

A LABORATORY STUDY ON AERATED STABILIZATION BASIN OPERATION AT 3°C

by

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B.A.Sc., University of British Columbia, 1969

A THESIS SUBMITTED IN PARTIAL FULFILMENT  
OF THE REQUIREMENTS  
FOR THE DEGREE OF  
MASTER OF APPLIED SCIENCE

in the  
Department of  
Civil Engineering

We accept this thesis as conforming to  
the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

September, 1973

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Date October 9, 1973

## A B S T R A C T

Aerated stabilization basins (ASB), like many other biological treatment systems, demonstrate a temperature dependency. A decrease in treatment efficiency usually results from a decreasing basin temperature and has often been related to a decrease in the reaction rate coefficient,  $K$ . This relationship to the reaction rate may well apply for other treatment systems, but it has not been clearly demonstrated for aerated stabilization basins.

This study develops data on steady-state performance at  $3^{\circ}\text{C}$  in order to present a coherent reference point for future ASB temperature studies and to define performance characteristics at  $3^{\circ}\text{C}$ . The following performance criteria were documented in the study:

1. Substrate removal in terms of filtered substrate removal. (61 - 80 per cent COD removal and 76 - 98 per cent  $\text{BOD}_5$  removal for retention times of 1 - 16 days).
2. System treatment efficiency defined in terms of gross effluent COD and  $\text{BOD}_5$ . (23 - 50 per cent COD removal and 18 - 80 per cent  $\text{BOD}_5$  removal for retention times of 1 - 16 days).
3. Net biological solids production (0.25 lbs/lb  $\text{BOD}_u$  or COD used).
4. Oxygen utilization requirements (0.123 lbs  $\text{O}_2$ /lb COD removed and 0.143 lbs  $\text{O}_2$ / $\text{BOD}_5$  removed for retention times of 2 - 16 days. Endogenous respiration - 0.75 mg/hr/gm MLSS).
5. Nitrogen transformation. (A transformation of Kjeldahl nitrogen in the biological solids to  $\text{NH}_3$  nitrogen in the filtrate was found apparently as a function of retention time).

6.. Post Settling. (One day's aeration with one day settling was found to give equivalent treatment as eight days aeration and one day settling).

Data was obtained at two loadings to provide information on the influence of influent concentration on overall performance.

Established in the experiment was that any of the common mathematical models used to describe ASB operation, McKinney's, Eckenfelder's, or first-order exponential, could predict system treatment efficiency at 3°C for retention times beyond two to four days. It was further shown that only the Chemostat model would describe the substrate removal measured in the study.

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## LIST OF TERMS

ASB	- <i>Aerated Stabilization Basin</i>
BOD <sub>5</sub>	- <i>5 Day Biochemical Oxygen Demand</i>
BOD <sub>u</sub>	- <i>Ultimate Biochemical Oxygen Demand</i>
COD	- <i>Chemical Oxygen Demand</i>
MEAN HYDRAULIC RETENTION TIME	- <i>Theoretical retention time of any given particle; equal to the reactor volume divided by the mean flow rate.</i>
MLSS	- <i>Mixed Liquor Suspended Solids</i>
NUTRIENTS	- <i>Elements in addition to carbon necessary for biological growth; usually refers, but not restricted, to nitrogen and phosphorus.</i>
PER CENT SUBSTRATE REMOVAL	- <i>Percentage decrease in applied substrate measured between the influent and the effluent.</i>
STEADY STATE	- <i>Condition existing in the reactors when there is hydraulic and biological equilibrium.</i>
SYSTEM TREATMENT EFFICIENCY	- <i>Per cent reduction in COD or BOD<sub>5</sub> measured between the influent and effluent; reflects the COD or BOD<sub>5</sub> of generated solids in the effluent.</i>
VSS	- <i>Volatile Suspended Solids</i>

## A C K N O W L E D G M E N T

The author wishes to express his thanks and appreciation to his supervisor, Dr. A. H. Benedict, for his guidance, enthusiasm and patience during the preparation and completion of this study. The author also wishes to thank his wife, Cheryl, and Dr. R. D. Cameron, Liza McDonald, Murray Hendren and Dale Wetter for their help and assistance.

This study was financed through National Research Council Grant, NRC 67-8253.

## CHAPTER I

### INTRODUCTION

#### I.1 GENERAL

The aerated stabilization basin (ASB) as a means of waste treatment was initially developed from the upgrading of waste water holding ponds. Today, however, the ASB treatment system is recognized as having a biological basis. Unlike other biological treatment systems, ASBs do not have the complexities of sludge recycle, which makes them ideal systems for rural industries and communities where land is cheap and operational supervision and available capital are minimal.

Included among the many users of ASBs are numerous communities and industries located in northern areas where severe winter conditions are encountered. ASBs operated in these northern areas have been successful, but they have invariably demonstrated a change in treatment efficiency with a change in basin temperature. It is this change which requires investigation.

Descriptions of lagoons and basins, aerated lagoons, aerobic lagoons, facultative lagoons, oxidation ditches, photosynthetic ponds, and aerated stabilization basins can be found throughout the current literature. Unfortunately, one man's photosynthetic pond has often turned out to be another man's aerated lagoon. Therefore, in an attempt to avoid any semantic difficulties, the treatment system described in this paper, modelled in the laboratory and called an aerated stabilization basin has the following characteristics :

1. The basin is hydraulically completely mixed, with the mean hydraulic retention time equal to the mean cell residence time (sludge age).
2. There is no sludge recycle incorporated into the system.
3. The chemical and biological oxygen requirements of the treatment process are satisfied by mechanical means -- generally, surface aerators, or diffuser systems.
4. Theoretically, there is sufficient energy within the basin to maintain all the solids in suspension. Solids loss occurs only through oxidation or effluent carry-over.

## I.2 RESEARCH OBJECTIVES

The principle objective of this study was to obtain data on the operation of laboratory-scale ASBs at a low operation temperature ( $3^{\circ}\text{C}$ ), and to analyze the performance of these systems in terms of existing mathematical models used to describe ASB operation. To do this, information on five operating parameters was collected: substrate utilization, system treatment efficiency, solids production, nitrogen transformations and oxygen uptake. Of these, the first two were used to evaluate the performance of the laboratory ASBs in terms of the existing mathematical models, while the other data were used to define performance characteristics. In addition information on the settling characteristics of ASB effluent at  $3^{\circ}\text{C}$  was collected.

## CHAPTER II

### LITERATURE SURVEY

#### II.1 GENERAL

The aerated stabilization basin is a recent innovation in the treatment of waste water, having only come into prominence since the early 1960s. It was not until 1959 that turbine aerators were used (21). Since their inception ASBs have been used with some success in northern climates, even though treatment efficiency reportedly decreases during the winter months (34)(42)(43). Today, the ASB is used for treating wastes throughout the industrial segment, from food processing to petrochemical wastes (14) (18). Besselièvre (4) presents an extensive list of references for industrial waste applications of ASB systems.

#### II.2 DESIGN FORMULATIONS FOR SUBSTRATE REMOVAL IN ASBs

Many of the ASBs now in operation developed from overloaded photo-synthetic or facultative lagoons which were modified through the installation of aeration equipment (23)(36). Other basins have been designed empirically using loading guidelines such as 1.7-2.3 lbs BOD/day/1000 ft.<sup>2</sup>, 700 people/day/acre, or 2000 lbs BOD<sub>5</sub>/acre/day for 10 foot depth (16)(8)(28). Today most ASB design manuals (19) (11) follow one or two design models.

The first design model was developed by O'Connor and Eckenfelder (30). For this model substrate removal in a completely mixed basin is described by the following equation:

$$\frac{S_e}{S_o} = \frac{1}{1 + Kt} \quad (1)$$

where

$S_e$  = effluent substrate concentration, mg/l;

$S_o$  = influent substrate concentration, mg/l;

$K$  = reaction rate coefficient, day<sup>-1</sup>;

and

$t$  = mean hydraulic retention time, days.

Equilibrium volatile solids in the ASB are described by the equation

$$X_v = \frac{S_o + aS_r}{1 + bt} \quad (2)$$

where

$X_v$  = volatile solids, mg/l;

$S_o$  = volatile solids in influent waste, mg/l;

$a$  = yield factor, mg volatile solids produced/mg substrate used;

$S_r$  = substrate utilized, mg/l;

$b$  = endogenous coefficient, % loss/mg volatile solids;

and

$t$  = mean hydraulic retention time, days.

In a completely mixed ASB mean hydraulic retention time (basin volume/flow),  $t$ , is equal to the treatment time and the concentration of reactants in the effluent is the same as the concentration in the basin. For a given waste and required soluble effluent concentration the mean hydraulic retention time,  $t$ , and therefore the basin size, can be calculated.



A second design model has been developed by McKinney (19). Unlike O'Connor and Eckenfelder, who assume a pseudo first-order substrate removal, McKinney assumes that all available BOD is metabolized in the first twenty-four hours. He further assumes that the remaining treatment time is used for oxidizing the biological solids produced in utilizing the substrate. The following three equations form the basis of McKinney's model:

$$F = \frac{F_1}{k_5 t + 1} \quad (3)$$

$$M_a = \frac{k_6 F}{1/t + K_7} \quad (4)$$

and

$$F_e = F + k_{10} M_a \quad (5)$$

where

$F$  = unmetabolized waste  $BOD_5$ , mg/l;

$F_1$  = influent waste  $BOD_5$ , mg/l;

$k_5$  = metabolism constant,  $120 \text{ day}^{-1}$  at  $5^\circ\text{C}$  to  $720 \text{ day}^{-1}$  at  $30^\circ\text{C}$ ;

$t$  = mean hydraulic retention time, days;

$M_a$  = active microbial mass, mg/l;

$k_6$  = synthesis constant,  $83 \text{ days}^{-1}$  at  $5^\circ\text{C}$  to  $500 \text{ days}^{-1}$  at  $30^\circ\text{C}$ ;

$k_7$  = endogenous metabolism coefficient,  $0.16 \text{ days}^{-1}$  at  $5^\circ\text{C}$  to  $0.48 \text{ days}^{-1}$  at  $20^\circ\text{C}$  for  $t < 5$  days and  $0.04 \text{ day}^{-1}$  at  $5^\circ\text{C}$  to  $0.12$  at  $20^\circ\text{C}$  for  $t \geq 20$  days;

$F_e$  = effluent  $BOD_5$ , mg/l;

and

$k_{10}$  =  $BOD_5$  proportionality constant,  $\sim 0.6$  dimensionless.

For a given input waste loading and effluent requirement the retention time,  $t$ , is calculated on a trial and error basis.

In addition to the two models described above, three other models have been developed to describe ASB operation; these are the Chemostat Model, the first-order exponential, and a specialized model for pulp and paper wastes.

The Chemostat is a name coined by Novick and Szilard (30) for a single, homogeneous, completely stirred, constant volume, flow through reactor; an ASB. The equation describing the substrate remaining in the Chemostat is the steady-state solution of two equations: the Monod formulation, describing substrate oxidation kinetics, and a differential equation describing reactor hydraulics. The Chemostat model is given by the equation

$$S = \frac{K_s (D)}{\mu_m - D} \quad (6)$$

where

$S$  = substrate concentration in the reactor, mg/l;

$K_s$  = a saturation constant, mg/l (numerically equal to substrate concentration when  $\mu = \frac{1}{2}\mu_{max.}$ ), ( $\mu$  = growth rate);

$\mu_m$  = maximum growth rate constant, days<sup>-1</sup>;

and

$D$  = dilution rate, days<sup>-1</sup> (reciprocal of hydraulic retention time).

The Chemostat Model has not been widely applied to waste treatment systems, although some applications are available.

The fourth model, the first-order exponential, is described by the equation

$$S_e/S_o = e^{-kt} \quad (7)$$

where

$S_e$  = effluent substrate concentration, mg/l;

$S_o$  = influent substrate concentration, mg/l;

$k$  = reaction rate coefficient, days<sup>-1</sup>;

and

$t$  = mean hydraulic retention time, days.

The first-order exponential model is often presented by Eckenfelder (10), but the history or reasoning behind this equation is unknown. It appears to be strictly based on empirical criteria.

The fifth mathematical model is described by the following equations (13):

$$L/L_o = (1 + 0.55t)^{-0.78} \quad (8)$$

for no nutrient addition; and

$$L/L_o = (1 + 0.95t)^{-1.05} \quad (9)$$

for nutrient addition, where

$L$  = effluent BOD<sub>5</sub>, mg/l;

$L_o$  = influent BOD<sub>5</sub>, mg/l;

and

$t$  = hydraulic retention time, days.

This model was developed to describe the treatment of mixed pulp and paper wastes in ASBs, and its use is therefore restricted to the pulp and paper industry. The coefficients were empirically derived.

### II.3 TEMPERATURE COMPENSATION IN DESIGN FORMULATIONS

The temperature dependency of biological systems has been reported by numerous authors (7)(9)(25)(32). O'Connor and Eckenfelder (31) decrease the reaction rate constant in their design model in order to compensate for a temperature drop. This decrease in the reaction rate constant,  $K$ , is related to the drop in temperature by the modified Van't Hoff-Arrhenius equation:

$$K_{T_1} = K_{T_R} \cdot \theta^{T_1 - T_R} \quad (10)$$

where

$K_{T_1}$  = reaction rate constant, days<sup>-1</sup> (at temperature  $T_1$  °C);

$K_{T_R}$  = reaction rate constant, days<sup>-1</sup> (at a reference temperature, normally 20°C);

$\theta$  = temperature coefficient, theta, dimensionless;

$T_1$  = ASB temperature, °C;

and

$T_R$  = reference temperature, °C.

The temperature coefficient,  $\theta$ , is a measure of the sensitivity of a system to temperature change. Reported values of  $\theta$  vary from 1.0 to 1.13, depending on the system in question. The commonly accepted  $\theta$  value for ASBs is 1.035 (7)(9)(37)(42). Table 1 shows a number of the reported  $\theta$  values for ASBs. Commonly assumed values for several other biological treatment systems are also shown (7)(9)(37).

TABLE 1  
TEMPERATURE COEFFICIENTS FOR BIOLOGICAL TREATMENT SYSTEMS

P R O C E S S	$\theta$	TEMPERATURE RANGE	WASTE
ASB	1.035	10-30°C	Cotton textile
ASB	1.046	13-20°C	Domestic sewage
ASB	1.026	2-10°C	Pulp and paper
ASB	1.058	10-30°C	Pulp and paper
ASB	1.16	4-20°C	Fruit processing
Stabilization ponds	1.072-1.085	3-35°C	---
Activated sludge	1.0 -1.041	4-45°C	---
Trickling filter	1.035	10-35°C	---
Aerobic-facultative lagoon	1.06-1.18	4-30°C	---
Extended aeration	1.037	10-30°C	---

McKinney compensates for temperature changes by varying three of the four constants,  $K_5$ ,  $K_6$  and  $K_7$ , used in his design equations. He assumes that the fourth constant,  $K_{10}$  (the ratio of  $BOD_5$  to unit weight of active solids generated), remains constant with temperature at  $\sim 0.6$ .

No information was found on temperature compensation for the Chemostat or first-order exponential models, although for the latter it is assumed that the  $\theta$ -concept can be applied to the reaction rate coefficient,  $k$ .

Eckenfelder (10) developed the following equation for predicting the temperature of ASB contents in terms of ambient air temperature, influent temperature, flow and expected heat loss:

$$T_i - T_w = \frac{(T_w - T_a) f A}{Q} \quad (11)$$

where

$T_i$  = influent temperature, °F;

$T_w$  = mean basin temperature, °F;

$T_a$  = mean air temperature, °F;

$A$  = basin area, square feet,

$Q$  = waste flow, U.S. mgd;

and

$f$  = proportionality factor accounting for heat transfer, surface turbulence, wind and humidity effects (for central United States,  $f \approx 12 \times 10^{-6}$ ) (mgd/ft<sup>2</sup>).

This equation is widely accepted in industry and has been reported to give excellent results (3)(19)(42).

## II.4 TREATMENT EFFICIENCY

Treatment efficiencies have been reported for a number of field and laboratory ASBs operating at cold temperatures and over a range of temperatures.

Carpenter, *et al.* (7) studying five different pulp and paper wastes at retention times of 2.5, 5 and 10 days and temperatures of 2°C, 10°C, 20°C and 30°C, found that treatment efficiency in the 2.5 day reactor increased from 56% at 2°C to 79% at 30°C, while in the ten day reactor treatment efficiency increased from 79% at 2°C to 88% at 30°C. Thus, the overall effect of temperature on treatment efficiency was shown to decrease with an

increase in retention time. Ling (24), studying the treatment of chemical wastes in aerated lagoons, also reported a significant effect of temperature on treatment efficiency which was lessened with increasing retention time.

Timpany, *et al.* (42), studying three full-scale, five-day aerated lagoons treating pulp and paper wastes in northern British Columbia and Alberta, found that treatment efficiency increased 20% for an increase of  $10^{\circ}\text{C}$  in the  $14^{\circ}\text{C}$  to  $30^{\circ}\text{C}$  range.

Bartsch and Randall (3), reporting on the state of the art, showed that for a five-day aerated lagoon system, where some settling was occurring,  $14.4^{\circ}\text{C}$  was a critical temperature as treatment efficiency decreased markedly from 90% at  $14.4^{\circ}\text{C}$  to 55% at  $5^{\circ}\text{C}$ .

Esvelt, *et al.* (14) reported treatment efficiencies for apple processing waste of 84 to 88% at  $4-7^{\circ}\text{C}$  with a retention time of ten to eleven days. Reid (34), studying a basin treating domestic sewage in Alaska, reported that treatment efficiency remained above 80% even though temperatures were near-freezing. Goodrow (20) reported similar results at Regina, Saskatchewan when the treatment basin had an ice-cover.

## II.5 SOLIDS PRODUCTION AND SETTLING

Literature directly pertaining to net solids production in ASBs at cold temperatures is almost non-existent. Goodman (19) shows the endogenous oxidation rate to be decreased at low temperature, as do Esvelt, *et al.* (14); however, most of the information available is general or refers to elevated temperatures. Eckenfelder (10) maintains that the equilibrium solids concentration in an ASB from a soluble feed will be 50% of the influent

BOD concentration. Gellman (17), citing a number of pulp and paper pilot studies at 25-35°C, found that sludge accumulated at a rate of 0.15 to 0.30 pounds per pound of BOD removed. It is not clear from Gellman's paper, or from the pilot studies cited, whether or not these figures refer specifically to net solids production.

Reported values of BOD associated with the bio-solids in ASBs are also of a general nature. Eckenfelder (10) graphs the BOD of the volatile solids vs. sludge age and shows mg of BOD per mg of volatile solids of 0.75 to 0.3 for sludge ages of 0 to 7 days. Goodman (19) shows the BOD per unit of active solids to be 0.6, regardless of sludge age or temperature. Gellman (17), again citing a number of pulp and paper pilot studies at 25-35°C, reports that the solids were well stabilized and the BOD per unit of solids was 0.1 to 0.2 pounds per pound for retention times of four to twenty days. However, it was not clear whether or not influent solids were included in the measurements.

Secondary settling or polishing ponds are commonly used to improve the solids quality of ASB effluents (17)(23)(36), and this in turn provides some improvement in the overall BOD removal. For pulp and paper wastes reported improvements in BOD removal vary with settling from 2-15% for aeration times of two to ten days (1)(7)(35)(46).

## II.6 NUTRIENT REQUIREMENTS

McKinney (27), discussing bacterial synthesis, shows the nitrogen and phosphorus requirements to be 11% and 2.5% of the dry weight of the bacterial cell or, expressed as a carbon:nitrogen:phosphorus ratio, 20:4.4:1. Eckenfelder (10) describes nutrient requirements in biological treatment



systems in terms of the volatile solids concentration by the following two empirical equations:

$$\text{Nitrogen (N)} = 0.12 \Delta X_v + 1.0 \text{ mg/l} \quad (12)$$

$$\text{Phosphorus (P)} = 0.02 \Delta X_v + 0.5 \text{ mg/l} \quad (13)$$

where

$\Delta X_v$  = change in volatile solids concentration, mg/l.

Esvelt *et al.* (14) found that nutrient requirements for fruit processing wastes were a function of BOD concentration and the removal rate constant,  $k$ . This relationship was expressed by the two empirical equations:

$$N/BOD_{\text{removed}} = 0.087 BOD_{\text{conc}} - 0.80 \times 0.087k \quad (14)$$

$$P/BOD_{\text{removed}} = 0.016 BOD_{\text{conc}} - 0.80 \times 0.016k \quad (15)$$

where

$N/BOD_{\text{removed}}$  = lbs nitrogen required/lb BOD removed;

$P/BOD_{\text{removed}}$  = lbs phosphorus required/lb BOD removed;

$k$  = removal rate constant (0.115 at 20°C).

These authors also indicate that temperature had an effect on the nutrient requirements in ASBs.

In the pulp and paper industry, the usual practice has been to describe nutrient requirements in terms of the BOD applied or removed. Eckenfelder (13) reports that for pulp and paper wastes optimum treatment should result from nutrient availability of 4.0 lbs of nitrogen and 0.6 lbs of phosphorus per 100 lbs of BOD removed. Carpenter *et al.* (7) supplied 5 lbs of nitrogen and 1.0 lb of phosphorus per 100 lbs of BOD applied in their study. Blosser (5), studying de-inking and white water waste, also reported nitrogen and phosphorus addition of 5.0 lbs and 1.0 lb per 100 lbs of BOD applied. Amberg (1), reporting on a full-scale mill system, found that a BOD:N:P ratio of 300:7.5:1 was sufficient to support synthesis.

## CHAPTER III

### RESEARCH METHODOLOGY

#### III.1 RATIONALE

The rationale for undertaking this study and therefore the basis of the objectives, stems more from a lack of clarification as to what people have done in the past, rather than a need for investigation of a new system under new conditions. ASBs operating at cold temperatures, and the effect of temperature changes on ASB operation, have been previously studied under both field and laboratory conditions (7)(42)(34). The majority of these studies have been deficient in two areas:

1. The operating conditions under which the studies were conducted have not been specified, i.e., there is no indication as to whether or not steady-state conditions were achieved.

2. There has been no definition of treatment efficiency; i.e., whether treatment efficiency is a measure of substrate utilization or a measure of the decrease in oxygen demand from the influent to the effluent. (The latter term is defined in this paper as system treatment efficiency).

The detailing of steady-state conditions is necessary because all mathematical models used to describe ASB operation are based on the assumption that steady-state conditions exist. Therefore, any study undertaken to evaluate these models must be conducted under steady-state conditions.

The need for a clear differentiation between substrate removal and the decrease in oxygen demand from the influent to effluent in ASBs is perhaps less obvious, but equally important. In treatment systems such as acti-

vated sludge or trickling filters, where there is a removal of biological solids by sedimentation, the difference between per cent substrate removal and the system treatment efficiency may be slight. However, for ASBs where there is a carry-over of biological solids, the numerical difference in the efficiency measurement can be significant. In terms of evaluating design models and predicting ASB operation, it becomes necessary to clearly define what constitutes treatment efficiency.

The models used to define ASB operation (O'Connor and Eckenfelder's, McKinney's, Chemostat, and first-order exponential) are reported to relate substrate utilized or remaining, as a function of a biological reaction rate constant (K) and treatment time (31)(19)(10); yet there has rarely been a clear distinction as to just what has been measured in previous ASB studies.

In addition to the lack of clarification in previous studies, several of the assumptions behind temperature compensation in current ASB design practice are questionable. In order to compensate for an expected decrease in treatment efficiency due to decreasing ASB temperatures, the current practice has been to increase treatment time by increasing the basin volume. The basis of this design practice is that current design models relate substrate removal or substrate remaining to treatment time and a reaction rate constant (K). Theoretically, any increase in substrate remaining due to a decrease in the reaction rate constant can be compensated for by increasing the treatment time. The reaction rate constant at the lower temperature is simply calculated using the modified version of the Van't Hoff-Arrhenius equation, presented earlier:

$$K_{T_1} = K_{T_R} \cdot \theta^{T_1 - T_R} \quad (10)$$

In current design practice, where temperature compensation for ASBs is considered, the following assumptions can be questioned:

1. The design models are applicable over the range of the temperature drop;
2. The biological population described by  $\theta$  does not change, either in population size or in species make-up; and
3. Only the residual substrate portion of the effluent is a function of temperature, i.e., the oxygen demand associated with effluent solids is not considered.

In summary, the rationale behind the objectives of this study were:

1. A need to clearly detail the operation conditions prior to the collection of ASB data, i.e., to establish steady-state operation;
2. A need for a definite differentiation between substrate removal and system treatment efficiency in ASB studies;
3. To question a fundamental assumption of cold temperature operation prediction, i.e., current design models described the operation of ASBs over a broad temperature range; and
4. To question a further assumption that only the residual substrate portion of ASB effluent changed with temperature.

On the basis of this rationale, the study was conducted so that

1. The laboratory ASB systems could function under steady-state conditions;
2. A clear differentiation between substrate utilization and system treatment efficiency existed (this was accomplished by measuring these parameters separately);
3. Sufficient data was collected to evaluate the mathematical models at a cold temperature ( $3^{\circ}\text{C}$ ); and
4. The proportions of the residual substrate and the biological solids could be determined and compared to similar data collected in the  $15 - 25^{\circ}\text{C}$  range.

It should be emphasized that this study was not undertaken to formulate a new model to describe ASB operation at cold temperatures, but simply to evaluate the existing models using data collected at 3°C under controlled steady-state conditions.

The nitrogen, oxygen uptake, and settling data were collected and are presented as general information for ASB operation at a cold temperature (3°C).

### III.2 GENERAL PROCEDURE

In order to develop experimental data on ASBs operating at a cold temperature, laboratory-scale continuous flow ASBs (operating at hydraulic retention times between one and sixteen days) were maintained at a controlled temperature of 3°C over a four month period. The reactor contents were fed a synthetic waste of powdered skim milk and tap water at two concentration levels: 630 mg/l COD and 1,240 mg/l COD. (Equivalent to 290 mg/l and 800 mg/l of BOD<sub>5</sub>, respectively).

The reactors were monitored for COD, MLSS and Kjeldahl nitrogen following start-up to determine when steady-state operation was achieved. Considerable effort was expended on maintaining a constant hydraulic and applied load to the reactors so that ideal steady-state conditions were approached. Attainment of steady-state was verified through the measured stabilization of the substrate concentration, effluent quality, total nitrogen concentration or solids concentration.

Once steady-state was attained, a full testing program consisting of COD, BOD<sub>5</sub>, Kjeldahl nitrogen, organic nitrogen, ammonia nitrogen, nitrate nitrogen, and MLSS analysis was started. The ASBs were operated at each of the two

loadings until sufficient data on substrate utilization, system treatment efficiency, solids production, nitrogen usage and oxygen uptake were collected. Batch settling tests were conducted following the completion of the continuous flow studies to evaluate the settling characteristics of the ASB effluent at 3°C.

### III.3 EQUIPMENT

A schematic of the laboratory's ASB system is shown in Figure 1.

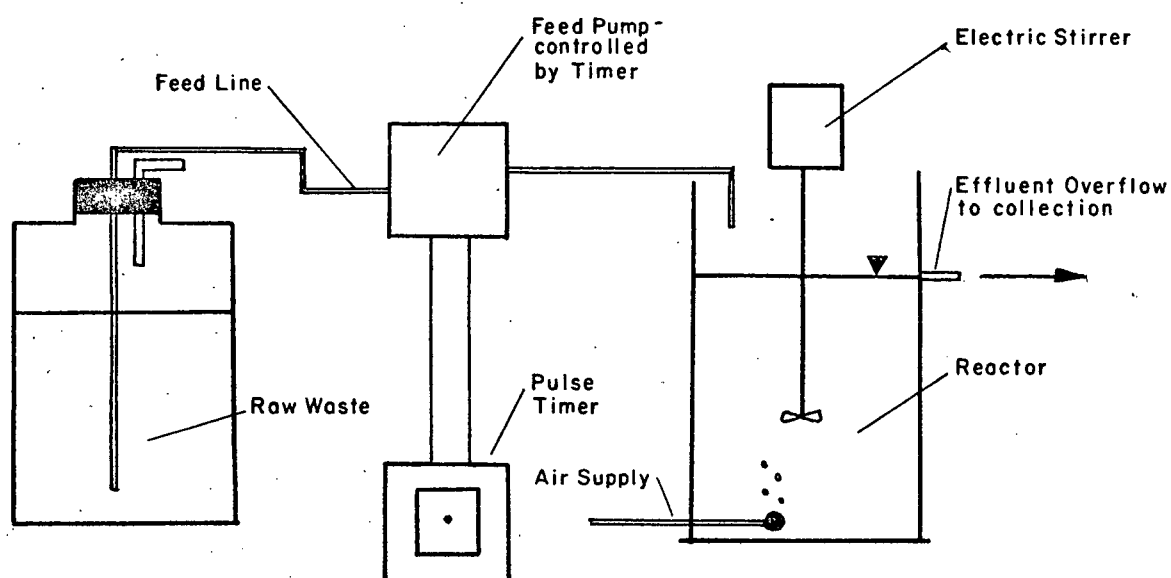


FIGURE 1 SCHEMATIC OF MODEL ASB

As shown in Figure 1, raw milk waste was fed to the ASB reactor by a precision volume pump which was controlled by a pulse timer. The reactor contents were kept completely mixed by an electric mixer and were aerated by diffusers. The reactors were plexiglass cylinders, capped at one end, and tapped along the sides so that the effluent would overflow into calibrated containers. The one-day reactor had a volume of 8.7 liters; the other four were nominally 20 liters. The experimental apparatus was contained within a walk-in temperature room set at  $3^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$ .

The feed for the two, four, eight and sixteen day reactors was pumped from a single 20 liter carboy, the contents of which were prepared and changed daily, Monday to Friday. The one day reactor was fed from another carboy which was refilled every other day. Feed was maintained over the week-ends by syphoning from additional carboys.

The carboys were stoppered and the air vents were plugged with cotton. Consequently, the build-up of bacterial solids in the feed bottles and feed lines was not a problem.

In order to achieve steady-state conditions in the reactors, the hydraulic and applied load to each unit had to be maintained at a steady value. As the concentration of the synthetic waste feed was easily controlled in preparation, both the hydraulic and applied load could be maintained at a fixed level by controlling the pumping rate.

The flow through each reactor was collected in calibrated containers and was checked daily. The pump flows were checked periodically using a graduated cylinder. Evaporation in the temperature room was found to be negligible.

Over the period of the study, the flows through the reactors were reasonably constant, as shown in Table 2. Listed in Table 2 are the

nominal hydraulic retention times, the mean hydraulic retention times (reactor volume/mean flow) and the standard deviation about the mean hydraulic retention time for the five reactors.

TABLE 2  
REACTOR HYDRAULIC RETENTION TIME

NOMINAL H.R.T., DAYS	MEAN H.R.T., DAYS	STANDARD DEVIATION H.R.T., DAYS
1	1.0	±0.11
2	1.97	±0.13
4	3.96	±0.24
8	8.6	±0.26
16	16.7	±1.05

The nominal hydraulic retention times are used in the discussion of reactor performance; however, the mean hydraulic retention times, as listed in Table 2, were used in all calculations and graphs.

#### III.4 SUBSTRATE

The substrate used in the experiment was a synthesized mixture of powdered skim milk and aged tap water. An analysis of the raw milk waste is given in Table 3.

The concentration of phosphorus and nitrogen in the milk, in the ratio of 100:7.5:1 ( $BOD_5:N:P$ ), was more than sufficient to supply any biochemical needs, assuming that both nutrients were in a readily useable form for the organisms.



TABLE 3  
ANALYSIS OF POWDERED MILK WASTE

---

1000 mg/l Mixture (Initial Analysis)

Phosphorus	7 mg/l
Inorganic carbon	3 mg/l
Organic carbon	43.2 mg/l
Organic nitrogen	52 mg/l
Inorganic nitrogen	0.0 mg/l
COD	1048 mg/l
BOD <sub>5</sub>	690 mg/l
BOD <sub>u</sub>	850 mg/l
Suspended solids (Gooch)	0.0 mg/l
Filtrable solids (Whatman #4)	0.0 mg/l
Filtrable solids (Millipore)	0.0 mg/l
	0.45 $\mu$ ) 0.0 mg/l
BOD <sub>5</sub> : Nitrogen:Phosphorus	100:7.5:1

600 mg/l Mixture (First Loading)

Organic nitrogen	30 mg/l
Inorganic nitrogen	0.3 mg/l
COD	630 mg/l
BOD <sub>5</sub>	290 mg/l

1200 mg/l Mixture (Second Loading)

Organic nitrogen	65.0 mg/l
Inorganic nitrogen	1.0 mg/l
COD	1240 mg/l
BOD <sub>5</sub>	800 mg/l

---

Also from Table 3, it can be seen that the COD/BOD<sub>u</sub> ratio is 1.25, which means that 80 per cent of the measured COD is biodegradable. The COD: BOD<sub>5</sub> ratio (high loading) of 1.53 falls within the reported COD/BOD<sub>5</sub> range for actual dairy wastes (38).

Typical physical and chemical characteristics of the Vancouver tap water, as determined by the Greater Vancouver Water District, are shown in Table 4 (47).

TABLE 4  
GREATER VANCOUVER WATER DISTRICT  
PHYSICAL & CHEMICAL ANALYSIS OF WATER SUPPLIES

CAPILANO INTAKE	
Appearance	Clear
Odour	Nil
Turbidity	0.4
pH	6.4
Total residue	17.5 ppm
Total fixed residue	9.6 ppm
Total volatile residue	7.9 ppm
Total alkalinity as $\text{CaCO}_3$	2.7 ppm
Total hardness as $\text{CaCO}_3$	4.6 ppm
Chloride as Cl	0.3 ppm
Sulphate as $\text{SO}_4$	1.7 ppm
Fluoride as $\text{F}^-$	Less than 0.05 ppm
Silica as $\text{SiO}_2$	3.2 ppm
Ammonia as $\text{N}^-$	Less than 0.01 ppm
Nitrate as N	Less than 0.1 ppm
Nitrite as N	Less than 0.002 ppm
Copper as Cu	Less than 0.02 ppm
Total Iron as Fe	0.09 ppm
Dissolved Oxygen	11.7 ppm
Specific Conductance in micromhos/cm at 25°C	13.7

Powdered milk was used in synthesizing the raw waste for the following reasons.

1. The waste would contain only a soluble and colloidal portion.
2. The feed mixture would pass through a 0.45 filter without a loss of colloidal solids, yet any biosolids in the effluent could be removed by this filtration. The residual substrate

concentration could then be determined using normal analytical techniques for COD or BOD<sub>5</sub>; a simple subtraction from the COD or BOD<sub>5</sub> feed concentration would give substrate utilization.

3. The milk solids would pass through a gooch crucible and glass filter; therefore the mixed liquor suspended solids determination would not be affected.

4. The mixture is representative of an industrial dairy waste.

### III.5 ANALYTICAL PROCEDURES

All of the analytical procedures used in this study, with the exception of the oxygen uptake rates, were as outlined in *Standard Methods*, Thirteenth Edition (40). Analyses were made on two types of sample: filtered effluent and gross effluent. The filtered samples were free of bacterial solids and contained only residual soluble and colloidal substrate. These samples were prepared in the following manner:

1. An aliquot of the reactor contents was centrifuged for 20 minutes at 2000 rpm to remove coarse solids.

2. The centrate was filtered through a gooch crucible and glass filter, yielding a rough filtrate.

3. The rough filtrate was passed through a 0.45 millipore filter, to remove bacterial cells and provide a sample having only substrates.

The gross effluent samples were unaltered samples of the reactor contents.

The following analyses were carried out on a continuing basis throughout the study.

#### 1. Chemical Oxygen Demand (COD) on:

(a) Feed: for the determination of influent oxygen demand.

(b) Reactor contents, gross: for the determination of system treatment efficiency.

- (c) Reactor contents, filtered: for the determination of substrate utilization.
  - (d) Settled effluent: for the determination of system treatment efficiency with post settling.
2. Biochemical Oxygen Demand -- 5 Day ( $BOD_5$ ) on:
- (a) Feed: for the determination of influent oxygen demand.
  - (b) Reactor contents, gross: for the determination of system treatment efficiency.
  - (c) Reactor contents, filtered: for the determination of substrate utilization.
3. Mixed Liquor Suspended Solids (MLSS) on:
- (a) Reactor contents, gross: for the determination of reactor solids concentration.
  - (b) Settled effluent: for the determination of suspended solids level in the settled effluent.
4. Kjeldahl Nitrogen on:
- (a) Feed: for the determination of the total nitrogen concentration in the feed.
  - (b) Reactor contents, gross: for the determination of the total nitrogen concentration in reactors.
5. Organic and Ammonia Nitrogen on:
- (a) Feed: for the determination of organic and ammonia nitrogen level in feed for comparison with total Kjeldahl.
  - (b) Reactor contents, filtered: for the determination of organic and ammonia nitrogen level in filtrate, in order to calculate the nitrogen content in the biological solids.
6. Nitrate Nitrogen on:
- (a) Feed: for the determination of the background nitrate level.
  - (b) Reactor contents, filtered: for the determination of nitrification.
7. pH:
- The pH of the reactor contents was determined periodically.

8. Settling:

At the completion of each loading run, batch settling tests were conducted at 3<sup>0</sup>C using Imhoff cones.

9. Oxygen Uptake:

The oxygen uptake rates were determined using a YSI Model 51 dissolved oxygen probe. The probe was calibrated periodically against a Winkler determination.

## CHAPTER IV

### RESULTS AND DISCUSSION

#### IV.1 GENERAL

The performance characteristics of the laboratory ASB systems operating at 3°C are presented and discussed in this section in terms of present-day knowledge of ASB operation. The data points presented are mean values collected over the several weeks of steady-state operation. Variations about the mean of the suspended solids values are presented due to large fluctuations.

The criteria used in determining steady-state operation, and the results from the batch settling tests are also presented. The raw steady-state data are presented in Appendix A.

#### IV.2 CRITERIA FOR STEADY-STATE OPERATION

Steady-state operation implies that both hydraulic and treatment equilibria have been reached. In a completely mixed, flow through system, such as that used in this study, one criterion for steady-state operation is that the solids level in the basin reaches a stable concentration. At that point, biological solids wash-out equals the net solids production from substrate utilization. Steady-state operation can also be documented by the stabilization of either substrate removal or system treatment efficiency at hydraulic equilibrium.

##### IV.2.1 Low Loading Study

Steady-state conditions were achieved at the low loading ( $BOD_5 = 290 \text{ mg/l}$ ) twenty-four to twenty-seven days after continuous flow operation was

initiated, as shown in Figure 2 for the 16-day reactor. At this point the Kjeldahl nitrogen concentration in the reactor had reached the feed level, signifying hydraulic equilibrium, and system treatment efficiency had reached a constant level. Similar data for the other reactors is presented in Appendix B.

#### IV.2.2 High Loading Study

Steady-state conditions were achieved in the high loading run ( $BOD_5 = 800$  mg/l) twenty-five to twenty-nine days after start-up. Two to three weeks after this run was started, an unusual but interesting phenomenon was noted in the reactors. The MLSS and filtered COD levels started to fluctuate in a cyclic manner, while the filtered  $BOD_5$  and gross  $BOD_5$  and COD levels were unaffected. This cyclic phenomenon is shown in Figure 3 for the two and sixteen-day reactors. Cycling in a bacterial system has been described by Gaudy, *et al.* (15) in their study of total oxidation of activated sludge and by Thirmurthi (41) studying photosynthetic ponds, who found wide and unexplained variations in filtered COD, but not BOD, values.

The fluctuations in the MLSS and filtered COD concentrations raise the question of non steady-state operation. However, an examination of Figures 4 and 5 shows that steady-state conditions were reached in all reactors after twenty-nine days. As can be seen from Figure 4, hydraulic equilibrium was achieved in all the reactors by twenty-nine days. By the same time, as shown in Figure 5, system treatment efficiency had stabilized.

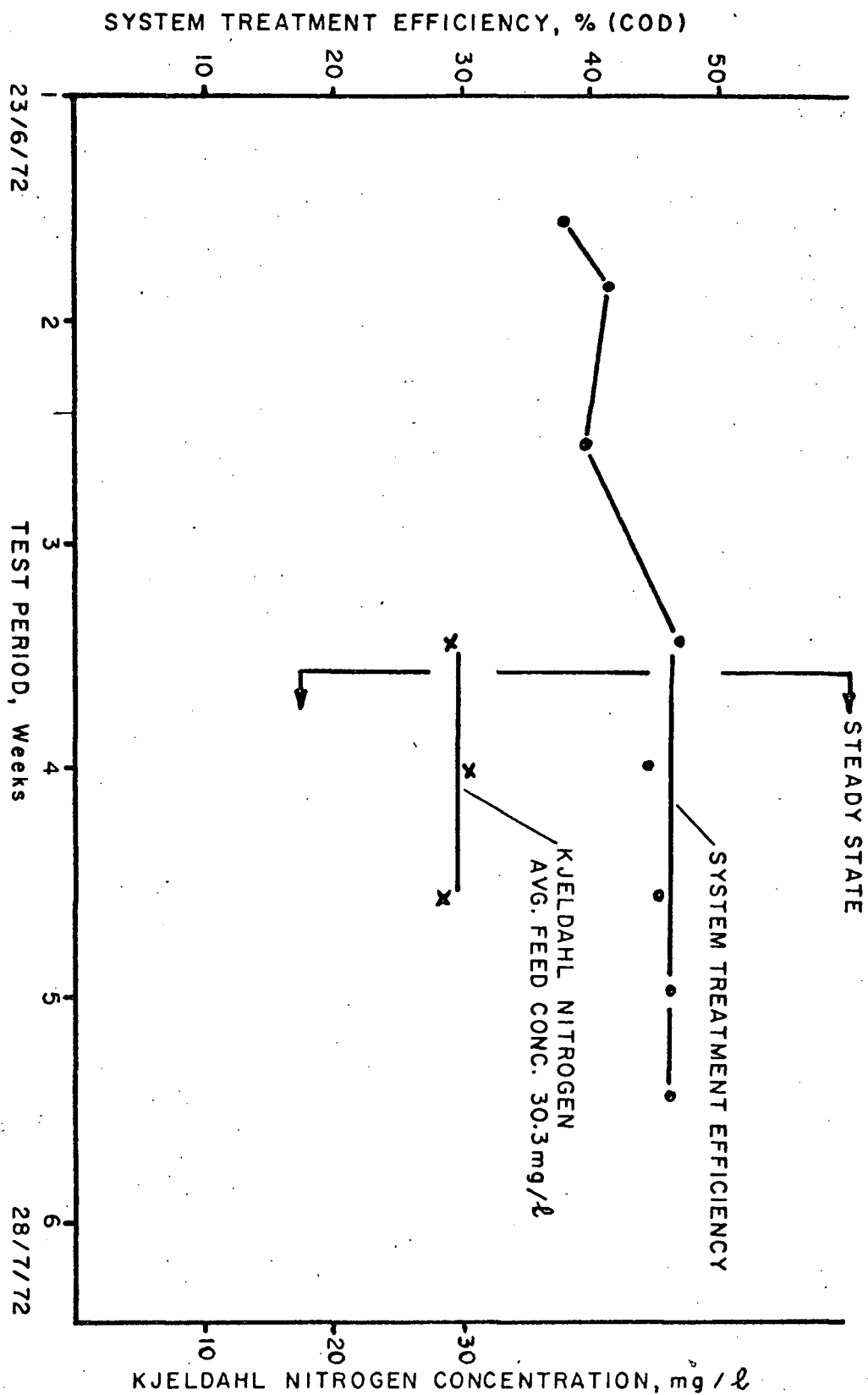


FIGURE 2. STEADY STATE - 16 DAY REACTOR - LOW LOADING



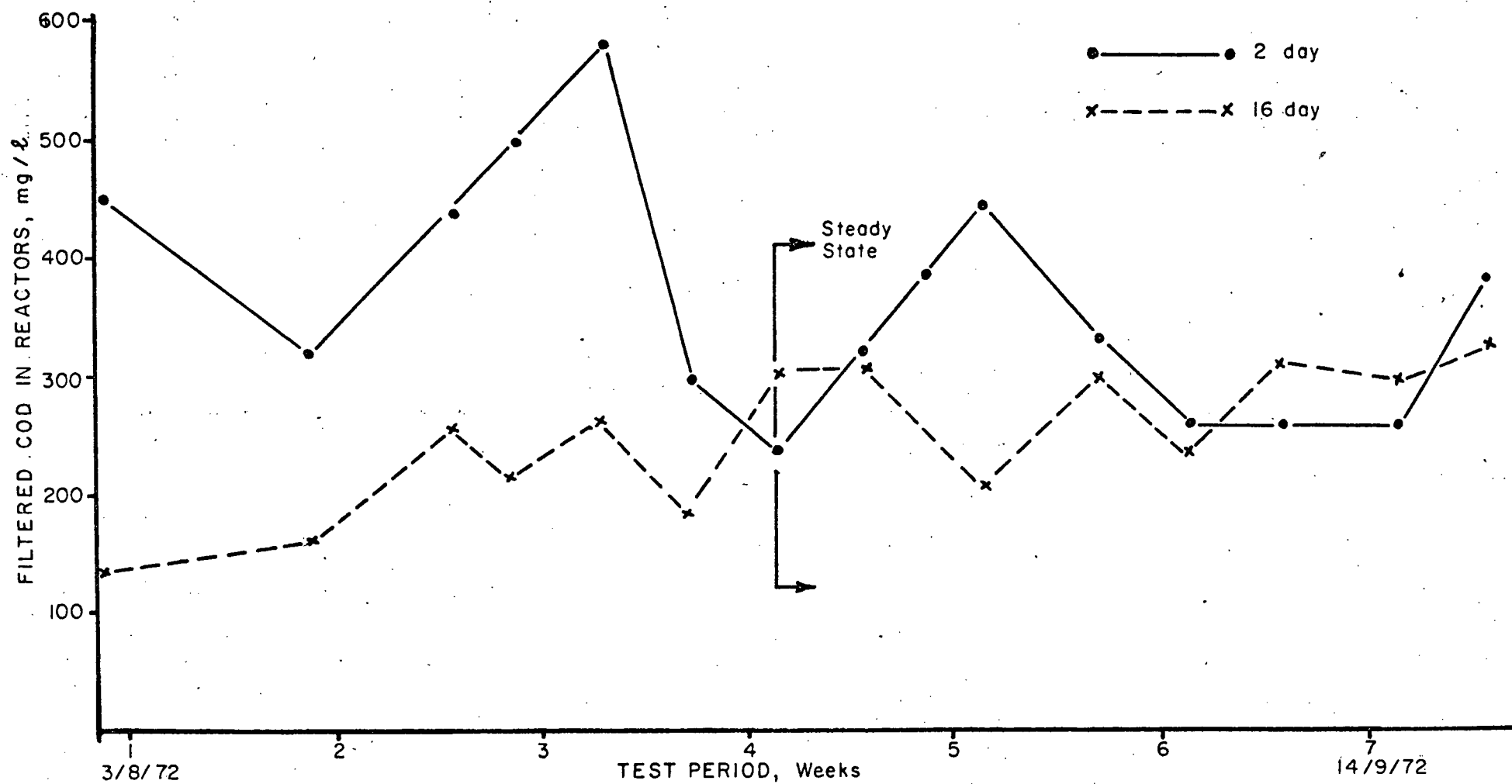


FIGURE 3. CYCLIC FLUCTUATIONS OF FILTERED COD CONCENTRATIONS

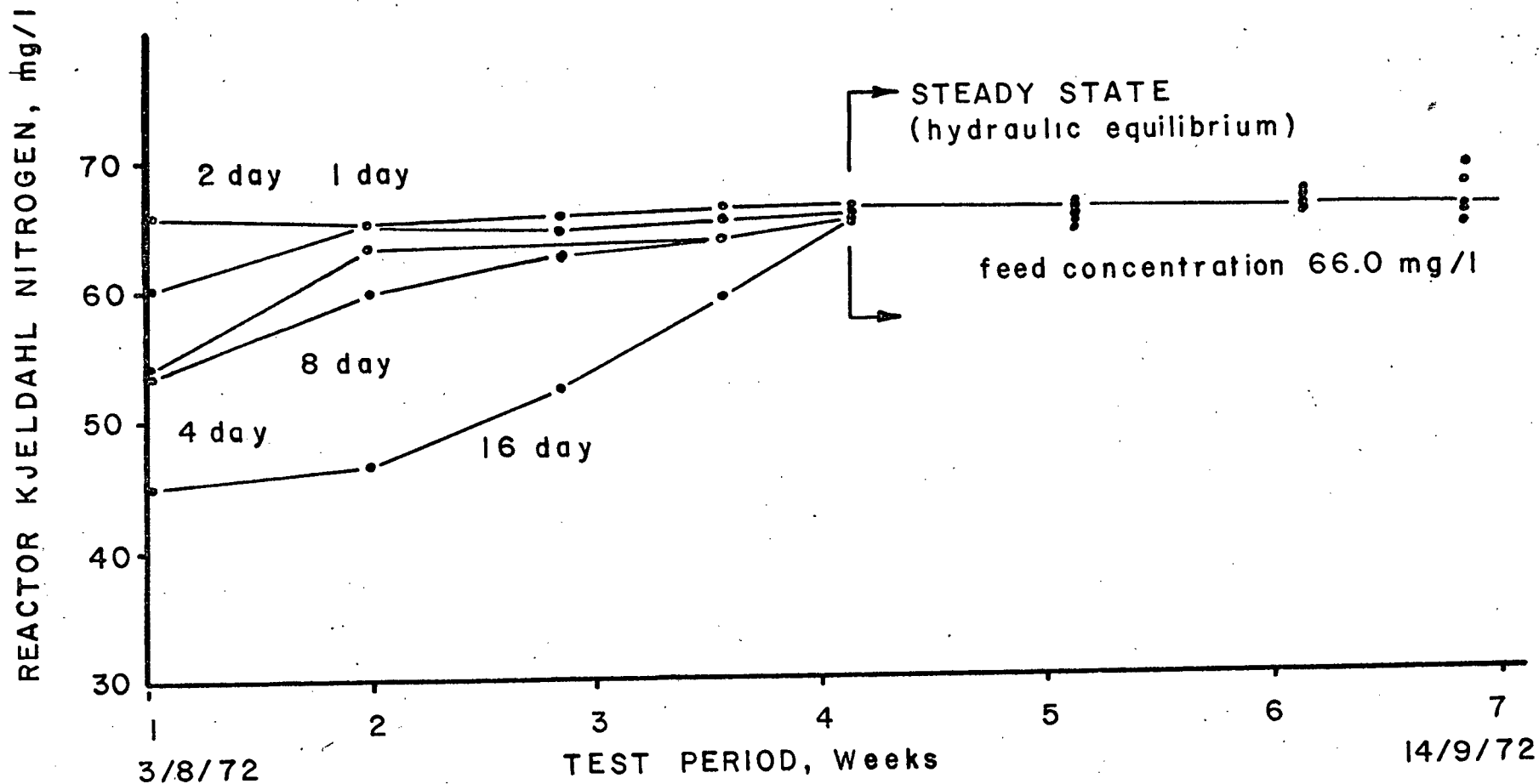


FIGURE 4. HYDRAULIC EQUILIBRIUM - HIGH LOADING

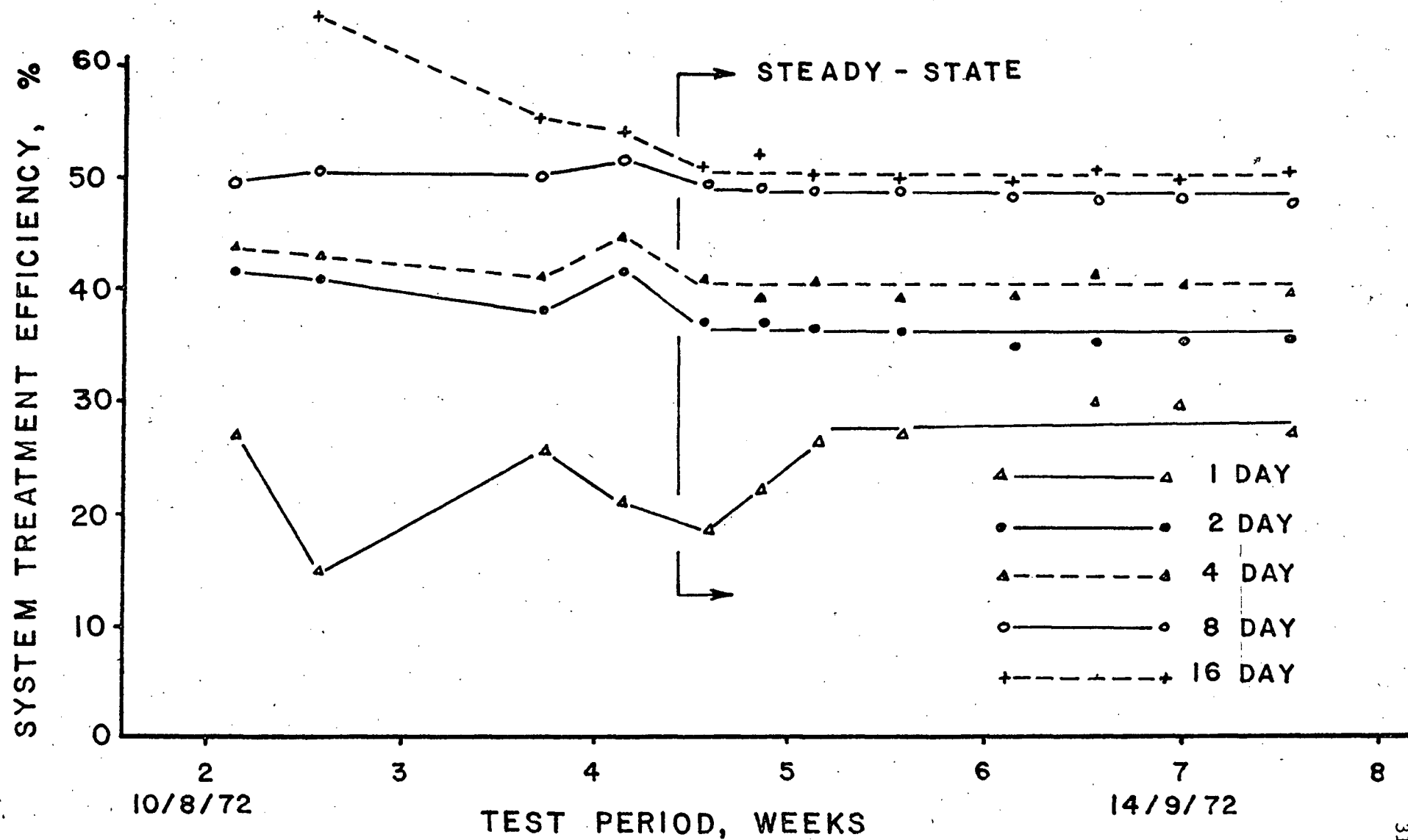


FIGURE 5. STEADY - STATE - SYSTEM TREATMENT EFFICIENCY  
COD HIGH LOADING

### IV.3 PER CENT SUBSTRATE REMOVAL AND SYSTEM TREATMENT EFFICIENCY

The principle operating parameter for an ASB is treatment efficiency. Presented in this section are the results for two efficiencies: per cent substrate removal and the system treatment efficiency. Per cent substrate removal is the per cent decrease in the applied substrate and is equal to 100 per cent minus the per cent of substrate remaining in the reactor. System treatment efficiency is the per cent decrease in the oxygen demand ( $BOD_5$  or COD) measured between the influent and the effluent, and as such, takes into consideration the oxygen demand associated with generated solids.

#### IV.3.1 Per Cent Substrate Removal (Substrate Utilization).

Per cent substrate removal as a function of mean hydraulic retention time is plotted in Figure 6. Curves A and B relate per cent substrate removal on a COD basis for the two loadings studied; curves C and D are on a  $BOD_5$  basis. As can be seen from Curves C and D in Figure 6, there is virtually complete utilization (94 - 98 per cent) of the substrate in two to three days, as measured by  $BOD_5$ . On a COD basis, Curves A and B, substrate removal continues until about eight days, after which per cent removal is constant at 77 - 80 per cent. From the milk waste analysis, Table 3, it can be seen that the  $BOD_u/COD$  ratio is 1:1.25, i.e., 80 per cent of the influent COD is biodegradable, indicating that for retention times beyond eight days, there is virtually complete utilization of the biodegradable portion of the substrate, measured by either COD or  $BOD_5$ . Applying this same reasoning, that is, only 80 per cent of the COD is biodegradable, there is 75 - 85 per cent utilization of the biodegradable substrate in one to two days.

A possible explanation for the difference in time needed to achieve the same per cent substrate removal when measured on a COD or  $BOD_5$  basis may be

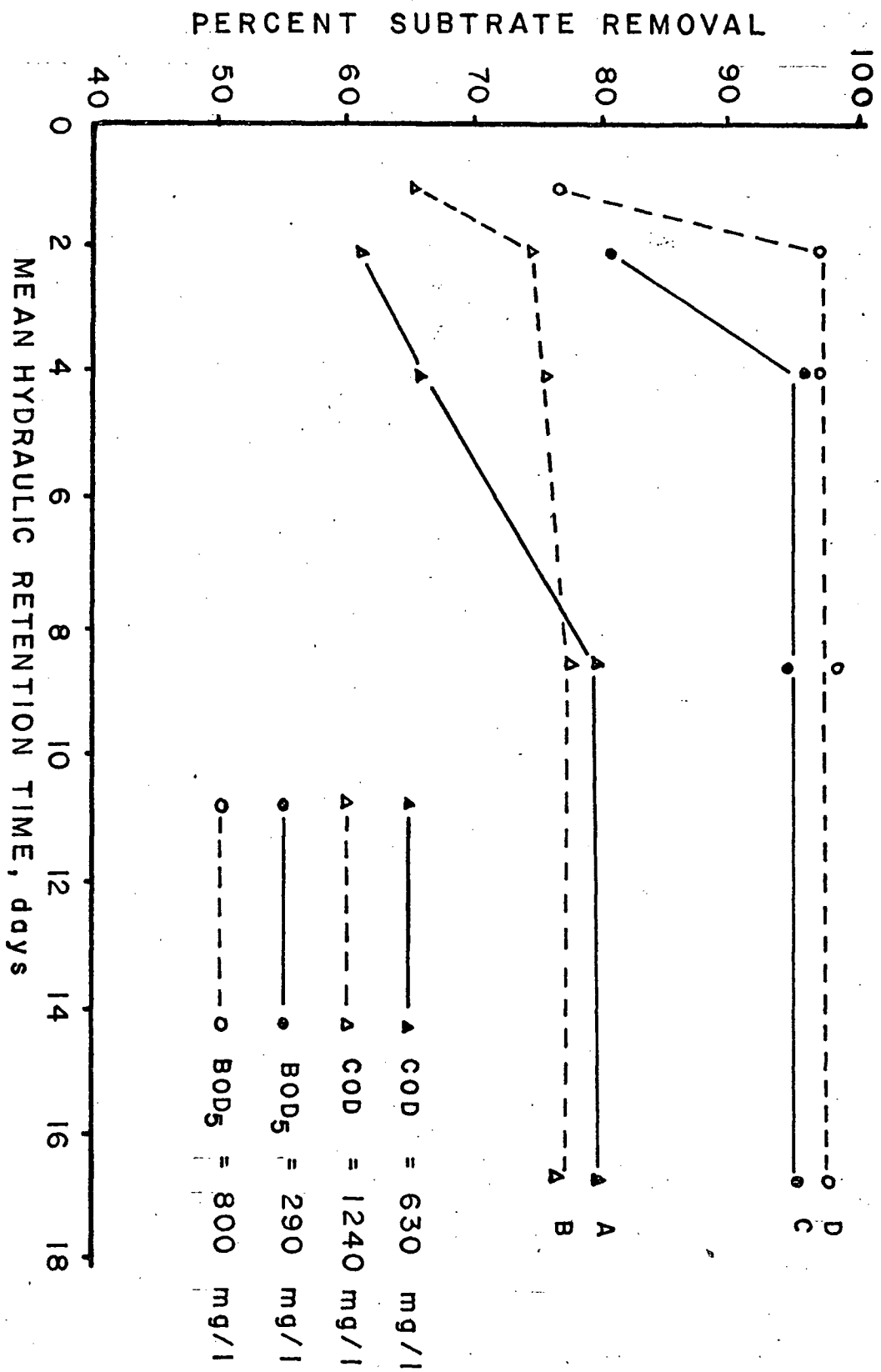


FIGURE 6. PERCENT SUBSTRATE REMOVAL AS A FUNCTION OF MEAN HYDRAULIC RETENTION TIME AT 3°C.

the formation of intermediate compounds in the reactors. It can be suggested, because of the limitations of the  $BOD_5$  test, that the COD curves are a better representation of the effect of mean hydraulic retention time on substrate removal at  $3^{\circ}C$ .

Comparative ASB substrate removal data could not be found in the literature. However, Hoover *et al.* (21) documented very rapid and complete oxidation of dairy wastes in batch studies at  $30^{\circ}C$ . They found that 500 ppm of sludge solids would oxidize 1000 ppm of milk solids in six hours. Comparing these data with data from this study, it would appear that milk wastes can be oxidized at least three times as rapidly at  $30^{\circ}C$  as they can at  $3^{\circ}C$ .

IV.3.2 System Treatment Efficiency. The system treatment efficiencies measured in the laboratory ASB systems are plotted in Figure 7 as a function of mean hydraulic retention time. Curves A and B are on a COD basis and Curves C and D are on a  $BOD_5$  basis for the two loadings.

As shown in Figure 7, system treatment efficiency continues to increase with mean hydraulic retention time over the range of the study, reaching 80 per cent ( $BOD_5$ ) or 51 per cent (COD) at sixteen days.

The system treatment efficiencies ( $BOD_5$ ) measured in this study at  $3^{\circ}C$  are generally equal to, or lower than, reported cold temperature ASB treatment efficiencies. Carpenter *et al.* (7), treating pulp and paper wastes in the laboratory at  $2^{\circ}C$ , found efficiencies of 56 per cent to 79 per cent for retention times of 2.5 to 10 days. Esvelt *et al.* (14), treating fruit processing waste, reported efficiencies of 85 to 88 per cent for retention times of 10.5 - 11.5 days in the  $4^{\circ} - 7^{\circ}C$  range. Reid (34) and Goodrow (20) report treatment efficiencies in excess of 80 per cent for domestic sewage treated in twenty day lagoons at near zero temperatures in Alaska and at Regina which are comparable to those found in this study.

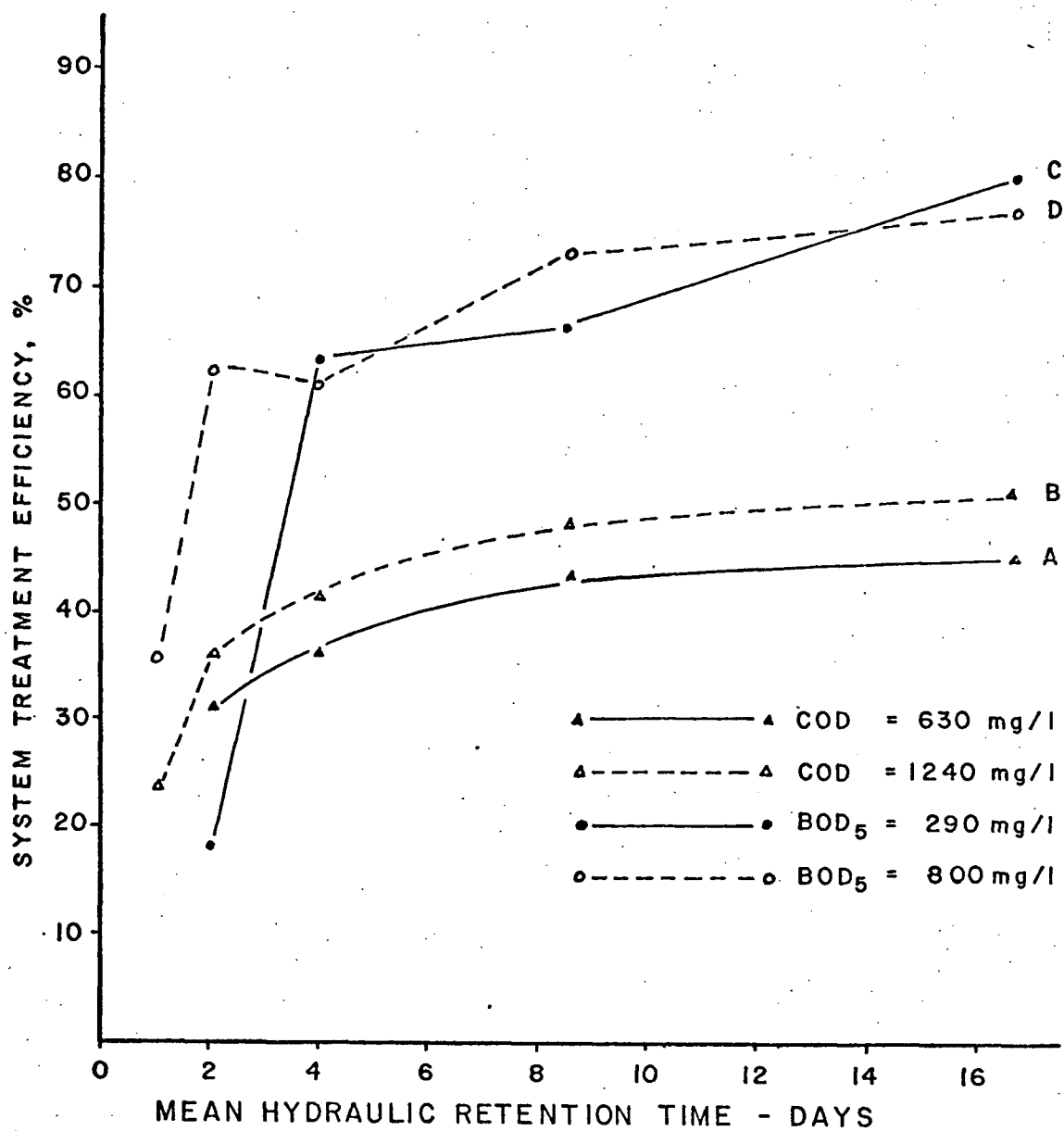


FIGURE 7. SYSTEM TREATMENT EFFICIENCY AS A FUNCTION OF MEAN HYDRAULIC RETENTION TIME AT 3° C.

#### IV.4 EVALUATION OF MATHEMATICAL MODELS USED IN ASB DESIGN

IV.4.1 General. A fundamental assumption in predicting ASB treatment efficiency at cold temperatures is that the design model used, given the right set of constants, will be applicable at a predicted temperature.

Four of the five models presented in the literature review were evaluated as to their applicability at 3°C on the basis of the per cent substrate removal and system treatment efficiency data collected in this study. The models evaluated were O'Connor and Eckenfelder's, McKinney's, the Chemostat, and the first-order exponential. The fifth model, the retardent form of O'Connor and Eckenfelder's equation, was not evaluated as its use is restricted to the pulp and paper industry.

IV.4.2 Evaluation of O'Connor and Eckenfelder's Model. By far the most commonly used and frequently reported model is O'Connor and Eckenfelder's given by Equation 1:

$$\frac{S_e}{S_o} = \frac{1}{1 + Kt} \quad (1)$$

To use O'Connor and Eckenfelder's model, the reaction rate constant, K, must be known or calculated. To calculate the constant, Equation (1) is manipulated into the linear form  $S_o/S_e = Kt + 1$ ;  $S_o/S_e$  (influent substrate concentration/effluent substrate concentration) is then plotted against t. The slope of the straight line drawn through the data points is then K.

Figure 8 is a plot of  $S_o/S_e$  against t on a COD basis for the two loadings. As can be seen from this figure, this relationship of  $S_o/S_e$  to t is non-linear and therefore O'Connor and Eckenfelder's model is not applicable. A similar plot of  $S_o/S_e$  against t on a BOD<sub>5</sub> basis would yield a straight line,



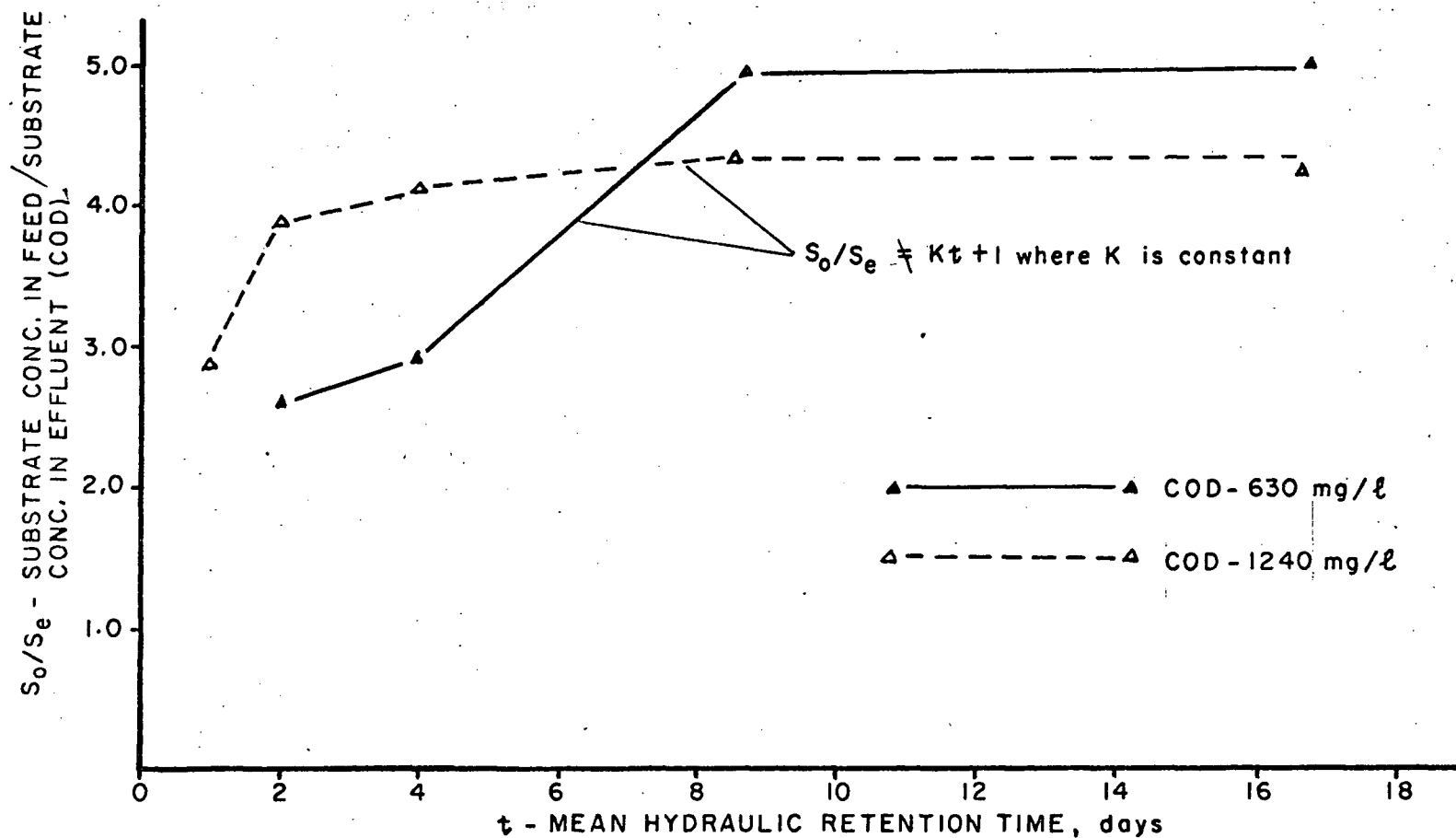


FIGURE 8. EVALUATION OF REACTION RATE CONSTANT ( $K$ ) FOR SUBSTRATE REMOVAL ( $S_e$ ). (O'CONNER and ECKENFELDER).

but with a zero slope ( $S_o/S_e$  is virtually constant with mean hydraulic retention time after one day), which is a non-solution. Thus, in terms of describing per cent substrate removal measured in the laboratory ASB at 3°C, O'Connor and Eckenfelder's model is not applicable.

Evaluating the same model in terms of system treatment efficiency,  $S_o/S_e$  (influent substrate concentration/effluent gross concentration) plots as a straight line function of the mean hydraulic retention time for  $t$  beyond two days, as shown in Figure 9. Reaction rate constants can be calculated from the study data for retention times beyond two days. The intercepts of these straight lines do not pass through 1.0, but vary from 1.3 to 2.1. The  $BOD_5$  data is fitted using only one line.

The measured system treatment efficiencies and the system treatment efficiencies calculated using O'Connor and Eckenfelder's model with the constants calculated from Figure 9, are listed in Table 5 for comparison.

As can be seen from Table 5, O'Connor and Eckenfelder's pseudo first order model will describe only the system treatment efficiency measured in the laboratory ASBs at 3°C for retention times beyond two days.

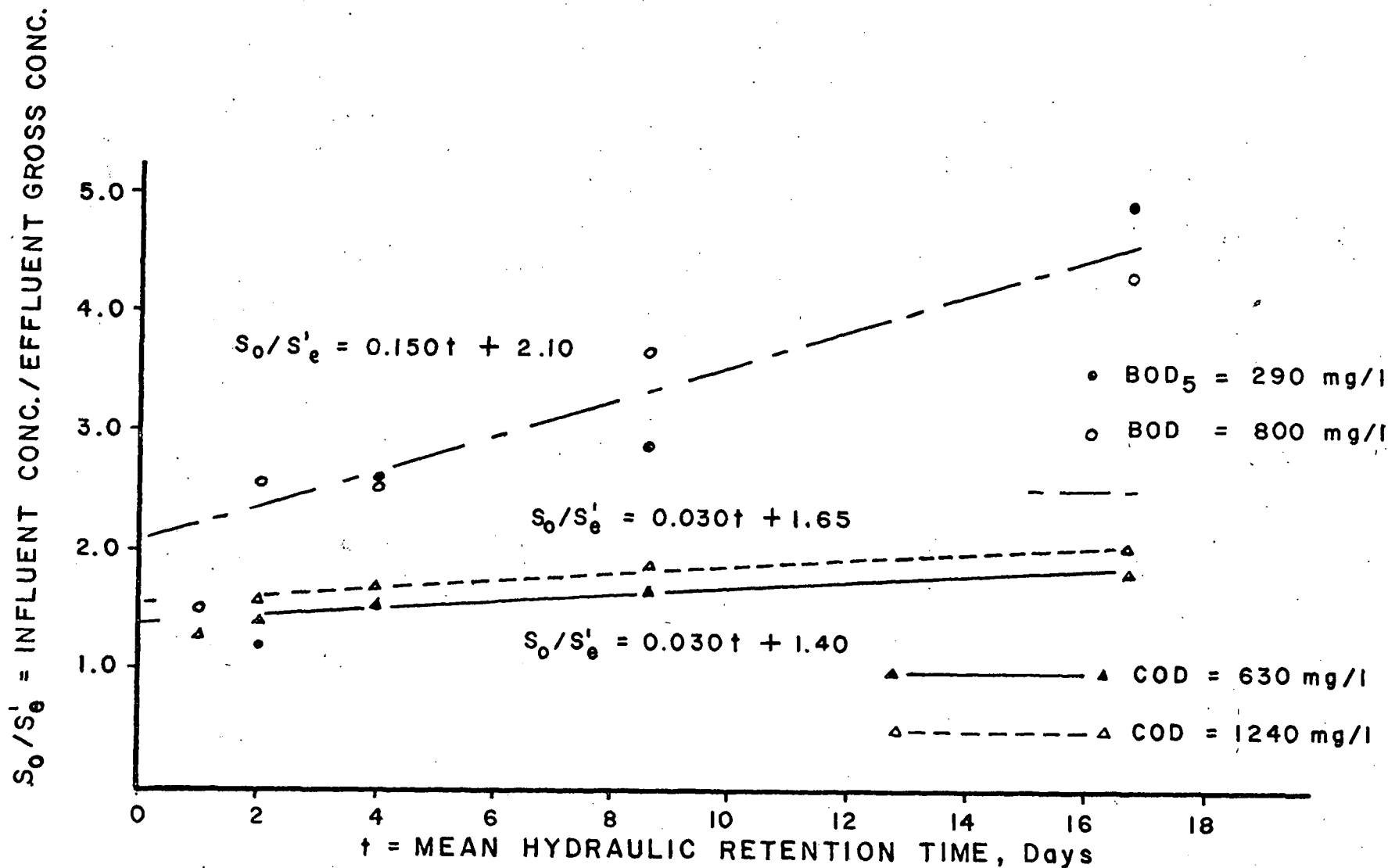


FIGURE 9. EVALUATION OF REACTION RATE CONSTANTS K FOR SYSTEM TREATMENT EFFICIENCY AT 3° C.  
(O'CONNER AND ECKENFELDER)

TABLE 5

MEASURED AND CALCULATED SYSTEM TREATMENT EFFICIENCIES  
O'CONNOR AND ECKENFELDER'S MODEL

$$E = \left( \frac{1}{C + Kt} \right) \times 100\%$$

RETENTION TIME (Days)	LOADING	COD EFFLUENT			BOD <sub>5</sub> EFFLUENT		
		MEASURED	CALCULATED	ABSOLUTE DIFFERENCE	MEASURED	CALCULATED	ABSOLUTE DIFFERENCE
1	High	23.5%	36.0%	12.5%	35.6%	56.7%	21.1%
2		36.0%	36.5%	0.5%	62.5%	59.0%	3.5%
4		40.4%	39.4%	1.0%	61.0%	63.3%	2.3%
8		46.0%	45.3%	0.7%	73.2%	70.3%	2.9%
16		50.5%	53.0%	2.5%	76.6%	77.8%	1.2%
2	Low	31.2%	31.0%	0.2%	18.0%	59.0%	41.0%
4		36.9%	33.2%	3.7%	63.2%	63.3%	1.1%
8		43.3%	39.0%	4.3%	66.0%	70.3%	4.3%
16		44.9%	45.0%	0.1%	80.0%	77.8%	2.2%

IV.4.3 McKinney's Model. McKinney's model, in very general terms, is based on the premise that all of the influent substrate is utilized within the first day and the remainder of the treatment or retention time is used for the oxidation of generated solids. Substrate remaining, active solids production, and the effluent oxygen demand are described by three inter-related equations:

$$F = \frac{F_1}{k_5 t + 1} \quad (3)$$

$$M_a = \frac{k_6 F}{1/t + k_7} \quad (4)$$

$$F_e = F + k_{10} M_a \quad (5)$$

Equation (3), which describes substrate remaining in the basin, is the same form as O'Connor and Eckenfelder's equation, and like their equation, it does not describe the substrate removal measured in this study.

Listed in Table 6 are the substrate concentrations measured in the laboratory ASBs and calculated using McKinney's equation,  $F = F_1 / (k_5 t + 1)$ . A similar comparison on a COD basis could not be made as COD constants are not available. The constant  $K_5$  for 3°C (108 day<sup>-1</sup>) was extrapolated from McKinney's values for 5°C to 20°C presented in Goodman (19).

As can be seen from Table 6, McKinney's model predicts a more rapid and complete substrate utilization than was measured in this study. This difference could suggest that McKinney's model cannot be extrapolated beyond 5°C.

TABLE 6  
MEASURED AND CALCULATED BOD<sub>5</sub> SUBSTRATE CONCENTRATION  
McKINNEY'S MODEL

RETENTION TIME	LOW LOADING		HIGH LOADING	
	MEASURED	CALCULATED	MEASURED	CALCULATED
1	--	--	187 mg/l	7.3 mg/l
2	55 mg/l	1.33 mg/l	22 mg/l	3.7 mg/l
4	12 mg/l	0.67 mg/l	23 mg/l	1.85 mg/l
8	17 mg/l	0.33 mg/l	16 mg/l	0.87 mg/l
16	14 mg/l	0.15 mg/l	17 mg/l	0.43 mg/l

Gross effluent concentrations were calculated using McKinney's three equations; i.e., relating  $F_e$ , the effluent BOD<sub>5</sub>, to  $F_i$ , the raw waste BOD<sub>5</sub>. Presented in Table 7 are the measured and calculated effluent BOD<sub>5</sub>. In these calculations the MLSS levels were assumed to be equivalent to the active mass when used in conjunction with an evaluated  $k_{10}$  constant.

As can be seen from Table 7, with the exception of the initial points in each loading, there is little difference between the measured and calculated concentrations.

The constants used in evaluating McKinney's model were extrapolated to 3°C from the values tabled in Goodman's Design Manual (19). Goodman tables a range of values for  $k_7$  from 0.04 days<sup>-1</sup> to 0.16 days<sup>-1</sup> for sludge of five to twenty days at 5°C. To find the appropriate value of  $k_7$  within McKinney's range tabled in Goodman (19), the test data was used to calculate an average  $k_7$  and

values of  $k_{10}$ . The  $k_7$  values calculated were  $0.086 \text{ days}^{-1}$  for low loading and  $0.076 \text{ days}^{-1}$  for high loading. The  $k_{10}$  values calculated were:  $0.79 \text{ days}^{-1}$  for the low loading and  $0.70 \text{ days}^{-1}$  for high loading. Details of the calculations used in defining constants  $k_7$  and  $k_{10}$  can be found in Appendix C.

TABLE 7  
MEASURED AND CALCULATED GROSS EFFLUENT  $\text{BOD}_5$  CONCENTRATIONS  
McKINNEY'S MODEL

290 mg/l $\text{BOD}_5$ RAW WASTE			
RETENTION TIME	CALCULATED $\text{BOD}_5$	MEASURED $\text{BOD}_5$	DIFFERENCE
2 days	131 mg/l	238 mg/l	107 mg/l
4 days	114 mg/l	109 mg/l	5 mg/l
8 days	88 mg/l	99 mg/l	11 mg/l
16 days	63 mg/l	59 mg/l	4 mg/l
800 mg/l $\text{BOD}_5$ RAW WASTE			
RETENTION TIME	CALCULATED $\text{BOD}_5$	MEASURED $\text{BOD}_5$	DIFFERENCE
1 day	344 mg/l	513 mg/l	169 mg/l
2 days	323 mg/l	300 mg/l	23 mg/l
4 days	286 mg/l	306 mg/l	20 mg/l
8 days	224 mg/l	215 mg/l	9 mg/l
16 days	165 mg/l	177 mg/l	12 mg/l

IV.4.4 Chemostat. The Chemostat model is described by the following steady-state equation:

$$S = \frac{K_s (D)}{\mu_m - D} \quad (5)$$

As noted in the literature review the Chemostat is based on the Monod equation and an equation describing ASB hydraulics.

As can be seen from Figure 10, a plot of biodegradable COD substrate concentration against dilution rate, the Chemostat model gives a reasonable estimate of the residual substrate concentration measured in the laboratory ASBs at all hydraulic retention times and at both loadings. As the Chemostat model describes available or useable substrate remaining in the reactor, the non-biodegradable portion of the feed COD was subtracted from that concentration measured in the reactors before it was plotted in Figure 10 (126 mg/l at the low loading and 250 mg/l at the high loading).

The Chemostat curve used in approximating the filtered substrate data at 3°C was fitted using the constants  $K_s = 323$  mg/l and  $\mu_{\max} = 2.2$  days<sup>-1</sup>. Calculating, using the Chemostat equation with the above constants, the washout retention times at the two substrate loadings are 14.8 hours and 17.9 hours, respectively, for the low and high loadings. The maximum growth rate under unlimited substrate conditions is 2.2 days<sup>-1</sup>, which implies a generation time of 10.9 hours. This generation time is of the same order as the reported generation times of a psychrophilic strain of Pseudomonads at low temperatures (32).

The BOD<sub>5</sub> substrate concentration measured in the reactors did not change with mean hydraulic retention time after one day, and therefore could not be described by the Chemostat model.



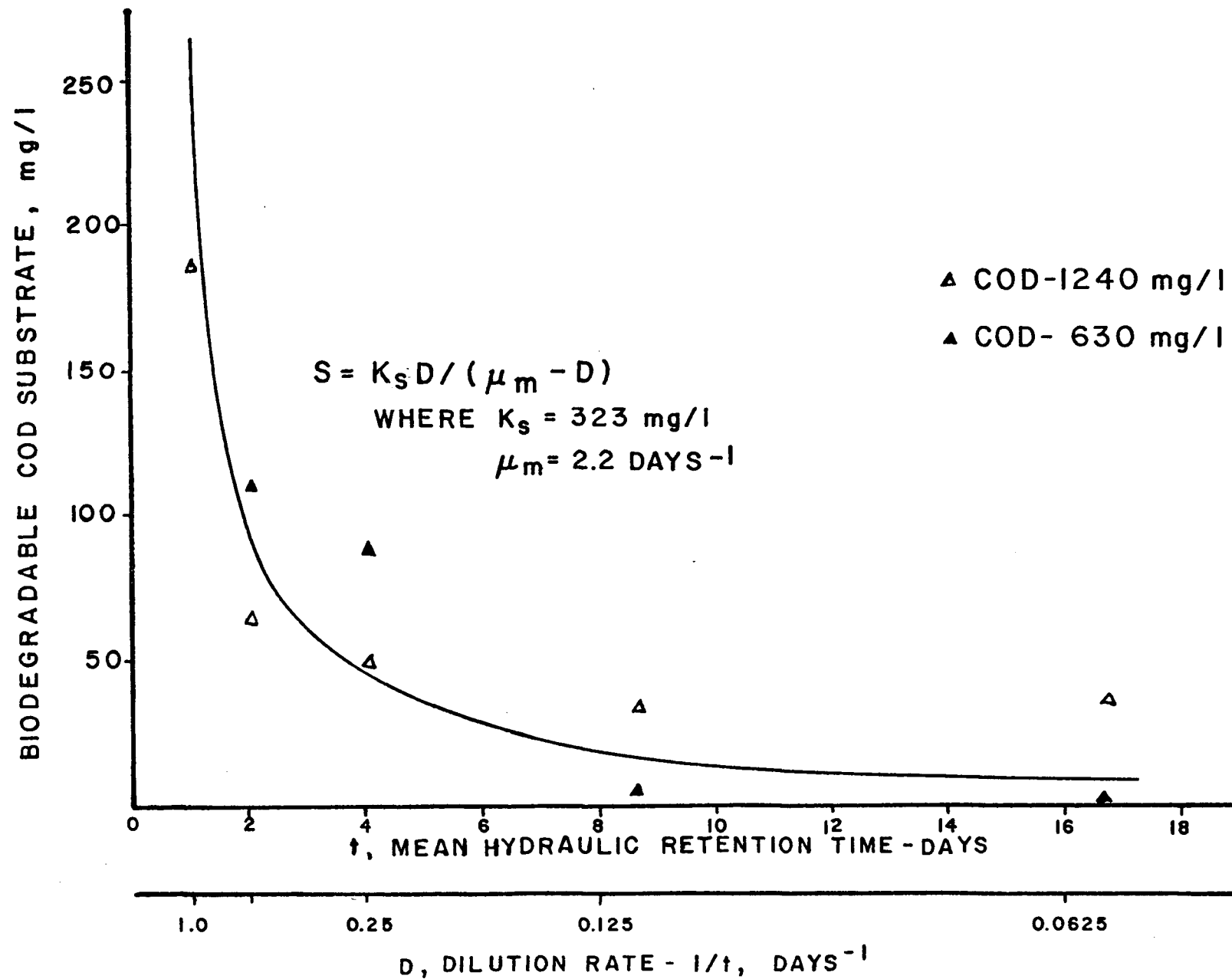


FIGURE 10. CHEMOSTAT FIT-COD SUBSTRATE CONCENTRATION

IV.4.5 First-Order Exponential. The first-order exponential model is described by the following equation:

$$S_e/S_o = e^{-kt} \quad (7)$$

Like O'Connor and Eckenfelder's model, the first-order exponential model can only be used when the reaction rate constant,  $k$ , is known. The reaction rate constant,  $k$ , can be calculated from a semi-log plot of  $S_e/S_o$  against the mean hydraulic retention time,  $t$ .

As can be seen from Figure 11, semi-log plots of  $S_e/S_o$  (COD and BOD<sub>5</sub> for both loadings) against  $t$ , the first-order exponential equation does not describe the substrate removal measured in the laboratory ASBs at 3°C. On a BOD<sub>5</sub> basis, the reaction rate constant is 0.0 or a non-solution. On a COD basis, the points cannot be approximated by a straight line.

The first-order exponential model can, however, be used to describe the gross effluent concentration (or on a per cent basis, system treatment efficiency) in the laboratory study. The reaction rate constants, on a COD and BOD<sub>5</sub> basis for the two loadings, are calculated from the semi-log plots shown in Figure 12. As can be seen from Figure 12, the gross effluent data can be approximated only for mean hydraulic retention times beyond two days. The first-order exponential equation used is in the form of  $S_e'/S_o = C_e^{-kt}$  where  $C$  varies from 0.44 to 0.70.

Listed in Table 8 are the system treatment efficiencies measured in the laboratory and those calculated using the first-order exponential equation. It can be seen that the absolute per cent difference between measured and calculated system treatment efficiency is less than four per cent for mean hydraulic retention times greater than two days.

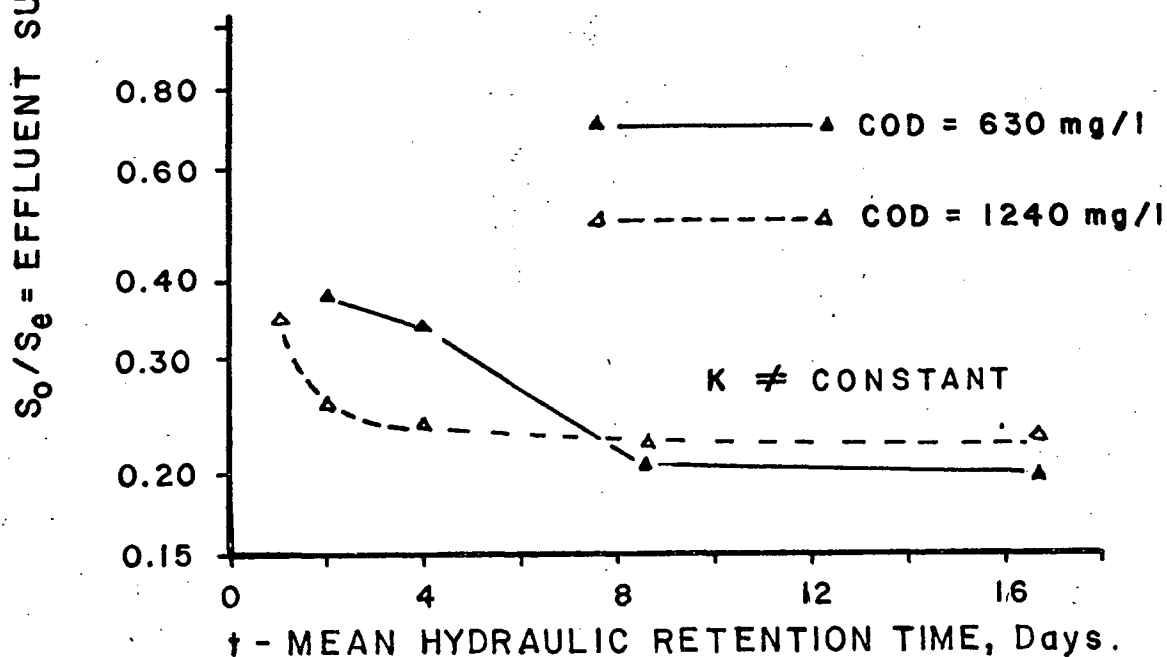
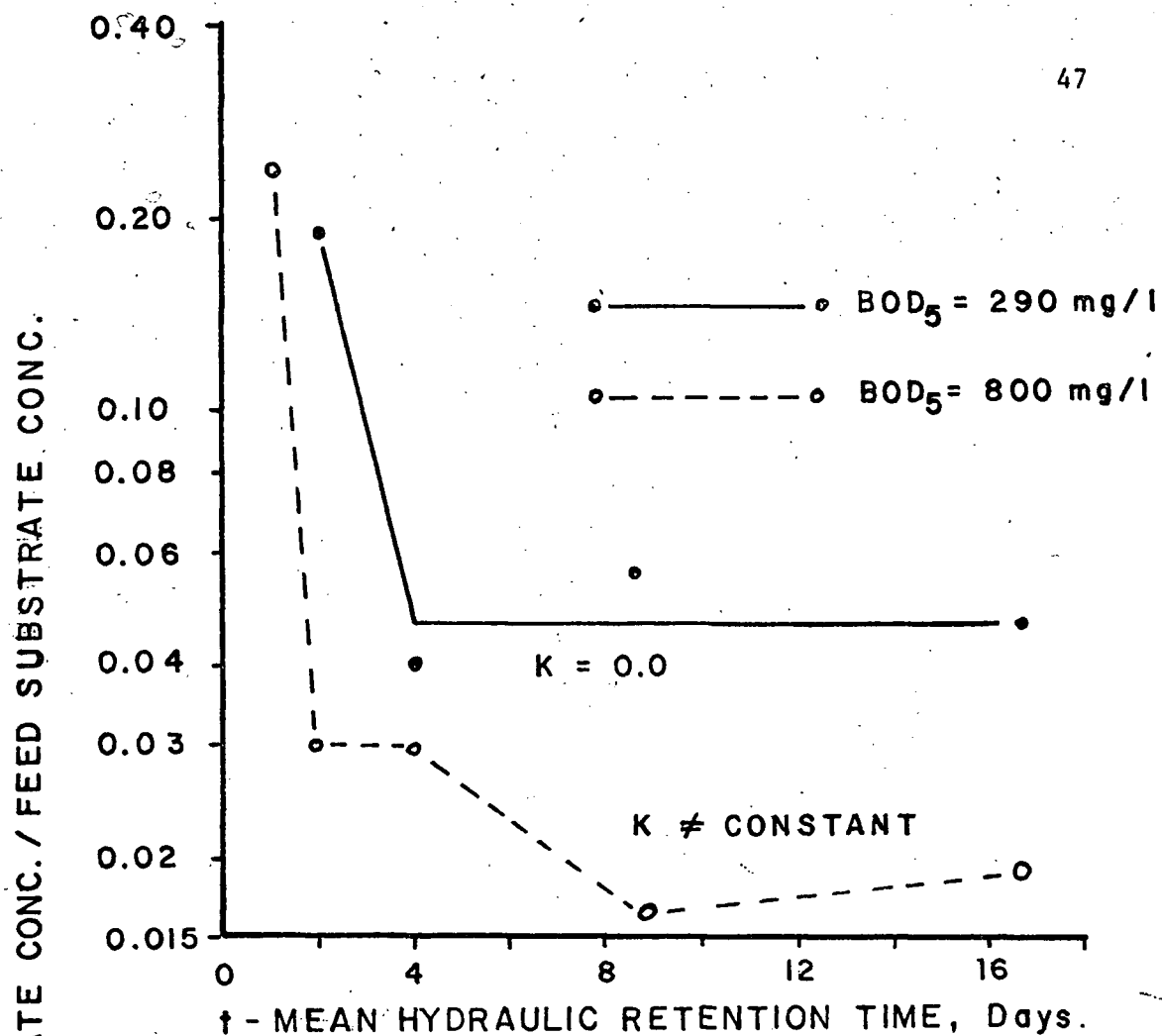


FIGURE II. EVALUATION OF REACTION RATE CONSTANT  $K$  FOR SUBSTRATE REMOVAL AT 3°C.

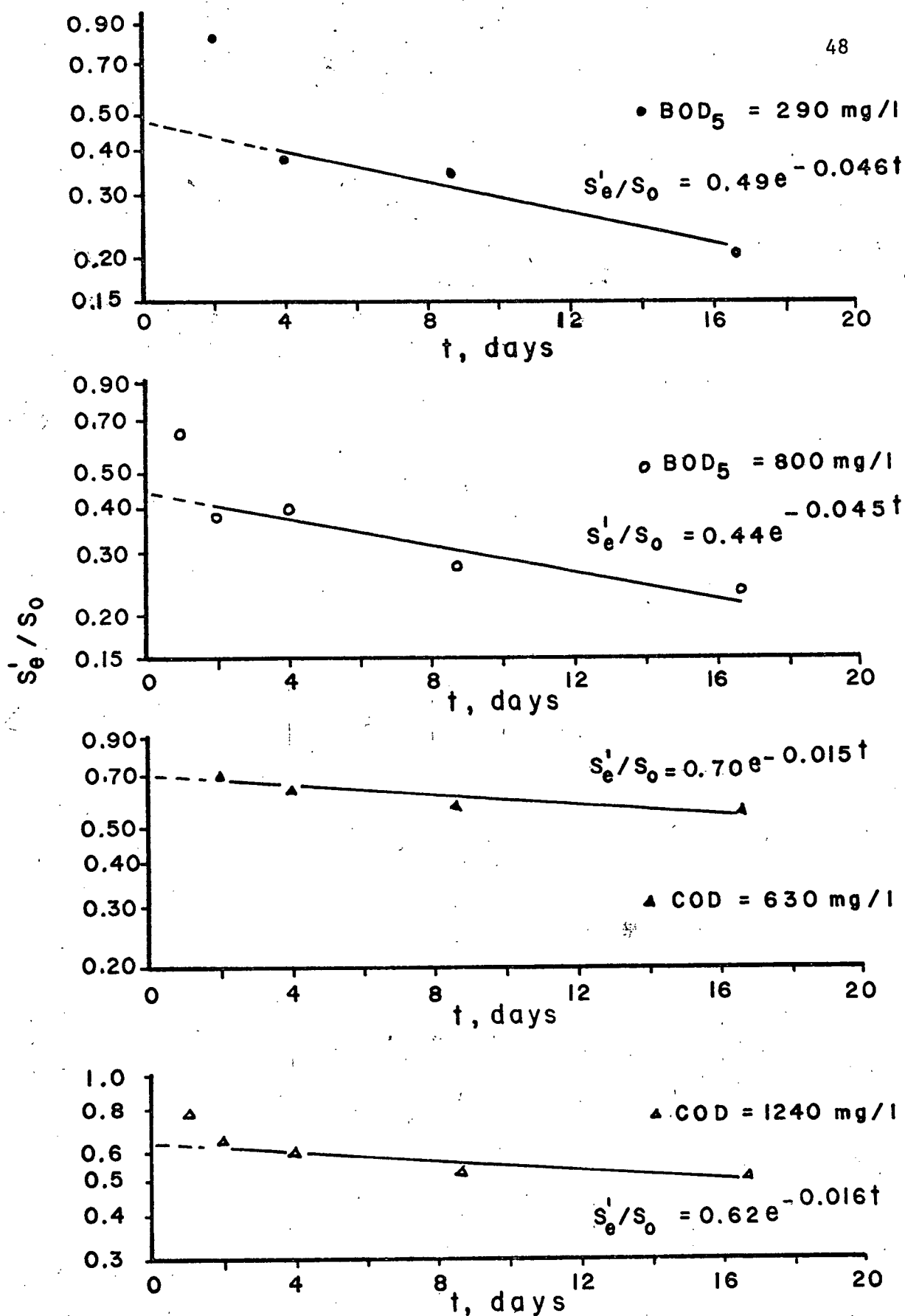


FIGURE 12. EVALUATION OF REACTION RATE CONSTANT  $K$  FOR SYSTEM TREATMENT EFFICIENCY.

TABLE 8

MEASURED AND CALCULATED SYSTEM TREATMENT EFFICIENCY,  
FIRST-ORDER EXPONENTIAL

$$E = (1 - Ce^{-kt}) \times 100\%$$

RETENTION TIME (Days)	LOADING	COD EFFLUENT			BOD <sub>5</sub> EFFLUENT		
		MEASURED	CALCULATED	ABSOLUTE DIFFERENCE	MEASURED	CALCULATED	ABSOLUTE DIFFERENCE
1	High	23.5%	39.0%	14.5%	35.6%	59.0%	23.4%
2		36.0%	40.0%	4.0%	60.0%	60.5%	0.5%
4		40.4%	42.0%	1.6%	61.0%	63.5%	2.5%
8		48.0%	46.0%	2.0%	73.2%	71.0%	2.2%
16		50.5%	51.0%	0.5%	76.6%	78.0%	1.4%
2	Low	31.2%	32.0%	0.8%	18.0%	56.0%	38.0%
4		36.9%	35.0%	1.9%	63.2%	60.0%	3.2%
8		43.3%	41.0%	2.3%	66.0%	68.0%	2.0%
16		44.9%	46.0%	1.1%	80.0%	79.0%	1.0%

## IV.5 ASB SOLIDS

### IV.5.1 Solids Production

Solids production in ASBs, and the resulting characteristics and concentration of these solids in the effluent stream, are a major factor in the effectiveness of the ASB in producing high quality effluents. The carry-over of solids produced in the basin can significantly deteriorate the quality of the effluent. In this study, there was an increase of as much as 300 mg/l COD or BOD<sub>5</sub> when the solids were included in the effluent measurements.

Shown in Figure 13 are the average mixed liquor suspended solids concentrations measured in the model reactors at the two loadings. The ranges of measured concentrations are also shown, as there was considerable variance due to the cycling previously discussed. The similarity between the curves in Figure 13 for hydraulic retention times of two to sixteen days, would suggest that the average values are representative. The trend in the solids concentration with hydraulic retention time is one of a slightly increasing concentration from two to eight days, followed by a slight decrease to sixteen days. This trend goes against the usual decrease in solids concentration expected with increasing hydraulic retention time (10).

Solids production in a closed biological treatment system is generally expressed by the equation:

$$Y = aS_r - bMLSS \quad (16)$$

where

$Y$  = yield or net solids production in lbs/day;

$a$  = yield factor, lbs solids/lbs substrate removed;

$S_r$  = substrate removed, lbs/day;

$b$  = endogenous coefficient in %/day;

MLSS = mixed liquor suspended solids, lbs.

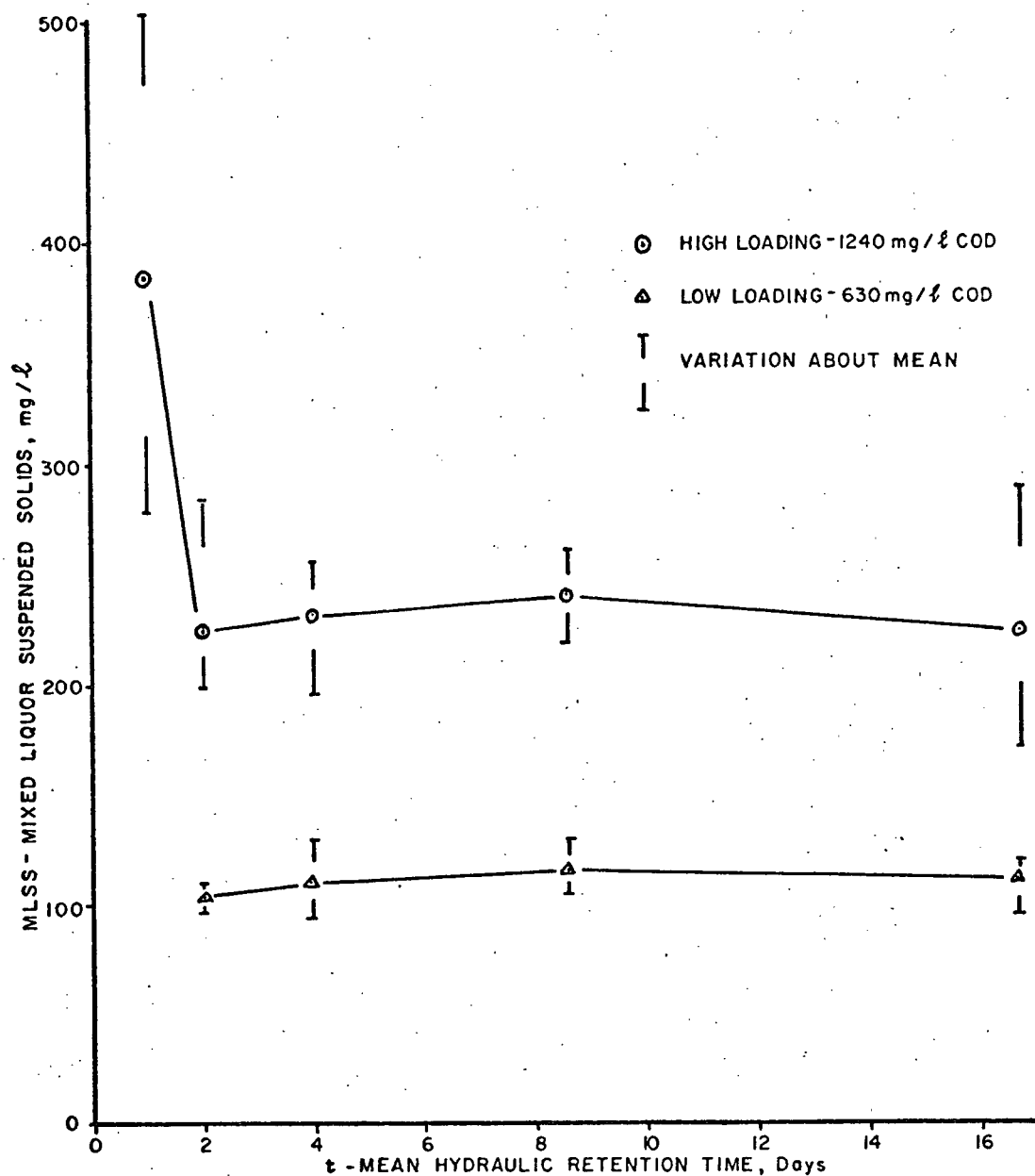


FIGURE 13. MIXED LIQUOR SUSPENDED SOLIDS AS A FUNCTION OF MEAN HYDRAULIC RETENTION TIME AT 3° C.

In a flow-through system without solids recycle, such as the model ASBs used in the laboratory, the hydraulic washout of solids under steady-state conditions is just offset by the biological yield or net solids production from substrate utilization. That is, net solids production equals the weight of solids washed out.

Listed below in Table 9 are the values of net solids production per pound of substrate removal, calculated for the two loadings on a  $BOD_u$  and COD basis.

TABLE 9  
NET SOLIDS PRODUCTION PER POUND SUBSTRATE REMOVED

Low Loading (630 mg/l COD)	0.27 lbs/lb COD	0.25 lbs/lb $BOD_u$
High Loading (1,240 mg/l COD)	0.25 lbs/lb COD	0.24 lbs/lb $BOD_u$

The values tabled are the calculated average of the data collected from the two to sixteen day reactors. The net solids production per pound of substrate removed, measured in the one-day reactor at the high loading, is 0.48 lbs/lb COD or 0.53 lbs/lb  $BOD_u$ .

Eckenfelder (10) maintains that ASB solids production from a soluble feed will be about 50 per cent of the influent feed concentration, i.e., 0.5 lbs/lb  $BOD_5$ . However, Gellman (17), citing several ASB pilot studies, reports net solids production of 0.10 to 0.25 lbs/lb BOD removed.



The solids production measured in the laboratory ASBs is the same for both the high and low loadings and is in line with the values reported by Gellman. The reason for the difference in the net solids production measured in the one-day reactor, and that measured in the other four reactors, is not readily apparent. It may possibly be due to a physical agglomeration of the milk solids in the bacteria in the one-day reactor, although there is no evidence to support this. Another possibility may be the difference in growth conditions in the reactors. The food to micro-organism ratio in the one-day reactor is considerably higher than in the other four. Busch (6) maintains that the yield coefficient, as well as the reaction rate of bacteria, is dependent on the substrate concentration, and, therefore, at a higher food to micro-organism ratio, the yield or net solids production would be higher.

#### IV.5.2 COD - BOD<sub>5</sub> of ASB Solids

The carry-over of solids in an ASB effluent can contribute significantly to the COD or BOD<sub>5</sub> of the effluent. This was particularly true for this study. A comparison of the respective curves in Figures 6 and 7 shows a marked difference between the per cent substrate removal and system treatment efficiency, the latter taking into consideration the BOD<sub>5</sub> or COD of the effluent solids. The difference between the respective COD or BOD<sub>5</sub> curves is a measure of the COD or BOD<sub>5</sub> tied up with the biological solids. The respective differences between the measured substrate remaining and the gross effluent concentration, the reactor MLSS, the calculated COD or BOD<sub>5</sub> per unit of MLSS, and the percentage of the effluent COD or BOD<sub>5</sub> contributed by the residual substrate and by the solids, are summarized in Table 10.

TABLE 10

EFFLUENT CHARACTERISTICS OF ASBs AT 3°C

NOMINAL RETENTION TIME (Days)	LOADING	EFFL. COD -EFFL. SUBSTRATE COD	MLSS	COD/ MLSS	EFFLUENT SUBSTRATE/ EFFLUENT COD %	EFFL. SOLIDS/ EFFL. COD %	EFFL. BOD <sub>5</sub> -EFFL. SUBSTRATE BOD <sub>5</sub>	MLSS	BOD <sub>5</sub> / MLSS	EFFLUENT SUBSTRATE/ EFFLUENT BOD <sub>5</sub> %	EFFL. SOLIDS/ EFFL. BOD <sub>5</sub> %
2 4 8 16	Low	201 mg/l	104 mg/l	1.93	54%	46%	160 mg/l	104 mg/l	1.54	32%	68%
		194 mg/l	108 mg/l	1.80	52%	48%	118 mg/l	108 mg/l	1.07	11%	89%
		230 mg/l	116 mg/l	1.97	37%	63%	95 mg/l	116 mg/l	0.82	13%	87%
		235 mg/l	112 mg/l	2.10	35%	65%	60 mg/l	112 mg/l	0.54	19%	81%
1 2 4 8 16	High	522 mg/l	385 mg/l	1.35	45%	55%	300 mg/l	385 mg/l	0.78	40%	60%
		459 mg/l	226 mg/l	2.03	42%	58%	300 mg/l	226 mg/l	1.33	6%	94%
		435 mg/l	232 mg/l	1.88	41%	59%	270 mg/l	232 mg/l	1.16	7%	93%
		368 mg/l	244 mg/l	1.51	43%	57%	195 mg/l	244 mg/l	0.80	9%	91%
		320 mg/l	224 mg/l	1.43	47%	53%	140 mg/l	224 mg/l	0.65	11%	89%

The data in Table 10 shows that the major portion of the effluent  $BOD_5$  is due to biological solids concentrations. Both Eckenfelder (11) and Goodman (19) show that the major portion of the effluent  $BOD_5$  will be contributed by the solids in the effluent. On the other hand, a study (28) of a number of ASBs treating pulp and paper wastes at various retention times found that only 30 per cent of the effluent  $BOD_5$  was contributed by suspended solids.

The  $BOD_5$  per unit of MLSS (0.54 - 1.54 lbs  $BOD_5$ /lb MLSS) listed in Table 10 are considerably higher than expected. Eckenfelder (10) shows a range of values from 0.75 to 0.30 lbs  $BOD_5$ /lb MLSS for sludge ages of 0 to seven days. However, in his design models he has used a factor as low as 0.25 lbs  $BOD_5$ /lb MLSS (11). Goodman (19) uses a value of 0.60 lbs  $BOD_5$ /lb active solids for all temperatures and sludge ages. Gellman (17) quotes a number of investigators who found ratios of 0.10 - 0.26 lbs  $BOD_5$ /lb solids for wastes treated at 20° to 35°C, as compared to 0.54 - 1.54 lbs  $BOD_5$ /lb MLSS found in this study at 3°C. A direct comparison of values may, however, be misleading, as it is possible that influent solids are incorporated in the values reported by Gellman. With the exception of the data for the one day reactor (high loading), the  $BOD_5$  per unit of MLSS decreases with an increasing retention time. This would be expected if endogenous oxidation was occurring. A similar trend exists on a COD basis at the high loading, whereas at the low loading the ratio is nearly constant.

It would appear that the pounds  $BOD_5$  per pound MLSS ratios measured in this study at 3°C are significantly higher than ratios measured at higher temperatures. It is also evident from the data presented in Table 10

that the major portion of the effluent  $BOD_5$ -COD is due to the presence of biological solids. Therefore, it could be argued that the decrease in treatment efficiency with decreasing temperature, as reported in other studies, is due largely to an increase in the COD or  $BOD_5$  of the biological solids, possibly through a decrease in the endogenous oxidation rate.

IV.5.3 Settling at 3°C. In order to reduce the solids concentration in ASB effluents, a common practice has been to follow an ASB with a settling basin. In conjunction with the settling of solids, system treatment efficiencies have been reported to increase by two to 10 per cent (7)(37)(46).

The results of the batch settling tests conducted in this study would seem to be somewhat unusual, in that the improvement in system treatment efficiency with settling (COD basis) was much greater than indicated by the literature. System treatment efficiency improved by as much as 62 per cent (from 23 per cent to 85 per cent) in the one-day ASB to a low of 14 per cent (from 51 per cent to 65 per cent) in the sixteen day reactor with five days' settling time. This can be seen by comparing the gross COD in the supernatant, as system treatment efficiency plotted against settling time, with the superimposed curve of COD removal with aeration time (Figures 14 and 15 respectively) for the low and high loading.

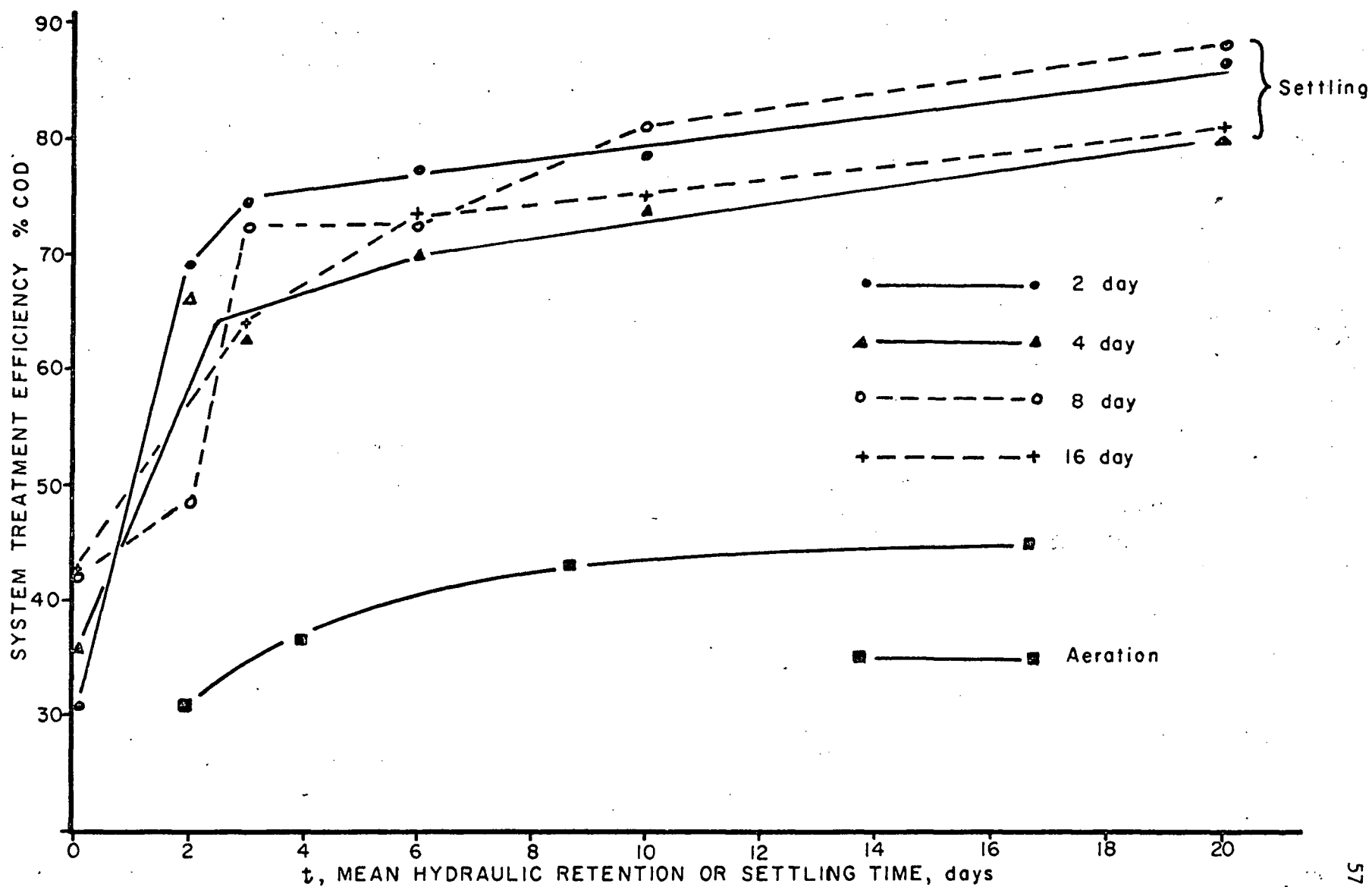


FIGURE 14. PERCENT COD REMOVAL WITH SETTLING TIME - 3°C - LOW LOADING

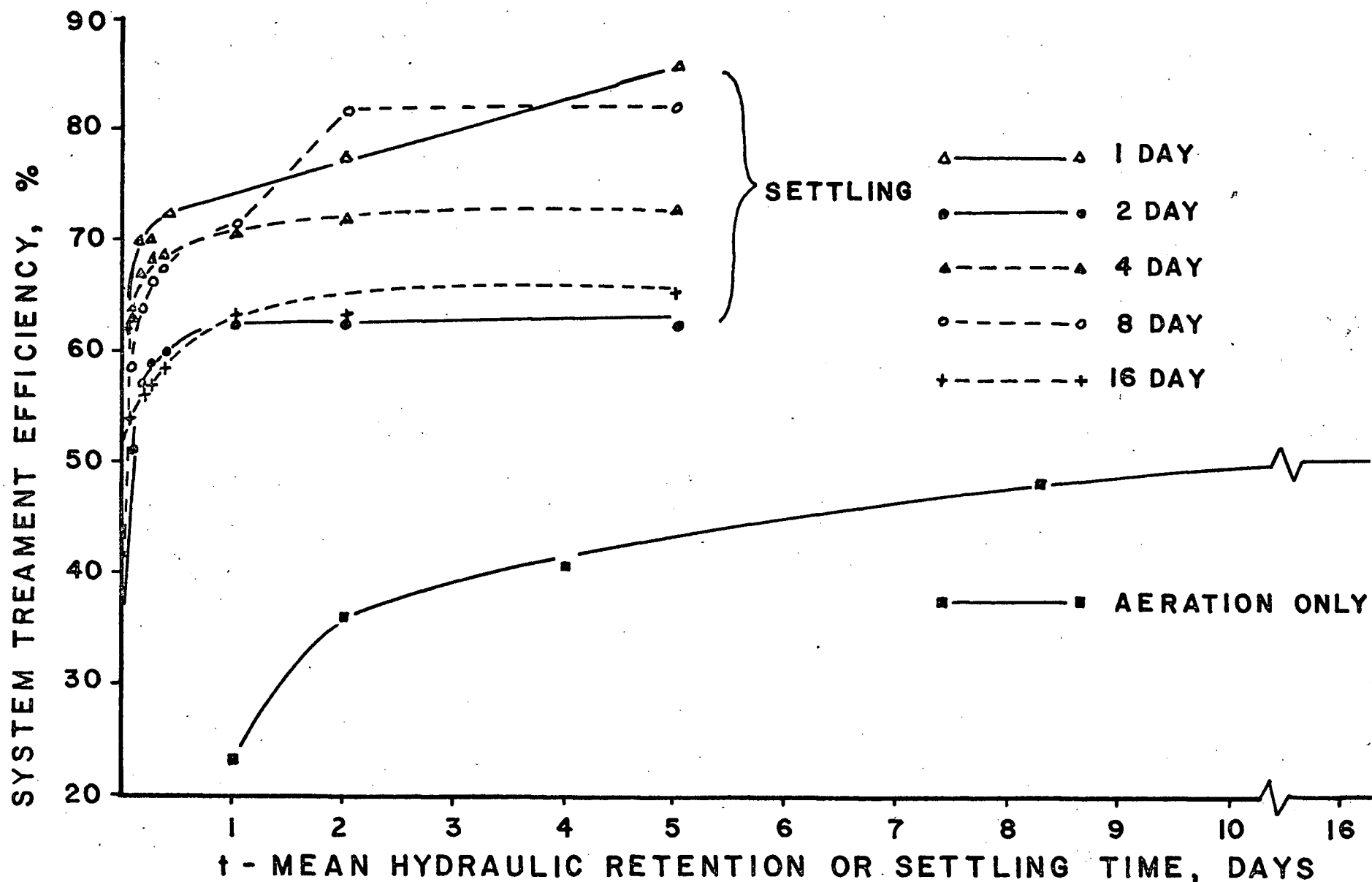


FIGURE 15. PER CENT COD REMOVAL WITH SETTLING TIME - HIGH LOADING <sup>58</sup>

The effect of aeration time on the settling rate does not follow any trend. However, the effluent from the reactors with the highest applied load for the two loadings responded most rapidly, and had the greatest overall improvement in system treatment efficiency (62 per cent for the one-day reactor at high loading and 47 per cent for the two-day reactor at low loading) after five days settling.

A comparison of Figure 15 with Figure 16, which is a plot of supernatant MLSS against settling time at the high loading, shows a general trend of decreasing COD with decreasing suspended solids. A numerical evaluation of COD removal in terms of MLSS settled, was not performed, as the MLSS numbers must be considered suspect. The very low MLSS levels, and the necessity of taking small samples (40 mls) so as not to unduly affect the settling test, resulted in very small weighing differences after one day (0.0 to 1.3 mg).

The substantial increase in system treatment efficiency with settling, relative to the two to 15 per cent reported (7)(35)(46), can be explained in part by the higher COD or  $BOD_5$  per unit of MLSS found in this study. The increase may also be due in part to a possible change in the settling characteristics of ASB biological solids at low temperature. This, however, would have to be substantiated by future studies.

Referring to Figures 15 and 16, and considering both MLSS and gross substrate removal, it can be seen that a number of combinations are available to give a desired removal efficiency and suspended solids level. For example, an effluent quality for 1200

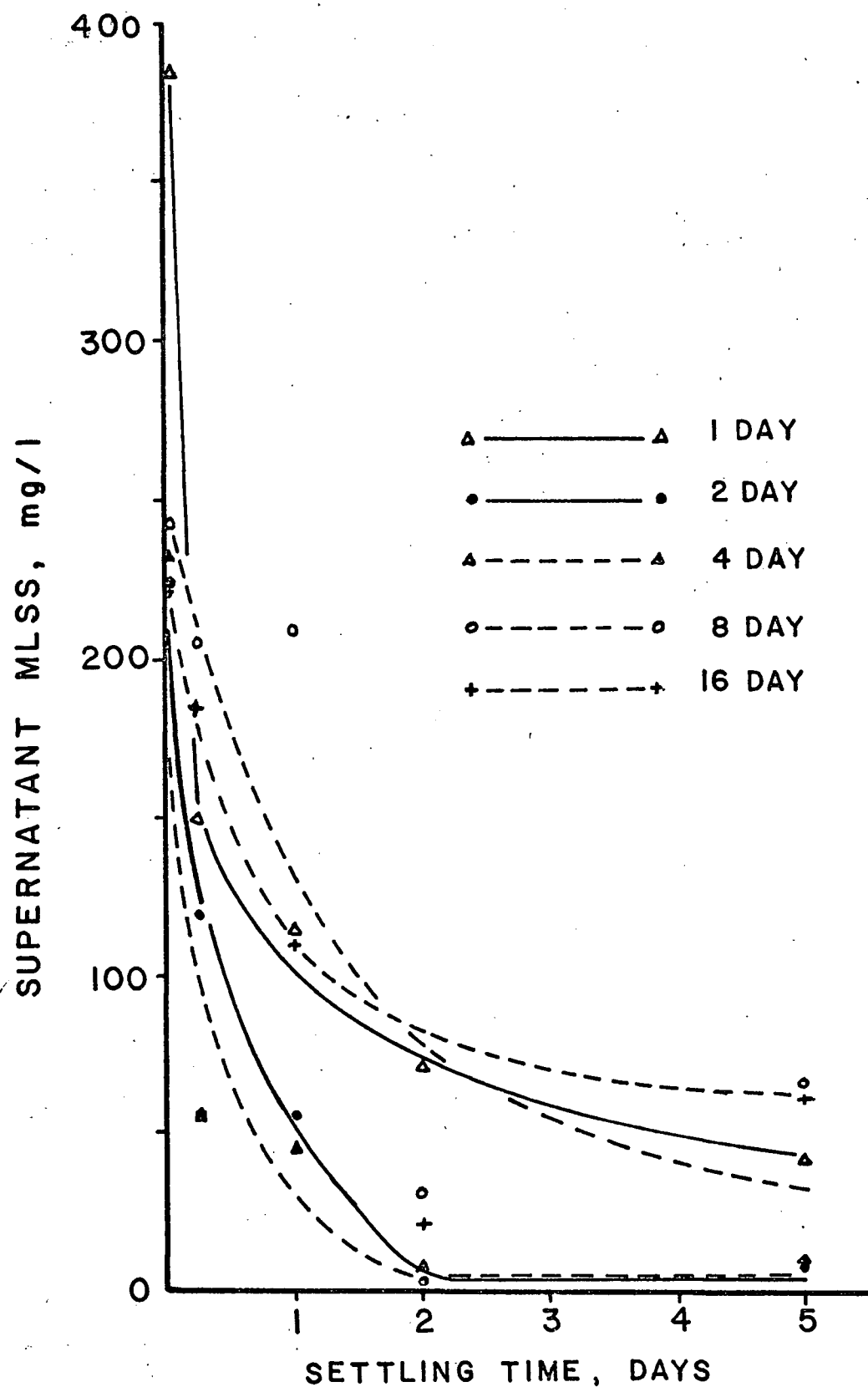


FIGURE 16. SUPERNATANT MLSS VS SETTLING TIME  
3° C - HIGH LOADING



mg/l feed, of 60 mg/l mixed liquor suspended solids and a system treatment efficiency of 70 per cent can be achieved by: (a) four days' aeration with one-half days' settling; (b) one day's aeration with  $2\frac{1}{2}$  days' settling; (c) eight days' aeration with  $2\frac{1}{2}$  days' settling. In contrast, the desired effluent quality could not be achieved by using any combinations of the two and sixteen day aerations. Therefore, in terms of both percentage removal and suspended solids level, the effluent quality does not necessarily reflect the length of retention time -- aeration or settling, but is a function of both.

It is not the intent of this discussion to suggest that the same results would be found for other wastes, or even for this waste, at a temperature other than  $3^{\circ}\text{C}$ . Rather, it is suggested that when there are effluent suspended solids restrictions and settling facilities are required, the design of the system should take into consideration the relationship between settling and gross substrate removal and, in turn, settling time with aeration time.

#### IV.6 NITROGEN STUDIES

IV.6.1 General. Analysis for the various nitrogen compounds was undertaken to find: (a) if nitrification was occurring at  $3^{\circ}\text{C}$ ; (b) the amount of nitrogen in the solids; and (c) if the retention time had any effect on the balance of nitrogen compounds. Sufficient nitrogen was available in the feed to ensure that it would not be growth limiting. The presence of  $\text{NH}_3$  nitrogen in the reactors substantiates this.

IV.6.2 Nitrate Nitrogen. The concentration of nitrate nitrogen in the reactors varied from 0.2 mg/l to 0.6 mg/l, with the majority of the samples falling between 0.3 mg/l and 0.5 mg/l. No apparent relation exists between

the nitrate concentration and retention time, loading, or test duration. The feed water contained about 0.4 mg/l nitrate nitrogen and it is likely that this is the major source of nitrate nitrogen in the reactors. Due to the high background level it was impossible to determine whether or not nitrification was taking place. Wild *et al.* (44), studying nitrification kinetics, documented very reduced nitrification at 5°C with a decrease in activity with decreasing temperature.

IV.6.3 Nitrogen Balance. The gross kjeldahl nitrogen or total nitrogen in the system, ignoring the nitrate concentration, averaged 29.6 mg/l at the low loading and 66.4 mg/l at the high loading and in each case was within experimental limits of the feed. Gross nitrogen concentrations measured in the reactors at the two loadings are listed in Table 11.

Plotted in Figure 17 against retention time are the concentrations of the filtered organic and  $\text{NH}_3$  nitrogen, and the concentrations of the nitrogen tied up with the solids for the high loading. As can be seen from Figure 17, the concentration of nitrogen in the solids decreases with retention time and is reflected by an increase in the filtered  $\text{NH}_3$  concentration. The organic nitrogen concentration remains constant with retention time, which suggests that bacteria capable of converting organic nitrogen to  $\text{NH}_3$  are well established in each reactor. A rigorous explanation as to why the proportion of nitrogen tied up with the solids decreases with retention time is not available. However, the increase in  $\text{NH}_3$  nitrogen concentration in the reactors, without a change in the organic nitrogen concentration, would suggest that the decrease in nitrogen in the bacterial solids is due to a release of  $\text{NH}_3$  through endogenous oxidation of the solids.

TABLE 11

## GROSS KJELDAHL NITROGEN CONCENTRATIONS

---

 Low Loading - Feed Concentration 30.3 mg/l:

RETENTION TIME (Days)	GROSS CONCENTRATION
2	29.4 mg/l
4	29.2 mg/l
8	30.4 mg/l
16	29.4 mg/l

---

High Loading - Feed Concentration 66.0 mg/l:

RETENTION TIME (Days)	GROSS CONCENTRATION
1	66.3 mg/l
2	65.5 mg/l
4	66.6 mg/l
8	67.1 mg/l
16	66.6 mg/l

---

The nitrogen data for the low loading, as can be seen in Table 12, does not show any relationship to retention time.

TABLE 12

## AVERAGE NITROGEN CONCENTRATIONS - LOW LOADING

RETENTION TIME (Days)	GROSS KJELDAHL NITROGEN	NH <sub>3</sub> NITROGEN	INORGANIC NITROGEN
2	29.0 mg/l	4.1 mg/l	4.8 mg/l
4	29.6 mg/l	4.9 mg/l	5.8 mg/l
8	30.4 mg/l	3.4 mg/l	5.3 mg/l
16	29.4 mg/l	3.3 mg/l	9.1 mg/l

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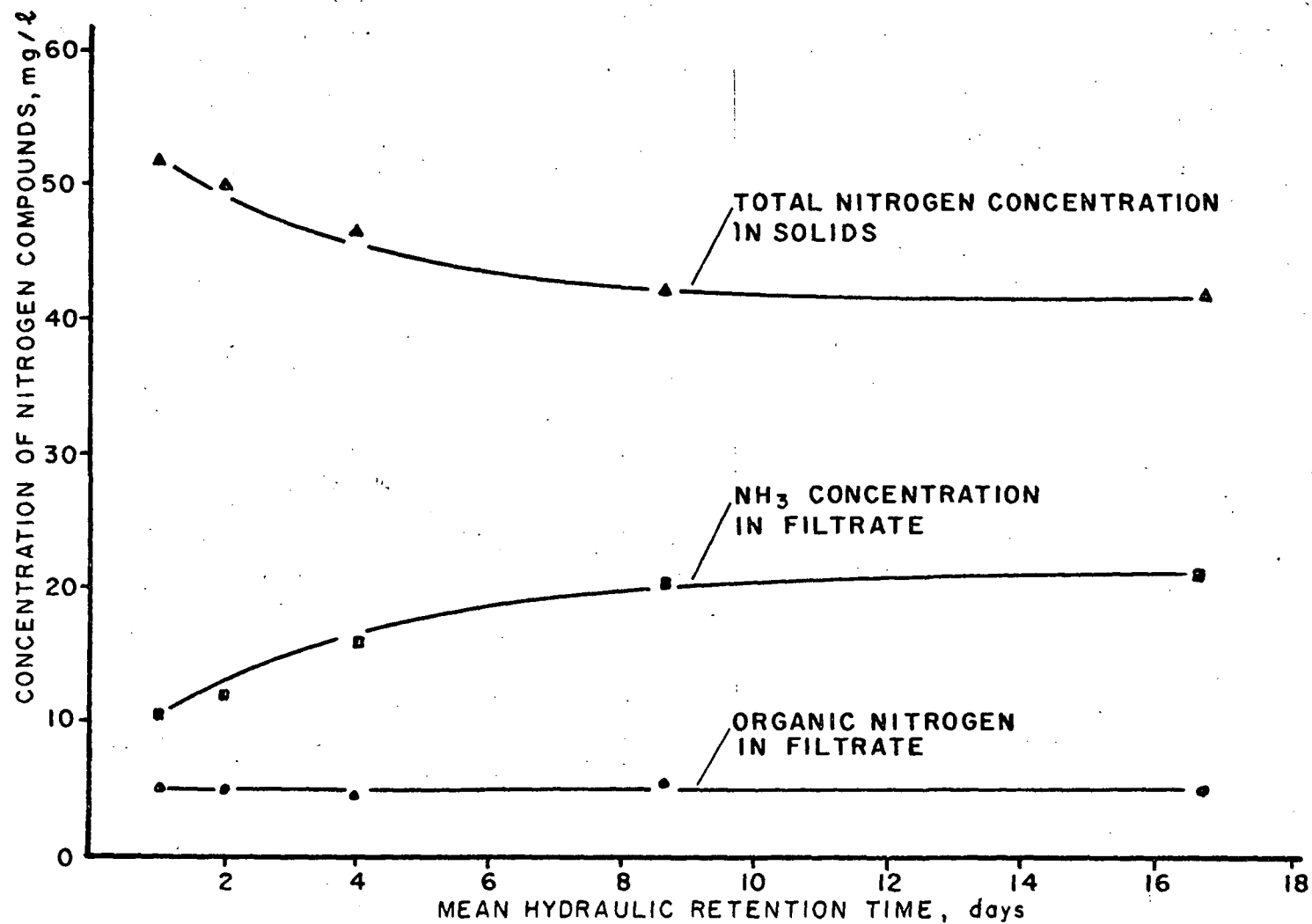


FIGURE 17 CONCENTRATION OF NITROGEN COMPOUNDS IN THE REACTOR SOLIDS AND FILTRATE AS A FUNCTION OF MEAN HYDRAULIC RETENTION TIME (HIGH LOADING).

The nitrogen used per hundred pounds of  $BOD_5$  applied measured in this study varied from 8.4 to 6.7 pounds at the low loading and 8.0 to 5.4 pounds at the high loading for hydraulic retention times of one to sixteen days. It should be noted that Ludzack *et al.* (25) found 5.6 to eight per cent nitrogen in activated sludge volatile suspended solids at  $5^{\circ}C$ . These values are approximately twice the nitrogen addition per hundred pounds of  $BOD_5$  removed reported for ASBs operating at temperatures of  $20^{\circ}C$  to  $35^{\circ}C$  (13)(7)(5)(1). This higher nitrogen requirement may be related to the higher COD and  $BOD_5$  of the biological solids measured in this study. However, it is quite possibly just an example of excess nutrient uptake by bacterial solids when there is a surplus of nutrients.

#### IV.7 pH

The pH of the reactor contents were nearly constant and remained slightly basic at 7.0 to 7.2.

#### IV.8 OXYGEN UTILIZATION

Oxygen uptake rates of 0.5 mg/l per hour in the sixteen day reactor to 5.3 mg/l per hour in the one day reactor were recorded at the high loading (see Figure 18). Oxygen utilization in biological systems is often expressed by the following equation:

$$O_2 \text{ lbs/day} = a' S_r \text{ lbs/day} - b' \text{ MLSS lbs/day} \quad (17)$$

where

- $a'$  = oxygen utilization coefficient, lbs  $O_2$  used/lb substrate removed;
- $S_r$  = substrate removed, lbs/day;
- $b'$  = endogenous respiration coefficient, %/day;
- MLSS = mixed liquor suspended solids, lbs.

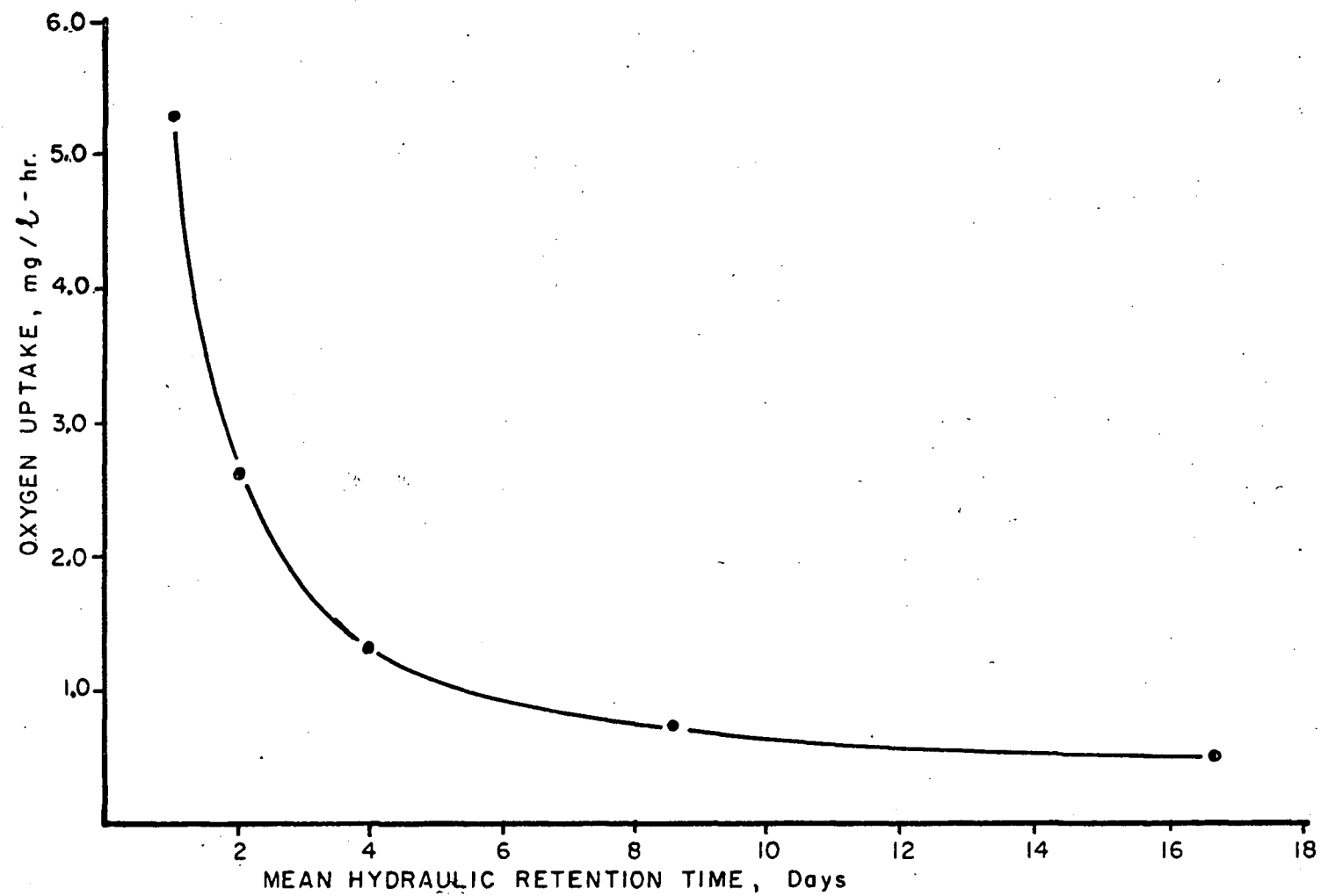


FIGURE 18. OXYGEN UPTAKE AGAINST RETENTION TIME

Figure 19, a plot of lbs oxygen used/lb MLSS against lbs substrate used/lb MLSS, yields  $a'$  as the slope and  $b'$  as the intercept. On a  $BOD_5$  basis,  $a'$  is 0.143 lbs  $O_2$ /lb substrate used in the two to sixteen day reactors. On a COD basis  $a'$  is 0.123 lbs  $O_2$ /lb substrate used in the two to sixteen day reactors and 0.156 lbs  $O_2$ /lb substrate used in the one day reactor. The endogenous respiration rate,  $b'$ , is 0.18 lbs  $O_2$ /lb MLSS per day, or 0.75 mg/hr per gram of MLSS in both cases -- as would be expected.

The endogenous respiration rate of 0.75 mg/hr per gram MLSS, or approximately 0.95 mg/hr per gram VSS (assuming VSS = 0.8 MLSS) is considerably lower than many reported values. Symons (10) reported a mean rate of 15 mg/hr per gram VSS for mixed sludges at room temperature. Porges (10) reported a rate of 12 mg/hr per gram VSS for dairy wastes. However, the rate is comparable to the 0.80 mg/hr per gram VSS respiration rate found by Esvelt *et al.* (14) for fruit processing wastes treated in an ASB at 6°C.

The depressed rate of endogenous respiration would indicate that endogenous oxidation is much slower at 3°C than at higher temperatures.

Shown in Figure 20 is a linear relationship between the filtered COD concentration remaining and the oxygen uptake rates. A comparison of Figures 19 and 20 would suggest that relationship between the oxygen uptake rate and the substrate remaining is likely better for the short retention times than the relationship between oxygen consumed and substrate removed.

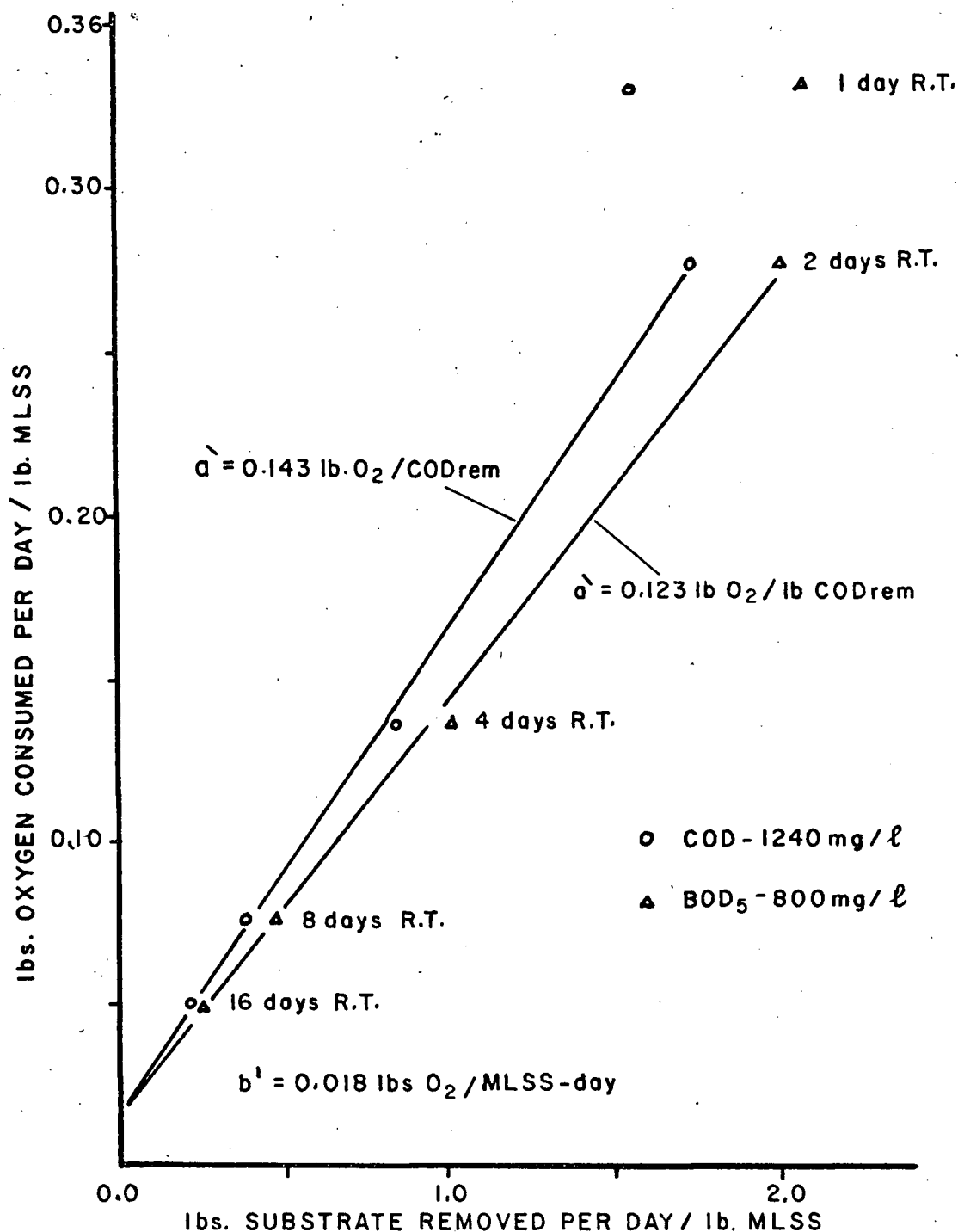


FIGURE 19. OXYGEN CONSUMPTION PER DAY AS A FUNCTION OF SUBSTRATE REMOVED PER DAY - HIGH LOADING.



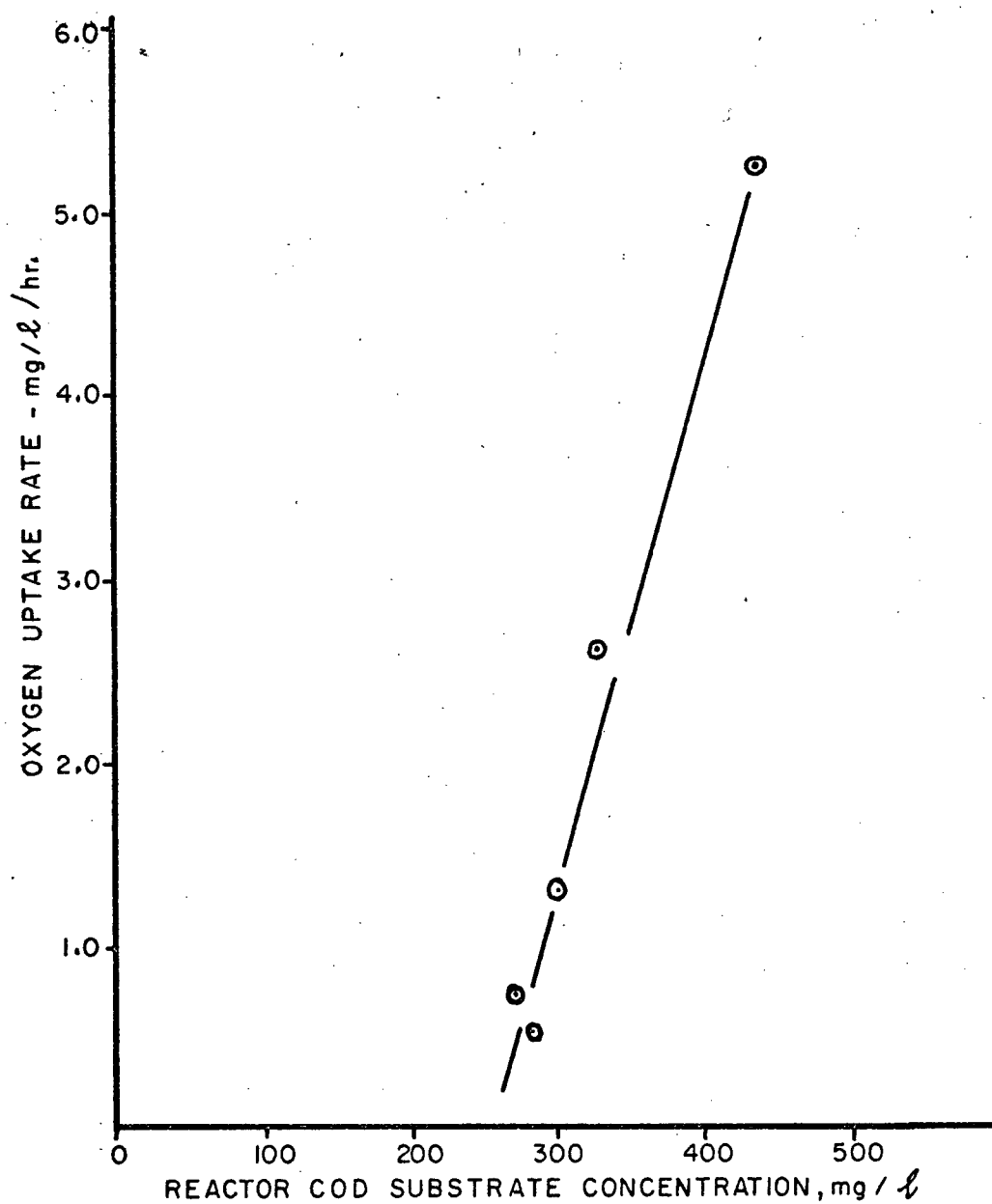


FIGURE 20. OXYGEN UPTAKE RATE AS A FUNCTION OF REACTOR SUBSTRATE CONCENTRATION

## CHAPTER V

### SUMMARY

The primary objectives of this study, the detailing of ASB operation at a cold temperature and the evaluation of that operation in terms of current ASB models, were fulfilled. Summarized below are the results of the study.

#### V.1 STEADY STATE

Steady state conditions were achieved at both loadings twenty-seven to twenty-nine days after the runs were initiated. Cyclic fluctuations of the filtered COD concentrations and, to a lesser extent, MLSS levels were noted at the higher loading.

#### V.2 PER CENT SUBSTRATE REMOVAL AND SYSTEM TREATMENT EFFICIENCY

1. Seventy-five to 85 per cent of the biodegradable portion of the raw milk waste was utilized in the ASBs within one to two days, and there was complete utilization of the biodegradable portion of the waste by eight days. The filtered COD data indicated the possible production of intermediate compounds which were utilized by about eight days at both loadings.

2. The system treatment efficiency varied with retention time from 18 per cent at two days to 80 per cent at 16 days on a  $BOD_5$  basis and from 23 per cent at one day to 51 per cent at 16 days on a COD basis.

3. The per cent substrate removal measured was higher than reported treatment efficiencies and is likely a different measurement. On the other hand,

the measured system treatment efficiencies were comparable to reported treatment efficiencies in ASBs operating at low temperature.

### V.3 MODEL EVALUATION

1. Only the Chemostat model would describe the substrate removal data measured in the laboratory ASBs at 3°C.

2. O'Connor and Eckenfelder's, McKinney's, and the first-order exponential models could not describe the substrate removal measured at 3°C. This inability to describe the substrate removal at 3°C could conceivably lessen the usefulness of these models.

3. O'Connor and Eckenfelder's, McKinney's, and the first-order exponential models would describe system treatment efficiency for mean hydraulic retention times greater than two days. These models appear to be applicable where endogenous oxidation is the main mechanism of BOD<sub>5</sub> or COD decay, but, on the basis of this study, are not applicable under growth conditions.

### V.4 SOLIDS PRODUCTION

1. Net solids production in the two to sixteen day ASBs was 0.25 - 0.27 lbs per pound of COD or BOD ultimate removed. In the one-day reactor, the net yield was higher, at 0.48 lbs per pound COD and 0.53 pounds per pound BOD ultimate. The net solids production was not significantly different from that reported in other ASB studies.

2. The COD and BOD<sub>5</sub> of the generated solids were significantly higher than reported values at higher temperatures; 1.35 - 2.10 mg COD per mg MLSS and 0.54 - 1.54 mg BOD<sub>5</sub> per mg MLSS. It is conceivable, although not proven, that the change in the characteristics of the generated solids may account in

part for the change in treatment efficiency reported with changes in the temperature of ASBs.

3. Post settling at 3°C of the ASB effluent resulted in significant increases (14% - 62%) in system treatment efficiency in addition to the removal of suspended solids. These increases in system treatment efficiency may be due to changes in settling characteristics as well as to the higher COD and BOD<sub>5</sub> of the MLSS measured at 3°C.

#### V.5 NITROGEN USAGE

1. Nitrification did not appear to be significant at 3°C.
2. The concentration of nitrogen compounds in the reactor solids decreased with retention time at the high loading. This decrease was reflected by an increase in the NH<sub>3</sub> nitrogen concentration in the effluent with increased retention time. The organic nitrogen concentration remains constant, suggesting endogenous oxidation as a possible mechanism for the release of NH<sub>3</sub> nitrogen.

#### V.6 pH

The pH in the reactors was slightly basic at 7.0 to 7.2.

#### V.7 OXYGEN UPTAKE

1. The oxygen uptake rates at the high loading varied from 5.25 mg/l/hr to 0.50 mg/l/hr for retention times of one to sixteen days.
2. The endogenous respiration rate was found to be 0.18 mg/l/hr or 0.75 mg/hr/gram MLSS.

3. Oxygen utilization was related linearly to substrate removed for retention times of two to sixteen days -- 0.143 lbs  $O_2$  used/lb  $BOD_5$  used and 0.123 lbs  $O_2$  used/lb COD used.

4. The oxygen uptake rate was related linearly to the COD substrate concentration remaining in the reactors for retention times of one to sixteen days.

## CHAPTER VI

### CONCLUSIONS

1. At 3°C twenty-seven to twenty-nine days were required at both loadings to achieve steady-state conditions in the reactors.
2. Seventy-five to 85 per cent of the biodegradable portion of raw milk was utilized within one to two days and there was virtually complete utilization within eight days.
3. System treatment efficiency varied from 18 to 80 per cent on a BOD<sub>5</sub> basis and 23 to 51 per cent on a COD basis.
4. The per cent substrate removal measured was higher than reported treatment efficiencies and is likely a different measurement. System treatment efficiency is comparable to and is assumed to be the same as reported treatment efficiencies.
5. The Chemostat method described the substrate removal data measured in the laboratory ASBs at 3°C. O'Connor and Eckenfelder's, McKinney's and the first-order exponential models could not describe the substrate removal measured at 3°C. This inability to describe the substrate removal could conceivably lessen the usefulness of these models.

6. O'Connor and Eckenfelder's, McKinney's and the first-order exponential models would describe system treatment efficiency for mean hydraulic retention times greater than two days. These models appear to be applicable where endogenous oxidation is the main mechanism of  $BOD_5$  or COD decay, but on the basis of this study are not applicable under growth conditions.

7. Net solids production for retention times of two days or greater is 25 to 27 per cent of the removed COD or  $BOD_u$ . For a retention time of one day net solids production is about 50 per cent of the removed COD or  $BOD_u$ .

8. The COD and  $BOD_5$  of the ASB solids were significantly higher than reported values at higher temperatures. It is conceivable although not proven, that the change in the characteristics of the generated solids may account in part for the changes in treatment efficiency reported with changes in the temperature of ASBs. The higher COD and  $BOD_5$  of the solids may be due to a decrease in the rate of endogenous oxidation.

9. Post settling of the ASB effluent at  $3^{\circ}C$  resulted in significant increases (14%-62%) in system treatment efficiencies. The most significant increases occurred at the shortest retention times and would suggest that dollars spent on increasing aeration time in response to expected cold temperatures, would be better spent on settling lagoons with a return of the solids for digestion during the warmer months. This point requires further investigation.

10. Nitrification did not appear to be significant at  $3^{\circ}C$ . The concentration of Kjeldahl nitrogen in the ASB solids decreased with retention time at

the high loading. This decrease was reflected by an increase in the  $\text{NH}_3$  nitrogen concentration in the reactor filtrate. The organic nitrogen concentration in the filtrate remained constant suggesting endogenous oxidation as a possible mechanism for the release of  $\text{NH}_3$  nitrogen.

11. The endogenous respiration rate was found to be 0.75 mg/hr/gram MLSS which supports the conclusion of the reduced rate of endogenous oxidation of solids at  $3^\circ\text{C}$ .

12. Oxygen utilization was related linearly to substrate removed for retention times of two to sixteen days - 0.143 lbs  $\text{O}_2$ /lb  $\text{BOD}_5$  removed or 0.123 lbs  $\text{O}_2$  used/lb COD used. The oxygen uptake rate was also related linearly to the COD substrate concentrate remaining in the reactors for retention times of one to sixteen days. In addition the curve showing oxygen uptake rate as a function of hydraulic retention time takes the same form as the Chemostat model which follows from the relationship to substrate concentration.



## CHAPTER VII

### RECOMMENDATIONS

1. The high levels of COD and BOD<sub>5</sub> per unit of suspended solids and the low endogenous respiration rate found in this study suggest that the decrease in system treatment efficiency at low temperatures may be related in part to the make-up of the solids produced and to endogenous oxidation. To prove this supposition, a continuation of this study at at least two other temperatures, preferably 8°C and 15°C is recommended. In addition, another two reactors with retention times of ½ and 3/4 days could be added to verify the Chemostat model. Particular attention should be paid to improving MLSS determination, possibly using a power filter. In addition to the tests conducted in this study, long-term oxidation studies are recommended in order to establish the temperature effect on endogenous oxidation.

2. Due to the inability of the current ASB models, with the exception of the Chemostat, to describe the substrate removal measured in this study, a complete evaluation of these models should be undertaken. The evaluation should take into consideration both substrate removal and system treatment efficiency over a range of temperatures.

3. In view of the practical implications of the settling tests, further and more comprehensive studies are recommended. These studies should include settling tests on the effluent from field installations, as well as from laboratory scale basins, over a range of retention times and temperatures.

4. A repetition of the tests using several industrial wastes is also recommended, in order to reinforce any conclusions drawn from the milk waste study.

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## APPENDIX A

### EXPERIMENTAL DATA





TABLE A-2

GROSS COD RESULTS  
(630 mg/l feed)

DATE	2 DAY		4 DAY		8 DAY		16 DAY	
	COD mg/l	% REMOVAL	COD mg/l	% REMOVAL	COD mg/l	% REMOVAL	COD mg/l	% REMOVAL
10/7/72	415	43.2	383	39.2	353	44.0	337	47.5
12/7/72	440	26.5	381	36.5	370	40.0	381	36.5
14/7/72	428	30.0	393	35.5	356	45.0	356	45.0
18/7/72	464	29.0	430	34.0	364	44.0	351	46.0
21/7/72	410	33.0	388	37.0	350	43.0	327	47.0
24/7/72	386	34.5	355	39.5	333	43.5	310	47.3
AVERAGES		31.2		36.9		43.3		44.9



TABLE A-5

MLSS DATA mg/l  
(600 mg/l milk feed)

D A T E	2 DAY	4 DAY	.8 DAY	16 DAY
3/7/72	104	111	108	105
10/7/72	112	140	123	120
17/7/72	102	128	127	122
21/7/72	111	90	-	96
24/7/72*	152	137	101	103
* Failure of temperature room				

TABLE A-6

NITROGEN DATA mg/l  
(600 mg/l milk feed)

	DATE	2 DAY	4 DAY	8 DAY	16 DAY
GROSS KJELDAHL NITROGEN	10/7/72	--	30.0	30.8	29.2
	14/7/72	29.7	29.7	30.0	30.3
	18/7/72	28.3	29.0	30.5	28.6
	AVERAGE	29.0	29.6	30.4	29.4
-----					
NH <sub>3</sub> NITROGEN	10/7/72	1.9	6.2	3.9	2.2
	14/7/72	5.9	3.3	3.4	3.1
	18/7/72	4.5	3.1	2.8	4.5
	AVERAGE	4.1	4.9	3.4	3.3
-----					
INORGANIC NITROGEN	10/7/72	3.4	2.8	5.3	5.6
	14/7/72	7.3	5.9	-	10.6
	18/7/72	3.9	8.6	5.3	11.2
	AVERAGE	4.8	5.8	5.3	9.1

TABLE A-7

SETTLING DATA  
(630 mg/1 COD feed)

SETTLING TIME	2 DAY EFFLUENT		4 DAY EFFLUENT		8 DAY EFFLUENT		16 DAY EFFLUENT	
	COD mg/1	% REMOVAL	COD mg/1	% REMOVAL	COD mg/1	% REMOVAL	COD mg/1	% REMOVAL
2 DAY	197	68.8	213	66.0	330	47.7	242	61.7
3 DAY	166	73.6	242	61.7	159	75.0	229	63.7
6 DAY	146	77.0	191	70.0	159	75.0	185	70.5
10 DAY	140	78.0	166	73.8	121	80.8	159	75.0
20 DAY	85	86.5	130	79.2	68	89.0	123	80.5

TABLE A-8

FILTERED COD DATA  
(1240 mg/l COD feed)

DATE	1 DAY		2 DAY		4 DAY		8 DAY		16 DAY	
	COD mg/l	% REMOVAL	COD mg/l	% REMOVAL	COD mg/l	% REMOVAL	COD mg/l	% REMOVAL	COD mg/l	% REMOVAL
25/8/72	478	61.7	237	74.3	403	68.2	221	82.7	299	76.6
28/8/72	486	61.2	320	68.9	217	82.6	--	--	312	75.0
30/8/72	474	62.1	388	64.5	306	74.6	140	88.8	342	72.6
1/9/72	457	63.7	442	72.8	466	62.5	202	83.8	213	82.7
3/9/72	455	64.0	332	78.7	248	79.6	316	74.0	301	75.2
8/9/72	348	71.2	256	78.9	248	79.7	310	74.2	233	80.4
11/9/72	402	68.3	258	78.9	205	83.2	455	62.7	311	74.5
14/9/72	374	69.4	253	79.2	298	75.4	351	71.0	298	75.4
AVERAGE	438	65.2	311	74.5	300	75.7	285	76.8	288	76.5

TABLE A-9  
GROSS COD DATA  
(1240 mg/l COD feed)

DATE	1 DAY		2 DAY		4 DAY		8 DAY		16 DAY	
	COD mg/l	% REMOVAL	COD mg/l	% REMOVAL	COD mg/l	% REMOVAL	COD mg/l	% REMOVAL	COD mg/l	% REMOVAL
25/8/72	990	20.5	764	40.4	695	45.5	602	51.7	595	53.5
28/8/72	1045	16.5	786	37.0	740	40.5	635	49.0	635	49.0
30/8/72	980	21.5	783	37.4	769	38.5	644	48.5	590	52.8
1/9/72	922	26.6	798	35.8	737	40.7	660	46.8	621	50.0
3/9/72	920	27.1	780	35.8	750	38.3	634	47.9	618	49.1
8/9/72	1135	14.0	805	33.5	736	39.0	645	46.5	619	48.6
11/9/72	880	30.6	796	34.8	713	41.7	637	47.8	607	50.2
14/5/72	857	29.2	789	35.0	728	40.0	637	47.5	615	49.4
18/9/72	915	25.5	788	34.7	750	39.6	659	46.0	609	50.0
AVERAGES		23.5		36.0		46.4		48.0		50.0

TABLE A-10  
 FILTERED BOD<sub>5</sub> DATA  
 (800 mg/l BOD<sub>5</sub>)

DATE	1 DAY		2 DAY		4 DAY		8 DAY		16 DAY	
	BOD5 mg/l	% REMOVAL	BOD5 mg/l	% REMOVAL	BOD5 mg/l	% REMOVAL	BOD5 mg/l	% REMOVAL	BOD5 mg/l	% REMOVAL
23/8/72	160	80.0	17	97.9	43	94.7	10	98.7	11	98.6
25/8/72	230	71.2	28	96.5	18	97.7	16	98.0	20	97.5
1/9/72	212	73.5	25	96.9	27	96.6	--	--	--	--
8/9/72	140	82.5	19	97.6	14	98.2	20	97.5	13	98.4
14/9/72	---	--	20	97.5	16	98.0	17	97.9	23	97.0
AVERAGES	187	76.6	22	97.0	23	97.1	16	98.0	17	97.9



TABLE A-11

GROSS BOD<sub>5</sub> DATA  
(800 mg/l BOD<sub>5</sub> feed)

DATE	1 DAY		2 DAY		4 DAY		8 DAY		16 DAY	
	BOD <sub>5</sub> mg/l	% REMOVAL	BOD <sub>5</sub> mg/l	% REMOVAL	BOD <sub>5</sub> mg/l	% REMOVAL	BOD <sub>5</sub> mg/l	% REMOVAL	BOD <sub>5</sub> mg/l	% REMOVAL
16/8/72	510	36.2	303	62.1	296	63.0	210	73.7	129 <sup>*</sup>	84.0
23/8/72	500	37.5	280	65.0	315	60.6	215	73.1	180	77.5
25/8/72	528	33.0	288	64.0	300	61.7	200	75.0	178	77.7
13/9/72	360	55.0 <sup>**</sup>	325	59.4	315	60.6	233	70.9	220	72.5
AVERAGES	515	35.6	300	62.5	306	61.0	215	73.2	177	76.6
	<sup>*</sup> Not at steady state <sup>**</sup> Not average									

TABLE A-12

MLSS DATA  
(1200 mg/l milk feed)

DATE	1 DAY	2 DAY	4 DAY	8 DAY	16 DAY
25/8/72	360	233	218	263	--
28/8/72	333	225	230	248	--
30/8/72	357	210	253	230	290
1/9/72	340	200	233	223	255
5/9/72	280	153	198	242	250
8/9/72	470	210	217	220	185
11/9/72	390	243	235	228	195
13/9/72	435	285	258	273	215
18/9/72	505	258	255	268	173

TABLE A-13

NITROGEN DATA mg/l  
(1200 mg/l milk feed)

	DATE	1 DAY	2 DAY	4 DAY	8 DAY	16 DAY
GROSS KJELDAHL NITROGEN	25/8/72	67.3	--	67.0	66.3	67.2
	1/9/72	65.0	65.0	66.9	66.1	66.6
	8/9/72	--	66.5	66.5	66.5	67.6
	13/9/72	63.0	65.0	66.5	67.5	69.5
-----						
NH <sub>3</sub> NITROGEN	28/8/72	18.0	9.8	21.8	24.0	14.6
	5/9/72	15.0	10.9	12.9	7.6	19.6
	18/9/72	5.6	10.7	14.0	24.2	22.8
	25/9/72	3.36	16.2	14.0	12.9	24.2
-----						
ORGANIC NITROGEN	28/8/72	6.2	5.6	4.5	4.2	4.8
	5/9/72	4.2	4.8	2.5	4.9	-
	18/9/72	4.5	5.5	3.4	5.0	4.5
	25/9/72	5.6	4.3	5.0	6.2	5.0

TABLE A-14

BATCH SETTLING DATA  
(1230 mg/l COD feed)

SETTLING TIME (Hours)	1 DAY EFFLUENT			2 DAY EFFLUENT			4 DAY EFFLUENT			8 DAY EFFLUENT			16 DAY EFFLUENT		
	COD mg/l	% REMOVAL	MLSS mg/l	COD mg/l	% REMOVAL	MLSS mg/l	COD mg/l	% REMOVAL	MLSS mg/l	COD mg/l	% REMOVAL	MLSS mg/l	COD mg/l	% REMOVAL	MLSS mg/l
2	475	61.7	--	606	51.1	--	468	62.2	--	521	58.0	--	575	53.5	--
4	375	69.7	--	530	57.2	--	413	66.6	--	452	63.6	--	552	58.0	--
6	375	69.7	150	521	58.0	120	390	68.5	55	413	66.6	205	552	58.0	185
8	343	72.3	--	502	59.5	--	399	67.8	--	399	67.8	--	516	58.3	--
24	343	72.3	115	478	61.4	55	359	71.0	45	351	71.6	210	454	63.4	110
48	276	77.7	65	470	62.1	0	347	72.0	0	213	82.8	30	466	62.4	20
120	171	86.0	40	490	60.4	10	314	74.7	10	250	79.8	40	432	65.2	60

TABLE A-15

## NITRATE NITROGEN DATA

	LOADING	1 DAY	2 DAY	4 DAY	8 DAY	16 DAY
12/7/72	Low	---	0.48 mg/l	0.35 mg/l	0.25 mg/l	0.20 mg/l
18/7/72	Low	---	0.43 mg/l	0.36 mg/l	0.56 mg/l	0.23 mg/l
24/7/72	Low	---	0.56 mg/l	0.41 mg/l	0.31 mg/l	0.46 mg/l
12/9/72	High	0.46 mg/l	0.36 mg/l	0.41 mg/l	0.34 mg/l	0.44 mg/l
28/9/72	High	0.49 mg/l	0.46 mg/l	0.45 mg/l	- negl -	0.51 mg/l

## APPENDIX B

### TEST DATA PERTAINING TO THE DETERMINATION OF STEADY STATE OPERATION

#### LOW LOADING

TABLE B-1

## SYSTEM TREATMENT EFFICIENCY

LOW LOADING -- COD

START UP TO STEADY STATE

DATE	TIME ELAPSED	2 DAYS R.T.	4 DAYS R.T.	8 DAYS R.T.
27/6/72	11 Days	33%	42%	40%
29/6/72	13 Days	45%	68%	47%
4/7/72	18 Days	39%	40%	41%
7/7/72	21 days	42%	42%	42%
----- STEADY STATE -----				
14/7/72	28 days	30%	35%	45%
18/7/72	32 days	29%	34%	44%
21/7/72	35 days	33%	37%	43%
24/7/72	39 days	34%	39%	44%

## APPENDIX C

CALCULATIONS OF THE CONSTANTS K7 AND K10  
FOR USE IN MCKINNEY'S DESIGN EQUATIONS



Average values for McKinney's constants  $K_7$  and  $K_{10}$  were found by fitting the test data to a linear equation incorporating McKinney's three equations.

$$F = \frac{F_i}{K_5 t + 1} \quad (3)$$

$$M_a = \frac{K_6 F}{1/t + K_7} \quad (4)$$

$$F_e = F + K_{10} M_a \quad (5)$$

where

$$K_5 = 108 \text{ day}^{-1} \quad (\text{extrapolated to } 3^\circ\text{C})$$

and

$$K_6 = 72 \text{ day}^{-1} \quad (\text{extrapolated to } 3^\circ\text{C})$$

Assume for purposes of this calculation

$$F_e \approx K_{10} M_a \quad \text{since} \quad K_{10} M_a \gg F$$

Substituting Equation (3) into Equation (4) gives

$$M_a = \frac{K_6 \cdot F_i}{(1/t + K_7)(K_5 \cdot t + 1)}$$

Substituting for  $M_a$  in Equation (5) gives

$$F_e = \frac{K_{10} \cdot K_6 \cdot F_i}{(1/t + K_7)(K_5 t + 1)}$$

which is reworked to

$$\frac{F_e (K_5 t + 1)}{F_1 \cdot K_6} \cdot \frac{1}{t} = \frac{-K_7 (F_e) (K_5 t + 1)}{F_1 \cdot K_6} + K_{10}$$

in a

$$y = mx + b \text{ form}$$

where

$$y = \frac{F_e (K_5 \cdot t + 1)}{F_1 \cdot K_6} \cdot \frac{1}{t}$$

$$x = \frac{F_e (K_5 t + 1)}{F_1 \cdot K_6}$$

$$m = -K_7$$

and

$$b = K_{10}$$

Listed in Table C-1 are the calculated x's and y's for the two loadings. Figure C-1 is the plot of x against y for the two loadings. From this plot the average  $K_7$  values are  $0.086 \text{ day}^{-1}$  for the low loading and  $0.076 \text{ day}^{-1}$  for the high loading.

The  $K_{10}$  values are  $0.79 \text{ mg/mg}$  for the low loading and  $0.70 \text{ mg/mg}$  for the high loading.

TABLE C-1

RETENTION TIME	FEED (mg/l)	$\frac{F_e \cdot (K_5 t + 1)}{F_1 \cdot K_6} \cdot \frac{1}{t}$	y	$\frac{K_7 (F_e) \cdot (K_5 t + 1)}{F_1 \cdot K_6}$	mx
1	800	$\frac{515(108 \cdot 1 + 1)}{800 \cdot 72} \cdot \frac{1}{1}$	0.955	$-K_7 \frac{515(108 \cdot 1 + 1)}{800 \cdot 72}$	$-0.955K_7$
2	290	$\frac{238(108 \cdot 1.97 + 1)}{290 \cdot 72} \cdot \frac{1}{1.97}$	1.22	$-K_7 \frac{238(108 \cdot 1.97 + 1)}{290 \cdot 72}$	$-2.44K_7$
2	800	$\frac{300(108 \cdot 1.97 + 1)}{800 \cdot 72} \cdot \frac{1}{1.97}$	0.57	$-K_7 \frac{300(108 \cdot 1.97 + 1)}{800 \cdot 72}$	$-1.15K_7$
4	290	$\frac{100(108 \cdot 3.96 + 1)}{290 \cdot 72} \cdot \frac{1}{3.96}$	0.57	$-K_7 \frac{137(108 \cdot 3.96 + 1)}{290 \cdot 72}$	$-2.25K_7$
4	800	$\frac{306(108 \cdot 3.96 + 1)}{800 \cdot 72} \cdot \frac{1}{3.96}$	0.57	$-K_7 \frac{306(108 \cdot 3.96 + 1)}{800 \cdot 72}$	$-2.25K_7$
8	290	$\frac{99(108 \cdot 8.6 + 1)}{290 \cdot 72} \cdot \frac{1}{8.6}$	0.52	$-K_7 \frac{99(108 \cdot 8.6 + 1)}{290 \cdot 72}$	$-4.46K_7$
8	800	$\frac{215(108 \cdot 8.6 + 1)}{800 \cdot 72} \cdot \frac{1}{8.6}$	0.40	$-K_7 \frac{215(108 \cdot 8.6 + 1)}{800 \cdot 72}$	$-3.44K_7$
16	290	$\frac{46(108 \cdot 16.7 + 1)}{290 \cdot 72} \cdot \frac{1}{16.7}$	0.31	$-K_7 \frac{215(108 \cdot 16.7 + 1)}{290 \cdot 72}$	$-5.12K_7$
16	800	$\frac{177(108 \cdot 16.7 + 1)}{800 \cdot 72} \cdot \frac{1}{16.7}$	0.35	$-K_7 \frac{177(108 \cdot 16.7 + 1)}{800 \cdot 72}$	$-5.8 K_7$

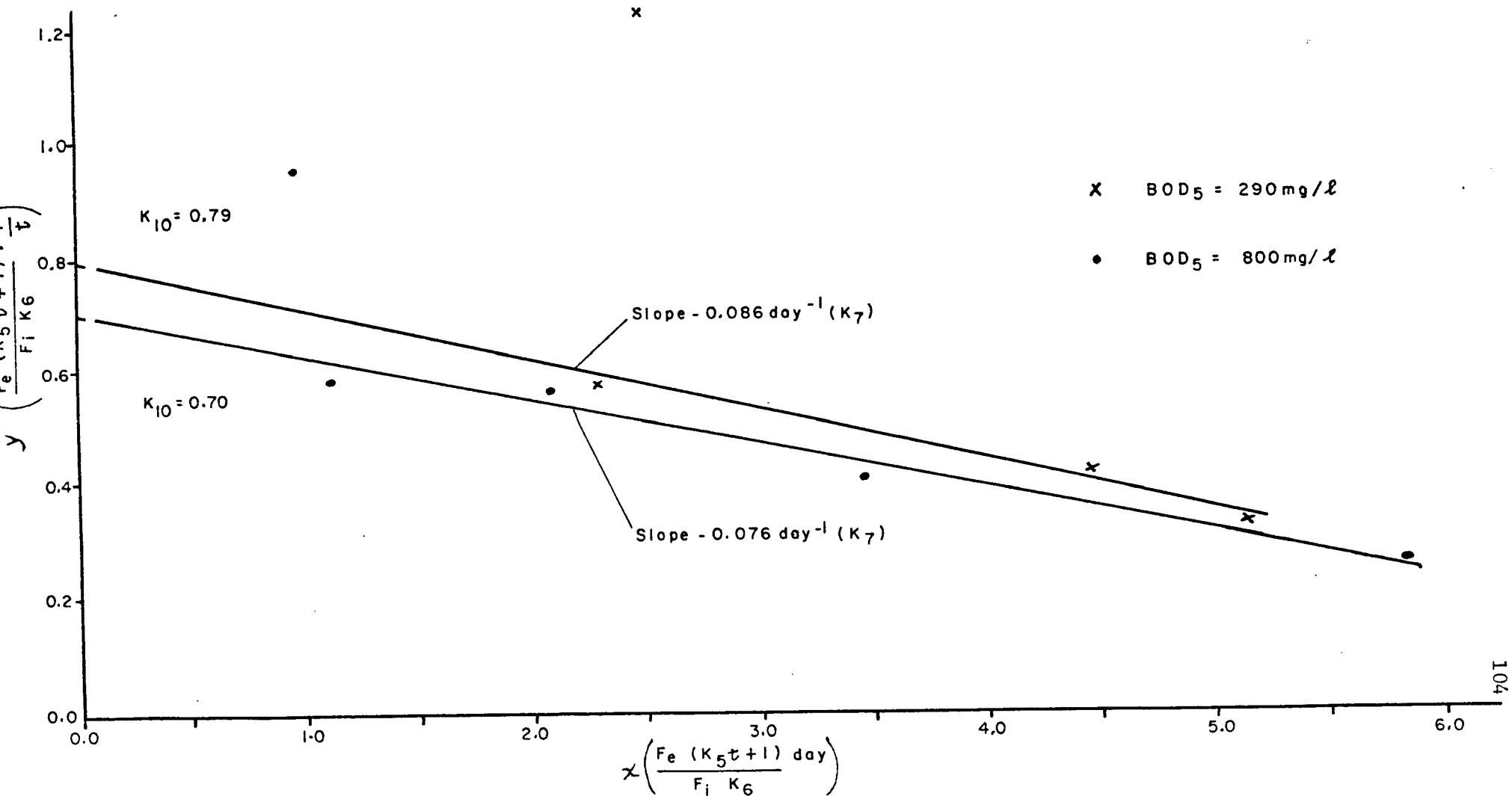


FIGURE C-1 GROSS EFFLUENT BOD<sub>5</sub> DATA IN  $y = mx + b$  FORM