

EFFECTS OF LOW TEMPERATURE ON THE
ACTIVATED SLUDGE PROCESS

by

Michael Schulz

Submitted in partial fulfillment
of the requirements for the degree of
Master of Applied Science

Department of Civil Engineering
School of Graduate Studies
University of Ottawa
Ottawa, Canada
July, 1972

PREFACE

This study was performed to investigate quantitatively the effect of low temperatures on the parameters used for the design and operation of conventional activated sludge sewage treatment plants. Reaction kinetics, sludge yield, oxygen utilization and efficiencies were evaluated at 5 and 20°C using laboratory scale activated sludge units which consisted of a simple reactor containing both an aeration and settling chamber. A total of 29 bench scale tests were conducted at various organic loading rates and sludge concentrations using a synthetic waste as substrate. Daily tests included chemical oxygen demand (COD) of the influent and effluent, suspended (SS) and volatile suspended solids (VSS) determinations of the mixed liquor and effluent as well as oxygen uptake measurements.

The data obtained experimentally was evaluated on an IBM computer using regression analysis and the results showed that the bio-oxidation of a substrate at low temperature produces a higher sludge yield but requires less oxygen than at higher temperatures. Furthermore, the reaction rate coefficient increases with temperature resulting in a temperature coefficient (θ) of 1.029 in the 5 to 20°C range.

In summary the study provides data that can be applied in the design and operation of conventional activated sludge treatment plants, including detention times, sludge concentrations, sludge handling facilities and aeration equipment.

ACKNOWLEDGEMENTS

The author wishes to express appreciation to Dr. K.T. Brodersen for his counsel, guidance and support during the academic and technical preparation of this work. Special thanks are also extended to Mr. W. Tai for his laboratory assistance.

The author especially thanks his wife, Kristina, for her patience, personal sacrifices and help in preparing this manuscript.

TABLE OF CONTENTS

PREFACE	i
ACKNOWLEDGEMENTS	iii
TABLE OF CONTENTS	iv
LIST OF TABLES AND ILLUSTRATIONS	vi
LIST OF SYMBOLS AND ABBREVIATIONS	viii
CHAPTER 1 - INTRODUCTION	1
CHAPTER 2 - LITERATURE SURVEY	7
2.1 Effect of Temperature on the Efficiency of the Activated Sludge Process	7
2.2 Effect of Temperature on Settling	13
2.3 Biological Considerations	14
2.4 Design Criteria in Bio-Oxidation	23
2.4.1 Reaction Rate Constant	23
2.4.2 Reaction Kinetics	25
2.4.3 Sludge Yield	27
2.4.4 Oxygen Utilization	29
CHAPTER 3 - EXPERIMENTAL METHODS	32
3.1 Selection of Experimental Parameters	32
3.2 Apparatus and Equipment	35
3.3 Analytical Techniques	38
3.3.1 Oxygen Demand	39
3.3.2 Dissolved Oxygen Test	40
3.3.3 Oxygen Uptake Rate	40
3.3.4 Suspended Solids Analyses	41
3.3.5 Settling Tests	41
3.4 Research Procedures	41

CHAPTER 4 - RESULTS	47
4.1 COD vs BOD Correlation	48
4.2 Reaction Kinetics	48
4.3 Sludge Yield Study	55
4.4 Oxygen Utilization	59
4.5 Efficiencies	59
CHAPTER 5 - DISCUSSION	64
5.1 Reaction Kinetics	64
5.2 Sludge Yield Study	66
5.3 Oxygen Utilization	68
5.4 Efficiencies	69
CHAPTER 6 - CONCLUSIONS	71
CHAPTER 7 - SUGGESTIONS FOR FURTHER RESEARCH	73
BIBLIOGRAPHY	74
ADDITIONAL REFERENCES	77
APPENDIX A - EXPERIMENTAL DATA	A-1
APPENDIX B - SETTLING RATES	B-1

LIST OF TABLES AND ILLUSTRATIONS

FIGURE		PAGE
1.1	Conventional Activated Sludge Process	3
2.1	Selected Results from Experiments by Ludzack et al (14)	9
2.2	Performance of Biological Treatment Processes in Ontario from Townshend (32)	11
2.3	Effect of Temperature on the Generation Time of a Typical Mesophile (<u>E. Coli</u>) and a Psychrophilic Pseudomonad from Ingraham and Stokes (11)	16
2.4	Generation Times in Minutes from Ingraham (10)	17
2.5	Rates of Oxidation from Stokes and Larkin (29)	21
2.6	Mass Balance Diagram	26
2.7	Sludge Yield vs Temperature from Ludzack et al (14)	30
3.1	Continuous Flow Reactor	36
3.2	Research Apparatus	43
3.3	Sludge Concentrations and Organic Loading Rates at which Continuous Flow Units were to be Operated	45
4.1	BOD Curves of Milk Waste and Activated Sludge System Effluent	49
4.2	COD:BOD Correlation of Milk Waste	50
4.3	Reaction Kinetics of Activated Sludge System Treating Milk Waste at 5°C	51

FIGURE		PAGE
4.4	Reaction Kinetics of Activated Sludge System Treating Milk Waste at 20°C	52
4.5	Summary of Reaction Kinetics data	54
4.6	Sludge Yield of Activated Sludge System Treating Milk Waste	57
4.7	Summary of Sludge Yield data	58
4.8	Oxygen Utilization of Activated Sludge System Treating Milk Waste	60
4.9	Summary of Oxygen Utilization data	61
4.10	Efficiency of Activated Sludge System Treating Milk Waste at 5°C	62
4.11	Efficiency of Activated Sludge System Treating Milk Waste at 20°C	63

LIST OF SYMBOLS AND ABBREVIATIONS

a	Fraction of BOD applied that is converted to cellular material
a^1	Fraction of oxygen used for respiration
b	Endogenous reaction rate coefficient (time^{-1})
b_1	Endogenous respiration rate coefficient (time^{-1})
BOD ₅	5 day Biochemical oxygen demand (mg/l)
BOD _u	Ultimate Biochemical oxygen demand (mg/l)
COD	Chemical oxygen demand (mg/l)
DO	Dissolved oxygen (mg/l)
DX	Amount of sludge grown (gr.)
gr.	Gram
k	Reaction rate constant (base 10)
mg	Milligram
mg/l	Milligram per liter
MLSS	Mixed liquor suspended solids (mg/l)
MLVSS	Mixed liquor volatile suspended solids (mg/l)
OX	Oxygen requirement
Q	Flow through treatment process
S_e	Effluent BOD (mg/l)
S_o	Influent BOD (mg/l)
S_r	BOD applied (mg/l)
SS	Suspended solids (mg/l)

S	Soluble BOD in Aeration Tank (mg/l)
SVI	Sludge Volume Index
t	Time (hours)
T	Temperature (°C)
θ	Temperature coefficient
V	Volume of treatment process
VSS	Volatile suspended solids (mg/l)
X_a	Sludge concentration (mg/l)
X_v	Total solids in aeration tank (gr)

CHAPTER 1

INTRODUCTION

Technological developments and a large supply of natural resources have insured that Canadians enjoy one of the highest standards of living in the world. However, in order to maintain this high standard of living we are consuming many of the natural resources at a faster rate than they can be replenished by nature and some resources may soon be depleted unless proper resource management is implemented.

Although Canada probably has a greater supply of potable water than any other country, much of it is located in isolated areas and unfortunately some supplies are being threatened by the demands of our affluent society. Many of our rivers are on the verge of becoming open sewers as a result of discharge of inadequately treated industrial and domestic sewage. Legislation to curb pollution of these waterways by providing the required treatment for all wastes must be enforced.

The technology of waste treatment has advanced to such an extent that virtually any waste can be treated and safely discharged into any water course. The processes that can be employed to ensure adequate waste treatment are physical, chemical and biological in nature.

The activated sludge process, a flow diagram of which is found in figure 1.1, is a physical-biological process which has been developed in this century and is now extensively used in the field of waste treatment. To meet particular waste treatment requirements many variations of the conventional activated sludge process have been developed, among those being

- 1) Tapered Aeration
- 2) Step Aeration
- 3) Modified Aeration
- 4) Contact Stabilization
- 5) High Rate Activated Sludge
- 6) Extended Aeration
- 7) Aerated Lagoons

It has long been recognized that low temperatures have an adverse effect upon physical and biological waste treatment processes, which is caused essentially by a decrease in both the biological oxidation rates and settling velocities. Low temperatures affect the activated sludge process by decreasing not only biological activity in the aeration tank but also settling rates of the mixed liquor suspended solids in the primary and secondary clarifier. Although it is generally considered that the activated sludge process is less seriously

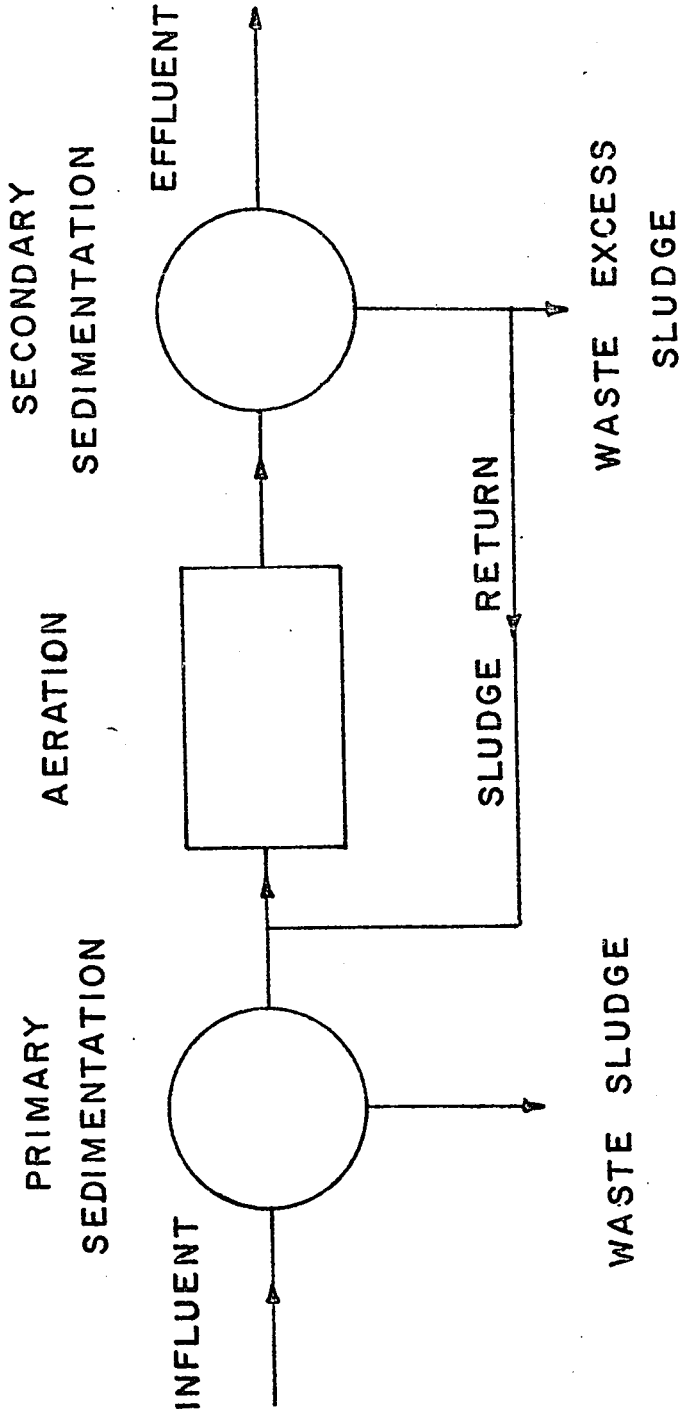


FIGURE 1-1 CONVENTIONAL ACTIVATED SLUDGE PROCESS

affected by temperature fluctuations than other biological treatment processes such as trickling filters and waste stabilization ponds, there is little agreement among various authors as to the extent that low temperatures influence the activated sludge process. Some authors feel that the efficiency is negligibly affected by temperature changes (Townshend (32) and Hawkes (7)) while others have noticed a significant difference (Ludzack et al (14), Keefer (12), Bloodgood (2) and Thomas (31)). Possible reasons for this discrepancy will be discussed in the next section. For the present let it suffice to say that in certain cases low temperatures have adversely affected the efficiencies of this process thus justifying research work in this field.

The opinion of some authors is that, while admitting possible adverse temperature effects during winter operation, the processes should be designed for conditions that prevail during the summer. McKinney (15) states that:

"Since the summer period is the most critical with regard to the stream's ability to absorb pollution the treatment plant design is usually based to handle the average load at summer temperatures."

While summer conditions may be critical for the climatic conditions encountered in most parts of the United States it may not be applicable for the majority of Canadian streams for the following two reasons:

(1) The higher D.O. saturation level at low temperatures is offset by the ice cover found on most Canadian rivers during the winter which reduces reaeration considerably.

(2) Canadian rivers are more likely to have low discharge conditions during the winter than their southern counterparts as more of the precipitation is in the way of snow which is stored until the spring thaw.

These two factors provide low assimilation capacities in most Canadian rivers during the winter. It should thus be obvious that, in order to maintain a sufficient dissolved oxygen level to sustain all life forms, the strength of organic wastes discharged into the river during the winter should be as low as possible. This dictates design and operation of treatment plants taking into account winter temperatures.

Present design practice to take into account low temperatures is to adjust the reaction rates of biological oxidation processes by means of a temperature coefficient, θ . However, this procedure is only appropriate if the biological species are the same at all temperatures which is not the case as will be shown later.

Presently, the effluent from secondary treatment plants is probably only a small total of the organic loading on a river as many wastes still receive no treatment or only primary treatment. When legislation is enforced that requires all water used either domestically or industrially be given secondary treatment it will be more important to achieve maximum efficiency from all plants. At that time it will be imperative to realize in what manner operating conditions can be adjusted in order to maintain optimum treatment at different temperatures.

Some of the factors that affect the operation of the activated sludge process are rates of biological oxidation, settling rates, organic loading, sludge concentration, sludge production and oxygen utilization.

The purpose of this study was to determine quantitatively the effect of low temperatures on the parameters used for design and operation of conventional activated sludge plants. More specifically, the factors affecting detention times, sludge handling facilities and oxygen requirements at 5 and 20°C were investigated by operating laboratory scale activated sludge units at various organic loading rates and sludge concentrations.

CHAPTER 2

LITERATURE SURVEY

Various authors have investigated the effect of low temperature on the efficiency of biological oxidation processes in general and the conventional activated sludge process in particular, however, there is little information in the literature concerning temperature effects at different organic loading rates. A review of the literature also reveals that various authors dealing with pure cultures have found that some micro-organisms grow quite well at low temperature while others do not. Furthermore, it has been observed that psychrophilic bacteria predominate in biological treatment processes at low temperatures whereas mesophiles predominate at higher temperatures. The effects of low temperature on the kinetics, sludge yield and oxygen utilization of the activated sludge process have also been covered in the literature.

2.1 Effect of Temperature on the Efficiency of the Activated Sludge Process

As early as 1944 Bloodgood (2) found that temperature affects the efficiency of the activated sludge process and that for a drop in temperature from 79°F (26°C) to 57°F (14°C) the aeration time had to be increased by 45 minutes to achieve

the same treatment. Similarly Thomas (31) presents data from an unidentified activated sludge plant during a severe winter and compares average effluent BOD values during February and August which show 13 and 9 mg/l respectively.

In a more recent study Keefer (12) gives data for an activated sludge plant in Baltimore which has a relatively constant hydraulic load. He notes that for flows between 18 and 22 mgd the efficiency measured in terms of BOD removed increased from 84.5 to 91.5 percent during a rise in temperature from 53°F (12°C) to 79°F (26°C). However, at a hydraulic load of 12 to 14 mgd the efficiency increases only from 90.5 to 92.1 percent during a temperature rise from 55°F (13°C) to 76°F (24°C).

In a laboratory study Ludzack et al (14) ran a series of activated sludge batch test to demonstrate the difference in performance at 5° and 30°C. A selection of their results is given in figure 2.1. It can be seen that efficiencies are generally lower at 5°C than at 30°C except in the case where a high BOD to nitrogen ratio was used.

Contrary to the above results Townshend (32) from a study of 90 conventional activated sludge plants in Ontario concluded that efficiencies are not appreciably affected during the

Figure 2.1 Selected Results from Experiments
by Ludzack et al (14)

Temperature °C	Feed Type	Length of run (wks)	Organic Loading ⁽¹⁾	5 day BOD removal (%)
5	A	5	.4	70-98
30	A	5	.6	88-97
5	B	1	.69	0-70
5	B	1	.72	70-96
5	B	1	.61	47-77
5	B	1	.80	40-77
5	B	1	1.23	40-60
30	B	5	.7	90-98
5	C	5	.5	57-86
30	C	5	.62	76-96
(2)				
5	D-1	5	.5	83-95
30	D-1	5	.75	49-94
5	D-2	5	.45	87-98
30	D-2	5	.5	88-98

(1) Organic loading is measured in terms of grams of ultimate BOD applied per gram of volatile suspended solids in the aeration tank.

(2) D-1 had a BOD to nitrogen ratio of 40:1 while D-2 had a 20:1 ratio.

A Slurried dog food meal
 B Dextrose and gelatin
 C Dog food meal, dextrose and gelatin
 D Phenol

winter. He did, however, note a marked decrease in performance during November and December. The deterioration of effluent quality of Extended Aeration plants is explained by the author to be a result of build up and loss of solids. The values given are those exceeded 50% of the time. 90 conventional activated sludge plants and 35 extended aeration plants are included in the study from which selected results are given in figure 2.2

Hawkes (7) without giving data, states that, although efficiency is expected to increase with temperature as a result of both increasing oxygen transfer rate and biological activity, little seasonal fluctuation in efficiency of Activated Sludge plants is noted.

The apparent discrepancy in the above research can probably be best explained on the basis of organic loading. Organic loading may be defined as a weight of oxygen demand applied per day per weight of micro-organisms. An example of this would be grams of ultimate BOD applied per gram of mixed liquor volatile suspended solids (M.L.V.S.S.) in the aeration tank. Again looking at Keefer's (12) results and assuming hydraulic and organic loading to be proportional, it is noted that at the higher loading rate twice as much organic material is discharged with the effluent at

Figure 2.2 Performance of Biological Treatment Processes in Ontario from Townshend (32)

Month	Type of Process	
	<u>Conventional Activated Sludge</u>	<u>Extended Aeration</u>
	Effluent BOD (mg/l)	Effluent BOD (mg/l)
January	13	11
February	15	16
March	14	12
April	15	7.2
May	16	7.8
June	17	8.2
July	17	6.2
August	15	7.6
September	14	5.8
October	17	8.0
November	20	9.0
December	20	13
Average	16	9.2

the lower temperature than at the higher one. However, when the hydraulic loading is reduced the difference becomes insignificant. Townshend (32) does not give results of individual plants nor loading data. However, as the majority of the conventional treatment plants are designed to function at a low level of organic loading, thus requiring only a low level of metabolic activity from the organisms involved, it is likely that only a small portion of the treatment plants studied by Townshend (32) operated at a high organic loading. Thus the few plants that were not underloaded during the summer and would cause most problems at lower temperature would not greatly affect the average.

As early as 1939 Ruchthof and Smith (21) in a laboratory study reported that loadings higher than 0.2 lbs of 5 day BOD per lb. of MLVSS indicated overloading at 6 to 8°C. In comparison Eckenfelder (3) has suggested that an organic loading range between 0.3 and 0.7 lbs of 5 day BOD per lb. of MLVSS be used for operation at summer temperatures.

In summary, it appears that the efficiency of the activated sludge plants that are organically underloaded during the summer may not be appreciably decreased while those that are designed to accommodate summer loadings may give problems during the winter.

2.2 Effect of Temperature on Settling

In the activated sludge process the bacteria oxidize, the non-settleable, finely divided, colloidal and dissolved organic matter. The bacteria then form flocs which, under quiescent conditions are allowed to settle and the supernatant is released as the treated effluent. If the floc has poor settling characteristics, part of it will be washed out together with the effluent decreasing the efficiency of the process. Thus the settling characteristics, which are generally considered to be a function of organic loading, must be adequate in order to produce a high quality effluent.

The settling velocity of a particle is governed by the viscosity of a fluid and is described by Stokes Law, however, in a sludge blanket settling is hindered by particle interference and aided by flocculation. Reed and Murphy (19), in a study of temperature effects upon settling at 0 and 20°C indicated that I. Tesarik had shown theoretically, that, for settling in sludge blankets velocities are inversely proportional to the cube root of the viscosity while Stokes Law predicts that velocities are inversely proportional to the viscosities. The theoretical ratios of settling velocity at 0°C to settling velocity at 20°C as calculated by Tesarik's formulation and Stoke's Law can be shown to be 0.825 and 0.563 respectively. Reed and Murphy (19) conducted pilot plant studies at organic loadings of 0.30 lbs. of 5 day BOD applied per day per lb. of VSS and showed that the influence of temperature on the settling

velocity as a ratio of velocity at 0°C to velocity at 20°C ranged from .55 to .86 at sludge concentration of 1000 mg/l and 6000 mg/l respectively. The authors indicated the necessity for verification of these results in the loading range of 0.2 to 1.0.

2.3 Biological Considerations

The type of micro-organism that will predominate in a biological treatment process depends upon the nature of the sewage, presence of oxygen and the temperature of the liquid environment. With regards to temperature, bacteria have been classified into 3 groups, namely thermophilic, mesophilic and psychrophilic. Only the latter two are encountered in the activated sludge process as a temperature in excess of 40°C is required for the growth of thermophiles. Psychrophiles can grow at low temperatures while mesophiles grow at moderate temperatures.

Micro-organisms, in order to oxidize organic material require organic catalysts called enzymes. These enzymes are synthesized by the bacteria, consist mostly of protein and may be either intracellular or extracellular. Enzymes act only as catalysts and do not undergo any change when a reaction takes place. However, they decay so that bacteria are forced to continuously produce new enzymes. Frank et al (6) showed that while enzyme decay was much slower at lower temperatures, both enzyme activity

and production decrease with a decrease in temperature. Thus at lower temperatures the oxidative potential of bacteria drops which in turn increases generation times. A review of the literature reveals that generation times of psychrophiles increase less rapidly than those of mesophiles with a decrease in temperature.

Ingraham and Stokes (1) show the difference in generation time between a typical psychrophile and mesophile at different temperatures (figure 2.3). It can be seen that this mesophile (E Coli) has a temperature growth range between 10 and 47° with maximum growth between 30 and 45°C as compared to the corresponding temperature for the psychrophilic Pseudomonad of 0 to 35°C for growth and maximum growth respectively.

Ingraham (10) gives values of generation times for 3 psychrophiles and 2 mesophiles, some of which are given in figure 2.4. From this data it appears as though the temperature at which generation times for the psychrophile is less than that for the mesophile occurs at about 25°C.

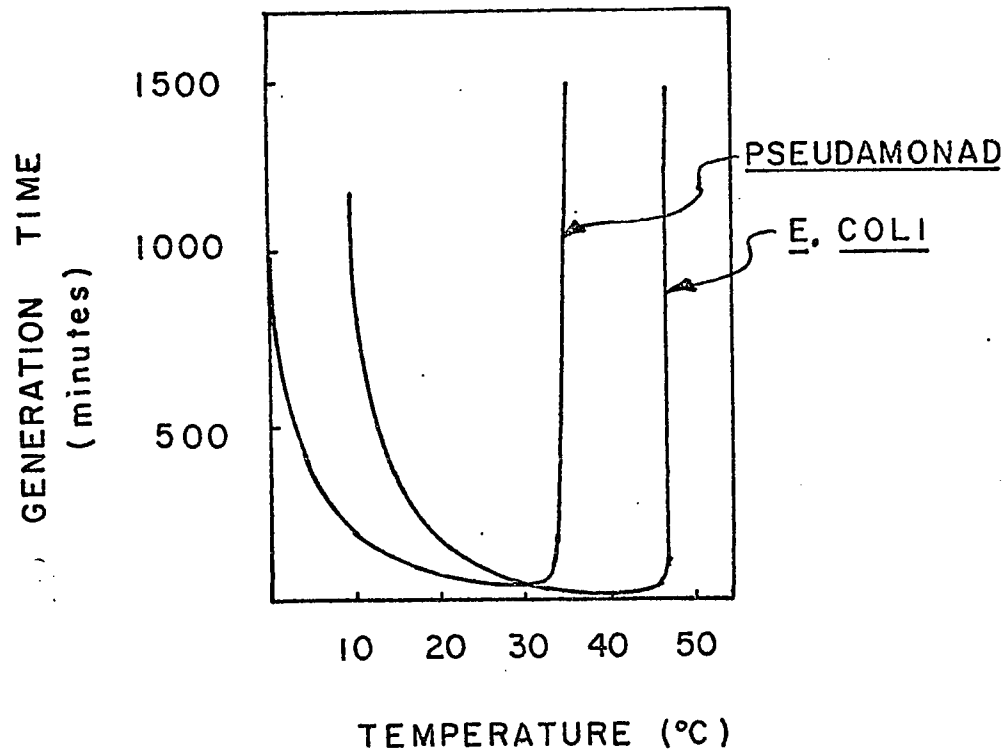


FIGURE 2·3 EFFECT OF TEMPERATURE ON THE GENERATION TIMES OF A TYPICAL MESOPHILE (E. COLI) AND A PSYCHROPHILIC PSEUDAMONAD (REPRODUCED FROM INGRAHAM AND STOKES (11))

Figure 2.4 Generation Times in Minutes
from Ingraham (10)

Temperature °C	Psychrophilic Pseudamonads (3 strains)			Mesophiles	
				<u>E Coli</u>	<u>Pseudamonas Aeruginosa</u>
40				21	22
34	180		60	28	
32	34	53	43	30	
30	46	56	51	33	36
20	77	95	92	170	120
14	120	140	130	400	160
10	190	160	240	1200	470
8	240	210	330	2500	1400
6	370	310	450		
4	440	420	600		
2	550	480	820		
0	1200	620	1200		

Psychrophiles are often thought of as bacteria that grow best at cold temperatures. However, this is not true as can be seen by the previous data. Ingraham and Stokes (11) defined psychrophiles as bacteria that grow well at 0°C within 2 weeks. The authors state that the lowest temperature for bacterial growth is about -10°C, below which growth is probably prevented by increasing desiccation and high salt concentration of the media due to progressive removal of water by freezing. The generation time of the bacteria Pseudomonas fluorescens used in their studies was 400 and 84 minutes at 5 and 20°C respectively.

Olsen and Jesewski (16) determined the mean generation times of Pseudomonas fluorescens at different temperatures and various carbon sources for growth. They found generation times to vary between 1.12 and 1.46 hours at 20°C and 4.17 to 6.68 hours at 4°C.

Quist and Stokes (18) conducted a study on the temperature range for the induction and activity of the enzyme hydrogenlyase in psychrophilic and mesophilic bacteria.

They found that in the psychrophile the enzyme was formed most rapidly (3½ hours) at 20°C, not at all at 25°C and in 16 hours at 5°C. For the mesophile the temperature at which most rapid induction occurred was 30°C. Total enzyme produced

was a maximum at 15 and 35°C for the psychrophile and mesophile respectively. They did not attempt to determine whether the much slower induction rate at lower temperature is related to the slower decay rate. That is, at lower temperatures the enzyme produced is available to the bacteria longer and production of new enzymes need not occur at such a great rate. The temperature for maximum enzyme activity was 30 and 40°C for the psychrophile and mesophile respectively, while at 15°C the psychrophile synthesized more enzyme than the mesophile. The authors also noted that at a pH of 6.4 enzyme induction did not occur in the psychrophile. However, when the pH was increased to 6.9 the enzyme was produced. This did not occur with the mesophile.

The authors concluded by saying that the inability of mesophiles to grow at low temperatures may be due to a decreased capacity to synthesize certain essential enzymes.

Contrary to the results of Quist and Stokes (18), Frank et al (6) who investigated the activity of the enzyme catalase of a psychrophile grown at 2 and 30°C, found that the enzyme activity at 2°C was greater than that at 30°C and that catalase production was 2 to 3 times higher at 2°C. However, when compared to the results of Quist and Stokes (18) it appears as though the experiment was not done at the expected temperature of maximum enzyme production. If enzyme

production is indeed a maximum at the lower temperature then this might be explained as follows. Catalase is the enzyme required to break down hydrogen peroxide (H_2O_2) which is poisonous to bacteria. At lower temperatures there is more dissolved oxygen and consequently more H_2O_2 requiring the bacteria to produce more catalase. If this were the case then it would decrease the rate of oxidation as the bacteria have to expend more of their energy to produce catalase and reduce their ability to create other essential enzymes.

An explanation of the difference between the behaviour of mesophiles and psychrophiles is given by Rose and Evinson (20) who state that the minimum temperatures for growth are probably determined, at least in part, by the inactivation of the mechanism for transporting sugars into the organism. This may be due to the hyperfolding of proteins at low temperatures in mesophiles thus inactivating the enzyme.

Stokes and Larkin (29) also stated that the enzymes of psychrophiles and mesophiles differ. Their studies were concerned with the rates of oxidation, selected results of which are given in figure 2.5. It should be noted that the oxidation rates of the psychrophile decrease less rapidly with a decrease in temperature than those of the mesophile.

Figure 2.5 Rates of Oxidation from
Stokes and Larkin (29)

Temperature °C	Rate of Oxidation in O ₂ consumed per vessel/hr.	
	<u>B psychrophilus</u> (psychrophile)	<u>B thuringiensis</u> (mesophile)
40	105	100
30	234	131
20	131	61
15		35
10	52	9
5	28	4

Sultzer (30) had earlier also suggested that the oxidative activity of psychrophilic bacteria is less sensitive than that of the mesophilic bacteria to a decrease in temperature.

In summary, it can be said that generation times of psychrophiles at 5°C are in the order of 4 to 7 hours while generation times for mesophiles at 20°C are in the order of 1 to 2 hours. Applying this to the activated sludge process it becomes apparent that a longer time period will be required to build up a culture at lower temperatures and that higher concentrations are desirable. Ingraham's (10) results indicate that the temperature below which psychrophiles have shorter generation times than mesophiles and would thus be more prevalent in mixed cultures occurs at about 25°C. However, it should be noted that Ingraham's (10) study, as well as all the others presented in the biological part of the literature survey, are limited to pure cultures as opposed to the mixed cultures found in biological oxidation processes. Based on the work of Townshend (32) it is suspected that, in mixed cultures, the temperature below which psychrophiles predominate is somewhat lower than in pure cultures. Perhaps in the 15°C range, as this is the temperature which was shown to influence biological treatment performance during the fall when the microbial population changes. If the temperature at

which the microbial population changes were actually 25°C perhaps few, if any, plants in Canada would experience problems.

In a more recent study of an aerated lagoon Bartsch and Randall (1) report 14.4°C as a threshold value above which no significant change in efficiency occurs but below which the efficiency of the system is greatly reduced. This study supports the assumption that the temperature at which the microbial population changes is approximately 15°C.

2.4 Design Criteria in Bio-Oxidation

Three treatment plant design parameters which are generally evaluated in laboratory studies are the reaction rate constant, sludge yield and oxygen requirement, all of which are affected by a change in temperature. Little information is available in the literature concerning the influence of temperature change on sludge yield or oxygen requirement.

2.4.1 Reaction Rate Constant

The rates of most chemical and biological reactions increase with temperature. An approximation being that the the rate of reaction will change by a factor of 2 for a 10°C change in temperature. The following equation, derived from the Arrhenius equation is generally suggested to describe the

influence of temperature change on the performance of the activated sludge process.

$$\frac{k_2}{k_1} = \theta^{(T_2 - T_1)} \text{ - - - - - 2.1}$$

- where - k_2 and k_1 are the reaction rate constants at temperatures T_2 and T_1 respectively
- θ is a temperature coefficient which is equal to $\frac{E_a}{R T_2 T_1}$

where - E_a is the activation energy which is a constant for a certain reaction

- R is the Universal gas constant.

Although θ is considered to be a constant it may vary significantly over a limited temperature range. Values of θ for the activated sludge process have been reported by Wuhrmann (34) to be 1.0 and by Pohl (17) to vary from 1.0 at high MLSS to 1.038 at low MLSS. The values of θ are generally higher for other biological oxidation processes and are given by Eckenfelder (4) as 1.06 to 1.09 in facultative lagoons, while Howland (9) has reported θ to be 1.035 for trickling filters and Sawyer (24) has reported θ to be 1.035 for aerobic lagoons.

Q_{10} values are defined as the ratio of reaction rates at a particular temperature to the rate at 10°C lower. These have been evaluated for activated sludge by Sawyer and McCarty (25) who reported values of 2.85 in the 10 to 20°C range and 2.22

in the 15 to 25°C range. From this data it would appear that a drop in temperature from 20 to 5°C would decrease the reaction rate by a factor in the order of 4 to 5.

Thus in order to achieve the same treatment the number of micro-organisms should also be increased by the same factor. However, earlier in the research it was stated that an increase in sludge concentration diminishes the temperature effect on the settling rate of the sludge. Furthermore, the values of θ assume that the same biological population is involved at all temperatures which has earlier been indicated to be erroneous. It is therefore felt that the biological population need not be increased by a factor as large as 4 or 5 in order to achieve the same degree of treatment at 5°C as at 20°C.

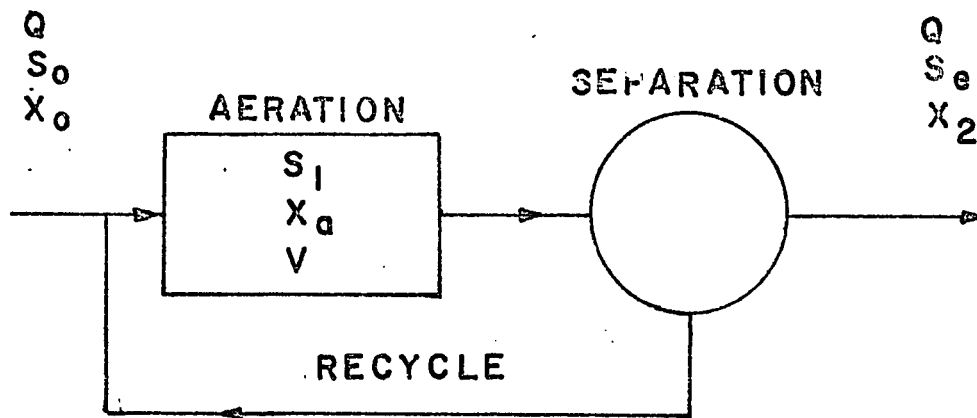
2.4.2 Reaction Kinetics

Eckenfelder (4) has developed a formulation which can be used to determine detention times or efficiencies for treatment plants from laboratory data. The author uses a material balance on the biological treatment system as shown in figure 2.6.

The change of BOD through the reactor is the BOD in the influent minus the cellular removal minus the BOD in the effluent which can be expressed by the following equation

$$\frac{dS}{dt} V = Q S_0 - X_a V (f(S)) - QS_e$$

$$\text{at steady state conditions } \frac{dS}{dt} = 0$$



WHERE

Q = FLOW

S_0 = INFLUENT BOD

S_1 = SOLUBLE BOD IN AERATION TANK

S_e = EFFLUENT BOD

X_0 = INFLUENT SUSPENDED SOLIDS

X_a = AVERAGE MLVSS IN AERATION

X_2 = EFFLUENT SUSPENDED SOLIDS

V = VOLUME OF AERATION TANK

FIGURE 2-6 MASC BALANCE DIAGRAM

$$\text{and } Q (S_o - S_e) = X_a V (f(S))$$

$$\text{rearranging } f(S) = Q \frac{(S_o - S_e)}{X_a V}$$

$$\frac{V}{Q} = t = \text{detention time}$$

$$\text{Therefore } f(S) = \frac{S_o - S_e}{X_a t}$$

From a consideration of units it can be shown that $f(S)$ has the units of rate of removal which is proportional to the concentration of substrate for the concentrations normally encountered, i.e. $\frac{dS}{dt} = kS$

Therefore the reaction kinetics of the activated sludge process can be expressed by the following equation:

$$\frac{S_o - S_e}{X_a t} = k S_e \text{ - - - - - 2.2}$$

where S_o - Oxygen demand of the influent in mg/l
 S_e - Oxygen demand of the effluent in mg/l
 X_a - Total amount of MLVSS in reactor at any one time in grams
 t - detention time in hours
 k - reaction rate coefficient

2.4.3 Sludge Yield

When an organic waste is oxidized biologically a portion of the BOD is used for synthesis of cellular material. The

remainder is either converted to energy or required for endogenous respiration. The amount of new cellular material produced depends upon the characteristics of the waste and is important in determining the sludge handling capacities in a treatment plant.

The accumulation of sludge is the algebraic sum of the cellular material produced from the oxidation of the substrate and cells in the endogenous growth phase.

The amount of sludge produced by the activated sludge process can be expressed by the following equation:

$$DX = a S_r - bX_v \text{ - - - - - 2.3}$$

where DX - sludge produced (lbs per day)

a - fraction of BOD applied that is converted to a cellular material

S_r - ultimate BOD removed (lbs per day)

b - endogenous reaction rate coefficient (t^{-1})

X_v - amount of sludge (MLVSS) in the aeration tank

Sawyer (23) and Lesperance (13) found that the rate of sludge growth is higher at low temperature. Sawyer (23) also found that at low temperatures a sludge of higher volatile content is formed. Contrary to this Helmers et al (8) found that low temperatures would decrease sludge growth.

Ludzack et al (14) determined temperature to sludge yield relationships using batch tests at 5 and 30°C.

Selected results from their experiments are shown in figure 2.7 which indicate higher yields at lower temperatures.

It is expected that sludge yields increase with a decrease in temperature as a greater microbial population is required to oxidize a substrate at lower temperatures.

2.4.4 Oxygen Utilization

The activated sludge process is operated as an aerobic process which requires that oxygen be supplied at a rate equal to or greater than its rate of utilization by the microbial population. Oxygen utilization rate may be defined as the weight of oxygen consumed by a given weight of microbial organisms per unit of time.

The oxygen is used by cells engaged in active waste degradation but must also be supplied for those cells undergoing endogenous respiration. The quantity of oxygen required in the aeration tank can thus be expressed by the following equation:

$$OX = a^1 S_r + b^1 X_v \text{ - - - - - 2.4}$$

where OX - oxygen required (lbs per day)

a^1 - fraction of BOD used for respiration

S_r - ultimate BOD removed (lbs per day)

Figure 2.7 Sludge Yield vs. Temperature
from Ludzack et al (14)

Feed Type	Temperature (°C)	Unit VSS loss or gain (gr/gr influent BOD)
A	5	+ .38
	30	+ .08
C	5	+ .15
	30	+ .10
D-1	5	+ .20
	30	- .02
D-2	5	+ .18
	30	+ .04

b^1 - endogenous respiration rate coefficient
(t^{-1})

X_v - amount of sludge (lbs. of MLVSS in
the aeration tank)

Sawyer and Rohlich (22) in working with sludge concentrations ranging between 1000 and 4000 mg/l found that the oxygen utilization at 25°C is equal to 4 times that at 10°C. However, they did not determine what ratios were required for active waste degradation or endogenous respiration.

Shih and Stack (27) determined the relationship between temperature and energy oxygen where they defined energy oxygen as the net consumption of oxygen in support of synthesis. This is equal to the $a^1 S_r$ term in equation 2.3. They concluded that energy oxygen vs temperature varies with different substrates possibly because at various temperatures different bacteria predominate and use various metabolic pathways to oxidize the substrate. The authors also found that endogenous respiration increases with an increase in temperature.

CHAPTER 3

EXPERIMENTAL METHODS

The apparatus used for the continuous flow laboratory tests consisted of a simple reactor which contained both an aeration and settling chamber. A synthetic waste was pumped into the aeration compartment and the treated effluent was withdrawn through the overflow weir and stored in a separate container. A total of 29 bench scale tests were conducted at various organic loading rates and sludge concentrations at both 5 and 20°C. Daily tests included chemical oxygen demand (COD) of the influent and effluent, suspended (SS) and volatile suspended (VSS) solids determinations of the mixed liquor and effluent as well as oxygen uptake measurements. Settling rates were determined less frequently.

3.1 Selection of Experimental Parameters

The object of this research is to evaluate the performance of the activated sludge process under various conditions of organic loading and sludge concentrations at low temperatures. A temperature of 5°C was chosen for the following reasons:

1. The density of water is a maximum at 4°C and thus settling problems are most severe at this temperature.
2. The majority of the existing research has been conducted at 5 degree intervals with 5°C being one of these temperatures.

3. Domestic and industrial sewage generally contains sufficient heat and with the exception of some of the small northern communities sewage temperatures in Canadian treatment plants of the conventional activated sludge type would not generally be expected to be below 5°C.

In order that results from the low temperature studies be meaningful it was essential that a basis of comparison at a standard temperature be used. The temperature chosen as a basis of comparison was 20°C and was chosen for the following reasons:

1. The majority of the research in this temperature range is conducted at 15, 20 and 25°C.
2. 15°C is too close to the temperature at which mesophilic and psychrophilic bacteria grow equally well.
3. 25°C is warmer than any sewage normally encountered in this country.

Studies of this nature can be conducted either in the laboratory or in larger scale field evaluations using pilot plants. The major advantage of a laboratory study is that environmental conditions can be controlled to a much greater extent than during a field evaluation. However, results of pilot plant studies are generally more applicable to treatment plants as the difference in size between the experimental and

operational facility is not as extreme. In conventional treatment plant design it is not uncommon to use results of laboratory studies to design pilot plants, the data of which is in turn used to design the treatment plant itself. For this study it was decided to use a laboratory evaluation the results of which could then possibly be used, by others, to design a pilot plant operation.

As the loading rate was one of the parameters to be studied in this research it was imperative that a relatively constant loading rate be maintained. This eliminated the use of batch tests as the loading fluctuates widely after the feed is introduced. Thus a continuous flow type reactor was required. A control of the amount of sludge returned was desired, necessitating separate aeration and settling tanks. Some trials using an Imhoff cone as settling tank and returning sludge by pumping were performed but did not function properly because the sludge would not settle to the bottom of the cone. It was thought that the above could be remedied with proper stirring equipment. However, this apparatus was not available and would have had to be designed. This was considered beyond the scope of this research and the unit described in section 3.2 was used.

A substrate, available in unlimited quantity and of known and constant strength was required for this study in

order that results from various tests be meaningful.

As the strength of a real waste is subject to fluctuation it was decided to use a synthetic waste. A number of synthetic wastes have been used in other studies, one of which is glucose combined with a nitrogenous compound. However, glucose is a rather ideal waste since it is readily biodegradeable and is not generally found in a real waste. Another synthetic waste commonly used in laboratory studies is skim milk which contains not only carbohydrates and proteins but also other essential nutrients required for biological growth. It was decided to use skim milk as the substrate for this study.

3.2 Apparatus and Equipment

The continuous flow reactor of which a total of six units were employed simultaneously, is illustrated in figure 3.1. This unit is constructed of plexiglass and has two compartments partially separated by an adjustable baffle. The larger compartment is provided with an air supply which not only supplies the necessary source of oxygen but also keeps the waste and mixed liquor completely mixed. The smaller unit is equipped with an overflow weir and acts as a settling chamber, the clear effluent being discharged through the overflow line.

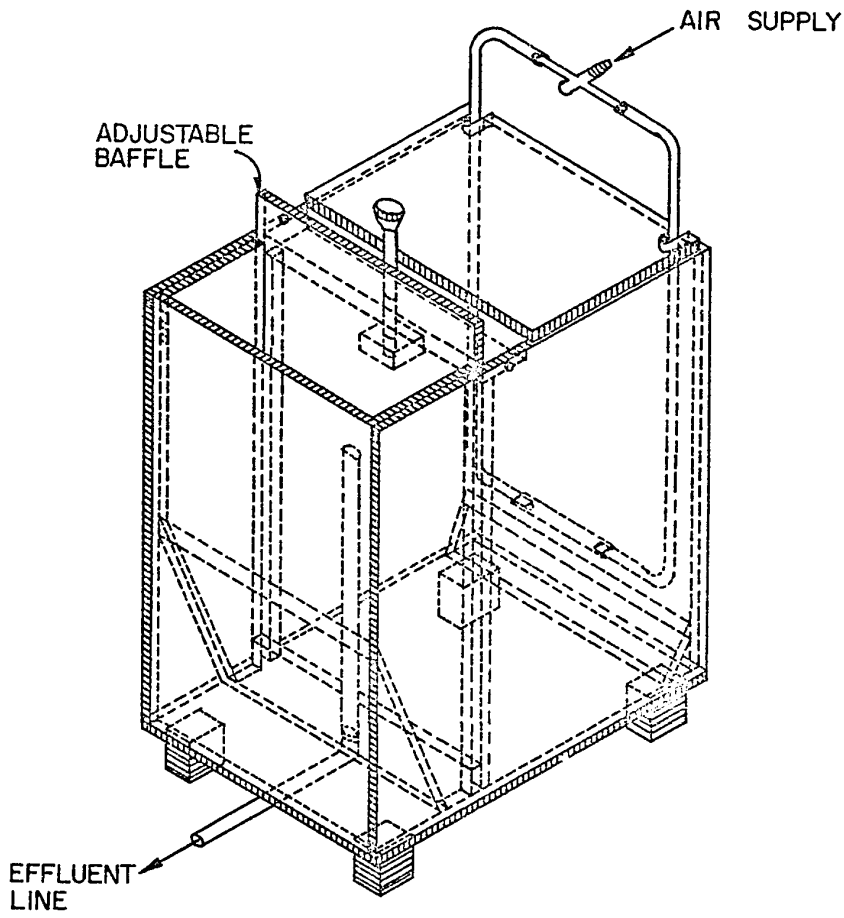


FIGURE 3.1 CONTINUOUS FLOW REACTOR

WORLDWIDE SCIENTIFIC EQUIPMENT

Sludge is returned from the bottom of the settling chamber to the aeration chamber through the opening between the baffle and the bottom of the unit. The airflow rate and baffle height must be adjusted carefully. If the airflow rate is excessive and the baffle too high, solids separation will not be efficient. If the airflow rate is insufficient and the baffle located too low, the rate of sludge return will be inadequate.

The feed was pumped into the larger compartment of this unit near the side that is furthest away from the settling compartment. The pumps used were Buchler Polystatic pumps each of which has four channels, thereby requiring two pumps to feed the six units. Initially it was intended to use similar pumps in order to waste mixed liquor continuously to keep the MLVSS concentration constant. However, the feed pumps broke down and required repair frequently so that a shortage of pumps prevented wasting in this manner.

Plastic carboys of 5 gallon capacity were employed as feed and effluent tanks. In order to prevent biological growth in the feed tank and plastic lines leading from these carboys to the reactor unit, both the tanks and the feed lines were cleaned with Javex every 2 days when operating at 20°C and every 3 days when operating at 5°C.

In order to have a supply of sludge that could be used if solids from any of the units were washed out with the effluent, a glass cylinder of 25 l capacity was operated approximately half-full as a batch tank. Air was supplied to this batch tank through a perforated glass tubing bent in the shape of a ring and placed at the bottom of this unit. The sludge wasted daily from the continuous flow units was added to the batch tank from which solids were also wasted daily.

3.3 Analytical Techniques

In order to evaluate the performance of the activated sludge process, determine the quality of the effluent and obtain the information necessary to operate the process, various tests must be carried out. The following tests were performed daily in this study.

1. Oxygen demand of the influent.
2. Oxygen demand of the effluent.
3. Suspended solids of the mixed liquor (MLSS).
4. Volatile suspended solids of the mixed liquor (MLVSS).
5. Suspended solids of the effluent.
6. Volatile suspended solids of the effluent.
7. Oxygen uptake of the mixed liquor.

Settling rates were determined less frequently.

3.3.1 Oxygen Demand

The oxygen demand of an organic waste can be measured using the Biochemical Oxygen Demand (BOD) or Chemical Oxygen Demand (COD). The required parameter in the design of biological treatment process is BOD as this is a measure of the amount of oxygen that must be provided to stabilize the organic material biologically. However, the standard BOD test requires 5 days to complete and is thus not suitable where operating conditions have to be adjusted daily on the basis of these tests. The COD test measures the amount of oxygen required to chemically oxidize a waste and takes approximately 3 hours to complete.

A correlation between the oxygen demand parameters is particularly useful because of the time saved in obtaining the data if the COD test can be used. For this study it was attempted to obtain a BOD:COD correlation for the substrate used.

To obtain a BOD:COD correlation the BOD test was extended to up to 16 days as the ultimate BOD was required. The test was performed in accordance with Standard Methods (28). A seeding material was required and it was found that approximately 2 ml of continuous flow unit effluent per 1 l of distilled water was sufficient.

The procedure used for the COD analyses follows that in Standard Methods (28). The sample was refluxed with the strong oxidizing agent Potassium dichromate and then titrated with ferrous ammonium sulphate. The COD of the waste is proportional to the amount of potassium dichromate used. When the expected strength of the sample was less than 25 to 30 mg/l the alternate procedure for dilute samples (section 4.6) was used.

3.3.2 Dissolved Oxygen (D.O.) Test

D.O. analyses were performed using the azide modification according to Standard Methods (28). 2 ml of each manganese sulphate solution and alkali-iodide-azide reagent were added to the sample followed by sulphuric acid to dissolve the precipitate formed. Titration was then performed with sodium thiosulphate.

3.3.3 Oxygen Uptake Rate

Oxygen uptake measurements were performed using a YSI sampler and recorder. This equipment was calibrated daily using samples that had been analyzed for D.O. as described in 3.3.2. 10 to 20 ml of sample were taken from the aeration chamber of the continuous flow unit and immediately placed in the small glass container of the oxygen uptake meter. The probe was then inserted into the sample taking care that all

air had been expelled. The meter was turned on and a continuous record of oxygen present in the sampler was obtained, from which the oxygen depletion rate was calculated.

3.3.4. Suspended Solids Analyses

Suspended solids were determined as described in Standard Methods (28) using Gooch crucibles and fiber filter pads. The volatile portion was determined by heating in an electric muffle furnace to 600°C.

3.3.5. Settling tests

The procedure and results of the settling rate tests are given in Appendix B.

3.4 Research Procedures

It had been intended to run simultaneous tests at 5 and 20°C in the temperature controlled room and the laboratory respectively. However, as the temperature in the laboratory was generally in excess of 25°C and fluctuated between 20 and 30°C, it was decided to run all the tests in the temperature controlled room starting with the lower temperature.

Mixed cultures were obtained from a local sewage treatment plant and were acclimatized in a batch tank to the feed and temperature employed during the research. Air was supplied to this batch tank through a perforated glass tubing bent in the shape of a ring and placed at the bottom of this unit. Sufficient feed was added to the batch tank to maintain an organic loading of approximately 0.15 gr of COD per gr of

MLVSS. The amount of skim milk required to obtain this organic loading was determined by a skim milk vs. COD correlation which showed that 1.00 gr of skim milk per liter of water gives a COD of approximately 1070 mg/l.

In order to remove the non biodegradeable fraction of this waste from the batch tank the air was turned off daily whereupon the sludge was allowed to settle and the supernatant was removed.

The reactors, feed tanks, effluent tanks, pumps and feed lines were arranged as shown in figure 3.2. The reactors were fed with the sludge from the batch tanks which had been acclimatized to the required feed and temperature for a period of several weeks. The skim milk waste was then fed to the reactors continuously at a rate such that the detention time was approximately 10 hours.

C.O.D.'s solids and oxygen uptake determination were then performed daily in the following manner:

- a) The effluent line was closed by means of a clamp.
- b) With the baffle left in place the contents were stirred vigorously by means of a stirrer and an air hose.
- c) A sample was taken and an oxygen depletion test was immediately performed.
- d) Suspended solids and volatile suspended solids were then determined.

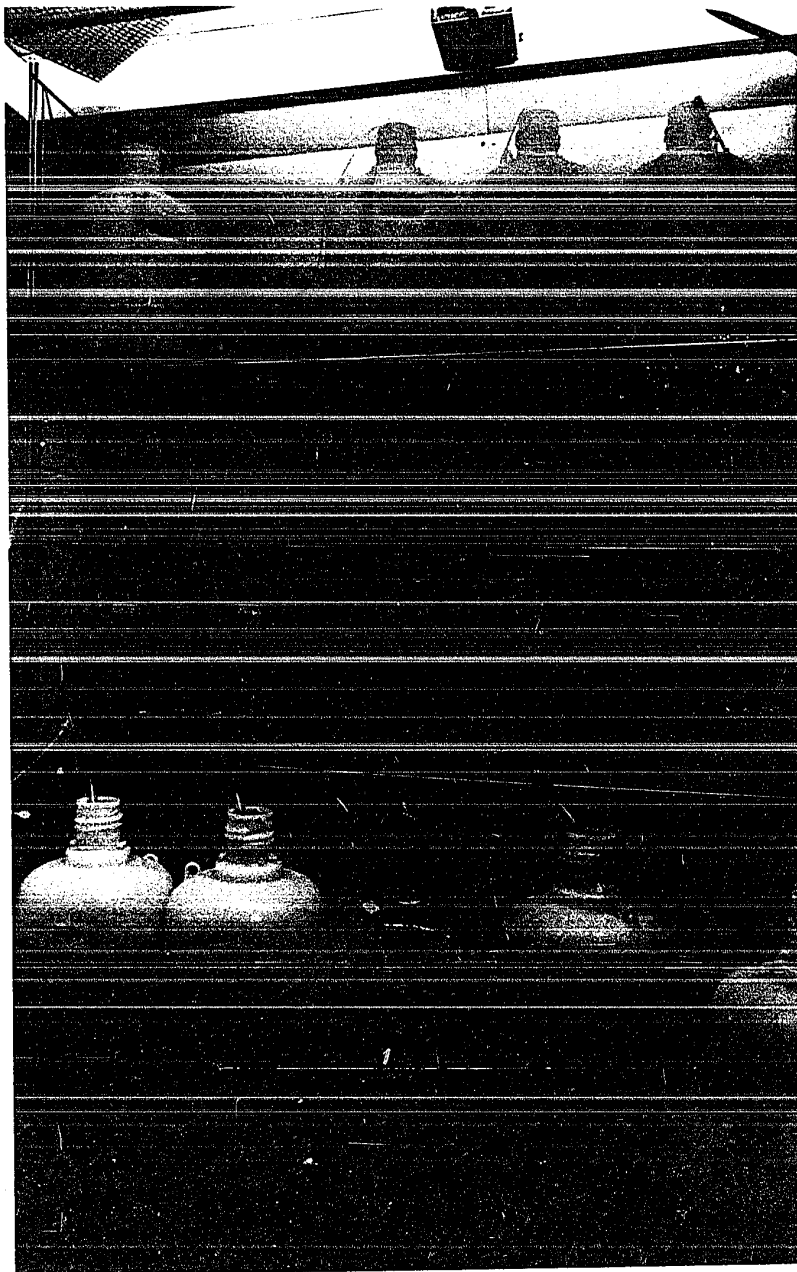
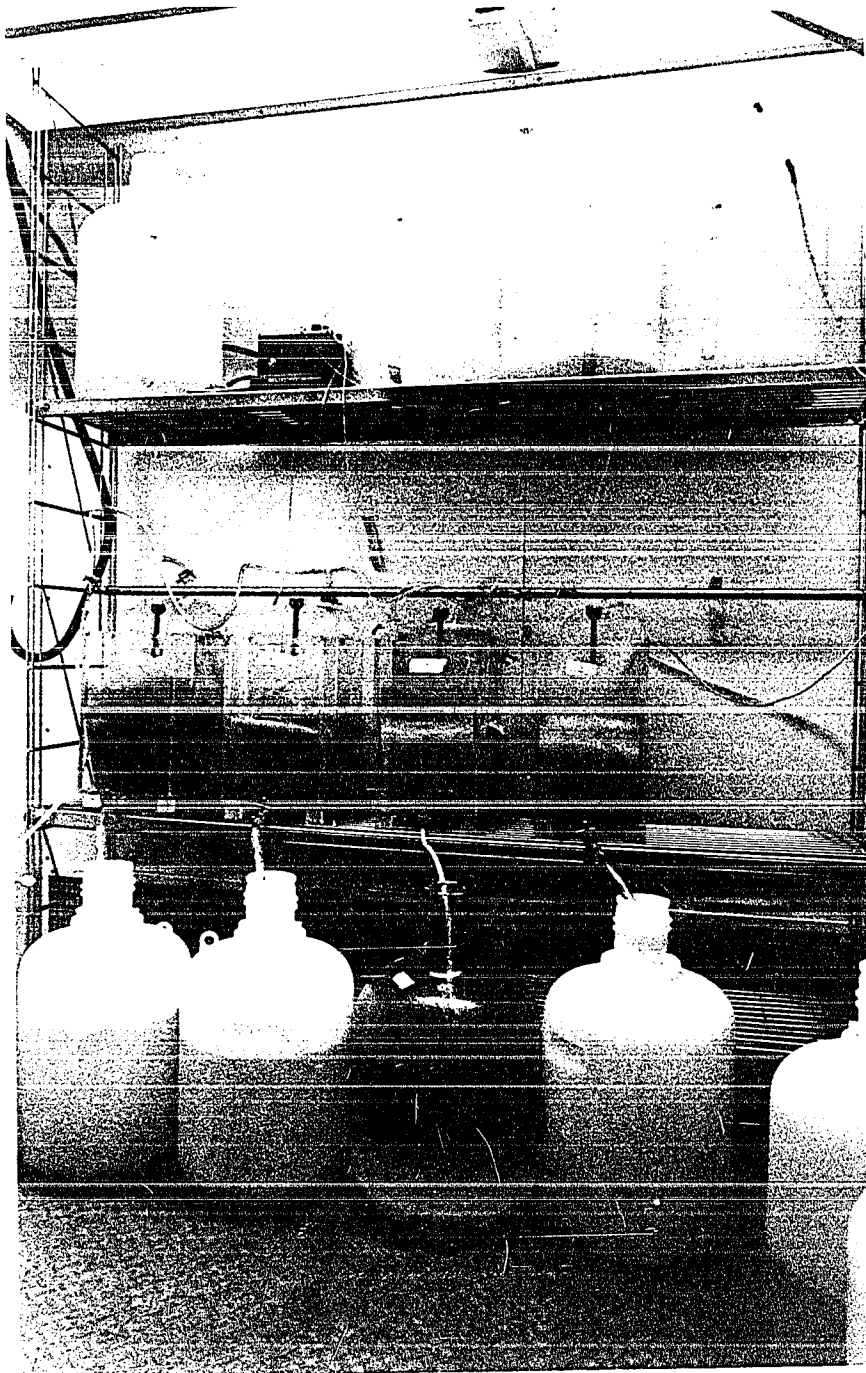


FIGURE 3.2 RESEARCH APPARATUS



e) The effluent collected during the previous 24 hours was mixed and 50, 100 or 200 cc were used to determine solids in the effluent.

f) COD's were run on the filtrate of the effluent as well as on the feed, which was prepared daily.

Sufficient solids were then wasted from each tank so that the solids remained at the predetermined level. This meant that the amount of solids grown daily were equal to the sum of those wasted and the solids in the effluent.

The feed and effluent tanks as well as the feed lines were cleaned out with a solution of 50% Javex and 50% water every 2 and 3 days at the higher and lower temperature respectively.

Once the systems had reached a steady state condition they were operated for a minimum of five days with analyses done daily to evaluate the various parameters required for design purposes. The organic loading was then changed and the procedure was repeated.

As the object of this research was to evaluate design parameters at various sludge concentrations and loading rates, the bench scale tests were intended to be operated at the three different sludge concentrations and 4 to 6 different organic loads shown in figure 3.3. At the beginning two reactors each were operated at 1500, 2500 and 3500 mg/l of

UNIVERSITY OF CALIFORNIA
LIBRARY



Figure 3.3 Sludge concentrations and organic loading rates at which continuous flow units were to be operated.

Temp- erature (°C)	Solids concentration (MLVSS) (mg/l)	Organic loading (gr. of BOD _u / gr of MLVSS)					
		.12	.20	.35	.55	.75	1.00
5	1500	x	x	x	x	x	x
5	2500	x	x	x	x	x	x
5	3500	x	x	x	x	(1)	(1)
20	1500	(2)	x	x	x	x	x
20	2500	(2)	x	x	x	x	x
20	3500	(2)	x	x	x	x	(1)

x indicates the analyses was to be performed.

1. It was expected that the large amount of sludge grown would cause operational difficulties.
2. Trials showed that solids levels could not be maintained.

MLVSS and low organic loadings. As these tests were finished the loading was increased and the tests were repeated. A total of 18 and 15 runs were planned at the low and high temperatures respectively.

CHAPTER 4

RESULTS

Generally the continuous flow units operated well over the duration of the study. However, solids separation in the clarifier was very poor at the highest solids concentration at the lower temperature. The operation of the continuous flow units at the other two solids concentrations at the low temperature showed good solids separation but SVI tests indicated very little settling. The lack of settling with the SVI test is believed to be a shortcoming of this test and are discussed in Appendix B.

Bulking did occur several times at both temperatures. When this happened at low to medium loading rates the sludge was discarded and replaced with sludge from the batch tank and the system reacclimatized before testing resumed.

In the instances where some data was collected at high loading rates before bulking commenced this data was used for all parameters that showed consistent results before bulking. Complete data is given in Appendix A.

The data for the sludge yield, oxygen utilization and reaction kinetics studies were evaluated using regression analysis. This was performed on an IBM computer and employing the IBM prepared Statpack program.

4.1 COD vs BOD correlation

The results of B.O.D. analysis on the feed and the effluent are shown in figure 4.1. Ultimate BOD's were calculated both by the method developed by Thomas and that developed by Moore as given in Fair and Geyer (5). The resulting ultimate BOD's together with the corresponding experimental COD's are shown in figure 4.2.

The average BOD:COD ratio of the feed is 0.80 which compares favourably with a study using similar waste by Schmidtke (26). The results of the effluent show a much lower ratio which is understandable in that a large portion of the organics are now non-biodegradeable.

4.2 Reaction Kinetics

Equation 2.2 states that

$$\frac{S_o - S_e}{X_a t} = k S_e$$

If $(S_o - S_e)/X_a t$ is plotted against S_e a straight line with slope k is obtained. A plot of $(S_o - S_e)/X_a t$ vs S_e using the data from Appendix A is given in figures 4.3 and 4.4 for the tests run at 5 and 20°C respectively. A regression analysis based on the least squares method was performed to determine the equation of the best fit

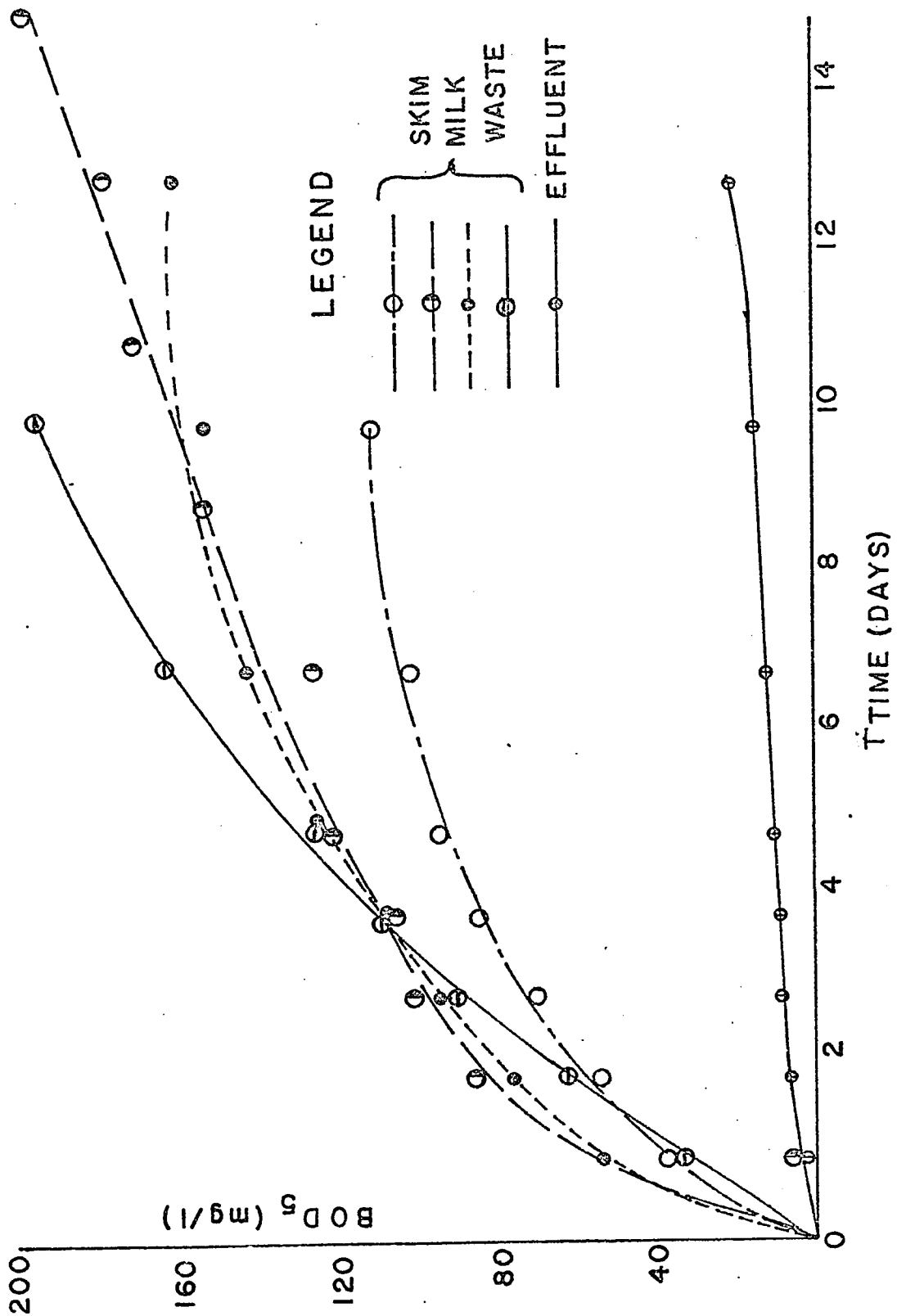


FIGURE 4.1 BOD CURVES OF MILK WASTE AND ACTIVATED SLUDGE SYSTEM EFFLUENT

Figure 4.2 COD:BOD correlation of Milk Waste

	C.O.D. (mg/l)	Method by Thomas		Method by Moore	
		B.O.D. (mg/l)	$\frac{\text{B.O.D.}}{\text{C.O.D.}}$	B.O.D. (mg/l)	$\frac{\text{B.O.D.}}{\text{C.O.D.}}$
Feed 1	195	141	.72	134	.69
2	313	249	.80	245	.78
3	186	150	.81	146	.78
4	123	114	.93	114	.93
Effluent	40	14	.35	14	.35

SAMPLE CALCULATIONS
(Method by Moore)

Time (days) (t)	BOD exerted (mg/l) (y)	yt
1	40	40
2	84	168
3	101	303
4	104	416
5	121	605
6	125	750
7	128	896

$$\sum y = 703$$

$$\sum yt = 3178$$

$$\sum y / \sum yt = .222$$

from graph $\sum y / L = 5.25$

$$L = 703 / 5.25$$

$$= 134 \text{ mg/l}$$

where L = ultimate BOD

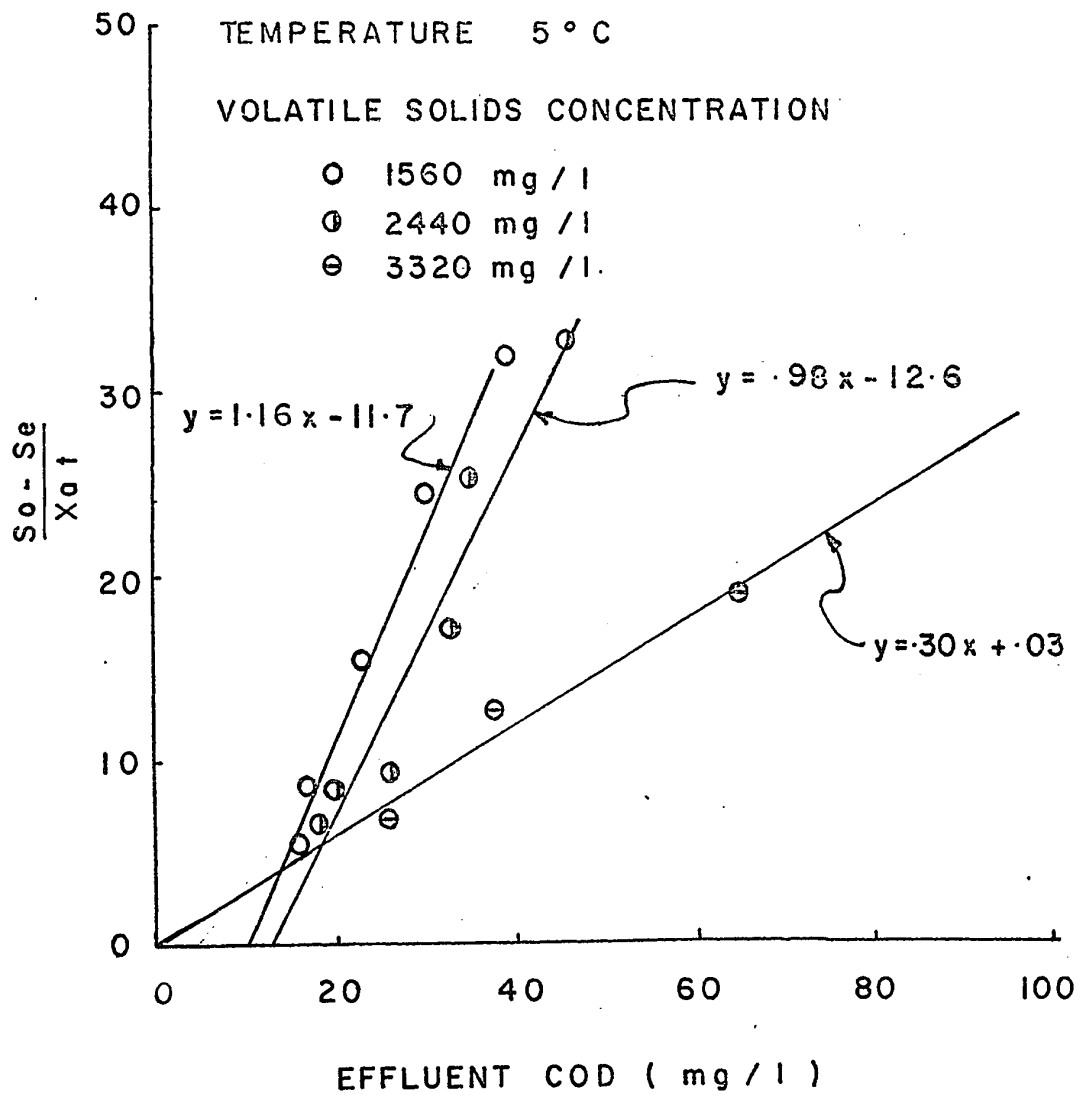


FIGURE 4.3 REACTION KINETICS OF ACTIVATED
SLUDGE SYSTEM TREATING MILK
WASTE AT 5 ° C

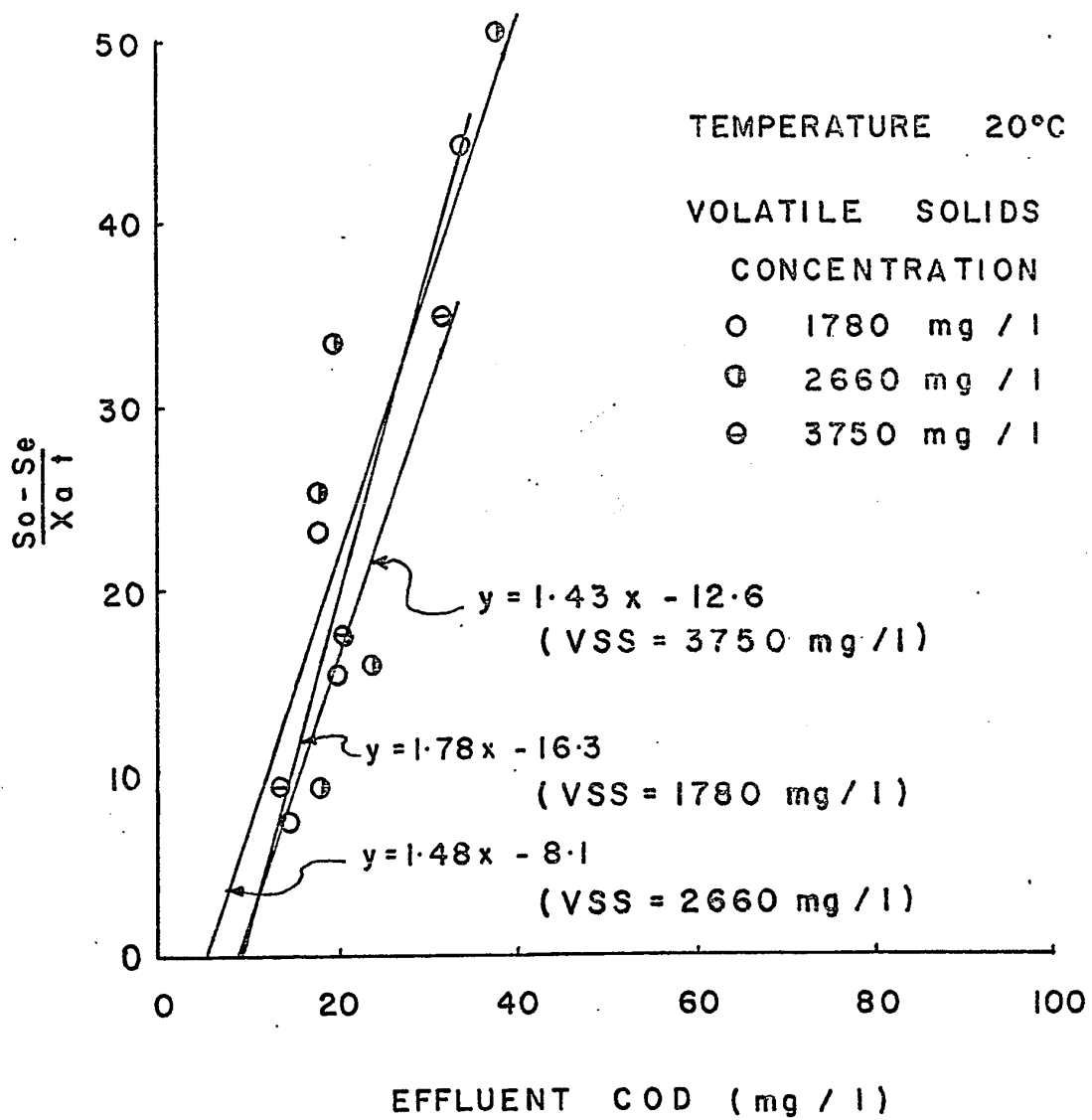


FIGURE 4.4 REACTION KINETICS OF ACTIVATED SLUDGE SYSTEM TREATING MILK WASTE AT 20°C

line for each sludge concentration and at each temperature. The slope of these lines represent the reaction rate constant, k , and are given in figure 4.5. Confidence intervals for the slope of the lines were estimated at certain confidence levels as described in Experimental Statistics (33). A sample calculation for the results at 5°C is given below:

Sludge concentration	=	1560 mg/l	
number of points	=	5	
confidence level $(1-\alpha)$	=	90%	60%
α	=	.10	.40
$t_{(1-\alpha/2, 3)}$	=	2.353	.978
S_{bl} (from computer print out)	=	.079	.079
$t_{(1-\alpha/2)} \frac{xS}{bl}$	=	.18	.08
slope (from computer print out)	=	1.16	1.16
confidence interval	=	0.98 to 1.34	1.08 to 1.24

The confidence intervals for the slope of the lines at various levels of confidence are included in figure 4.5.

Values of the temperature coefficient, θ , of equation 2.1 are calculated below using the average k values for the lower concentrations from figure 4.5. The values of k at the highest concentrations are not included as they were obtained from only 3 points and are thus not considered very reliable.

Figure 4.5 Summary of Reaction Kinetics data.

Temperature	Solids concentration		
	MLVSS (mg/l)		
5°C	1560	2440	3320
Reaction rate coefficient k (hours ⁻¹ gr ⁻¹)	1.16	0.98	0.30
Interval estimate of k at 40% c.l.	1.11 to 1.21	0.91 to 1.05	-
Interval at 60% c.l.	1.08 to 1.24	0.86 to 1.10	-
Interval at 90% c.l.	0.98 to 1.34	0.72 to 1.24	0 to 0.61
Correlation coefficient	.993	.970	.982
20°C	1780	2660	3750
Reaction rate coefficient k (hours ⁻¹ gr ⁻¹)	1.78	1.48	1.43
Interval of k at 20% c.l.	1.65 to 1.91	1.29 to 1.67	1.39 to 1.47
Interval of k at 40% c.l.	1.51 to 2.05	1.08 to 1.88	1.35 to 1.51
Correlation coefficient	.945	.773	.997

Note - c.l. denotes confidence level.

Thus from figure 4.5 k , at $5^{\circ}\text{C} = 1.07 = k_1$
 k , at $20^{\circ}\text{C} = 1.63 = k_2$

from equation 2.1

$$k_2/k_1 = \theta^{(t_2 - t_1)}$$

$$\text{where } T_2 = 20^{\circ}\text{C}$$

$$T_1 = 5^{\circ}\text{C}$$

$$\log \frac{1.63}{1.07} = (20-5) \log \theta$$

$$\log \theta = \log \frac{1.52}{15} \quad -$$

$$= 1.82/15$$

$$= .0122$$

$$\theta = 1.029$$

4.3 Sludge Yield Study

The calculation of sludge yield is accomplished by the use of equation 2.3 ($DX = aS_r - bX_v$). The coefficients a , the fraction of BOD applied that is converted to cellular material, and b , the endogenous rate coefficient, are calculated from the results of several bench scale tests at various organic loads. Dividing equation 2.3 by X_v gives:

$$DX/X_v = aS_r/X_v - b.$$

If DX , X_v and S_r are known for several different loading rates a plot of DX/X_v vs S_r/X_v gives a straight line, the slope of which is the coefficient a and intercept is the coefficient b in the above equation.

From the data for DX , X_v and S_r given in Appendix A DX/X_v vs S_r/X_v has been plotted in figure 4.6 for a total of 16 and 13 experimental results at 5 and 20°C respectively. A straight line obtained from a computer evaluated least squares regression analysis was then plotted for each temperature. The values of the coefficients 'a' and 'b' thus obtained are shown in figure 4.7 together with confidence intervals for 'a' which were calculated as described in section 4.2 and confidence intervals for 'b' which were calculated in accordance with Experimental Statistics (33) as described below:

Number of points	= 13	
confidence level $(1-\alpha)$	= 20%	40%
$1 - \alpha/2$	= .60	.70
$t_{(1-\alpha/2, 11)}$	= .260	.540
S_y	= 0.029	0.029
$(\frac{1}{n} + \frac{\bar{x}^2}{S_{xx}})^{\frac{1}{2}}$	= .590	.590
$t_{(1-\alpha/2)} S_y (\frac{1}{n} + \frac{\bar{x}^2}{S_{xx}})^{\frac{1}{2}}$	= .004	.009
intercept	= -.042	-.042
confidence interval	= -.038 to -.046	-.033 to -.051

Note: the terms n , $t_{(1-\alpha/2)}$, S_y , \bar{x} and S_{xx} are defined

in Experimental Statistics (33). The values of the last three terms are determined from the computer print-out.

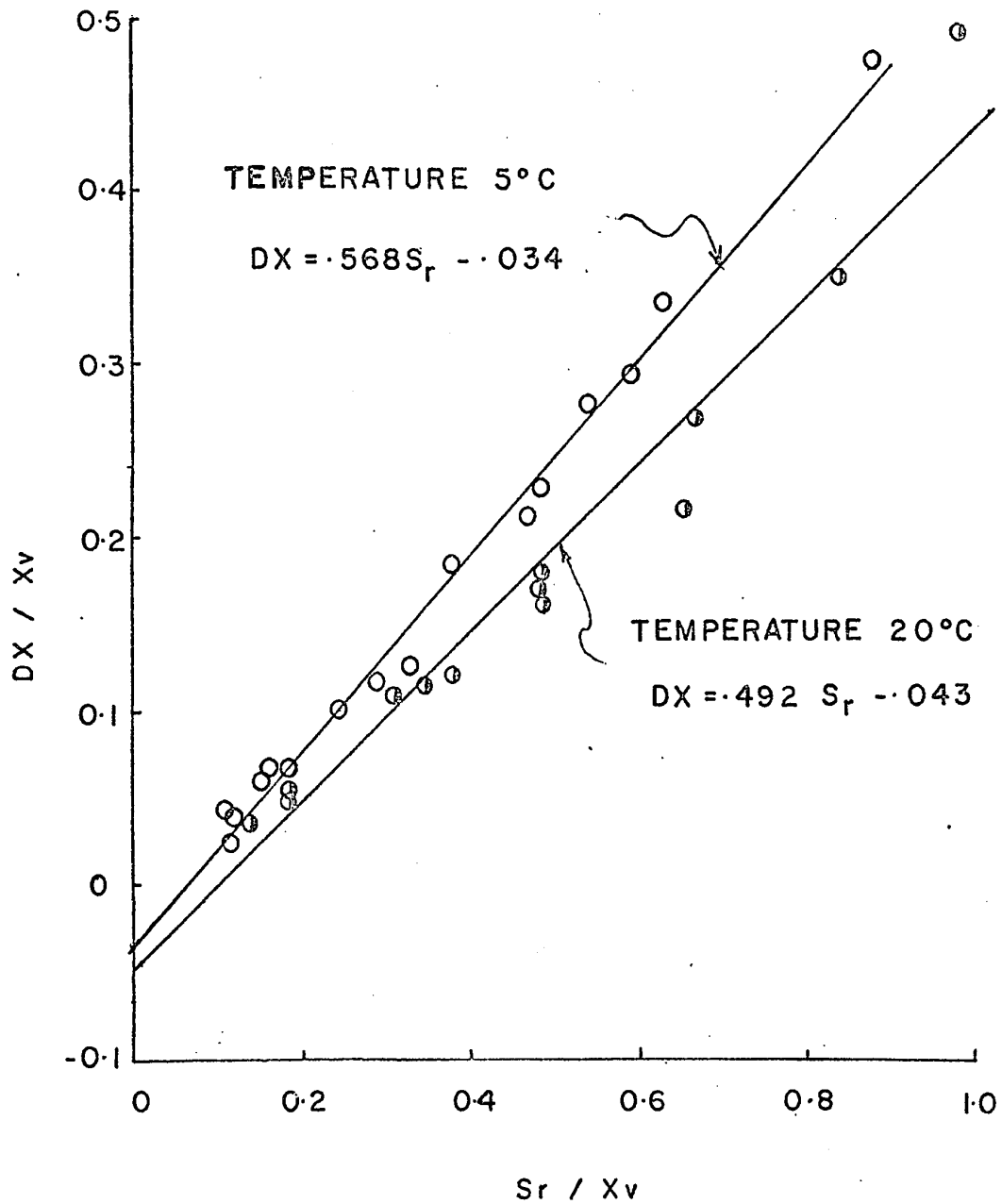


FIGURE 4.6 SLUDGE YIELD OF ACTIVATED SLUDGE SYSTEM TREATING MILK WASTE

Figure 4.7 Summary of Sludge Yield data

Temperature	5°C	20°C
a	.566	.487
Interval estimate at 80% c.l.	.546 to .586	.442 to .532
Interval estimate at 90% c.l.	.540 to .592	.428 to .546
b	-.034	-.042
Interval estimate at 20% c.l.	-.032 to -.036	-.038 to -.046
Interval estimate at 40% c.l.	-.031 to -.037	-.033 to -.051
Correlation coefficient	.995	.976

Note: c.l. denotes confidence level.

4.4 Oxygen Utilization

The calculation of oxygen utilization is accomplished by the use of equation 2.4 ($OX = a^1 S_r + b^1 X_v$). The coefficients ' a^1 ', the fraction of BOD used for respiration, and ' b^1 ', the endogenous reaction respiration coefficient are calculated from the laboratory results. The procedure used in calculating these coefficients is similar to the evaluation of ' a ' and ' b ' in the sludge yield study, in that equation 2.4 is divided by X_v , yielding: $OX/X_v = a^1 S_r/X_v + b^1$. Then by plotting OX/X_v vs S_r/X_v , ' a^1 ' can be obtained from the slope of the resulting straight line and ' b^1 ' from the intercept. Using the data for OX , S_r and X_v ; OX/X_v vs S_r/X_v has been plotted as shown in figure 4.8 for a total of 13 and 11 experimental results at 5 and 20°C respectively. From a least squares regression analysis the values of ' a^1 ' and ' b^1 ', which are shown in figure 4.9, were obtained together with confidence intervals which were calculated as described in section 4.2 and 4.3.

4.5 Efficiencies

Plots of efficiencies based on COD removal rates vs the organic loading rates are given in figures 4.10 and 4.11 for the results at 5 and 20°C respectively.

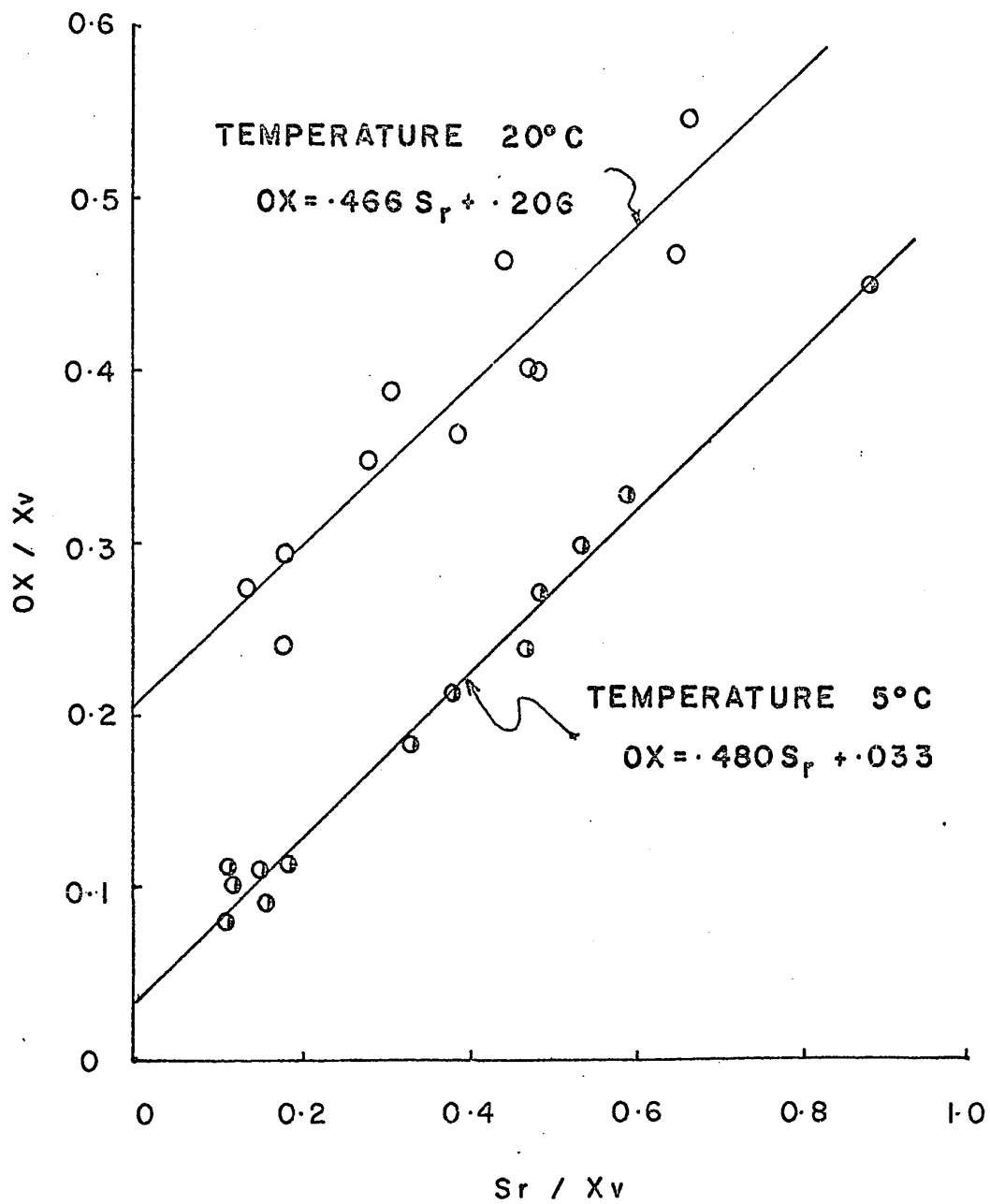


FIGURE 4.8 OXYGEN UTILIZATION OF ACTIVATED
SLUDGE SYSTEM TREATING MILK
WASTE

Figure 4.9 Summary of Oxygen Utilization data

Temperature	5 ^o C	20 ^o C
a ¹	.475	.466
Interval estimate at 40% c.l.	.466 to .484	.447 to .485
Interval estimate at 20% c.l.	.421 to .479	.457 to .475
b ¹	.034	.206
Interval estimate at 90% c.l.	.022 to .046	.164 to .248
Interval estimate at 99% c.l.	.013 to .056	.124 to .288
Correlation coefficient.	.994	.931

Note: c.l. denotes confidence limit

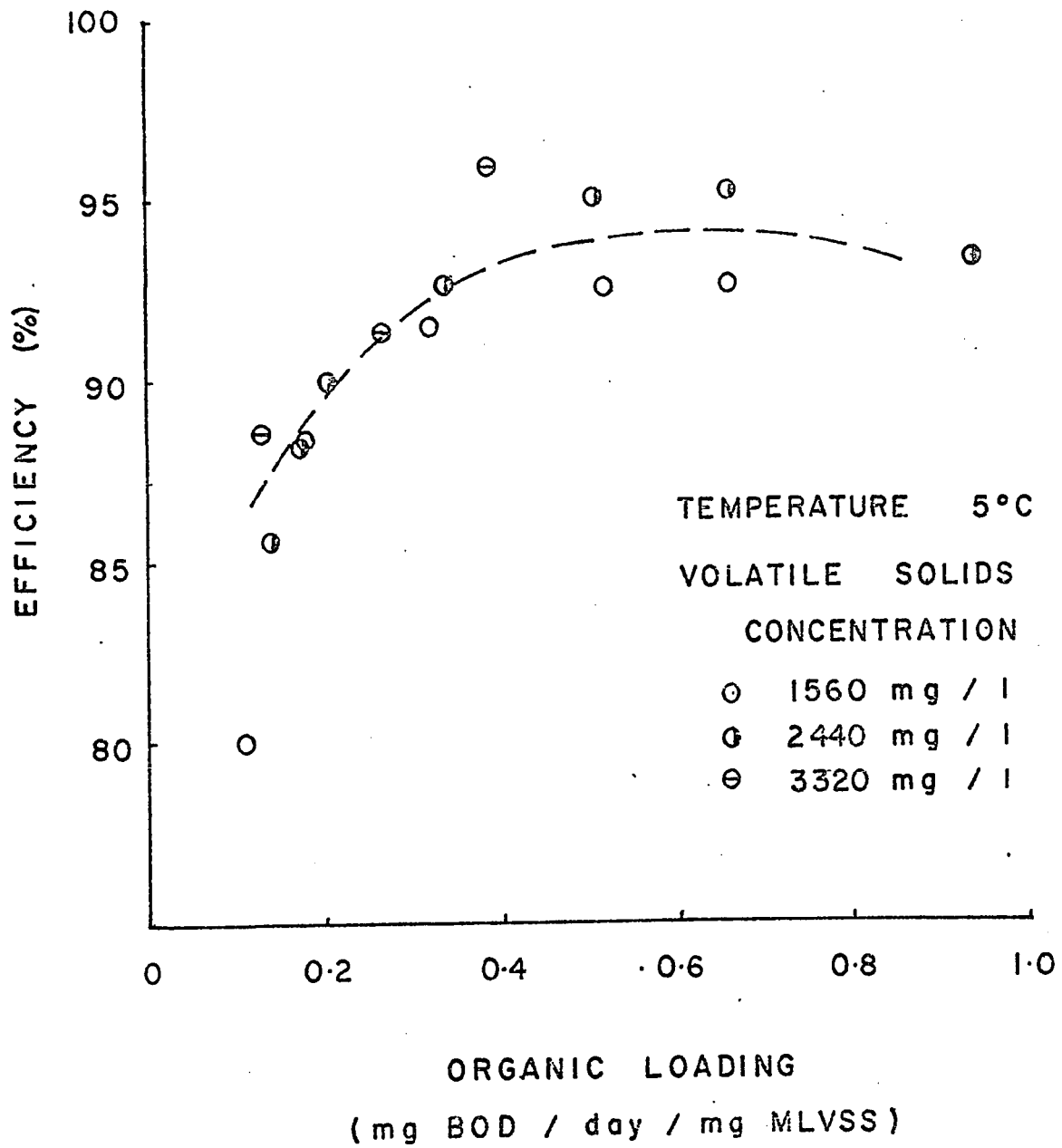


FIGURE 4-10 EFFICIENCY OF ACTIVATED SLUDGE
SYSTEM TREATING MILK WASTE
AT 5 °C

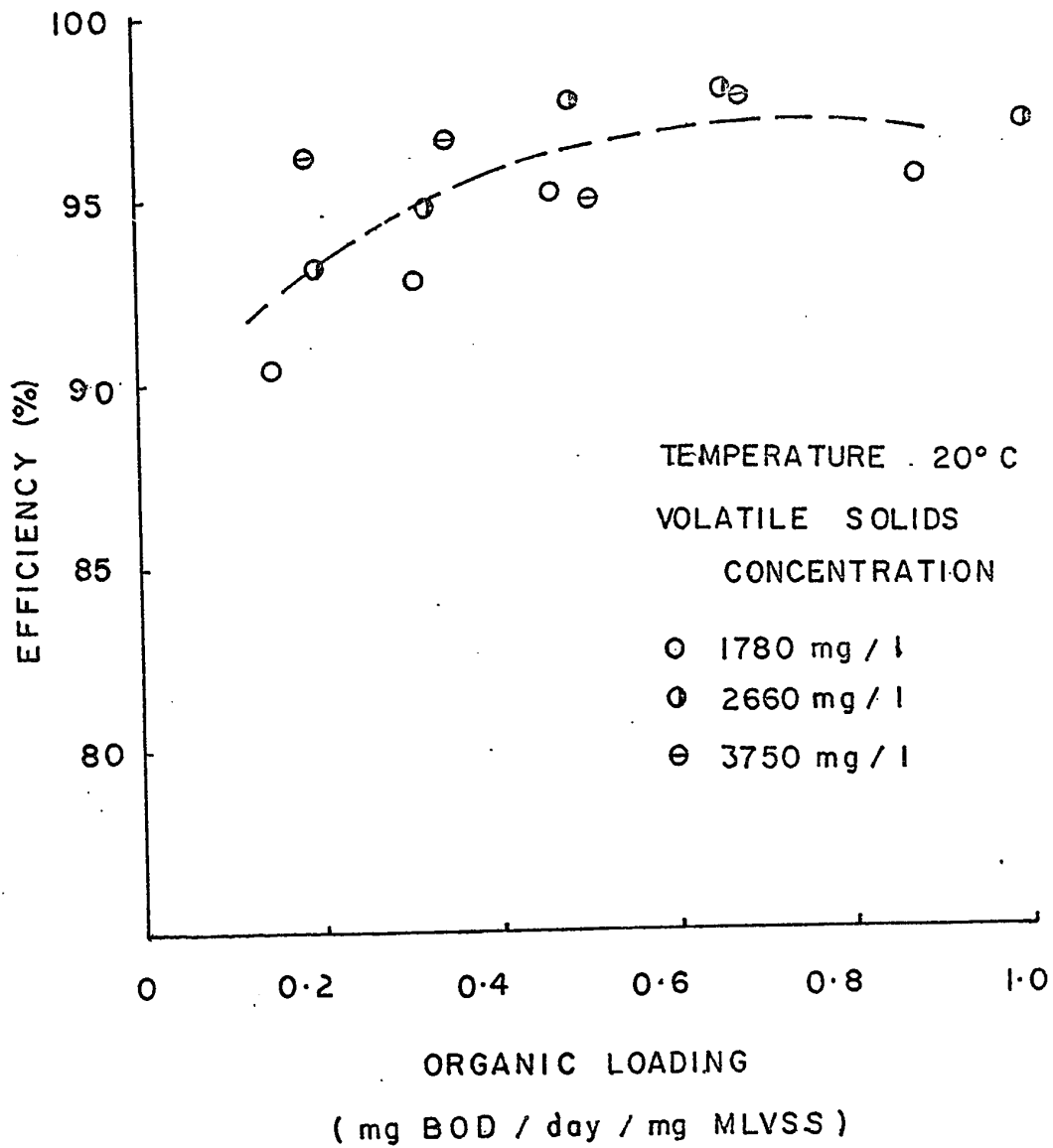


FIGURE 4-II EFFICIENCY OF ACTIVATED SLUDGE
SYSTEM TREATING MILK WASTE
AT 20° C

CHAPTER 5
DISCUSSION

The results of this study are satisfactory as evidenced by the high correlation coefficients obtained in the majority of the regression analyses. The major shortcoming of the study is that the validity of some of the regression lines may be questioned as only a few points are available for those lines that compare parameters for the same temperature but at different sludge concentrations. However, it should again be emphasized that the time required to complete one continuous flow test averages approximately two weeks of daily testing thus limiting the number of data points that can be obtained in a reasonable amount of time.

5.1 Reaction kinetics

From the results obtained (figure 4.5) it appears that the reaction rate constant, k , decreases with a decreasing temperature and increasing solids concentration. The decrease in k with temperature can easily be explained by the decrease in microbial activity at lower temperatures. However, to determine whether the difference in the values of k with solids concentration is statistically significant, confidence interval estimates at various confidence levels have been calculated in figure 4.5.

At a confidence level of 40 per cent the confidence intervals of the results of k at 20°C all coincide thus indicating that the difference at the 40 per cent confidence level is not significant. Similarly the difference between k at the low and medium solids concentration at 5°C is not significant at the 60 per cent confidence level. However, when considering k at the highest sludge concentration there is a significant difference at the 90 per cent confidence level as compared to the results at the lower concentrations but this may be discounted by the fact that only three data points were available for the determination of this plot (see figure 4.3). Furthermore, the plot obtained for the data at this high sludge concentration appears to be shifted considerably by only one point and therefore the reliability of the curve may be questioned. On the basis of the above discussion it may then be considered that k does not significantly change with solids levels at either 5°C or 20°C .

When comparing the average values of k for the low and medium solids concentration at 5 and 20°C a value of 1.029 for the temperature coefficient, θ , is determined which compares favourably with the value obtained by Pohl (17). However, this θ value which converts to a Q_{10} value of 1.32

is considerably lower than those reported by Sawyer and McCarty (25) of 2.85 and 2.22 in the 10 to 20°C and 15 to 25°C ranges respectively. The difference between the experimental results and those of Sawyer and McCarty (25) again indicate that different microbial population predominate in a biological oxidation process at different temperatures. It is suspected that the figures quoted by Sawyer and McCarty (25) were from identical microbial populations at different temperatures in which case their results appear to be in the right order of magnitude.

5.2 Sludge Yield Study

The results showing the fraction of the waste that is converted into cellular material, 'a', shown in figure 4.7 indicate that more organic material is converted to sludge at 5°C than at 20°C. The intervals shown in figure 4.7 show that the difference in 'a' is not significant at the 90% confidence level but is significant at the 80% confidence level. Interpolation shows that 'a' is smaller at 20°C than at 5°C at about the 87% confidence level. The significant difference can be explained in two related ways:

- 1) When a substrate is oxidized biologically it can be

converted into energy or used in support of synthesis.

At the lower temperature the activity of the micro-organism is decreased resulting in a lower energy requirement and therefore greater synthesis or sludge yield.

2) As the activity of the micro-organisms is less at the lower temperature the waste concentration remains initially at a higher concentration than it would at a higher temperature. The higher waste concentration results in a larger food to micro-organisms ratio (F:M) at which more micro-organisms are synthesized.

The coefficient 'b' represents the endogenous activity of the organisms or that amount of cellular material converted into energy when no waste organic material is available to be oxidized. As the energy requirements are greater at the larger temperature because of greater activity, 'b' should be smaller at 5°C than at 20°C as indicated by the experimental results.

The results indicate that a significant difference exists only at the 20% confidence level. However, the experiments performed at 5°C and at an organic loading rate of about 0.12 gr of ultimate BOD per gr. of MLVSS resulted in a small sludge yield indicating that the loading required for endogenous activity had been exceeded. At the same

organic loading at 20°C the required sludge concentration could not be maintained and it was necessary to increase the organic loading to 0.20 gr of ultimate BOD per gr of MLVSS to obtain a sludge yield. On the basis of the above it is felt that the experimental value for 'b' at 20°C should have been higher.

The results of this portion of the study confirms the hypothesis of Sawyer (23) and Lesperance (13) and the batch test results from Ludzack, et al (14) that a decrease in temperature increases sludge yield.

5.3 Oxygen Utilization

No significant difference in the value of 'a', the amount of oxygen required to oxidize organic material was exhibited, which is to be expected as the amount of oxygen needed to oxidize a waste should not be temperature dependent. However, Shih and Stack (27) concluded that there is a change in the amount of oxygen consumed in support of synthesis, with a change in temperature for some substrates possibly because at different temperatures the predominant bacteria employ different metabolic pathways to oxidize the substrate. As this change in oxygen utilization with temperature was not noted in this study it must be presumed that the readily biodegradable nature of the waste used does not result in different oxygen requirements at

different temperatures.

The results for the value of ' b^1 ', which represents the amount of oxygen utilized for endogenous respiration only, indicated that ' b^1 ' was significantly lower at 5°C than at 20°C even at the 99% confidence level. The decreasing value of ' b^1 ' with temperature is to be expected as the activity of the organisms increases with temperature.

The results of the oxygen utilization data therefore indicate that for a given loading rate the oxygen utilization is always less at the lower temperature by an amount equal to the difference in the endogenous respiration rates.

5.4 Efficiencies

The efficiency at 5°C is lower for all tests than at the corresponding conditions at the higher temperature. At loading rates in excess of 0.2 mg BOD per mg MLVSS the efficiency at 5°C is above 90% while at 20°C it is above 93%. As can be expected the lower efficiencies for both temperatures are at the lower sludge concentrations.

It should be pointed out that at 5°C and an organic loading rate less than 0.2 mg BOD per mg MLVSS the COD of the effluent was always less than 20 mg/l. The accuracy of the COD test at this strength is questionable and may well

be the cause for the low efficiency obtained during these tests.

Although the optimum organic loading rate should be established from a settling rate study performed at different loadings, an indication of the optimum organic loading rate can be obtained from the efficiency plots. At 20°C the optimum loading range is approximately .2 to .9 mg BOD₅ per mg MLVSS which can be converted to .13 to .68 mg BOD_u per mg MLSS using the experimentally obtained relationships of BOD₅/BOD_u of .81 (median value) and MLVSS/MLSS of .80 (estimated value). The results compare favourably with Eckenfelders often quoted range of .3 to .7 mg BOD per mg of MLSS.

At 5°C the optimum loading rate ranges between approximately .3 and .7 mg BOD_u per mg of MLVSS which converts to .2 and .46 mg BOD₅ per mg of MLSS.

CHAPTER 6
CONCLUSIONS

The effect of low temperatures on reaction kinetics, sludge yield, oxygen utilization and efficiency of the conventional activated sludge process have been evaluated quantitatively. These bio-oxidation parameters were evaluated in a laboratory study at 5 and 20°C for a mild waste. It is postulated that the ratio of these parameters at 5°C to those at 20°C can be applied to other substrates and used for full scale sewage treatment plants. Under the conditions employed in this study the following conclusions can be made:

- 1) The reaction rate constant (k) decreases with temperature which results in a temperature coefficient (θ) value of 1.029 and a Q_{10} value of 1.32.
- 2) The quantity of organic material that is converted into sludge during the oxidation of a waste is greater at 5°C than at 20°C. At 5°C 56.8 per cent of the applied organic loading is converted to cellular material while at 20°C only 49.2 per cent is converted to cellular material. Applying the results of the laboratory study to a sewage treatment plant with a 1,000,000 gallon aeration tank, MLVSS of 2000 mg/l and an organic loading of 0.4 lbs BOD_u per day per lb. of MLVSS the increase in sludge yield, as calculated by equation 2.3, at 5°C to that at 20°C is 23 per cent. If the organic loading is decreased to 0.2 the increase in sludge production at the lower temperature is 45 per cent.

- 3) A biological oxidation process can be operated at lower organic loading rates at low temperatures as the energy requirements are less and a larger fraction of the waste is available for production of new cells.
- 4) The amount of oxygen required to oxidize a waste decreases with a decrease in temperature. The endogenous respiration rate coefficient decrease from .206 per hour at 20°C to .033 per hour at 5°C. Applying the results of the study to the same hypothetical sewage treatment plant used in section 2 the oxygen requirements, as calculated by equation 2.4, gives an increased oxygen requirement of 74 per cent at 20°C as compared to 5°C at an organic loading of 0.4. At an organic loading of 0.2 the increased oxygen requirement at 20°C as compared to 5°C is 128 per cent.
- 5) Both the efficiency and the optimum organic loading range are less at 5°C than at 20°C.

CHAPTER 7
SUGGESTIONS FOR FURTHER RESEARCH

Suggested areas for further research of temperature effects on the conventional activated sludge process include the following:

- 1) A pilot plant study to determine whether the results of this study concerning changes in reaction rate constant, sludge yield, oxygen utilization, efficiency and organic loading range with temperature are directly applicable to treatment plants.
- 2) Since one of the problems of operating treatment plants at high sludge concentrations is insufficient oxygen transfer in the aeration unit and since less oxygen is required at low temperatures to oxidize wastes, operation at increased sludge concentrations at lower temperatures should be investigated. Furthermore, since settling characteristics of the activated sludge floc appear to hinder low temperature operations at high sludge concentrations rapid settling techniques such as inclined tubes should be investigated for low temperature operations.
- 3) A biological study should be conducted to determine flocculation characteristics of the biological populations that predominate at high and low temperatures.

BIBLIOGRAPHY

1. Bartsch, E.H., Randall C.W., "Aerated Lagoons - A Report on the State of the Art." Journal Water Pollution Control Federation, 43, 699, (1971).
2. Bloodgood, D.E., "The Effect of Temperature and Organic Loading upon Activated Sludge Plant Operation." Sewage Works Journal, 16, 913, (1944).
3. Eckenfelder, W.W., Jr. "Water Pollution Control." The Pemberton Press, Jenkins Publishing Co., Austin and New York, 132, (1970).
4. Eckenfelder, W.W., Jr. "Industrial Water Pollution Control." McGraw-Hill Book Co., Inc., New York, N.Y., 206, (1966).
5. Fair, G.M., Geyer, J.C., "Water Supply and Waste Water Disposal." John Wiley & Sons Ltd., New York, N.Y., 522, (1965).
6. Frank, H.A. Ishibashi, S.T. Reid, A., Ito, J.S., "Catalase Activity of Psychrophilic Bacteria Grown at 2 and 30°C." Applied Microbiology, 11, 151, (1961).
7. Hawkes, H.A. "Ecology of Waste Water Treatment." Pergamon Press, 117, (1963).
8. Helmers, E.N., Frame, J.D., Greenberg, A.E., Sawyer, C.N., "Nutritional Requirements in the Biological Stabilization of Industrial Wastes. II Treatment with Domestic Sewage." Sewage and Industrial Wastes, 23, 884, (1951).
9. Howland, W., "Flow over Porous Media as in a Trickling Filter." Proceedings 12th Industrial Waste Conference, Purdue University, Extension Series, 94, 435, (1958).

10. Ingraham, J., "Growth of Psychrophilic Bacteria." *Journal Bacteriology*, 76, 75, (1958).
11. Ingraham, J.L., Stokes, J.L., "Psychrophilic Bacteria." *Bacteriological Reviews*, 23, 97, (1959).
12. Keefer, C.E., "Temperature and Efficiency of the Activated Sludge Process." *Journal Water Pollution Control Federation*, 34, 1186, (1962).
13. Lesperance, T.W., "A Generalized Approach to Activated Sludge." *Journal of Water Works and Waste Engineering*, 5, 52, (1965).
14. Ludzack, F.J., Schaffer, R.B., Etinger, M.B., "Temperature and Feed as Variables in Activated Sludge Performance." *Journal Water Pollution Control Federation*, 33, 141, (1961).
15. McKinney, R.E., "Microbiology for Sanitary Engineers." McGraw-Hill Book Company Inc., 226, (1962).
16. Olsen, R.H., Jezewski, J.J., "Some Effects of Carbon Source, Aeration and Temperature on Growth of a Psychrophilic Strain of Pseudomonas Fluorescens." *Journal of Bacteriology*, 86, 429, (1963).
17. Pohl, E.F., "The Effect of Low Temperature on Aerobic Waste Treatment Processes." Master's Thesis, University of Washington (1967).
18. Quist, R.G., Stokes, J.L., "Temperature Range for Formic Hydrogenlyase Induction and Activity in Psychrophilic and Mesophilic Bacteria." *Antonie Van Leeuwenhoek*, 35, 1, (1969).
19. Reed, S.C., Murphy, R.S., "Low Temperature Activated Sludge Settling." *Journal Sanitary Engineering Division, ASCE*, SA4, 747, (1969).

20. Rose, A.H., Evinson, L.M., "Studies on the Biochemical Basis of the Minimum Temperature for Growth of Certain Psychrophilic and Mesophilic Organisms." *Journal of General Microbiology*, 38, 131, (1965).
21. Ruchthof, C.C., Smith, R.S., "Studies of Sewage Purification: X Changes in Characteristics of Activated Sludge Induced by Variations in Applied Load." *Sewage Works Journal*, 11, 409, (1939).
22. Sawyer, C.N., Rohlich, G.A., "Activated Sludge Oxidations. IV. Temperature Effects." *Sewage Works Journal*, 11, 946, (1939).
23. Sawyer, C.N., "Activated Sludge Oxidations. VI. Results of Feeding Experiments to Determine the Effect of the Variables Temperature and Sludge Concentration." *Sewage Works Journal*, 12, 244, (1940).
24. Sawyer, C.N., "New Concepts in Aerated Lagoon Design and Operation." In "Advances in Water Quality Improvement." E.F. Gloyna and W.W. Eckenfelder, Jr. (Eds.) University of Texas Press, Austin, 325, (1968).
25. Sawyer, C.N., McCarty, P.L., "Chemistry for Sanitary Engineers." McGraw-Hill Book Co., Inc., New York, N.Y., 228, (1967).
26. Schmidtke, N.W., Unpublished Data (1969).
27. Shih, C.S., Stack, V.T., "Temperature Effects on Energy Oxygen Requirements in Biological Oxidation." *Journal Water Pollution Control Federation*, 41, 461, (1969).
28. Standard Methods for the Examination of Water and Wastewater. 12th Edition, American Public Health Association, American Water Works Association, Water Pollution Control Federation (1965).

29. Stokes, J.L., Larkin, "Comparative Effect of Temperature on the Oxidative Metabolism of Whole and Disrupted Cells of a Psychrophilic and Mesophilic Species of Bacillus." *Journal of Bacteriology*, 95, 95, (1968).
30. Sultzer, B.M., "Oxidative Activity of Psychrophilic and Mesophilic Bacteria on Saturated Fatty Acids." *Journal of Bacteriology*, 82, 492, (1961).
31. Thomas, H.A., "Low Temperature Sewage Treatment." *Journal of Sewage and Industrial Wastes*, 23, 1, (1951).
32. Townshend, A.R., "Statistical Analysis of the Effluent Quality of Biological Sewage Treatment Processes." *Proceedings of the 3rd Canadian Symposium on Water Pollution Research*, University of Toronto, Volume 111, 272, (1968).
33. United States Department of Commerce, "Experimental Statistics, National Bureau of Standards," Handbook 91, 5-12, (1963).
34. Wuhrmann, K., "Advances in Biological Waste Treatment." Pergamon Press, Oxford, England (1963).

ADDITIONAL REFERENCES

1. Benedict, A.H., "Organic Loading and Temperature in Bio-Oxidation." Doctoral Dissertation, University of Washington, (1968).
2. Brodersen, K.T., Shannon, E.E., Schmidtke, N.W., Fisher, C.P., Lacroix, P.G., "Modern Waste Treatment Concepts (a short course)." University of Ottawa, (1971).
3. Dawson, R.N., Grainge, J.W., "Proposed Design Criteria for Wastewater Lagoons in Arctic and Sub Arctic Regions." Journal Water Pollution Control Federation, 41, 237, (1969).
4. Henry, J.G., "Psychrophilic Bacteria." Unpublished data, (1965).
5. Sinclair, N.A., Stokes, J.L., "Role of Oxygen in the High Cell Yields of Psychrophiles and Mesophiles at Low Temperatures." Journal of Bacteriology, 85, 164, (1963).
6. Teng-chung Wu, "Factors Affecting Growth and Respiration in Activated Sludge Process." Doctoral Dissertation, Case Institute of Technology, (1963).

A P P E N D I X A

20250111 14:10:00

DATA PRESENTATION

Listed below are explanations of data presentation, symbols and units used in subsequent pages. The numbers refer to the subscripts on page A.3.

1. Av. Sol. (mg/l) - The average solids level measured in terms of MLVSS is the average of the solids level after wasting at any one day and the level before wasting on the following day.
2. Load (BOD/VSS) - The organic loading is expressed in terms of gr. of ultimate BOD per gr. of MLVSS.
3. Oxy. Uptake - Oxygen uptake is expressed in terms of mg. of oxygen per hour per gr. of sludge (MLVSS).
4. Waste (mg/day) - The amount of solids wasted is the sum of the solids in the effluent and the solids wasted daily to maintain a constant solids level measured in terms of MLVSS.
5. Solids gained - Solids gained is the difference between initial and final solids levels and is not based upon average MLVSS concentrations.
6. DX - solids grown daily in grams.

7. S_r - grams of BOD removed daily
8. X_v - grams of MLVSS in reactors.
9. O_2/X_v - Oxygen utilization in terms of gr. of oxygen per day per gr. of MLVSS.
10. S_o - Influent COD (mg/l)
 S_e - Effluent COD (mg/l)
 X_a - Solids concentration (gr./l)
 t - Detention time (hours)

DATA SHEET NUMBER

Temperature . . . °C Influent C.O.D. . . . mg/l

Day	Av. Sol. (mg/l) (1)	Load (BOD) VSS (2)	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake (3)	Waste (mg/day) (4)	BOD removed (mg/day)
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
Av. Tot.							

SOLIDS BALANCE

Amount wasted = mg/ days
 (5) Solids gained = mg/l = mg
 Solids grown = mg/ days
 (6) DX = gr/day

BOD removed = mg/ days (7) Sr. = gr/day	Av. solids = mg/l (8) Xv = gr.
DX/Xv =	SR/Xv = (9) O ₂ /Xv =

REACTION KINETICS

(10) $\frac{S_o - S_e}{X_a t.} = \text{_____} =$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 1

Temperature . . . 20 °C Influent C.O.D. . 157 mg/l

Day	Av. Sol. (mg/l)	Load (BOD) / VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1					12.45		
2	1845		14	91.1	11.35		
3	1845	.16	14	91.1	13.80	444	1662
4	1880	.16	21	86.7	11.40	232	1542
5	1885	.13	15	90.4	-	216	1332
6	1875	.14	11	93.0	9.90	270	1512
7	1920	.15	15	90.4	9.90	444	1536
8							
9							
10							
11							
12							
Av. Tot.	1881	.15	15	90.4	68.80	1806	7584

SOLIDS BALANCE

Amount wasted = 1806 mg/ 5 days

Solids gained = 30 mg/l . . = 180 mg

Solids grown = 1986 mg/ 5 days
DX = .397 gr/day

BOD removed = 7584 mg/ 5 days Sr. = 1.52 gr/day	Av. solids = 1881 mg/l Xv = 11.29 gr.
DX/Xv = .035	SR/Xv = .135
	O ₂ /Xv = .275

REACTION KINETICS

$$\frac{S_0 - S_e}{X_a t} = \frac{157 - 15}{1.88 \times 10.6} = 7.12$$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 2

Temperature . . . 20 °C Influent C.O.D. . 275mg/l

Day	Av. Sol. (mg/l)	Load (BOD) VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1					16.55		
2	1690	.32	20	92.7	17.85	708	3042
3	1620	.35	22	92.0	14.25	1656	3120
4	1620	.33	24	91.2	12.05	636	2898
5	1690	.30	-	-	14.45	708	2850
6	1780	.26	18	93.5	15.75	672	2604
7							
8							
9							
10							
11							
12							
Av. Tot.	1680	.31	20	92.8	107.3	4380	14514

SOLIDS BALANCE

Amount wasted = 4380 mg/ 5 days

Solids gained = 315 mg/l . . = 1890 mg

Solids grown = 6270 mg/ 5 days
DX = 1.255 gr/day

BOD removed = 14514mg/ 5 days	Av. solids = 1680 mg/l
Sr. = 2.90gr/day	Xv = 10.08gr.
DX/XV = .125	SR/XV = .290
	O ₂ /XV = .368

REACTION KINETICS

$$\frac{S_0 - S_e}{X_a t} = \frac{275 - 20}{1.68 \times 9.90} = 15.3$$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 3

Temperature . . . 20 °C Influent C.O.D. . 430 mg/l

Day	Av. Sol. (mg/l)	Load (BOD) VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1					18.50		
2	1920				17.75		
3	1910	.48	23	94.6	19.15	2742	5220
4	1810	.48	17	96.0	-	2682	5004
5	1760	.43			19.85	2166	4392
6	1845	.46	14	96.7	19.55	2166	4950
7							
8							
9							
10							
11							
12							
Av. Tot.	1849	.46	18	95.8	94.80	9756	19566

SOLIDS BALANCE

Amount wasted = 9756 mg/ 4 days

Solids gained = -250mg/l . . = -1500 mg

Solids grown = 8256 mg/ 4 days
DX = 2.064 gr/day

BOD removed = 19566mg/ 4 days Sr. = 4.891gr/day	Av. solids = 1849 mg/l Xv = 11.09 gr.
DX/XV = .186	SR/XV = .442
	O ₂ /XV = .455

REACTION KINETICS

$$\frac{S_0 - S_e}{X_a t} = \frac{412}{1.85 \times 9.60} = 23.15$$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 4

Temperature . . . 20 °C Influent C.O.D. . . 780mg/l

Day	Av. Sol. (mg/l)	Load (BOD) VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1							
2	1930	.78	16	97.9		2148	8820
3	1865	.84	27	96.5	Not	4626	9120
4	1600	1.02	42	94.6	con -	4944	9300
5	1510	1.06	46	94.1	sis -	3066	9000
6	1660	.88			tent.	786	8370
7	2070	.80	41	94.8		1938	9450
8	1690	.82	32	95.9		7560	7980
9							
10							
11							
12							
Av. Tot.	1761	.88	34	95.6		25068	62040

SOLIDS BALANCE

Amount wasted = 25068mg/ 7 days

Solids gained = 60 mg/l . . = 360mg

Solids grown = 25428mg/ 7 days
DX = 3.63gr/day

BOD removed = 62040mg/ 7 days Sr. = 8.87 gr/day	Av. solids = 1761 mg/l Xv = 10.57 gr.
DX/Xv = .345	SR/Xv = .840
	O ₂ /Xv =

REACTION KINETICS

$$\frac{S_0 - S_e}{X_a t} = \frac{780 - 34}{1.76 \times 9.6} = 44.2$$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 5

Temperature . . . 20 °C Influent C.O.D. . . 262 mg/l

Day	Av. Sol. (mg/l)	Load (BOD) VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1							
2	2725	.18				342	2820
3	2790	.18	13	94.6	12.30	426	2832
4	2535	.19	14	94.7	12.40	2364	2760
5	2370	.21	19	92.7	11.90	2106	2772
6	2345	.21	24	90.8	13.85	546	2748
7	2380	.21	18	93.1	11.20	912	2778
8							
9							
10							
11							
12							
Av. Tot.	2523	.20	18	93.2	61.65	6696	16710

SOLIDS BALANCE

Amount wasted = 6696 mg/ 6 days

Solids gained = -275 mg/l . . -- 1650 mg

Solids grown = 5046 mg/ 6 days

DX = .841 gr/day

BOD removed = 16710 mg/ 6 days	Av. solids = 2523 mg/l
Sr. = 2.78 gr/day	Xv = 15.13 gr.
DX/XV = .055	SR/XV = .183
	O ₂ /XV = .296

REACTION KINETICS

$$\frac{S_0 - S_e}{X_a t} = \frac{244}{2.52 \times 10.15} = 9.55$$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 6

Temperature . . . 20 °C Influent C.O.D. . 457 mg/l

Day	Av. Sol. (mg/l)	Load (BOD) VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1					14.35		
2	2690	.34	36	92.1	16.10	4314	5052
3	2690	.33	25	94.5	16.15	1908	4980
4	2690	.30	16	96.5	16.75	1812	4728
5	2665	.32	18	96.1	17.95	1980	4980
6							
7							
8							
9							
10							
11							
12							
Av. Tot.	2684	.32	24	94.8	81.30	10014	19740

SOLIDS BALANCE

Amount wasted = 10014 mg/ 4 days

Solids gained = -470 mg/l . . = -2820 mg

Solids grown = 7194 mg/ 4 days
DX = 1.798 gr/day

BOD removed = 19740 mg/ 4 days Sr. = 4.94 gr/day	Av. solids = 2684 mg/l Xv = 16.10 gr.
DX/Xv = .112	SR/Xv = .308
	O ₂ /Xv = .390

REACTION KINETICS

$$\frac{S_0 - S_e}{X_a t} = \frac{433}{2.68 \times 10.1} = 16.10$$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 7

Temperature . . . 20 °C Influent C.O.D. . 720 mg/l

Day	Av. Sol. (mg/l)	Load (BOD) / VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1							
2	2750	.49	19	97.4	17.55	600	7950
3	2880	.40				2724	6660
4	2850	.50	16	97.8	19.05	2106	8370
5	2825	.50	19	97.4	16.70	3018	8190
6	2805	.52	16	97.8	15.60	3180	8520
7	2810	.49	14	98.1	15.00	3138	8070
8	2675	.50			17.55	3408	7860
9							
10							
11							
12							
Av. Tot.	2799	.48	18	97.7	101.45	18174	55620

SOLIDS BALANCE

Amount wasted = 18174mg/ 7 days

Solids gained = 370 mg/l . . = 2220mg

Solids grown = 20394mg/ 7 days
DX = 2.91 gr/day

BOD removed = 55620 mg/ 7 days Sr. = 7.94 gr/day	Av. solids = 2799 mg/l Xv = 16.79 gr.
DX/XV = .174	SR/XV = .473
	O ₂ /XV = .406

REACTION KINETICS

$$\frac{S_o - S_e}{K_a t} = \frac{702}{2.80 \times 9.9} = 25.5$$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 8

Temperature . . . 20 °C Influent C.O.D. . 980 mg/l

Day	Av. Sol. (mg/l)	Load (BOD) VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1							
2	2665	.62	15	98.5	17.30	4422	9840
3	2790	.62	14	98.6	16.90	3588	10320
4	2715	.66	20	98.0	23.20	3462	10410
5	2650	.66	23	97.6	18.65	3852	10290
6	2725	.64	26	97.3	23.50	3450	10140
7	2540	.77	22	97.7	17.75	3864	11430
8							
9							
10							
11							
12							
Av. Tot.	2681	.66	20	98.0	17.30	23538	62430

SOLIDS BALANCE

Amount wasted = 23538 mg/ 6 days

Solids gained = -270 mg/l . . = -1620 mg

Solids grown = 21918 mg/ 6 days

DX = 3.65 gr/day

BOD removed = 62430 mg/ 6 days	Av. solids = 2681 mg/l
Sr. = 10.40 gr/day	Xv = 16.09 gr.
DX/Xv = .221	SR/Xv = .648
	O ₂ /Xv = .470

REACTION KINETICS

$$\frac{S_0 - S_e}{X_a t} = \frac{960}{2.68 \times 10.65} = 33.6$$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 9

Temperature . . . 20 °C Influent C.O.D. . 1310mg/l

Day	Av. Sol. (mg/l)	Load (BOD) VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1							
2	2770	.95	27	97.9		3696	15420
3	2245	1.14			Not	13908	14950
4	2305	1.15	38	97.1	con -	4506	15420
5	2300	1.13	38	97.1	sis -	11604	15120
6	2800	.93	43	96.7	tent	630	15180
7	3230	.82	44	96.6		7980	15300
8							
9							
10							
11							
12							
Av. Tot.	2607	1.00	38	97.1		42324	91380

SOLIDS BALANCE

Amount wasted = 42324 mg/ 6 days

Solids gained = 715 mg/l . . = 4290 mg

Solids grown	= 46614 mg/ 6 days
DX	= 7.76 gr/day

BOD removed = 91380 mg/ 6 days	Av. solids = 2607 mg/l
Sr. = 15.23 gr/day	Xv = 15.64 gr.
DX/Xv = .497	SR/Xv = .975
	O ₂ /Xv =

REACTION KINETICS

$$\frac{S_o - S_e}{X_a t} = \frac{1272}{2.61 \times 9.65} = 50.6$$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 10

Temperature . . . 20 °C Influent C.O.D. . 365 mg/l

Day	Av. Sol. (mg/l)	Load (BOD) / VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1					10.00		
2	3855	.18	11	97.0	9.80	1638	3972
3	3655	.19	15	95.9	10.00	2424	3912
4	3675	.19	14	96.2	9.75	1014	4008
5	3655	.19	13	96.5	10.30	1854	3972
6	3530	.19	13	96.5		2328	3948
7	3470	.19	17	95.3	10.10	834	3840
8							
9							
10							
11							
12							
Av. Tot.	3640	.19	14	96.2	59.95	10092	23652

SOLIDS BALANCE

Amount wasted = 10092 mg/ 6 days
 Solids gained = -550 mg/l . . = -3300 mg

Solids grown = 6792 mg/ 6 days
 DX = 1.13 gr/day

BOD removed = 23652 mg/ 6 days Sr. = 3.94 gr/day	Av. solids = 3640 mg/l Xv = 21.84 gr.
DX/Xv = .052	SR/Xv = .181
	O ₂ /Xv = .242

REACTION KINETICS

$$\frac{S_o - S_e}{X_a t} = \frac{351}{3.64 \times 10.3} = 9.36$$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 11

Temperature . . . 20 °C Influent C.O.D. . 638 mg/l

Day	Av. Sol. (mg/l)	Load (BOD) VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1							
2	3680	.33	18	97.2		2412	7170
3	3645	.35	19	97.0		2250	7350
4	3785	.34	20	96.8		1794	7440
5	3795	.34	21	96.6	14.15	3018	7410
6	3460	.36	24	96.2	14.95	4428	7200
7	3525	.35	27	95.8		2004	7170
8	3635	.36	24	96.2	16.25	2646	7530
9	3545	.35	23	96.4	13.85	2496	7080
10	3575	.35	15	97.6	14.10	2298	7380
11							
12							
Av. Tot.	3627	.35	21	96.6	73.30	23346	65730

SOLIDS BALANCE

Amount wasted = 23346 mg/ 9 days

Solids gained = 10 mg/l . . = 60 mg

Solids grown = 23406 mg/ 9 days
DX = 2.60 gr/day

BOD removed = 65730 mg/ 9 days Sr. = 7.30 gr/day	Av. solids = 3627 mg/l Xv = 21.76 gr.
---	--

DX/XV = .120	SR/XV = .337	O ₂ /XV = .351
--------------	--------------	---------------------------

REACTION KINETICS

$$\frac{S_o - S_e}{X_a \cdot t} = \frac{617}{3.63 \times 9.7} = 17.6$$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 12

Temperature . . . 20 °C Influent C.O.D. . 1000 mg/l

Day	Av. Sol. (mg/l)	Load (BOD) / VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1							
2	3870	.50	21	97.9	17.30	1026	11340
3	3485	.53	64	93.6	16.15	5088	10440
4	3830	.51	42	95.8	16.75	2382	11100
5	3845	.51	76	92.4	22.70	5118	10920
6	3565	.51			20.2	4854	10350
7							
8							
9							
10							
11							
12							
Av. Tot.	3719	.51	51	94.9	93.10	18468	54150

SOLIDS BALANCE

Amount wasted = 18468 mg/ 5 days

Solids gained = -10 mg/l . . = -60 mg

Solids grown = 18408 mg/ 5 days
DX = 3.68 gr/day

BOD removed = 54150 mg/ 5 days Sr. = 10.83 gr/day	Av. solids = 3719 mg/l Xv = 22.31 gr.
DX/XV = .165	SR/XV = .485
	O ₂ /XV = .402

REACTION KINETICS

$$\frac{S_0 - S_e}{X_a t} = \frac{949}{3.72 \times 10.0} = 24.6$$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 13

Temperature . . . 20 °C Influent C.O.D. . 1490 mg/l

Day	Av. Sol. (mg/l)	Load (BOD) VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1					25.9		
2	3980	.72			23.4	2340	15600
3	4200	.69	44	97.0	20.9	5904	16980
4	4125	.68	38	97.5	25.2	7404	16440
5	3895	.66	21	98.6	19.4	7374	15300
6	3930	.69	27	98.2		5442	15960
7							
8							
9							
10							
11							
12							
Av. Tot.	4027	.68	32	97.8	114.8	28464	80280

SOLIDS BALANCE

Amount wasted = 28464 mg/ 5 days

Solids gained = 780 mg/l . . = 4680 mg

Solids grown = 33144 mg/ 5 days
DX = 6.63 gr/day

BOD removed = 80280 mg/ 5 days Sr. = 16.06 gr/day	Av. solids = 4027 mg/l Xv = 24.16 gr.
DX/Xv = .275	SR/Xv = .664
	O ₂ /Xv = .552

REACTION KINETICS

$$\frac{S_0 - S_e}{X_a t} = \frac{1458}{4.03 \times 10.35} = 34.9$$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 14

Temperature . . . 5 °C Influent C.O.D. . 80 mg/l

Day	Av. Sol. (mg/l)	Load (BOD) / VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1					3.05		
2	1500	.12	16	83.1	2.49	624	1140
3	1565	.14	19	80.5	3.24	548	1092
4	1595	.14	18	81.0	3.56	408	1110
5	1595	.14	23	75.7	4.17	516	1038
6	1600	.12	19	74.7	2.96	462	810
7	1485	.12	24	68.0	3.85	552	738
8	1370	.13	15	80.0	2.07	570	864
9	1380	.13	11	85.3	3.81	294	918
10	1470	.12	13	82.7	3.65	360	900
11	1440	.12	11	85.3		582	918
12	1340	.13	12	84.0	4.37	462	900
Av. Tot.	1485	.13	16	80.0	37.22	5388	10428

SOLIDS BALANCE

Amount wasted = 5388 mg/ 11 days
 Solids gained = -190 mg/l . . = -1140 mg

Solids grown = 4248 mg/ 11 days
 DX = .386 gr/day

BOD removed = 10428 mg/ 11 days Sr. = .948 gr/day	Av. solids = 1485 mg/l Xv = 8.91 gr.
DX/Xv = .044	SR/Xv = .106
	O ₂ /Xv = .081

REACTION KINETICS

$$\frac{S_0 - S_e}{X_a t} = \frac{64}{1.48 \times 8.0} = 5.41$$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 15

Temperature . . . 5 °C Influent C.O.D. . 150 mg/l

Day	Av. Sol. (mg/l)	Load (BOD) / VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1					3.97		
2	1660	.18	13	91.3		144	1632
3	1775	.17	15	90.0		486	1608
4	1765	.17	15	90.0	3.59	348	1608
5	1600	.19	17	88.7	4.65	1092	1590
6	1590	.19	19	87.4	3.94	594	1566
7	1610	.19	19	87.4	3.79	900	1566
8	1680	.18	21	86.1		960	1542
9	1550	.18				942	1458
10	1435	.21	17	88.7	3.84	804	1590
11	1460	.20	19	87.4	3.07	810	1566
12							
Av. Tot.	1612	.18	17	88.6	26.85	7080	15726

SOLIDS BALANCE

Amount wasted = 7080 mg/ 10 days

Solids gained = -50 mg/l . . = - 300 mg

Solids grown	=	6780 mg/ 10 days
DX	=	.678 gr/day

BOD removed = 15726 mg/ 10 days	Av. solids = 1612 mg/l
Sr. = 1.57 gr/day	Xv = 9.67 gr.
DX/XV = .071	SR/XV = .162
	O ₂ /XV = .092

REACTION KINETICS

$$\frac{S_0 - S_e}{X_a t} = \frac{133}{1.61 \times 9.66} = 8.57$$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 16

Temperature . . . 5 °C Influent C.O.D. . 264 mg/l

Day	Av. Sol. (mg/l)	Load (BOD) VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1							
2	1505	.30	20	92.1	Not con - sis- tent	348	2484
3	1480	.34	27	89.8		816	2724
4	1530	.33	20	92.1		894	2778
5	1535	.29	24	90.9		1296	2460
6							
7							
8							
9							
10							
11							
12							
Av. Tot.	1510	.32	23	91.2		3354	10446

SOLIDS BALANCE

Amount wasted = 3354 mg/ 4 days

Solids gained = 150 mg/l . . = 900 mg

Solids grown = 4254 mg/ 4 days
DX = 1.06 gr/day

BOD removed = 10446 mg/ 4 days Sr. = 2.61 gr/day	Av. solids = 1510 mg/l Xv = 9.06 gr.
DX/XV = .118	SR/XV = .288
	O ₂ /XV =

REACTION KINETICS

$$\frac{S_0 - S_e}{X_a t} = \frac{241}{1.51 \times 10.42} = 15.3$$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 17

Temperature . . . 5 °C Influent C.O.D. . 420 mg/l

Day	Av. Sol. (mg/l)	Load (BOD) VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1							
2	1565	.46	29	92.8		912	4062
3	1515	.54	29	93.1	9.34	2154	4554
4	1480	.55	24	93.9	9.05	1746	4572
5	1490	.53	33	92.1	10.50	1758	4398
6	1610	.48	34	91.8	11.00	1344	4260
7							
8							
9							
10							
11							
12							
Av. Tot.	1532	.51	30	92.7	39.89	7914	21846

SOLIDS BALANCE

Amount wasted = 7914 mg/ 5 days

Solids gained = 325 mg/l . . = 1950 mg

Solids grown = 9864 mg/ 5 days
DX = 1.97 gr/day

BOD removed = 21846 mg/ 4 days Sr. = 5.46 gr/day	Av. solids = 1532 mg/l Xv = 9.19 gr.
DX/Xv = .215	SR/Xv = .476
	O ₂ /Xv = .239

REACTION KINETICS

$$\frac{S_0 - S_e}{X_a t} = \frac{390}{1.53 \times 10.28} = 24.8$$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 18

Temperature . . . 5 °C Influent C.O.D. . 570 mg/l

Day	Av. Sol. (mg/l)	Load (BOD) / VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1							
2	1755	.57	30	94.7		2334	5574
3	1640	.63	37	93.5	12.15	3738	5844
4	1545	.71	37	93.5	13.15	3126	6150
5	1485	.73	45	92.1	14.82	3264	5970
6	1505	.72	45	92.1	14.90	4044	6030
7							
8							
9							
10							
11							
12							
Av.	1586	.66	39	93.2			
Tot.					55.02	16506	29568

SOLIDS BALANCE

Amount wasted = 16506mg/ 5 days

Solids gained = -270mg/l . . = -1620mg

Solids grown . 14886mg/ 5 days
DX = 2.98gr/day

BOD removed = 29568mg/ 5 days	Av. solids = 1586 mg/l
Sr. = 5.91gr/day	Xv = 9.52 gr.
DX/XV = .310	SR/XV = .620
	O ₂ /XV = .330

REACTION KINETICS

$$\frac{S_o - S_e}{X_a t} = \frac{531}{1.59 \times 10.35} = 32.3$$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 19

Temperature . . . 5 °C Influent C.O.D. . 125 mg/l

Day	Av. Sol. (mg/l)	Load (BOD) VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1							
2	2160	.14	18	85.6	3.93	558	1542
3	2130	.14	20	84.0	3.59	684	1512
4	2120	.14	18	85.6	5.40	828	1542
5	2060	.15	17	86.4	4.15	1044	1560
6							
7							
8							
9							
10							
11							
12							
Av. Tot.	2114	.14	18	85.6	17.07	3114	6156

SOLIDS BALANCE

Amount wasted = 3114mg/ 4 days

Solids gained = -180mg/1 . . = -1080mg

Solids grown = 2024mg/ 4 days
DX = .506gr/day

BOD removed = 6156mg/ 4 days	Av. solids = 2114mg/l
Sr. = 1.54 gr/day	Xv = 12.78gr.
DX/Xv = .040	SR/Xv = .121
	O ₂ /Xv = .102

REACTION KINETICS

$$\frac{S_0 - S_e}{X_a t} = \frac{107}{2.11 \times 8.0} = 6.33$$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 20

Temperature . . . 5 °C Influent C.O.D. . 170 mg/l

Day	Av. Sol. (mg/l)	Load (BOD) / VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1							
2	2425	.17	23	86.5	4.07	966	2118
3	2355	.17	18	89.4	5.50	1122	2190
4	2225	.18	22	87.1	4.50	912	2136
5	2245	.18	19	88.8	4.12	1062	2172
6	2240	.18	17	90.0	4.60	852	2202
7							
8							
9							
10							
11							
12							
Av. Tot.	2298	.18	20	88.4	22.79	4914	10818

SOLIDS BALANCE

Amount wasted = 4914 mg/ 5 days

Solids gained = -110 mg/l . . = -660 mg

Solids grown = 4254 mg/ 5 days
DX = .851 gr/day

BOD removed = 10818 mg/ 5 days Sr. = 2.16 gr/day	Av. solids = 1803 mg/l Xv = 2.17 gr.
DX/Xv = .062	SR/Xv = .157
	O ₂ /Xv = .110

REACTION KINETICS

$$\frac{S_0 - S_e}{X_a t} = \frac{150}{2.30 \times 8.0} = 8.15$$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 21

Temperature . . . 5 °C Influent C.O.D. . . 262 mg/l

Day	Av. Sol. (mg/l)	Load (BOD) / VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1							
2	2175	.23	27	89.7	5.03	450	2712
3	2260	.22	26	90.0	5.20	282	2724
4	2550	.19	23	91.2	4.80	654	2760
5	2725	.18	24	90.8	3.57	792	2748
6	2565	.20	21	91.6		1278	2784
7	2420	.21	26	90.0	4.88	722	2724
8	2560	.20	26	90.0	3.59	852	2724
9	2570	.20	30	88.5	5.50	1440	2676
10	2400	.21	31	88.2	4.41	1380	2664
11	2370	.21	28	89.3		1398	2700
12	2315		24	90.8	5.85	1056	2748
Av.	2446	.21	26	90.0			
Tot.					42.83	10404	29964

SOLIDS BALANCE

Amount wasted = 10404 mg/ 11 days

Solids gained = 140 mg/l . . = 840 mg

Solids grown = 11244 mg/ 11 days
DX = 1.02 gr/day

BOD removed = 29964 mg/ 11 days Sr. = 2.72 gr/day	Av. solids = 2446 mg/l Xv = 14.68 gr.
DX/Xv = .070	SR/Xv = .185
	O ₂ /Xv = .114

REACTION KINETICS

$$\frac{S_0 - S_e}{X_a t} = \frac{236}{2.45 \times 10.0} = 9.65$$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 22

Temperature . . . 5 °C Influent C.O.D. . 459 mg/l

Day	Av. Sol. (mg/l)	Load (BOD) VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1					6.15		
2	2080	.33	34	92.1	7.07	1338	3768
3	2170	.35	32	93.0	6.23	648	4248
4	2265	.34	33	92.8	7.88	852	4248
5	2165	.37	35	92.4	8.38	4674	4428
6							
7					8.34		
8	2515	.33	30	93.5	8.78	1890	4620
9	2350	.36	34	92.6	7.78	1842	4682
10	2235	.40	31	93.2	8.93	4236	4974
11	2130	.42	31	93.2	7.24	1848	4992
12	2375	.37	37	91.9	6.28	720	4896
Av. Tot.	2254	.36	33	92.7	83.60	18048	40856

SOLIDS BALANCE

Amount wasted = 18048 mg/ 9 days

Solids gained = -380 mg/l . . = -2280 mg

Solids grown = 15768 mg/ 9 days
DX = 1.75 gr/day

BOD removed = 40856 mg/ 9 days Sr. = 4.54 gr/day	Av. solids = 2254 mg/l Xv = 13.52 gr.
DX/Xv = .130	SR/Xv = .337
	O ₂ /Xv = .182

REACTION KINETICS

$$\frac{S_0 - S_e}{\bar{X}_a t} = \frac{426}{2.25 \times 10.85} = 17.45$$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 23

Temperature . . . 5 °C Influent C.O.D. . . 720 mg/l

Day	Av. Sol. (mg/l)	Load (BOD) / VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1							
2	2765	.50	41	94.3	12.8	966	7740
3	2875	.48	37	94.9	14.1	2016	7875
4	2700	.50	36	95.0	12.4	5028	7752
5	2715	.51	40	94.4	13.0	3630	7812
6	2605	.53	43	94.0	12.5	4752	7824
7							
8	2380	.50	27	96.1	9.1	3066	6810
9	2640	.47	28	96.0	8.8	2106	7200
10	2520	.54	28	96.0	8.3	4704	7770
11	2370	.57	27	96.1	11.6	5940	7830
12	2470	.53	40	94.4	10.2	2634	7470
Av. Tot.	2604	.51	35	95.1	112.8	34842	76083

SOLIDS BALANCE

Amount wasted = 34842 mg/ 10 days
 Solids gained = 180 mg/l . . = 1080 mg
 Solids grown = 35922 mg/ 10 days
 DX = 3.59 gr/day

BOD removed = 76083 mg/ 10 days Sr. = 7.61 gr/day	Av. solids = 2604 mg/l Xv = 15.62 gr.
DX/Xv = .230	SR/Xv = .485
	O ₂ /Xv = .271

REACTION KINETICS

$$\frac{S_o - S_e}{X_a t} = \frac{685}{2.60 \times 10.32} = 25.5$$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 24

Temperature . . . 5 °C Influent C.O.D. . 980 mg/l

Day	Av. Sol. (mg/l)	Load (BOD) VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1							
2	2665	.66	41	95.8	Not	5940	10170
3	2760	.64			con -	4926	10170
4	2750	.64	47	95.2	sis -	6012	10140
5	2600	.66	48	95.1	tent	6564	9720
6	2655	.71	46	95.3		4952	10830
7							
8							
9							
10							
11							
12							
Av. Tot.	2686	.66	46	95.3		28404	51030

SOLIDS BALANCE

Amount wasted = 28404 mg/ 5 days

Solids gained = -205mg/l . . = -1230 mg

Solids grown = 27174 mg/ 5 days
DX = 5.43 gr/day

BOD removed = 51030 mg/ 5 days	Av. solids = 2686 mg/l
Sr. = 10.21gr/day	Xv = 16.12 gr.
DX/XV = .337	SR/XV = .631
	O ₂ /XV =

REACTION KINETICS

$$\frac{S_0 - S_e}{X_a t} = \frac{934}{2.69 \times 10.58} = 32.8$$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 25

Temperature . . . 5 °C Influent C.O.D. . 1300 mg/l

Day	Av. Sol. (mg/l)	Load (BOD) / VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1							
2	2705	.92	38	97.0	20.6	5772	14520
3	2745	.91	65	95.0	20.9	6684	14220
4	2555	.97	123	90.5	17.5	10362	13410
5	2580	.98	107	91.8	16.7	8622	13860
6							
7							
8							
9							
10							
11							
12							
Av. Tot.	2646	.94	83	93.6	75.7	31440	56010

SOLIDS BALANCE

Amount wasted = 31440 mg/ 4 days

Solids gained = -180 mg/l . . = -1080 mg

Solids grown	= 30360 mg/ 4 days
DX	= 7.59 gr/day

BOD removed = 56010 mg/ 4 days	Av. solids = 2646 mg/l
Sr. = 14.00 gr/day	Xv = 15.88 gr.
DX/XV = .478	SR/XV = .88
	O ₂ /XV = .455

REACTION KINETICS

$$\frac{S_0 - S_e}{X_a t} = \frac{1217}{2.65 \times 10.0} = 45.9$$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 26

Temperature . . . 5 °C Influent C.O.D. . 233 mg/l

Day	Av. Sol. (mg/l)	Load (BOD) VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1					3.83		
2	3425	.13	25	87.1	6.16	1608	2298
3	3110		24	87.8	5.27	804	702
4	3175	.15	31	87.7	3.92	636	2502
5	3215	.15	26	89.6	5.72	1776	2592
6	3095	.16	25	90.0	5.42	588	2604
7	3045	.16	27	89.2		1332	2574
8							
9							
10							
11							
12							
Av. Tot.	3177	.13	26	88.6	28.32	6744	13290

SOLIDS BALANCE

Amount wasted = 6744 mg/ 6 days

Solids gained = -630 mg/l . . = -3780 mg

Solids grown = 2964 mg/ 6 days
DX = .494 gr/day

BOD removed = 13290 mg/ 6 days Sr. = 2.22 gr/day	Av. solids = 3177 mg/l Xv = 19.06 gr.
DX/Xv = .026	SR/Xv = .116
	O ₂ /Xv = .113

REACTION KINETICS

$$\frac{S_o - S_e}{X_a t.} = \frac{207}{3.18 \times 9.48} = 6.87$$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 27

Temperature . . . 5 °C Influent C.O.D. . . 422 mg/l

Day	Av. Sol. (mg/l)	Load (BOD) VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1							
2	3255	.25	31	92.7	Not	2370	4530
3	3300	.25			con -	1770	4476
4	3040	.27	38	91.0	sis -	4530	4428
5	2615	.31	44	89.6	tent	3468	4356
6							
7							
8							
9							
10							
11							
12							
Av. Tot.	3052	.27	38	91.0		12138	17790

SOLIDS BALANCE

Amount wasted = 12138 mg/ 4 days

Solids gained = -770mg/l . . = -4620 mg

Solids grown = 7518 mg/ 4 days
DX = 1.88 gr/day

BOD removed = 17790mg/ 4 days Sr. = 4.45 gr/day	Av. solids = 3052 mg/l Xv = 18.31 gr.
DX/XV = .103	SR/XV = .243
	O ₂ /XV =

REACTION KINETICS

$$\frac{S_0 - S_e}{X_a t} = \frac{384}{3.05 \times 10.0} = 12.6$$

N.B. For explanation of data presentation, symbols and units see page A-1.

DATA SHEET NUMBER 28

Temperature . . . 5 °C Influent C.O.D. . 1615 mg/l

Day	Av. Sol. (mg/l)	Load (BOD) / VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1							
2	3480	.44	53	96.9	8.85	180	8850
3	3585	.38	69	96.0	7.50	3792	7920
4	3605	.38	60	96.5	9.95	4524	7920
5	2960	.38	78	94.8	9.40	9060	6312
6							
7							
8							
9							
10							
11							
12							
Av. Tot.	3408	.39	65	96.0	35.70	17556	31002

SOLIDS BALANCE

Amount wasted = 17556 mg/ 4 days

Solids gained = -400 mg/l . . . = -2400 mg

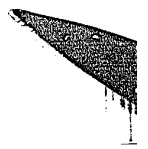
Solids grown = 15156 mg/ 4 days
DX = 3.79 gr/day

BOD removed = 31002 mg/ 4 days Sr. = 7.75 gr/day	Av. solids = 3408 mg/l Xv = 20.45gr.
DX/XV = .185	SR/XV = .379
	O ₂ /XV = .214

REACTION KINETICS

$$\frac{So-Se.}{X_a t.} = \frac{1550}{3.41 \times 23.95} = 18.95$$

N.B. For explanation of data presentation, symbols and units see page A-1.



DATA SHEET NUMBER 29

Temperature . . . 5 °C Influent C.O.D. . . 2890mg/l

Day	Av. Sol. (mg/l)	Load (BOD) / VSS	Effl. COD (mg/l)	Eff. (%)	Oxy. Uptake	Waste (mg/day)	BOD removed (mg/day)
1							
2	3840	.53	101	96.3		582	11760
3	3980	.56			13.1	10134	12720
4	3680	.61	186	93.2	12.3	6258	12720
5	3355	.60	236	91.4	11.9	10578	11010
6	3300	.61	418	84.7	12.7	2346	10200
7							
8							
9							
10							
11							
12							
Av. Tot.	3631	.58		Not consistent	50.0	29898	58410

SOLIDS BALANCE

Amount wasted = 29898 mg/ 5 days

Solids gained = 80 mg/l . . = 480 mg

Solids grown = 30378 mg/ 5 days
DX = 6.08 gr/day

BOD removed = 58410 mg/ 5 days Sr. = 11.68 gr/day	Av. solids = 3631 mg/l Xv = 21.79 gr.
DX/Xv = .279	SR/Xv = .537
	O ₂ /Xv = .300

REACTION KINETICS

$$\frac{S_o - S_e}{X_a t} = \frac{2700}{3.63 \times 24} = 30.0$$

N.B. For explanation of data presentation, symbols and units see page A-1.

A P P E N D I X B

SETTLING TESTS

The results of this portion of the study were intended to provide an indication of the loading ranges at which the settling rates of the activated sludge floc were a maximum. The test initially used to determine settleability at 5°C was the Sludge Volume Index (SVI) as measured in a 1000 ml graduated cylinder. Results of the first few tests showed that, although separation in the settling portion of the continuous flow unit was very good, readings on the graduated cylinder were usually in excess of 800 resulting in extremely high SVI values. A few of the results showed SVI values of up to 970 and it was decided to run a settling test in a standard 1000 ml beaker in the hope that any sidewall effect would be diminished in the larger container. Results improved only slightly in the beaker even though tests were extended from 30 minutes to 4 hours in order to obtain greater settlement.

At 20°C reasonable results were obtained from the standard SVI test. A summary of the results of the settling study are given in figures B1 and B2 for 5 and 20°C respectively, with the detailed data given on subsequent pages.

In figure B1 the SVI are those calculated from 4 hour settling in a standard 1000 ml beaker. Poor operation, as evidenced by little separation in the settling chamber of the

continuous flow units, was noted at only three points (organic loading values of 0.38, 0.72 and 0.98). A possible explanation between the settleability in the SVI test and the continuous flow unit is that flocculation is poor at 5°C and a very loose lattice is formed by the micro-organisms which is broken up by constant motion in the continuous flow unit but hinders settling in the quiescent column. A biological study to determine floc characteristics might explain the above but was considered beyond the scope of this study.

At 20°C the results of the SVI were considerably better, however, two of the three points with an SVI value in excess of 200 (organic loadings of .63 and 1.00) showed good separation in the continuous flow unit. The line in figure B-1 indicates that the optimum loading rate ranges between 0.3 and 0.6 gr BOD/gr MLVSS as compared to 0.2 and 0.9 gr BOD/gr MLVSS obtained from the efficiency study.

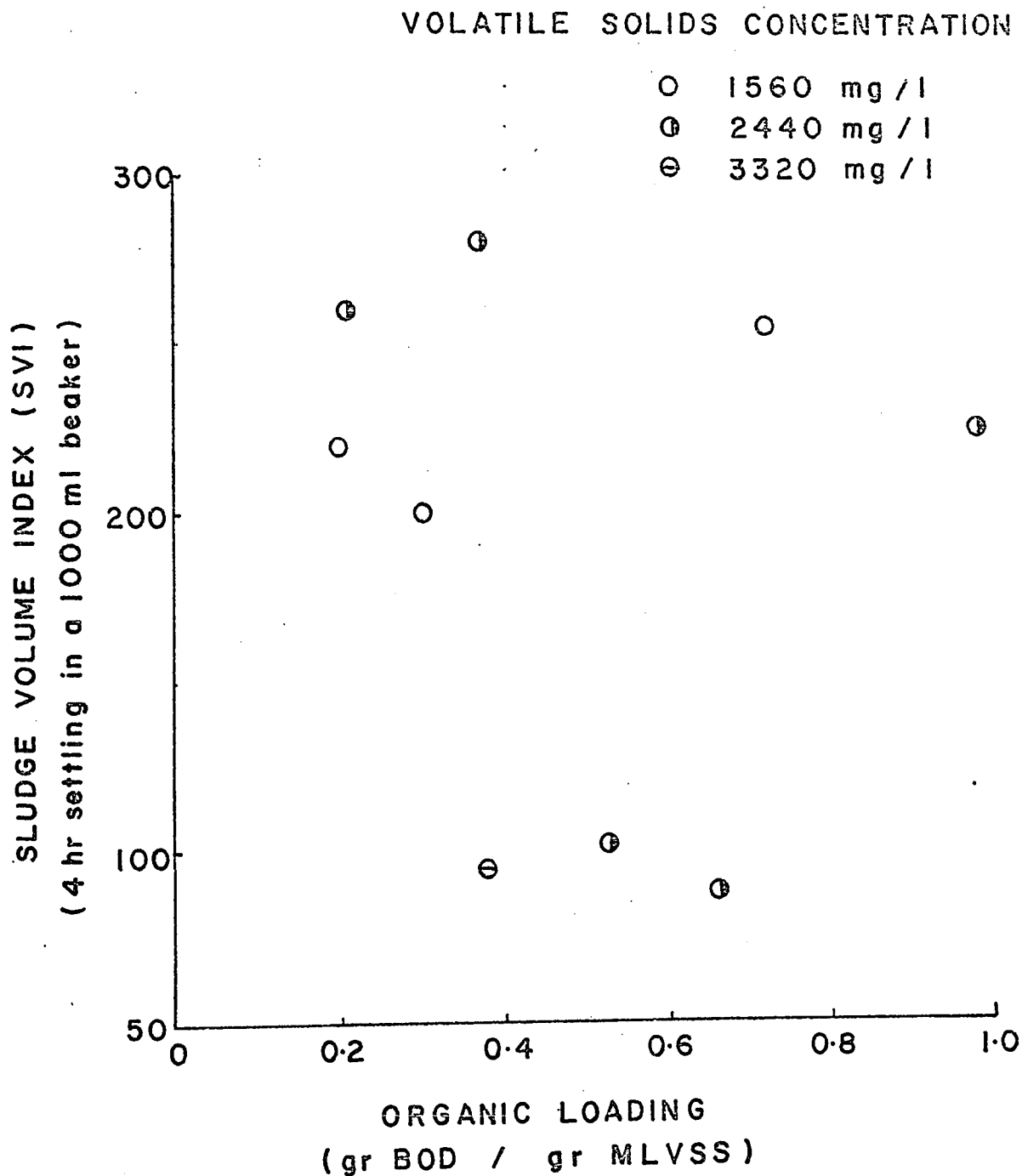


FIGURE B-1 SLUDGE VOLUME INDEX OF ACTIVATED
SLUDGE SYSTEM TREATING MILK WASTE
AT 5°C

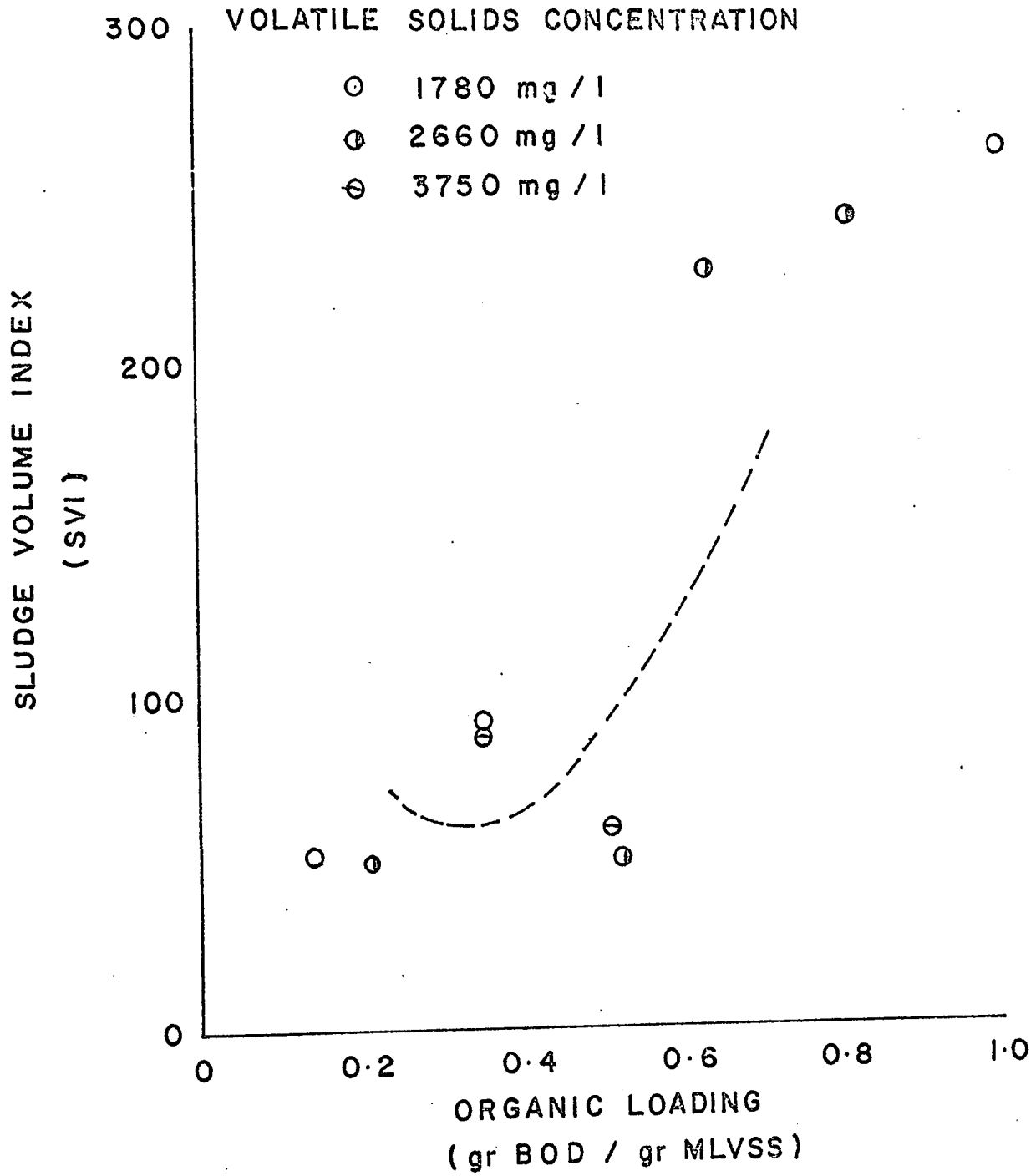


FIGURE B-2 SLUDGE VOLUME INDEX OF ACTIVATED
SLUDGE SYSTEM TREATING MILK WASTE
AT 20°C

SETTLING TEST - 5°C

Solids concentration MLSS (mg/l)	Organic Loading (gr BOD/gr MLVSS)	Reading on 1000 ml beaker						
		1	1½	2	2½			
Time (hrs.)								
		½	1	1½	2	2½	3	4
2920	0.21	940	880	820	760			
2955	0.37	995	970	950	920	900	870	830
3415	0.53	880	750	630	530	450	400	350
3410	0.66	875	750	625	520	440	360	300
3250	0.98		970	955	945		910	870
1825	0.20	770	580	460	400			
3170	0.38							300
1750	0.30	650	460	400	370			340
1840	0.72	940	850	770	695	610	560	470

SETTLING TESTS AT 20°C

Solids Concentration <u>MLSS (mg/l)</u>	Organic Loading <u>(gr BOD/gr MLVSS)</u>	Readings on 1000 ml <u>graduated cylinder</u>					
		5	10	15	20	30	45
Time (min.)							
2320	0.14	230	160	125	125	120	
2070	1.02	950	830	645	645	550	
5040	0.35	880	680	570	500	440	350
2000	0.35	410	300	220	220	185	
4415	0.51	515	380	300	300	275	
3175	0.21	200	170	160	160		
3800	0.52	340	270	215	215	190	
3430	0.64	960	930	890	850	780	
4150	0.82	1000	970	950	950	930	

SETTLING TESTS AT 20°C

Solids Concentration <u>MLSS (mg/l)</u>	Organic Loading <u>(gr BOD/gr MLVSS)</u>	Reading on 1000 ml <u>beaker</u>					
		5	10	15	20	30	45
Time (min.)							
2320	0.14	150	120	110	110	110	110
2070	1.02	900	800	600	600	500	500
5040	0.35	980	945	720	575	485	415
2000	0.35	340	240	160	160	130	130
4415	0.51	400	330	300	300	275	275
3175	0.21	300	215	160	160	160	160
3800	0.52	260	200	170	170	160	160
3430	0.64	920	840	760	680	580	580
4150	0.82	1000	940	870	870	830	830