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Richard I. Kermode
University of Kentucky

Robert W. J. Brett
University of Kentucky

Joseph D. Pault Jr.
University of Kentucky

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PROCESS CONTROL OF ACTIVATED SLUDGE TREATMENT,

PHASE II

Dr. Richard I. Kermode
Dr. Robert W. J. Brett
Principal Investigators

Joseph D. Pault, Jr.
Graduate Student Assistant

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University of Kentucky Water Resources Institute
Lexington, Kentucky

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ABSTRACT

Material balances on substrate and microorganisms were derived in conjunction with various mixing configurations thought to accurately describe the activated sludge process. These models include the completely mixed with bypass, plug flow, and plug flow with bypass. Two sets of kinetic mechanisms for substrate utilization and bacterial growth were employed.

A feed forward controller was designed from linear approximations of the material balances derived in the completely mixed with bypass mixing model. Utilizing frequency response methods, the controller was found essentially identical to a completely mixed modeled controller developed in a prior investigation.

Through computer simulation the controller's effectiveness was tested. The controller maintained suitable effluent quality principally through proportional control on the influent flow rate. Additional proportional derivative control on influent substrate concentration produced further reductions in substrate levels; however, when employing realistic forcing functions,these reductions were minor. Comparison of mixing models was dependent upon the degree of substrate loading inflicted on the system. Bypassing had a detrimental effect on effluent quality and process control.

Experimental studies were performed to find a representative kinetic and mixing model which reproduces the diurnal fluctuations of key activated sludge process parameters found at the Lexington Wastewater Treatment Plant. A suitable model was not found as experimental and theoretical results did not agree.

DESCRIPTORS:

Activated sludge*, environmental engineering, mathematical models, optimization, quality control, settling basins, sewage treatment*.

IDENTIFIERS:

Digital simulation, process control.

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CHAPTER I

INTRODUCTION

Project Objectives

It was the intent of this research to continue the study of the feed forward control of the activated sludge process. In addition to extending the analytical and simulation work begun during phase I, experimental studies to establish aeration tank kinetic parameters were to be initiated. The resulting experimental data were then to be compared with the computer simulation results. If favorable agreement was achieved, then actual feed-forward control on the recycle flow would be tried on the Lexington treatment plant.

Background Information

A comprehensive review of the principles of process control as applied to the activated sludge process has been presented by Kermode and Brett[6]. In this same reference, the models proposed by various authors for both the aeration tank and the settler are discussed in detail. Computer simulation studies carried out for the case of perfect mixing and instantaneous settling indicated that operational improvements could be obtained using feed forward proportional control with measurement of substrate flow rate, and derivative control with inlet substrate concentration, and manipulation of the rate of return by both controllers. Changing the settler dynamics to a variable time delay caused degredation in the control. It was also concluded that for a given controller the more non-linear the aerator model used the less effective was feed forward control. Finally, a comprehensive literature survey thru March, 1973, is given.

CHAPTER II

RESEARCH PROCEDURES

Because of the two-part nature of this project, procedures for evaluating experimental as well as computer simulation results were essential. The steps taken for the computer simulation are briefly listed below:

i. The effect of various mixing patterns in the aerator such as completely mixed with bypass, plug flow, and plug flow with bypass on process performance was established.

ii. These results were then compared with the perfectly mixed case.

iii. The perfect feed forward controllers for the various types of mixing patterns were then derived to establish the effect of bypass on the control algorithm.

iv. Establish by computer simulation the effectiveness of these controllers in reducing the detrimental effect of bypass flow.

v. Derive the perfect feed forward controllers for the case of plug flow.

vi. Use the computer to establish the effect of the type of forcing functions, the use of sludge storage, and changes in important parameters on system performance.

The experimental steps were carried out as follows:

i. Discrete dynamic measurements of the following quantities were made at the Lexington sewage treatment plant.

a. Inlet and exit aerator substrate concentration

b. Exit settler substrate concentration

c. Mixed liquor suspended solids

d. All necessary flow rates

ii. Kinetic rate constants were then determined by data evaluation.

iii. A comparison of experiment results with those predicted by the various postulated models was then carried out.

CHAPTER III

CONTROLLER DEVELOPMENT

General System Equations and Model Development

The development of computer simulation models in this study was actually an extension of prior work carried out by Brett, Kermode and Burrus[1] and Davis, Kermode and Brett[3].

Brett used a mathematical model of a completely mixed process developed by Westburg[13, 14] to derive a feed forward controller to manipulate the sludge recycle rate.

Davis continued the computer work on the completely mixed system after developing a feed forward controller from design equation involving kinetic models derived by Lawrence and McCarty[7] and Eckenfelder[5].

Both Brett and Davis assumed an ideal separator following the aeration unit as described by equation 1. Thus any contribution of escaping sludge solids to the effluent organic concentration was not considered. Later Debelak, Brett, Kermode and Davis[4] included more realistic settler dynamics represented by a variable time delay; however, in this present study the settler was again assumed ideal.

Completely Mixed with Bypass Model

A flow diagram of an activated sludge process modeled with a completely mixed plug bypass aeration unit is illustrated in Figure 1. The process includes an internal sludge recycle with sludge wasting from the recycle line. The separation unit is assumed to be ideal in that it produces

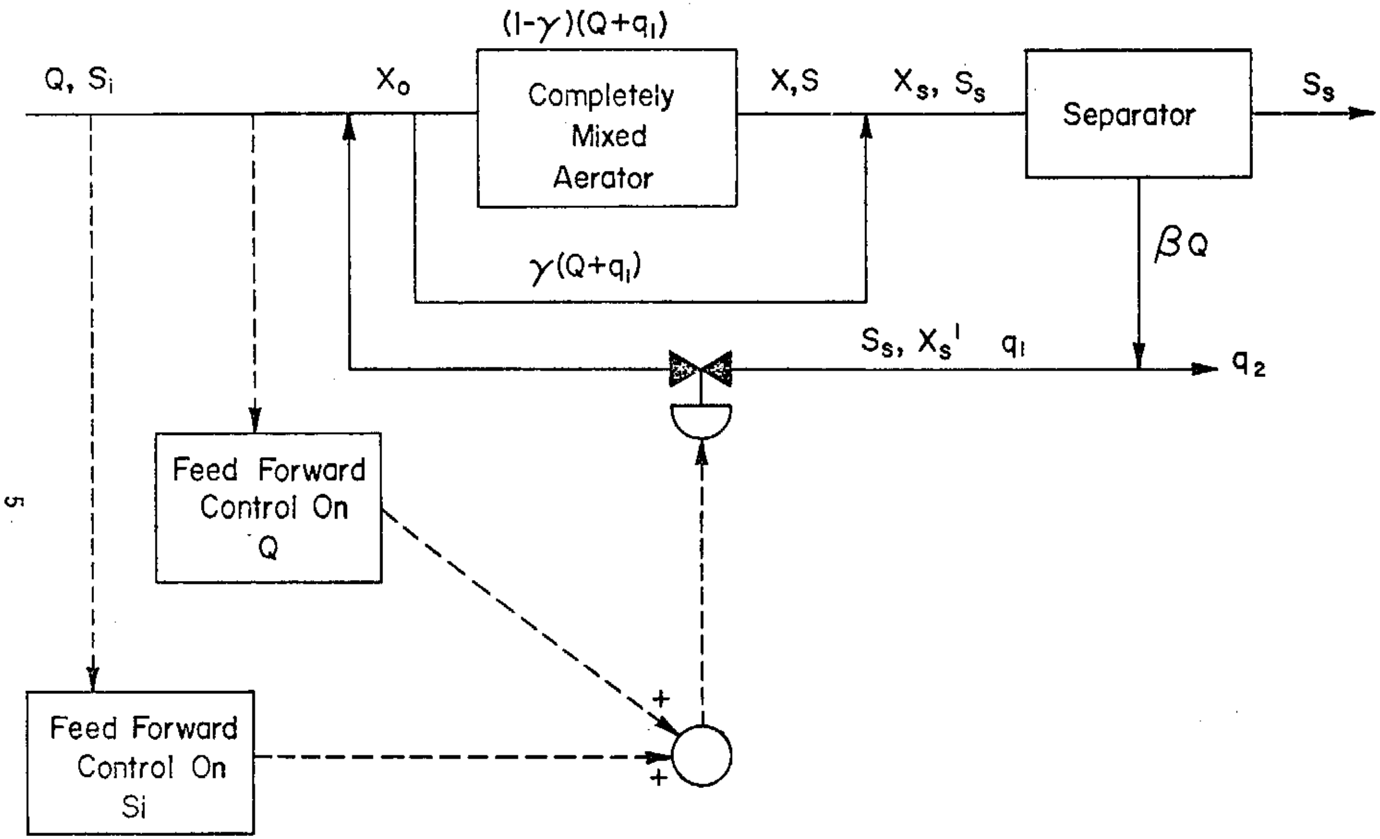

Figure 1. Flow Diagram For Control Of Completely-Mixed Activated Sludge Process With Bypass.

a clean overflow at a rate $(Q-q_2)$, and a concentrated underflow at a rate $(q_1 + q_2)$. The sedimentation step can be described by a material balance around the sludge settler (separator) namely:

$$q_1 + q_2 = \beta Q \qquad (1)$$

The aeration unit is modeled to simulate a less than perfect completely mixed unit by bypassing a fraction of the inlet flow around the completely mixed unit. The two streams are mixed immediately following the aerator to form the inlet concentrations of substrate and live bacteria fed into the separator. The bypass model was chosen to simulate incomplete biological degradation of the substrate while using the complete volume of the aerator.

Material balances were derived for the bypass model using Lawrence & McCarty and Eckenfelder kinetic expressions for substrate utilization and bacterial growth. These are:

$$V \frac{dS}{dt} = (QS_i + q_1 S_s)(1 - \gamma) - (Q + q_1)(1 - \gamma)\, S - V \left(\frac{dF}{dt}\right), \qquad (2)$$

and

$$V \frac{dX}{dt} = (1 - \gamma)(Q + q_1)\, X_o - (Q + q_1)(1 - \gamma)\, X + V \left(\frac{dG}{dt}\right) \qquad (3)$$

where $\frac{dF}{dt}$ and $\frac{dG}{dt}$ are the internal substrate utilization rate and internal synthesis rate respectively and γ the fraction bypassed. The Lawrence & McCarty and Eckenfelder kinetic terms, $\frac{dF}{dt}$, $\frac{dG}{dt}$ are shown in Table I.

Table I Kinetic Models

Model	dF/dt	dG/dt	f(S)	g(S)
Lawrence & McCarty	$X[f(S)]$	$X[g(S)]$	$\frac{kS}{K_s + S}$	$\frac{ykS}{K_s + S}$
Eckenfelder	$X[f(S)]$	$X[g(S)]$	$\frac{K_1 S}{a}$	$K_1 S$

Additional material balances on the living bacteria may be written around stream junction points yielding:

$$X_s' = [Q + q_1)/(q_1 + q_2)]X_s, \tag{4}$$

$$X_o = [q_1/(Q + q_1)]X_s', \tag{5}$$

$$X_s(Q + q_1) = X(1 - \gamma)(Q + q_1) + X_o\gamma(Q + q_1) \tag{6}$$

A material balance on the substrate concentration may be written around the junction of the bypass and main stream to give

$$S_s = \frac{\gamma Q S_i}{Q + q_1 - \gamma q_1} + \frac{(1 - \gamma)(Q + q_1)S}{Q + q_1 - \gamma q_1} \tag{7}$$

Equations 1, 3, 4, 5 and 6 may be combined to eliminate X_o, X_s', and X_s yielding:

$$V \frac{dX}{dt} = V \left(\frac{dG}{dt}\right) - X\left[\frac{(\beta Q - q_1)(Q + q_1)(1 - \gamma)}{\beta Q - \gamma q_1}\right] \tag{8}$$

Similarly, combination of equations 2 and 8 eliminates S_s leaving:

$$V \frac{dS}{dt} = (1 - \gamma) \left(\frac{Q + q_1}{Q + q_1 - \gamma q_1}\right) Q(S_i - S) - V \left(\frac{dF}{dt}\right) \tag{9}$$

Feed Forward Controller Design

Because the methodology necessary to derive the perfect feed forward controllers has been presented in detail by Kermode and Brett[6] in a previous report, and the actual steps for the present study are given by Pault[8], only a brief summary will be given. The first step is a linearization of equations 7, 8, and 9 about a steady state. All the variables are then written as deviation variables from their steady state values. The resulting equations are then Laplace transformed and solved simultaneously to eliminate $\overline{X}$ and $\overline{S}$. The resulting equation becomes:

$$\overline{q}_1 = -\left(\frac{P_{14}}{P_{34}}\right)\overline{Q} - \left(\frac{P_{24}}{P_{34}}\right)\overline{S}_1 \qquad (10)$$

Where after assuming that $q_{1ss} = \beta Q_a$ (negligible sludge wasting) the feed forward controllers become

$$\left(\frac{P_{14}}{P_{34}}\right) = -\frac{D_1}{D_2}\left[\frac{AAs^2 + BBs + 1.0}{CCs^2 + DDs + 1.0}\right] \text{ and} \qquad (11)$$

$$\left(\frac{P_{24}}{P_{34}}\right) = -\frac{D_3}{D_4}\left[\frac{AAAs^2 + BBBs + 1.0}{CCCs^2 + DDDs + 1.0}\right] \qquad (12)$$

where

$$D_1 = \left[\frac{Q(1-\gamma)(1+\beta)^2}{V^2}\right]ss + \left[\frac{\partial}{\partial S}\left(\frac{dG}{dt}\right)\frac{\partial}{\partial X}\left(\frac{dF}{dt}\right)\right]ss\left[\frac{\gamma\beta}{Q(1+\beta)}\right]ss,$$

$$D_2 = \left[\frac{(1+\beta)^2(1-\gamma)Q}{\beta V^2}\right]ss + \left[\frac{\partial}{\partial S}\left(\frac{dG}{dt}\right)\frac{\partial}{\partial X}\left(\frac{dF}{dt}\right)\right]ss\left[\frac{\gamma}{Q(1+\beta)}\right]ss$$

$$D_3 = \left[\frac{\gamma}{(1-\gamma)(1+\beta)}\right]\left(\frac{\partial}{\partial S}\left(\frac{dG}{dt}\right)\frac{\partial}{\partial X}\left(\frac{dF}{dt}\right)\right)]ss,$$

$$D_4 = \left[\frac{(1+\beta)^2(1-\gamma)Q}{\beta V^2} + \frac{\gamma}{Q+(1+\beta)}\left(\frac{\partial}{\partial S}\left(\frac{dG}{dt}\right)\frac{\partial}{\partial X}\left(\frac{dF}{dt}\right)\right)\right]_{ss} \times$$

$$\left[\frac{(S_i - S)}{(1+\beta(1-\gamma))}\right]_{ss}$$

$$AA = \left[\frac{\gamma\beta}{D_1 Q(1+\beta)}\right]_{ss}, \qquad CC = \left[\frac{\gamma}{D_2 Q(1+\beta)}\right]_{ss},$$

$$BB = \left[\frac{1}{D_1}\left\{\left(\frac{1-\gamma}{V}\right)\left(\frac{(1+\beta)^2 - \beta\gamma(2+\beta)}{1+\beta(1-\gamma)}\right) + \frac{\gamma\beta}{Q(1+\beta)}\left(\frac{Q(1-\gamma)(1+\beta)}{V(1+\beta(1-\gamma)} + \right.\right.\right.$$

$$\left.\left.\left.\frac{\partial}{\partial S}\left(\frac{dF}{dt}\right)\right\}\right]_{ss}$$

$$DD = \left[\frac{1}{D_2}\left\{\left(\frac{\gamma}{Q(1+\beta)}\right)\left(\frac{Q(1-\gamma)(1+\beta)}{V(1+\beta(1-\gamma))} + \frac{\partial}{\partial S}\left(\frac{dF}{dt}\right)\right) - \frac{(1-\gamma)\gamma}{V(1+\beta(1-\gamma))}\right\}\right]_{ss},$$

$$AAA = \frac{1.0}{\frac{\partial}{\partial S}\left(\frac{dG}{dt}\right)\frac{\partial}{\partial X}\left(\frac{dF}{dt}\right)}, \qquad CCC = \left[\frac{(S_i S)\gamma}{D_4 Q(1+\beta)(1+\beta(1-\gamma))}\right]_{ss},$$

$$BBB = \frac{1.0}{\frac{\partial}{\partial S}\left(\frac{dG}{dt}\right)\frac{\partial}{\partial X}\left(\frac{dF}{dt}\right)}\left\{\frac{Q(1-\gamma)^2(1+\beta)^2}{V\ (1+\beta(1-\gamma))} + \frac{\gamma(1-\gamma)(S_i - S)}{V(1+\beta(1-\gamma))^2}\right. \text{ and}$$

$$DDD = \frac{1}{D_4}\left\{\frac{(S_i - S)}{(1+\beta(1-\gamma))}\right\}\left\{\frac{\gamma}{Q(1+\beta)}\left(\frac{Q(1-\gamma)(1+\beta)}{V(1+\beta)(1-\gamma))} + \frac{\partial}{\partial S}\left(\frac{dF}{dt}\right)\right) - \right.$$

$$\left.\frac{(1-\gamma)\gamma}{V(1+\beta(1-\gamma))}\right\}_{ss}.$$

A similar operation was carried out by Davis in devising a controller expression for a completely mixed tank. Davis' Laplacian controller equation was of the same form as Equation 10; however, his final expression for the controllers was independent of the kinetic model whereas expressions 11 and 12 are not. An attempt was made to analytically simplify the expressions by examining the magnitude of each term. This proved unsuccessful and the familiar Bode diagram was used instead.

The Effect of Bypass on Controller Bode Plots

Further comparisons were made using frequency response techniques found in Coughanowr and Koppel[2], specifically the use of Bode diagrams. Bode plots were drawn from Equations 11 and 12 for five different bypass fractions and compared with the Davis[3] expressions.

Figure 2 compares the (P_{14}/P_{34}) expressions of the bypass and completely mixed models with the Eckenfelder kinetic terms included. Analysis of Figure 2 illustrates that for an operating frequency of $\omega = \pi/12.0$ or (.262), that the feed forward control with Q the inlet substrate flow rate reduces to proportional alone even with a bypass as high as 25% ($\gamma = 0.25$). Thus, for all practical purposes the Davis controllers should do as well as the more complicated one derived in equation 11. The (P_{14}/P_{34}) expressions were also plotted using Lawrence & McCarty kinetic terms, and although the plots were shifted slightly to the left the results were identical with those observed using Eckenfelder's kinetics; thus, the (P_{14}/P_{34}) expression seems to reduce to proportional control, $(P_{14}/P_{34}) = -\beta$.

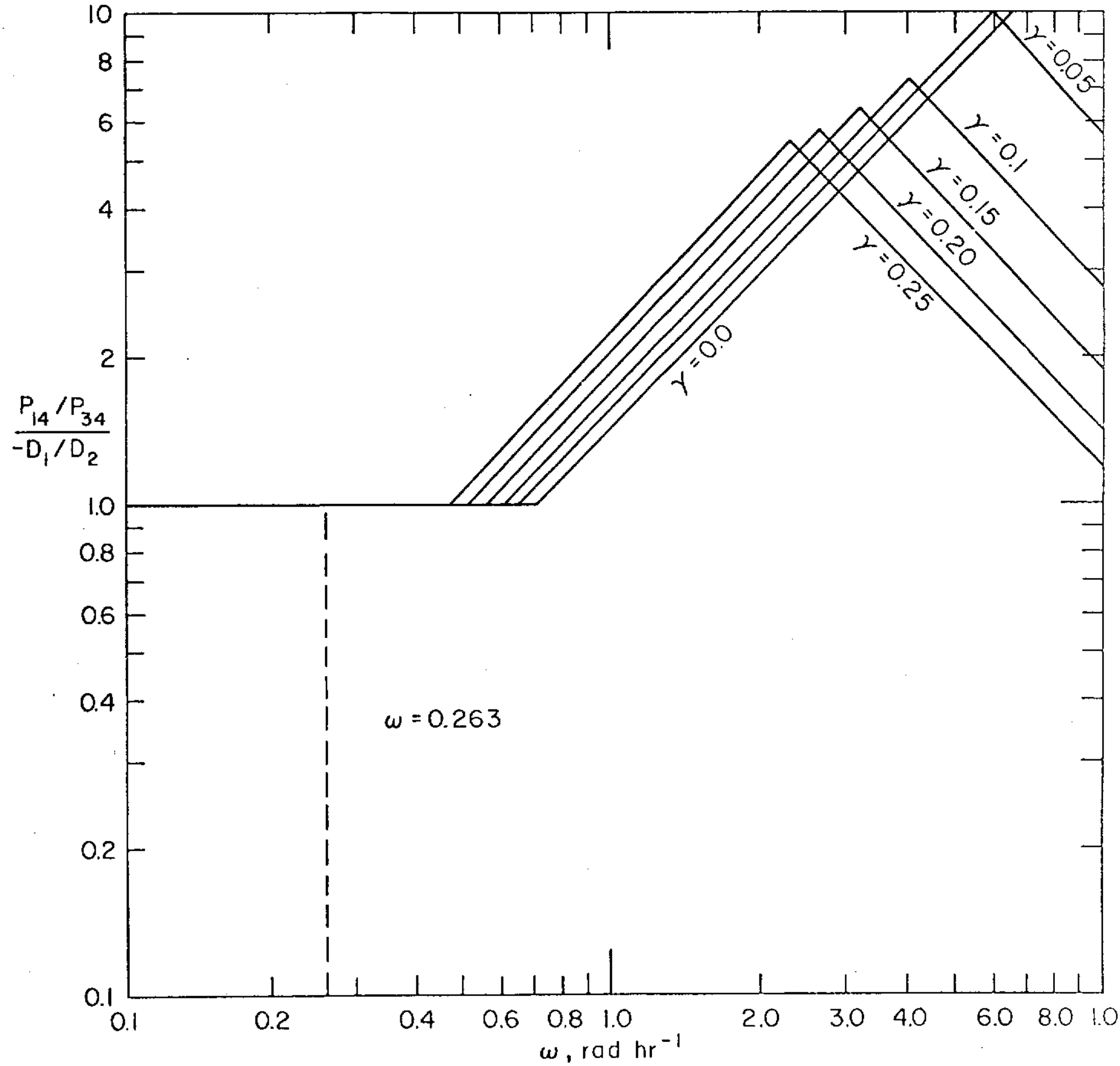

Figure 2 Bode Diagram of P_{14}/P_{34} Expressions Using Eckenfelder Kinetic Terms.

Figure 3 compares the two expressions for (P_{24}/P_{34}), an analysis of the plots show that for the same operating frequency as before, the expression (P_{24}/P_{34}) essentially reduces to a derivative type control expression, $-D_3/D_4(\tau^*s)$. Table II summarizes the results of Figure 3 and illustrates that the maximum deviation is quite small, 12% in the most extreme case, and the assumption that both (P_{24}/P_{34}) expressions, were identical is justified.

Therefore, the Bode plots show that the bypassing of a fraction of the inlet stream around the aeration unit has little or no effect on the control algorithm.

Table II Amplitude Ratio - P_{24}/P_{34}

	ECKENFELDER			LAWRENCE & McCARTY		
γ	$-D_3/D_4$	τ^*s	(P_{24}/P_{34})	$-D_3/D_4$	τ^*s	P_{24}/P_{34}
0.0	Davis controller		-23.324s	Davis controller		-23.324s
0.05	- .4833	47.789s	-23.096s	-.37821	61.201s	-23.147s
0.1	-1.011	22.521s	-22.769s	-.79226	28.892s	-22.89s
0.15	-1.5908	14.013s	22.292s	-1.2483	18.038s	-22.517s
0.20	-2.2322	9.6672s	-21.579s	-1.7541	12.521s	-21.963s
0.25	-2.9474	6.946s	-20.473s	-2.3193	9.1048s	-21.117s

τ^* = effective time constant of (P_{24}/P_{34}) expression in $\omega = \pi/12.0$ range.

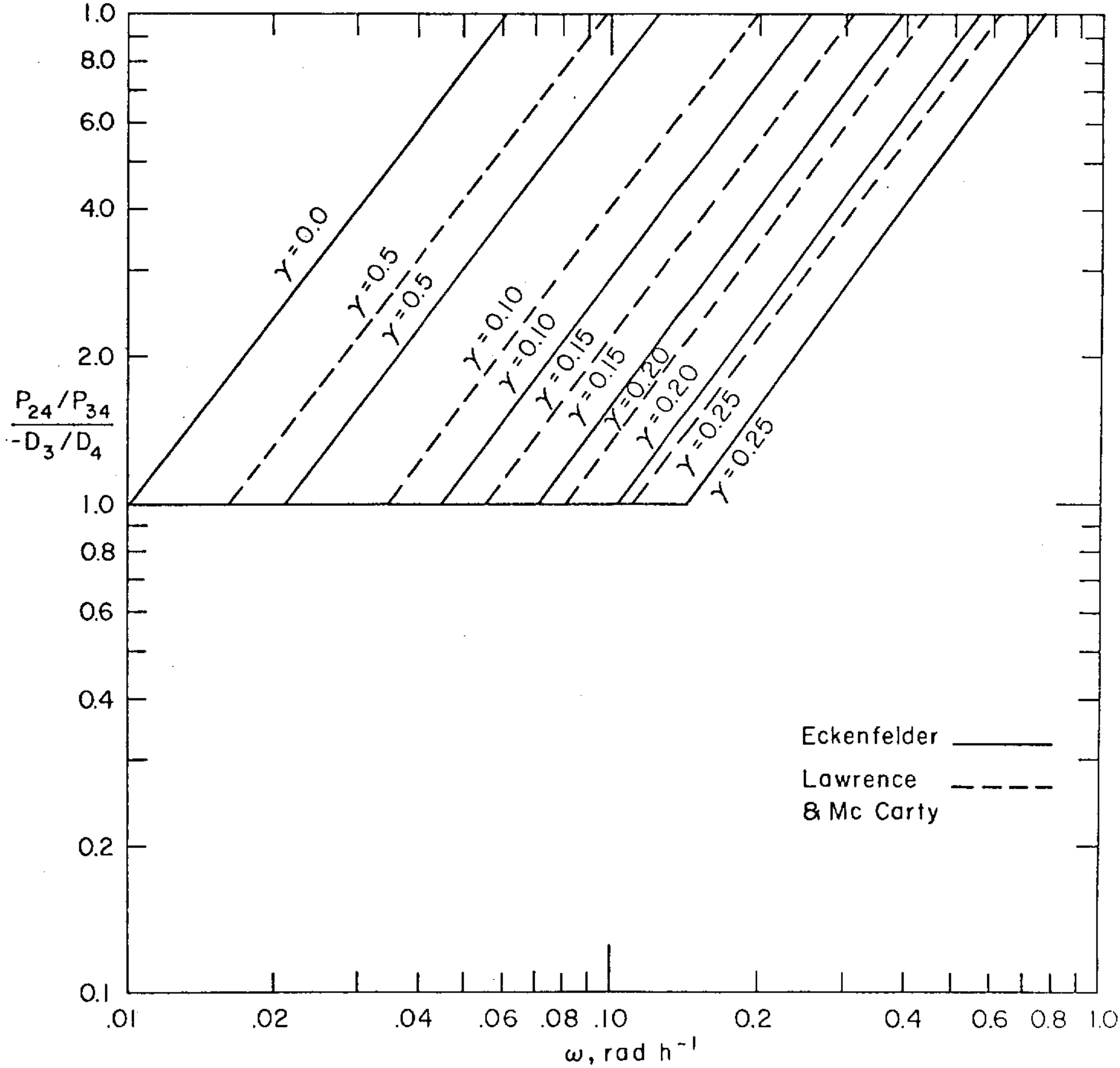

Figure 3. Bode Diagram of P_{24} / P_{34} Expressions

Equation 10 may be written in Standard control form as

$$q_1 = q_{1ss} + K_c(\tau_D s+1)(Q-Q_a) + K_c'\tau_D'(S_i - S_{ia})s \tag{13}$$

where $K_c = [\frac{\beta Q^2 + q_1^2}{Q(Q - \beta Q + 2q_1)}]ss$, $\tau_D = [\frac{V\beta Q}{\beta Q^2 + q_1^2}]ss$ and

$$K_c'\tau_D' = [\frac{QV\beta}{(S_i - S)(Q + \beta Q + 2q_1)}]ss .$$

Rewriting Equation 13 back to the time domain yielded:

$$q_1 = q_{1ss} + K_c(\tau_D \frac{d}{dt} + 1)(Q - Q) + K_c'\tau_D' \frac{d}{dt} (S_i - S_{ia}). \tag{14}$$

Equation 14 was the control algorithm used in the computer simulations.

Plug Flow Model

In order to examine another mixing regime in the aerator, an approximate plug flow mixing model was formulated. This was accomplished by using N completely mixed tanks in series with a total volume equal to that of the original completely mixed tank used in the bypass simulations. A flow schematic is shown in Figure 4.

Material balances on the substrate and live bacteria concentrations for the N number of tanks are:

$$V_1 \frac{dS_1}{dt} = QS_i + q_1S_N - (Q + q_1)S_1 - V_1 (\frac{dF}{dt})_1 , \tag{15}$$

$$\sum_{t=2}^{N} [V_t \frac{dS_t}{dt} = (Q + q_1)(S_{t-1} - S_t) - V_t (\frac{dF}{dt})_t], \tag{16}$$

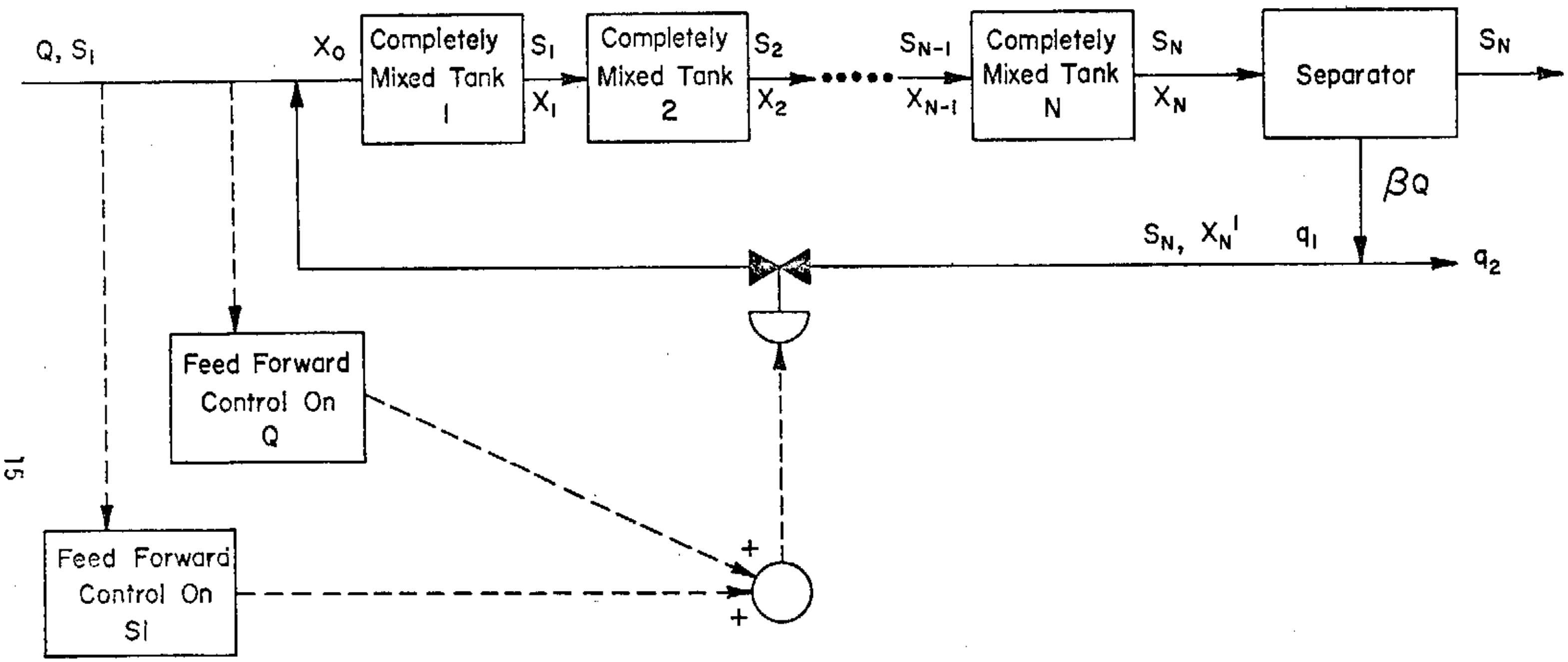

Figure 4. Flow Diagram For Control Of Plug Flow Activated Sludge Process.

$$V_1 \frac{dX_1}{dt} = q_1 X_n \frac{(Q + q_1)}{(q_1 + q_2)} - (Q + q_1)X_1 + V_1 \left(\frac{dG}{dt}\right)_1 \quad , \tag{17}$$

$$\sum_{t=2}^{N} [V_t \frac{dX_t}{dt} = (Q + q_1)(X_{t-1} - X_t) + V_t \left(\frac{dG}{dt}\right)_t] \; , \tag{18}$$

where $V_t = V_{total}/N$. The kinetic terms are again described in Table I.

Plug Flow with Bypass Model

This model was the final system tested with the objective of reassuring us of the detrimental effect of a bypassed stream around the aerator but this time using a plug flow modeled aerator. For the sake of brevity a description of the model will not be discussed as the material balances on the substrate and live bacteria flows were found in manners similar to the previous two models. A schematic of the model is identical with Figure 4 except for the substitution of a series of completely mixed tanks in place of the completely mixed aerator.

CHAPTER IV

COMPUTER SIMULATION

Component Description

The computer testing was carried out using the IBM System/360 Continuous Systems Modeling Program 11. Interpretation of the results can be simplified if one keeps in mind the four basic parts involved, namely, the forcing functions, the controller, sludge storage availability, and the dynamic model employed.

Forcing Functions

The forcing functions are approximations of diurnal fluctuations in inlet flow rate, $Q(t)$, and inlet substrate concentration, $S_i(t)$, that cause the upsets or derivations from steady state values in the process. They are functions of time only and are independent of the process and model. Three different forcing functions were used in these simulations. The first was in phase sinusoidal changes in Q and S_i.

$$Q(t) = Q_a/2\ (2 + \sin \frac{\pi t}{12})\ \text{, and} \qquad (19)$$

$$S_i(t) = S_{ia}/2\ (2 + \sin \frac{\pi t}{12}). \qquad (20)$$

The second was out of phase by 90°, or:

$$Q(t) = Q_a/2\ (2 + \sin \frac{\pi t}{12}) \quad \text{and} \qquad (19)$$

$$S_i(t) = S_{ia}/2\ (2 + \sin (\frac{\pi t}{12} + \frac{\pi}{2})). \qquad (21)$$

Third was a fourth order polynomial.

$$Q(t) = Q_a(E_1 + E_2t + E_3t^2 + E_4t^3 + E_5t^4) \text{ and} \quad (22)$$

$$S_i(t) = S_{ia}(F_1 + F_2t + F_3t^2 + F_4t^3 + F_5t^4). \quad (23)$$

The constants in equations 22 and 23 were determined by fitting the literature values of Wallace and Zollman[12].

Controller

This was already described in detail and presented as Equation 14. The abbreviations PD, D, and P were used to designate the control modes proportional derivative, derivative alone, and proportional only (see Tables III and IV).

Sludge Storage

Examination of Figures 1 and 4 indicates that the underflow rate from the separator is $\beta Q = q_1 + q_2$. This is split into two unequal flows, the recycle flow, q_1, and the sludge waste flow, q_2. If no restrictions are imposed upon q_2 then it is possible in times of required high recycle rate ($q_1 > \beta Q$) that the value of q_2 may become negative, i.e., stored sludge must be supplied to the system. Whether or not sludge storage was available was an added dimension that could be imposed upon the system during the simulations.

Dynamic Models

These have been described in detail in a previous section.

Computer Results

To facilitate the comparison of different models, the values of following parameters were kept the same as those used by Davis: $\beta = 0.4$, $S_{ia} = 267\ g/m^3$, $Q_a = 10000\ m^3/hr$, $S_{ss} = 22\ g/m^3$ and $V = 20{,}000\ m^3$. The steady state expression for the live bacteria concentration [X]ss and the recycle flow rate $[q_1]_{ss}$ as functions of bypass fraction, γ, were found by solving Equations 7 and 9 under steady state conditions.

Completely Mixed with Bypass Model

The first bypass system tested included Lawrence & McCarty kinetic expressions and the simulation results are summarized in Table III. Kinetic coefficients were the same as the values used by Davis, $Y = 0.67$ g/g, $b = 0.00291\ hr^{-1}$, $k = 0.233$ g/g·h and $K_s = 22.0\ g/m^3$.

Runs 1 thru 3 show the effect of increasingly more complicated control on the Lawrence & McCarty model with sinusoidal forcing functions. No restrictions were made on the sludge wasting flow rate, q_2. It can be seen from Table III that the most elaborate control, PD-Q D-S_i, substantially reduced S_s maximum, with 70% of this reduction due to the proportional control on the inlet flow rate, P-Q. This is of practical importance since fluctuations in flow can be measured more easily than changes in substrate concentrations.

Runs 4 and 5, when compared to runs 2 and 3, show the favorable effect of a phase difference between the two forcing functions. This is easily explained since low values of influent substrate coincide with high influent flow rates and vice versa, thus easing the controller's task.

TABLE III Results of Feed Forward Control of Lawrence & McCarty, Bypass Model

Run No.	Control Q(t)	Mode $S_i(t)$	Forcing Functions	Controller Constants	Sludge Storage Available	S_s max			S_s min		
						$\gamma = 0.0$	$\gamma = .10$	$\gamma = .25$	$\gamma = 0$	$\gamma = .10$	$\gamma = .25$
1	No	No	Sinusoidal	None	Yes	290.6	288.2	284.7	2.3	10.6	23.6
2	P	No	"	Davis	Yes	87.7	111.4	149.4	3.1	13.3	29.6
3	PD	D	"	Davis	Yes	22.0	44.6	90.3	10.1	18.5	32.5
4	P	No	Phase Diff.	Davis	Yes	65.8	88.7	125.4	6.2	16.3	31.9
5	PD	D	"	Davis	Yes	48.1	73.4	114.1	22.5	30.7	43.4
5A	No	No	4^{th} order	None	Yes	40.2	59.8	91.4	9.2	26.4	53.9
6	P	No	4^{th} order	Davis	Yes	32.4	52.7	85.8	16.4	34.0	61.1
7	PD	D	"	Davis	Yes	27.1	45.7	79.2	22.6	39.7	64.9
8	PD	D	Sinusoidal	Davis	No	57.8	71.9	113.4	14.2	21.9	34.9
9	"	D	Phase Diff.	Davis	No	75.9	96.6	130.7	22.0	31.4	43.8
10	No	No	Sinusoidal	None	No	290.6	288.2	284.7	12.3	20.5	33.6

The fourth order polynomial functions were imposed upon the system in runs 6 and 7, and a comparison can be made with the previous four simulations just discussed. These realistic forcing functions are less severe as can be seen from Figure 12. This resulted in lower effluent substrate concentrations.

The fluctuating value of the sludge wasting flow rate, q_2, was computed throughout the twenty-four hour simulations in runs 1 through 7. With proportional control alone on inlet flow rate, q_2 remained positive throughout the cycle and sludge storage was not necessary. However, the value of q_2 did occasionally drop below zero as shown in runs 1, 3, and 5 and, therefore, the restriction $q_2 \geq 0.0$ was added to these simulations with the results shown in runs 8, 9, and 10. For the no control cases, runs 1 and 10, stored sludge availability had no effect on the effluent quality. For the controlled cases, approximately a 10% reduction in S_s maximum was possible when sludge storage is available. This improvement probably does not warrant the addition of sludge storage.

In all these simulations, the values of S_s maximum were reported for the bypass fractions 0%, 10%, and 25%. Examination of Figures 5 through 11 illustrates the detrimental effect of bypassing. A comparison of the detrimental effect of the bypass fraction on the controller action is shown in Table VIII for runs 1 through 3.

The second bypass system tested included the Eckenfelder kinetic terms, these results are summarized in Table IV. The kinetic constants were assigned values: $a = 0.39$ g/g, and $K_1 = 0.00227$ $m^3/g \cdot h$. The effluent quality proved to be substantially better in the Eckenfelder simulations.

TABLE IV Results of Feed Forward Control of Eckenfelder Bypass Model

Run No.	Control Q(t)	Mode S (t)	Forcing Functions	Controller Constants	Sludge Storage Available	S_s max			S_s min		
						$\gamma = 0.0$	$\gamma = .10$	$\gamma = .25$	$\gamma = 0$	$\gamma = .10$	$\gamma = .25$
11	No	No	Sinusoidal	None	Yes	102.5	121.7	153.9	2.3	10.6	23.4
12	P	No	"	Davis	Yes	41.4	68.0	111.1	5.1	14.9	30.7
13	PD	D	"	Davis	Yes	22.0	46.1	91.4	13.1	21.2	34.5
14	P	No	Phase Diff.	"	Yes	36.7	62.7	105.7	9.2	19.1	34.2
15	PD	D	"	"	Yes	32.3	58.7	101.6	22.9	31.3	44.4
15A	No	No	4^{th} order	None	Yes	28.4	49.2	82.5	12.2	28.9	55.9
16	P	No	4^{th} order	Davis	Yes	26.7	47.4	80.1	18.5	35.5	61.9
17	PD	D	"	"	Yes	24.6	44.1	78.5	22.6	39.0	64.3
18	PD	D	Sinusoidal	"	No	46.0	60.9	104.8	18.6	26.1	38.6
19	PD	D	Phase Diff.	"	No	47.4	72.7	113.6	22.0	32.1	45.1
20	No	No	Sinusoidal	None	No	102.5	121.7	153.9	11.1	19.9	34.1

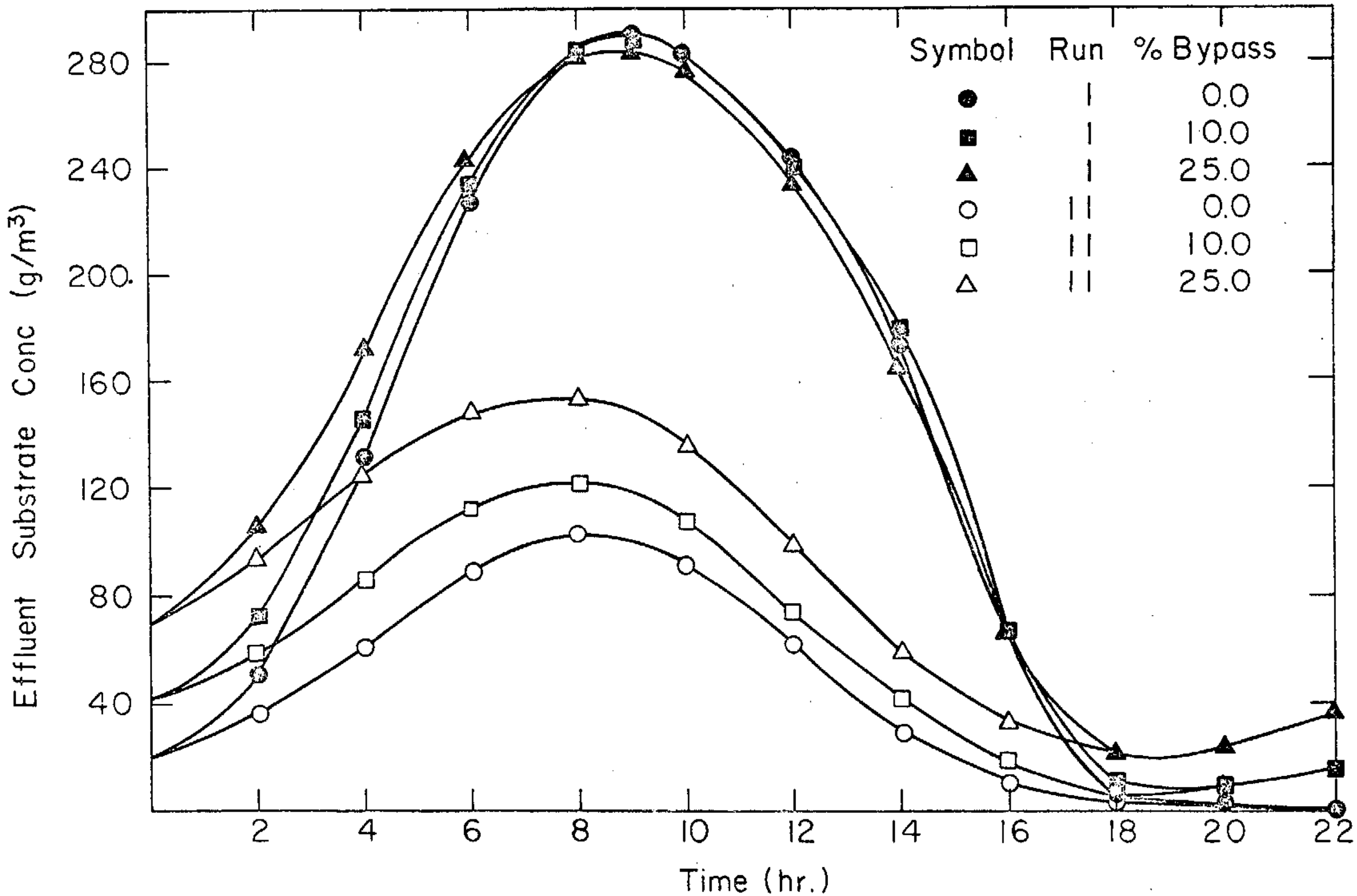

Figure 5. The Effect of Bypass on Eckenfelder's Model and Lawrence and McCarty's Model with No Control.

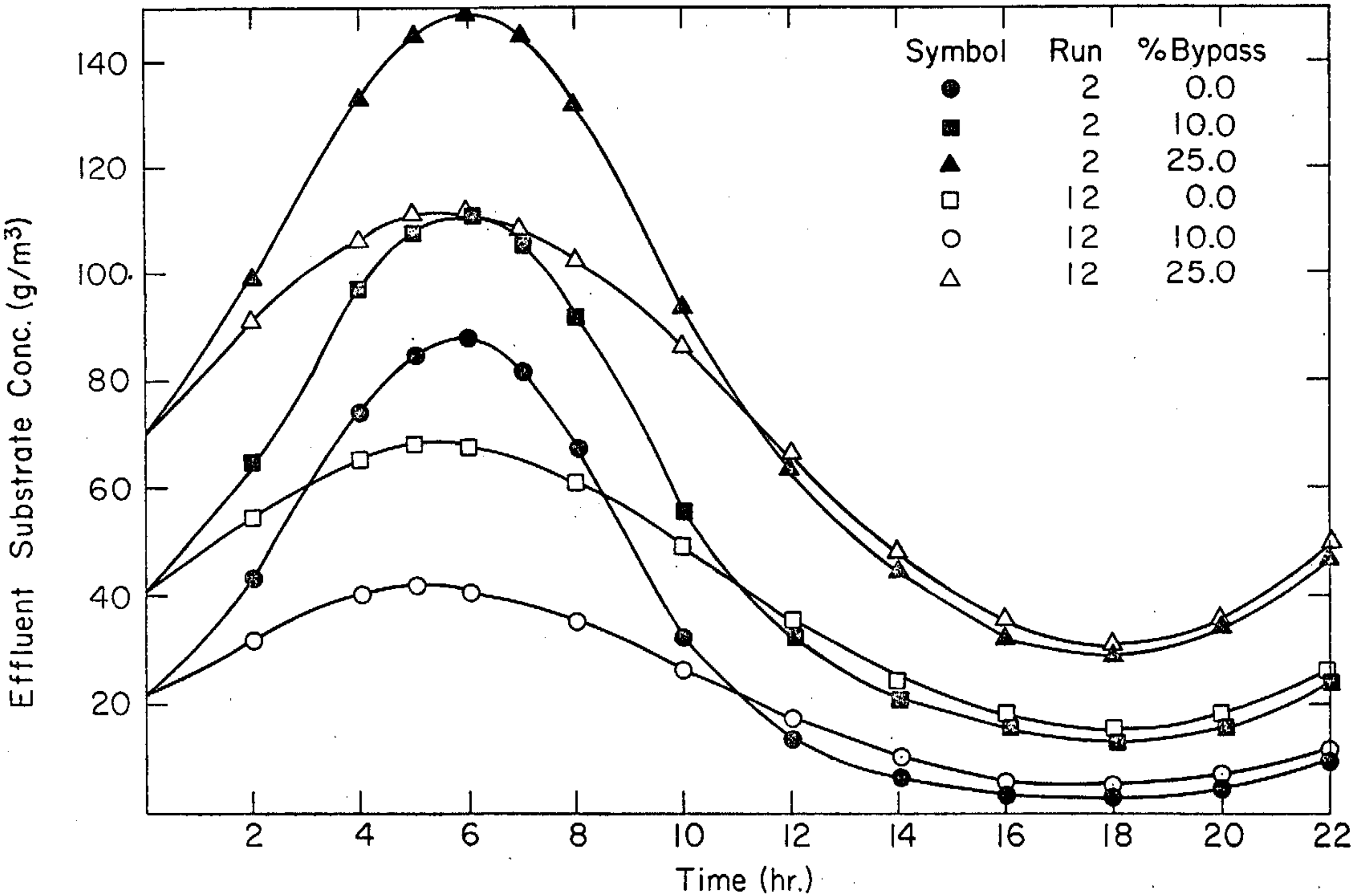

Figure 6. The Effect of Bypass on Lawrence and McCarty's Model and Eckenfelder's Model with Proportional Control - Q.

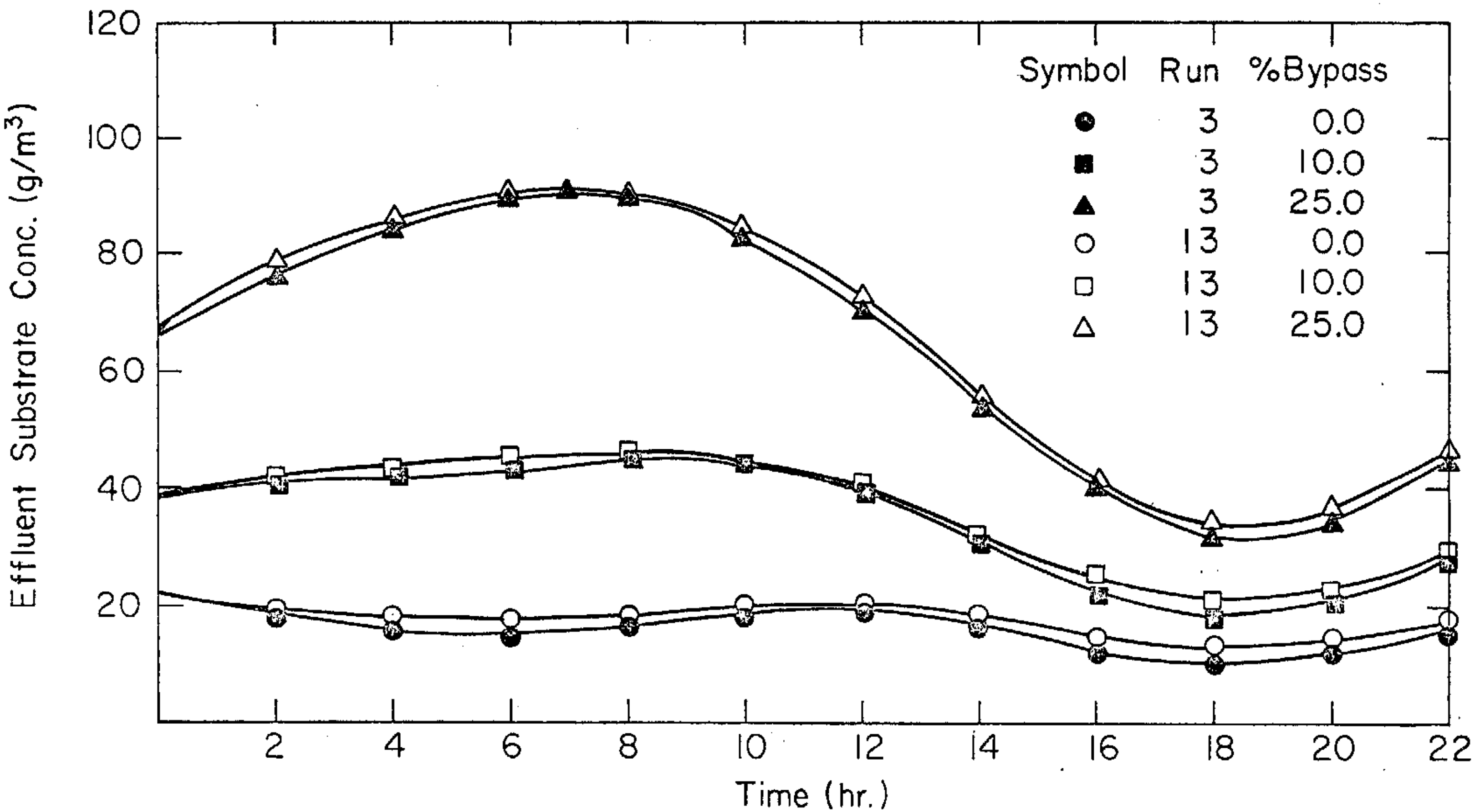

Figure 7. The Effect of Bypass on Lawrence and McCarty's Model and Eckenfelder's Model with Prop. and Derivative Control – Q, Derivative – S_i.

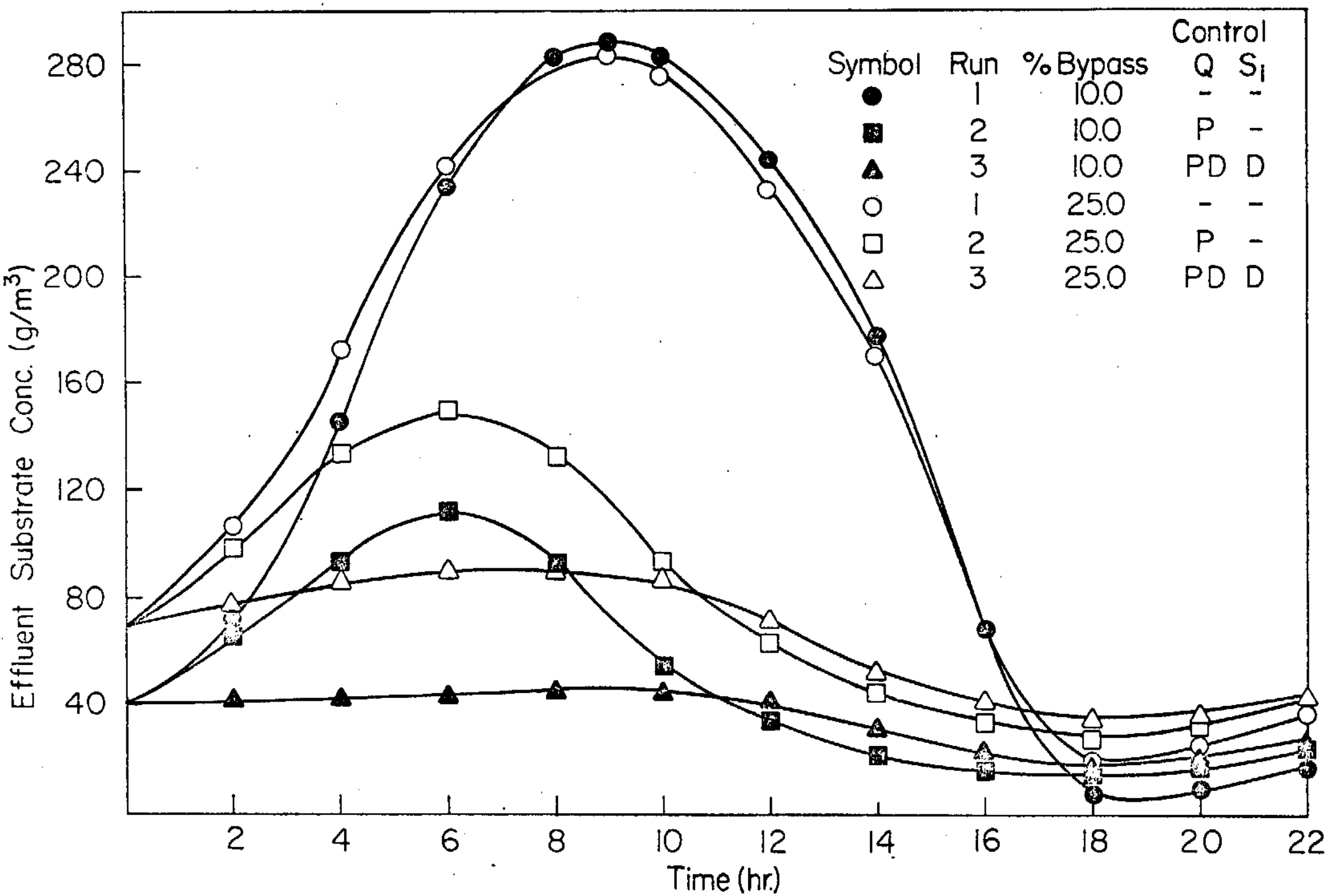

Figure 8. The Effect of Various Control Modes on Lawrence & McCarty's Model for Two Bypass Fractions (10%, 25%).

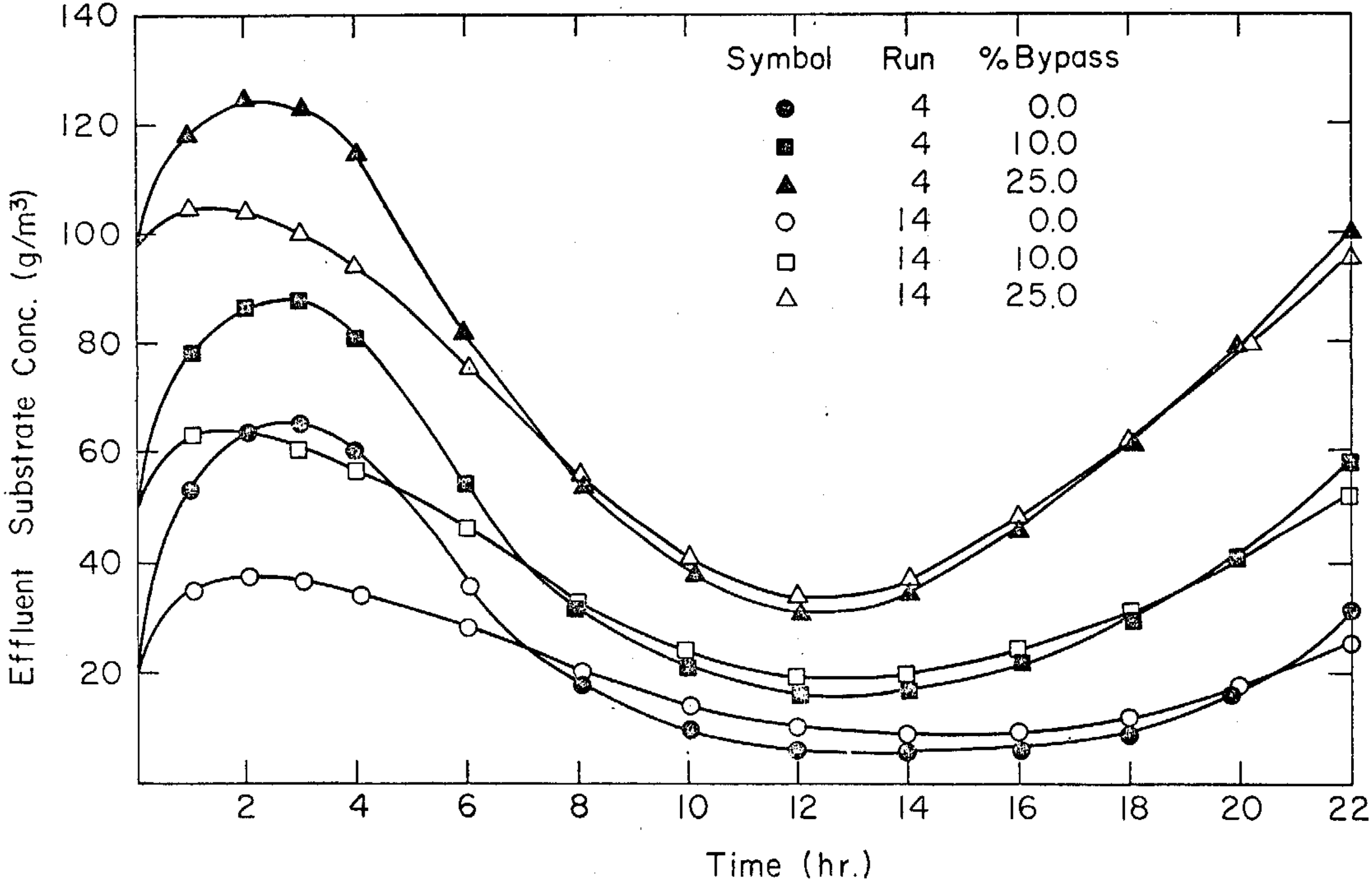

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Figure 9. The Effect of Bypass on Lawrence and McCarty's Model and Eckenfelder's Model with P-Q Control, Phase Diff. Forcing Func.

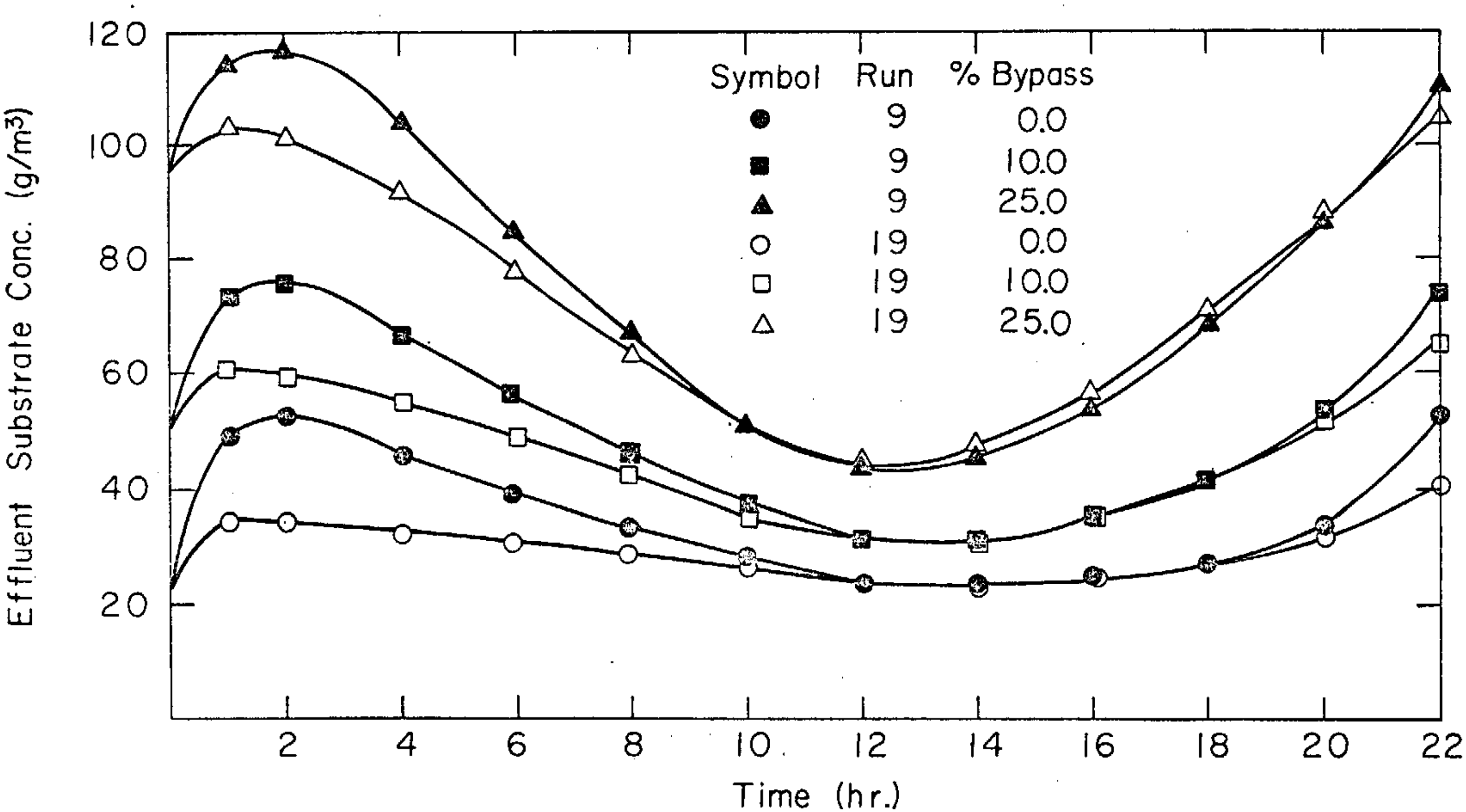

Figure 10. The Effect of Bypass on Lawrence and McCarty's Model and Eckenfelder's Model with PD-Q, D-SI Control, No Sludge Stor., Phase Diff.

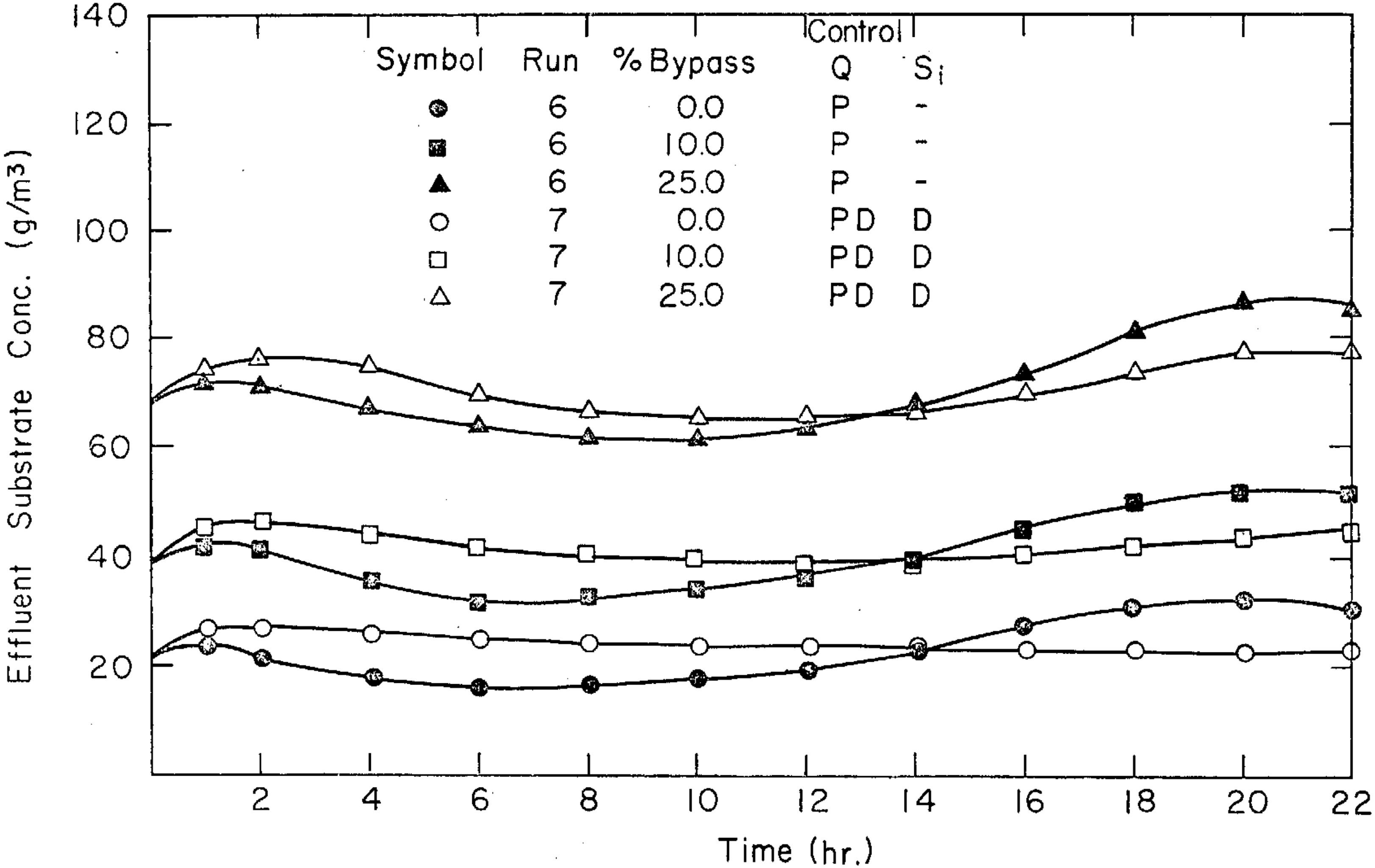

Figure 11. The Effect of Bypass on Lawrence and McCarty's Model with P-Q, PD-Q D-S_i Control, 4th Order Poly. Forcing Func.

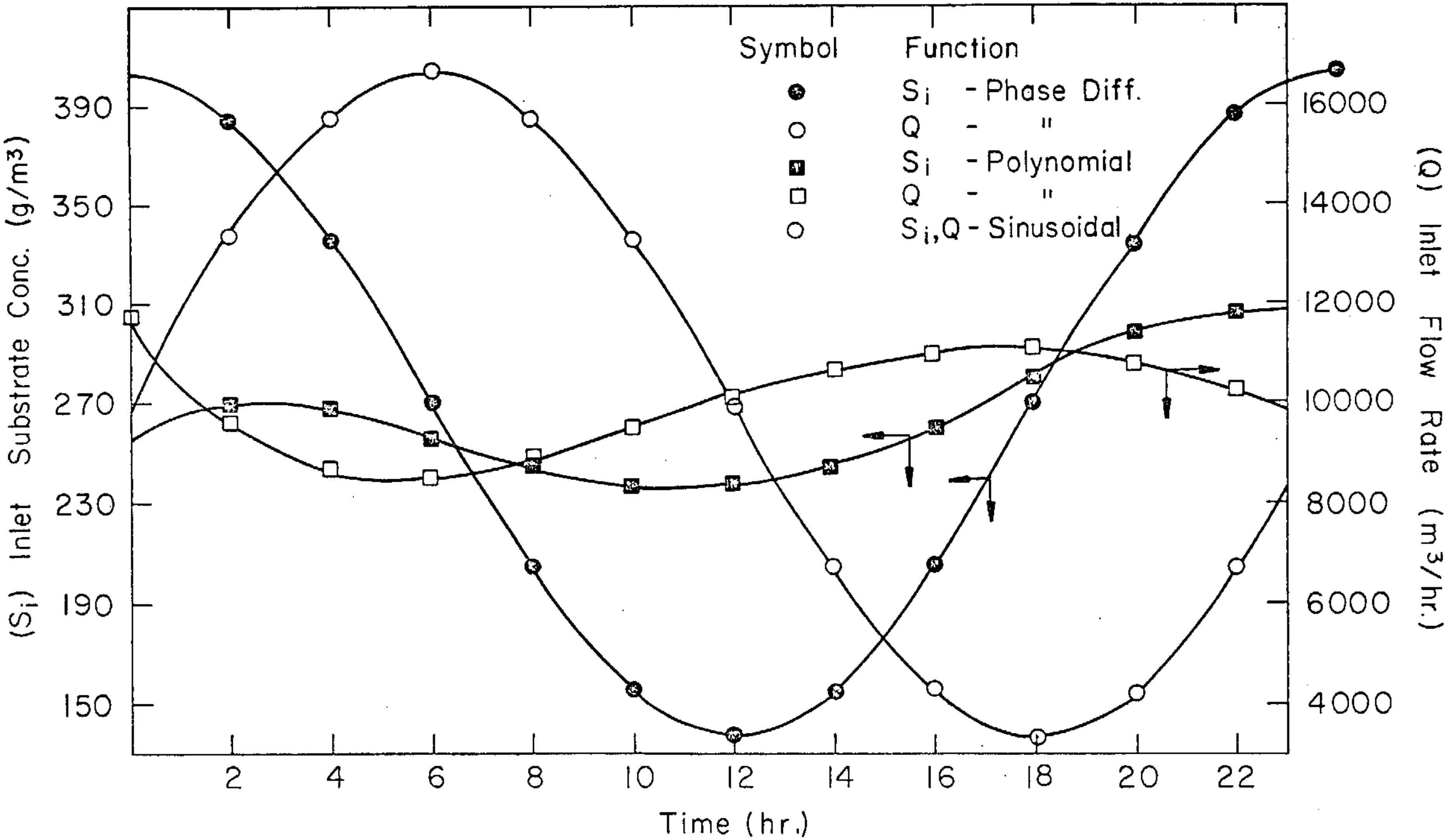

Figure 12. Comparison of Forcing Functions - Sinusoidal In-Phase, Sinusoidal Phase Diff., and 4th Order Polynomial.

This was expected due to the favorable effect of the kinetic growth rates. The same control modes, stored sludge availability, forcing functions, and bypassing effects when applied to the Eckenfelder simulations proved to have similar effects as those exhibited in the Lawrence & McCarty simulations. However, for the no control case, run 11, the bypass fraction had a more detrimental influence on the effluent quality than that experienced in the Lawrence & McCarty model as seen in Figure 5.

Plug Flow Model

The required steady state values of substrate and bacteria concentrations in each of the N aerators were computed using the steady state values, Q_a and S_{ia}, and solving all the system equations dynamically on the computer. As time became large, the derivatives went to zero and the steady state values were obtained. However, the recycle flow rate, q_1, had to be adjusted until the final effluent, S_N, reached its steady state value of 22.0 g/m^3. Thus, a trial and error procedure was required.

The first plug flow system tested included the Lawrence & McCarty kinetic terms with the results summarized in Table V. The identical kinetic coefficients used in the bypass mixing model were used for plug flow.

Runs 20, 21, and 22 exhibit the increasingly desirable effect of a more sophisticated control on the three tank system using sinusoidal forcing functions and stored sludge.

The strong effect of proportional control on flow rate Q(t) in controlling the system is not as dominant in the plug flow system as P-Q produces a 56% reduction in exit substrate levels as compared to 70% in

TABLE V

Results of Feed Forward Control of

Lawrence & McCarty, Plug Flow Model

Run No.	Control Q(t)	Mode S (t)	Forcing Functions	Controller Constants	Sludge Storage Available	Effuent Max.	Substrate Min.	N# of Tanks
20	No	No	Sinusoidal	None	Yes	348.5	1.2	3
21	P	No	Sinusoidal	Davis	Yes	152.3	0.3	3
22	PD	D	Sinusoidal	Davis	Yes	45.4	4.7	3
23	No	No	Sinusoidal	None	Yes	361.6	1.0	10
24	P	No	Sinusoidal	Davis	Yes	172.6	~ 0.0	10
25	PD	D	Sinusoidal	Davis	Yes	82.4	1.1	10
26	No	No	4^{th} order	None	Yes	85.8	0.3	10
27	P	No	4^{th} order	Davis	Yes	43.0	6.9	10
28	PD	D	4^{th} order	Davis	Yes	41.5	13.3	10
29	No	No	Phase Diff.	None	Yes	239.4	22.0	10
30	P	No	Phase Diff.	Davis	Yes	139.5	0.1	10
31	No	No	Sinusoidal	None	No	361.6	22.0	10
32	PD	D	Sinusoidal	Davis	No	123.0	22.0	10

the bypass case. The addition of derivative control produces an 87% reduction from the no control run and practically speaking this case seems to warrant its application.

Runs 23, 24, and 25 illustrate the effect of a ten tank plug flow approximation. Proportional control on Q(t) alone accounted for a 52% reduction in effluent substrate, while proportional derivative control on Q(t) and derivative control on $S_i(t)$ increased this to 77%. Thus, the 10 tank approximation changed the results only slightly.

Comparison of runs 1 through 3 (bypass model) with the above cases illustrates an unexpected result. The completely mixed case with no bypass proved to give a better quality effluent than the plug flow approximation, even in the no control case. The closer the approximation approached an actual plug flow model the worse was the resulting effluent substrate concentration, or in other words

$$S_{N10} > S_{N3} > S_{CSTR} \quad .$$

At first this result was thought to be caused by the high fluctuation of Q(t) and S(t) associated with the sinusoidal forcing function; however, two runs, 5A and 15A, displayed the same result. A reason for this was found in the experimental section of this study. Data from a local treatment plant was used to find realistic forcing functions, and these were used with both a CSTR and plug flow mixing model. This time the plug flow model gave the lower effluent substrate level as originally expected. An explanation for these combined results is that the experimental forcing functions, while no less invariant than Equations 22 and 23, fluctuated about a lower average value for Q(t) and $S_i(t)$, or in other words the average substrate loading on the system was much lower.

Thus, the plug flow mixing model will not receive high average loadings, characteristic for that system, as efficiently as the CSTR model, thus giving higher effluent concentrations.

Examination of runs 26 through 30 illustrate the same effects of the various control modes on the system but using less severe forcing function namely, the 90° phase different functions and the 4^{th} order polynomial approximations.

The effluent substrate S_{10} maximum for the no control, phase difference case was ~ 66% of the S_{10} maximum for the in-phase, no control case. Also, the no control, 4^{th} order polynomial maximum was ~ 24% of the no control, in-phase simulation.

The use of proportional derivative control resulted only in a 3% reduction in effluent substrate maximum levels for the 4^{th} order polynomial forcing function. This is contrary to the favorable results experienced with derivative control using sinusoidal forcing functions.

The detrimental effect caused by no sludge storage can be seen by inspection of runs 31 and 32. Using the most sophisticated control case, loss of stored sludge results in a 62% increase in S_{10} maximum. Again the sophisticated control (PD-Q, D-SI) seems to be unjustified, as its reduction in the maximum effluent substrate concentration for the more realistic 4^{th} order forcing functions is minimal, and part of its effectiveness is provided by sludge stored in the system. The results of the above are presented in Figures 13 thru 16.

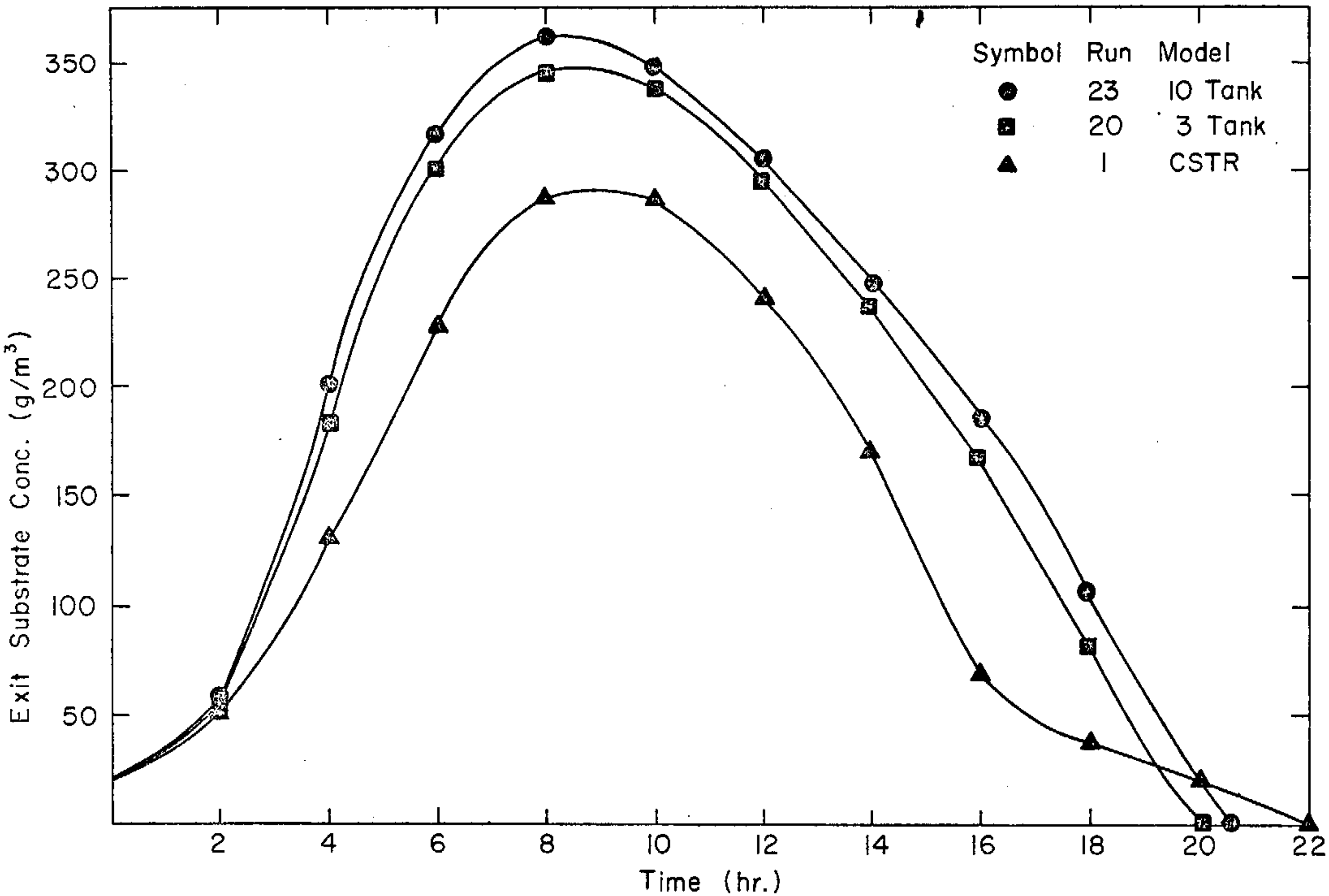

Figure 13. Comparison of Completely Mixed (CSTR) and Plug Flow using Lawrence and McCarty's Model with No Control.

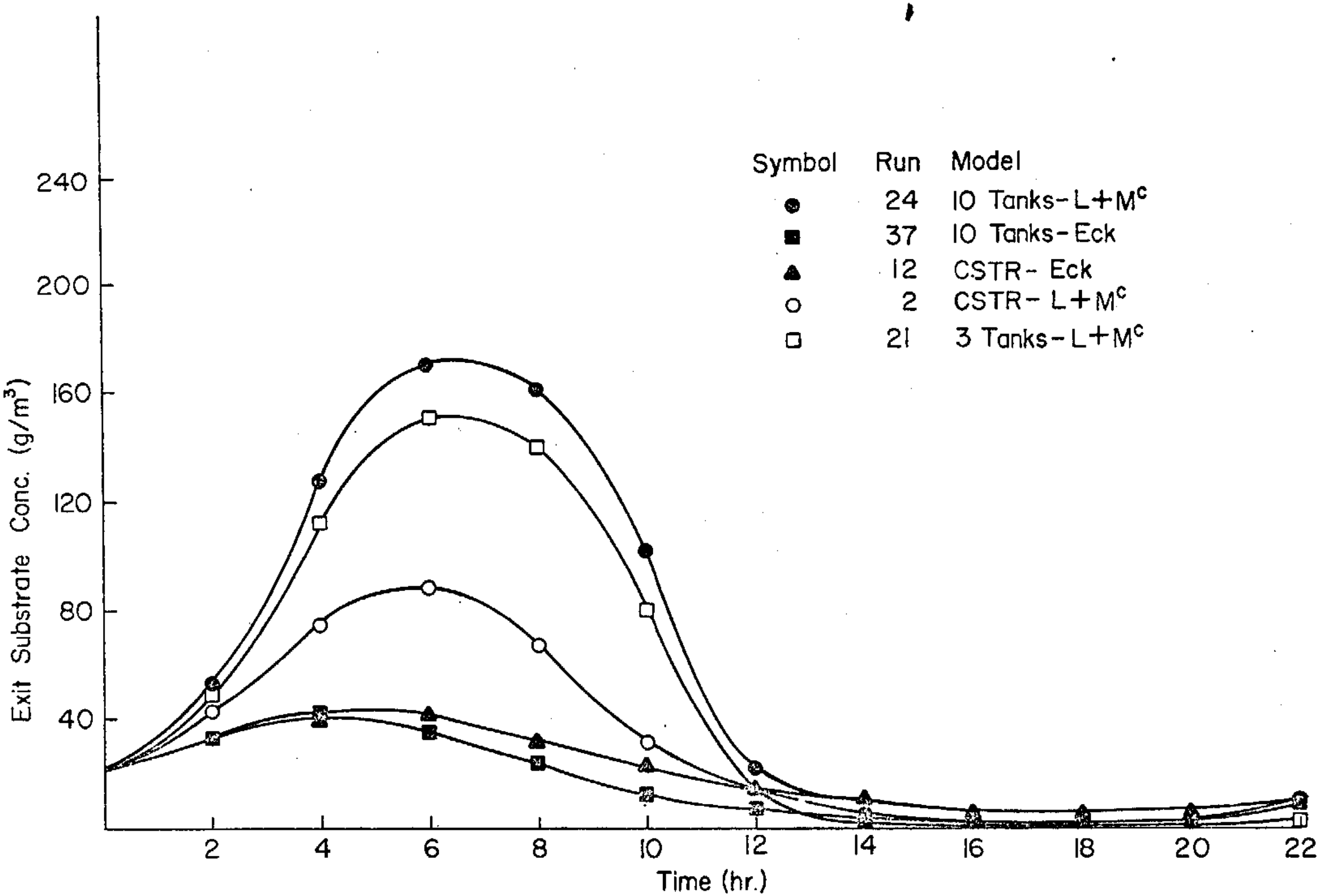

Figure 14. Comparison Of Completely Mixed And Plug Flow For Both Kinetic Models With P-Q.

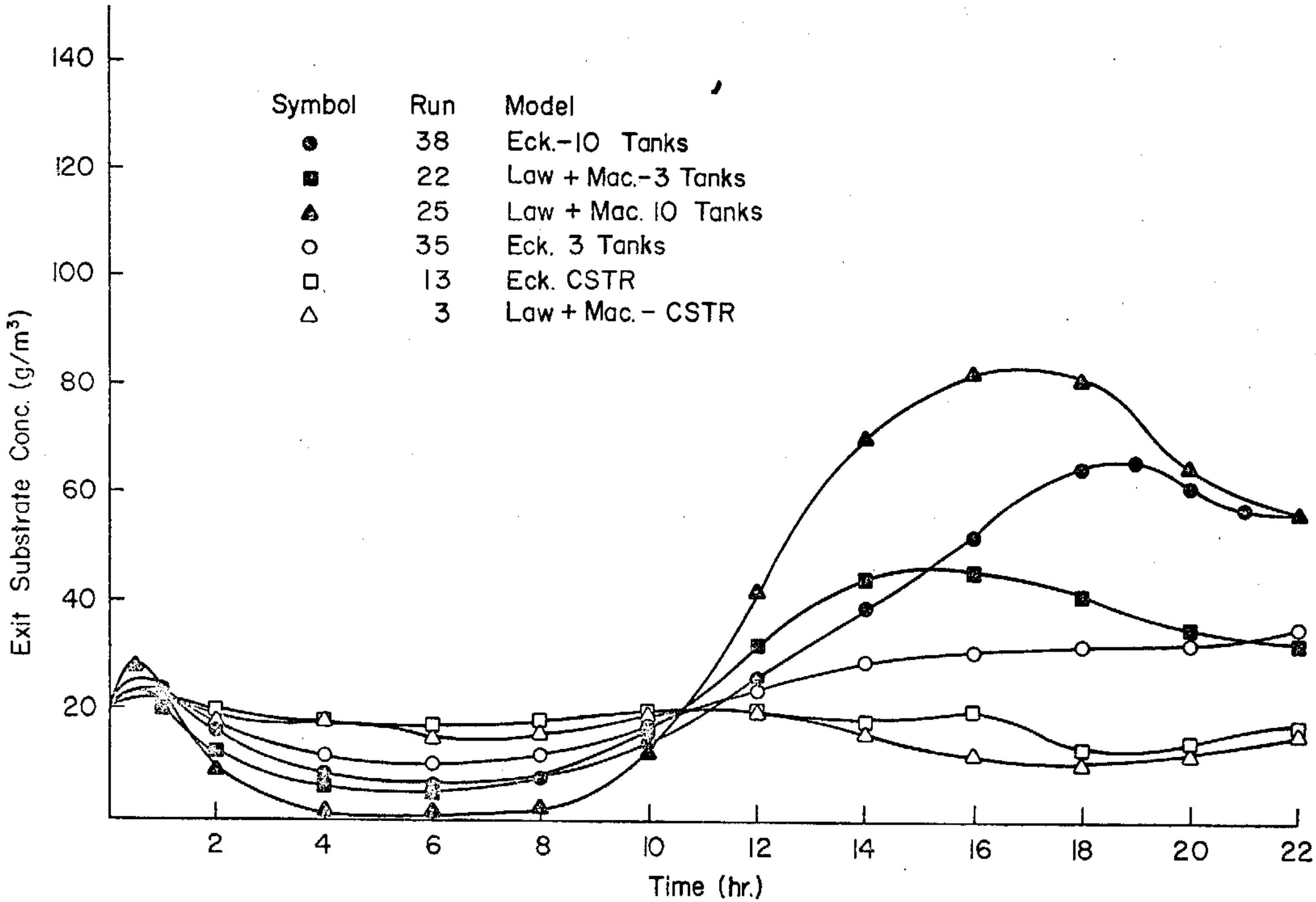

Figure 15. Comparison Of Completely Mixed (CSTR) And Plug Flow Using Various Kinetic And Mixing Models With PD-Q, D-Si.

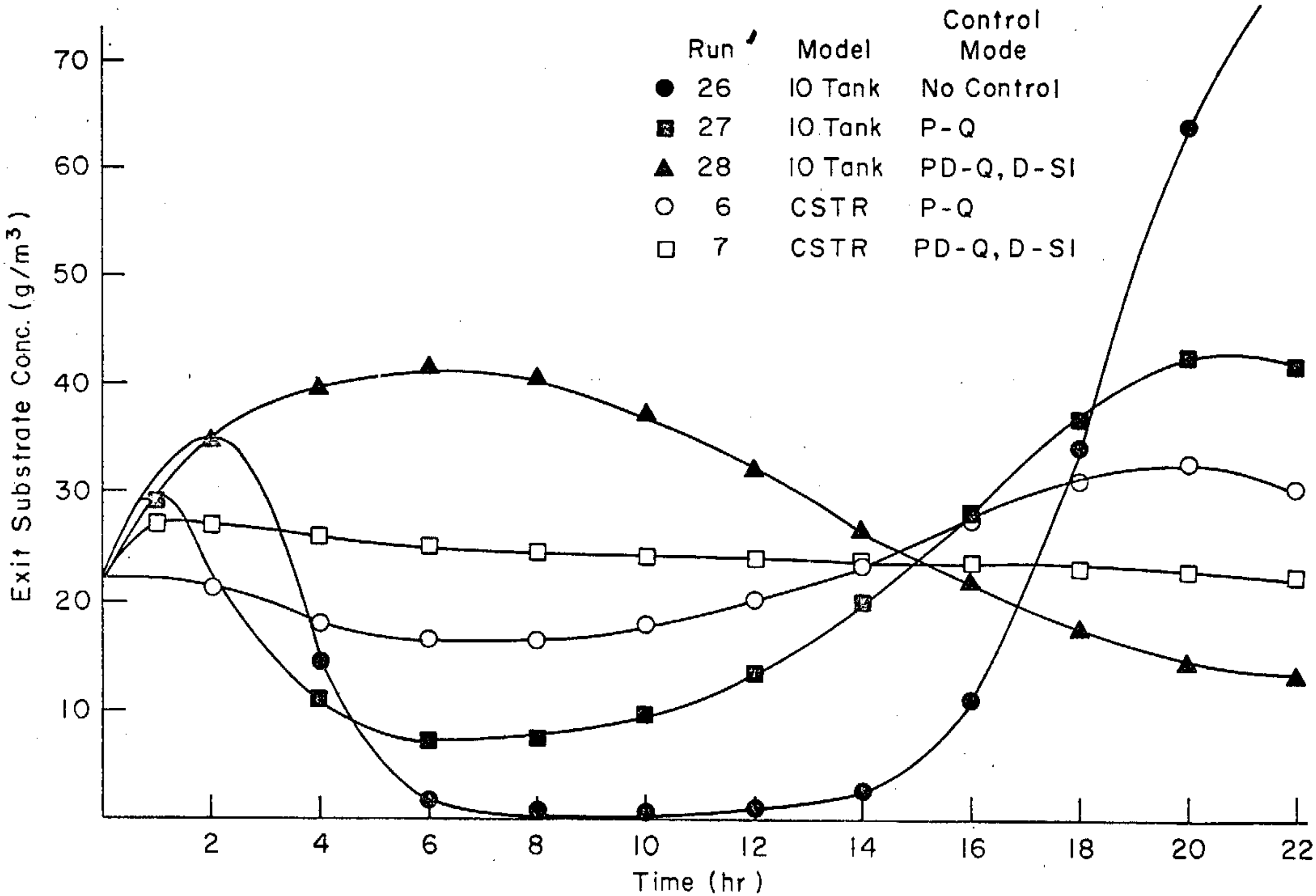

Figure 16. Comparison of Various Control Modes on Lawrence & Mc Carty Mixing Models with 4th Order Forcing Functions.

The second plug flow system tested involved Eckenfelder kinetic expressions with the results summarized in Table VI. Again, the Eckenfelder kinetic terms yielded faster bacterial growth and substrate utilization rates. This resulted in better effluent substrate quality. The effects of various control modes, different forcing functions, and stored sludge availability were similar in runs 33 through 45 to runs 20 through 32; this is evident by comparison of Tables V & VI.

In all the computer simulations, either plug flow or completely mixed with bypass, the results were evaluated by examination of maximum effluent substrate concentrations. Although the maximums presented are accurate representation of the process effectiveness, one should also examine the actual fluctuations occurring throughout the 24 hour period, and selected simulation results are illustrated in Figures 5 through 16.

Plug Flow With Bypass

Again, the values of the process parameters used in the previous two models were kept the same for comparative purposes.

For simplicity, only the three tank plug flow approximation and Lawrence and McCarty kinetics was tested with bypass, the results being shown in Table VII.

The effect of bypass on the 3 tank system can be seen by inspection of Table VII and Figures 17, 18, and 19. The following were a few of the results:

1 - bypass had a definite negative effect on the system as the fraction was increased, except for the no control, sinusoidal case - run 46.

TABLE VI

Results of Feed Forward Control of Eckenfelder, Plug Flow Model

Run No.	Control Q(t)	Mode S (t)	Forcing Functions	Controller Constants	Sludge Storage Available	Effluent Max.	Substrate Min.	N# of Tanks
33	No	No	Sinusoidal	None	Yes	124.8	0.6	3
34	P	No	Sinusoidal	Davis	Yes	41.7	2.6	3
35	PD	D	Sinusoidal	Davis	Yes	35.9	10.0	3
36	No	No	Sinusoidal	None	Yes	143.2	0.1	10
37	P	No	Sinusoidal	Davis	Yes	41.7	1.6	10
38	PD	D	Sinusoidal	Davis	Yes	65.7	6.1	10
39	No	No	4^{th} order	None	Yes	40.0	8.0	10
40	P	No	4^{th} order	Davis	Yes	31.1	15.9	10
41	PD	D	4^{th} order	Davis	Yes	28.7	17.1	10
42	No	No	Phase Diff.	None	Yes	110.4	2.3	10
43	P	No	Phase Diff.	Davis	Yes	44.9	6.7	10
44	No	No	Sinusoidal	None	No	143.2	1.4	10
45	PD	D	Sinusoidal	Davis	No	67.4	10.3	10

TABLE VII

Results of Feed Forward Control

Lawrence & McCarty, Plug Flow with Bypass Model

Run No.	Control Q(t)	Mode $S_i(t)$	Forcing Functions	Controller Constants	Sludge Storage Available	S_s Max $\gamma = 0.0$	S_s Max $\gamma = 0.10$	S_s Max $\gamma = 0.25$	S Min $\gamma = 0.0$	S Min $\gamma = 0.10$	S Min $\gamma = 0.25$
46	No	No	Sinusoidal	None	Yes	348.5	347.9	345.6	1.2	11.8	27.2
47	P	No	Sinusoidal	Davis	Yes	152.9	174.6	206.2	0.3	10.9	27.9
48	PD	D	Sinusoidal	Davis	Yes	45.5	52.5	84.2	4.8	33.4	43.6
49	No	No	4 order	None	Yes	75.0	93.8	120.3	2.3	20.2	48.9
50	P	No	4 order	Davis	Yes	43.6	65.6	98.2	10.9	29.7	58.4
51	PD	D	4 order	Davis	Yes	34.2	52.2	81.0	19.3	42.4	70.5
52	No	No	Phase Diff.	None	Yes	218.6	221.3	225.5	9.2	32.7	66.2
53	P	No	Phase Diff.	Davis	Yes	117.1	137.0	165.6	1.4	12.4	28.8

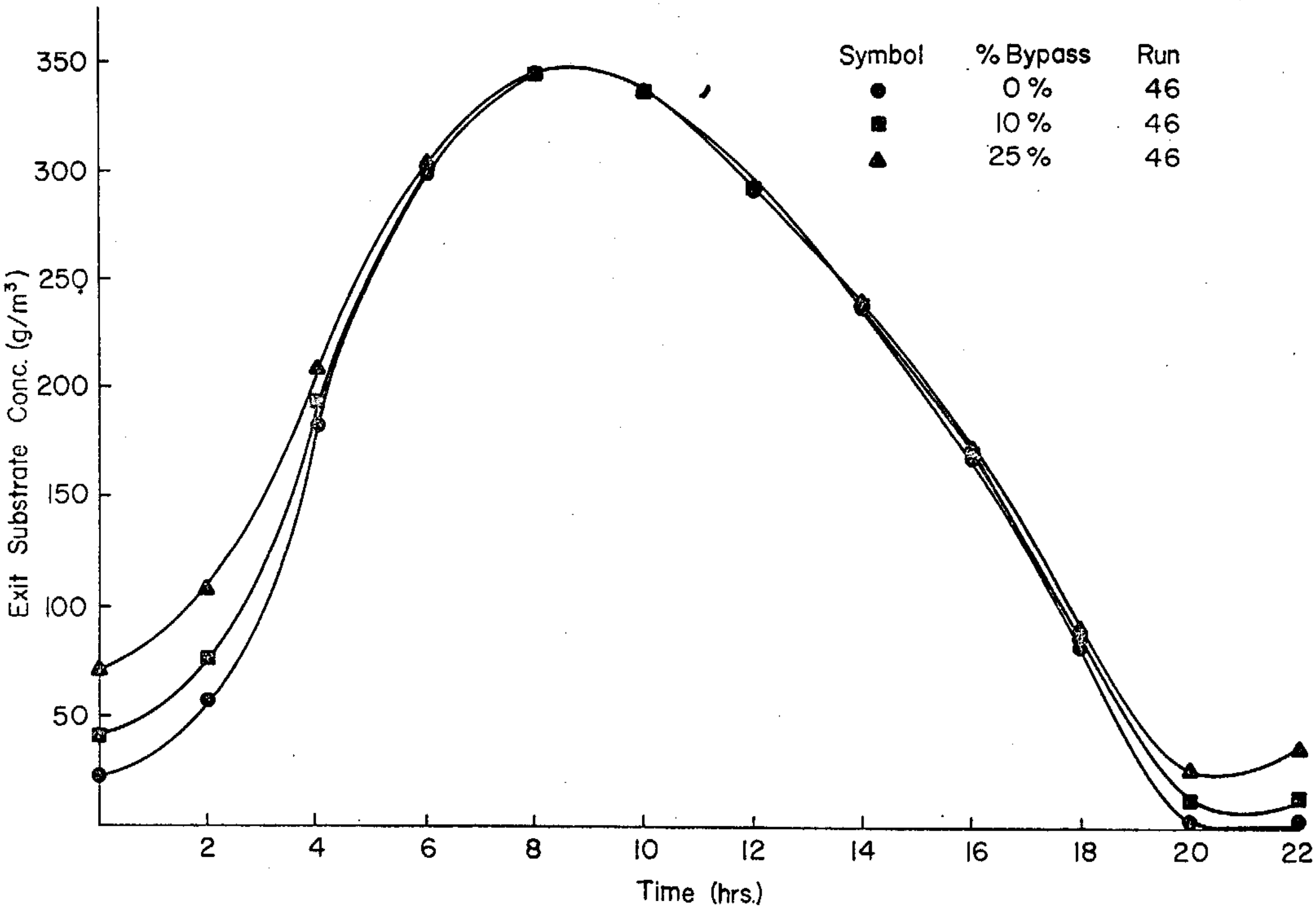

Figure 17. The Effect Of Bypass On Plug Flow - Lawrence & McCarty's Model With No Control.

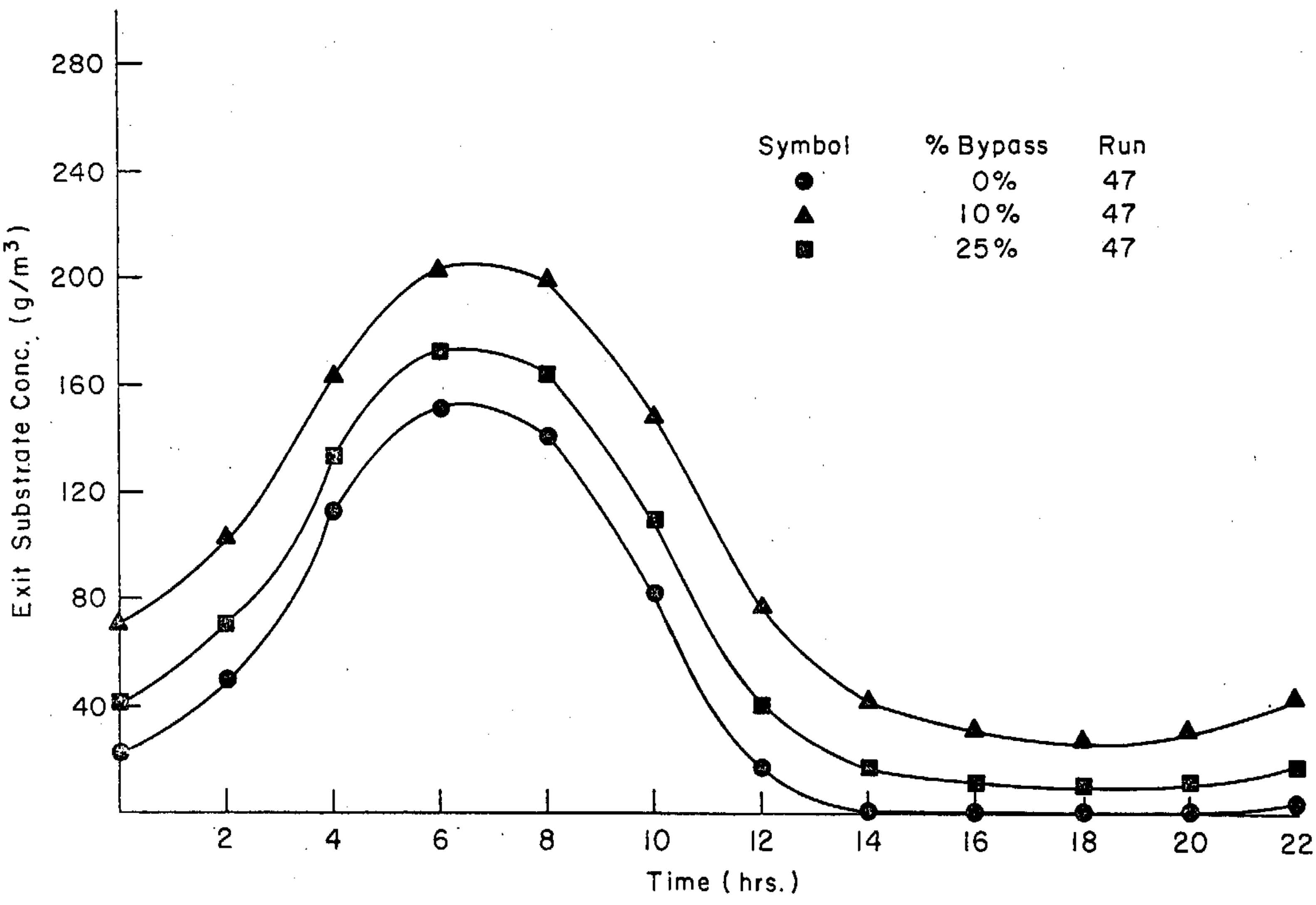

Figure 18. The Effect of Bypass on Plug Flow - Lawrence & Mc Carty's Model with P-Q Control.

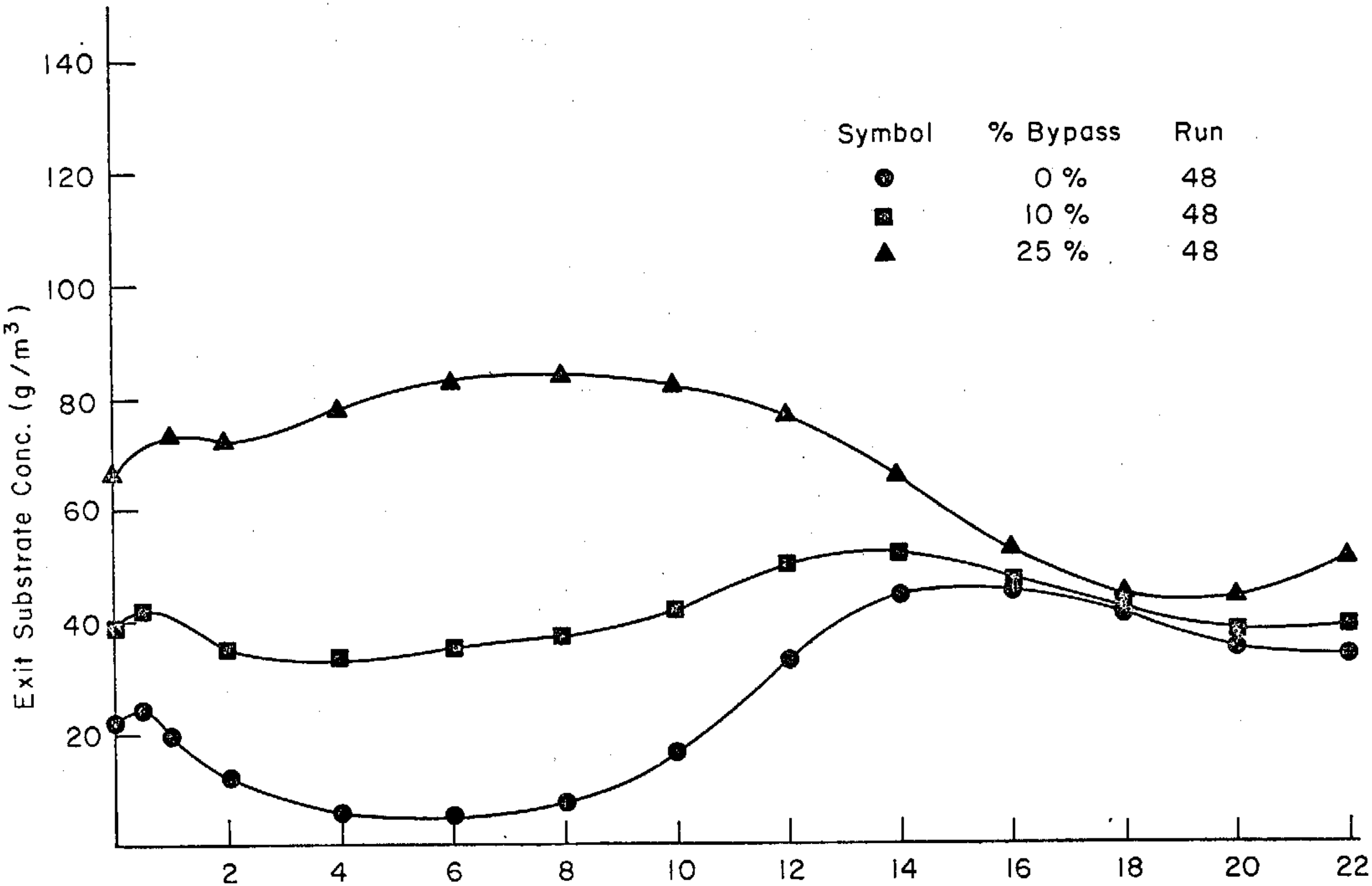

Figure 19. The Effect of Bypass on Plug Flow - Lawrence & Mc Carty's Model with PD-Q, D-Si Control.

2 - bypass had its most drastic effect on the system when the PD-Q, D-S_i control was used.

Comparisons of the negative effects of bypass on the controller operation is shown in Table VIII and can be compared with the completely mixed case.

TABLE VIII

Effect of Bypass on %

Reduction of Effluent Substrate*

Type Control	Bypass Fraction 0%	10%	25%	Aerator Model
P-Q	70	61	48	Completely
PD-Q, D-S_i	92	85	68	Mixed
P-Q	56	50	40	Plug Flow
PD-Q, D-S_i	87	85	76	(3 Tanks)

* Lawrence & McCarty Kinetic Model; Sludge Storage Available; Sinusoidal Forcing Functions.

CHAPTER V

EXPERIMENTAL ANALYSIS

This section involved a study of the secondary treatment operations of the Lexington Municipal Treatment facility. The objectives of the analysis were to establish the most representative kinetic and mixing models, and to develop more realistic time dependent forms of typical inlet flow rate and substrate concentrations.

Lexington Treatment Plant Data Collection

A flow diagram of the activated sludge secondary treatment facility as well as sampling sites is shown in Figure 20. The 10 aeration tanks are situated in parallel, each with a volume of 45,000 ft^3, and each employing diffused air type aerators. The separator is 6 parallel settling tanks with volumes of 31,000 ft^3 each.

On July 1^{st} and 30^{th} data samples were collected for a full 24 hours with the purpose of obtaining diurnal fluctuations of the inlet substrate concentrations (point A), the effluent substrate concentration (point B) and the aerator live bacteria concentration (taken from each tank) for the Lexington plant. Flow rates, Q, q_1, and q_2 were also obtained during the sampling operations from a monitoring station located at the plant. The organic content of the substrate samples was evaluated using the 5-day BOD (BOD_5) test. Biological solids in the aerators was evaluated using the volatile suspended solids test. All laboratory procedures were followed as outlined in Standard Methods[10]. Data obtained from the analysis on the

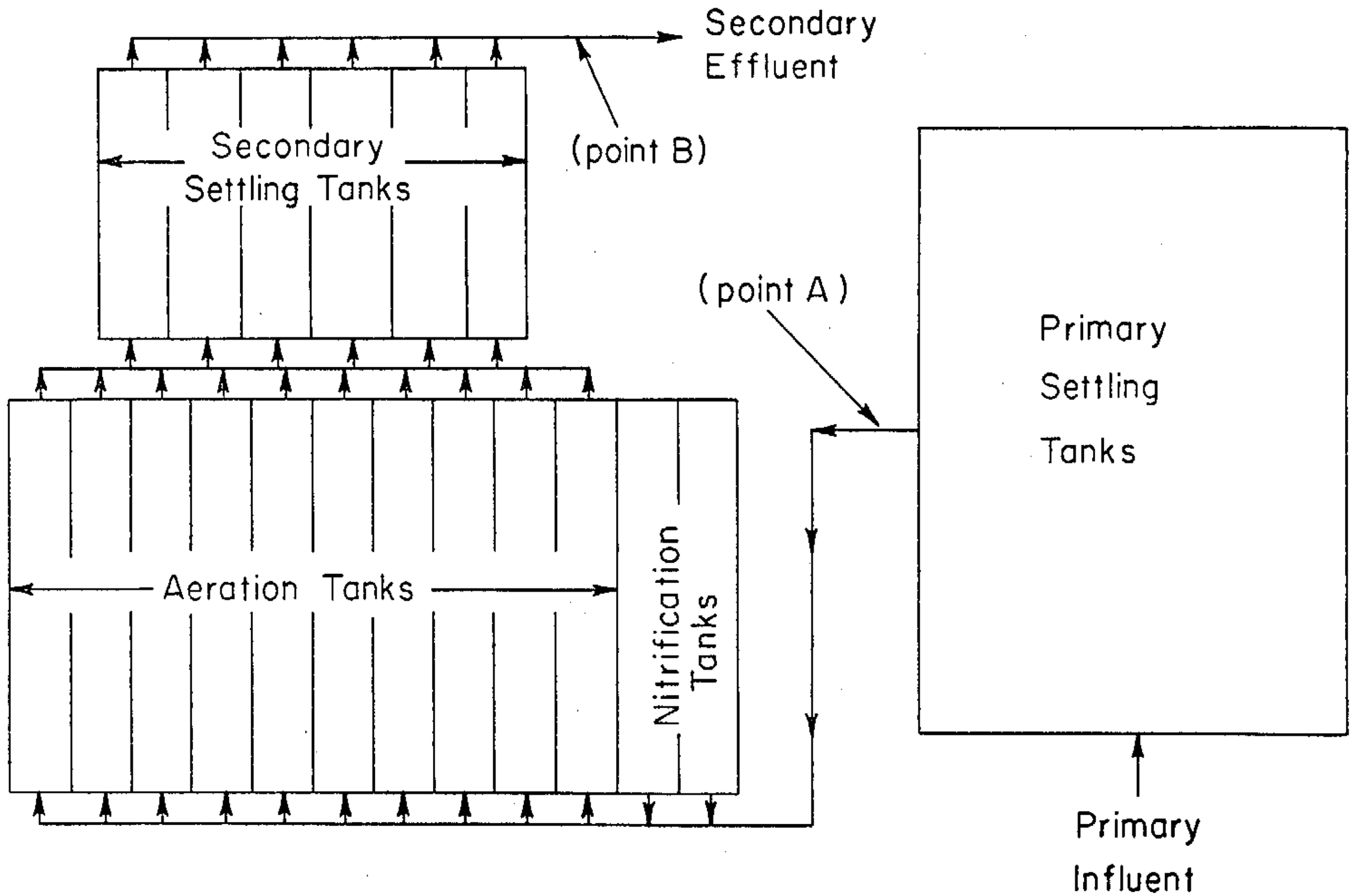

Figure 20. Lexington Secondary Treatment Facility

two different days in July is shown in Tables IX and X. The realistic time dependent forms of inlet flow rate and substrate concentrations could then be developed from this data by approximating the actual fluctuations with 4^{th} order polynomial expressions.

Data Analysis

The next objective was to establish the most representative kinetic and mixing models. The first method tried was an attempt to solve for the kinetic expressions f(S) and g(S) (from Table I) using the simpler CSTR mixing model. This involved solving equations 8 and 9 for f(S) and g(S) using the experimental data for the time dependent parameters and setting the bypass fraction, γ, equal to zero.

$$(\frac{Q}{V})\ S_i - (\frac{Q}{V})\ S - \frac{dS}{dt} = X\ f(S) \tag{24}$$

$$X\ (\frac{Q + q_1}{V}) - \frac{q_1}{V}\ (\frac{Q + q_1}{q_1 + q_2})\ X + \frac{dX}{dt} = X\ g(S). \tag{25}$$

The following assumptions were made:

1. The 24 hour data of bacteria concentration, influent substrate concentration, and effluent substrate concentration could be smoothed out to eliminate data point scatter.
2. $\frac{dS}{dt}$ and $\frac{dX}{dt}$ could be approximated by $\frac{\Delta S}{\Delta t}$ and $\frac{\Delta X}{\Delta t}$ respectively with a time increment equaling one hour.
3. The values of the time dependent parameters Q, q_1, q_2, S_i, S, and X were assumed to vary linearly over the time interval Δt = 1 hour, and that an average value could be assumed for each parameter over that interval.

TABLE IX

Analysis of Secondary Treatment (Lexington Plant) - 7/1/74

Time	BOD (5-day)		MLVSS (mg/l)	Influent Flow (MGD)	Sludge Recycled (GPM)	Sludge Wasted (GPM)
	Influent	Effluent				
6:00 AM	22.7	4.0	1510	11.0	5590	440
7:00	22.9	4.4	1600	13.0	5590	440
8:00	26.5	5.4	1490	16.3	5530	440
9:00	46.0	4.7	1490	18.0	5530	440
10:00	59.0	6.6	1400	20.5	5553	440
11:00	78.2	6.5	1340	21.0	5730	0.0
12:00 noon	106.1	5.8	1450	20.0	5730	0.0
1:00 PM	105.0	7.2	1490	18.4	5730	0.0
2:00	114.0	10.6	1300	19.0	5730	0.0
3:00	114.1	13.1	1540	18.0	5730	0.0
4:00	115.0	13.0	1650	17.5	5730	0.0
5:00	108.4	14.4	1540	17.0	5730	0.0
6:00	91.1	13.5	1830	17.0	5400	0.0
7:00	80.6	13.6	1680	17.0	5290	160
8:00	80.9	----	1710	17.0	5330	130
9:00	71.6	11.1	1690	16.0	5250	350
10:00	78.1	9.9	1920	15.5	5260	340
11:00	82.5	9.7	1750	15.0	5300	300
12:00 mid	78.6	7.3	1640	15.0	5300	300
1:00 AM	65.3	4.0	2210	13.0	5300	300
2:00	58.9	5.4	1750	11.0	5380	220
3:00	49.1	2.9	1770	10.0	5250	410
4:00	46.9	3.5	1810	10.0	5250	410
5:00	44.1	3.0	1790	10.0	5260	400

TABLE X

Analysis of Secondary Treatment (Lexington Plant) - 7/30/74

Time	BOD (5-day)		MLVSS	Primary Ef. Flow	Sludge Recycled	Sludge Wasted
	Influent	Effluent	(mg/l)	(MGD)	(GPM)	(GPM)
6:00 AM	40.3	3.1	2040	5.0	5460	440
7:00	44.2	2.6	1970	10.0	5460	440
8:00	25.9	3.7	2180	14.0	5470	430
9:00	27.3	5.3	1970	16.0	5470	430
10:00	53.7	4.5	1480	17.5	5475	425
11:00	60.4	4.0	1620	16.2	5530	370
12:00 noon	91.7	5.6	1820	17.0	5570	330
1:00	99.0	6.5	1660	16.0	5590	310
2:00	98.1	5.2	1610	16.0	5585	315
3:00	91.9	5.5	1840	15.5	5590	310
4:00	----	4.8	1870	16.0	5350	550
5:00	95.8	5.1	1710	14.0	5360	540
6:00	89.3	6.3	1530	15.0	5360	540
7:00	78.7	6.3	1670	14.0	5360	540
8:00	78.3	3.9	1630	13.5	5360	540
9:00	81.9	4.7	1760	13.0	5360	540
10:00	85.5	3.4	1640	13.5	5370	630
11:00	96.1	3.4	1700	13.0	5370	530
12:00 mid	75.7	4.6	1660	12.0	5370	530
1:00 AM	67.2	2.2	1780	12.0	5370	530
2:00	61.4	3.0	1700	5.0	5360	540
3:00	55.2	4.2	1860	5.0	5360	540
4:00	47.0	5.4	1930	5.0	5360	540
5:00	45.8	---	2020	5.0	5360	540

4. The retention time in the settling tanks was assumed small enough that the substrate levels at point B, (Figure 20), were representative of substrate levels in the aerator at any time, t. This was later verified.

Once values for f(S) and g(S) were obtained for over the 24 hour cycle one could attempt to find the most representative kinetic model. From Table I,

$$f(S) = \left[\frac{kS}{K_s + S}\right] \quad \text{for the Lawrence \& McCarty model,} \qquad (26)$$

$$f(S) = \frac{K_1}{a} S \quad \text{for the Eckenfelder model.} \qquad (27)$$

A plot of Equations 26 and 27 for the two kinetic models is shown in Figure 21. If one plots the values obtained for f(S) versus substrate concentration, S, over the 24 hours one should be able to determine the more representative kinetic model by comparison with Figure 21. A straight line would indicate Eckenfelder kinetics, and an asymptotic line would infer Lawrence & McCarty kinetics. The values of the kinetic constants could be determined from the f(S) vs. S plot, and with the use of an additional plot, g(S) vs. f(S), since with both models this would yield a straight line with the slopes and intercepts giving the remaining kinetic constants.

It should be noted that the values of the kinetic constants k and K_s in the Lawrence & McCarty model are more accurately determined by plotting $\frac{1}{f(S)}$ vs. $\frac{1}{S}$, yielding a straight line with slope = K_s/k and intercept = $\frac{1}{K}$.

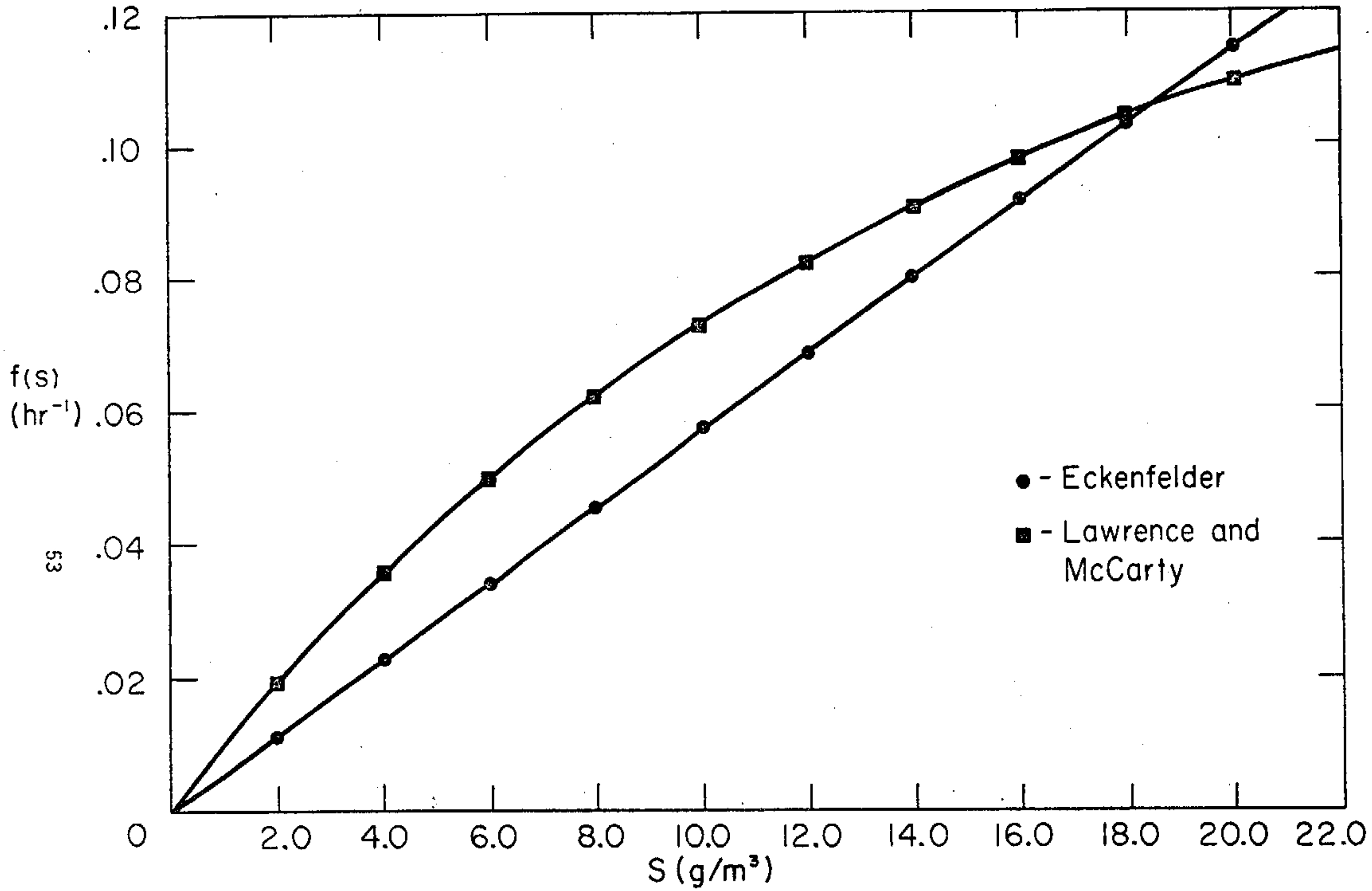

Figure 21. Theoretical Plot of Lawrence and McCarty and Eckenfelder Kinetics.

The second method attempted in the evaluation of a mixing and kinetic model involved the use of computer simulation. The data obtained during the two days in July could be fed into the completely-mixed, plug flow, or completely-mixed with bypass models, and using literature values for the kinetic constants in both kinetic expressions (Table I), one could determine the most representative mixing model by examination of the effluent substrate curve, S, and the live bacteria curve, X. The closer these curves came to the actual curves obtained experimentally would indicate the most representative model, provided the biological kinetics of the actual plant was approximately that described in Table I. The following assumptions were made:

1. The sludge recycle flow rate, q_1, was assumed constant and set equal to its arithmetic mean.
2. The sludge wasting rate, q_2, was also assumed constant and equal to its arithmetic mean.
3. The influent flow rate, Q, and influent substrate concentration, S_i, could be represented by 4^{th} order polynomials as shown in Figure 22.

<u>Experimental and Theoretical Comparison</u>

The 4^{th} order polynomial representation, Equations 41 and 42, of Q and S_i are shown in Figure 22. The coefficients are given in Table XI.

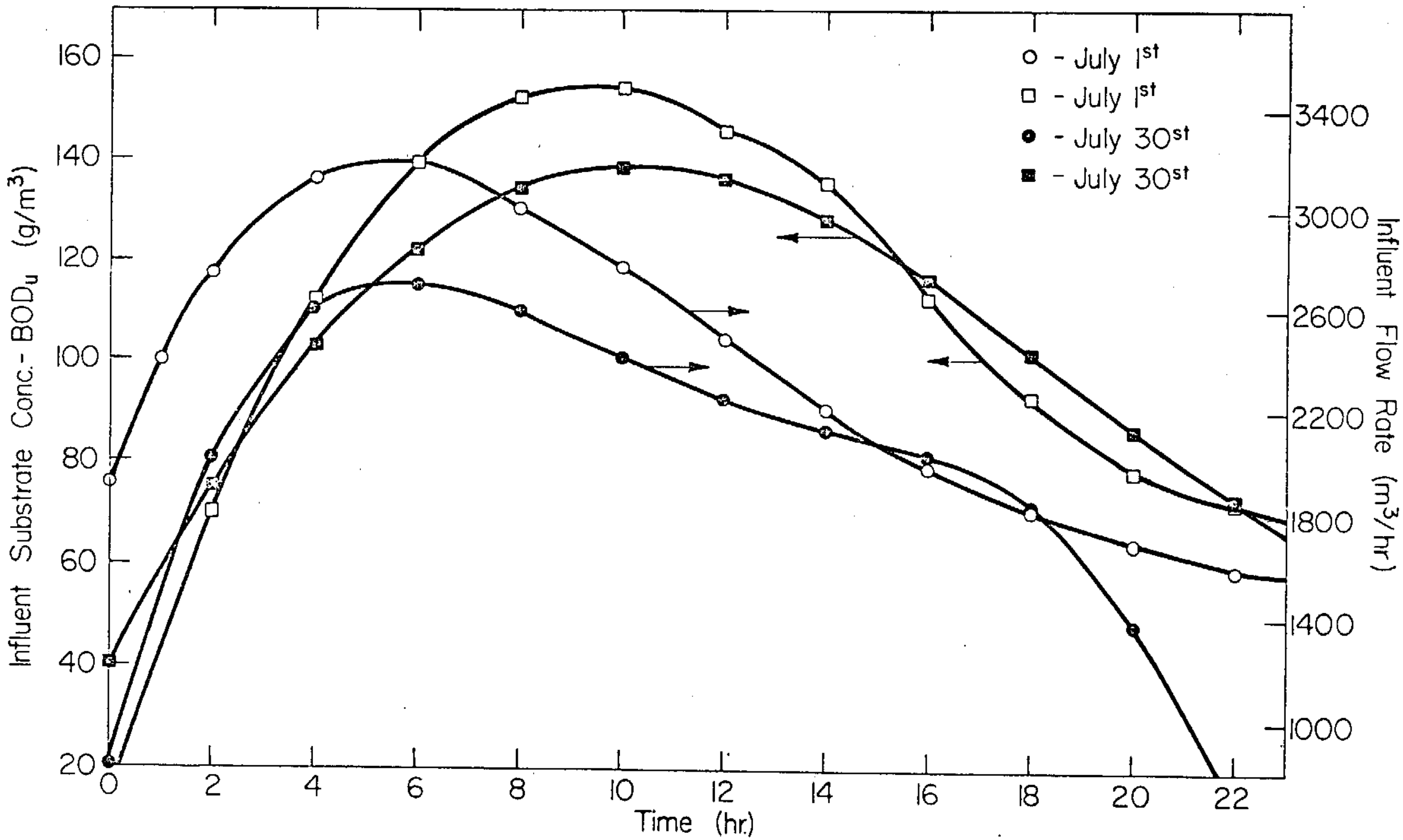

Figure 22. 4th Order Polynomial Approximations of Actual Experimental Data.

Table XI Values of 4^{th} Order Polynomial Coefficients

	July 1^{st}	July 30^{th}		July 1^{st}	July 30^{th}
e_1	1913.395	894.911	f_1	13.179	39.77
e_2	554.21	815.7209	f_2	32.5152	19.3067
e_3	-76.0486	-124.3174	f_3	-1.9729	-0.857
e_4	3.4651	7.3474	f_4	0.000025	-0.01769
e_5	-0.0538	-0.15557	f_5	0.00127	0.000906

The next objective was to find a representative kinetic and mixing model for the activated sludge treatment process. Solutions of equation 24 and 25 gave values of f(S) and g(S) and are listed in columns 1 and 3 in Tables XII and XIII. Columns 2, 3, 5 and 6 list theoretical values of the Lawrence and McCarty or Eckenfelder equations for comparison.

Analysis of columns (2) and (3) in Table XII indicate that both theoretical kinetic models yield approximately the same values for f(S). This can be explained by inspection of Figure 21 as both models converge at the substrate levels experienced on July 1^{st}. However, on July 30^{th} the substrate levels were considerably lower and the two kinetic models predict somewhat different results as seen in Table XIII.

If one compares the experimental values of f(S), column 1, with the previous two columns it is evident that in most cases, $f(S)_{EXP.}$ is approximately one sixth the theoretical values calculated. Possible explanations for these low experimental values could be:

TABLE XII First Method of Analysis - 7/1/74

Column	(1)	(2)	(3)	(4)	(5)	(6)
Time	f(S) EXP.	f(S) L + M^c	f(S) ECK.	g(S) EXP.	g(S) L + M^c	g(S) ECK.
0	.00231	.05123	.03609	.0313	.03141	.0141
1	.00322	.05501	.03958	.000515	.0340	.0154
2	.00610	.05865	.04307	-.00353	.03639	.0168
3	.01151	.06326	.04773	.01168	.03947	.0186
4	.01599	.06765	.05238	.0198	.04242	.02043
5	.01989	.07430	.05995	.0139	.04687	.02338
6	.02127	.08179	.06926	.0239	.05189	.02701
7	.02140	.09179	.08323	.0300	.05859	.03246
8	.02067	.10120	.09837	.0259	.06489	.03836
9	.01965	.10830	.11120	.0253	.06965	.04336
10	.01862	.11210	.11870	.0186	.0722	.04631
11	.01602	.11295	.12050	.0182	.07276	.04699
12	.01384	.11124	.11700	.0119	.07162	.04563
13	.01287	.10797	.11060	.0149	.06943	.04313

TABLE XII First Method of Analysis - 7/1/74 (Cont'd)

Column	(1)	(2)	(3)	(4)	(5)	(6)
Time	f(S) EXP.	f(S) $L+M^c$	f(S) ECK.	g(S) EXP.	g(S) $L+M^c$	g(S) ECK.
14	.01239	.10323	.10190	.0101	.06625	.03972
15	.01211	.09703	.09140	.0234	.0621	.03564
16	.01255	.08982	.08030	.0226	.05727	.03133
17	.01274	.08134	.06870	.0207	.05159	.02679
18	.01103	.06923	.05413	.0205	.04347	.0211
19	.00788	.05982	.04420	.0184	.03717	.01725
20	.00585	.05123	.03610	.01425	.03201	.01407
21	.00493	.04450	.03030	.0228	.02691	.0118
22	.00448	.04100	.02730	.0229	.02456	.0107

TABLE XIII First Method of Analysis - 7/30/74

Column	(1)	(2)	(3)	(4)	(5)	(6)
Time	f(S) EXP.	f(S) L+M^c	f(S) ECK.	g(S) EXP.	g(S) L+M^c	g(S) ECK.
0	.00175	.04294	.02852	-.02830	.02552	.0111
1	.00347	.04727	.03259	-.02610	.02876	.0127
2	.00534	.05123	.03609	-.0102	.03141	.01407
3	.00706	.05501	.03958	-.00958	.03395	.01544
4	.00903	.05865	.04307	-.01071	.03639	.01679
5	.01218	.06198	.04598	-.00343	.03862	.01793
6	.01492	.06438	.04889	-.00020	.04022	.01907
7	.01574	.06493	.04947	.00180	.04059	.01929
8	.01566	.06548	.05006	.00982	.04096	.01592
9	.01574	.06493	.04947	.01695	.04059	.01929
10	.01486	.06383	.04831	.01964	.03986	.01884
11	.01373	.06213	.04656	.02369	.03872	.01816
12	.01280	.05924	.04365	.02527	.03678	.01702
13	.01161	.05563	.04016	.02436	.03436	.01566
14	.01136	.05187	.03667	.02533	.03184	.0143

TABLE XIII First Method of Analysis - 7/30/74 (Cont'd.)

Column	(1)	(2)	(3)	(4)	(5)	(6)
Time	f(S) EXP.	f(S) L+M^c	f(S) ECK.	g(S) EXP.	g(S) L+M^c	g(S) ECK.
15	.01190	.04993	.03492	.02936	.03054	.01362
16	.01209	.04795	.03717	.03827	.02922	.01294
17	.01055	.04592	.03143	.04017	.02786	.01226
18	.00862	.04385	.02968	.04489	.02647	.01158
19	.00538	.04244	.02852	.04056	.02552	.0111
20	.00285	.04100	.02735	.04186	.02456	.01067
21	.00248	.03883	.02561	.05153	.02311	.00999
22	.00237	.03883	.02561	.06005	.02311	.00999

1. The literature values of the theoretical kinetic constants were based on a COD basis; however, the experimental results were based on an ultimate BOD basis. This would tend to lower the theoretical values of f(S).
2. The time lag involved in the clarifiers between the actual substrate level in the aerators and the substrate level at point A where the samples were taken was approximately 2 hours. The detrimental effect of this 2 hour lag was tested by shifting effluent substrate values back two hours. The procedure proved to have negligible effects on f(S).
3. The Lawrence & McCarty and Eckenfelder kinetic models are based on only one limiting concentration, namely the substrate concentration, S. However, actual aeration tanks, especially long narrow tanks, sometimes exhibit oxygen demands greater than D.O. levels present at the inlet section, thus decreasing the substrate utilization and bacterial growth rates with this additional limiting concentration.
4. Experimental error due to faulty sampling procedures and inaccurate laboratory analysis.

Comparison of theoretical versus experimental values of g(S), columns 4, 5 and 6, indicate the following results:

1. The Lawrence & McCarty model predicts larger values for g(S) than does the Eckenfelder model due mainly to the magnitude of its yield coefficient, i.e. y = 0.67 as compared to a = 0.39 for the Eckenfelder model.
2. In most cases, the theoretical models yield larger values for g(S) than those found experimentally. $g(S)_{EXP.}$ is approximately 45% of

that predicted by Lawrence & McCarty's, column (5), and approximately 70% of that predicted by Eckenfelders, column (6).

3. The yield factor, $g(S)/f(S)$, for the experimental figures averaged out to be 1.6 for Table XII and 1.85 for Table XIII. Since these values exceed unity, they had no physical significance.

The next step taken was to make plots of $f(S)_{EXP.}$ versus substrate concentration, S, and $g(S)_{EXP.}$ versus $f(S)_{EXP.}$. Because the kinetic rate constants are based on ultimate BOD, it was decided to convert the measured 5 day values to ultimate values. It was also necessary to plot averaged values of ultimate because derivatives were approximated by letting $\Delta S/\Delta t = dS/dt$, thus the S plotted should be on the half hour not the hour. Finally, this meant that only 23 points could be plotted for a 24 hour period. These plots are shown in Figures 23 through 26.

Inspection of Figures 23 and 9 shows no consistent resemblance to either kinetic model described in Figure 21. The magnitude of $f(S)_{EXP.}$ seemed to depend on some other function in conjunction with S as identical values of S often yielded quite different values for $f(S)_{EXP.}$. The data points are connected to indicate the path of the function over the 24 hour cycle. Figures 24 and 25 also did not yield the expected results, as the data points did not form straight lines with a positive slope. It was concluded that this method was ineffective for the determination of a representative kinetic expression.

The computer simulation results of the second method of analysis in the determination of a kinetic and mixing model are listed in Table XIV.

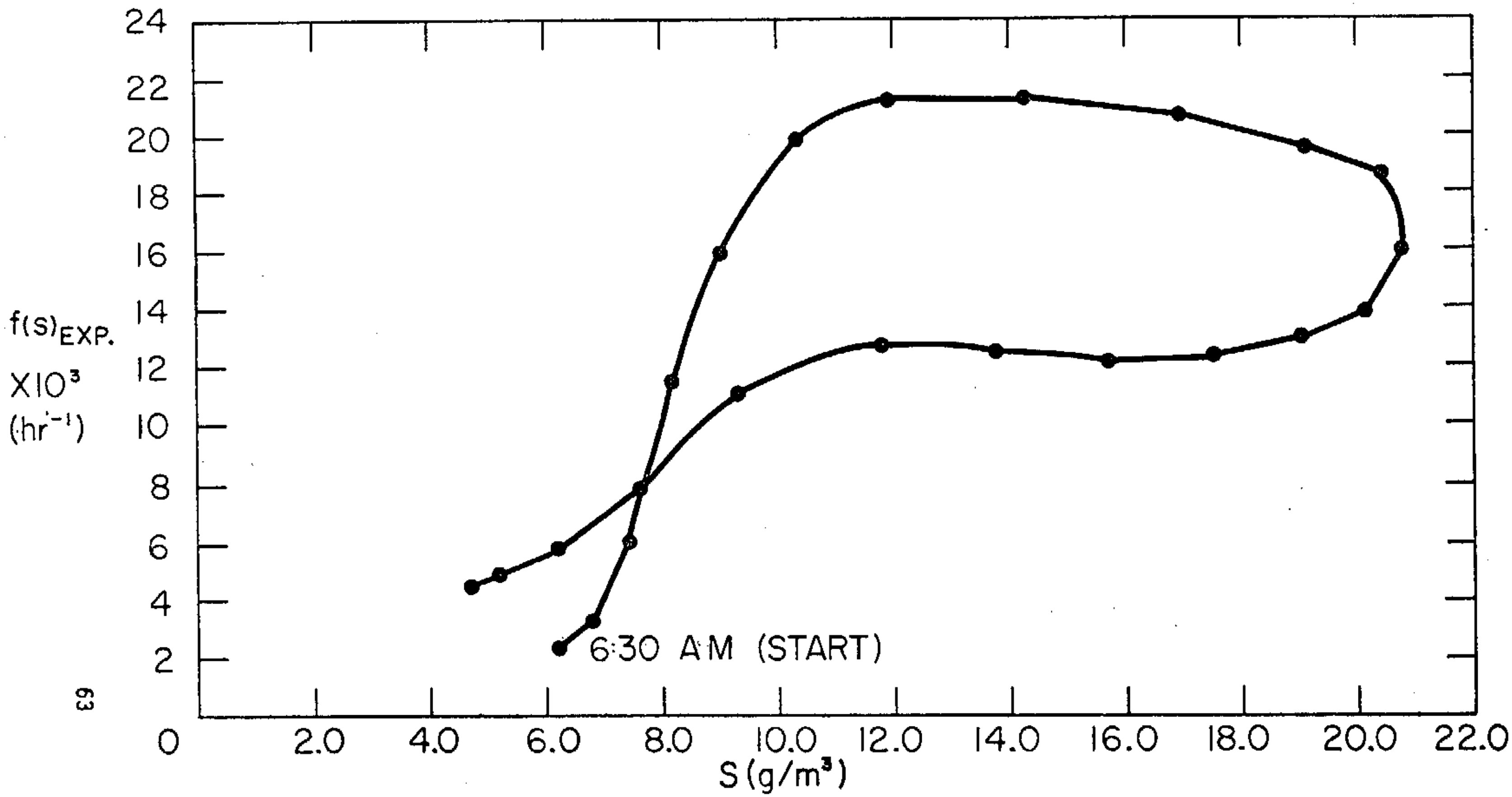

Figure 23. $f(s)_{EXP.}$ vs. Smoothed Ultimate BOD.

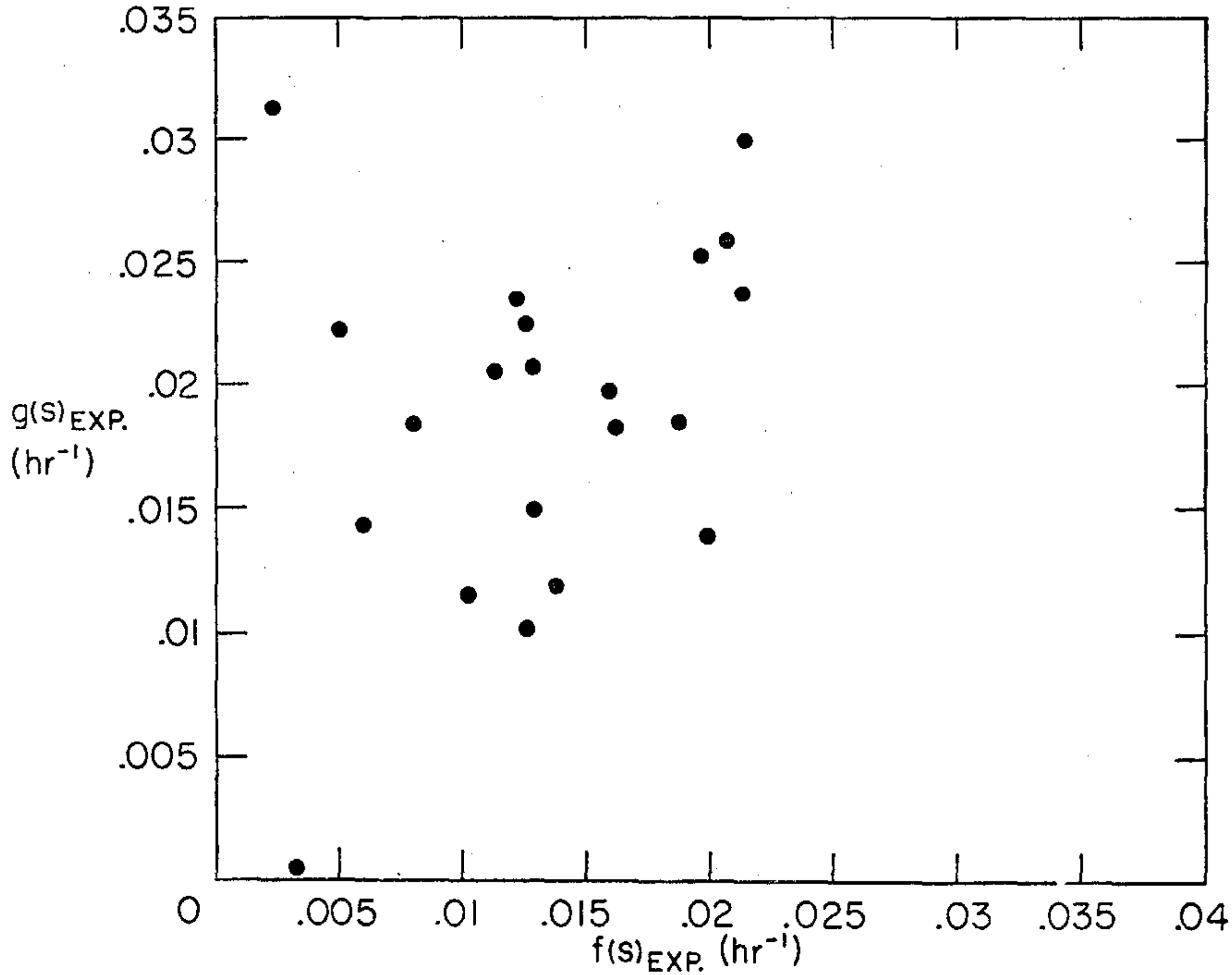

Figure 24. Plot of $g(s)_{EXP.}$ vs. $f(s)_{EXP.}$ – July 1st.

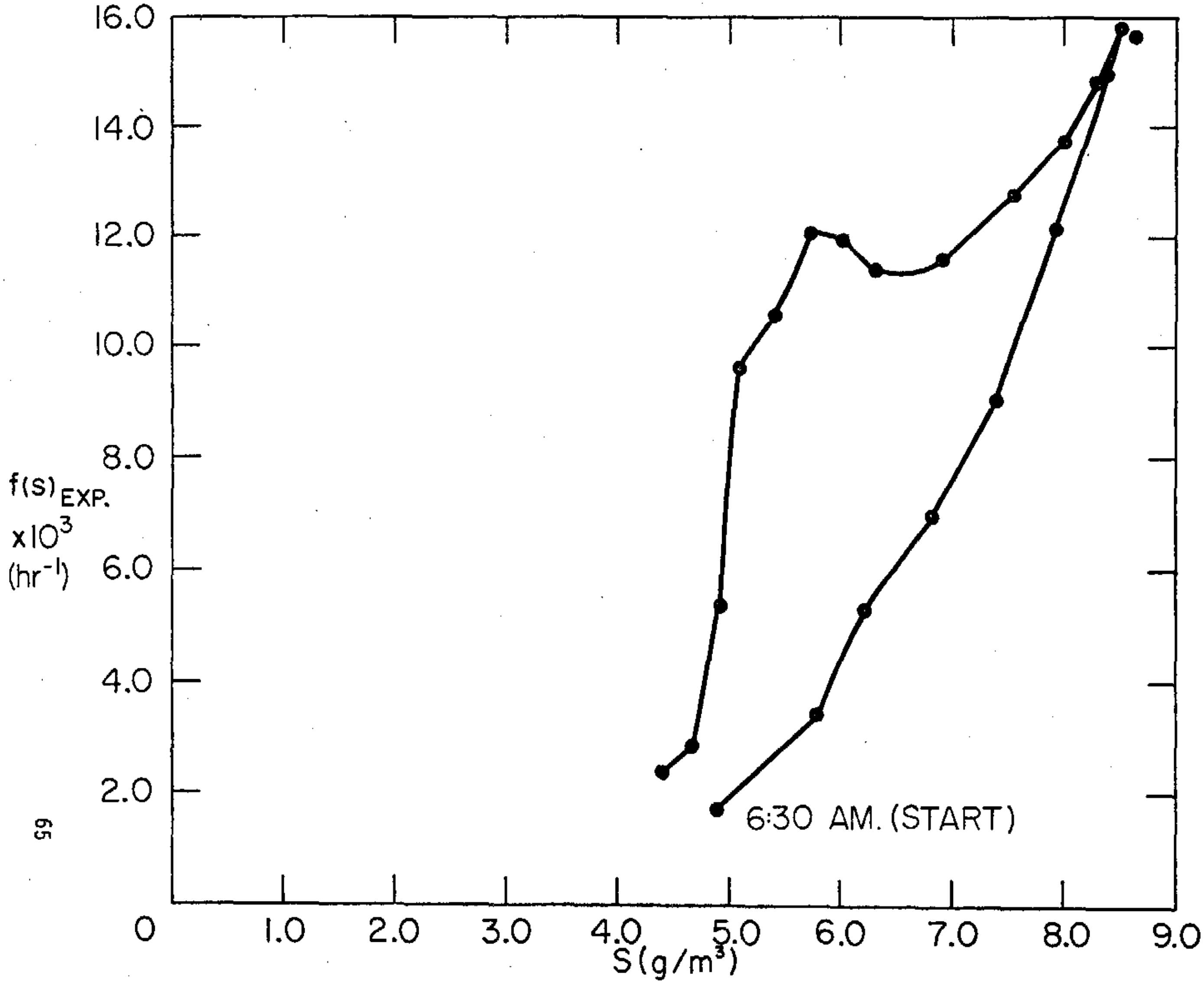

Figure 25. $f(s)_{EXP.}$ vs. Smoothed Ultimate BOD.

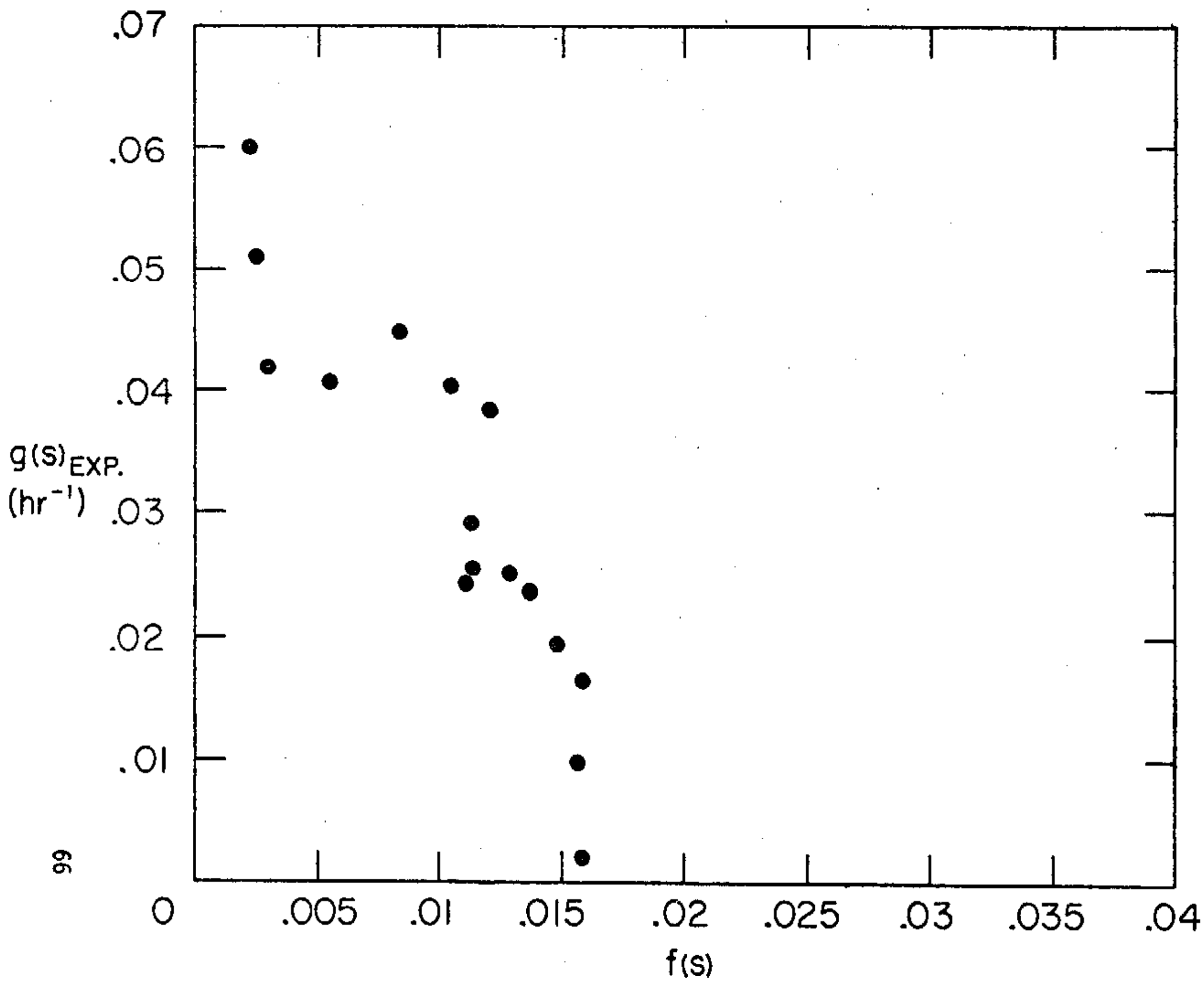

Figure 26 Plot of $g(s)_{EXP.}$ vs. $f(s)_{EXP.}$–June 30th.

TABLE XIV Results of Experimental Computer Simulations

Run #	Kinetic	Forcing Functions	Mixing Model	S_{max}	S_{min}	X_{max}	X_{min}
54	$L+M^c$	July 1	CSTR	6.6	1.1	674.7	629.3
55	EcKN	July 1	CSTR	14.4	3.7	410.7	381.4
56	$L+M^c$	July 30	CSTR	7.1	0.0	483.5	439.6
57	EcKN	July 30	CSTR	14.2	0.0	308.3	286.9
58	$L+M^c$	July 1	Plug flow	1.5×10^{-2}	4.4×10^{-5}	677.3	619.3
59	$L+M^c$	July 30	Plug flow	7.7×10^{-5}	4.3×10^{-10}	173.0	167.5
60	$L+M^c$	July 1	30% bypass	44.2	15.5	370.5	288.5
61	$L+M^c$	July 30	30% bypass	36.9	8.5	334.4	288.0

The first mixing model, the completely mixed tank, was tested in order to compare results with the previous method of analysis. It was observed in runs 54 through 57 and from Figures 27, 28, and 29 that the effects of the theoretical kinetics on the July 1^{st} and July 30^{th} data were the following:

1. Theoretical substrate levels experienced on July 1^{st} and July 30^{th} were approximately the same as those found experimentally and shown in Figure 27.
2. Live bacteria concentrations in runs 54 through 57 were lowered drastically when theoretical kinetics were employed.

The equivalent substrate levels can be explained since the high theoretical values for f(S) multiplied by the low values of X tend to compensate for each other when compared to experimental values and thus the substrate utilization rates, $\frac{dF}{dt}$, are of the same approximate magnitude. However, the low values of theoretical X must first be explained. If one compares the magnitudes of f(S) and g(S) found both experimentally and theoretically in Tables XII and XIII,the reasons become obvious. The experimental values of g(S) are lower than those predicted by Lawrence & McCarty's or Eckenfelder's models, but not as drastic as the differences found for values of f(S). Thus experimentally one has very low substrate utilization but at the same time receives high bacterial growth due to a high yield factor. This results in an abundance of food for the bacterial growth when compared with theoretical food supplies resulting in larger experimental values of X than predicted theoretically.

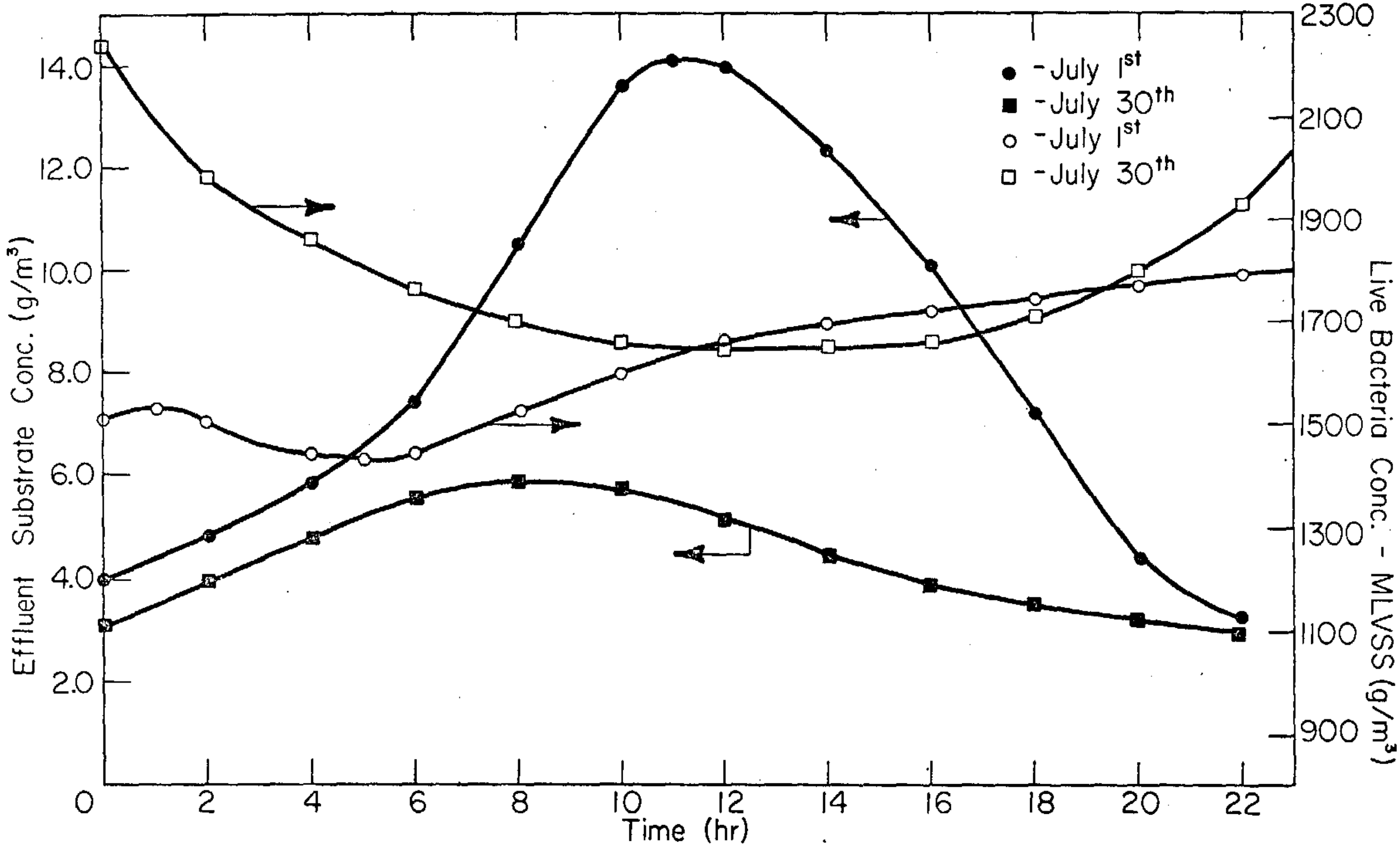

Figure 27. Smoothed Experimental Data of Effluent Substrate and Live Bacteria Concentrations.

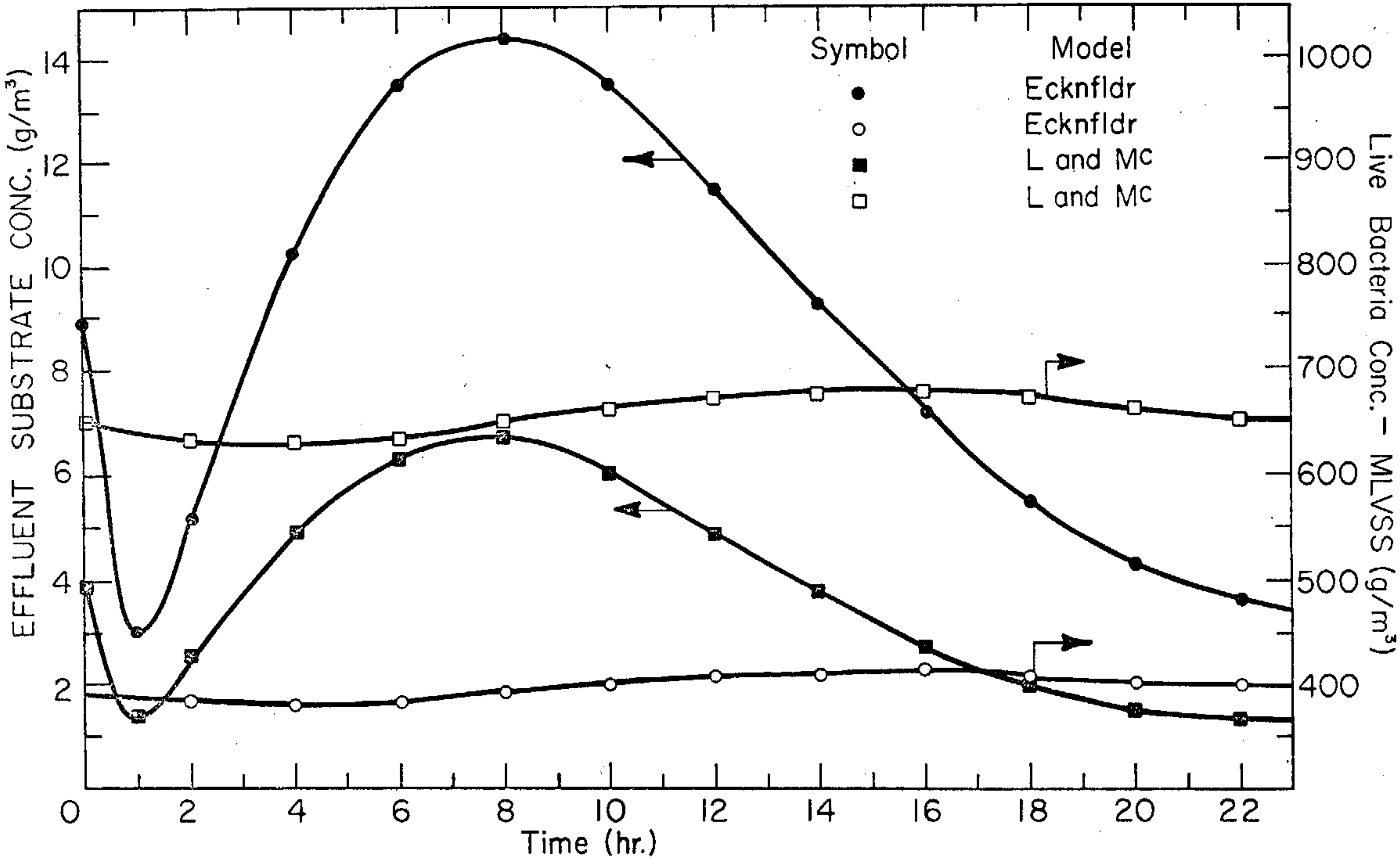

Figure 28. Computer Simulations of July 1st Data using CSTR Mixing Model.

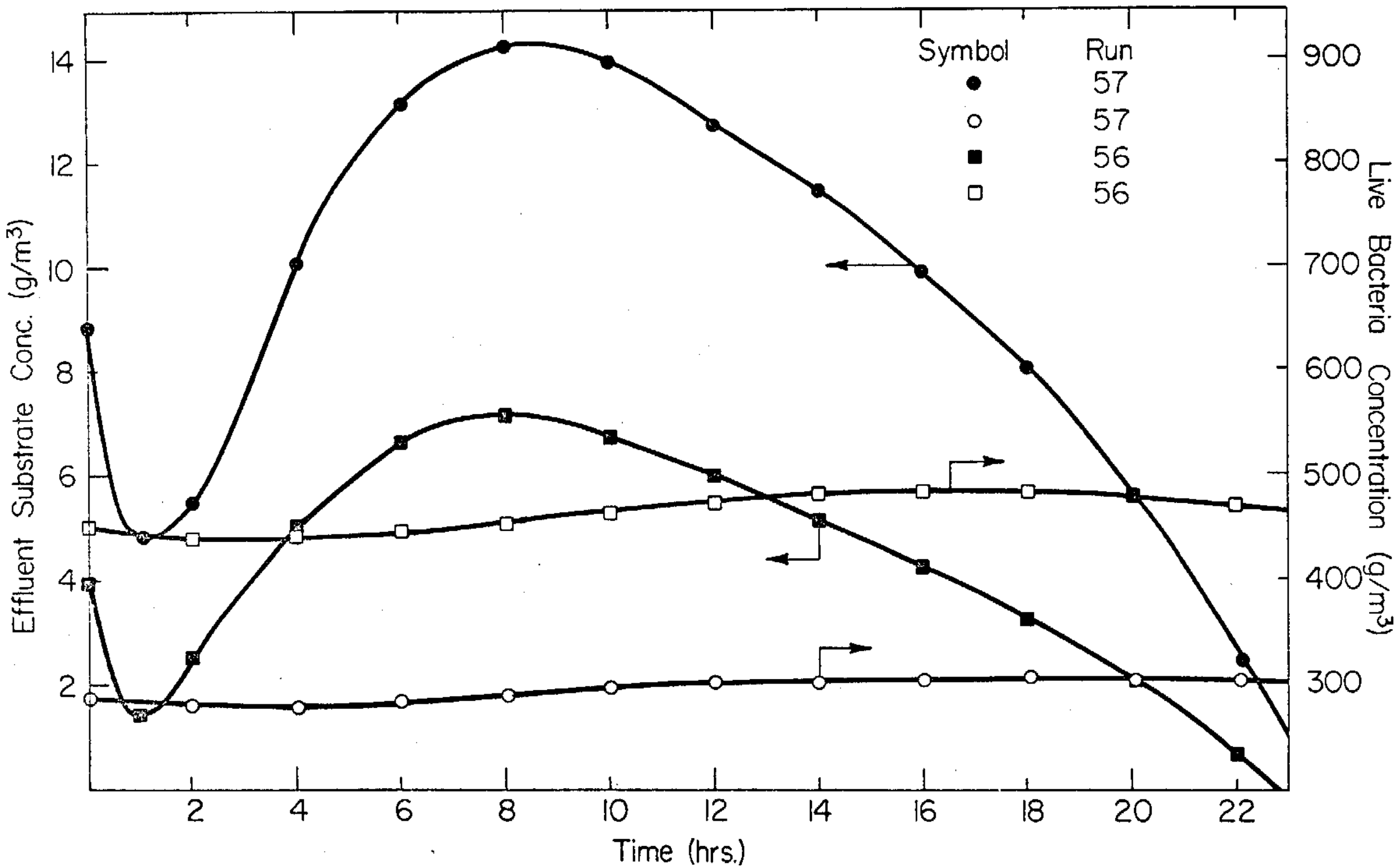

Figure 29. Computer Simulations of July 30th Data using a CSTR Mixing Model.

As expected from examination of Tables XII and XIII the Eckenfelder kinetics, in runs 55 and 57, predict higher effluent substrate concentrations than does Lawrence & McCarty.

Runs 58 through 61 were results of attempts made in search of a more representative model. The 10 tank plug flow model proved to give extremely low values of effluent substrate while sludge concentrations still remained very low. Bypassing a fraction of the inlet stream around a CSTR aerator likewise proved to decrease the sludge concentration as the bypass fraction was increased. The extreme 30% bypass fraction case is shown in runs 60 and 61. It was concluded that none of these mixing models gave satisfactory result in approaching the actual mixing mode at the Lexington facility. Therefore, it seems that either the sampling or laboratory procedures were in error or that the theoretical kinetic rates described in Table I are actually ideal expressions for frequent non-ideal conditions.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. The controller, derived from CSTR with bypass model design equations, was practically identical with that derived for the simpler CSTR model and therefore was independent of the kinetic model chosen.
2. Bypassing a fraction of the inlet stream around the aerator caused deterioration in the controllers effectiveness in controlling effluent quality.
3. Proportional control-flow rate Q was responsible for a large percentage of the controller's effectiveness. This percentage decreased from a CSTR to a plug flow mixing model.
4. When 4^{th} order polynomial forcing functions were employed, the more sophisticated derivative control did not substantially enhance the controller's effectiveness.
5. Sludge storage was not required when the 4^{th} order polynomials forcing functions were employed, or when proportional control on flow rate Q was used.
6. The plug flow model did not receive high substrate loadings as efficiently as did the CSTR model, thus yielding higher effluent substrate concentrations.
7. It was difficult to obtain a representative kinetic or mixing model of a local plant as experimental data did not coincide with theoretical prediction.

Recommendations

The following are recommendations for future research.

1. Continue the computer simulations of the kinetic and mixing models but include more realistic settler dynamics, utilizing information such as that recently given by Roper and Grady.[9]
2. Obtain considerably more experimental data of diurnal fluctuations of activated sludge process parameters in order to successfully find a realistic model for the process.

NOTATION

a	Activated sludge synthesis per removal of substrate for Echenfelder model, dimensionless.
b	Bacteria decay coefficient for the Lawrence & McCarty model, hr^{-1}.
dF/dt	Internal substrate utilization rate per unit volume, $g\,m^{-3}\,hr^{-1}$.
dG/dt	Internal activated sludge synthesis rate per unit volume, $g\,m^{-3}\,hr^{-1}$.
f(S)	Internal substrate utilization kinetic mechanism
g(S)	Internal sludge growth kinetic mechanism
K_c	Gain of PD controller, dimensionless
K_c'	Gain of D controller, $m^3(g\,m^3)^{-1}$
K_s	Half velocity coefficient in Lawrence & McCarty model, $g\,m^{-3}$

K_1	First order growth rate for Eckenfelder model, $m^3 (g\,hr)^{-1}$
k	Maximum rate of substrate utilization per unit wght. of sludge hr^{-1}
MLVSS	Mixed liquor volatile suspended solids
P_{ij}	Transfer function from index i to index j
Q	Influent substrate flow rate, $m^3 hr^{-1}$
q_1	Sludge recycle flow rate, $m^3\ hr^{-1}$
q_2	Sludge wasting flow rate, $m^3 hr^{-1}$
S	Aerator substrate concentration, $g\,m^{-3}$
S_i	Influent substrate concentration, $g\,m^{-3}$
S_N	Effluent substrate concentration from N^{th} tank, $g\,m^{-3}$
S_s	Effluent substrate concentration from bypass model, $g\,m^{-3}$
t	Time, hr.
V	Aerator volume, m^3
X	Concentration of activated sludge in aerator, $g\,m^{-3}$
X_o	Influent concentration of sludge to aerator, $g\,m^{-3}$
X_s'	Sludge concentration in recycle stream, $g\,m^{-3}$
y	Growth yield coefficient for Lawrence & McCarty model, dimensionless

Greek

β	Underflow from settling tank as proportion of substrate influent flow, dimensionless
γ	Percent of aerator inlet stream bypassed, dimensionless
ω	Angular frequency of sinusoidal forcing functions, rad min^{-1}
τ^*	Effective time constant of (P_{24}/P_{34}) expression for CSTR with bypass model, hr^{-1}
τ_D	Derivative time constant of PD controller, hr^{-1}
τ_D'	Derivative time constant of D controller, hr^{-1}

Subscript

ss	Steady state value
a	Average value over one day

Superscript

—	Deviation from steady state value

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