reached which they attribute to the rate of substrate utilization for synthesis becoming equal to the rate at which new substrate is supplied by cell lysis.

The quantity of cells produced by synthesis and the quantity lost by natural death or endogenous respiration has been estimated by many investigators. It is believed that a part of the organic substrate utilized

reappears in the form of new cells while the remaining part of the substrate utilized is oxidized to supply the energy necessary for synthesis. This is often expressed as follows:

$$COD_{Food} = COD_{Cells} + O$$

Dividing both sides by COD_{Food} gives:

$$1 = f_s + f_e \tag{22}$$

where f_s is the fraction of the substrate which reappears as viable cells and f_e is the fraction of the substrate oxidized.

The quantity of substrate utilized has been measured as COD, 5-day BOD, or ultimate carbonaceous BOD. Ultimate BOD is believed to be equivalent to about 90-100% of COD. The ratio between 5-day BOD and ultimate carbonaceous BOD varies with the value of the rate constant (k) in the following equation which represents the dissolved oxygen measured in the BOD test as a function of time.

$$y = L(1 - e^{-kt})$$

The ratio of 5-day BOD to ultimate BOD is about 0.9 for primary effluent and as low as 0.55 for secondary effluent. Cells produced by synthesis are about 90% volatile. The COD of cells produced by synthesis has been measured as 1.42 lb COD per lb of volatile solids.

The yield coefficient (Y) expressed as pounds of volatile suspended solids produced per pound of substrate (COD) utilized can, therefore, be found as follows:

$$Y_{COD} = f_s(1/1.42) \tag{23}$$

The fraction of substrate which reappears as cells has been estimated by McKinney[13] as 2/3. McCarty[20] has summarized measurements for this fraction

for various pure substrates and these values range from (0.63) to (0.28). Thus, McKinney concluded that 0.47 lb of volatile suspended solids are produced by utilization of one pound of ultimate BOD. Yield is believed to be independent of water temperature.

One of the first measurements of sludge production was made by Heukelekian, Orford, and Manganelli[21]. They found the following relationship to express the production of volatile suspended solids in terms of the 5-day BOD in the feed stream.

lb VSS/day = 0.5(lb 5-day BOD fed/day) - 0.055(lb VSS in aerator)

McCarty and Brodersen[22] in an analysis of measurements made by others concluded that the yield coefficient in terms of 5-day BOD removed was 0.65 lb VSS per lb 5-day BOD utilized. McCarty and Brodersen evaluated the endogenous respiration constant as (0.18). The endogenous respiration constant (K_e) is temperature dependent. McCarty[23] found the following relationship to hold:

$$K_e = K_{e28}(1.047)^{T-28} \qquad (24)$$

McCarty and Brodersen concluded that about 82% of the lysed cell is converted to $CO_2 + H_2O$ to meet endogenous respiration requirements while 18% of the cell is particulate non-biodegradable debris (MLDSS).

Sawyer[24] estimated the growth of volatile suspended solids in full-sized plants as (0.5) lb of volatile solids per lb of 5-day BOD removed from the influent stream. He also concluded that the yield coefficient is independent of water temperature.

Hetling, Washington, and Rao[25] performed experiments with pure cultures and pure synthetic substrates. They found the effective yield coefficient was not a constant but varied significantly with the substrate, the type of

organism, and with detention time. They found yield coefficients in the range of (0.16) to (0.35) in terms of mg of cells per mg of substrate COD. Measured values of K_e varied from 0.01 to 0.067.

Gaudy, Ramanathan, and Rao[11] found that yield coefficients measured in batch experiments were on the average, 45% smaller than yield coefficients measured in continuous experiments.

Postgate and Hunter[26] investigated the amount of substrate returned to solution as a result of cell lysis and concluded that it was negligable.

Klei[27] has found an interesting effect of increased pressure on the production of sludge in model activated sludge continuous experiments without recycle. He found a marked decrease in the amount of waste sludge formed when the pressure was greater than 60 psi gage.

To summarize, values for the yield coefficient vary over a considerable range depending on the kind of experiment, on the precision of measurements, and on the method used to evaluate the numerical value. The yield coefficient cannot be inferred or computed but must be evaluated from experimental data. The value of the yield coefficient does not appear to depend on temperature. The temperature dependent endogenous respiration coefficient is generally small and is sometimes combined with the growth relationship (G*) to give an effective growth rate. Substrate contributed by cell lysis is about equal to that required for endogenous respiration. Activated sludge effluent normally contains dissolved non-biodegradable COD equal to about 15% of the influent COD. One researcher found the COD of metabolic end products to be equivalent to about 5% of the influent COD.

4. WHAT IS THE FATE OF COLLOIDAL AND PARTICULATE BIODEGRADABLE MATTER IN THE AERATOR? HOW CAN THE ACCUMULATION OF SOLIDS IN THE AERATOR BE EXPRESSED?

One of the most troublesome and complex problems associated with selecting a model for the activated sludge process is representing properly the character of the solids held in the aerator. Since new cells (MLASS) are continually produced in the aerator; solids must be removed continuously to hold the aerator solids at a stable value. The rate of sludge wasting is determined by the rate of substrate utilization and the yield coefficient. This required wasting rate then determines the concentration of various classes of solids present in the aerator. The six classes generally assumed to be present are listed below:

1. Active heterotrophs, MLASS, mg/l mass
2. Active nitrifying bacteria, mg/l mass
3. Organic biodegradable solids, MLBSS, mg/l mass
4. Organic non-biodegradable solids, MLNBSS, mg/l mass
5. Organic debris solids, non-biodegradable, MLDSS, mg/l mass
6. Inorganic solids, MLISS, mg/l mass

It will be shown later that the inorganic solids in the aerator (MLISS) are often largely attributable to precipitation of inorganic salts and not to inorganic particulate entering the process. Since the nature of this inorganic precipitation is not well known, we have chosen to omit this phenomenon from the model and to deal only with organic or volatile suspended solids. The total of all solids in the aerator considered by the model will, therefore, be called mixed liquor volatile suspended solids (MLVSS).

The small concentration of nitrifiers which is present when conditions are correct is also omitted from the computed value for MLVSS. This error is about 1-2% of the total MLVSS and, if necessary,

the program could be revised to account for this omission. The yield coefficient for Nitrosomonas is about 0.05 cells/lb N oxidized. The corresponding coefficient for Nitrobacter is 0.02 lb cells/N oxidized. The concentration of Nitrosomonas in the aerator is printed out and this plus the corresponding concentration of Nitrobacter can be added to MLVSS by hand if great precision is required. The difficulty associated with making this computation in the program is that the calculation assumes that sufficient air is supplied. If this is not the case, then nitrification cannot occur. In order to make the computation in the program, the air supplied and the transfer efficiency would have to be known.

The concentration of active heterotrophs (MLASS) is inferred from the computational scheme as that concentration which produces the best agreement between computed and measured values around the process. MLBSS is the concentration of organic solids in the aerator which are available for synthesis. To compute MLBSS, it is necessary to make some assumption about the relative biodegradability of dissolved and particulate fractions of the influent BOD. The two limiting assumptions are first, that only dissolved BOD is available for synthesis, and second, that both dissolved and particulate fractions are equally available. It will be shown later that the second of these assumptions allows better agreement between computed and measured values. The large variability of measured values and other uncertainties make intermediate assumptions seem impractical.

The particulate BOD over total BOD is called SFBOD in the program. This can be measured at station 20 and called $SFBOD_{20}$. It is then necessary to estimate SFBOD at station 1 in order to begin the computation. $SFBOD_1$ can be computed from $SFBOD_{20}$ using the following mass balance equations and the assumption that dissolved and particulate BOD are equally available. Let station 2 be upstream of the aerator and station 1 be downstream of the aerator.

$$S_{20}Q_{20}SFBOD_{20} + Q_{17}S_{17}SFBOD_{17} = (Q_{20}+Q_{17})S_2\ SFBOD_2$$

$$S_{17} = S_1(1-SFBOD_1) + S_1\ SFBOD_1\ URSS$$

$$S_2Q_2 = Q_{20}S_{20} + Q_{17}S_{17}$$

$$SFBOD_2 = SFBOD_1$$

These equations can be combined to give the following relationship for $SFBOD_1$ in terms of $SFBOD_{20}$ and other variables known or assumed in the computational scheme.

$$B = URSS - 1$$

$$A = \frac{S_{1,20}\,Q_{20}}{S_{1,1}\,Q_{17}}$$

$$SFBOD = \frac{B - A + \sqrt{(A - B)^2 + 4A \cdot B \cdot SFBOD_{20}/S_{1,20}}}{2B} \qquad (25)$$

If the normal range of values are substituted in this equation it can be shown that $SFBOD_1$ is always near in value to $SFBOD_{20}$. The computation, however, is made in the program. MLBSS is then computed as $S(1,1)*SFBOD_1/0.8$. Using this assumption the contribution of MLBSS to BOD in the effluent stream (14) is always small and the particulate fraction of BOD in the effluent is almost wholly due to MLASS.

One of the most critical elements of the model is to compute the concentration of organic non-biodegradable solids in the aerator (MLNBSS). If both total and dissolved BOD and COD are measured at station 20 this can be approximated in the following way:

$$\frac{\text{Biodegradable Volatile Suspended Solids}}{\text{Total Volatile Suspended Solids}} = \frac{\text{Ultimate Carbonaceous BOD of Particulate}}{\text{COD of Particulate}} \tag{26}$$

To solve this equation for biodegradable volatile suspended solids it is necessary to infer the ultimate carbonaceous BOD of the particulate from the measured 5-day BOD of the particulate. This rate constant has never been precisely determined but some measurements made by T. Margolies are given in Table I. In analysis of data from the Hyperion Plant the ratio of 5-day BOD to ultimate carbonaceous BOD was taken as (0.9). The non-biodegradable volatile suspended solids (VIS20) is then taken as total volatile suspended solids minus the biodegradable volatile suspended solids. The accumulation of MLNBSS in the aerator is then computed as follows:

$$\text{MLNBSS} = \frac{Q_{20}\ \text{VIS20}}{Q_{14}\ \text{XRSS} + Q_{15}\ \text{URSS}} \tag{27}$$

If we assume that 18% of the cells which die remain as non-biodegradable debris, the following mass balance can be written around control volume "A" for MLDSS:

$$Y(0.18)(S_{20} - S_1)Q_{20} = (\text{MLDSS} + .18\text{MLASS})(\text{XRSS}.Q_{14} + \text{URSS}.Q_{15}) \tag{28}$$

This equation can be solved for MLDSS.

TABLE I

STUDY OF 'K' VALUES OF OWL'S HEAD*
INFLUENT AND EFFLUENT

Composite and grab samples taken for analysis - Total and filtrate. Dilutions incubated at 20°C for 1,2,3,4, and 5 days for the purpose of determining reaction rates.

Date	Sample		Days Incubated at 20°C 1	2	3	4	5	'K' Values
3/16/53	Influent -	Total	43	85	101	122	136	0.132
		Filtrate	28	41	47	51	54	0.302
3/23/53	Influent -	Total	51	86	130	150	171	0.098
		Filtrate	30	44	63	71	75	0.168
4/6/53	Inf. Grab -	Total	45	81	109	132	143	0.114
	9:00 AM	Filtrate	27	48	67	76	83	0.122
	Inf. Grab -	Total	84	103	122	138	149	0.302
	10:00 AM	Filtrate	47	67	85	100	107	0.200
	Inf. Grab -	Total	50	140	217	295	337	0.102
	1:00 PM	Filtrate	47	85	115	134	141	0.132
4/21/53	Influent -	Total	82	118	147	170	185	0.208
		Filtrate	41	54	67	70	72	0.330
	Effluent -	Total	25	44	54	59	62	0.208
		Filtrate	14	27	37	41	43	0.145
4/13/53	Influent -	Total	56	76	92	104	116	0.240
		Filtrate	30	46	53	55	59	0.302
	Same-Dec -	Total	50	75	97	105	113	0.220
	added	Filtrate	27	37	45	52	56	0.236
	Decant -	Total	115	185	275	350	425	-----
		Filtrate	0	0	70	95	125	-----
	Effluent -	Total	22	39	47	56	59	0.168
		Filtrate	12	23	30	34	36	0.150
	Thickener -	Total	23	48	55	61	66	0.188
		Filtrate	12	25	32	36	39	0.140

* Measurements by T. Margolies

5. WHAT FACTORS CONTROL THE NITRIFYING BACTERIA WHICH CONVERT AMMONIA TO NITRATES?

Two species of autotrophic bacteria, Nitrosomonas and Nitrobacter are believed to be responsible for nitrification of ammonia nitrogen in the aerator. Nitrosomonas converts ammonia nitrogen to nitrite (NO_2^-) and Nitrobacter converts nitrite to nitrate (NO_3^-). Downing, et al.[31] has shown first, that the growth rate of both species of bacteria can be represented by the Monod relationship and second, that the growth rate of Nitrobacter is much greater than the growth rate of Nitrosomonas. It is generally true that the growth rate of Nitrobacter is sufficiently greater than the growth rate of Nitrosomonas that only the growth of Nitrosomonas need be considered in studying the nitrification of ammonia in the aerator. The following Monod equation constants were measured by Downing et al.[31] for Nitrosomonas at 20°C.

$$K_r = 0.33 \text{ day}^{-1}$$

$$K_s = 1.0 \text{ mg/l Nitrosomonas}$$

$$Y = 0.05 \text{ lb Nitrosomonas/lb } NH_3 - N$$

The principal environmental controls on Nitrosomonas are the water temperature and the specific wasting rate (D_c) which must be set to control the build-up of heterotrophic bacteria in the aerator. Since the maximum growth rate for Nitrosomonas is less than 10% of the maximum growth rate for heterotrophs (see Figure 2) the tendency is to waste nitrifying bacteria at a greater rate than it is possible to replace them by synthesis of new cells. The behavior of Nitrosomonas in the activated sludge process can be evaluated if we assume that the same values for XRSS

and URSS apply to both Nitrosomonas and heterotrophs. Then the same value of (D_c) must apply to both classes of bacteria. For lack of something better, this approach is usually taken in writing a mathematical model. The details of how this assumption can be used to compute the extent of nitrification will be given in the discussion of the CSSAS program which appears later in this report.

6. HOW CAN THE OXYGEN REQUIREMENTS OF THE SYSTEM BE COMPUTED?

Oxygen must be supplied to the aerator for three purposes:

1. Synthesis of new heterotroph cells
2. Endogenous respiration of heterotrophs
3. Synthesis of Nitrosomonas and Nitrobacter

Oxygen used in synthesis of new cells is, theoretically, related to the value used for the yield coefficient. The yield coefficient for heterotrophs can be based on utilization of COD, ultimate carbonaceous BOD, or 5-day BOD. Yield coefficient is defined as follows:

$$Y_{COD} = \text{(lb VSS formed)/lb COD utilized}$$

$$Y_{BOD_\mu} = \text{(lb VSS formed)/lb } BOD_\mu \text{ utilized}$$

$$Y_{BOD_5} = \text{(lb VSS formed)/lb } BOD_5 \text{ utilized}$$

If the ultimate BOD is estimated as 90% of COD and the ratio of 5-day BOD/ultimate BOD is taken as (0.9), the two ratios (5-day BOD/COD) and (Y_{COD}/Y_{BOD_5}) will have the value of (0.81). It was shown in equation (23) that Y_{COD} must be equal to ($f_s/1.42$). f_s can, therefore, be calculated from the 5-day BOD yield coefficient as follows:

$$f_s = Y_{BOD_5}\,(0.81)(1.42) = 1.15 \cdot Y_{BOD_5}$$

Using the input yield coefficient for heterotrophs, f_e (lb O_2/lb COD synthesized) can then be expressed as follows:

$$f_e = 1. - 1.15\ CY(1)$$

Converting to pounds of oxygen per pound of 5-day BOD the following final relationship is found:

$$\text{lb } O_2/\text{lb } BOD_5 \text{ used} = 1.235 - 1.42\ CY(1) \qquad (29)$$

It has been mentioned previously that the substrate utilized for endogenous respiration is about equal to 82% of the lysed cells. The mass of cells which lyse per day can be expressed as ($K_e \cdot MLASS \cdot VAER \cdot 8.33$). The oxygen requirement for endogenous respiration of heterotrophs can, therefore, be expressed as follows:

$$\text{lb } O_2 \text{ used/day} = (1.42)(.82)\ K_e \cdot MLASS \cdot VAER \cdot 8.33 \qquad (30)$$

In the work of Downing et al.[28] the growth of nitrifying bacteria was expressed as the effective growth so that no measurement was made of (K_e) for nitrifying bacteria. In computing oxygen requirements for nitrifying bacteria Downing et al. gives the following stoichiometric relationship:

$$2NH_4^+ + 4O_2 \longrightarrow 2NO_3^- + 2H_2O + 4H^+$$

Four moles of oxygen are, therefore, required to convert one mole of ammonia nitrogen to nitrate. The yield coefficient for Nitrosomonas is given as 0.05 lb of cells produced per lb of nitrogen converted. Thus, a negligible amount (0.8%) of the nitrogen used as food is converted to cell material. The pounds of oxygen required per pound of nitrogen converted to nitrate is therefore, 64/14 or 4.57.

7. HOW CAN THE PERFORMANCE OF THE FINAL SETTLER BE EXPRESSED?

The two principal performance parameters associated with the final settler are XRSS the fraction of mixed liquor suspended solids which escapes over the final weirs and URSS the compaction ratio. Both of these parameters are known to depend on the physical characteristics of the final settler and on the characteristics of the activated sludge. Characteristics of activated sludge are determined, in part, by the design and operating decisions adopted for the aerator.

Villiers[40] made settling column measurements on sludge from bench scale batch experiments. This work, which was performed at room temperature, yielded the following empirical expression for XRSS where (GSS) equals the settler overflow rate in gpd/sq ft, (MLSS) is the mixed liquor suspended solids concentration, mg/l, and (TA) is the aerator detention time (V/Q_{20}) in hours.

$$XRSS = \frac{556(GSS)^{0.494}}{(MLSS)^{1.82}(TA)^{0.439}} \tag{31}$$

The range of MLSS used by Villiers was 900-3800 mg/l. This relationship expresses the fact that XRSS is not a constant but becomes smaller as MLSS increases. The effect of water temperature is not shown and the expression tends to predict better performance than is generally realized in full-sized plants operating with MLSS in the range 300-500 mg/l.

In a recent study sponsored by Federal Water Pollution Control Administration (Contract No. 14-12-194) Rex Chainbelt Inc. attempted to find empirical relationships between key design parameters and the

efficiency (XRSS) and compaction ratio (URSS) for the final settler in the activated sludge process. The following relationship between BOD loading and Sludge Volume Index (SVI) was found:

$$SVI = 56.1 + 113.\ (\text{lb } BOD_5/\text{day/lb MLVSS})(1.05)^{T-20} \qquad (32)$$

where SVI = Sludge Volume Index

BOD_5 = 5-day BOD, mg/l

MLVSS = mixed liquor volatile suspended solids in aerator, mg/l

T = water temperature, degrees Centrigrade

This empirical relationship was based on 41 observations and the correlation coefficient was 0.78.

If we assume that the sludge concentration in the underflow stream from the settler is equal to concentration of the sludge in the SVI graduate cylinder after 30 minutes settling, the following mass balance relationship first derived by Bloodgood can be written.

$$\frac{Q_{15} + Q_{16}}{Q_1} = \frac{SVI\ MLSS}{10^6} = \frac{1}{URSS} \qquad (33)$$

By combining equations (32) and (33) a maximum value for URSS can be found from the BOD loading on the process. Of course, URSS can be set at any value below this maximum by increasing the pumping rate above that required to return the sludge at the maximum concentration.

Rex Chainbelt Inc. also derived the following equation for XRSS:

$$XRSS = \frac{382.\ (\text{overflow rate, gal./day/sq ft})^{0.12}(\text{BOD Loading})^{0.27}}{MLSS^{1.35}\ (\text{Detention Time})^{1.03}} \qquad (34$$

where BOD Loading = lb 5-day BOD/day/lb MLVSS

Detention Time = Aerator Volume, mg/Aerator effluent flow, mgd

The correlation coefficient for this empirical relationship was only 0.63 indicating a poor correlation.

Pflanz[38] of Federal Republic of Germany made measurements on the efficiency of the settler with aerator suspended solids ranging from 3000-10,000 mg/l. He found that a reasonably good relationship existed between suspended solids in the effluent and the surface solids loading rate expressed as kilograms/hr/ sq meter. He also observed a pronounced effect of water temperature. For example, at a surface solids loading rate of 2.0 the suspended solids in the effluent was 19 mg/l at 13-15^{o}C and about 42 mg/l at a temperature of 2-3^{o}C.

To summarize, no completely satisfactory method of estimating the efficiency and compaction ratio of the final settler has yet been presented. For this reason these two parameters were classified as input to the program.

8. WHAT IS THE EFFECT OF SECONDARY PARAMETERS SUCH AS WATER TEMPERATURES, DISSOLVED OXYGEN CONCENTRATION, pH, TOXIC SUBSTANCES, ETC?

Synthesis rate constants, CR(I), and endogenous respiration constants, CE(I), have both been shown to be temperature dependent. The yield coefficient, however, is believed to be independent of temperature. No temperature corrections are performed in the program. All synthesis and endogenous respiration constants must be temperature corrected by hand before being supplied to the program. Generally accepted relationships for temperature corrections are shown below.

$$CR(1) = CR(1)_{20}\ (1.047)^{T-20} \qquad \text{(for Heterotrophs)}$$

$$CE(1) = 0.1245\ (1.047)^{T-20} \qquad \text{(for Heterotrophs)}$$

$$CR(2) = 0.33\ (1.123)^{T-20} \qquad \text{(for Nitrosomonas)}$$

where $CR(1)_{20}$ = maximum rate constant for synthesis for heterotrophs, day^{-1}

T = water temperature, ^{o}C

No endogenous respiration constant is needed for Nitrosomonas because the rate constant for synthesis represents the net growth rate.

Although it has been suggested that the rate of synthesis increases with the dissolved oxygen concentration this has never been shown conclusively and no such relationship is included in the model.

Much work has been done on the effect of toxic substances but this kind of information has not been incorporated into the model.

One important effect which should be included in the model is the effect of adsorption in the contact stabilization process. The effect could be evaluated by using the program if sufficiently complete measurements were available. The contact tank should be a separate tank and not the downstream portion of the aerator. This effect will be evaluated when data becomes available.

GRAPHICAL ANALYSIS OF DATA FROM ACTIVATED SLUDGE PROCESS

To find relationships suitable for describing the efficiency of the activated sludge process as a whole we can substitute one of the alternative expressions for G* into equation (5). The most generally accepted forms of G* are the Monod expression (8) and the two phase relationship proposed by Garrett and Sawyer (11) and (12). Substituting equation (11) into equation (5) gives the following three equivalent forms:

$$1/S_{14} - 1/S_{20} = (K_{r1}/Y)(1/L) \tag{35}$$

$$\frac{S_{20} - S_{14}}{X \cdot T} = \frac{K_{r1} \cdot S_{14}}{Y} \tag{36}$$

$$\frac{S_{14}}{S_{20}} = \frac{1}{1 + K_{r1} T \, X/Y} \tag{37}$$

L = loading, lb 5-day BOD/day/lb active microorganisms, $Q_{20}S_{20}/VX$

T = detention time, days, V/Q_{20}

Substituting the Monod relationship (8) into equation (5) yields the following expression for efficiency of substrate removal:

$$1/S_{14} - 1/S_{20} = \frac{K_r}{Y(K_s + S_{14})} \quad (1/L) \tag{38}$$

Several problems are involved in using these equations to fit data from full-sized plants treating wastewater containing both particulate and dissolved biodegradable fractions. For example, the concentration of active microorganisms in the aerator (X) is difficult to measure. A measure of MLSS or volatile suspended solids is often substituted for (X). The implicit assumption is then made that active solids concentration is a fixed

percentage of the total or volatile solids concentration over the range of operating conditions studied. Second the assumption has been made that remaining substrate at stations (1) and (14) is totally dissolved. Actually, MLASS and MLBSS held in the aerator are known to exert a BOD and some solids are almost always found in stream (14). Mancini and Barnhart[32] attempted to account for this by measuring S_{14} as dissolved BOD only and then adding a term (Z, day^{-1}) to the righthand side of equation (36) to account for the BOD contributed by the particulate matter in stream (14). Jenkins and Garrison[17] have also recommended measurement of dissolved COD only at station (14) in attempting to describe the efficiency of the activated sludge process. Eckenfelder[33] has used equation (36) successfully to fit data from several full-sized plants.

Steady state expressions for the quantity of active solids produced by the process per unit of time can be found by first, setting the left-hand term of equations (2) and (4) equal to zero and second, solving for G* in each case as follows:

$$G^* = \frac{Q_{14}X_{14} + Q_{15}X_{15}}{V \cdot X_1} + \frac{D_e}{V \cdot X_1} \qquad (39)$$

$$G^* = \left[\frac{Q_{20}(S_{20} - S_{14})}{V \cdot X_1}\right] Y \qquad (40)$$

The grouping on the right-hand side of equation (40) which is multiplied by (Y) is known as the specific substrate removal rate (q), lb substrate utilized per lb of active microorganisms present. The first term on the right-hand side of equation (39) is called the specific waste rate (D_c), lb of active solids wasted per day per lb of active solids present in the

system. The second term on the right-hand side of (39) is the endogenous respiration coefficient (K_e), death rate of active solids, lb/day per lb of active solids in the system. Equations (39) and (40) can be summarized as follows:

$$D_c = qY - K_e \tag{41}$$

When it is possible to measure the concentration of active cells in the aerator and in streams 14 and 15, equation (41) can be used to evaluate the yield coefficient (Y) and the endogenous respiration constant, K_e, by plotting D_c versus q on a linear scale. The slope then corresponds to Y and the intercept to K_e. This is generally possible in bench scale experiments where dissolved substrates are used.

This procedure presents some difficulty, however, when used to analyze data from a full-sized activated sludge process in which a major fraction of the solids held in the aerator are inert. It can be reasonably assumed that the ratio of (X_{14}/X_1) equals the ratio (VSS_{14}/VSS_1) and that the ratio (X_{15}/X_1) equals the ratio (VSS_{15}/VSS_1) where VSS represents the concentration of volatile suspended solids, mg/l. D_c can therefore be seen to equal the following expression which can be measured.

$$D_c = \frac{Q_{14}VSS_{14} + Q_{15}VSS_{15}}{V(VSS_1)} \tag{42}$$

Since we cannot measure X_1 we cannot find a value for q directly. By using VSS_1 instead of X_1 we can measure q* as follows:

$$q^* = \frac{Q_{20}(S_{20} - S_{14})}{V(VSS_1)} \tag{43}$$

$$q^* = q(VSS_1/X_1)$$

Now if we plot D_c versus q* the slope will be equal to $Y(VSS_1/X_1)$ and the intercept will be K_e.

Equation (35) which is a linear relationship between inverse loading and the performance measure ($1/BOD_{out} - 1/BOD_{in}$) can be used to roughly correlate plant data. Data from various plants and bench scale experiments are shown plotted in this way in Figures 6 - 29.

As a management surveillance tool the slope of this linear relationship might be plotted as a function of time. Such a plot which is similar to a quality control chart would have the advantage of showing the overall performance of the process with respect to time. Increasing values for the slope indicate superior performance. Charts based on 24-hr composite measurements for the Hyperion Plant in Los Angeles and the Whittier-Narrows Plant near Los Angeles are shown in Figures 30 and 31. A horizontal limit line might be drawn on these charts such that points falling below the limit line might signal an upset in the process. In Figure 30 the gradual upward trend during the summer is probably due to increased sewage temperature. A correction for temperature should logically be made. During the winter months at Hyperion significant one month cycles can be noted. The Whittier-Narrows data shows a great random variation but some cycling seems to be present. The effluent BOD was total rather than filtered.

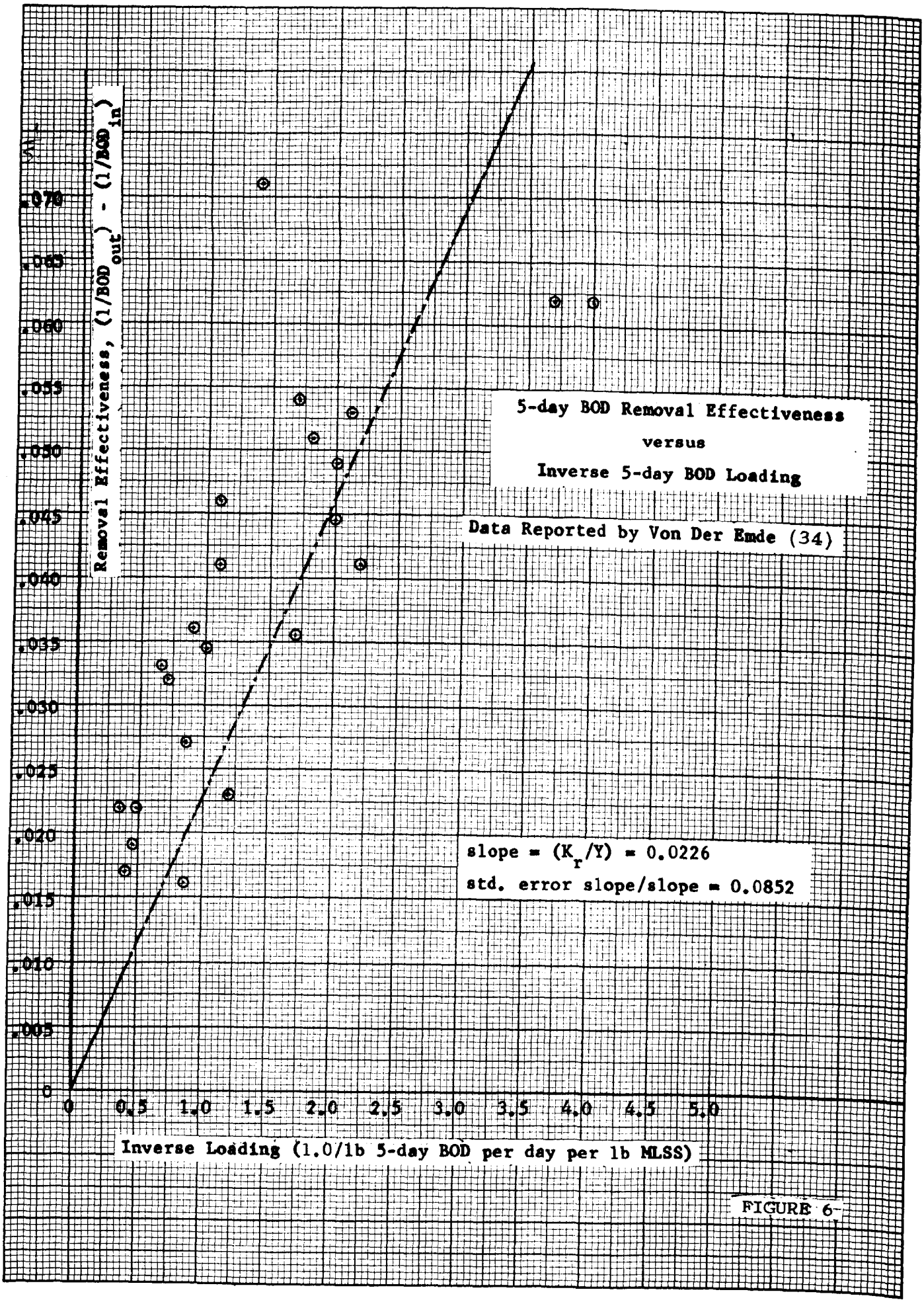

Removal Effectiveness, $(1/BOD_{out}) - (1/BOD_{in})$
.070
.065
.060
.055
.050
.045
.040
.035
.030
.025
.020
.015
.010
.005
0
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Inverse Loading (1.0/lb 5-day BOD per day per lb MLSS)
5-day BOD Removal Effectiveness
versus
Inverse 5-day BOD Loading
Data Reported by Von Der Emde (34)
slope = (K_r/Y) = 0.0226
std. error slope/slope = 0.0852

FIGURE 6-

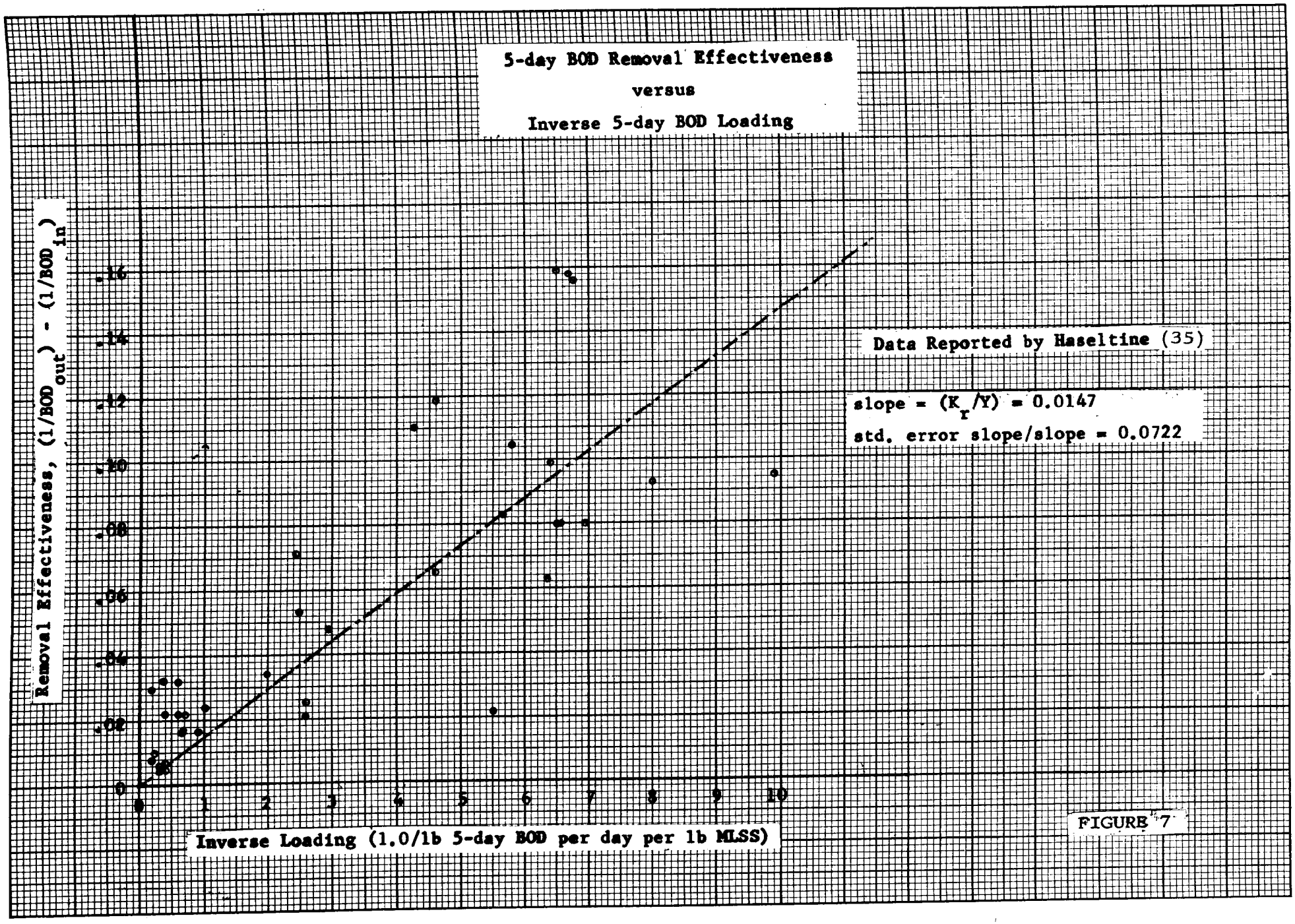

5-day BOD Removal Effectiveness
versus
Inverse 5-day BOD Loading
Removal Effectiveness, $(1/BOD_{out}) - (1/BOD_{in})$
.16
.14
.12
.10
.08
.06
.04
.02
0
0
1
2
3
4
5
6
7
8
9
10
Inverse Loading (1.0/lb 5-day BOD per day per lb MLSS)
Data Reported by Haseltine (35)
slope = (K_r/Y) = 0.0147
std. error slope/slope = 0.0722

FIGURE 7

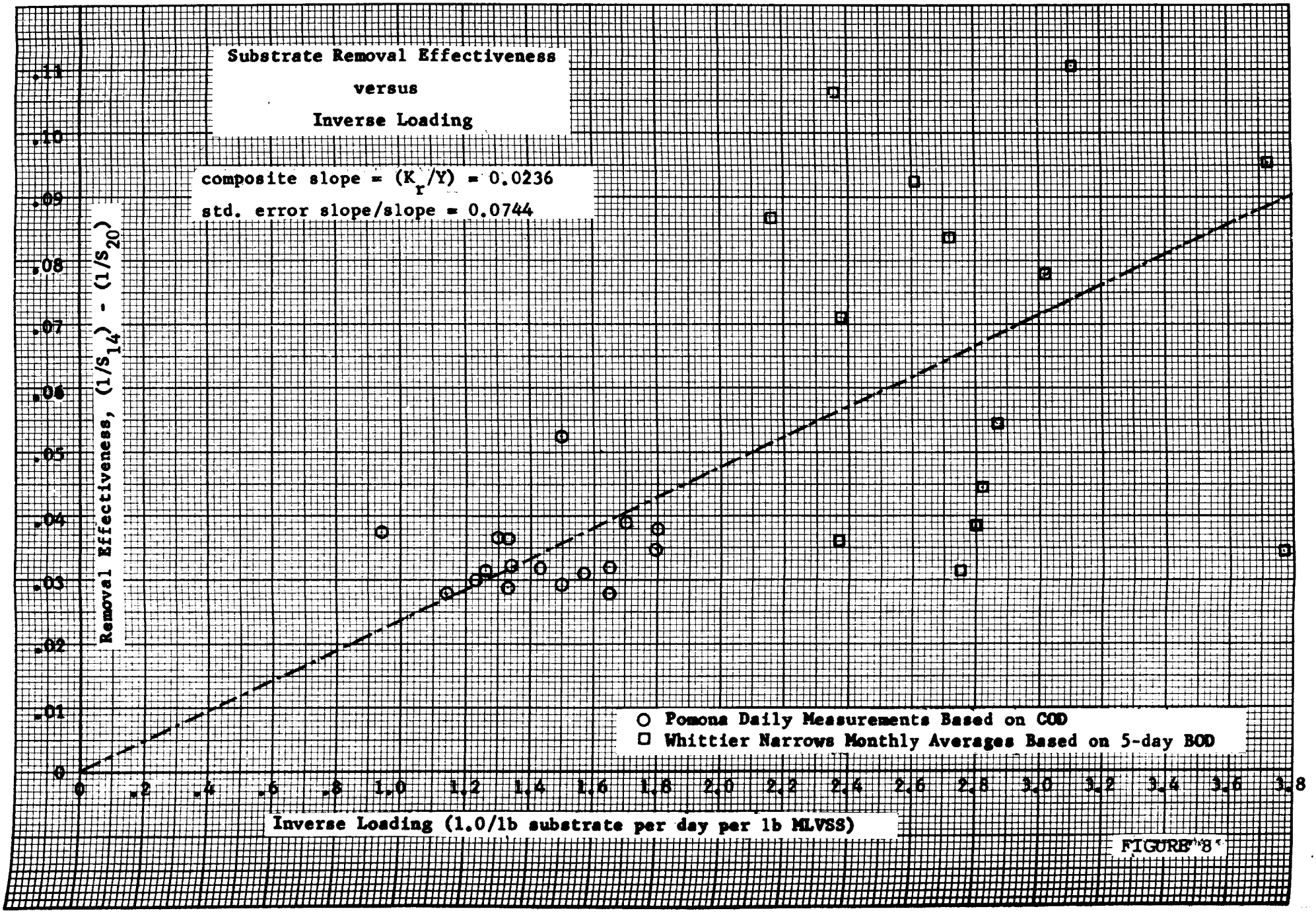

Substrate Removal Effectiveness
versus
Inverse Loading
composite slope = (K_r/Y) = 0.0236
std. error slope/slope = 0.0744
Removal Effectiveness, $(1/S_{14}) - (1/S_{20})$
.11
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
0
0 .2 .4 .6 .8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6 2.8 3.0 3.2 3.4 3.6 3.8
Inverse Loading (1.0/lb substrate per day per lb MLVSS)
○ Pomona Daily Measurements Based on COD
□ Whittier Narrows Monthly Averages Based on 5-day BOD

FIGURE 8

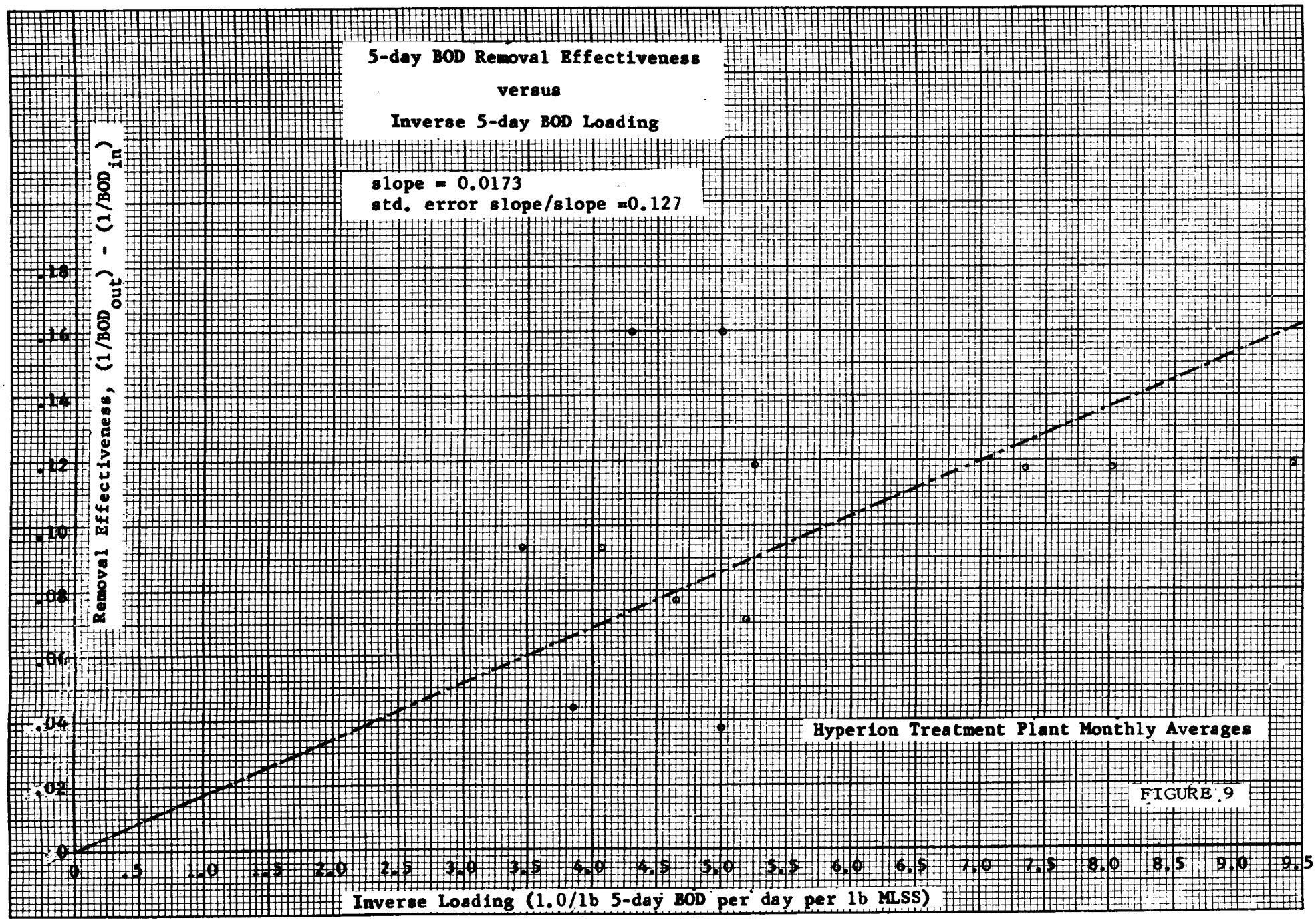

5-day BOD Removal Effectiveness
versus
Inverse 5-day BOD Loading
slope = 0.0173
std. error slope/slope =0.127
Removal Effectiveness, (1/BOD out) - (1/BOD in)
.18
.16
.14
.12
.10
.08
.06
.04
.02
0
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
9.0
9.5
Inverse Loading (1.0/lb 5-day BOD per day per lb MLSS)
Hyperion Treatment Plant Monthly Averages

FIGURE 9

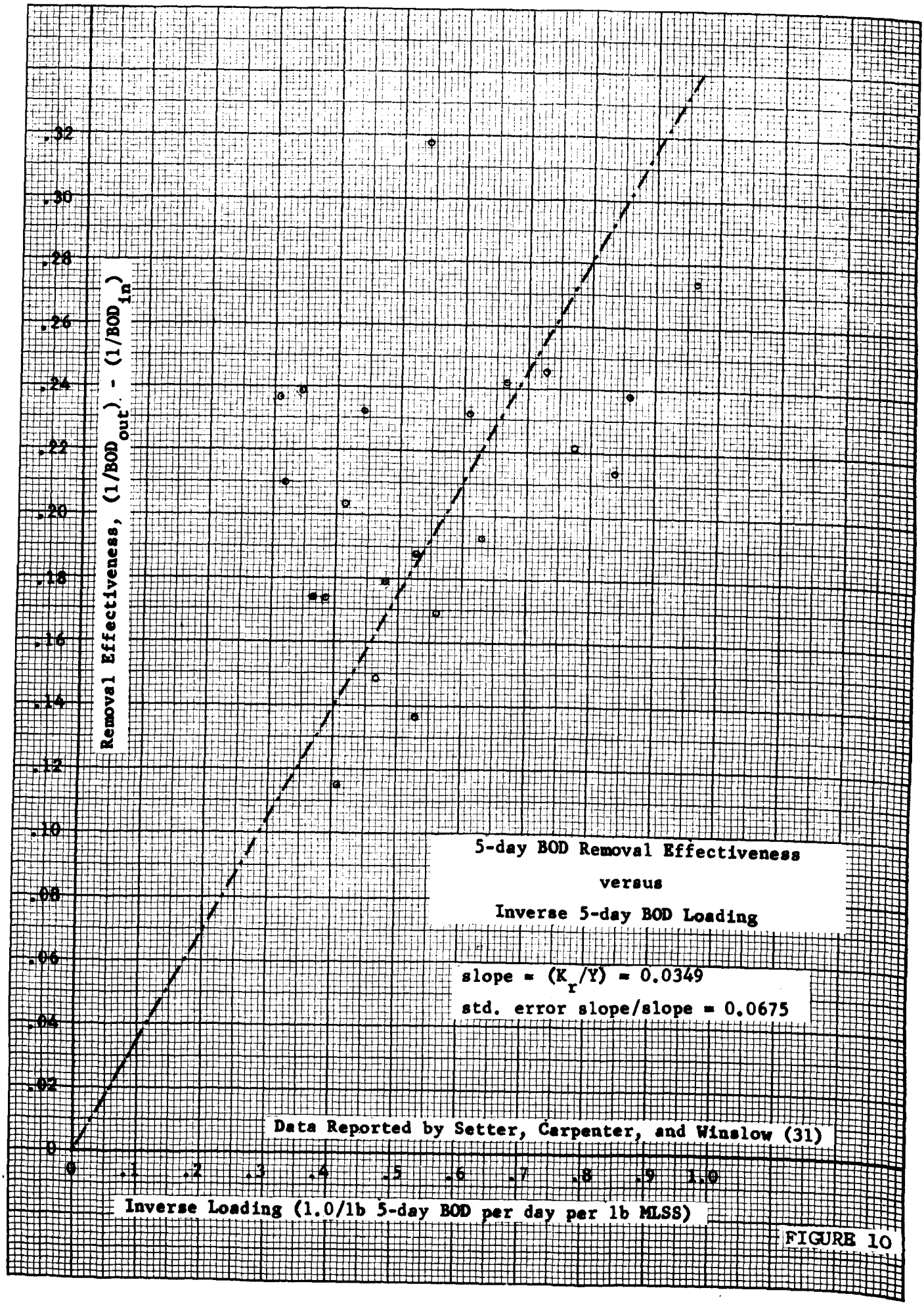

Removal Effectiveness, $(1/BOD_{out}) - (1/BOD_{in})$
.32
.30
.28
.26
.24
.22
.20
.18
.16
.14
.12
.10
.08
.06
.04
.02
0
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
Inverse Loading (1.0/lb 5-day BOD per day per lb MLSS)
5-day BOD Removal Effectiveness
versus
Inverse 5-day BOD Loading
slope = (K_r/Y) = 0.0349
std. error slope/slope = 0.0675
Data Reported by Setter, Carpenter, and Winslow (31)

FIGURE 10

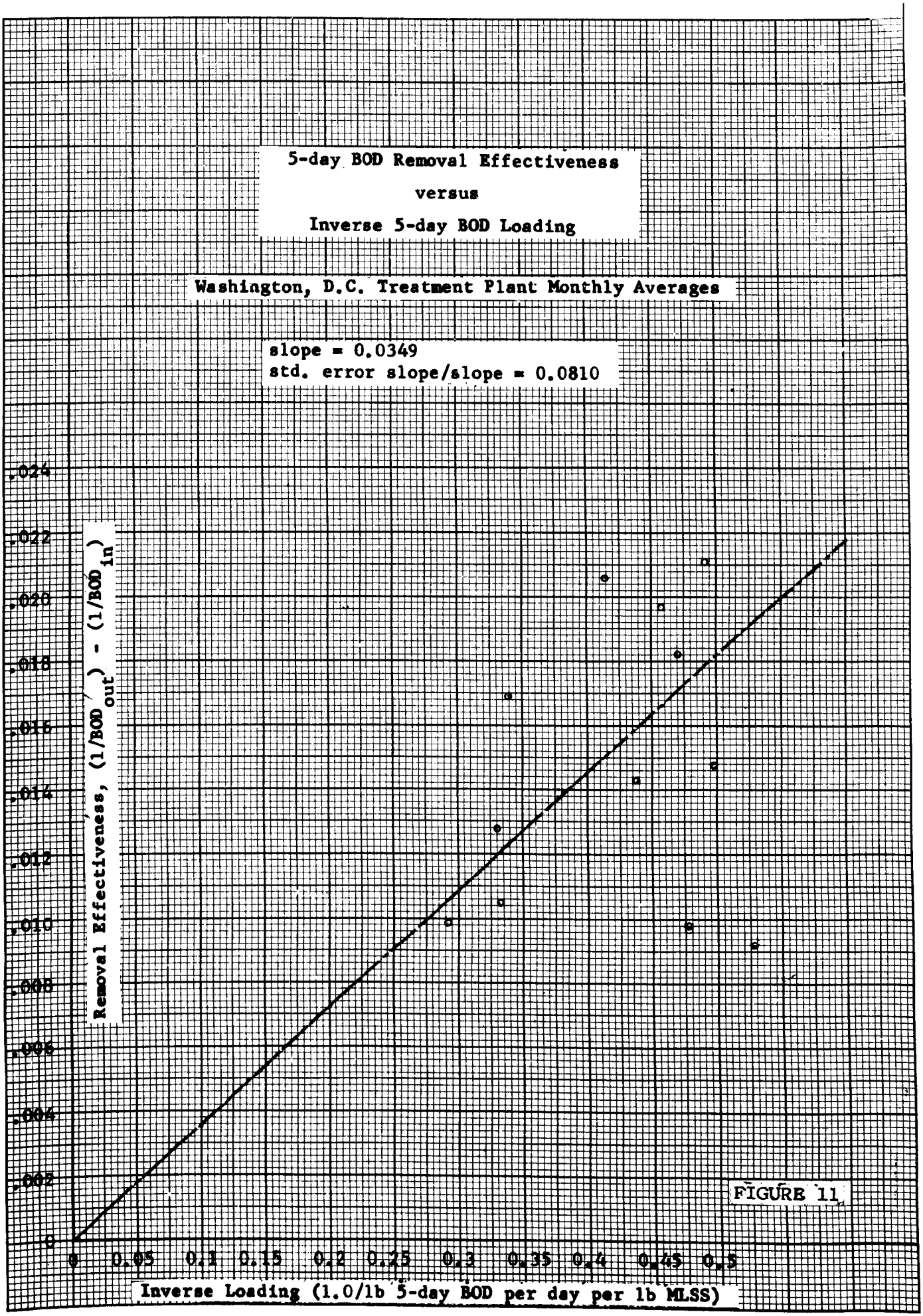

5-day BOD Removal Effectiveness
versus
Inverse 5-day BOD Loading
Washington, D.C. Treatment Plant Monthly Averages
slope = 0.0349
std. error slope/slope = 0.0810
Removal Effectiveness, $(1/BOD'_{out}) - (1/BOD_{in})$
.024
.022
.020
.018
.016
.014
.012
.010
.008
.006
.004
.002
0
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5
Inverse Loading (1.0/lb 5-day BOD per day per lb MLSS)

FIGURE 11

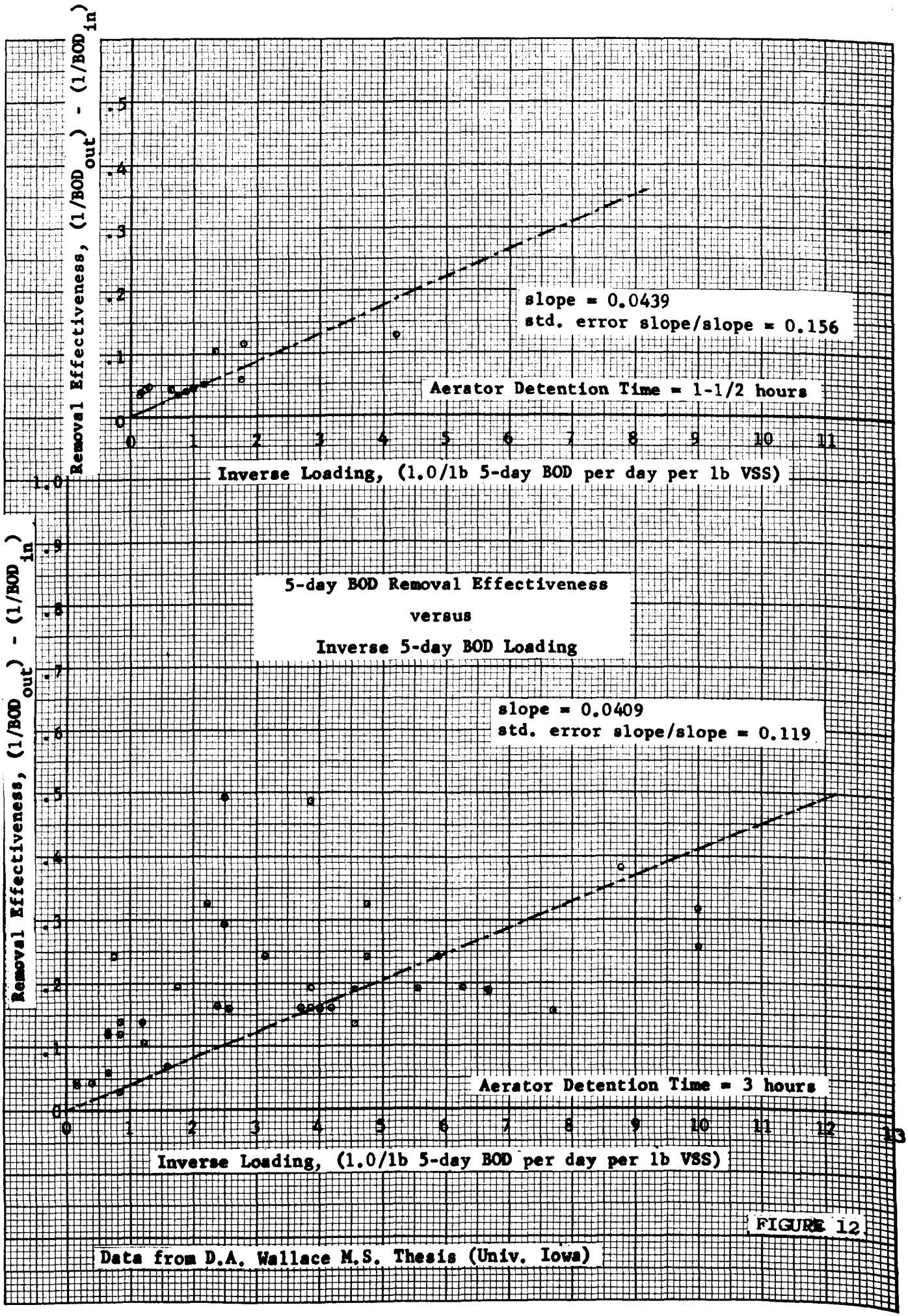


FIGURE 12

Data from D.A. Wallace M.S. Thesis (Univ. Iowa)

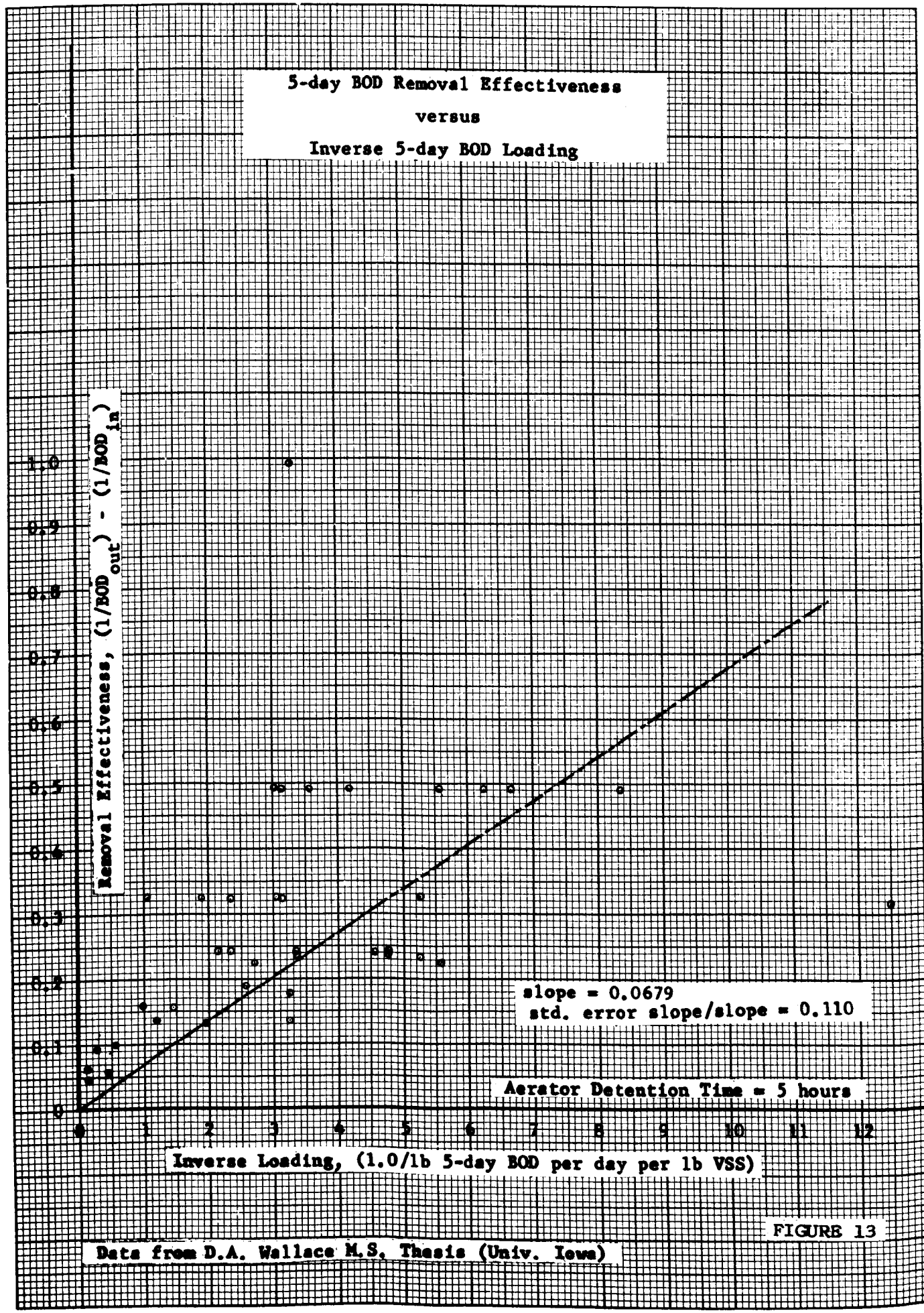


FIGURE 13

Data from D.A. Wallace M.S. Thesis (Univ. Iowa)

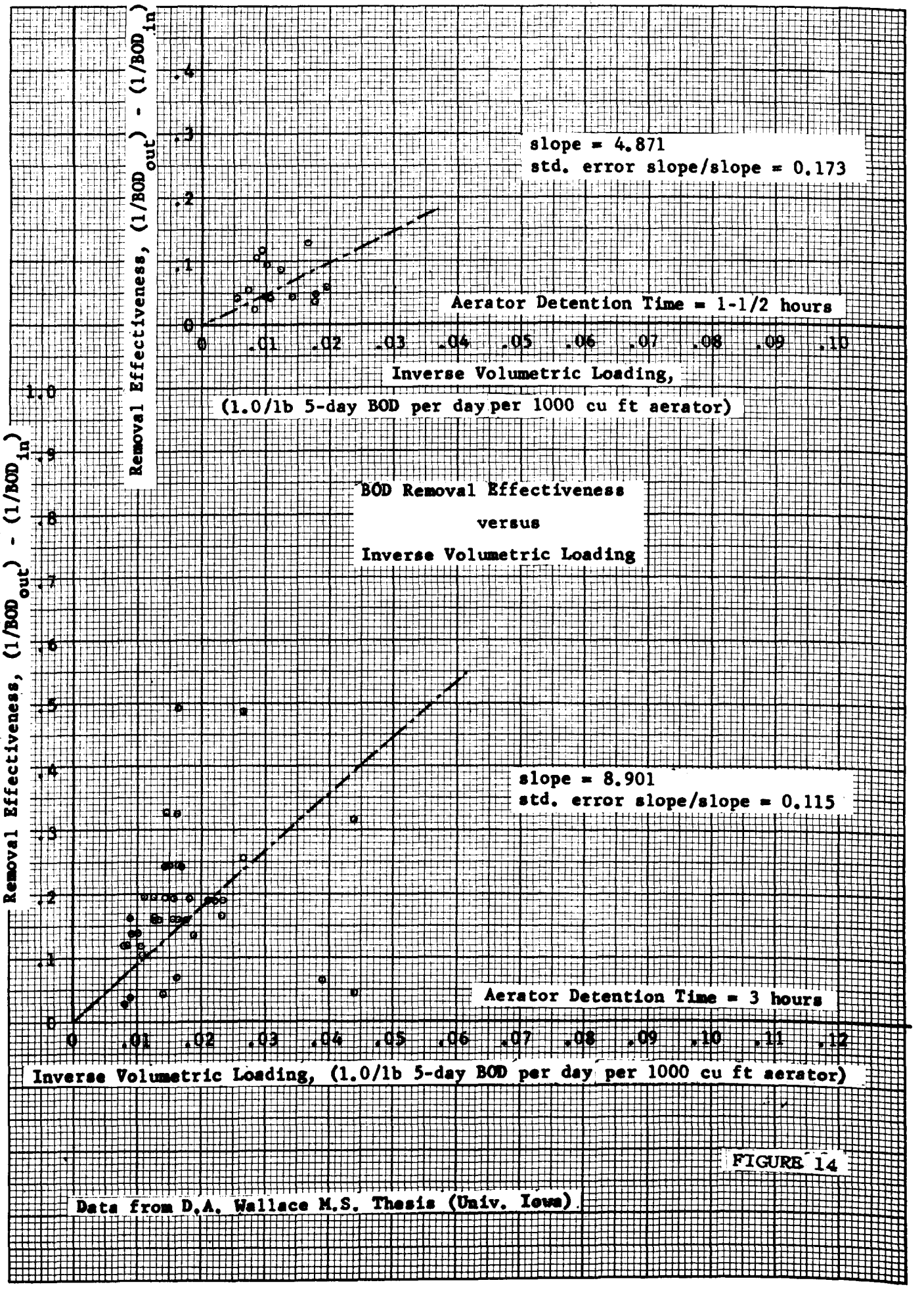


FIGURE 14

Data from D.A. Wallace M.S. Thesis (Univ. Iowa)

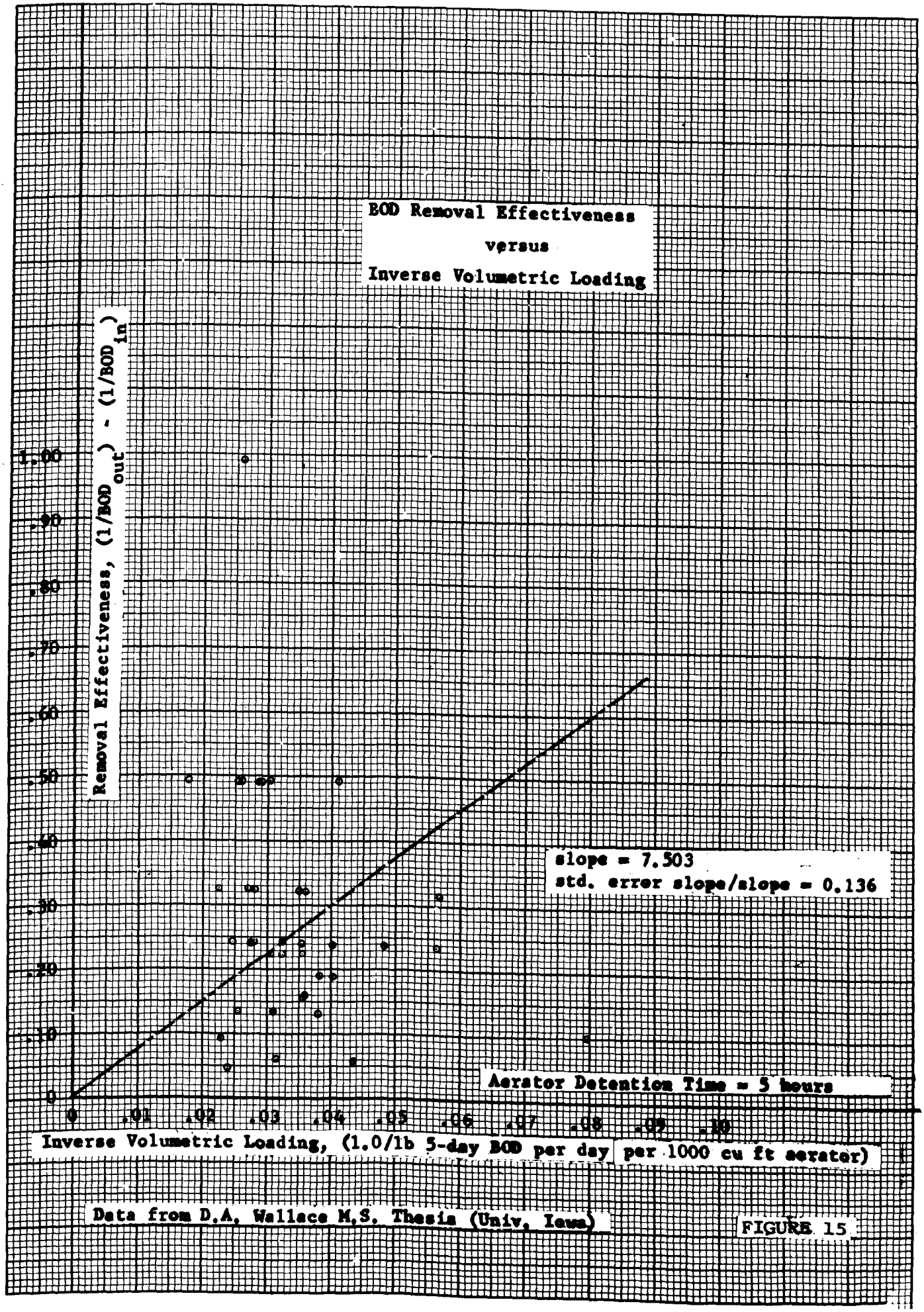

BOD Removal Effectiveness
versus
Inverse Volumetric Loading
Removal Effectiveness, $(1/BOD_{out}) - (1/BOD_{in})$
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
slope = 7.503
std. error slope/slope = 0.136
Aerator Detention Time = 5 hours
0
.01
.02
.03
.04
.05
.06
.07
.08
.09
.10
Inverse Volumetric Loading, (1.0/lb 5-day BOD per day per 1000 cu ft aerator)
Data from D.A. Wallace M.S. Thesis (Univ. Iowa)

FIGURE 15

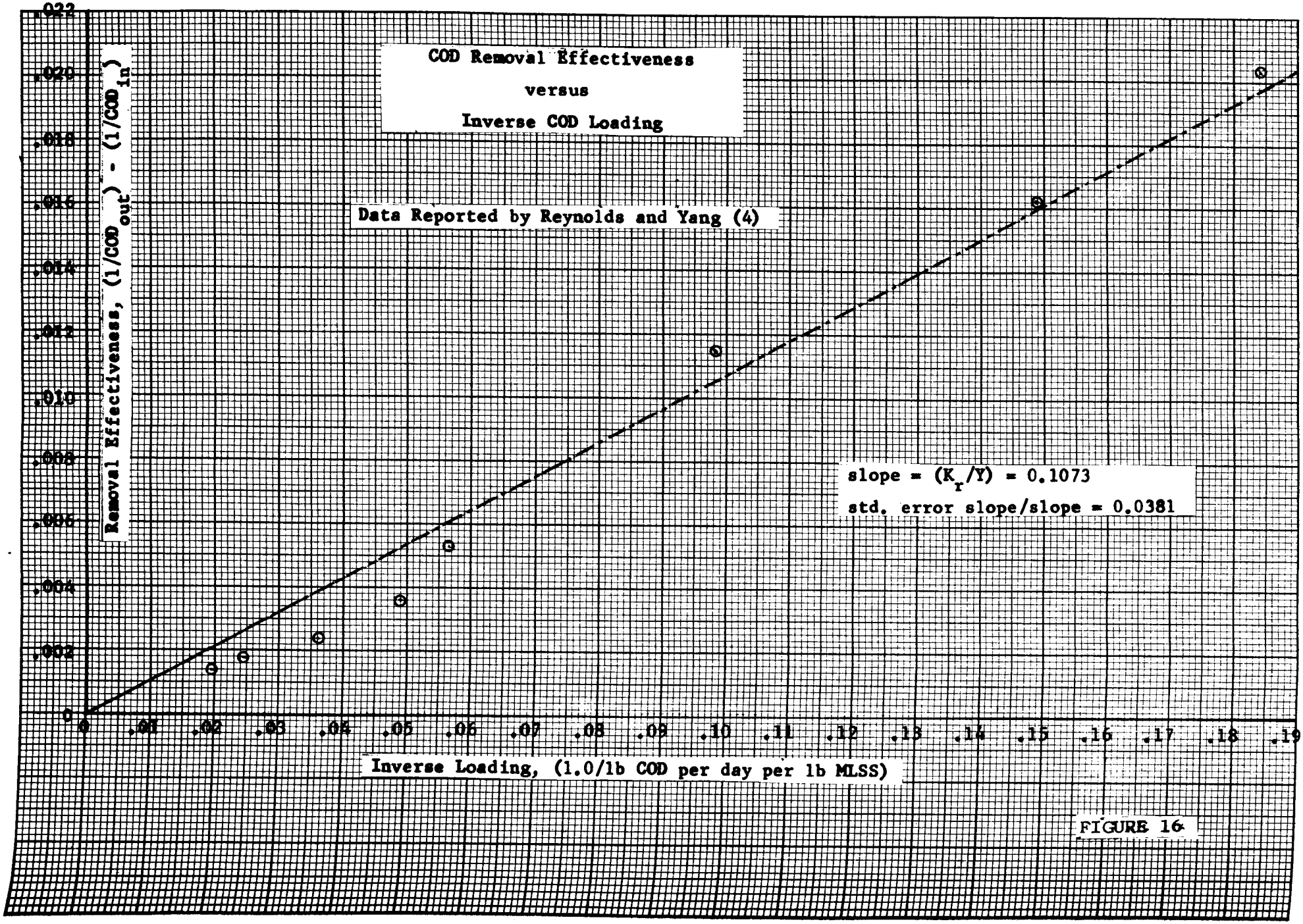

COD Removal Effectiveness
versus
Inverse COD Loading
Data Reported by Reynolds and Yang (4)
slope = (K_r/Y) = 0.1073
std. error slope/slope = 0.0381
Removal Effectiveness, (1/COD_out) - (1/COD_in)
Inverse Loading, (1.0/lb COD per day per lb MLSS)
0
.002
.004
.006
.008
.010
.012
.014
.016
.018
.020
.022
.01
.02
.03
.04
.05
.06
.07
.08
.09
.10
.11
.12
.13
.14
.15
.16
.17
.18
.19

FIGURE 16

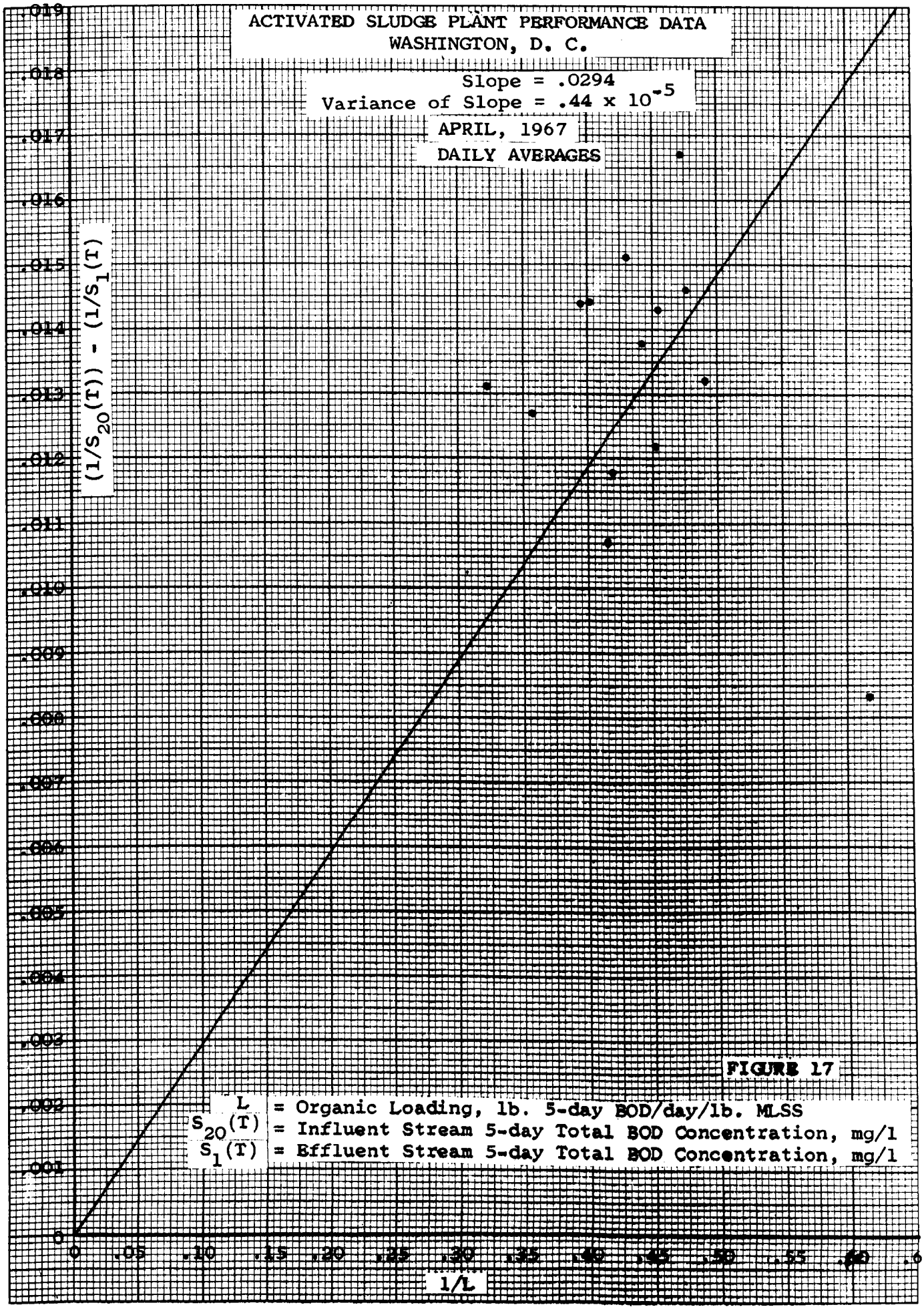

ACTIVATED SLUDGE PLANT PERFORMANCE DATA
WASHINGTON, D. C.
Slope = .0294
Variance of Slope = .44 x 10^-5
APRIL, 1967
DAILY AVERAGES
(1/S20(T)) - (1/S1(T))
1/L
.019
.018
.017
.016
.015
.014
.013
.012
.011
.010
.009
.008
.007
.006
.005
.004
.003
.002
.001
0
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50
.55
.60
.65
L = Organic Loading, lb. 5-day BOD/day/lb. MLSS
S20(T) = Influent Stream 5-day Total BOD Concentration, mg/l
S1(T) = Effluent Stream 5-day Total BOD Concentration, mg/l

FIGURE 17

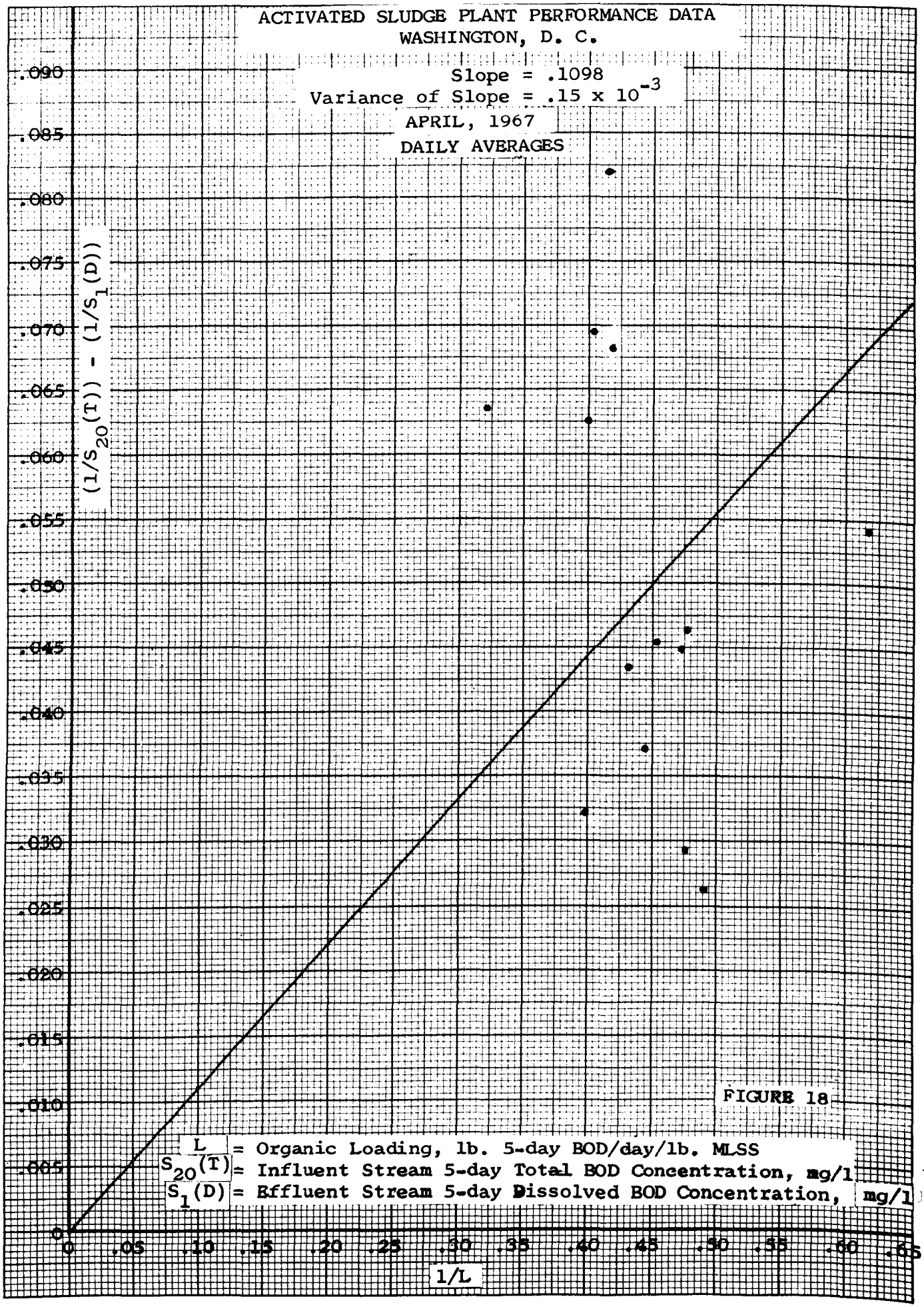


FIGURE 18

$\frac{L}{S_{20}(T)}$ = Organic Loading, lb. 5-day BOD/day/lb. MLSS

$S_{20}(T)$ = Influent Stream 5-day Total BOD Concentration, mg/l

$S_1(D)$ = Effluent Stream 5-day Dissolved BOD Concentration, mg/l

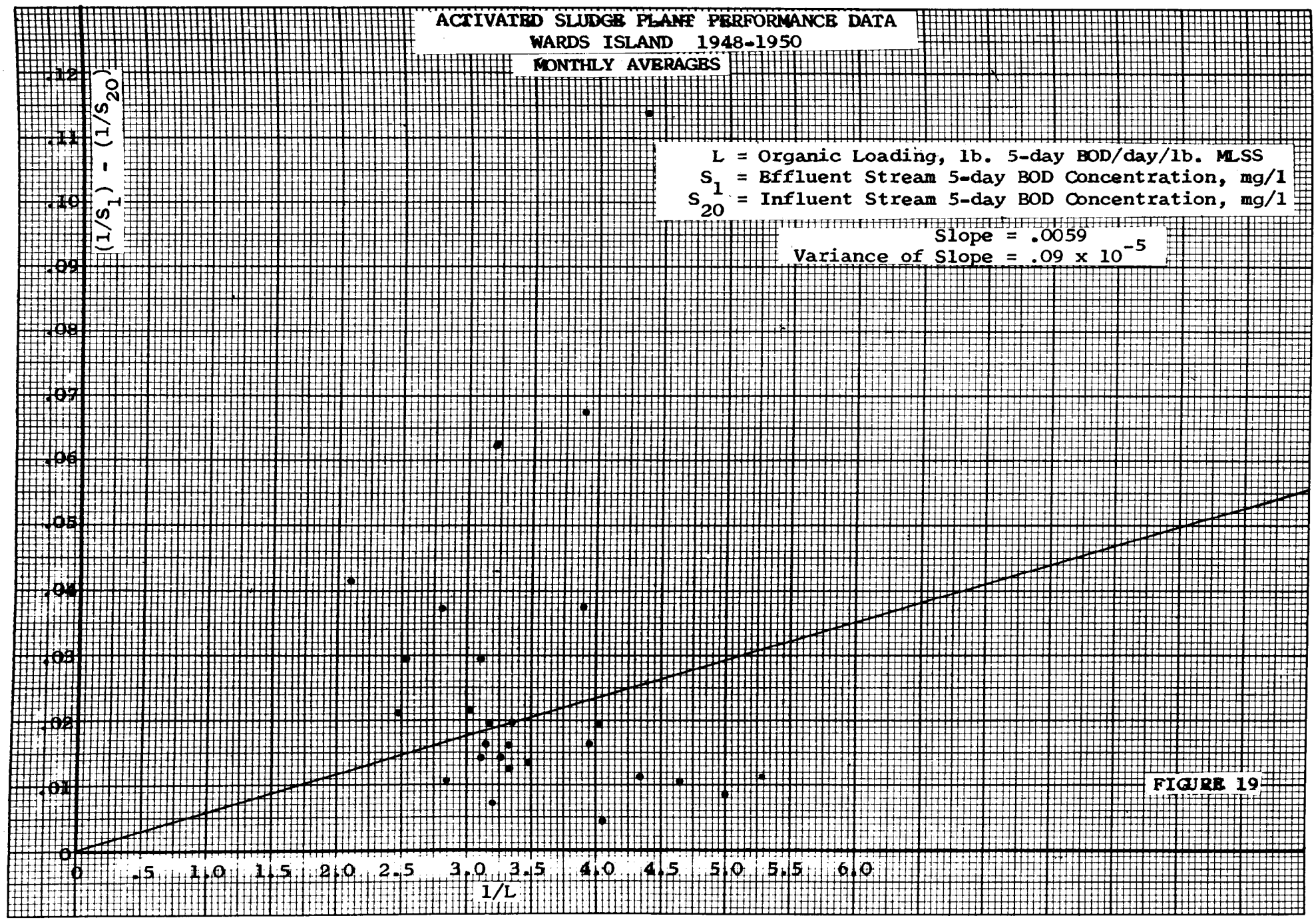

ACTIVATED SLUDGE PLANT PERFORMANCE DATA
WARDS ISLAND 1948-1950
MONTHLY AVERAGES
L = Organic Loading, lb. 5-day BOD/day/lb. MLSS
S_1 = Effluent Stream 5-day BOD Concentration, mg/l
S_{20} = Influent Stream 5-day BOD Concentration, mg/l
Slope = .0059
Variance of Slope = .09 x 10^{-5}
$(1/S_1) - (1/S_{20})$
.12
.11
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
0
0 .5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0
1/L

FIGURE 19

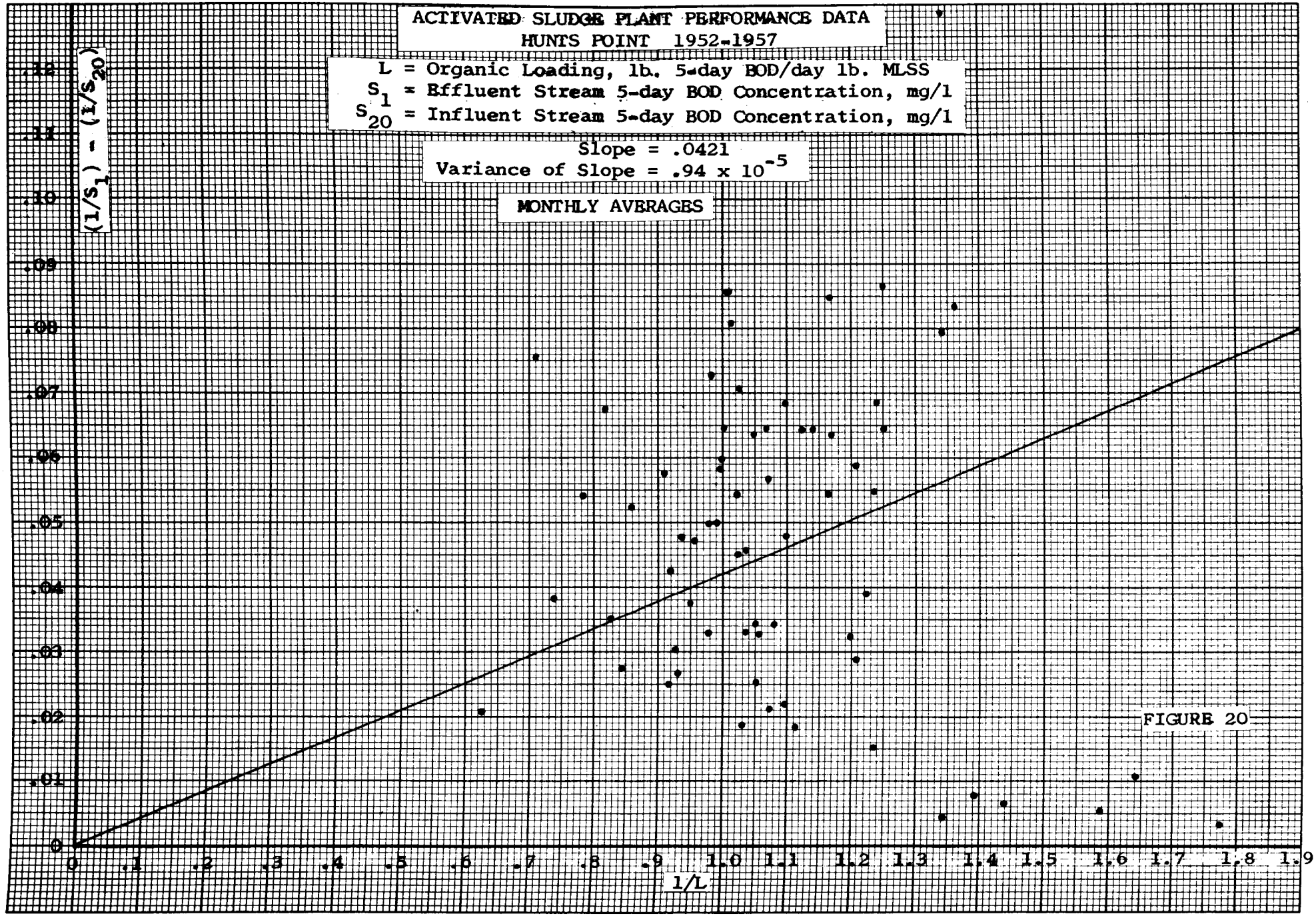
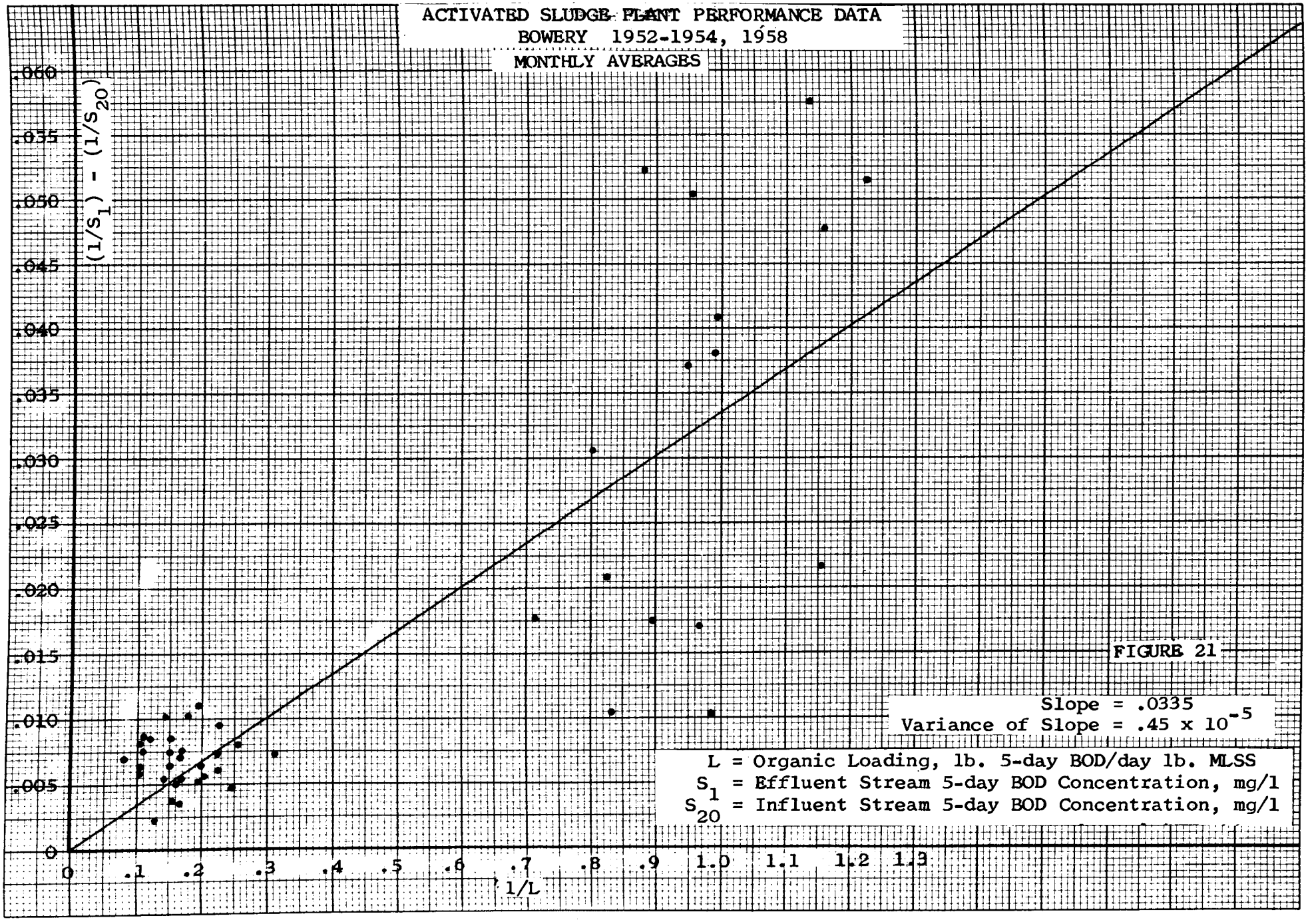

ACTIVATED SLUDGE PLANT PERFORMANCE DATA
HUNTS POINT 1952-1957
L = Organic Loading, lb. 5-day BOD/day lb. MLSS
S_1 = Effluent Stream 5-day BOD Concentration, mg/l
S_{20} = Influent Stream 5-day BOD Concentration, mg/l
Slope = .0421
Variance of Slope = .94 x 10^{-5}
MONTHLY AVERAGES
$(1/S_1) - (1/S_{20})$
.12
.11
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
0
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
1/L

FIGURE 20


ACTIVATED SLUDGE PLANT PERFORMANCE DATA
BOWERY 1952-1954, 1958
MONTHLY AVERAGES
$(1/S_1) - (1/S_{20})$
.060
.055
.050
.045
.040
.035
.030
.025
.020
.015
.010
.005
0
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2
1.3
1/L
FIGURE 21
Slope = .0335
Variance of Slope = .45 x 10^{-5}
L = Organic Loading, lb. 5-day BOD/day lb. MLSS
S_1 = Effluent Stream 5-day BOD Concentration, mg/l
S_{20} = Influent Stream 5-day BOD Concentration, mg/l

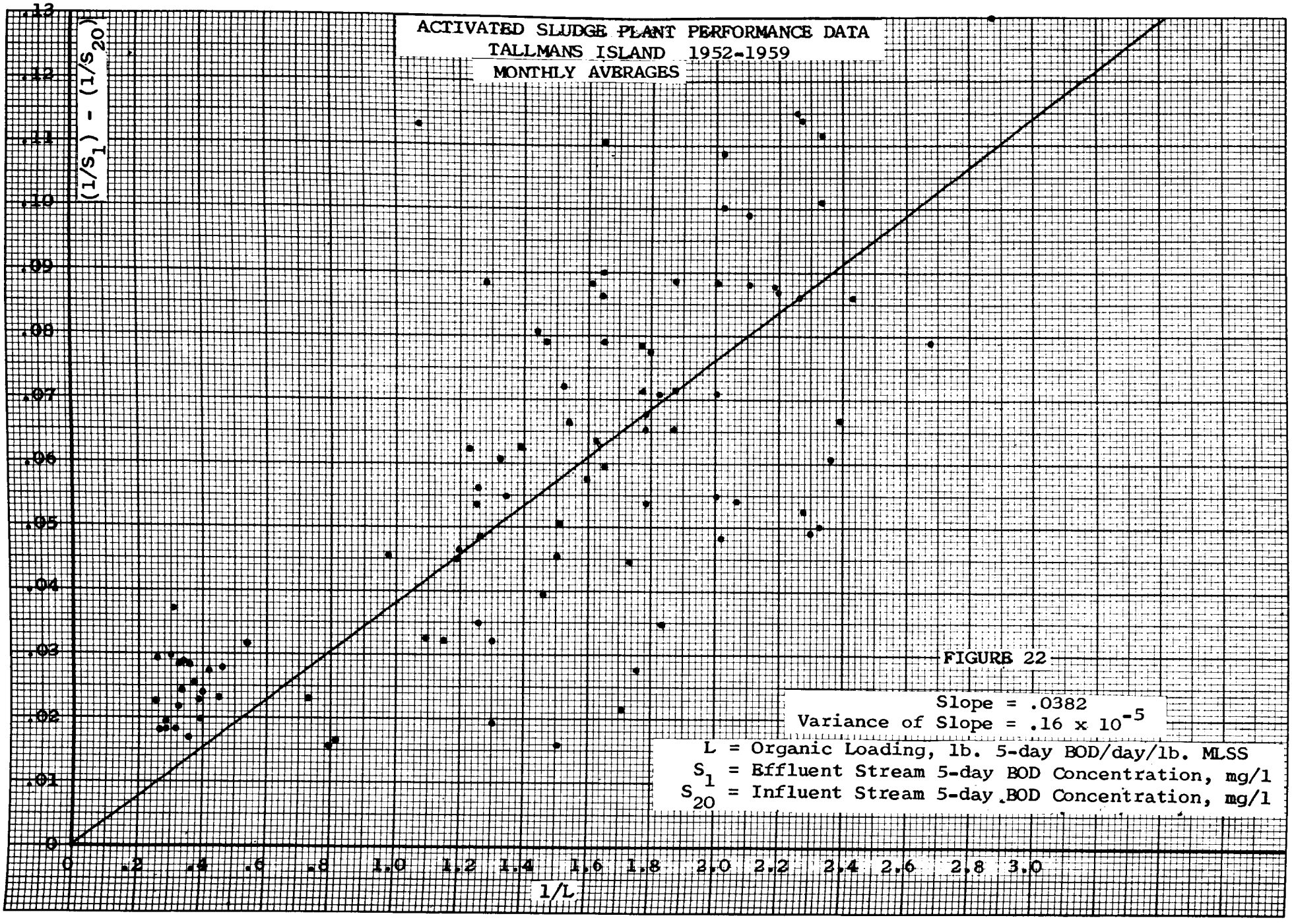
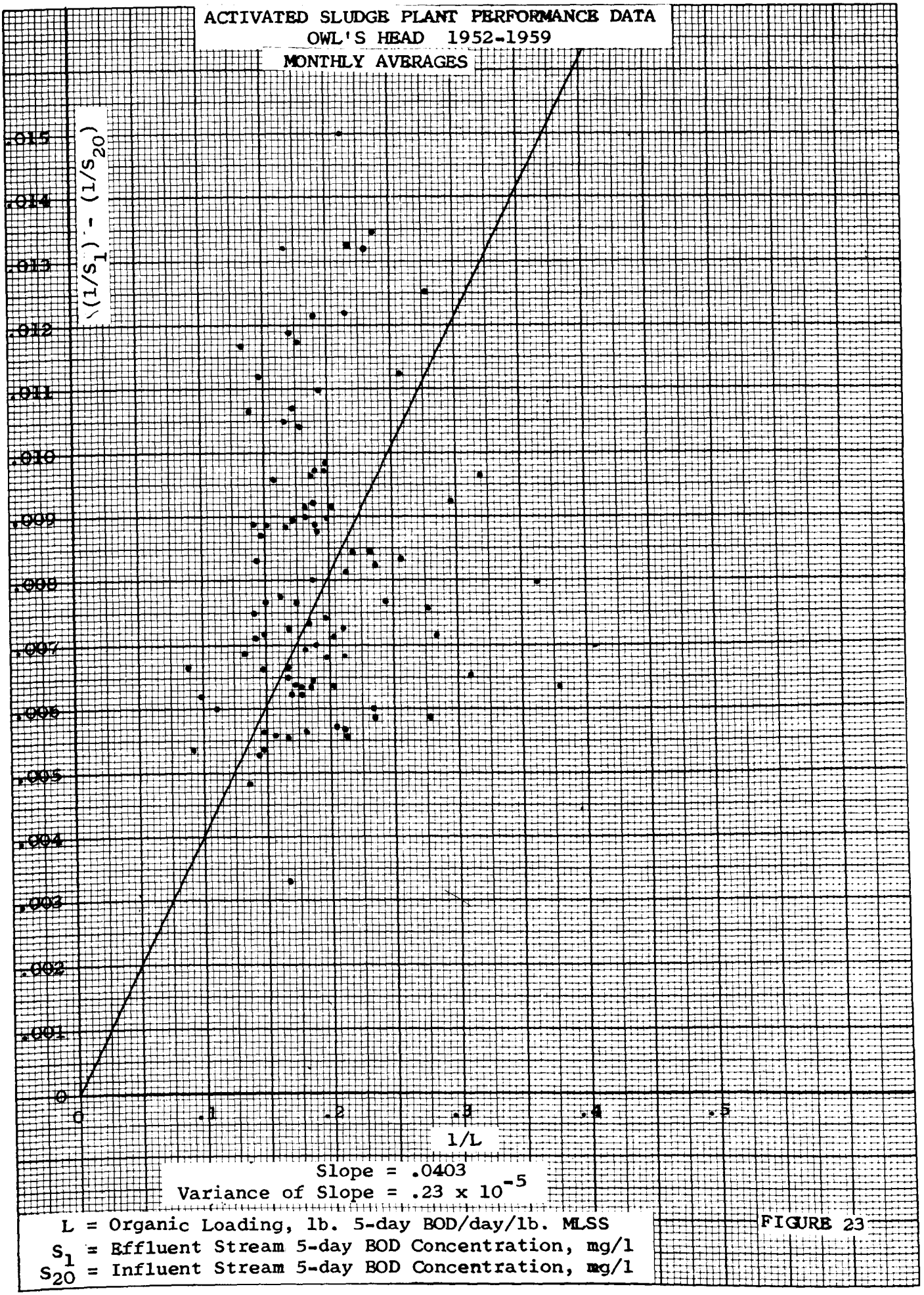

ACTIVATED SLUDGE PLANT PERFORMANCE DATA
TALLMANS ISLAND 1952-1959
MONTHLY AVERAGES
$(1/S_1) - (1/S_{20})$
.13
.12
.11
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
0
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
1/L
Slope = .0382
Variance of Slope = .16 x 10^{-5}
L = Organic Loading, lb. 5-day BOD/day/lb. MLSS
S_1 = Effluent Stream 5-day BOD Concentration, mg/l
S_{20} = Influent Stream 5-day BOD Concentration, mg/l

FIGURE 22



L = Organic Loading, lb. 5-day BOD/day/lb. MLSS
S_1 = Effluent Stream 5-day BOD Concentration, mg/l
S_{20} = Influent Stream 5-day BOD Concentration, mg/l

FIGURE 23

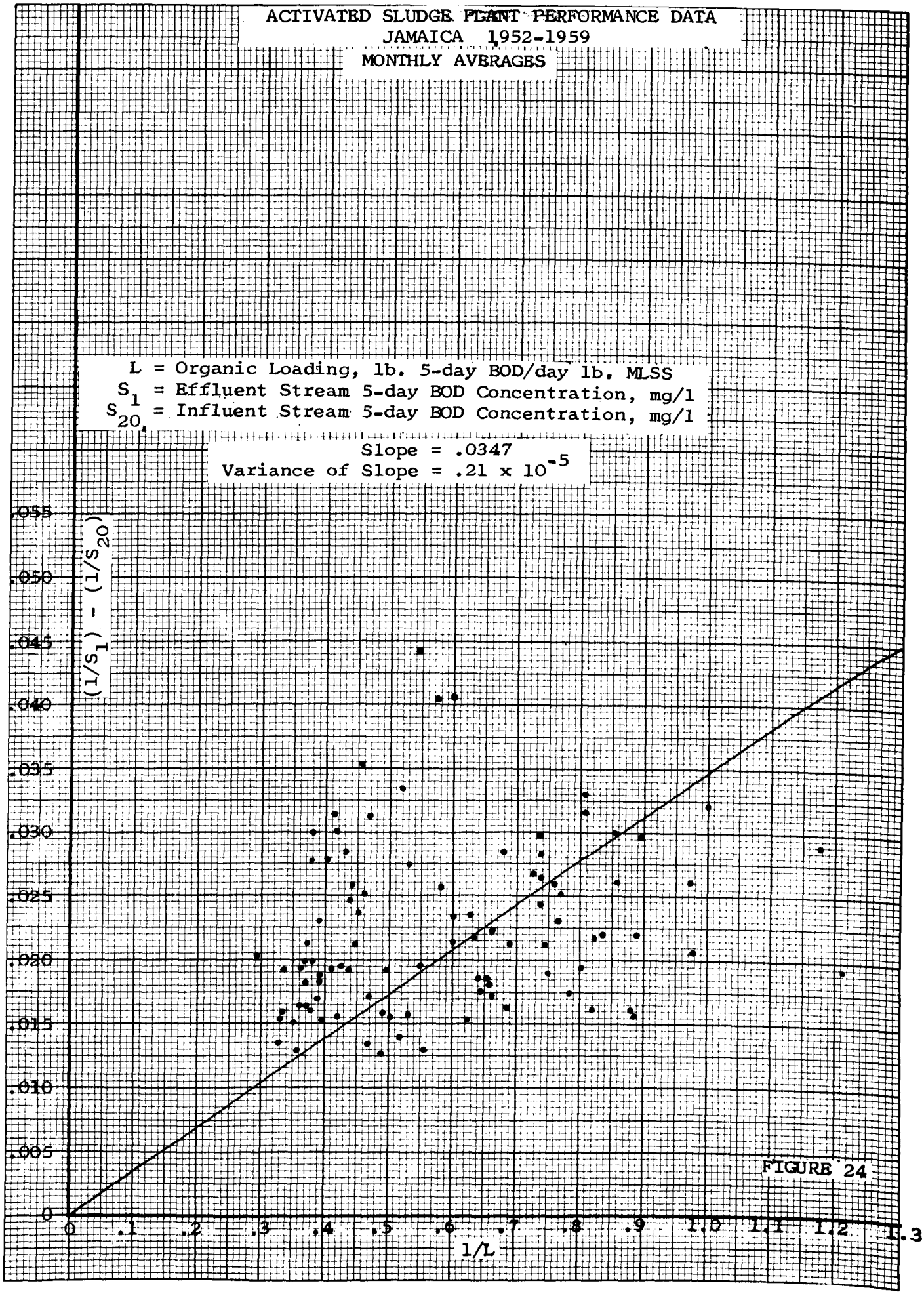

ACTIVATED SLUDGE PLANT PERFORMANCE DATA
JAMAICA 1952-1959
MONTHLY AVERAGES
L = Organic Loading, lb. 5-day BOD/day lb. MLSS
S_1 = Effluent Stream 5-day BOD Concentration, mg/l
S_{20} = Influent Stream 5-day BOD Concentration, mg/l
Slope = .0347
Variance of Slope = .21 x 10^{-5}
$(1/S_1) - (1/S_{20})$
.055
.050
.045
.040
.035
.030
.025
.020
.015
.010
.005
0
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2
1.3
1/L

FIGURE 24

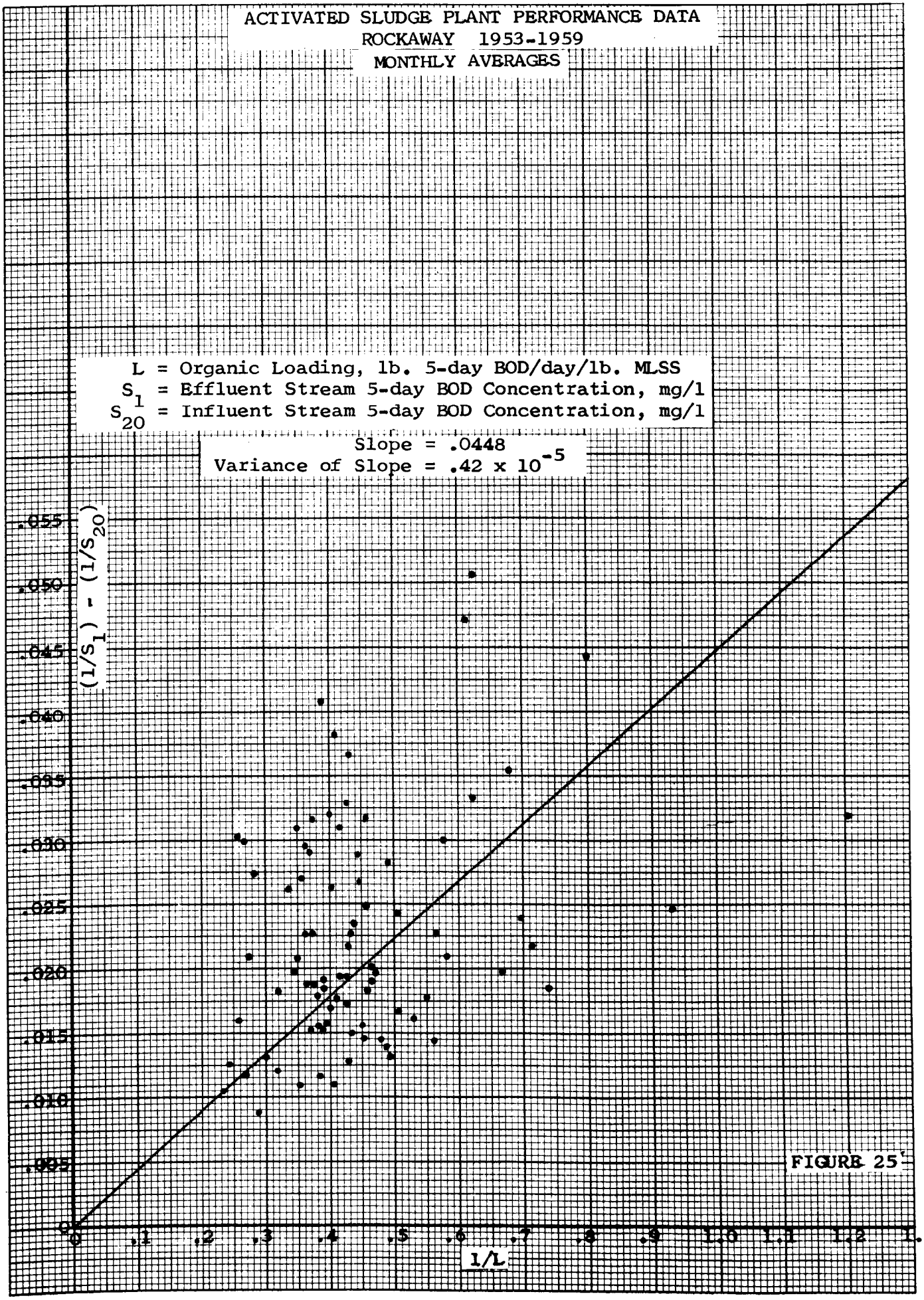

ACTIVATED SLUDGE PLANT PERFORMANCE DATA
ROCKAWAY 1953-1959
MONTHLY AVERAGES
L = Organic Loading, lb. 5-day BOD/day/lb. MLSS
S_1 = Effluent Stream 5-day BOD Concentration, mg/l
S_{20} = Influent Stream 5-day BOD Concentration, mg/l
Slope = .0448
Variance of Slope = .42 x 10^{-5}
$(1/S_1) - (1/S_{20})$
.055
.050
.045
.040
.035
.030
.025
.020
.015
.010
.005
0
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2
1.3
1/L

FIGURE 25

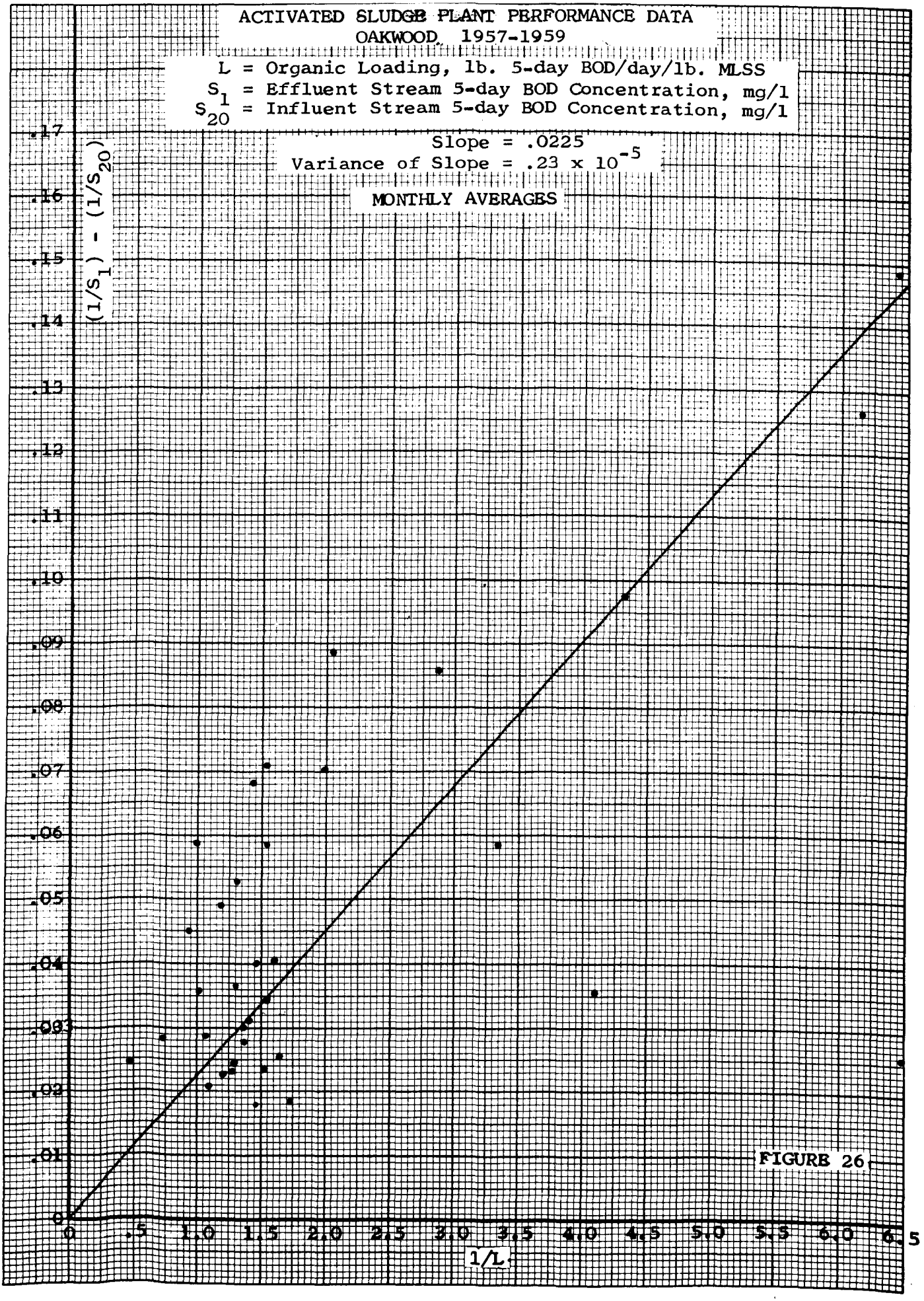

ACTIVATED SLUDGE PLANT PERFORMANCE DATA
OAKWOOD 1957-1959
L = Organic Loading, lb. 5-day BOD/day/lb. MLSS
S_1 = Effluent Stream 5-day BOD Concentration, mg/l
S_{20} = Influent Stream 5-day BOD Concentration, mg/l
Slope = .0225
Variance of Slope = .23 x 10^{-5}
MONTHLY AVERAGES
$(1/S_1) - (1/S_{20})$
.17
.16
.15
.14
.13
.12
.11
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
0
0 .5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5
1/L

FIGURE 26

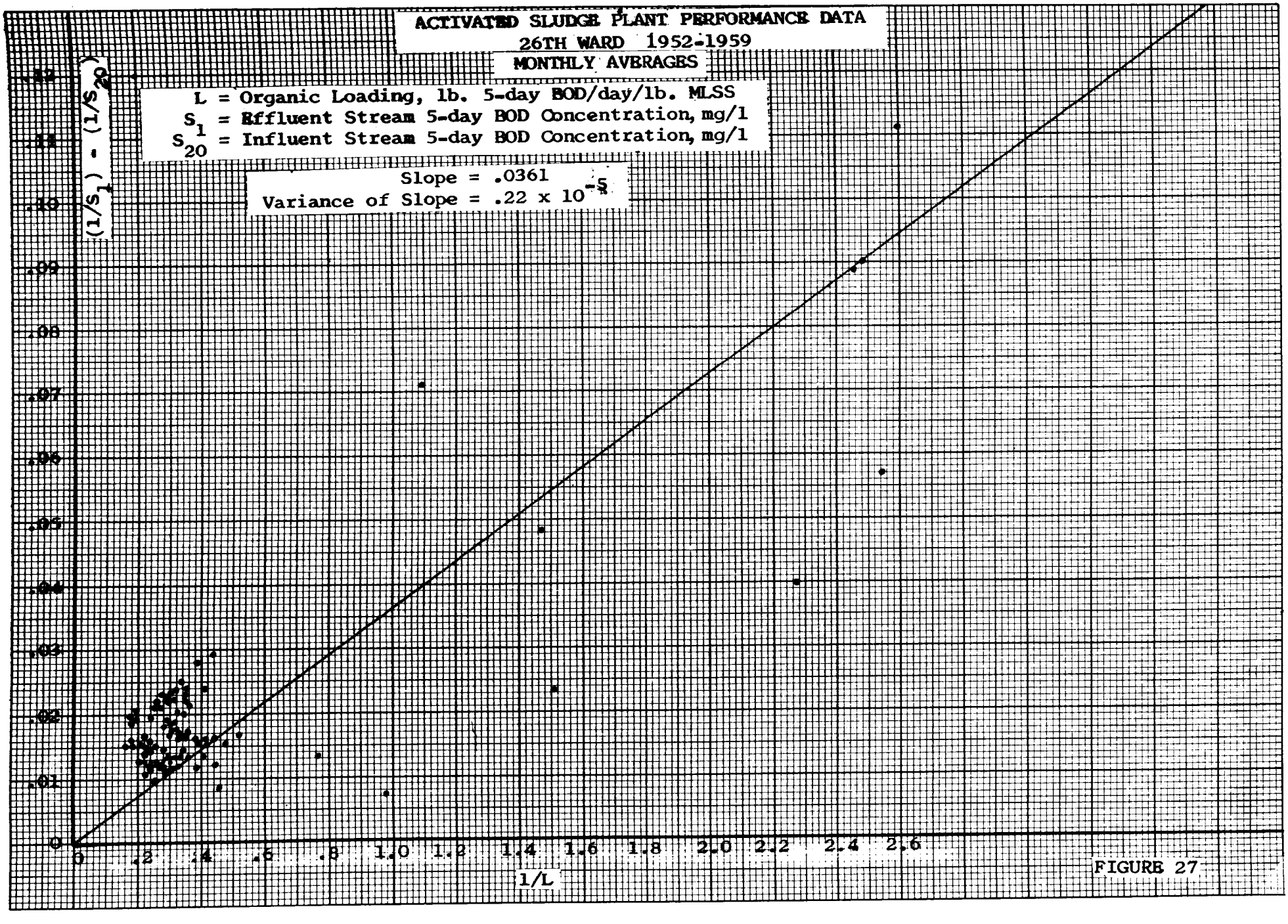

ACTIVATED SLUDGE PLANT PERFORMANCE DATA
26TH WARD 1952-1959
MONTHLY AVERAGES
L = Organic Loading, lb. 5-day BOD/day/lb. MLSS
S_1 = Effluent Stream 5-day BOD Concentration, mg/l
S_{20} = Influent Stream 5-day BOD Concentration, mg/l
Slope = .0361
Variance of Slope = .22 x 10^{-5}
$(1/S_1) - (1/S_{20})$
1/L
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
.09
.08
.07
.06
.05
.04
.03
.02
.01

FIGURE 27

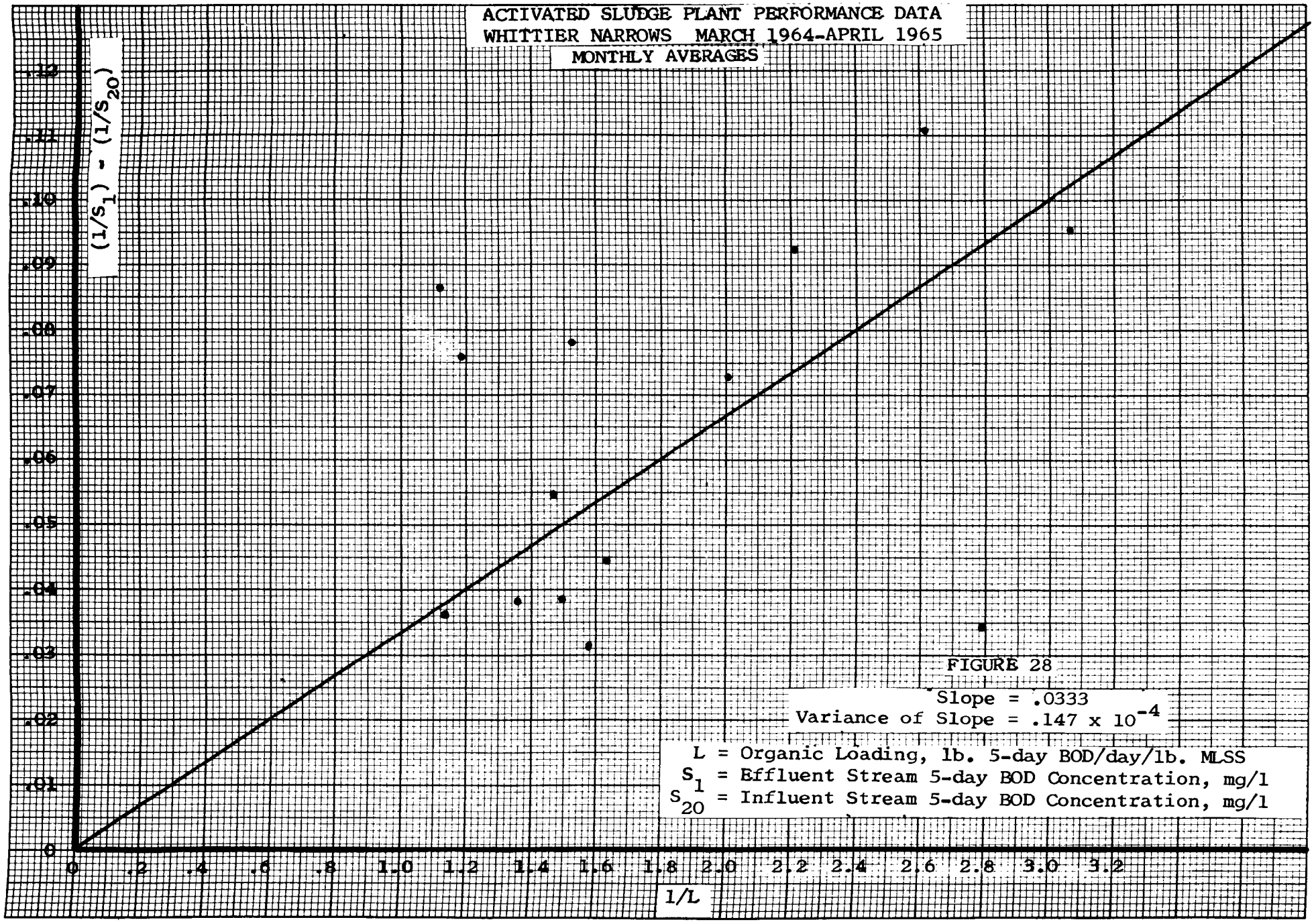


FIGURE 28

Slope = .0333

Variance of Slope = $.147 \times 10^{-4}$

L = Organic Loading, lb. 5-day BOD/day/lb. MLSS

S_1 = Effluent Stream 5-day BOD Concentration, mg/l

S_{20} = Influent Stream 5-day BOD Concentration, mg/l

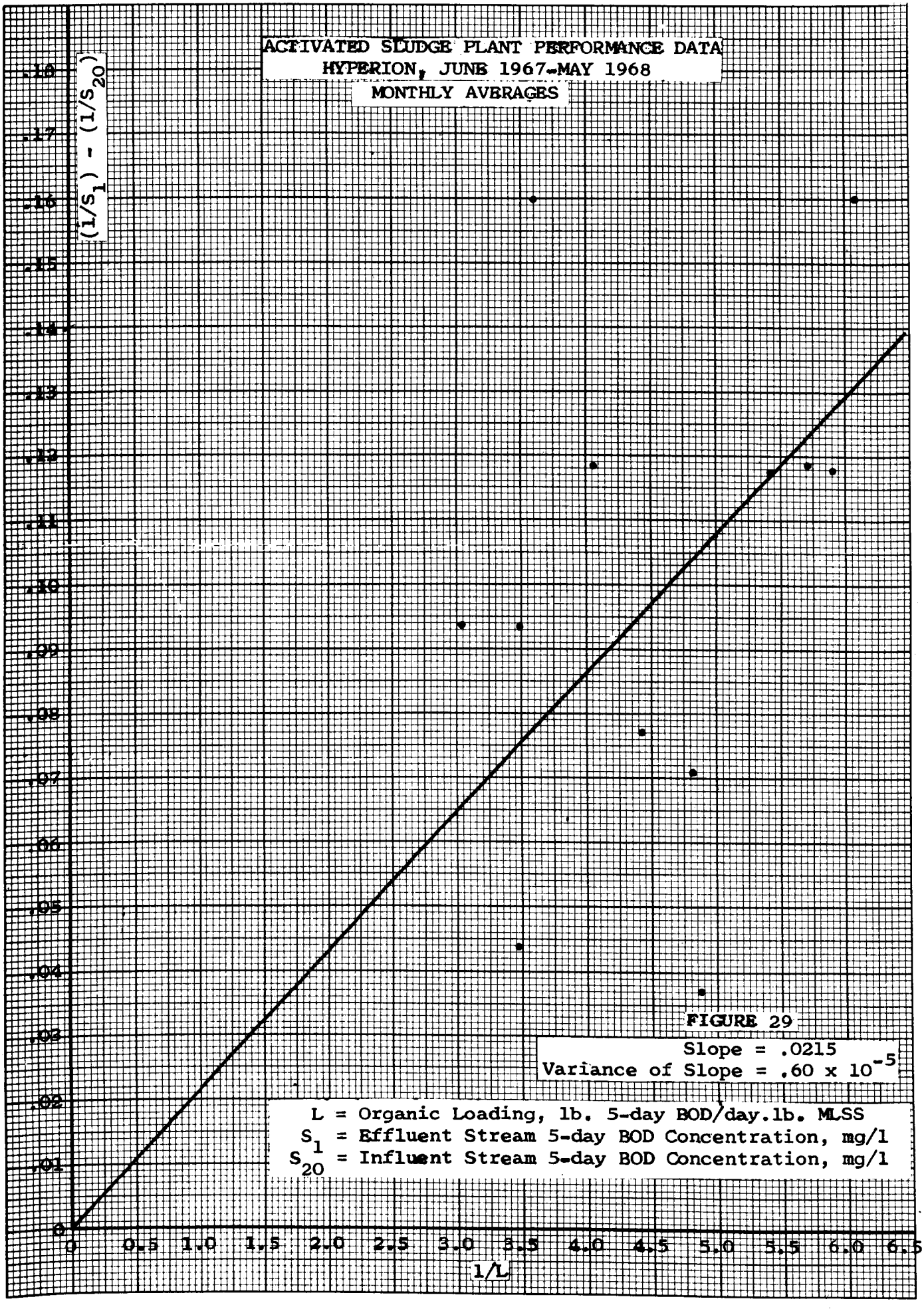
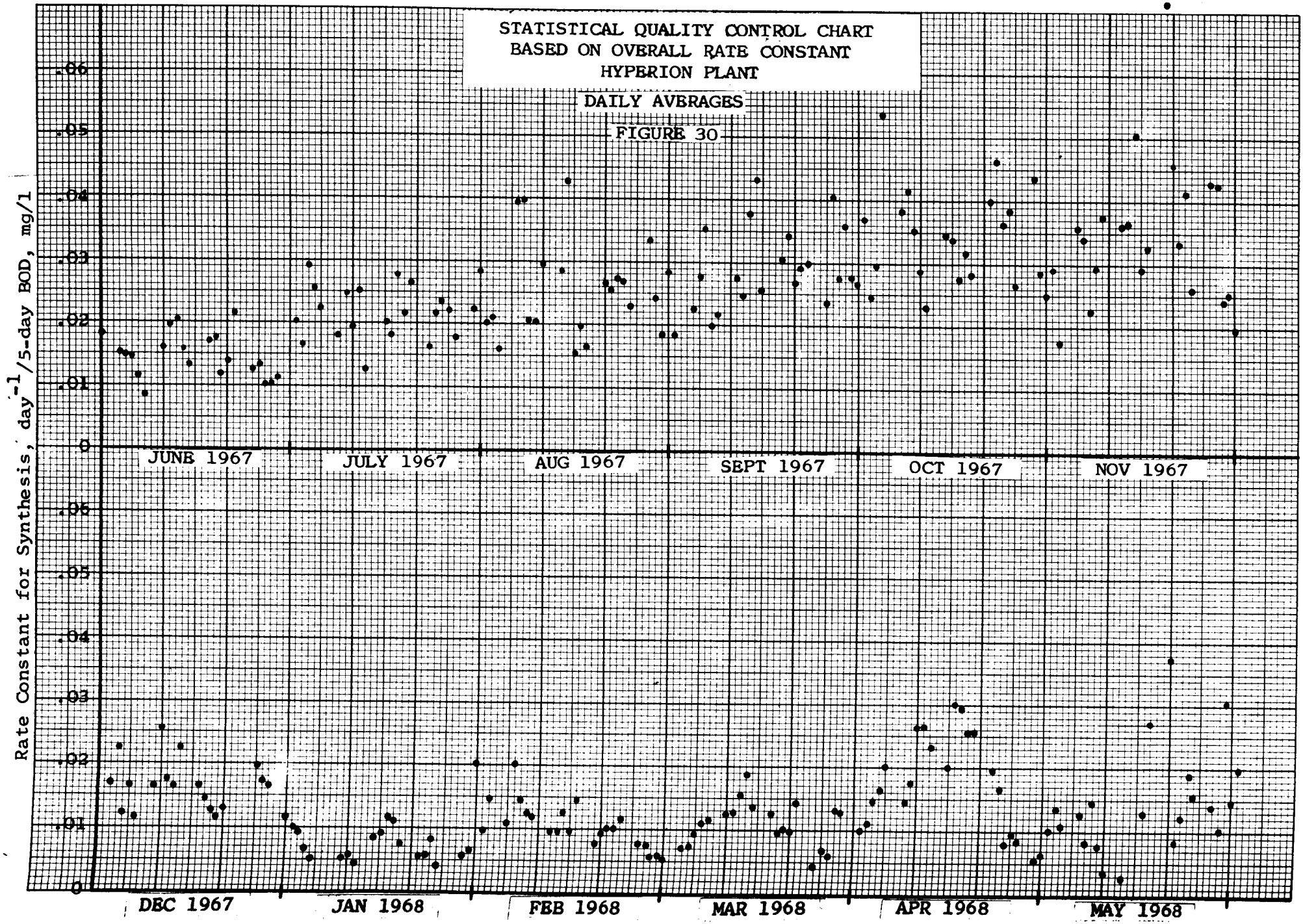

ACTIVATED SLUDGE PLANT PERFORMANCE DATA
HYPERION, JUNE 1967-MAY 1968
MONTHLY AVERAGES
$(1/S_1) - (1/S_{20})$
.18
.17
.16
.15
.14
.13
.12
.11
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
0
0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5
1/L
Slope = .0215
Variance of Slope = .60 x 10^{-5}
L = Organic Loading, lb. 5-day BOD/day.lb. MLSS
S_1 = Effluent Stream 5-day BOD Concentration, mg/l
S_{20} = Influent Stream 5-day BOD Concentration, mg/l

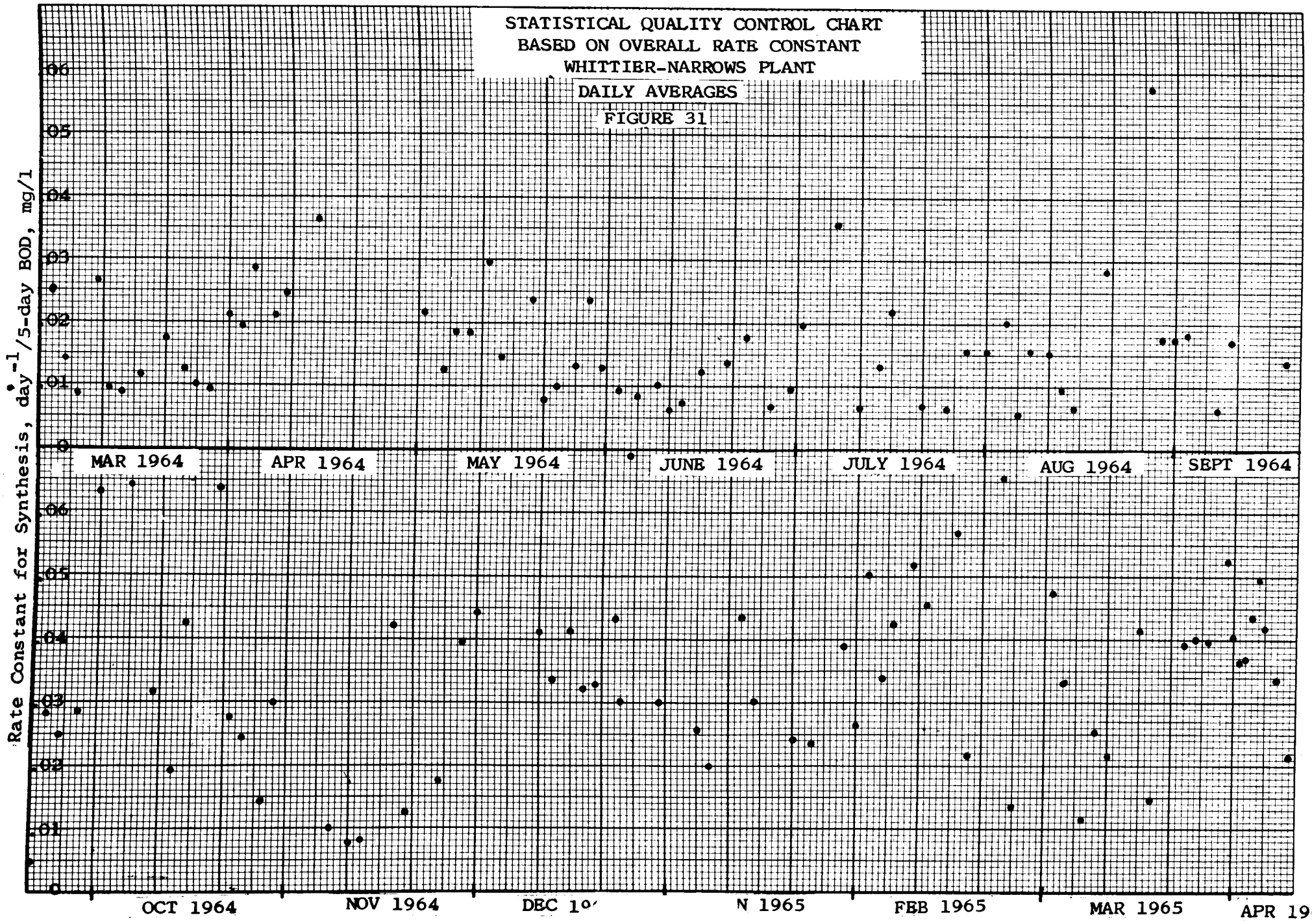
FIGURE 29

STATISTICAL QUALITY CONTROL CHART
BASED ON OVERALL RATE CONSTANT
HYPERION PLANT

DAILY AVERAGES

FIGURE 30




STATISTICAL QUALITY CONTROL CHART
BASED ON OVERALL RATE CONSTANT
WHITTIER-NARROWS PLANT
DAILY AVERAGES
FIGURE 31
Rate Constant for Synthesis, day^{-1}/5-day BOD, mg/l
.06
.05
.04
.03
.02
.01
0
MAR 1964
APR 1964
MAY 1964
JUNE 1964
JULY 1964
AUG 1964
SEPT 1964
OCT 1964
NOV 1964
DEC 19
N 1965
FEB 1965
MAR 1965
APR 1965

DESCRIPTION OF FILL AND DRAW ACTIVATED SLUDGE PROGRAM (FADAS)

The FADAS program uses the Runge-Kutta method of numerical integration to compute the biological activity as a function of time in a batch activated sludge experiment. Initial concentrations of substrate and heterotrophic bacteria are supplied as input. The program then computes the concentration of substrate and heterotrophs at any number of time points separated by a specified time interval. The Monod expression for synthesis is used in the program. It is assumed that a fixed fraction (K_e) of the bacteria are destroyed each day. The rate of growth can then be expressed as follows:

$$\frac{dX}{dt} = \frac{K_r\ S\ X}{K_s + S} - K_e X \qquad (44)$$

Some investigators, for example, Bhatla, Stack and Weston[19] believe that a portion of the lysed cells return to solution to be reused as substrate. Others, such as McCarty[22] believe that only a non-biodegradable fraction is returned to solution as a result of natural destruction of cells. The rate of change of substrate with time is expressed in the program as follows:

$$\frac{dS}{dt} = \frac{R\ K_e X}{Y} - \frac{K_r\ S\ X}{Y(K_s + S)} \qquad (45)$$

R is the coefficient which converts the lysed cell mass to substrate returned to solution. If we assume that all of the cell protoplasm is returned to solution, the value for R should be about (0.84). If we assume that the cell protoplasm is used for endogenous respiration, R would have a value of zero. The form of the growth relationship can be easily changed in the program. Typical computed results are shown in Figures 32 and 33.

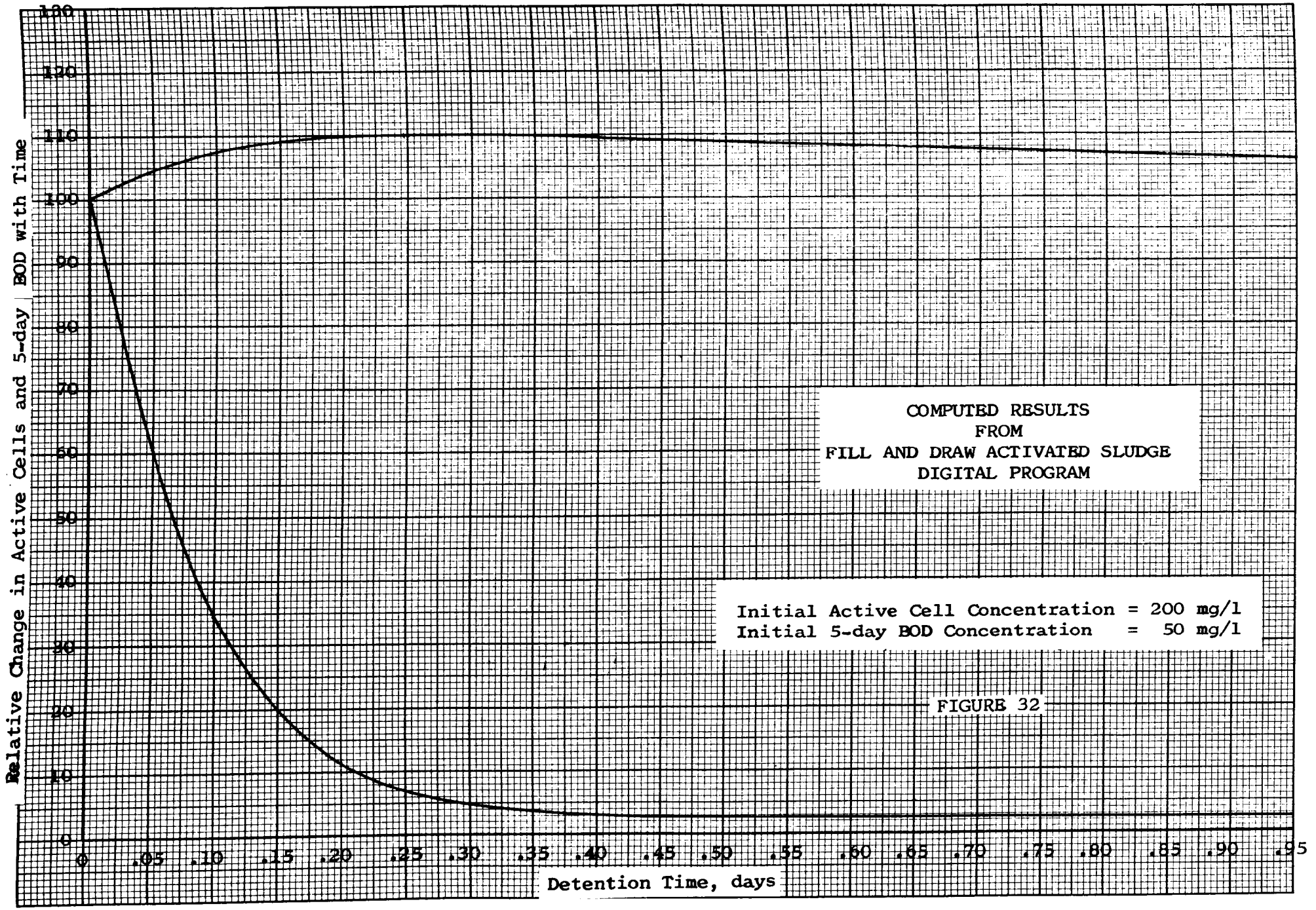

Relative Change in Active Cells and 5-day BOD with Time
120
110
100
90
80
70
60
50
40
30
20
10
0
0
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50
.55
.60
.65
.70
.75
.80
.85
.90
.95
Detention Time, days
COMPUTED RESULTS
FROM
FILL AND DRAW ACTIVATED SLUDGE
DIGITAL PROGRAM
Initial Active Cell Concentration = 200 mg/l
Initial 5-day BOD Concentration = 50 mg/l

FIGURE 32

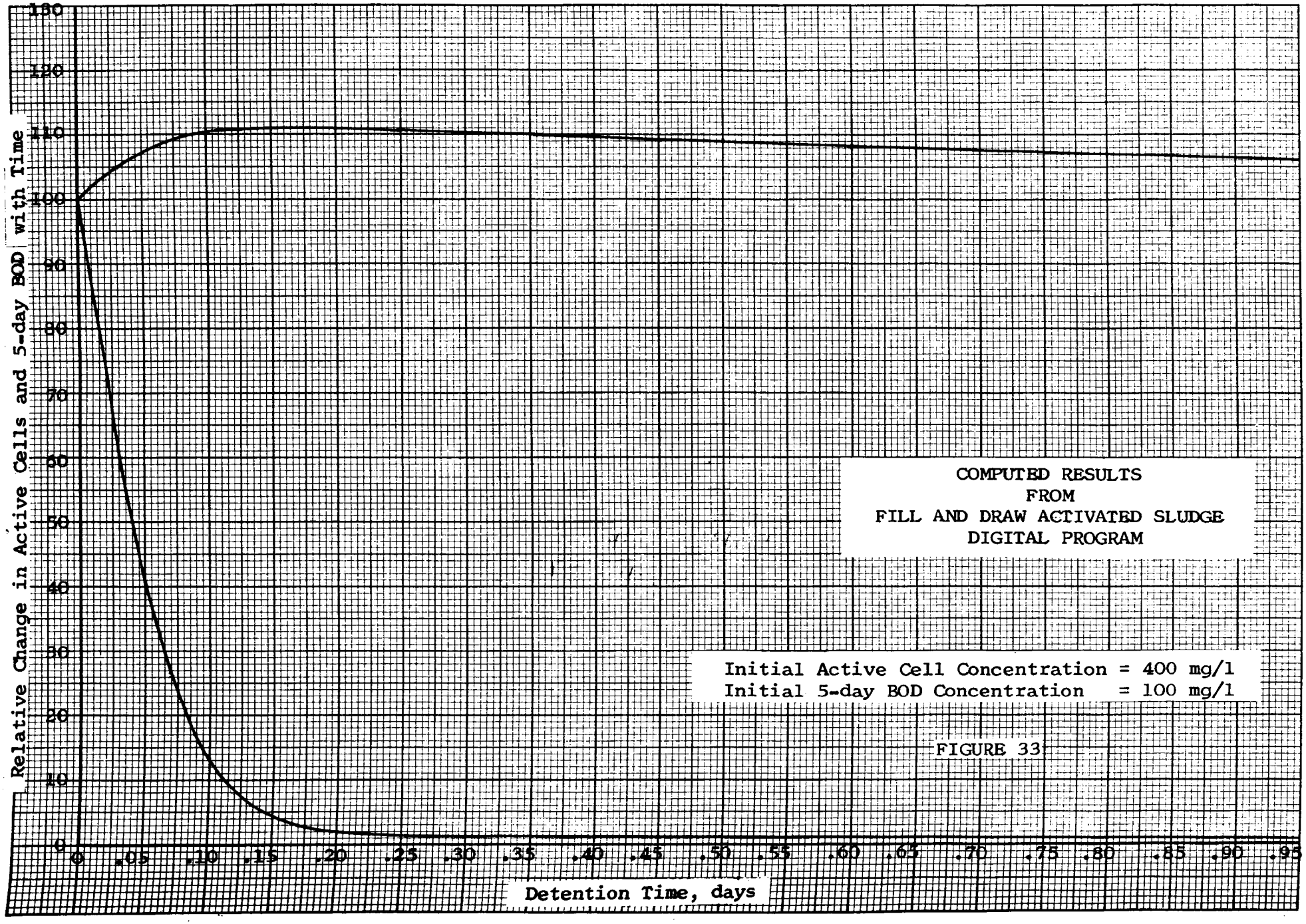

Relative Change in Active Cells and 5-day BOD with Time
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50
.55
.60
.65
.70
.75
.80
.85
.90
.95
Detention Time, days
COMPUTED RESULTS
FROM
FILL AND DRAW ACTIVATED SLUDGE
DIGITAL PROGRAM
Initial Active Cell Concentration = 400 mg/l
Initial 5-day BOD Concentration = 100 mg/l

FIGURE 33

DESCRIPTION OF CONTINUOUS STEADY STATE ACTIVATED SLUDGE PROGRAM (CSSAS)

The CSSAS program is a computational scheme programmed for the digital computer which simultaneously solves all of the mass balance and rate equations which describe the activated sludge process. The computation is strictly for steady state conditions and the program is arranged to simulate most, if not all, of the modifications of the activated sludge process. For example, conventional, high rate, extended aeration, step aeration, and contact stabilization modifications can be simulated with the program. The hydraulic flow diagram for the program is shown in Figure 34. In addition to the modifications mentioned above, the return sludge stream can be divided among the sub-aerators as shown in the diagram.

The system shown in Figure 34 is solved first for heterotrophic bacteria, then for nitrifying bacteria, and finally air requirements for all sub-aerators are computed. A computational flow diagram for the program is shown in Figure 35. The program provides for dividing the total aerator volume (VAER) into any number of equal volume sub-aerators between one and ten. This provision is for simulating the mixing model for long slender aerators or for investigating the performance of segmented aerators.

The Monod form of the growth equation is used for both heterotrophs and Nitrosomonas. K_r, K_s, K_e and Y for both classes of bacteria must be supplied as input to the program. Total aerator volume (VAER), the number of equal volume sub-aerators (NTKS), and the compaction ratio (URSS) for the final settler are also supplied as input. Characteristics listed below of the influent stream (20) are read into the program.

Q(20), S(1,20), S(2,20), SBOD(20), VIS20

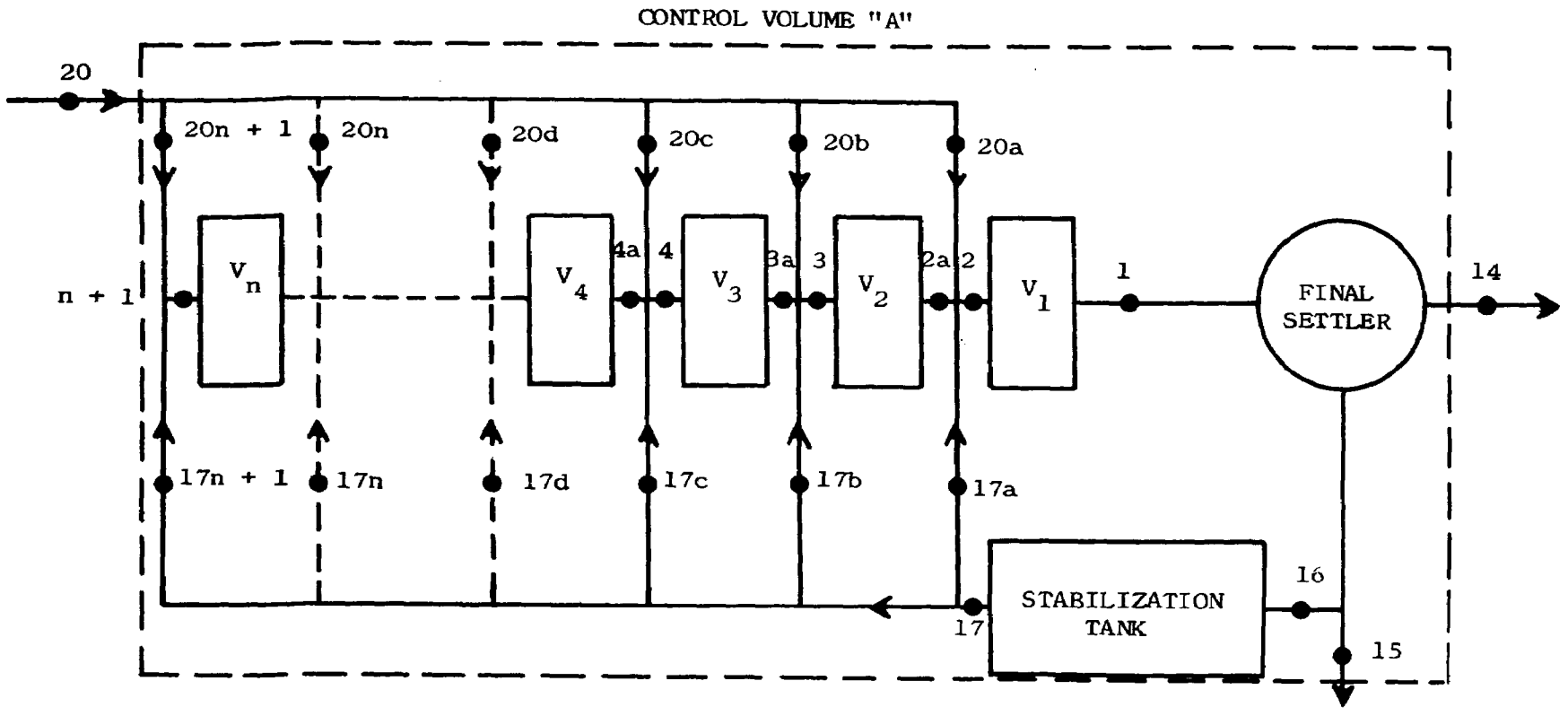

CONTROL VOLUME "A"
20
20n + 1
20n
20d
20c
20b
20a
n + 1
V_n
V_4
V_3
V_2
V_1
4a
4
3a
3
2a
2
1
FINAL SETTLER
14
17n + 1
17n
17d
17c
17b
17a
17
STABILIZATION TANK
16
15

FIGURE 34

FLOW DIAGRAM FOR CSSAS ACTIVATED SLUDGE PROGRAM

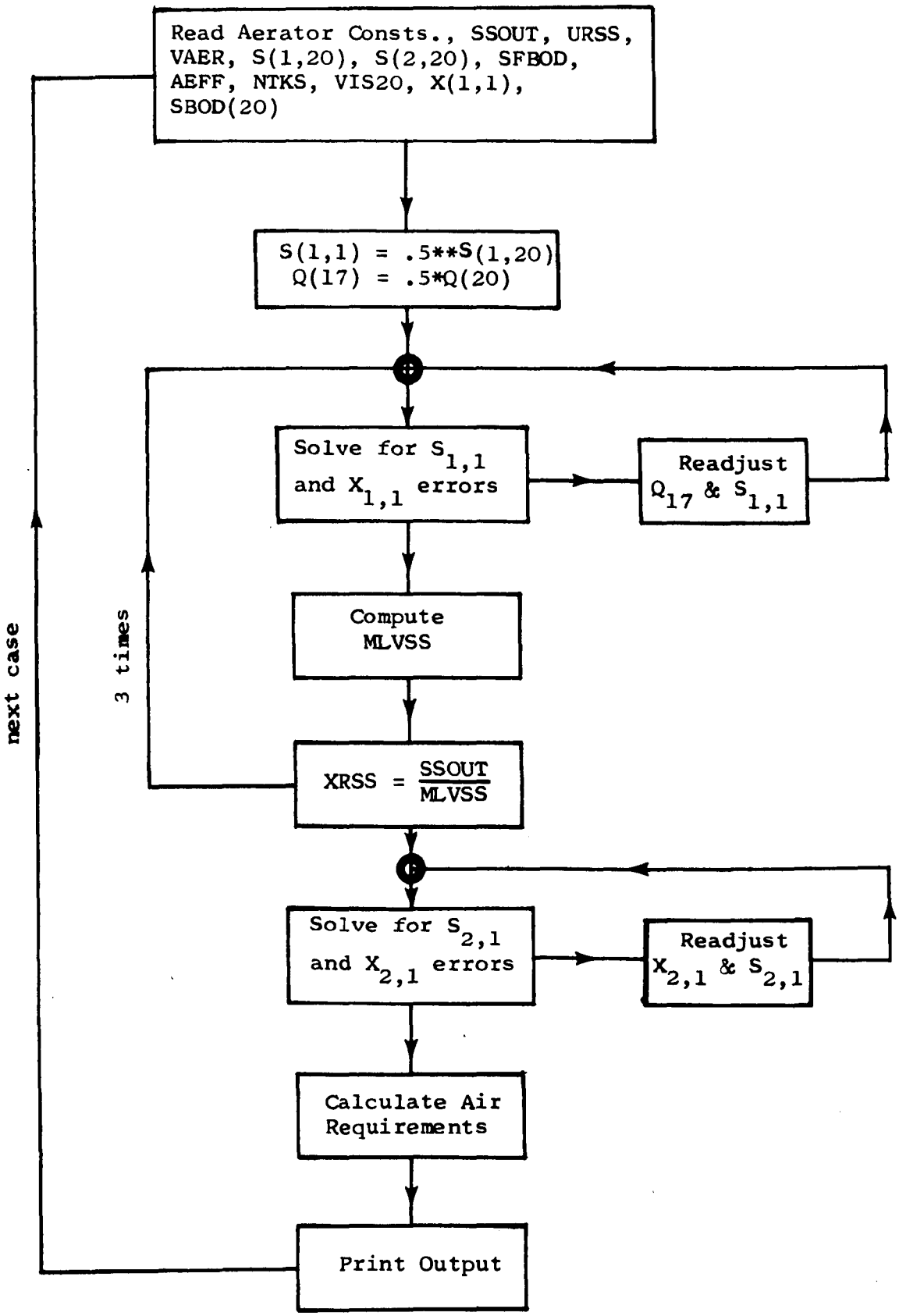


FIGURE 35

A value for efficiency of the aeration equipment (AEFF) is read into the program. Since the performance of the final settler cannot be expressed with any reliability in terms of the design parameters such as overflow rate, detention time, or weir loading the computational scheme is constrained to hold a set value (SSOUT) for volatile suspended solids in stream No. 14

The volume of the stabilization tank (V_{17}) is supplied as input. If a value of zero is supplied the stream vector for station 17 is set equal to the stream vector at station 16. The fractions (between 0 and 1.) of influent flow (PCTFL(I)) are supplied as input as well as the fractions of return flow (PCTRN(I)). The integer (I) refers to the station number just downstream of the entry point; thus PCTFL(1) and PCTRN(1) are both always equal to zero.

The following mass balance relationships are used to compute concentrations of 5-day BOD and mass of heterotrophs at stations (1) through (NTKS + 1). (n) is the station number downstream of each sub-aerator.

$$S_{n+1} = S_n + \frac{K_r\ S_n\ X_n\ DT}{Y(K_s + S_n)} \tag{46}$$

$$X_{n+1} = X_n + K_e\ X_n\ DT - \frac{K_r\ S_n\ X_n\ DT}{K_s + S_n} \tag{47}$$

$$DT = V/(Q_{20} + Q_{17}) \tag{48}$$

All iterations use the Bolzano or "halfing" technique. As shown in the flow diagram (Figure 34) the first iteration solves the system for heterotrophs. The concentration of heterotrophs (MLASS, or $X_{1,1}$) is supplied as input. The independent variables for this two

dimensional iteration are Q_{17}, the return sludge volume, and $S_{1,1}$, the 5-day BOD of substrate at the effluent end of the sub-aerator just upstream of the final settler. Beginning at station No. 1 the concentrations of heterotrophs and substrate are computed in a direction opposite to the direction of flow across all sub-aerators and back through the stabilization tank. The computed value for MLASS must equal the input value within the set tolerance and the value of $S_{1,1}$ must equal the beginning value. The values for $S_{1,1}$ and Q_{17} are readjusted in a systematic way until the tolerances are satisfied.

After the iteration for heterotrophs has been completed, the concentration of total volatile suspended solids at station No. 1 is computed. XRSS is then recomputed as SSOUT/MLVSS and the iteration for heterotrophs is recomputed two more times. It has been found that this is usually sufficient to make XRSS equal to the ratio of input value for SSOUT over the computed MLVSS.

The values for all stream volumes is now fixed and the next iteration is designed to compute the concentration of ammonia and Nitrosomonas at all stations. The independent variables for this iteration, which is also of the Bolzano type, are the concentrations of ammonia nitrogen at station No. 1 ($S_{2,1}$) and the concentration of Nitrosomonas at station No. 1 ($X_{2,1}$). The object of the iteration is to find values for ammonia nitrogen and Nitrosomonas at station No. 1 which will satisfy the system equations with all of the values for flow fixed. The computational scheme used for heterotrophs is used for Nitrosomonas except that the biological constants are changed. The errors are taken as the difference between guess and

computed values for ammonia nitrogen at station No. 1 and the difference between the previously computed TEMP1 and a new variable, X2, computed after each iteration. The reasoning behind this scheme can be seen by considering control volume "A" in Figure 34. The net growth of heterotrophs within the control volume must equal the net wasting rate from the control volume since it is assumed that none enter at station No. 20. The mass of heterotrophs wasted from the control volume can be expressed as 8.33*X(1,1)*(XRSS Q_{14} + URSS Q_{15}) or 8.33*X(1,1)*TEMP1. The net growth within the control volume can be equated to the wasting rate as follows:

$$Q_{17}X_{17} - Q_{16}X_{16} + \sum_{i=1}^{i=n} Q_{i+1}X_{i+1} - Q_iX_i = X_1 \text{ TEMP1} \qquad (49)$$

where: X = concentration of heterotrophs, mg/l
Q = volume flow, mgd
n = number of sub-volumes

Exactly the same reasoning can be applied to the growth of Nitrosomonas within the control volume. We then have the following identity:

$$X2 = \frac{Q_{17}Z_{17} - Q_{16}Z_{16}}{Z_1} + \frac{1}{Z_1} \sum_{i=1}^{i=n} Q_{i+1}\, Z_{i+1} - Q_iZ_i = \text{TEMP1} \qquad (50)$$

where: Z = concentration of Nitrosomonas, mg/l

The expression on the left of equation (50) is computed after each iteration and if the answer does not agree with TEMP1 within some acceptable tolerance, the trial concentration of Nitrosomonas at station No. 1 is readjusted by the Bolzano scheme and the system is solved again. When both the computed concentration of ammonia at station No. 1 and the computed value for X2 fall within the specified

tolerances, the iteration is terminated. A detailed description of the iterative scheme is given in Appendix I.

The initial guess for ammonia nitrogen is one half of the influent value. The initial guess for Nitrosomonas is found by assuming that half of the ammonia is converted to the oxidized form. The following equation applies:

$$Q(20)*S(2,20)*Y(2) = X(2,1)*(Q(14)*XRSS + Q(15)*URSS)$$

Solving for Nitrosomonas concentration:

$$X(2,1) = Q(20)*S(1,20)*Y(2)/(Q(14)*XRSS + Q(15)*URSS) \quad (51)$$

After this iteration has been completed the air requirement for each subaerator is computed and these are summed to give the total air requirement. Air requirements are expressed first as standard cubic feet of air per gallon of water (AIRPG(I)) and as standard cubic feet per minute (BSIZE).

In the extended aeration modification of the activated sludge process there is no sludge wasting from the underflow of the final settler; in other words the volume of stream No. 15 is zero. Since sludge must be wasted to satisfy the mass balance equations, the wasting must occur over the final settler weirs in stream No. 14. The program can be readily adapted to simulate extended aeration by setting IEA = 1 which automatically makes the following changes within the program:

1. Q(15) = 0.0
2. XRSS = 1. - Q(17)*(URSS - 1.)/Q(20)

Any value for SSOUT can be used as input because the program will never make use of the input value. The tolerance used in the main iteration is normally set at 0.1 mg/l BOD. For extended aeration this should be reduced to 0.01 mg/l.

Some computed results using the CSSAS program are shown in Figures 36 and 37 and for one, two, and three sub-aerators. The performance curve for plug flow was computed from the closed form equations 20 and 21.

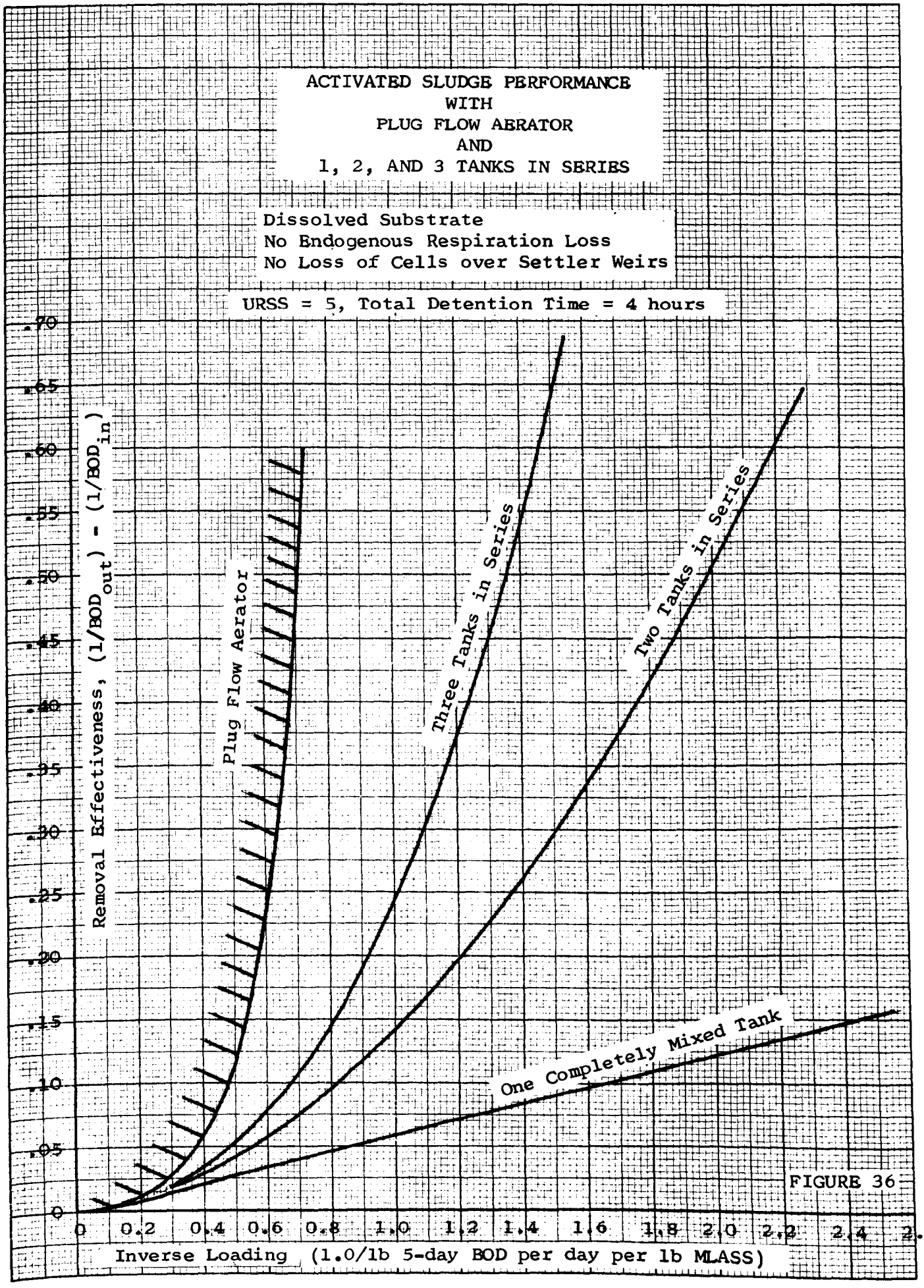

ACTIVATED SLUDGE PERFORMANCE
WITH
PLUG FLOW AERATOR
AND
1, 2, AND 3 TANKS IN SERIES
Dissolved Substrate
No Endogenous Respiration Loss
No Loss of Cells over Settler Weirs
URSS = 5, Total Detention Time = 4 hours
Removal Effectiveness, $(1/BOD_{out}) - (1/BOD_{in})$
.70
.65
.60
.55
.50
.45
.40
.35
.30
.25
.20
.15
.10
.05
0
Plug Flow Aerator
Three Tanks in Series
Two Tanks in Series
One Completely Mixed Tank
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
Inverse Loading (1.0/lb 5-day BOD per day per lb MLASS)

FIGURE 36

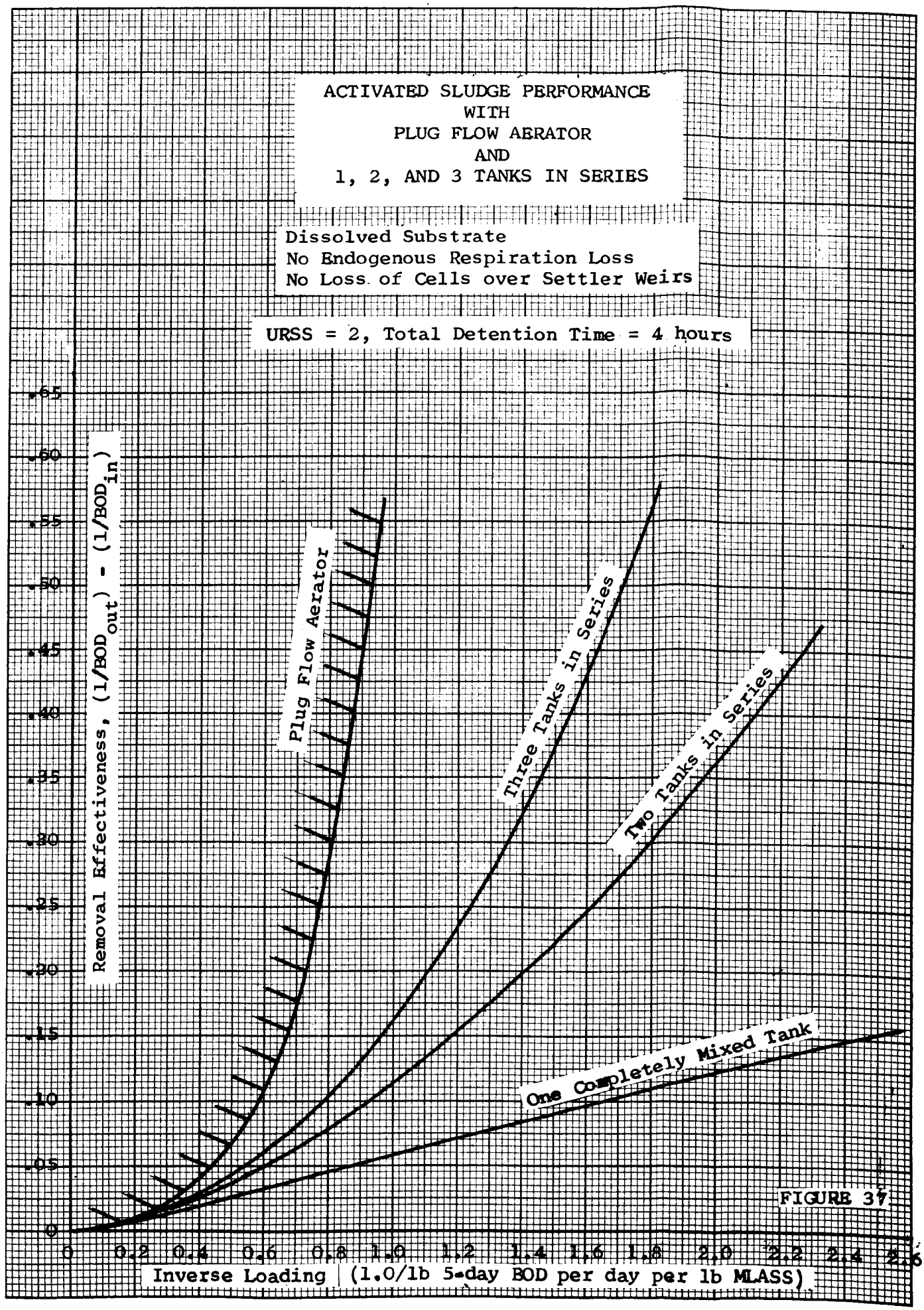

ACTIVATED SLUDGE PERFORMANCE
WITH
PLUG FLOW AERATOR
AND
1, 2, AND 3 TANKS IN SERIES
Dissolved Substrate
No Endogenous Respiration Loss
No Loss of Cells over Settler Weirs
URSS = 2, Total Detention Time = 4 hours
Removal Effectiveness, (1/BOD$_{out}$) - (1/BOD$_{in}$)
.65
.60
.55
.50
.45
.40
.35
.30
.25
.20
.15
.10
.05
0
Plug Flow Aerator
Three Tanks in Series
Two Tanks in Series
One Completely Mixed Tank
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
Inverse Loading (1.0/lb 5-day BOD per day per lb MLASS)

FIGURE 37

COMPARISON OF COMPUTED AND MEASURED DATA USING THE CSSAS DIGITAL PROGRAM

Validation of the process model by comparing computed versus measured values is an essential part of all modeling work. In this way the strengths and weaknesses of the model are discovered and functional relationships between model parameters necessary to make the computed results approximate the measurements are found.

The CSSAS model was validated primarily with data gathered at the Hyperion Plant in Los Angeles where the conventional activated sludge process is used. Data gathered at the Washington, D.C. Blue Plains Plant, which uses the high rate or modified modification of the activated sludge process, was also used to validate the model. Extended aeration data gathered at various Ohio plants by the University of Cincinnati was also used. (See Appendix III)

Measurements used to validate the CSSAS model are shown in Table II and III together with the corresponding variables computed with the model. Table II shows computed variables assuming that both dissolved and particulate fractions of 5-day BOD are equally available in the process. Table III shows computed variables assuming that only the dissolved 5-day BOD is available for synthesis. In Table IV other measured and computed data are shown using the assumption that dissolved and particulate BOD are equally available.

When the model was first written, it was believed that the inorganic or non-volatile fraction of the mixed liquor suspended solids was due to inorganic particulate entering the process at station No. 20 and accumulating in the aerator. The Hyperion data, however, showed conclusively that this assumption was not consistent with observation and it was concluded that inorganic precipitates formed in the process were

SIMULATION OF ACTIVATED SLUDGE MEASUREMENTS USING
CSSAS DIGITAL PROGRAM
DISSOLVED AND PARTICULATE BOD AVAILABLE FOR SYNTHESIS

Test No.	Nom. Aeration Time, hr.	Nominal MLSS, mg/l	Water Temperature, °C	Total 5-day BOD In	Dissolved 5-day BOD In	Nonbiodegradable VSS In, mg/l	Suspended Volatile Solids Out, mg/l	Compaction Ratio, URSS	No. Tanks	Synthesis Rate Constant, day-1	Yield Constant lb MLASS/lb BOD	Comp. VSS in Aerator	Meas. VSS in Aerator	Comp. Total BOD Out, mg/l	Meas. Total BOD Out, mg/l	Comp. Dissolved BOD Out, mg/l	Measured Dissolved BOD Out, mg/l	Comp. Waste Stream, mgd	Meas. Waste Stream, mgd	Comp. Active Solids, mg/l
HYPERION DATA																				
1	6	2000	26.8	140.5	34.6	23.3	4.4	2.86	2	4.8	.65	1372	1376	4.7	4.4	2.3	2.5	1.00	1.00	873
2	6	3000	26.2	155.5	38.7	20.1	5.5	2.46	2	4.0	.65	2016	2016	5.0	5.0	2.1	3.6	.72	.63	1245
3	5	3500	24.3	163.3	28.6	49.6	12.6	2.24	2	3.3	.45	2656	2652	8.2	8.0	4.0	4.9	.68	.58	1074
4	4	3000	23.4	164.3	47.3	26.5	11.6	2.54	2	4.8	.65	2149	2150	9.6	8.7	3.0	4.6	.83	.88	1460
5	4	1800	21.6	157.7	49.6	10.2	22.8	3.20	2	5.6	.65	1378	1377	18.8	12.2	2.8	3.0	.76	1.00	1150
6	4	1600	19.4	158.4	51.4	39.2	12.2	3.39	2	5.7	.50	1198	1199	10.7	10.9	4.6	4.8	1.11	1.10	715
7	4	1000	19.0	163.0	41.9	44.1	16.3	3.59	2	8.4	.45	829	830	12.6	13.5	4.7	4.6	1.52	1.40	474
8	6	1000	17.5	130.0	35.8	42.6	12.8	3.55	2	5.6	.45	797	797	10.7	11.3	5.3	5.2	1.34	1.27	398
9	6	600	18.1	153.8	58.8	39.7	17.3	4.55	2	7.6	.45	500	500	13.8	17.2	5.2	5.2	1.84	1.85	290
10	6	600	17.6	136.6	58.2	35.7	22.4	5.36	2	8.4	.45	435	434	15.6	18.7	4.5	4.0	1.44	1.44	251
11	6	700	19.8	151.1	49.8	38.1	17.1	4.73	2	7.1	.40	569	568	11.8	19.0	3.8	3.8	1.33	1.24	312
12	6	1500	21.8	170.1	58.7	29.8	12.6	3.35	2	4.2	.45	1193	1193	9.8	11.2	3.4	3.6	.91	.78	715
WASHINGTON, D.C. DATA																				
1	2.5	460	18.2	114.8	74.4	0.0	28.9	44.0	2	7.1	.75	346	346	40.9	45.5	16.8	18.4	.699	.921	290
EXTENDED AERATION DATA																				
1	24.	4300	20.0	195.0	121.	69.	114.	2.50	1	.68	.65	3116	3101	35.3	35.6	8.4	9.2	0.0	0.0	843

TABLE II

SIMULATION OF ACTIVATED SLUDGE MEASUREMENTS USING
CSSAS DIGITAL PROGRAM
ONLY DISSOLVED BOD AVAILABLE FOR SYNTHESIS

Test No.	Nom. Aeration Time, hr.	Nominal MLSS, mg/l	Water Temperature, °C	Total 5-day BOD In	Dissolved 5-day BOD In	Nonbiodegradable VSS In, mg/l	Suspended Volatile Solids Out, mg/l	Compaction Ratio, URSS	No. Tanks	Synthesis Rate Constant, day-1	Yield Constant lb MLASS/lb BOD	Comp. VSS in Aerator	Meas. VSS in Aerator	Comp. Total BOD Out, mg/l	Meas. Total BOD Out, mg/l	Comp. Dissolved BOD Out, mg/l	Measured Dissolved BOD Out, mg/l	Comp. Waste Stream, mgd	Meas. Waste Stream, mgd	Comp. Active Solids, mg/l
HYPERION DATA																				
1	6	2000	26.8	105.9	34.6	23.3	4.4	2.86	2	6.6	.40	1374	1376	5.1	4.4	2.5	2.5	1.15	1.00	370
2	6	3000	26.2	116.3	38.7	20.1	5.5	2.46	2	6.0	.45	2022	2016	5.5	5.0	2.1	3.6	.95	.63	560
3	5	3500	24.3	134.8	28.6	49.6	12.6	2.24	2	4.1	.40	2650	2652	10.4	8.0	4.7	4.9	.90	.58	675
4	4	3000	23.4	117.0	47.3	26.5	11.6	2.54	2	7.3	.45	2153	2150	10.4	8.7	3.2	4.6	1.03	.88	625
5	4	1800	21.6	108.1	49.6	10.2	22.8	3.20	2	9.3	.40	1377	1377	19.7	12.2	3.2	3.0	.95	1.00	420
6	4	1600	19.4	107.0	51.4	39.2	12.2	3.39	2	10.3	.30	1187	1199	11.9	10.9	5.1	4.8	1.44	1.10	235
7	4	1000	19.0	121.1	41.9	44.1	16.3	3.59	2	12.6	.25	831	830	13.7	13.5	5.2	4.6	1.76	1.40	173
8	6	1000	17.5	94.2	35.8	42.6	12.8	3.55	2	10.7	.30	791	797	10.9	11.3	4.6	5.2	1.72	1.27	160
9	6	600	18.1	95.0	58.8	39.7	17.3	4.55	2	13.1	.25	509	500	17.7	17.2	8.0	5.2	2.53	1.85	75
10	6	600	17.6	78.5	58.2	35.7	22.4	5.36	2	16.7	.20	434	434	19.1	18.7	6.4	4.0	2.13	1.44	47
11	6	700	19.8	101.3	49.8	38.1	17.1	4.73	2	11.1	.20	566	568	15.3	19.0	6.0	3.8	1.86	1.24	80
12	6	1500	21.8	111.4	58.7	29.8	12.6	3.35	2	11.1	.35	1194	1193	10.0	11.2	2.2	3.6	1.53	.78	262
WASHINGTON, D.C. DATA																				
1	2.5	460	18.2	40.4	74.4	0.0	28.9	44.0	2	23.6	.65	349	346	44.4	45.5	21.2	18.4	1.15	.921	40
EXTENDED AERATION DATA																				
1	24.	4300	20.0	74.0	121.	69.	114.	2.5	1	---	---	---	3101	---	35.6	---	9.2	---	0.0	---

TABLE III

COMPUTED AND MEASURED RESULTS USING HYPERION DATA

DISSOLVED AND PARTICULATE BOD EQUALLY AVAILABLE FOR SYNTHESIS

Test No.	No. Tanks	Tank No. 1 Comp. scf/gal.	Tank No. 2 Comp. scf/gal.	Total Air Comp. scf/gal.	Total Air Meas. scf/gal.	MLASS mg/l	MLBSS mg/l	MLNBSS mg/l	MLDSS mg/l	Return Flow Comp. mgd	Return Flow Meas. mgd	Effluent NH_3-N, mg/l	Nitrosomonas in aerator mg/l
1	2	1.64	0.43	2.07	1.29	873.	0.96	388.	110.	25.3	23.8	0.09	14.8
2	2	2.18	0.55	2.73	1.30	1245.	0.87	526.	244.	32.7	29.1	0.03	26.0
3	2	1.68	0.45	2.13	1.36	1074.	1.08	1410.	172.	38.9	34.0	0.08	25.5
4	2	1.66	0.61	2.27	1.40	1460.	1.53	557.	130.	30.9	30.8	0.78	16.8
5	2	0.84	0.30	1.14	1.40	1150.	2.66	157.	68.	21.2	20.1	18.1	0.0
6	2	0.74	0.27	1.01	1.33	715.	4.45	452.	27.	18.8	17.1	18.6	0.0
7	2	0.74	0.24	0.98	1.40	474.	3.28	340.	11.9	16.5	17.6	18.5	0.0
8	2	0.58	0.23	0.81	1.42	398.	4.04	379.	16.0	17.2	18.1	13.6	0.0
9	2	0.66	0.24	0.90	1.40	290.	6.07	198.	5.8	11.3	11.5	16.5	0.0
10	2	0.59	0.21	0.80	1.40	251.	6.24	173.	4.6	9.0	9.4	14.6	0.0
11	2	0.70	0.22	0.92	1.40	312.	3.65	243.	10.2	11.1	12.8	16.8	0.0
12	2	1.60	0.59	2.19	1.40	715.	2.33	418.	58.4	19.8	19.2	1.4	11.6

TABLE IV

largely responsible for the non-volatile fraction of mixed liquor suspended solids. Mass balances for non-volatile suspended solids for the first four tests performed at the Hyperion Plant are shown in Table V. From Table V it can be seen that the non-volatile suspended solids leaving the process is two or three times that entering the process.

Since modeling of salt precipitation within the activated sludge process is known to be far more complex than available simple theory would suggest, it was decided to base the model on the behavior of organic or volatile materials and to exclude consideration of inorganic materials.

The model as it now stands is relatively flexible in that it can be arranged to compute performance under various sets of assumptions. For example, the availability of dissolved and particulate fractions of substrate for heterotrophs can be arranged in two ways. First, it can be assumed that only dissolved substrate is available for synthesis and second, that both dissolved and particulate fractions are equally available. When the first assumption is used, the particulate BOD observed in stream 20 accumulates within the process and appears again in the effluent stream as part of the inputed SSOUT. Under the second assumption the particulate BOD not synthesized in the aerator also exerts a BOD in the effluent stream. Under both assumptions, however, the active solids which escape over the final weirs contribute to the BOD of the effluent stream.

The model can be arranged to simulate conventional, modified, extended aeration, or contact stabilization. In addition, the influent stream can be split and distributed to the various sub-aerators and the

TABLE V

MASS BALANCES FOR NON-VOLATILE SUSPENDED SOLIDS

	Sta. 20	Sta. 14	Sta. 15
HYPERION PLANT - Test No. 1			
Volume Flow, mgd	49.51	.95	48.56
Suspended Solids, mg/l	74.46	5720.	5.7
Fraction Volatile	.832	.68	.777
Non-Volatile Mass Flow, lb/day	619.33	1738.88	61.72
Percent Error in Mass Balance	191%		
HYPERION PLANT - Test No. 2			
Volume Flow, mgd	49.6	.63	48.97
Suspended Solids, mg/l	67.8	7408.	7.09
Fraction Volatile	.843	.685	.784
Non-Volatile Mass Flow, lb/day	527.97	1470.12	74.99
Percent Error in Mass Balance	193%		
HYPERION PLANT - Test No. 3			
Volume Flow, mgd	49.8	.557	49.24
Suspended Solids, mg/l	99.8	7867.	14.
Fraction Volatile	.868	.755	.901
Non-Volatile Mass Flow, lb/day	656.05	1073.57	68.25
Percent Error in Mass Balance	74%		
HYPERION PLANT - Test No. 4			
Volume Flow, mgd	50.02	.88	49.14
Suspended Solids, mg/l	96.	7340.	15.2
Fraction Volatile	.855	.747	.764
Non-Volatile Mass Flow, lb/day	696.28	1634.18	176.28
Percent Error in Mass Balance	160%		

concentrated sludge from the final settler underflow can be distributed to the individual sub-aerators.

COD or TOC could be used as substrate for heterotrophs by changing the Monod relationship constants. This, however, has not been attempted.

It should be pointed out that the model has not been adequately tested on the contact stabilization process and, therefore, the adsorption process which is believed to be important has not been evaluated.

In the first attempt to make the CSSAS program simulate measurements the Hyperion conventional activated sludge data was used. Since no tracer studies were available, it was assumed that the aerator could be simulated best by two equal volume completely mixed tanks in series. The input was prepared as described on page 20. The CSSAS program was then used to compute all process variables using various values for MLASS as input. MLASS was adjusted by trial and error until the computed MLVSS at the aerator exit (Station No. 1) equalled the measured value within some reasonable tolerance. To test the simulation, computed values for effluent dissolved BOD, effluent total BOD, and volume of waste activated sludge stream were compared to the measured values. If the comparison between computed and measured variables was not adequate, the maximum rate constant for synthesis, (K_r) and the yield coefficient (Y) were adjusted by trial and error until the best agreement between all computed and measured variables was achieved. The saturation constant (K_s) was found to have little independent effect at the low substrate concentrations characteristics of municipal sewerage. The value used for K_s was 150 mg/l 5-day BOD on all computations.

The final comparison between computed and measured variables using the assumption that dissolved and particulate 5-day BOD are equally available is shown in Table II. Similar comparisons for the modified activated sludge data from the Washington, D.C. plant and the extended aeration plant with no deliberate sludge wasting are also shown in Table II. It can be seen that the agreement between computed and measured variables is quite acceptable provided the proper values for K_r and Y are used. The yield coefficient required to make the computed results agree with measured results varied between 0.40 and 0.75 with no apparent relationship to process design and operating parameters. For example, the yield coefficient for heterotrophs is shown plotted versus inverse loading in Figure 38. No relationship is evident. The maximum rate constant for synthesis (K_r), on the other hand, varied as a fairly definite exponential function of inverse loading as shown in Figure 39.

As shown in Table IV, the computed and measured volumes of the return stream agree well. The measured value for URSS was supplied as input to the program because no reliable relationship between URSS and process design parameters is known. The amount of waste activated sludge, however, was accurately predicted by the program. The computed air usage rate is in agreement with the measured values provided nitrification does not occur as in Test Nos. 5-11. The program predicted nitrification in Test Nos 1-4 and 12. The measurements showed, however, that no nitrification occurred in all twelve tests. This discrepancy is probably due to the lack of available air as shown by the computed requirements which are always greater than the amount supplied.

A similar analysis was made based on the assumption that only dissolved BOD is available for synthesis. The results of this study is shown in Table III and Figure 40. Again, no definite relationship was observed for yield coefficient but a reasonable relationship was found for all points except the extended aeration point. For extended aeration the data were simply not compatible with the assumption that only dissolved BOD is used for synthesis. The rate constants found by trial and error are also significantly higher than those found under the first assumption.

Probably neither assumption is strictly correct but it appears from this work that the first assumption is closer to the truth. If the rate constant for synthesis is read from Figure 39 corresponding to the input value for MLASS, there is every reason to expect that the program will yield performance estimates which are nearly correct for domestic sewage. Estimating the performance of the final settler in terms of the physical characteristics of the settler and the character of the influent activated sludge remains the most significant unsolved problem in the process design technology for the activated sludge process.

Finally, the CSSAS program was used to compute performance charts based on the assumption that both dissolved and particulate fractions are available and the empirical relationship between rate constant and inverse loading. This computer data using average Hyperion influent data are shown in Figures 41 - 43. The lines shown in Figure 41 are straight for most of the useful range but do not intersect the origin. This tends to justify further the use of this kind of plot for interpretation of data provided the line is not constrained to pass through the origin and provided the effluent is either filtered or contains a

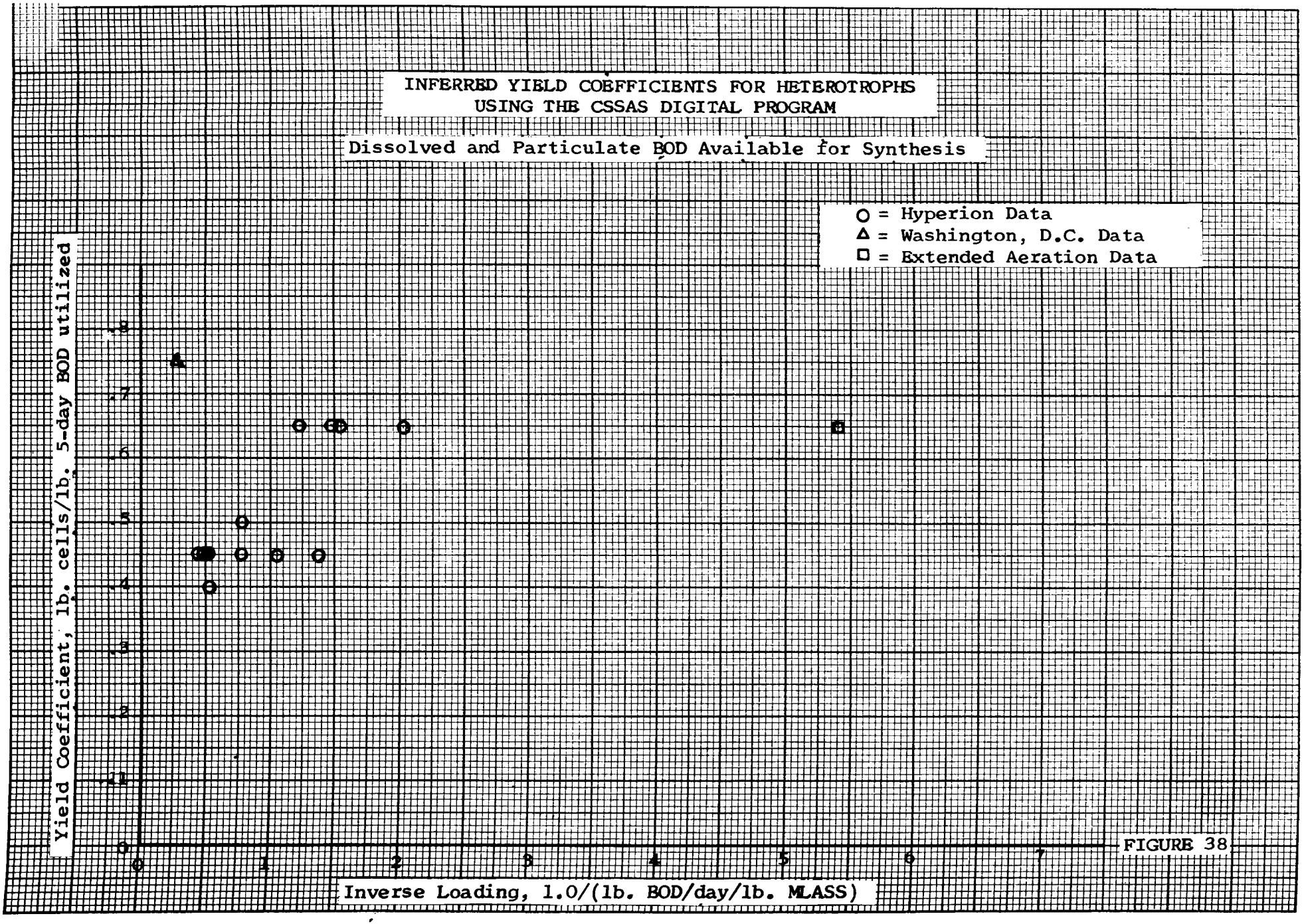

INFERRED YIELD COEFFICIENTS FOR HETEROTROPHS
USING THE CSSAS DIGITAL PROGRAM
Dissolved and Particulate BOD Available for Synthesis
O = Hyperion Data
Δ = Washington, D.C. Data
□ = Extended Aeration Data
Yield Coefficient, lb. cells/lb. 5-day BOD utilized
Inverse Loading, 1.0/(lb. BOD/day/lb. MLASS)
0
1
2
3
4
5
6
7

FIGURE 38

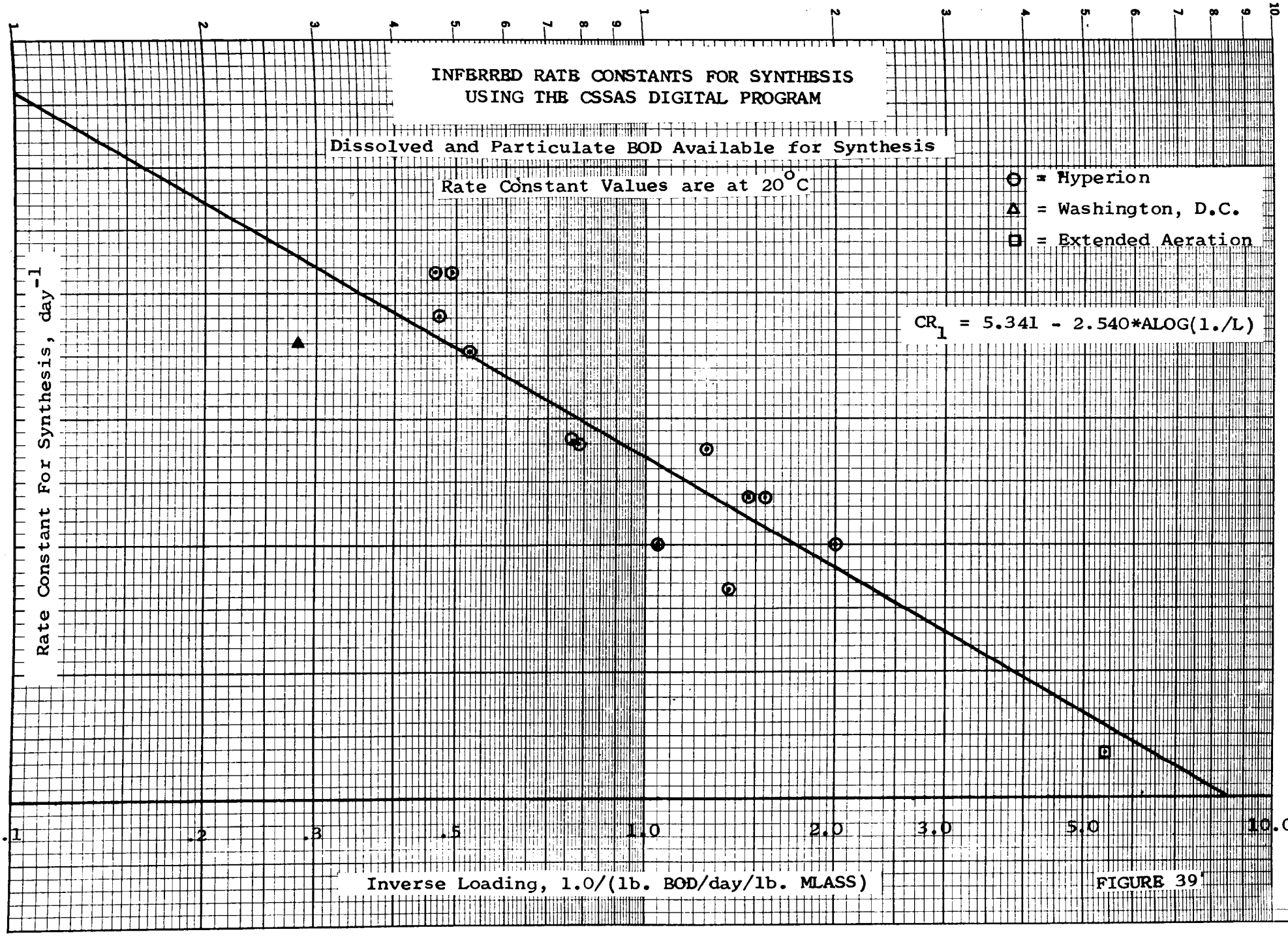

INFERRED RATE CONSTANTS FOR SYNTHESIS
USING THE CSSAS DIGITAL PROGRAM
Dissolved and Particulate BOD Available for Synthesis
Rate Constant Values are at 20°C
O = Hyperion
Δ = Washington, D.C.
□ = Extended Aeration
CR1 = 5.341 - 2.540*ALOG(1./L)
Rate Constant For Synthesis, day-1
Inverse Loading, 1.0/(lb. BOD/day/lb. MLASS)
.1
.2
.3
.5
1.0
2.0
3.0
5.0
10.0

FIGURE 39

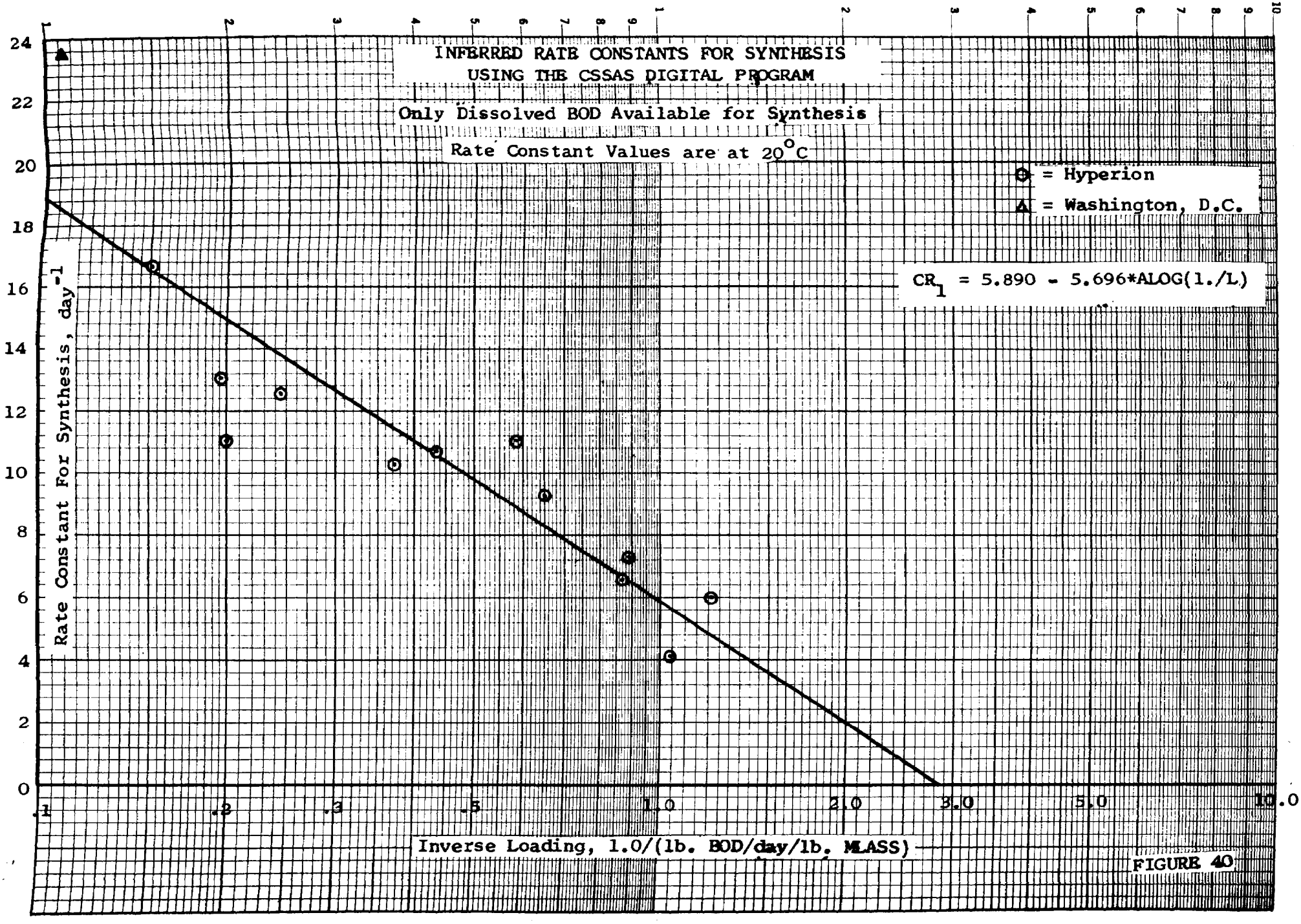

INFERRED RATE CONSTANTS FOR SYNTHESIS
USING THE CSSAS DIGITAL PROGRAM
Only Dissolved BOD Available for Synthesis
Rate Constant Values are at 20°C
= Hyperion
= Washington, D.C.
CR1 = 5.890 - 5.696*ALOG(1./L)
Rate Constant For Synthesis, day-1
Inverse Loading, 1.0/(lb. BOD/day/lb. MLASS)
0
2
4
6
8
10
12
14
16
18
20
22
24
.1
.2
.3
.5
1.0
2.0
3.0
5.0
10.0

FIGURE 40

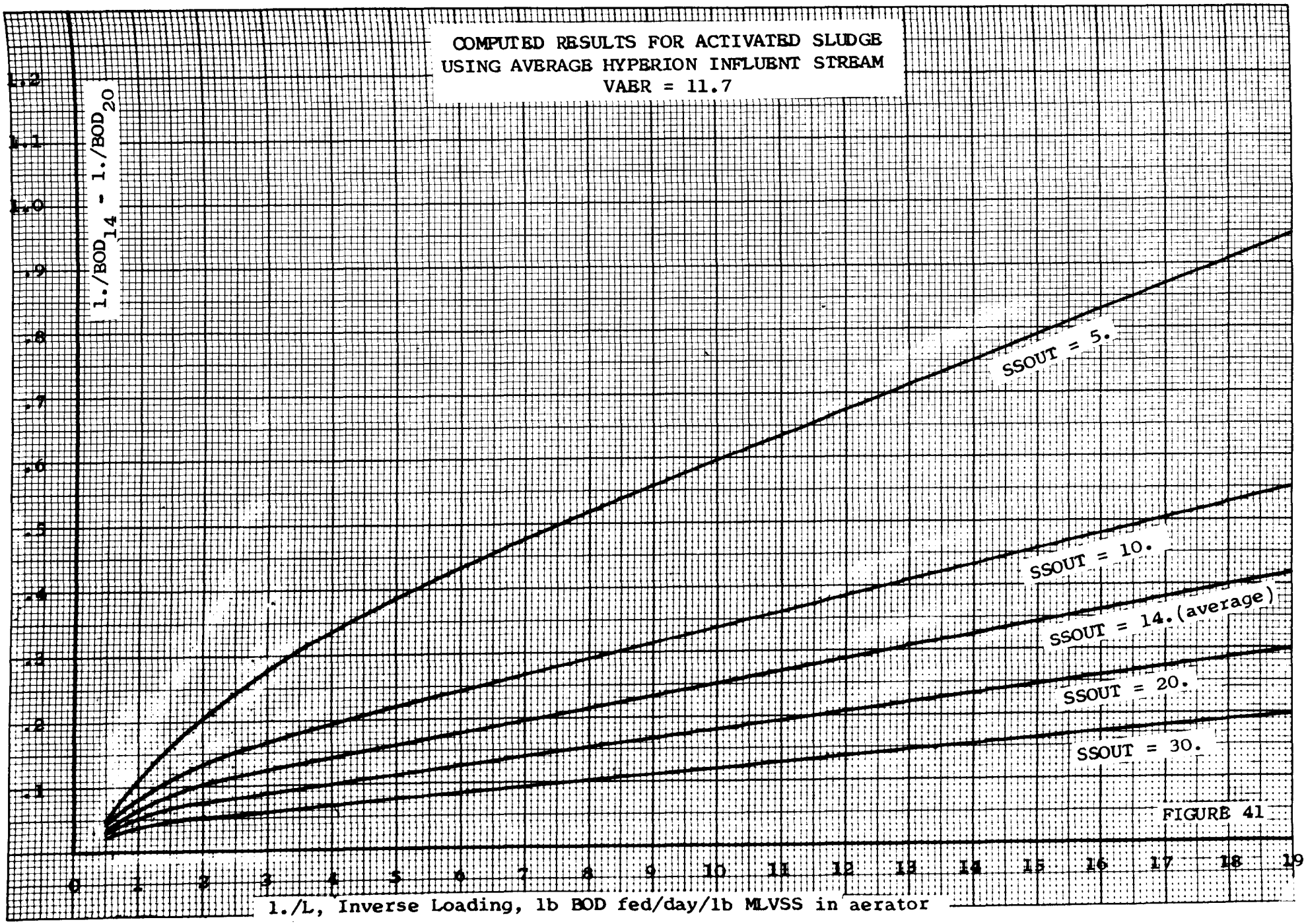

COMPUTED RESULTS FOR ACTIVATED SLUDGE
USING AVERAGE HYPERION INFLUENT STREAM
VABR = 11.7
1./BOD14 - 1./BOD20
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
SSOUT = 5.
SSOUT = 10.
SSOUT = 14.(average)
SSOUT = 20.
SSOUT = 30.
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
1./L, Inverse Loading, lb BOD fed/day/lb MLVSS in aerator

FIGURE 41

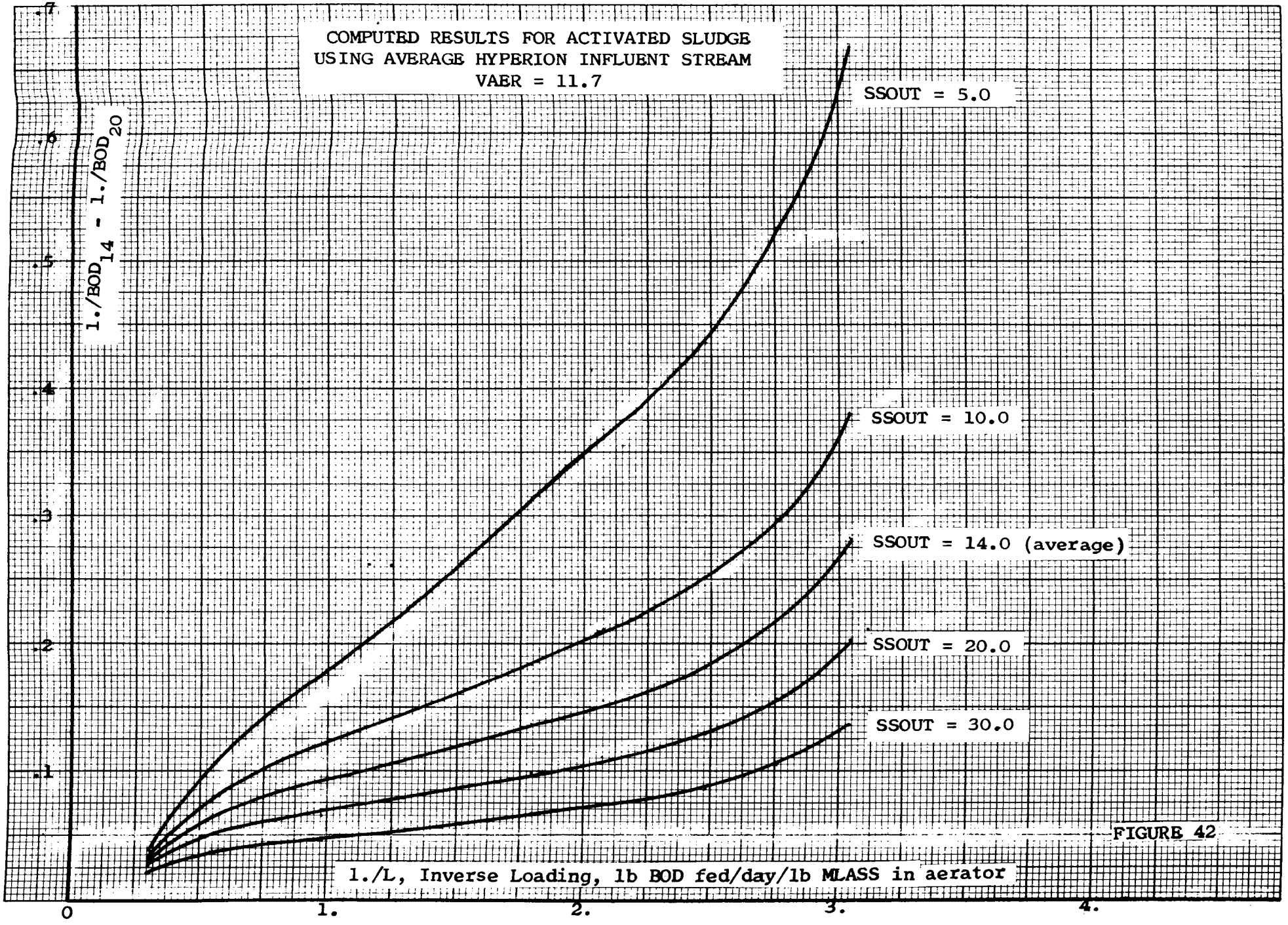

COMPUTED RESULTS FOR ACTIVATED SLUDGE
USING AVERAGE HYPERION INFLUENT STREAM
VAER = 11.7
SSOUT = 5.0
SSOUT = 10.0
SSOUT = 14.0 (average)
SSOUT = 20.0
SSOUT = 30.0
1./BOD14 - 1./BOD20
.7
.6
.5
.4
.3
.2
.1
0
1.
2.
3.
4.
1./L, Inverse Loading, lb BOD fed/day/lb MLASS in aerator

FIGURE 42

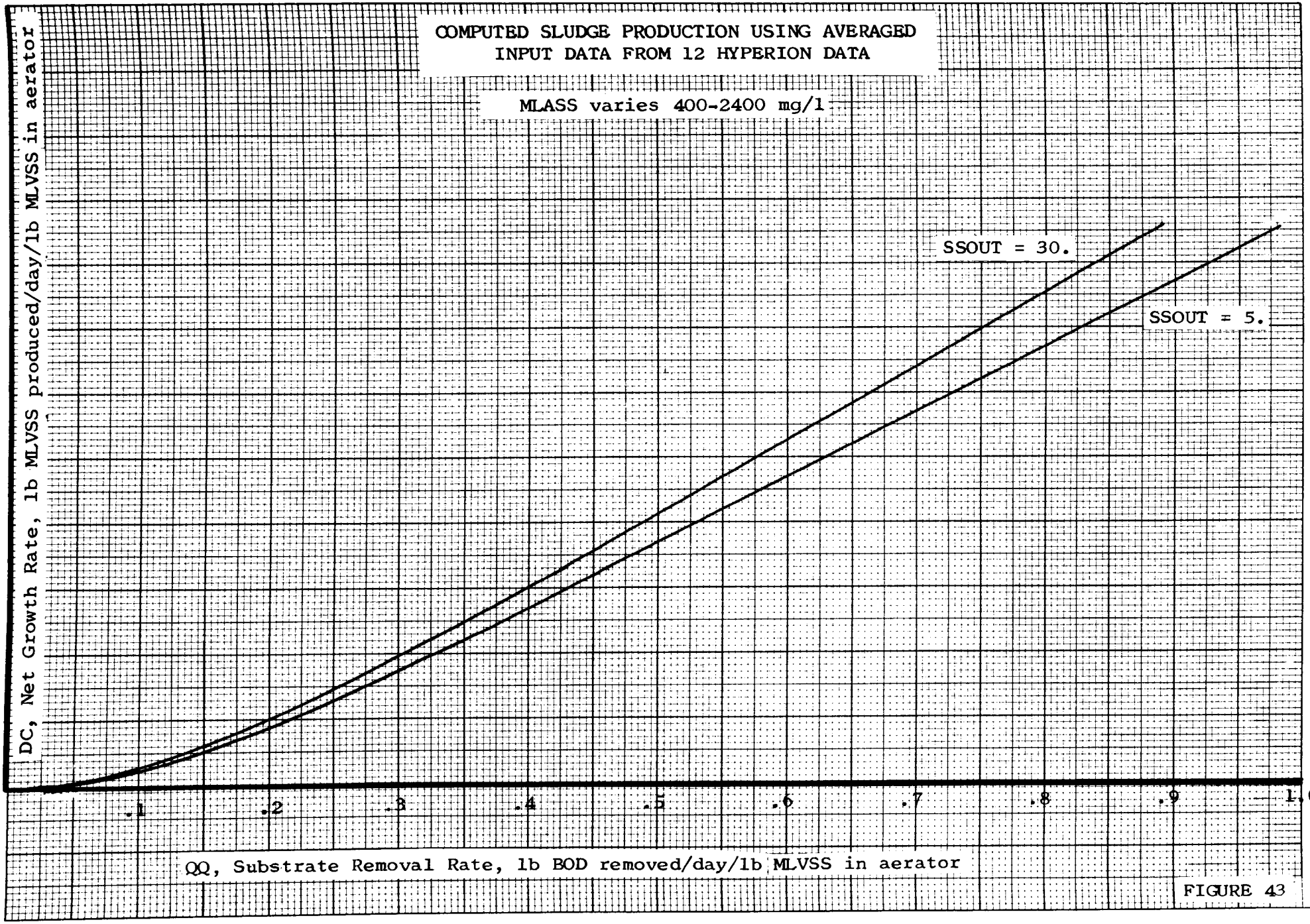

COMPUTED SLUDGE PRODUCTION USING AVERAGED INPUT DATA FROM 12 HYPERION DATA
MLASS varies 400-2400 mg/l
SSOUT = 30.
SSOUT = 5.
DC, Net Growth Rate, lb MLVSS produced/day/lb MLVSS in aerator
.5
.4
.3
.2
.1
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
QQ, Substrate Removal Rate, lb BOD removed/day/lb MLVSS in aerator

FIGURE 43

fixed concentration of organic suspended solids. The importance of SSOUT can be seen clearly in Figure 41. Figure 42 is a similar plot except that inverse loading is based on active solids rather than total volatile suspended solids. The lines in this diagram are clearly less linear.

Finally, Figure 43 shows computed results where net growth rate is plotted as a function of substrate removal rate and SSOUT. Notice, first, that SSOUT has a minimal effect on the plot. Using the simplified theory described on pages 28 - 31, this plot is predicted to be linear as shown by equation (41). According to the simple theory, the slope of the line should equal the yield coefficient, and the intercept should equal the negative of the endogenous respiration constant (K_e). Using the computer program, the slope of the lines are 0.50 for the SSOUT = 5. line and 0.57 for the SSOUT = 30. line. The yield coefficient used in the program was the average for the Hyperion data which had a value of 0.517. The extrapolated intercept of the two lines have values of 0.07 and 0.085. The actual value used for the endogenous respiration constant (K_e) was 0.18. This shows the limitations inherent in over simplified representations of the process and helps to explain the range of values reported in the literature for process biokinetic constants.

CONCLUSIONS AND RECOMMENDATIONS

A computing tool (CSSAS program) has been developed to aid in understanding the relationships which govern the quasi-steady-state performance of the activated sludge process. A start has been made towards fitting the model to measurements made on full-sized plants. The FADAS program which has not been validated will be useful in interpretation of bench scale fill-and-draw experiments.

The observed variation of the maximum rate constant for synthesis (K_r) with inverse loading is important for quasi-steady-state process design and will also be useful for time-dependent models of the process. The assumption that both dissolved and particulate 5-day BOD are equally available for synthesis appears to be more consistent with observation than the assumption that only dissolved 5-day BOD is available. Some sort of intermediate assumption would probably improve the correspondence between measured and computed results. The lack of a relationship between the yield coefficient and some process design parameters was disappointing and further study is needed to resolve this question. Precision of measurement might be a significant factor.

Additional work is needed to better understand the effect of mixing in the aerator. Measurements are needed on aerators deliberately divided into completely mixed sub-aerators.

The adsorption mechanism believed to be important in the contact stabilization process should be investigated. A separate sludge stabilization tank will be necessary if meaningful data are to be obtained. That is, using the downstream portion of the aerator as the stabilization zone yields confusing data because of the backmixing.

The model has not been properly tested for nitrification because an adequate supply of air was not available at the Hyperion Plant. Additional measurements are needed to validate the model for the computation of nitrification performance.

No adequate relationship between the efficiency (XRSS) and sludge compaction (URSS) in the final settler and process design parameters is known. The fraction of volatile solids which escape over the final settler weirs is an important factor in effective design and operation of the process. The compacting characteristics, on the other hand, is less important.

To summarize, the CSSAS program represents the most complete state-of-the-art computational procedure for quasi-steady-state performance of the activated sludge process but some important questions relating to design and operation of the process remain unresolved. The program, however, will serve as a focal point for any new information developed through experimentation and should ultimately represent a thoroughly reliable design tool.

DEFINITIONS OF TEXT SYMBOLS

Text Symbols	Nominal Value	Definitions and Comments
NTKS		Number of equal volume sub-aerators
V		Volume of each sub-aerator, mg
VAER		Total volume of all sub-aerators, V·NTKS, mg
Q		Volume flow, mgd
X or $X_{1,J}$		Concentration of heterotrophs, mg/l at station J
S or $S_{I,J}$	(see footnote)	Concentration of substrate, 5-day BOD, mg/l
Y		Yield coefficient, lb cells synthesized per lb of substrate utilized
K_r or CR(I)	(see footnote)	Maximum rate constant for synthesis, day^{-1}
K_s or CS(I)		Saturation constant, mg/l of substrate
S*	160 mg/l	Point on substrate scale where discontinuity falls (5-day BOD)
URSS		Final settler compaction ratio
MLASS		Concentration of heterotrophs, mg/l
COD_{food}		Chemical oxygen demand of substrate used, mg/l
COD_{cells}		Chemical oxygen demand of cells formed, mg/l
O		Oxygen used in synthesis, mg/l
L		Total carbonaceous BOD, mg/l
K_e or CE(I)		Endogenous respiration constant, fraction of viable cells which lyse per day, lb cells/day

DEFINITIONS OF TEXT SYMBOLS

Text Symbols	Nominal Value	Definitions and Comments
VIS20		Concentration of non-biodegradable volatile suspended solids at station 20, mg/l
XRSS		Final settler efficiency, volatile suspended solids at station 14/volatile suspended solids at station 1
D_c		Specific wasting rate, lb MLASS wasted per day/lb MLASS in aerator
q		Specific substrate removal rate, lb substrate removed per day/lb active solids in aerator
SBOD(20)		Concentration of particulate 5-day BOD at station 20, mg/l
SSOUT		Concentration of volatile suspended solids at station 14, mg/l (input to program)

NOTE:
I = 1 for heterotrophs or 5-day BOD
I = 2 for nitrosomonas or ammonia nitrogen
J = station number

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APPENDIX I

DETAILS OF ITERATION SCHEMES USED IN CSSAS PROGRAM

ITERATION FOR HETEROTROPHS, X(1,1)

A double "halfing" iteration is performed on contours of S(1,1) (concentration of BOD at station 1, mg/l) and Q(17) (return flow, mgd) to find the values for S(1,1) and Q(17) that satisfy the governing mass balance within a tolerance of .01 mg/l and rate equations for the system. S1 and X1 must agree with S(1,1) and X(1,1) within a tolerance of 0.01 mg/l:

$$S(1,1) = S1 = S(1,16)/(SFBOD*(URSS-1.)+1.)$$

$$X(1,1) = X1 = X(1,16)/URSS$$

where X(1,1) is the concentration of active solids at station 1.

The program computes initial estimates for the iteration of S(1,1) = .5*S(1,20) and Q(17) = .5*Q(20), since it is known that 0. < S(1,1) < S(1,20) and 0. < Q(17) < Q(20). A value S1 is computed based on the initial estimates of S(1,1) and Q(17). If the absolute value of (S(1,1)-S1) does not satisfy the tolerance and S(1,1) > S1, then a larger value of S(1,1) is needed to satisfy the system, i.e. .5*S(1,20) < S(1,1) < S(1,20), so the next estimate for S(1,1) is $\frac{1}{2}$ of this remaining interval. If S(1,1) < S1, then a smaller value of S(1,1) is needed, i.e. 0. < S(1,1) < .5*S(1,20), so the next estimate for S(1,1) would be $\frac{1}{2}$ of this remaining interval. This type of iteration, taking $\frac{1}{2}$ of the remaining valid interval for each successive estimate, is performed on S(1,1) until the tolerance is satified or until 20 passes are completed. Once a satisfactory S(1,1) has been found for the initial Q(17) estimate, the absolute value of (X(1,1)-X1) is tested against the tolerance. If the tolerance is not satisfied, and X(1,1) > X1, then a smaller value of Q(17) is needed to satisfy the system, i.e. 0. < Q(17) < .5*Q(20), so the next estimate for Q(17)

is ½ of this remaining interval. If X(1,1) < Xl, then a larger value of Q(17) is needed, i.e. .5*Q(20) < Q(17) < Q(20), so the next estimate of Q(17) is ½ of this remaining interval. After the new estimate of Q(17) is calculated for the system, the program re-iterates on S(1,1) in the same manner as previously described. This process continues until both tolerances are satisfied, or until Q(17) has been iterated on 20 times. When both tolerances are satisfied, the value of S(1,1) which satisfies the system has been found. If the iteration has not converged after 20 passes on Q(17), an error comment is printed, and the program proceeds to execute the next case.

ITERATION FOR NITROSOMONAS, X(2,1)

A double "halfing" iteration is performed on contours of S(2,1) (concentration of ammonia at station 1, mg/l) and X(2,1) (concentration of nitrosomonas at station 1, mg/l) to find the values of S(2,1) and X(2,1) that satisfy the governing mass balance and rate equations of the system for nitrosomonas. S2 and X2 must agree with S(2,1) and TEMP1 within a tolerance of 0.01.

S(2,1) = S2 = S(2,16)

TEMP1 = X2 = (refer to page 36)

where TEMP1 = Q(14)*XRSS+Q(15)*URSS.

The program computes initial estimates for the iteration of S(2,1) = .5*S(2,20) and X(2,1) = XE = CY(2)*Q(20)*S(2,20)/(DC*VAER), since it is known that 0. < S(2,1) < S(2,20) and 0 < X(2,1) < 2*XE. A value S2 is computed based on the initial estimates of S(2,1) and X(2,1). If the absolute value of (S(2,1)-S2) does not satisfy the tolerance and S(2,1) > S2, then a larger value of S(2,1) is needed to satisfy the system, i.e. .5*S(2,20) < S(2,1) < S(2,20), so the next estimate for S(1,1) is ½ of this remaining interval. If S(2,1) < S2, then a smaller value of S(2,1) is needed, i.e. 0 < S(2,1) < .5*S(2,20), so the next estimate for S(2,1) would be ½ of this remaining interval. This type of iteration, taking ½ of the remaining valid interval for each successive estimate, is performed on S(2,1) until the tolerance is satisfied or until 20 passes are completed. Once a satisfactory S(2,1) has been found for the initial X(2,1) estimate, the absolute value of (X(2,1)-X2) is tested against the tolerance. If the tolerance is not satisfied, and X(2,1) > X2, then a smaller value of X(2,1) is

needed to satisfy the system, i.e. 0. < X(2,1) < XE, so the next estimate for X(2,1) is ½ of this remaining interval. If X(2,1) < X2, then a larger value of X(2,1) is needed, i.e. XE < X(2,1) 2*XE, so the next estimate of X(2,1) is ½ of this remaining interval. After the new estimate of X(2,1) is calculated for the system, the program re-iterates on S(2,1) in the same manner as previously described. This process continues until both tolerances are satisfied, or until X(2,1) has been iterated on 20 times. When both tolerances are satisfied, the values of S(2,1) and X(2,1) which satisfy the system have been found. If the iteration has not converged after 20 passes on X(2,1), an error comment is printed, and the program proceeds to execute the next case.

APPENDIX II

LISTING AND OPERATING INSTRUCTION FOR

CSSAS AND FADAS DIGITAL COMPUTER PROGRAMS

Input Data for the CSSAS Program

Input Card 1: FORMAT (4I10)
NCASE, MULT, IEA, IDIS

Input Card 2: FORMAT (5F8.3,F8.4,4F8.3)
CR(1), CS(1), CE(1), CY(1), URSS, XRSS, SBOD(20), VIS20, DNBC, Q(20)

Input Card 3: FORMAT (10F8.3)
CR(2), CS(2), CE(2), CY(2), VAER, V17, S(1,20), S(2,20), AEFF, SSOUT

Input Card 4: FORMAT (11F5.3,23X,I2)
(PCTFL(I),I= 1,11), NTKS

Input Card 5: FORMAT (11F5.3)
(PCTRN(I),I = 1,11)

Input Card 6: FORMAT (F10.3)
X(1,1)

Input Card 7: If MULT = 1, start over with Input Card 2.
If MULT = 0, continue on with (NCASE-1) additional cards like Input Card 6.

Figure II-1 gives examples of both card input forms to the CSSAS program.

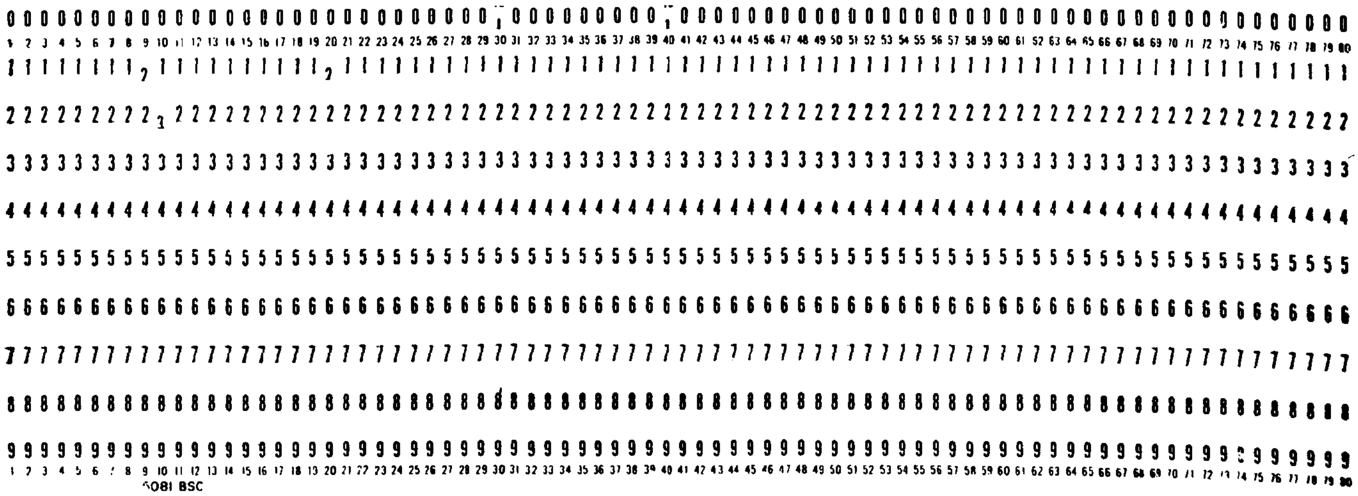
Figure II-2 gives definitions of the FORTRAN variables used by the CSSAS program.

Figure II-3 gives the FORTRAN listing of the CSSAS program.

Figure II-4 gives a sample printout from the CSSAS program.

```
  1245.
0.    0.    1.    0.    0.    0.    0.    0.    0.    0.    0.
0.    0.    1.    0.    0.    0.    0.    0.    0.    0.    0.
                                                                           2
 .60      1.      0.      .05     12.5      0.  155.539   19.63    .043   5.56
 5.32    150.    .166     .65     2.46   .0026   32.67    20.1    14.57   49.6
  873.
0.    0.    1.    0.    0.    0.    0.    0.    0.    0.    0.
0.    0.    1.    0.    0.    0.    0.    0.    0.    0.    0.
                                                                           2
 .707     1.      0.      .05     12.5      0.   140.5    18.1     .05    4.43
 6.55    150.    .171     .65     2.86   .0029    34.6    23.3    11.85   50.
      12        1         0         0
```

Input Form With MULT = 1



```
  876.
  875.
  874.
  873.
0.    0.    1.    0.    0.    0.    0.    0.    0.    0.    0.
0.    0.    1.    0.    0.    0.    0.    0.    0.    0.    0.
                                                                           2
 .707     1.      0.      .05     12.5      0.   140.5    18.1     .05    4.43
 6.55    150.    .171     .65     2.86   .0029    34.6    23.3    11.85   50.
      12        0         0         0
```

Input Form With MULT = 0

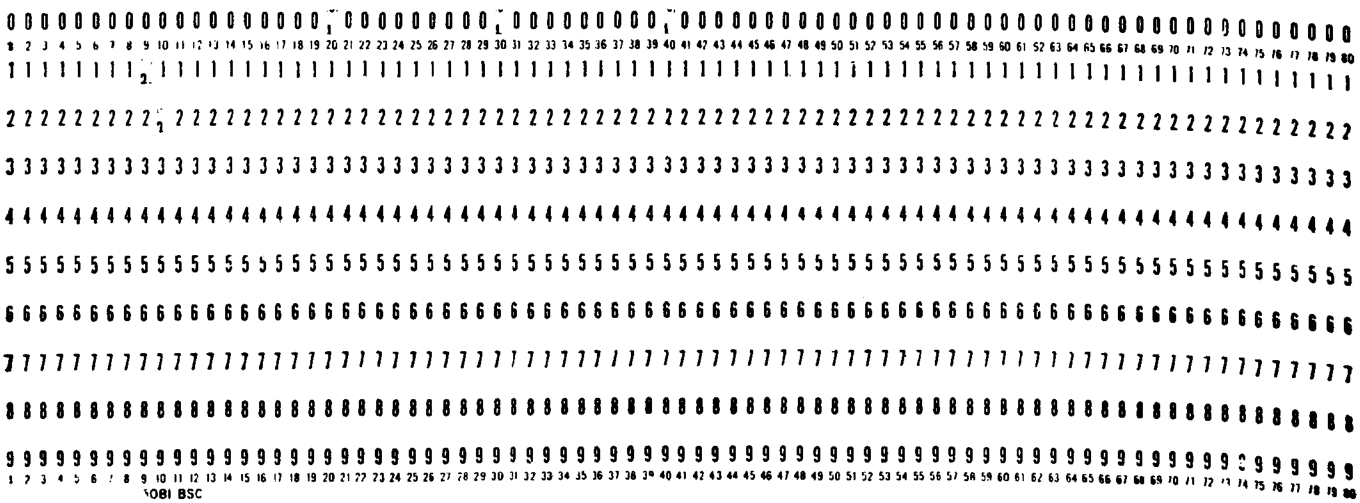


FIGURE II-1

FIGURE II-2
DEFINITIONS OF FORTRAN SYMBOLS
CSSAS PROGRAM

Computer Symbol	Definitions and Comments
AEFF	Efficiency of diffusers in aerator
AIRPG(I)	Air requirements for sub-aerators, scf/gallon
BOD14	Total 5-day BOD at station 14, mg/l oxygen
BSIZE(I)	Required size of blower for supplying air to aerator, scf/min.
CR(I)	Maximum rate constant for synthesis, day^{-1}: I = 1 for heterotrophs, I = 2 for nitrosomonas
CS(I)	Saturation constant, mg/l of substrate
CE(I)	Endogenous respiration constant, fraction of viable cells which lyse per day
CY(I)	Yield coefficient, lbs cells synthesized per lb of substrate utilized
D	Ratio of volume flow to total aerator volume, days
DBOD	Dissolved 5-day BOD at station 14, mg/l oxygen
DC	Specific wasting rate, lb MLASS wasted per day/lb MLASS in aerator
DNBC	Concentration of dissolved non-biodegradable carbon at station 20, mg/l carbon
DT	Detention time for sub-aerators, V(I)/Q(I+1) days
IDIS	Program control: set equal to 0 to allow both dissolved and particulate BOD to be available for synthesis; set equal to 1 to allow only dissolved BOD to be available for synthesis
IEA	Program control: set equal to 0 to run regular aeration data; set equal to 1 to run extended aeration data

DEFINITIONS OF FORTRAN SYMBOLS

CSSAS PROGRAM

Computer Symbol	Definitions and Comments
MLASS	Concentration of active solids held in aerator, mg/l mass
MLBSS	Concentration of unmetabolized biodegradable solids held in aerator, mg/l mass
MLDSS	Concentration of non-biodegradable solids in the aerator caused by destruction of active solids by natural causes, mg/l mass
MLNBS	Concentration of inert organic solids in aerator caused by inert organic solids in influent, mg/l mass
MLVSS	Concentration of volatile suspended solids held in aerator, mg/l mass
MULT	Program control: set equal to 0 to run several cases varying MLASS with one set of input; set equal to 1 to run several cases each with a different set of input
NCASE	Program control: number of cases to be executed by the program
NTKS	Number of equal volume sub-aerators
PCTFL(I)	Fraction of influent flow at station I downstream of entry point
PCTRN(I)	Fraction of return flow at station I downstream of entry point
Q(I)	Volume flow at station I, mgd
QQ	Specific substrate removal rate, lb substrate removed per day/lb active solids in aerator

DEFINITIONS OF FORTRAN SYMBOLS

CSSAS PROGRAM

Computer Symbol	Definitions and Comments
S(I,J)	Concentration of substrate at station I, mg/l: J = 1 for 5-day BOD, J = 2 for ammonia
SBOD(I)	Concentration of particulate 5-day BOD at station I, mg/l oxygen
SFBOD	Solid fraction of BOD at station 20
SSOUT	Concentration of volatile suspended solids at station 14, mg/l
URSS	Final settler compaction ratio
Vi7	Volume of the stabilization tank, millions of gallons
V(I)	Volume of individual sub-aerators, millions of gallons
VAER	Total volume of aerator, millions of gallons
VIS20	Concentration of non-biodegradable volatile suspended solids at station 20, mg/l
WAS(I)	lb heterotrophs in the Ith sub-aerator
WDN(I)	lb ammonia nitrogen used per day in the Ith sub-aerator
WFOOD(I)	lb 5-day BOD used per day in Ith sub-aerator
X(I,J)	Concentration of micro-organisms at station I, mg/l: J = 1 for heterotrophs, J = 2 for nitrosomonas
XL	5-day BOD loading, lb 5-day BOD per day per 1 lb MLVSS
XRSS	Final settler efficiency, VSS at station 14/VSS at station 1
XS	5-day BOD removal effectiveness, BOD14/S(1,20)

DEFINITIONS OF FORTRAN SYMBOLS

CSSAS PROGRAM

Computer Symbol	Definitions and Comments
XXL	Inverse 5-day BOD loading, 1./lb 5-day BOD per day per 1 lb MLVSS
XXS	5-day BOD removal effectiveness, 1./BOD14 - 1./S(1,20)

FIGURE II-3


```
      REAL MLVSS,MLASS,MLBSS,MLNBS,MLDSS
      DIMENSION S(3,20),X(3,20),CR(3),CS(3),CE(3),CY(3),Q(20),SBOD(20),
     . WFOOD(10),WAS(10),WDN(10),BSIZE(10),AIRPG(10),V(10),
     . PCTFL(11),PCTRN(11),BTEMP(11),ATEMP(11),BUSER(11),AUSER(11)
      IN=2
      IO=5
      ISET=1
    3 FORMAT(1H1,///,55X,'INPUT',/)
    4 FORMAT(1X,'CR(1)',5X,'CS(1)',5X,'CE(1)',5X,'CY(1)',6X,'URSS',
     . 5X,'XRSS',4X,'SBOD(20)',4X,'VIS20',7X,'DNBC',4X,'Q(20)',//1X,
     . 'CR(2)',5X,'CS(2)',5X,'CE(2)',5X,'CY(2)',6X,'VAER',5X,'V(17)',3X,
     . 'S(1,20)',4X,'S(2,20)',6X,'AEFF',4X,'SSOUT',//1X,'PCTFL(I)',//1X,
     . 'PCTRN(I)',///)
   11 FORMAT(55X,'OUTPUT',//)
   12 FORMAT(1X,'X(1,1)',4X,'X(1,NTKS+1)',2X,'S(1,1)',2X,'S(1,NTKS+1)',
     . 3X,'NTKS',6X,'Q(14)',5X,'Q(15)',4X,'Q(17)',3X,'DBOD14',5X,'BOD14'
     . ,7X,'XRSS',6X,'DT',//1X,'MLVSS',8X,'MLASS',6X,'MLBSS',5X,'MLNBSS'
     . ,5X,'MLDSS',4X,'X(1,16)',3X,'X(1,17)',2X,'S(1,16)',2X,'S(1,17)',
     . 4X,'SFBOD',9X,'D',7X,'DC',/)
   14 FORMAT(1X,'X(2,1)',5X,'X(2,NTKS+1)',2X,'S(2,1)',2X,'S(2,NTKS+1)',
     . 4X,'L',8X,'1/L',7X,'S/S',4X,'1/S-1/S',4X,'QQ',//,1X,
     . 'V(I)',//,1X,'BSIZE(I)',//1X,'AIRPG(I)',////)
      WRITE(IO,3)
      WRITE(IO,4)
      WRITE(IO,11)
      WRITE(IO,12)
      WRITE(IO,14)
C
C     NCASE IS THE NUMBER OF CASES TO BE EXECUTED.
C     MULT=0 ONE SET OF INPUT FOR ALL POINTS.
C     MULT=1 SEPARATE INPUT FOR EACH POINT.
C     IEA=1 SETS THE DECK UP TO RUN EXTENDED AERATION DATA
C     IDIS=1 SETS THE DECK UP TO RUN WITH ONLY DISSOLVED BOD AVAILABLE.
C
      READ(IN,1) NCASE,MULT,IEA,IDIS
    1 FORMAT(4I10)
      WRITE(IO,13) NCASE,MULT,IEA,IDIS
   13 FORMAT(1X,'NCASE=',I3,3X,'MULT=',I3,3X,'IEA=',I3,3X,'IDIS=',I3///)
C
C     THIS LOOP PERFORMS A COMPLETE SET OF CALCULATIONS FOR EACH CASE.
C
      DO 200 J=1,NCASE
      IF(ISET) 81,84,81
C
C     READ IN AND PRINT OUT ALL OF THE INPUT DATA.
C
   81 READ(IN,5) CR(1),CS(1),CE(1),CY(1),URSS,XRSS,SBOD(20),
     . VIS20,DNBC,Q(20)
      READ(IN,6) CR(2),CS(2),CE(2),CY(2),VAER,V17,S(1,20),S(2,20),
     . AEFF,SSOUT
      READ(IN,76) (PCTFL(I),I=1,11),NTKS,(PCTRN(I),I=1,11)
   76 FORMAT(11F5.3,23X,I2/11F5.3)
      WRITE(IO,7) CR(1),CS(1),CE(1),CY(1),URSS,XRSS,SBOD(20),
     . VIS20,DNBC,Q(20)
      WRITE(IO,8) CR(2),CS(2),CE(2),CY(2),VAER,V17,S(1,20),S(2,20),
     . AEFF,SSOUT
      KK=NTKS+1
```

```
      WRITE(IO,192) (PCTFL(I),I=1,KK)
      WRITE(IO,194)
      WRITE(IO,192) (PCTRN(I),I=1,KK)
      WRITE(IO,194)
    5 FORMAT(5F8.3,F8.4,4F8.3)
    6 FORMAT(10F8.3)
    7 FORMAT(5F10.3,F10.4,4F10.3,/)
    8 FORMAT(10F10.3,/)
      IF(MULT) 84,83,84
   83 ISET=0
   84 READ(IN,9) X(1,1)
    9 FORMAT(F10.3)
      SFBOD=SBOD(20)/S(1,20)
      IF(IDIS) 53,55,53
   53 SFBOD=0.
   55 DO 19 IJ=1,NTKS
   19 V(IJ)=VAER/NTKS
      V17=0.
      IF(V17) 72,73,72
   73 S(1,1)=.5*S(1,20)
      S(1,17)=S(1,1)*SFBOD*URSS+S(1,1)*(1.-SFBOD)
      GO TO 78
   72 S(1,17)=0.
   78 X(1,17)=URSS*X(1,1)
C
C     THIS LOOP ITERATES ON XRSS 3 TIMES.
C
      DO 70 JJ=1,3
      IF(JJ-1) 17,16,17
C
C     A DOUBLE HALFING ITERATION IS PERFORMED ON S(1,1) AND Q(17).
C     S(1,1) AND Q(17) ARE BOTH ITERATED ON FOR 20 PASSES EACH.
C
   16 Q(17)=.5*Q(20)
   17 QLOW=0.
      QUP=Q(20)
      IX=0
      IF(JJ-1) 18,10,18
   10 S(1,1)=.5*S(1,20)
   18 SLOW=0.
      SUP=S(1,20)
      IS=0
      DT17=V17/Q(17)
      A=S(1,20)*Q(20)/(Q(17)*S(1,1))
      B=URSS-1.
      SFBOD=(B-A+SQRT((A-B)**2+4.*A*B*SBOD(20)/S(1,20)))/(2.*B)
      IF(IDIS) 56,15,56
   56 SFBOD=0.
   15 K1=0
      BTEMP(1)=S(1,1)
      BUSER(1)=X(1,1)
      DO 64 I=1,NTKS
      FLOWA=Q(20)+Q(17)
      K1=K1+1
      DO 62 K=1,K1
      FLOWA=FLOWA-(Q(20)*PCTFL(K)+Q(17)*PCTRN(K))
   62 FLOWB=FLOWA-(Q(20)*PCTFL(K+1)+Q(17)*PCTRN(K+1))
```

```
      DT=V(I)/FLOWA
      S(1,I+1)=S(1,I)+CR(1)*S(1,I)*X(1,I)*DT/(CY(1)*(CS(1)+S(1,I)))
      X(1,I+1)=X(1,I)+CE(1)*DT*X(1,I)-(CR(1)*S(1,I)*X(1,I)*DT)/(CS(1)+
     . S(1,I))
      BTEMP(I+1)=S(1,I+1)
      BUSER(I+1)=X(1,I+1)
      IF(NTKS-K1) 63,64,63
   63 S(1,I+1)=(S(1,I+1)*FLOWA-S(1,20)*Q(20)*PCTFL(I+1)-S(1,17)*Q(17)*
     . PCTRN(I+1))/FLOWB
      X(1,I+1)=(X(1,I+1)*FLOWA-X(1,17)*Q(17)*PCTRN(I+1))/FLOWB
   64 CONTINUE
      S(1,17)=(S(1,NTKS+1)*(Q(20)*PCTFL(NTKS+1)+Q(17)*PCTRN(NTKS+1))-
     . S(1,20)*Q(20)*PCTFL(NTKS+1))/(Q(17)*PCTRN(NTKS+1))
      X(1,17)=(X(1,NTKS+1)*(Q(20)*PCTFL(NTKS+1)+Q(17)*PCTRN(NTKS+1)))/
     . (Q(17)*PCTRN(NTKS+1))
      S(1,16)=S(1,17)+CR(1)*S(1,17)*X(1,17)*DT17/(CY(1)*(CS(1)+S(1,17)))
      X(1,16)=X(1,17)+CE(1)*DT17*X(1,17)-(CR(1)*S(1,17)*X(1,17)*DT17)/
     . (CS(1)+S(1,17))
      IF(V17) 68,66,68
   66 S(1,16)=S(1,17)
      X(1,16)=X(1,17)
   68 S1=S(1,16)/(SFBOD*(URSS-1.)+1.)
      DS1=S(1,1)-S1
      IF(ABS(DS1)-.01) 29,29,22
   22 IF(IS-20) 24,29,29
   24 IF(DS1) 27,27,25
   25 SLOW=S(1,1)
      S(1,1)=S(1,1)+.5*(SUP-SLOW)
      IS=IS+1
      GO TO 15
   27 SUP=S(1,1)
      S(1,1)=S(1,1)-.5*(SUP-SLOW)
      IS=IS+1
      GO TO 15
   29 X1=X(1,16)/URSS
      DX1=X(1,1)-X1
      IF(ABS(DX1)- .1) 50,50,30
   30 IF(IX-20) 31,40,40
   31 IF(DX1) 37,37,35
   35 QUP=Q(17)
      Q(17)=Q(17)-.5*(QUP-QLOW)
      IQ=IQ+1
      GO TO 10
   37 QLOW=Q(17)
      Q(17)=Q(17)+.5*(QUP-QLOW)
      IQ=IQ+1
      GO TO 10
   40 WRITE(IO,45) X(1,1)
   45 FORMAT(//,5X,'BOD ITERATION DOES NOT CONVERGE',5X,'X(1,1)=',
     . F10.3,//)
      GO TO 200
C
C     THIS THE FINAL COMPUTED S(1,1).
C
   50 SF1=S(1,1)
      DBOD=S(1,1)*(1.-SFBOD)
      Q(15)=(Q(20)*(1.-XRSS)-Q(17)*(URSS-1.))/(URSS-XRSS)
```

```
      IF(IEA) 52,54,52
   52 Q(15)=0.
   54 Q(14)=Q(20)-Q(15)
      D=Q(20)/VAER
      TEMP1=Q(14)*XRSS+Q(15)*URSS
      MLASS=X(1,1)
      MLBSS=S(1,1)*SFBOD/.8
      IF(IDIS) 58,59,58
   58 MLBSS=SBOD(20)*Q(20)/.8/TEMP1
   59 MLNBS=VIS20*Q(20)/TEMP1
      MLDSS=.18*CY(1)*(S(1,20)-S(1,1))*Q(20)/TEMP1-.18*MLASS
      IF(MLDSS) 74,74,75
   74 MLDSS=0.
   75 MLVSS=MLASS+MLBSS+MLNBS+MLDSS
      IF(JJ-3) 70,71,70
   70 XRSS=SSOUT/MLVSS
      IF(IEA) 92,71,92
   92 XRSS=1.-Q(17)*(URSS-1.)/Q(20)
   71 BOD14=(.84*MLASS+.80*MLBSS)*XRSS+S(1,1)*(1.-SFBOD)
      X(1,14)=XRSS*X(1,1)
      X(1,15)=URSS*X(1,1)
      DC=(Q(14)*X(1,14)+Q(15)*X(1,15))/(VAER*MLVSS)
      XL=Q(20)*S(1,20)/(VAER*MLVSS)
      XS=BOD14/S(1,20)
      XXL=1./XL
      XXS=1./BOD14-1./S(1,20)
      QQ=Q(20)*(S(1,20)-BOD14)/(VAER*MLVSS)
      WRITE(IO,80) X(1,1),X(1,NTKS+1),S(1,1),S(1,NTKS+1),NTKS,Q(14),
     . Q(15),Q(17),DBOD,BOD14,XRSS,DT
   80 FORMAT(4F10.3,I10,F10.3,F10.6,3F10.3,F10.5,F10.3,/)
      WRITE(IO,90) MLVSS,MLASS,MLBSS,MLNBS,MLDSS,X(1,16),X(1,17),
     . S(1,16),S(1,17),SFBOD,D,DC
   90 FORMAT(12F10.3,/)
C
C     A DOUBLE HALFING ITERATION IS PERFORMED ON S(2,1) AND X(2,1).
C     S(2,1) AND X(2,1) ARE BOTH ITERATED ON FOR 20 PASSES EACH.
C
      X(2,1)=CY(2)*Q(20)*S(2,20)/(DC*VAER)
      IF(X(2,1)) 101,101,217
C
C     IF X(2,1) IS NEGATIVE GOING IN, THERE ARE NO NITRIFICATION CALCULATIONS.
C
  101 WRITE(IO,102) X(1,1),X(2,1)
  102 FORMAT(///,5X,48HNO NITRIFICATION OUTPUT SINCE X(2,1) IS NEGATIVE,
     . 5X,7HX(1,1)=,F10.3,5X,7HX(2,1)=,F10.3,///)
      GO TO 200
  217 XLOW=0.
      XUP=2.*X(2,1)
      IX=0
  210 S(2,1)=.5*S(2,20)
      SLOW=0.
      SUP=S(2,20)
      IS=0
      DT17=V17/Q(17)
      IF(V17) 272,273,272
  273 S(2,17)=S(2,1)
      GO TO 278
```

```
272 S(2,17)=.5*S(2,1)
278 X(2,17)=URSS*X(2,1)
215 K1=0
    ATEMP(1)=S(2,1)
    AUSER(1)=X(2,1)
    DO 264 I=1,NTKS
    FLOWA=Q(20)+Q(17)
    K1=K1+1
    DO 262 K=1,K1
    FLOWA=FLOWA-(Q(20)*PCTFL(K)+Q(17)*PCTRN(K))
262 FLOWB=FLOWA-(Q(20)*PCTFL(K+1)+Q(17)*PCTRN(K+1))
    DT=V(I)/FLOWA
    S(2,I+1)=S(2,I)+CR(2)*S(2,I)*X(2,I)*DT/(CY(2)*(CS(2)+S(2,I)))
    X(2,I+1)=X(2,I)+CE(2)*DT*X(2,I)-(CR(2)*S(2,I)*X(2,I)*DT)/(CS(2)+
   . S(2,I))
    ATEMP(I+1)=S(2,I+1)
    AUSER(I+1)=X(2,I+1)
    IF(NTKS-K1) 263,264,263
263 S(2,I+1)=(S(2,I+1)*FLOWA-S(2,20)*Q(20)*PCTFL(I+1)-S(2,17)*Q(17)*
   . PCTRN(I+1))/FLOWB
    X(2,I+1)=(X(2,I+1)*FLOWA-X(2,17)*Q(17)*PCTRN(I+1))/FLOWB
264 CONTINUE
    S(2,17)=(S(2,NTKS+1)*(Q(20)*PCTFL(NTKS+1)+Q(17)*PCTRN(NTKS+1))-
   . S(2,20)*Q(20)*PCTFL(NTKS+1))/(Q(17)*PCTRN(NTKS+1))
    X(2,17)=(X(2,NTKS+1)*(Q(20)*PCTFL(NTKS+1)+Q(17)*PCTRN(NTKS+1)))/
   . (Q(17)*PCTRN(NTKS+1))
    S(2,16)=S(2,17)+CR(2)*S(2,17)*X(2,17)*DT17/(CY(2)*(CS(2)+S(2,17)))
    X(2,16)=X(2,17)+CE(2)*DT17*X(2,17)-(CR(2)*S(2,17)*X(2,17)*DT17)/
   . (CS(2)+S(2,17))
    IF(V17) 268,266,268
266 S(2,16)=S(2,17)
    X(2,16)=X(2,17)
268 S2=S(2,16)
    DS2=S(2,1)-S2
    IF(ABS(DS2)-.01) 229,229,222
222 IF(IS-20) 224,229,229
224 IF(DS2) 227,227,225
225 SLOW=S(2,1)
    S(2,1)=S(2,1)+.5*(SUP-SLOW)
    IS=IS+1
    GO TO 215
227 SUP=S(2,1)
    S(2,1)=S(2,1)-.5*(SUP-SLOW)
    IS=IS+1
    GO TO 215
229 X1=0.
    X2=0.
    DO 251 I=1,NTKS
    X1=X1+(Q(20)-Q(20)*PCTFL(I)+Q(17)-Q(17)*PCTRN(I))*AUSER(I)
251 X2=X2+(Q(20)-Q(20)*PCTFL(I)+Q(17)-Q(17)*PCTRN(I))*X(2,I+1)
    X2=(X1-X2)/X(2,1)
    DX2=TEMP1-X2
    IF(ABS(DX2)- .1) 250,250,230
230 IF(X(2,1)-.001) 250,250,232
232 IF(IX-20) 231,240,240
231 IF(DX2) 237,237,235
235 XUP=X(2,1)
```

```
      X(2,1)=X(2,1)-.5*(XUP-XLOW)
      IX=IX+1
      GO TO 210
  237 XLOW=X(2,1)
      X(2,1)=X(2,1)+.5*(XUP-XLOW)
      IX=IX+1
      GO TO 210
  240 WRITE(IO,245) X(1,1)
  245 FORMAT(//,5X,'NH3 ITERATION DOES NOT CONVERGE',5X,'X(1,1)=',
     . F10.3,//)
      GO TO 200
C
C     THIS IS THE FINAL COMPUTED X(2,1) AND S(2,1).
C
  250 SF2=S(2,1)
      XF2=X(2,1)
      Q1=Q(20)+Q(17)
      TSIZE=0.
      TPG=0.
      DO 185 I=1,NTKS
      WFOOD(I)=Q1*(BTEMP(I+1)-S(1,I))*8.33
      WAS(I)=X(1,I)*V(I)*8.33
      WDN(I)=Q1*(ATEMP(I+1)-S(2,1))*8.33
      BSIZE(I)=(.577*WFOOD(I)+1.16*CE(1)*WAS(I)+4.6*WDN(I))/
     . (AEFF*.232*.075*1440.)
      AIRPG(I)=BSIZE(I)*1440./(Q(20)*1000000.)
      TSIZE=TSIZE+BSIZE(I)
      TPG=TPG+AIRPG(I)
  185 Q1=Q1-Q(20)*PCTFL(I)-Q(17)*PCTRN(I)
      WRITE(IO,190) X(2,1),X(2,NTKS+1),S(2,1),S(2,NTKS+1),XL,XXL,
     . XS,XXS,QQ
  190 FORMAT(9F10.3,/)
      WRITE(IO,192) (V(I),I=1,NTKS),VAER
      WRITE(IO,194)
      WRITE(IO,193) (BSIZE(I),I=1,NTKS),TSIZE
      WRITE(IO,194)
      WRITE(IO,192) (AIRPG(I),I=1,NTKS),TPG
      WRITE(IO,196)
  192 FORMAT(11F10.3)
  193 FORMAT(11F10.1)
  194 FORMAT( )
  196 FORMAT(////)
  200 CONTINUE
      CALL EXIT
      END
```

INPUT

CR(1)	CS(1)	CE(1)	CY(1)	URSS	XRSS	SBOD(20)	VIS20	DNBC	Q(20)
CR(2)	CS(2)	CE(2)	CY(2)	VAER	V(17)	S(1,20)	S(2,20)	AEFF	SSOUT
PCTFL(I)									
PCTRN(I)									

OUTPUT

X(1,1)	X(1,NTKS+1)	S(1,1)	S(1,NTKS+1)	NTKS	Q(14)	Q(15)	Q(17)	DBOD14	BOD14	XRSS	DT
MLVSS	MLASS	MLBSS	MLNBSS	MLDSS	X(1,16)	X(1,17)	S(1,16)	S(1,17)	SFBOD	D	DC
X(2,1)	X(2,NTKS+1)	S(2,1)	S(2,NTKS+1)	L	1/L	S/S	1/S-1/S	QQ			
V(I)											
BSIZE(I)											
AIRPG(I)											

NCASE= 12 MULT= 1 IEA= 0 IDIS= 0

6.550	150.000	0.171	0.650	2.860	0.0029	34.600	23.300	11.850	50.000		
0.707	1.000	0.000	0.050	12.500	0.000	140.500	18.100	0.050	4.430		
0.000	0.000	1.000									
0.000	0.000	1.000									
873.000	838.175	3.058	94.840	2	49.004	0.995810	25.265	2.293	4.663	0.00322	0.083
1371.801	873.000	0.956	387.529	110.316	2496.912	2496.912	4.481	4.481	0.250	4.000	0.153
14.782	14.184	0.091	12.054	0.409	2.440	0.033	0.207	0.396			
6.250	6.250	12.500									
14772.1	57047.8	71819.9									
0.425	1.642	2.068									

FIGURE II-4

Input Data for the FADAS Program

Input Card 1: FORMAT (I3)
NCASE

Input Card 2: FORMAT (8F8.2,F8.3,I8)
XO, SO, XM, XKS, XKE, Y, R, TEST, H, NINC

Input Card 3: Continue on with (NCASE-1) additional cards like Input Card 2

Figure II-5 gives an example of the card input form to the FADAS program.

Figure II-6 gives definitions of the FORTRAN variables used by the FADAS program.

Figure II-7 gives the FORTRAN listing of the FADAS program.

Figure II-8 gives a sample printout from the FADAS program.

```
400.     100.     4.8      150.     .1       .5       .8       2.55     .002          200
400.     200.     4.8      150.     .1       .5       .8       2.55     .002          200
400.     400.     4.8      150.     .1       .5       .8       2.55     .002          200
400.     100.     4.8      150.     .1       .5       .8       20.      .002          100
```

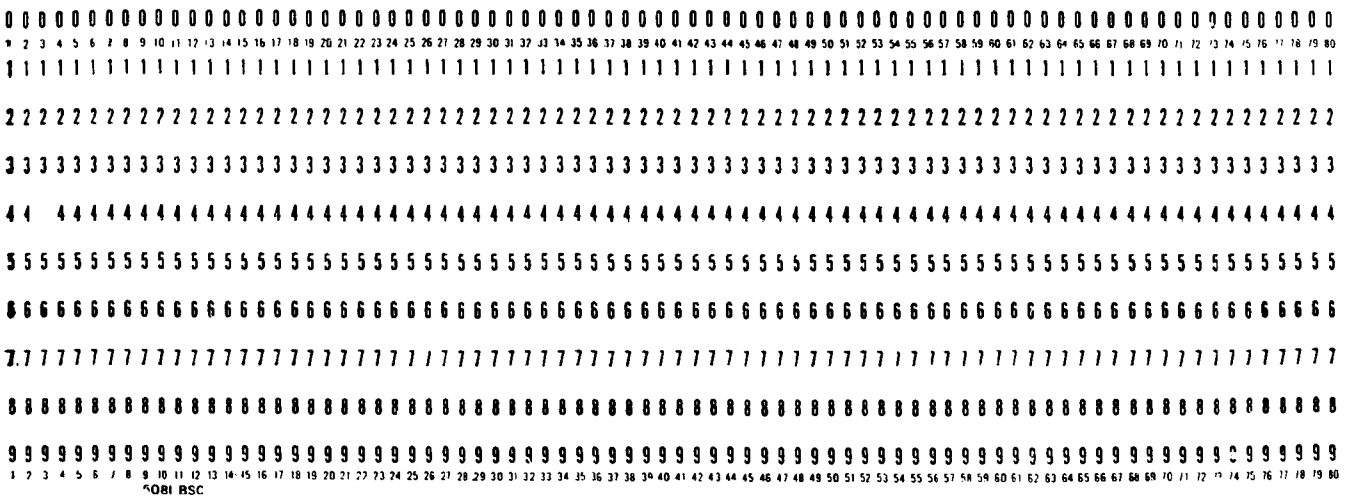


FIGURE II-5

FIGURE II-6

DEFINITIONS OF FORTRAN SYMBOLS

FADAS PROGRAM

Computer Symbol	Definitions and Comments
FACTO	Current concentration of substrate/initial concentration of substrate
FACTX	Current concentration of heterotrophs/initial concentration of heterotrophs
H	Time interval for numerical integration, days
I	Number of time increment
NINC	Total number of time intervals the program is to calculate
R	Coefficient which converts the lysed cell mass to substrate returned to solution
SDOT	Rate of change of 5-day BOD with time, mg/l day
SO	Initial concentration of 5-day BOD, mg/l
SS	Current value for substrate, 5-day BOD, mg/l
TEST	Desired effluent concentration of 5-day BOD, mg/l
XDOT	Rate of change of XX with time, mg/l day
XKE	Endogenous respiration rate, day^{-1}
XKS	Saturation constant, 5-day BOD, mg/l
XM	Maximum rate constant for synthesis, day^{-1}
XO	Initial concentration of heterotrophic bacteria, mg/l
XX	Current value for concentration of heterotrophs, mg/l
Y	Yield coefficient, lb cells/lb substrate

```
      FUNC1(XX,SS,XM,XKS,XKE)=XX*(XM*SS/(XKS+SS)-XKE)
      FUNC2(XX,SS,XM,XKS,XKE,R,Y)=XX/Y*(R*XKE-XM*SS/(XKS+SS))
      IN=2
      IO=5
  700 FORMAT(I3)
  702 FORMAT(10X,'N',10X,'X',14X,'X/XO',13X,'XDOT',14X,'SDOT',13X,
     . 'S/SO',14X,'S')
  703 FORMAT(7X,I5,5X,E10.4,7X,E10.4,7X,E10.4,7X,E11.4,7X,E10.4,
     . 7X,E10.4)
  704 FORMAT(1H1,50X,'INPUT  DATA',//,10X,'CASE NO.',I3)
      READ(IN,700) NCASE
      DO 200 N=1,NCASE
      WRITE(IO,704)  N
      READ(IN,701) XO,SO,XM,XKS,XKE,Y,R,TEST,H,NINC
  701 FORMAT(8F8.2,F8.3,I8)
      WRITE(IO,706)
  706 FORMAT(/,16X,'XO',8X,'SO',9X,'XM',6X,'XKS',8X,'XKE',8X,'Y',9X,'R',
     . 7X,'TEST',8X,'H',8X,'NINC')
      WRITE(IO,705) XO,SO,XM,XKS,XKE,Y,R,TEST,H,NINC
  705 FORMAT(/,10X,9F10.3,I10,//)
      WRITE(IO,702)
      XX=XO
      FXO=XO
      SS=SO
      FSO=SO
      DO 100  I=1,NINC
      SO=SS
      XO=XX
      XK1=FUNC1(XX,SS,XM,XKS,XKE)
      XL1=FUNC2(XX,SS,XM,XKS,XKE,R,Y)
      XDOT=XK1
      SDOT=XL1
      XK1=XK1*H
      XL1=XL1*H
      XX=XO+XK1/2
      SS=SO+XL1/2
      XK2=FUNC1(XX,SS,XM,XKS,XKE)
      XL2=FUNC2(XX,SS,XM,XKS,XKE,R,Y)
      XL2=XL2*H
      XK2=XK2*H
      XX=XO+XK2/2.
      SS=SO+XL2/2.
      XK3=FUNC1(XX,SS,XM,XKS,XKE)
      XL3=FUNC2(XX,SS,XM,XKS,XKE,R,Y)
      XK3=XK3*H
      XL3=XL3*H
      XX=XO+XK3
      SS=SO+XL3
      XK4=FUNC1(XX,SS,XM,XKS,XKE)
      XL4=FUNC2(XX,SS,XM,XKS,XKE,R,Y)
      XL4=XL4*H
      XK4=XK4*H
      DX=.1667*(XK1+2.*XK2+2.*XK3+XK4)
      DS=.1667*(XL1+2.*XL2+2.*XL3+XL4)
      XX=XO+DX
      SS=SO+DS
      FACTX=XX/FXO
```

```
      FACTO=SS/FSO
      WRITE(IO,703) I,XX,FACTX,XDOT,SDOT,FACTO,SS
      IF(SS-TEST) 200,200,100
  100 CONTINUE
  200 CONTINUE
      CALL EXIT
      END
```

INPUT DATA

CASE NO. 1

XO	SO	XM	XKS	XKE	Y	R	TEST	H	NINC
400.000	100.000	4.800	150.000	0.100	0.500	0.800	20.000	0.002	100

N	X	X/XO	XDOT	SDOT	S/SO	S
1	0.4014E 03	0.1003E 01	0.7280E 03	-0.1472E 04	0.9707E 00	0.9707E 02
2	0.4028E 03	0.1007E 01	0.7169E 03	-0.1449E 04	0.9419E 00	0.9419E 02
3	0.4042E 03	0.1010E 01	0.7056E 03	-0.1427E 04	0.9136E 00	0.9136E 02
4	0.4056E 03	0.1014E 01	0.6941E 03	-0.1404E 04	0.8858E 00	0.8858E 02
5	0.4069E 03	0.1017E 01	0.6823E 03	-0.1380E 04	0.8584E 00	0.8584E 02
6	0.4083E 03	0.1020E 01	0.6703E 03	-0.1357E 04	0.8315E 00	0.8315E 02
7	0.4096E 03	0.1024E 01	0.6581E 03	-0.1332E 04	0.8051E 00	0.8051E 02
8	0.4109E 03	0.1027E 01	0.6457E 03	-0.1307E 04	0.7791E 00	0.7791E 02
9	0.4121E 03	0.1030E 01	0.6332E 03	-0.1282E 04	0.7537E 00	0.7537E 02
10	0.4133E 03	0.1033E 01	0.6204E 03	-0.1257E 04	0.7288E 00	0.7288E 02
11	0.4145E 03	0.1036E 01	0.6075E 03	-0.1231E 04	0.7045E 00	0.7045E 02
12	0.4157E 03	0.1039E 01	0.5945E 03	-0.1205E 04	0.6806E 00	0.6806E 02
13	0.4169E 03	0.1042E 01	0.5813E 03	-0.1179E 04	0.6573E 00	0.6573E 02
14	0.4180E 03	0.1045E 01	0.5680E 03	-0.1152E 04	0.6345E 00	0.6345E 02
15	0.4191E 03	0.1047E 01	0.5547E 03	-0.1126E 04	0.6122E 00	0.6122E 02
16	0.4202E 03	0.1050E 01	0.5412E 03	-0.1099E 04	0.5905E 00	0.5905E 02
17	0.4212E 03	0.1053E 01	0.5277E 03	-0.1072E 04	0.5693E 00	0.5693E 02
18	0.4222E 03	0.1055E 01	0.5142E 03	-0.1045E 04	0.5487E 00	0.5487E 02
19	0.4232E 03	0.1058E 01	0.5006E 03	-0.1018E 04	0.5286E 00	0.5286E 02
20	0.4242E 03	0.1060E 01	0.4870E 03	-0.9911E 03	0.5090E 00	0.5090E 02
21	0.4251E 03	0.1062E 01	0.4735E 03	-0.9640E 03	0.4900E 00	0.4900E 02
22	0.4260E 03	0.1065E 01	0.4600E 03	-0.9370E 03	0.4715E 00	0.4715E 02
23	0.4269E 03	0.1067E 01	0.4465E 03	-0.9101E 03	0.4536E 00	0.4536E 02
24	0.4277E 03	0.1069E 01	0.4331E 03	-0.8834E 03	0.4362E 00	0.4362E 02
25	0.4286E 03	0.1071E 01	0.4198E 03	-0.8568E 03	0.4193E 00	0.4193E 02
26	0.4294E 03	0.1073E 01	0.4066E 03	-0.8304E 03	0.4030E 00	0.4030E 02
27	0.4301E 03	0.1075E 01	0.3935E 03	-0.8043E 03	0.3871E 00	0.3871E 02
28	0.4309E 03	0.1077E 01	0.3806E 03	-0.7784E 03	0.3718E 00	0.3718E 02
29	0.4316E 03	0.1079E 01	0.3678E 03	-0.7529E 03	0.3570E 00	0.3570E 02
30	0.4323E 03	0.1080E 01	0.3552E 03	-0.7277E 03	0.3427E 00	0.3427E 02
31	0.4330E 03	0.1082E 01	0.3427E 03	-0.7028E 03	0.3289E 00	0.3289E 02
32	0.4336E 03	0.1084E 01	0.3305E 03	-0.6783E 03	0.3156E 00	0.3156E 02
33	0.4343E 03	0.1085E 01	0.3184E 03	-0.6543E 03	0.3027E 00	0.3027E 02
34	0.4349E 03	0.1087E 01	0.3066E 03	-0.6307E 03	0.2903E 00	0.2903E 02
35	0.4354E 03	0.1088E 01	0.2950E 03	-0.6075E 03	0.2784E 00	0.2784E 02
36	0.4360E 03	0.1090E 01	0.2837E 03	-0.5848E 03	0.2669E 00	0.2669E 02
37	0.4365E 03	0.1091E 01	0.2726E 03	-0.5627E 03	0.2559E 00	0.2559E 02
38	0.4370E 03	0.1092E 01	0.2617E 03	-0.5410E 03	0.2453E 00	0.2453E 02
39	0.4375E 03	0.1093E 01	0.2511E 03	-0.5198E 03	0.2351E 00	0.2351E 02
40	0.4380E 03	0.1095E 01	0.2408E 03	-0.4992E 03	0.2253E 00	0.2253E 02
41	0.4385E 03	0.1096E 01	0.2308E 03	-0.4791E 03	0.2159E 00	0.2159E 02
42	0.4389E 03	0.1097E 01	0.2210E 03	-0.4596E 03	0.2069E 00	0.2069E 02
43	0.4393E 03	0.1098E 01	0.2115E 03	-0.4406E 03	0.1983E 00	0.1983E 02

FIGURE II-8

APPENDIX III

EXPERIMENTAL DATA USED TO VALIDATE THE CSSAS MODEL

BLUE PLAINS PLANT, WASHINGTON, D.C. - April 17-30, 1969

Primary Effluent:	
1. Temperature, °C	18.2
2. Flow volume, mgd	230.7
3. Suspended solids, mg/l	111.8
4. % Volatile SS	71.
5. TOC, uf, mg/l	69.1
6. 5-day BOD, uf, mg/l	114.8
7. 5-day BOD, f, mg/l	40.4
8. Ammonia as N, mg/l	14.7
9. Water temperature, °F	61.
Aerator:	
1. Mixed liquor SS, mg/l	457.0
2. Mixed liquor volatile SS	346.0
3. Aerator volume, mg	24.8
Return and Waste Streams:	
1. Return flow, mgd	29.1
2. Waste flow, mgd	.921
3. Volatile SS, return, mg/l	2960.
4. Volatile SS, waste, mg/l	15255.
Secondary Effluent:	
1. Volatile suspended solids, mg/l	28.9
2. 5-day BOD, uf, mg/l	45.4
3. 5-day BOD, f, mg/l	18.4
4. TOC, uf, mg/l	32.1

EXTENDED AERATION, UNIVERSITY OF CINCINNATI DATA, Plant 2-B, Nov. 1965

Raw Influent Stream:	
1. Flow volume, gpd	31,700.
2. 5-day BOD, uf, mg/l	195.
3. COD, uf, mg/l	516.8
4. Volatile SS, mg/l	213.
Aerator:	
1. Volume, gallons	40,000.
2. Mixed liquor SS, mg/l	4340.
3. Volatile SS, mg/l	3101.
4. Air supplied, scf/gal.	6.1
Effluent Stream:	
1. Suspended solids, mg/l	176.
2. Volatile SS, mg/l	114.
3. 5-day BOD, mg/l	35.6
4. COD, uf, mg/l	169.6
5. COD, f, mg/l	43.6
6. Final setter overflow, gpd/sq ft	331.
Waste Stream:	
1. Flow volume, gpd	0.0

HYPERION TEST NO.	1	2	3	4
Primary Effluent Flow Volume, mgd	49.50	49.60	49.83	50.01
Return Sludge Flow Volume, mgd	23.81	29.07	33.98	30.83
Waste Sludge Flow Volume, mgd	.950	.633	.520	.877
Aerator Volume, mg	12.50	12.50	10.42	8.33
Final Settler Surface Area, sq. ft.	95000.	95000.	95000.	95000.
Air Supplied, scf/gallon	1.29	1.30	1.36	1.40

HYPERION TEST NO.	5	6	7	8
Primary Effluent Flow Volume, mgd	49.68	49.11	49.18	49.28
Return Sludge Flow Volume, mgd	20.14	17.09	17.60	18.13
Waste Sludge Flow Volume, mgd	1.160	1.100	1.402	1.270
Aerator Volume, mg	8.33	8.33	8.33	12.50
Final Settler Surface Area, sq. ft.	95000.	95000.	95000.	95000.
Air Supplied, scf/gallon	1.40	1.33	1.40	1.42

HYPERION TEST NO.	9	10	11	12
Primary Effluent Flow Volume, mgd	50.11	49.33	49.22	50.18
Return Sludge Flow Volume, mgd	11.48	9.35	12.82	19.19
Waste Sludge Flow Volume, mgd	1.850	1.440	1.240	.779
Aerator Volume, mg	12.50	12.50	12.50	12.50
Final Settler Surface Area, sq. ft.	95000.	95000.	95000.	95000.
Air Supplied, scf/gallon	1.40	1.40	1.40	1.40

Note: In the Hyperion experiments the flow rate into the activated sludge process was fixed at approximately 50 mgd and did not vary significantly with time

HYPERION TEST NO.	1	2	3
Primary Effluent:			
1. Water Temp. ^{o}F	80.3	79.2	75.8
2. COD, uf, mg/l	280.2	295.7	320.1
3. COD, f, mg/l	219.1	245.5	245.6
4. NH_3 as N, mg/l	22.0	19.6	17.8
5. TKN, uf, mg/l	29.3	28.5	26.5
6. TKN, f, mg/l	27.8	25.9	23.7
7. P, uf, mg/l	14.8	14.1	12.7
8. P, f, mg/l	14.0	13.5	11.5
9. SS, mg/l	76.9	67.8	99.2
10. % volatile	83.2	84.3	89.4
11. BOD_5, uf, mg/l	140.3	155.5	157.1
12. BOD_5, f, mg/l	106.5	116.3	129.2
Aerator Effluent:			
1. COD, uf, mg/l	1959.4	3358.0	4016.0
2. COD, f, mg/l	35.8	39.2	36.5
3. NH_3 as N, mg/l	16.2	17.6	16.2
4. NO_3 as N, mg/l	0.4	0.1	0.1
5. TKN, uf, mg/l	176.6	243.3	277.1
6. TKN, f, mg/l	18.0	19.1	18.0
7. P, uf, mg/l	155.0	201.0	146.2
8. P, f, mg/l	17.6	17.8	14.4
9. SS, mg/l	1996.9	3010.8	3436.4
10. % volatile	68.9	67.0	75.1
11. BOD_5, uf, mg/l	613.1	727.5	842.2
12. BOD_5, f, mg/l	23.2	17.7	6.4
Return Sludge Stream:			
1. COD, uf, mg/l	5190.8	7471.5	8593.6
2. COD, f, mg/l	71.7	75.1	57.4
3. NH_3 as N, mg/l	18.3	19.9	19.0
4. NO_3 as N, mg/l	0.3	0.1	0.1
5. TKN, uf, mg/l	435.7	562.8	625.3
6. TKN, f, mg/l	23.1	23.9	22.9
7. P, uf, mg/l	393.2	474.0	338.9
8. P, f, mg/l	83.4	60.1	49.7
9. SS, mg/l	5696.9	7407.6	7866.6
10. % volatile	68.0	68.5	75.5
11. BOD_5, uf, mg/l	1620.0	1753.7	1627.8
12. BOD_5, f, mg/l	41.2	18.6	16.6
Final Effluent:			
1. COD, uf, mg/l	28.9	33.3	39.9
2. COD, f, mg/l	26.1	27.4	27.5
3. NH_3 as N, mg/l	15.5	16.5	14.9
4. NO_3 as N, mg/l	0.4	0.1	0.2
5. TKN, uf, mg/l	16.7	17.8	17.0
6. TKN, f, mg/l	16.5	17.7	16.1
7. P, uf, mg/l	4.7	7.1	6.9
8. P, f, mg/l	4.2	7.1	5.8
9. SS, mg/l	5.5	9.1	14.0
10. % volatile	77.8	79.2	90.1
11. BOD_5, uf, mg/l	4.5	4.9	8.0
12. BOD_5, f, mg/l	2.7	3.6	4.1

HYPERION TEST NO.	4	5	6
Primary Effluent:			
1. Water Temp. ^{o}F	73.9	70.9	66.9
2. COD, uf, mg/l	317.9	301.1	346.5
3. COD, f, mg/l	237.0	235.5	245.1
4. NH_3 as N, mg/l	17.5	18.3	18.6
5. TKN, uf, mg/l	26.1	27.4	28.4
6. TKN, f, mg/l	23.3	24.3	24.7
7. P, uf, mg/l	12.5	12.6	12.2
8. P, f, mg/l	11.3	11.5	11.1
9. SS, mg/l	97.5	96.3	106.0
10. % volatile	86.0	91.3	84.6
11. BOD_5, uf, mg/l	163.0	147.9	158.4
12. BOD_5, f, mg/l	118.4	104.9	107.0
Aerator Effluent:			
1. COD, uf, mg/l	3004.4	2009.1	1859.1
2. COD, f, mg/l	36.3	46.7	52.0
3. NH_3 as N, mg/l	12.0	11.8	14.8
4. NO_3 as N, mg/l	0.3	0.5	0.4
5. TKN, uf, mg/l	227.2	161.4	146.0
6. TKN, f, mg/l	14.1	14.2	17.4
7. P, uf, mg/l	157.3	98.4	92.1
8. P, f, mg/l	12.3	10.4	10.0
9. SS, mg/l	2756.0	1935.4	1597.1
10. % volatile	73.1	75.5	75.1
11. BOD_5, uf, mg/l	992.7	772.3	647.5
12. BOD_5, f, mg/l	6.8	8.2	7.8
Return Sludge Stream:			
1. COD, uf, mg/l	7307.0	6084.3	6619.4
2. COD, f, mg/l	52.2	76.4	96.8
3. NH_3 as N, mg/l	15.1	13.4	16.9
4. NO_3 as N, mg/l	0.2	0.3	0.2
5. TKN, uf, mg/l	522.1	461.6	455.9
6. TKN, f, mg/l	18.4	19.0	22.5
7. P, uf, mg/l	423.8	308.7	285.6
8. P, f, mg/l	46.5	38.1	39.2
9. SS, mg/l	7310.9	5543.6	5624.3
10. % volatile	73.8	75.4	72.4
11. BOD_5, uf, mg/l	1778.0	1725.8	1913.3
12. BOD_5, f, mg/l	12.4	22.4	22.3
Final Effluent:			
1. COD, uf, mg/l	39.5	100.1	76.5
2. COD, f, mg/l	30.5	40.8	48.6
3. NH_3 as N, mg/l	10.9	10.7	14.5
4. NO_3 as N, mg/l	0.4	0.6	0.4
5. TKN, uf, mg/l	13.0	13.3	16.7
6. TKN, f, mg/l	12.5	13.6	16.2
7. P, uf, mg/l	2.6	2.9	2.8
8. P, f, mg/l	2.2	2.3	2.4
9. SS, mg/l	15.1	24.8	15.6
10. % volatile	77.0	88.7	78.2
11. BOD_5, uf, mg/l	9.2	13.1	10.9
12. BOD_5, f, mg/l	4.7	4.1	4.8

HYPERION TEST NO.	7	8	9
Primary Effluent:			
1. Water Temp. °F	66.2	63.5	64.6
2. COD, uf, mg/l	331.6	286.8	349.8
3. COD, f, mg/l	228.2	181.2	217.0
4. NH_3 as N, mg/l	18.5	13.6	16.5
5. TKN, uf, mg/l	28.0	22.9	25.8
6. TKN, f, mg/l	24.7	20.0	21.3
7. P, uf, mg/l	12.0	9.8	10.4
8. P, f, mg/l	11.1	9.0	9.2
9. SS, mg/l	97.4	87.0	109.0
10. % volatile	82.3	78.5	71.7
11. BOD_5, uf, mg/l	163.0	130.0	153.8
12. BOD_5, f, mg/l	121.1	94.2	95.0
Aerator Effluent:			
1. COD, uf, mg/l	1298.2	1215.0	894.0
2. COD, f, mg/l	75.3	52.2	49.0
3. NH_3 as N, mg/l	15.3	10.7	12.8
4. NO_3 as N, mg/l	0.2	1.0	0.3
5. TKN, uf, mg/l	99.2	91.4	66.2
6. TKN, f, mg/l	18.5	13.8	15.6
7. P, uf, mg/l	35.4	22.6	16.7
8. P, f, mg/l	12.4	9.8	8.8
9. SS, mg/l	1050.0	999.2	628.3
10. % volatile	79.0	79.8	79.6
11. BOD_5, uf, mg/l	488.2	532.5	282.5
12. BOD_5, f, mg/l	9.3	13.8	8.3
Return Sludge Stream:			
1. COD, uf, mg/l	4254.5	3872.5	3876.0
2. COD, f, mg/l	108.5	86.5	89.0
3. NH_3 as N, mg/l	16.6	12.3	14.2
4. NO_3 as N, mg/l	0.1	0.2	0.1
5. TKN, uf, mg/l	337.4	280.4	243.2
6. TKN, f, mg/l	23.4	18.4	20.4
7. P, uf, mg/l	101.2	47.6	38.0
8. P, f, mg/l	31.6	15.9	10.9
9. SS, mg/l	3770.0	3546.2	2858.0
10. % volatile	81.9	77.8	81.0
11. BOD_5, uf, mg/l	1690.0	1605.0	1315.0
12. BOD_5, f, mg/l	31.8	24.2	28.0
Final Effluent:			
1. COD, uf, mg/l	97.5	56.6	66.0
2. COD, f, mg/l	49.8	43.3	45.0
3. NH_3 as N, mg/l	14.4	10.0	12.7
4. NO_3 as N, mg/l	0.2	0.9	0.2
5. TKN, uf, mg/l	17.2	13.0	16.2
6. TKN, f, mg/l	16.6	12.0	14.7
7. P, uf, mg/l	8.2	8.1	8.8
8. P, f, mg/l	7.5	7.5	8.2
9. SS, mg/l	19.0	17.0	17.3
10. % volatile	86.4	75.0	79.6
11. BOD_5, uf, mg/l	13.5	11.2	17.2
12. BOD_5, f, mg/l	4.6	5.2	5.2

HYPERION TEST NO.	10	11	12
Primary Effluent:			
1. Water Temp. ^{o}F	63.7	67.7	71.2
2. COD, uf, mg/l	290.3	318.1	324.8
3. COD, f, mg/l	170.5	209.2	221.2
4. NH_3 as N, mg/l	14.7	16.8	17.7
5. TKN, uf, mg/l	23.1	25.4	26.6
6. TKN, f, mg/l	20.2	22.0	23.2
7. P, uf, mg/l	9.6	10.4	11.5
8. P, f, mg/l	8.4	9.5	10.2
9. SS, mg/l	100.6	97.1	100.3
10. % volatile	77.2	79.8	80.1
11. BOD_5, uf, mg/l	136.6	151.1	170.1
12. BOD_5, f, mg/l	78.5	101.3	111.4
Aerator Effluent:			
1. COD, uf, mg/l	736.7	1037.4	1933.0
2. COD, f, mg/l	52.5	60.0	53.8
3. NH_3 as N, mg/l	12.8	13.8	14.1
4. NO_3 as N, mg/l	.4	.2	.4
5. TKN, uf, mg/l	61.0	79.7	133.6
6. TKN, f, mg/l	15.8	16.4	16.7
7. P, uf, mg/l	13.6	16.4	35.0
8. P, f, mg/l	8.1	8.8	11.1
9. SS, mg/l	570.0	706.8	1485.5
10. % volatile	76.2	80.3	80.3
11. BOD_5, uf, mg/l	262.0	298.3	606.7
12. BOD_5, f, mg/l	8.3	7.4	9.4
Return Sludge Stream:			
1. COD, uf, mg/l	3629.0	4259.8	6006.0
2. COD, f, mg/l	105.0	102.8	101.7
3. NH_3 as N, mg/l	14.9	16.0	16.1
4. NO_3 as N, mg/l	.1	0.0	.1
5. TKN, uf, mg/l	238.8	288.9	406.8
6. TKN, f, mg/l	22.5	23.5	21.9
7. P, uf, mg/l	28.5	42.2	74.5
8. P, f, mg/l	10.4	11.6	20.3
9. SS, mg/l	2900.0	3309.2	5010.9
10. % volatile	80.3	81.2	79.7
11. BOD_5, uf, mg/l	1347.0	1438.8	1911.0
12. BOD_5, f, mg/l	33.0	35.1	32.8
Final Effluent:			
1. COD, uf, mg/l	84.5	76.2	58.3
2. COD, f, mg/l	54.0	46.6	44.3
3. NH_3 as N, mg/l	12.4	13.2	14.5
4. NO_3 as N, mg/l	.3	.1	.2
5. TKN, uf, mg/l	16.5	17.5	17.3
6. TKN, f, mg/l	14.8	15.3	16.3
7. P, uf, mg/l	8.2	9.1	8.9
8. P, f, mg/l	7.7	8.2	8.3
9. SS, mg/l	28.9	22.1	16.0
10. % volatile	77.5	69.5	78.6
11. BOD_5, uf, mg/l	18.7	19.0	11.2
12. BOD_5, f, mg/l	4.0	3.8	3.6