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PRELIMINARY INVESTIGATIONS INTO THE
EFFECTS OF OXYGEN TENSION
ON SLUDGE SETTLING CHARACTERISTICS

BY

BRIAN J. McCORMICK, B.ENG.

A PROJECT REPORT

SUBMITTED TO THE SCHOOL OF GRADUATE
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TITLE: Preliminary Investigations into the Effects of
Oxygen Tension on Sludge Settling Characteristics

AUTHOR: Brian John McCormick

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141

ABSTRACT

Investigations were conducted into a possible relationship between oxygen tension and activated sludge settling characteristics. Using sewage as substrate, two parallel activated sludge units were operated at different oxygen tensions effectively simulating operation at conventional and saturation levels of dissolved oxygen. Under controlled mixing conditions, settling characteristics were monitored at several sludge ages. At the same time preliminary comparisons were made between the two systems in terms of sludge production, sludge activity, nitrifying ability, floc size and appearance and several other physical characteristics.

Results indicated a greater uniformity of operation at the higher oxygen tension along with a somewhat better effluent quality. However, no improvement in settling characteristics was noted at the higher level of dissolved oxygen.

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1. INTRODUCTION

Molecular oxygen is normally the final electron acceptor in the aerobic oxidation of substrate by micro-organisms. Thus it is important to the performance of a biological treatment system to maintain a sufficient supply of dissolved oxygen at all times.

The mass transfer of oxygen from the gas phase to the liquid phase is proportional to the oxygen deficit. Maximum transfer rates are, therefore, achieved by maintaining the dissolved oxygen concentration as low as is consistent with the requirements of the biomass. Operating experience has indicated that in excess of 0.5 to 2.0 mg/l dissolved oxygen must be maintained to stay above the critical levels which will influence the metabolic activity of micro-organisms. Normally a maximum driving force of approximately 7 mg/l is available.

The typical approach to improve oxygen transfer has been to develop more efficient aeration equipment. Practical limits, however are encountered that are difficult to overcome through equipment innovation.

An alternate approach has been to increase the driving force for oxygen transfer by using high purity oxygen in the gas phase. The driving force for oxygen transfer can be raised approximately five-fold. The saturation concentration of oxygen in water is 43 mg/l at 20°C and 1 atmosphere pressure, while with air at a corresponding temperature and pressure it is 9.02 mg/l.

With the availability of oxygen gas at reasonable cost, considerable interest has been stimulated over the past twenty years in its application to the activated sludge process. There remains, however, considerable disagreement concerning the fundamental merits of the oxygenation process and specifically the effects of oxygen tension on biological waste treatment.

In addition to the greater ease of oxygen transfer, some of the benefits claimed include:

- 1) lower solids production
- 2) improved sludge settling characteristics,
- 3) higher metabolic rates by the organisms and
- 4) lower treatment costs.

These claims have been evaluated in this report. The major variable of interest was the influence of oxygen tension on the settling properties of activated sludge.

1.1 OBJECTIVES.

The principle objective of this investigation was to determine whether a fundamental relationship exists between high oxygen tension and the settling characteristics of activated sludge. The specific objectives were:

- 1) to develop a pilot plant unit and the methodology to

analyze the biological responses of a high dissolved oxygen system relative to a conventional system,

- 2) to determine the relative effect of oxygen tension on settleability under varying conditions of sludge age and mixing intensity,
- 3) to compare the differences in sludge yield and substrate removal between conventional dissolved oxygen and high dissolved oxygen activated sludge systems,
- 4) to compare the extent of nitrification between both systems,
- 5) to observe microbial responses to different waste loadings, mixing conditions and oxygen tensions by the use of phase contrast microscopy, and
- 6) to determine whether distinguishable differences can be measured in physical characteristics (aggregate size and density, Capillary Suction Time) and metabolic activity (through oxygen uptake, plate counts, dehydrogenase activity, ATR, etc).

Because of the complexity of the problem, the study was limited to a preliminary investigation into the effects of oxygen tension on sludge settling characteristics. The equipment was designed and developed in the hope that future more detailed work could be attempted and was intended to develop operating procedures and obtain some appreciation of the effects of the above operational parameters.

2. LITERATURE REVIEW

2.1 OXYGEN AND AEROBIC SYSTEMS

In the field of waste treatment, Okun (1948) initiated work into pure oxygen biological treatment. In studies on a modified activated sludge system, Figure 1, Okun reported that the pure oxygen biological system inherently required less reactor volume than a conventional system. Okun indicated possible reductions of up to 75 percent:

In the process, called "Bio-precipitation", the mixed liquor was not directly aerated but rather oxygen was predissolved in the feed wastewater. The bio-oxidation then followed in a gently agitated vessel which acted as an integral reactor and clarifier. Treated effluent was then separated from the sludge in the clarifier section and was discharged or recycled back to the absorber.

The high apparent treatment efficiency of the bio-precipitation process on the laboratory apparatus prompted further pilot plant studies and the belief by others that there was an increased microbial activity in the biological floc resulting from the higher oxygen concentrations.

With some support, (Waksman and Carey, 1935; Heukelekian, 1936; and Smith and Johnson, 1954) reporting the rate of oxygen utilization to be a function of oxygen tension, this interpretation has persisted. Such

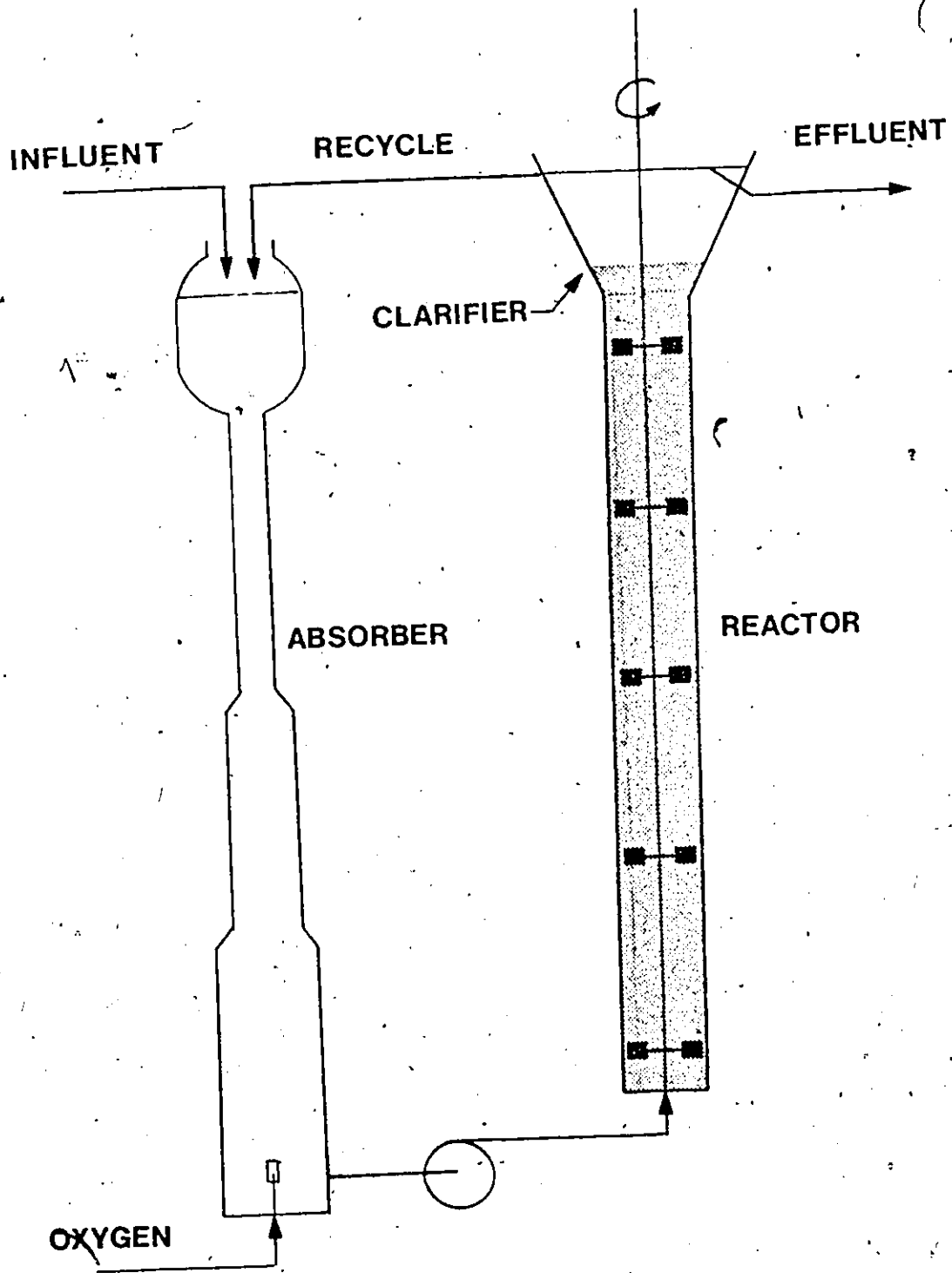


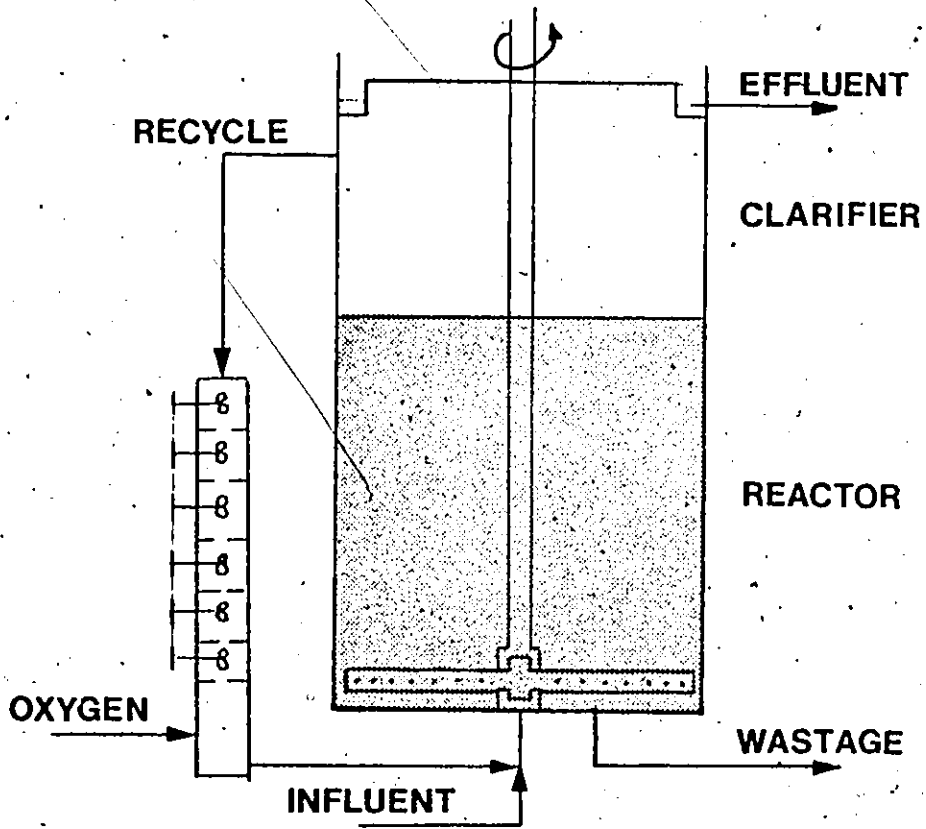
FIGURE 1 BIOPRECIPITATION UNIT
OKUN (1948)

interpretations were made on a comparison of efficiency of removal versus reactor volume rather than the amount of organisms present. However, in fact Okun's view was that aside from the greater driving force for oxygen dissolution, the only improvement was a consistently greater sludge density in the high purity oxygen system.

The "Bio-precipitation" process was eventually marketed by Dorr-Oliver Incorporated after small scale testing at Baltimore, Md. in 1953 and Stamford, Conn. in 1955. The unit, designed for a nominal flowrate of 125 USGPM did not meet Okun's original prediction of a 75 percent volume reduction (Figure 2). Estimates by Dorr-Oliver were in the order of 30 percent (Budd and Lambeth, 1957). It was suggested by Ball and Humenick (1972) that the difference was due to the inability of the pilot plant to maintain the MLSS concentrations of the laboratory reactor.

Following conclusion of the pilot study, further work on oxygenation was rather limited.

Okun and Lynn (1956) in an attempt to explain the slight but consistently higher degree of treatment in the "Bio-precipitation" process suggested that the greater oxygen resources reduced or eliminated periods of zero D.O. Supported by some evidence in the literature, Okun and Lynn indicated that sludge may be deleteriously affected during oxygen deficient settling periods and during the initial period of aeration following the



**FIGURE 2 BIOPRECIPITATION
PILOT PLANT
BUDD & LAMBETH (1957)**

addition of fresh sewage. Somewhat greater oxygen requirements in the air-fed system were attributed to the need for oxidation of organic matter in the sludge which was reduced during the period of oxygenation starvation. In later work, however, Westgarth et al (1964) concluded that prolonged periods of anaerobiosis did not have a detrimental effect on the biological activity of activated sludge nor on the overall treatment process.

Interest lessened considerably through the late nineteen fifties and early sixties. Work included a study by Robbins (1961) utilizing the "Bio-precipitation" process on neutral sulfite semi-chemical paper mill waste and a state of the art review by Pfeffer and McKinney (1965).

A resurgence of interest in the late 1960's followed the submission of a report to the US Federal Water Quality Administration by Union Carbide Corporation. Results from a pilot-plant study led to a FWQA contract financing conversion of one-half of the Batavia, New York municipal treatment plant to a pure oxygen system. The Batavia report (Albertsson et al 1970) concluded that oxygenation system treatment costs in comparison to conventional air aeration revealed significant potential savings attributable to high purity oxygen usage.

The Union Carbide Unox System differs in several ways from the Okun reactor. As shown in Figure 3, oxygen is transferred within the reactor

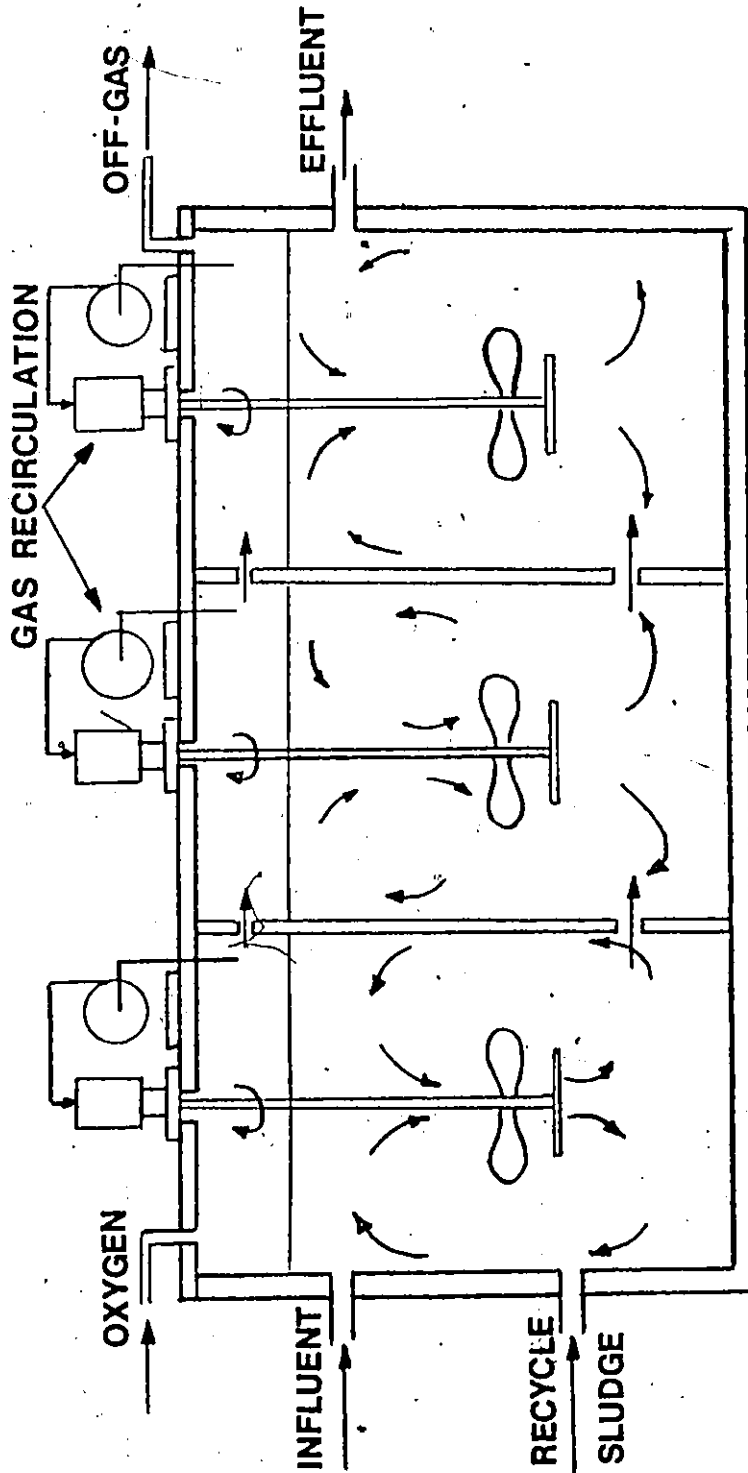


FIGURE 3 UNOX OXYGENATION SYSTEM
ALBERTSSON et al (1970)

by submerged turbine-sparger contacting units rather than through an external absorber. The reactor features a staged design, each completely mixed. Oxygen is fed to the first stage at a pressure of 1-3 inches of water. The enclosed tankage allows recirculation of the exhaust gas to the same stage and provides a more efficient oxygen utilization. The successive stages are connected allowing passage of gas through the system. Gas is vented in the last stage to control the level of nitrogen and carbon dioxide and yet maintaining a 90 to 95 percent transfer efficiency.

In the cost estimate, the reduced aeration tank volume requirements for equivalent treatment and the reduced production of waste activated sludge more than offset oxygen generation costs. The biomass generated by the oxygenation system was claimed to be highly flocculent and settleable. Recycle solids of 3-4 percent were achieved.

Two-thirds of the cost reduction was attributed to cost reduction in sludge disposal. These savings were also available in conversion of existing facilities from aeration to oxygenation (in addition to expanding capacity without further tankage).

Other features claimed were:

- 1) improved control of mixed liquor dissolved oxygen concentrations and enhanced capability for responding to wide variations in oxygen demand (hence a more

uniform and consistently high quality effluent),

- 2) high dissolved oxygen concentrations in the secondary effluent and
- 3) elimination of odour problems because of low exhaust gas flows and covered aeration tank design.

Results from this study indicated that high purity oxygenation was a realistic alternative to conventional aeration. There still remained a need for improved understanding of the effects of dissolved oxygen concentration on the behaviour of a natural biological population operating under continuous flow conditions, as it would apply to waste treatment systems.

2.1.1 Sludge Yield

The yield factor, " Y ", is expressed as the ratio of the weight of biomass produced per unit weight of substrate removed. Commonly substrate removal is defined in terms of BOD, COD or TOC in waste water treatment. In waste treatment, minimal yield is desirable because of the high cost of solids disposal.

Theoretically, the weight of excess sludge produced is determined by the following factors:

- 1) the total weight of suspended solids in the aeration tank influent, minus that quantity which is solubilized during aeration by exo-enzymes and discharges with the effluent,
- 2) the solids which are produced by coagulation from originally dissolved material,
- 3) the growth rate of sludge organisms (which is related to the strength and nutritional value of the waste and the accessibility of the organism to the nutrients), and
- 4) the degree of auto-oxidation and autolysis of sludge organisms within the treatment plant.

With the introduction of the Union Carbide oxygenation process, by Albertsson et-al (1970) an apparent further parameter (oxygen tension) was introduced. Yield coefficients of 1.0 lb VSS/lb BOD compared favourably to values of 1.38 lb VSS/lb BOD for air. Almost two-fold differences in the extent of auto-oxidation was also noted,

Poon and Wang (1972) found in pure oxygen studies, that in a biological waste treatment process with high solids concentrations both the substrate removal rate and auto-oxidation rate can be enhanced. They also

suggested that smaller treatment units could be used, and a lower amount of excess sludge handled.

Later work by the Environmental Protection Agency (Stamberg, 1972) in part supported the work of Albertsson et al. Using parallel oxygenation and step aeration activated sludge, Stamberg concluded that the total production of excess biological solids was significantly lower with the oxygen system at mean sludge retention times above 6 days. As little as 0.35 pounds of excess solids were produced per pound of BOD added at a sludge age of 13 days.

On the other hand, in studies with a continuous culture chemostat, using a mixed municipal sewage, Rickard and Gaudy (1968) found that biological solids yield was independent of oxygen tension. In later chemostat studies, for low sludge ages Thabaraj and Gaudy (1969) found that the biological solids yield, respiration rate and COD removal efficiency were unaffected by oxygen tension.

Ball, Humenick and Speece (1972) attempted to investigate differences in solids production in relation to both oxygen tension and the method of air and oxygen introduction. The authors concluded that there was no significant difference in sludge yield with oxygen as opposed to air. Test conditions involved the use of completely mixed activated sludge units employing synthetic feed, at oxygen tensions from one to 14 mg/l

and mixing intensities from 40 to 160 sec⁻¹.

The authors also commented on the interpretation of results in the Batavia study by Albertsson et al (1970). For the yield coefficient to be meaningful and have utility in calculating sludge production, coefficients must be based on the volatile suspended solids leaving the system which are attributed to organisms. The Batavia Sewage Treatment Plant was without primary treatment, and incomplete digestion of high influent solids was said to be responsible for differences in the calculated yield.

2.1.2 Metabolic Activity and Oxygen Uptake

The effect of dissolved oxygen tension on the metabolic activity of aerobic bacterial systems has been the subject of continuing research in the fields of microbiology and biological waste treatment. With pure culture systems, the oxygen uptake rate of a given micro-organism has generally been found to be independent of oxygen tension if the dissolved oxygen concentration (D.O.) is maintained above a minimum or critical level of 0.2-0.8 mg/l (Porges et al, 1956; Phillips et al, 1961).

Smith et al (1954) have demonstrated that viable count and cell mass yield are also unaffected by changes in oxygen tension above this level.

However, Zobell and Stadler (1940) stated that one should not infer that this generalization applies to bacteria under all conditions. They found

that in concentrated nutrient solutions, rich in particulate matter or with high bacterial concentrations, oxygen concentration becomes a limiting factor while oxygen is still present. They believe that the oxygen becomes depleted in the immediate vicinity of the respiring cells faster than it can be replaced by diffusion.

Ball and Humenick (1972) pointed out that the early belief in the effect of oxygen tension on organism activity possibly arose from the measurement of activity by the plate count technique (Waksman and Carey, 1935; Heukelekian, 1936; Smith and Johnson, 1954). Others, (Amberson et al, 1924; Pomeroy, 1938) have found a dependence using oxygen uptake.

The obvious contradictions in the literature prompted Okun and Lynn (1956) to investigate the phenomena. Three five litre batch reactors were operated by a fill and draw technique. Identical gas flows were introduced to each reactor but composed of pure oxygen, equal portions of oxygen and nitrogen, and compressed air, respectively. The oxygen uptake rates during the operation were the same for the three reactors although the pure oxygen reactor consistently attained superior removal. D.O. levels varied (in the batch reactors) as a function of time with levels of 27, 16 and 6 mg/l respectively after six hours. The authors concluded that the rate of oxygen utilization was not affected measurably by oxygen concentration.

A number of investigators, (Porges et al, 1953; Von der Emde, 1963;

Gaudy and Turner, 1964) have demonstrated the existence of a critical D.O. in the activated sludge process in terms of both respiration rate and substrate removal. Minimum D.O. levels recommended for operation of activated sludge plants have ranged from 0.5 mg/l (Porges et al, 1953) to 2.0 mg/l (Von der Emde, 1963). This is consistent with minimum permissible guidelines set out by the APHA Committee on Sewage Disposal (1942) and still in use today.

In more recent work, with completely mixed activated sludge studies, Rickard and Gaudy (1968) concluded that oxygen uptake rate and biological solids yield remained relatively constant for the range of D.O. concentrations between 1.4 and 7.1 mg/l under constant agitation. This conclusion was re-iterated by Thabaraj and Gaudy (1969) in concluding,

"In the steady state, such parameters as COD removal efficiency, percent substrate respired, respiration rate, biological solids yield, ammonia nitrogen utilization and sludge protein were unaffected by oxygen tension",

in completely mixed activated sludge operation.

As a consequence of this work, it seems that no significant difference exists between the metabolic activity of organisms acclimated under differing oxygen tensions above critical D.O. levels. When confusion has arisen, it is often based on the failure to compare the activity on a unit weight basis. At the same time, however, somewhat better effluent quality with oxygen systems have been claimed (Okun and Lynn, 1956;

Albertsson et al, 1970; Koehrsen and Archuleta, 1973).

There is a conflict of opinion whether this difference exists, (Ball and Humenick, 1972; Thabaraj and Gaudy, 1969) and as yet little understanding why it may be true.

Matsch (1972) has offered some hypotheses:

- 1) staged operation more closely approaching plug flow (not applicable in case of Okun (1969) and Okun and Lynn (1956)),
- 2) higher D.O. allows essentially all the biomass to participate fully in the metabolic process (as opposed to possible anoxic conditions within flocs at lower D.O.) and
- 3) differences in the biological process (presumably meaning differences in predominating species of organisms at different D.O. tensions as suggested by Wuhrmann (1960), Heukelekian (1936) and Van der Emde (1963)).

2.1.3 Settling Characteristics

The biomass in high purity oxygen systems has generally

been found to exhibit greater sludge settleability and compactability. Observations, however have been of a qualitative nature, with settling properties having been assigned less importance than the varied aspects of microbial assimilation of organic matter.

In early studies with the "Bio-precipitation" process, Okun (1948) made no conclusions regarding improved sludge settling characteristics. No direct comparisons between air and oxygen generated sludges through sludge volume index, effluent clarity or zone settling velocity were made. The capability of the "Bio-precipitation" process to maintain higher sludge concentrations has been interpreted by Ball and Hümenick (1972) as the direct result of improved settling properties.

Okun and Lynn (1956) in later fill and draw studies did note, however, that "the sludge from the oxygen-fed unit settled much more rapidly and was more compact than the air-fed sludge". In a comparison of different turbidities the authors stated,

"in general the operation of the air-fed system tended to be more erratic, and its effluent averaged slightly although consistently higher turbidities than pure oxygen fed, or a mixture of 50 percent nitrogen, 50 percent oxygen".

A direct comparison of parallel aeration and oxygenation systems was not attempted until the Batavia study in 1969 and 1970. Sludge settleability was characterized by zone settling velocity and sludge volume index. The biomass generated by the oxygenation system was reported to

be,

"highly flocculant and rapidly settleable, yielding sludge volume index values as low as an average of 36."

The authors went further to state,

"despite the hindrance imposed by an approximate two-fold higher suspended solids level in the oxygenation system, initial settling rates were comparable to those of the air activated sludge."

A summary of results, under parallel operation of the air and oxygenation systems are presented in Tables 1 and 2. Interpretation of the data is difficult because of differences in both the food to mass ratio and the mixed liquor suspended solids concentration for each system. Both of these parameters have been shown to be related to the zone settling velocity (Ford, 1967; Eckenfelder, 1973):

Sludge volume index values were found to be low, particularly at high MLSS values for the oxygen system. Figure 4, although illustrating the lack of comparable data, does indicate that at higher MLSS levels, lower SVI values are attainable with oxygen.

However, the high emphasis placed on lower sludge volume index values for the oxygenated sludge may have arisen from data misinterpretation. Ball, Humenick and Speece (1972) have questioned the basic premise of the test as used by Albertsson et al (1970), in the assumption that if: 1 gram of sludge settles to x mls in 30 minutes, therefore 4 grams of

TABLE 1

AIR AND OXYGEN SYSTEM PERFORMANCE
BATAVIA STUDY - PHASE I

	Food to Biomass Ratio lb BOD/D/lb	MLSS mg/l	SVI	Zone Settling Velocity ft/hr	Effluent Turbidity JTU
Air Oxygen	0.67 0.42	2670 3120	87 60	7.0 6.4	- -
Air Oxygen	0.50 0.41	2490 2940	84 54	8.0 9.4	2.4 2.8
Air Oxygen	0.80 0.64	2570 3210	76 55	7.8 7.1	3.4 4.8
Air Oxygen	0.51 0.40	2480 3150	62 59	9.2 8.1	8.4 4.5
Air Oxygen	0.47 0.36	2030 3500	60 65	9.0 6.7	8.1 6.7
Air Oxygen	0.42 0.31	2580 3270	74 70	6.8 6.3	7.8 11.3
Air Oxygen	0.60 0.36	2280 3250	91 87	6.0 6.2	4.0 3.6

Reference Albertsson et al (1970)

data reported are weekly averages of 24 hour mean values

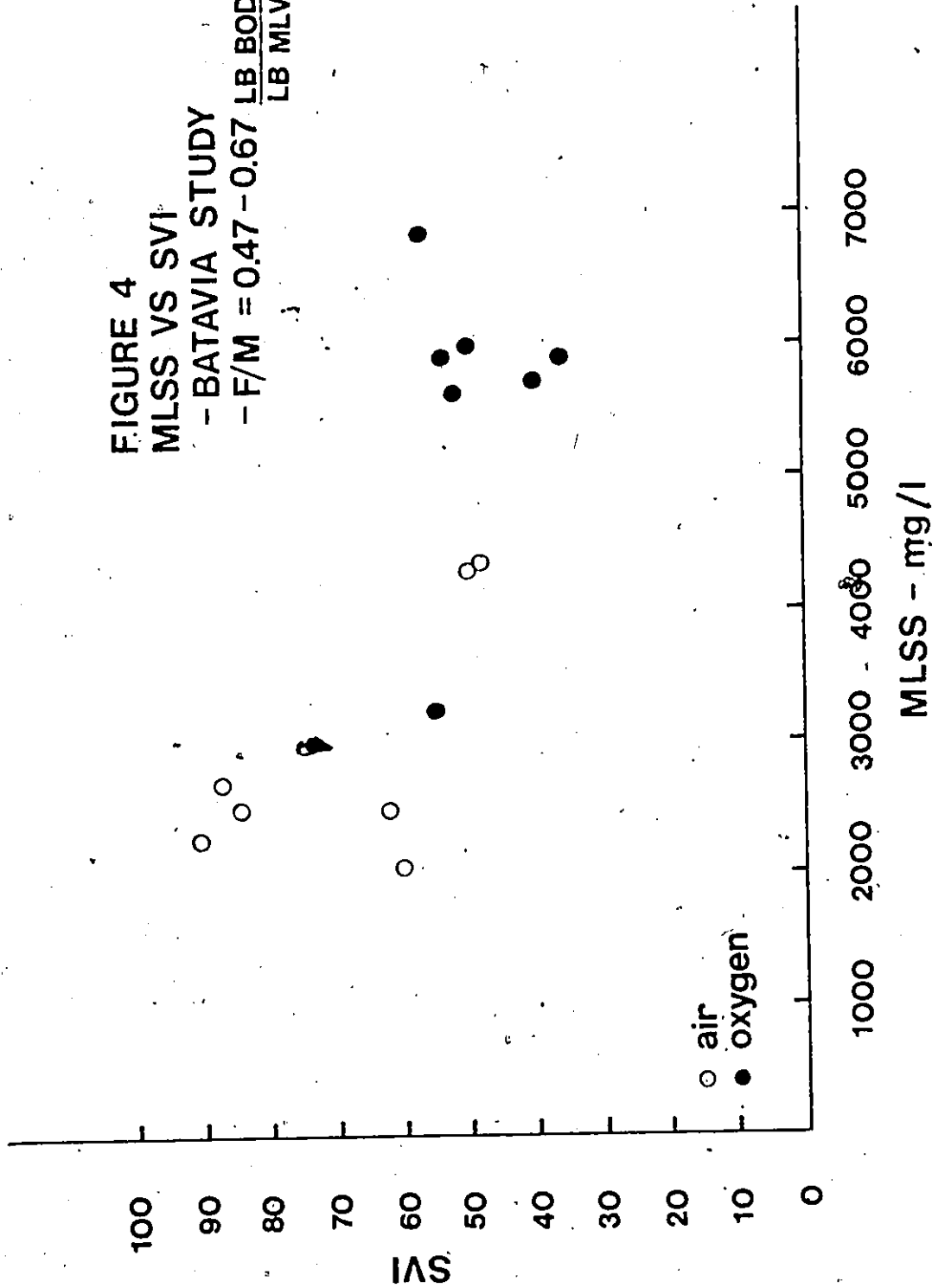
TABLE 2
AIR AND OXYGEN SYSTEM PERFORMANCE
BATAVIA STUDY - PHASE III

	Food to Biomass Ratio lb BOD/D/VSS	MLSS mg/l	SVI	Zone Settling Velocity	Effluent Turbidity JTU
Air	0.57	4340	48	8.5	8.8
Oxygen	0.55	5890	54	4.4	9.2
Air	0.57	4290	45	9.4	5.4
Oxygen	0.38	6810	80	1.7	6.4
Air	0.95	3680	46	7.9	3.5
Oxygen	0.47	6840	57	4.2	2.8
Air	1.04	3180	55	8.3	6.6
Oxygen	0.57	5890	36	6.7	6.2
Air	0.92	3890	96	5.8	4.5
Oxygen	0.69	5700	40	5.9	1.7
Air	0.93	2810	77	7.2	5.5
Oxygen	0.40	7400	34	6.3	3.8
Air	0.79	3650	69	7.3	4.2
Oxygen	0.55	5620	52	5.1	2.4
Air	0.89	3640	73	6.4	5.2
Oxygen	0.77	5560	41	6.0	3.3
Air	0.92	3260	60	8.4	7.7
Oxygen	0.62	5970	50	5.4	3.8

Reference: Albertsson et al (1970)

data reported are weekly averages of 24 hour mean values

FIGURE 4
MLSS VS SVI
 - BATAVIA STUDY
 - $F/M = 0.47 - 0.67 \frac{LB\ BOD/D}{LB\ MLVSS}$



sludge will settle to 4x mls in 30 minutes.

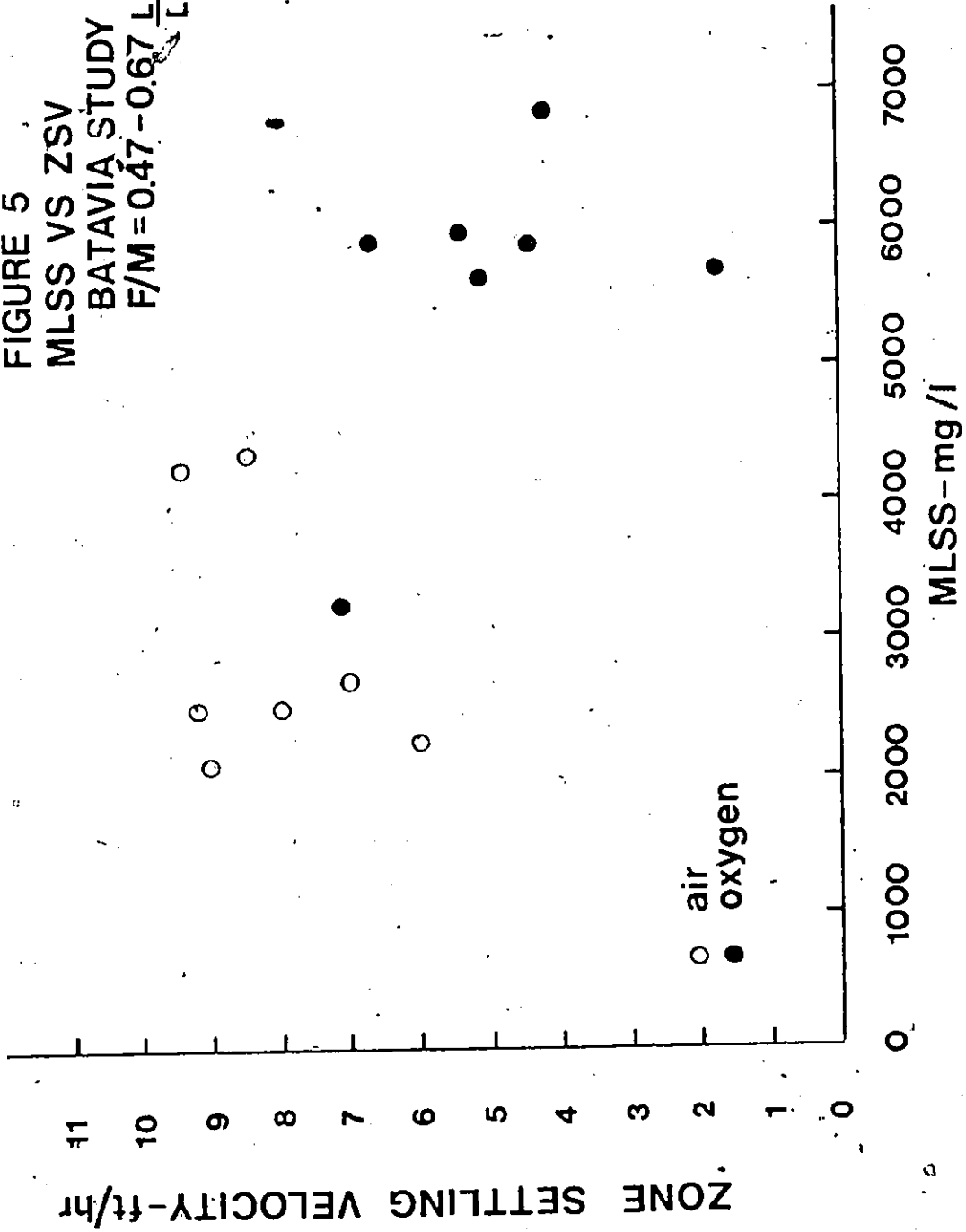
The authors suggest that a lower SVI value will naturally result at higher sludge concentrations with neither zone settling velocity (or SVI) being a direct linear function of the initial solids concentration.

Generally, after a period of 30 minutes, the sludge has entered the compaction phase of the settling test. The weight of the overburden sludge during this phase of the SVI test will have a significant effect on the 30 minutes sludge volume. In a sample problem the authors indicate that the sludge may settle to considerably less than 4x mls, (248 mls compared to 320 mls predicted) and hence the sludge volume index is "naturally" lower. This may well be an over generalization but should have been considered by Albertsson et al in their heavy reliance on SVI. Observations on the dependency of SVI and MLSS have also been noted by Chudova (1973).

Justification for statements suggesting improvements in zone settling velocity with oxygenation are also weak. As shown in Figure 5, or can be seen in Tables 1 and 2, directly comparable operating conditions are lacking.

Koehrsen and Archuleta (1973) concluded that oxygen systems generally exhibit better settleability and compaction resulting in overall sludge

FIGURE 5
MLSS VS ZSV
BATAVIA STUDY
 $F/M = 0.47 - 0.67 \frac{LB\ BOD/D}{LB\ MLVSS}$



handling and disposal, operational and cost benefits. Air and Oxygen studies were not carried out concurrently, however, and no data was presented to substantiate the claims.

Jewell et al (1971) investigated the use of air, air plus oxygen and pure oxygen in a study of brewery wastewaters. They concluded that under pure oxygen operation, sludge volume index values were unusually low when operated at relatively high food to micro-organism ratios. This observation prompted speculation that higher than normal loadings could be employed and yet retain reasonable solids separation with conventional clarifier overflow rates.

Ball, Humenick and Speece (1972) attempted to determine the relative effects of oxygenation on settleability in comparison with the effects caused by changes in sludge age and mixing intensity. They concluded that there was no significant difference in the initial settling velocity of activated sludge developed under air or pure oxygen conditions when compared at the same solids concentrations, sludge age and mixing intensity. They also suggested that the increased rate of oxygen transfer under oxygenation allows reduced gas flow to the reactor, lower mixing levels and therefore, improved settling velocities are a byproduct of oxygenation.

There is evidence for the belief that highly turbulent conditions

common to conventional aeration tanks result in the occurrence of excessive floc break-up and an environment which is not generally conducive to optimum aggregation, and solids separation. The lower mixing intensities of oxygenation systems, resulting from the reduced gas flow necessary for oxygen transfer, more nearly approach velocity gradients common to good water treatment flocculation practice. Experimentation was carried out by Ball et al (1972) in laboratory scale reactors utilizing synthetic waste, Table 3. Only oxygenation process results could be obtained for the lower velocity gradient (40 sec^{-1}). Data was generated at this mixing intensity from both a diffused oxygen system and an Okun type absorbed oxygen system.

Again comparative oxygen and air settling data are weak. The data, as plotted in Figure 6 do not substantiate conclusions that,

"oxygen tension and oxygen source do not materially affect settleability as measured by the initial settling velocity at the same mean cell retention time, MLSS concentration and mixing intensity".

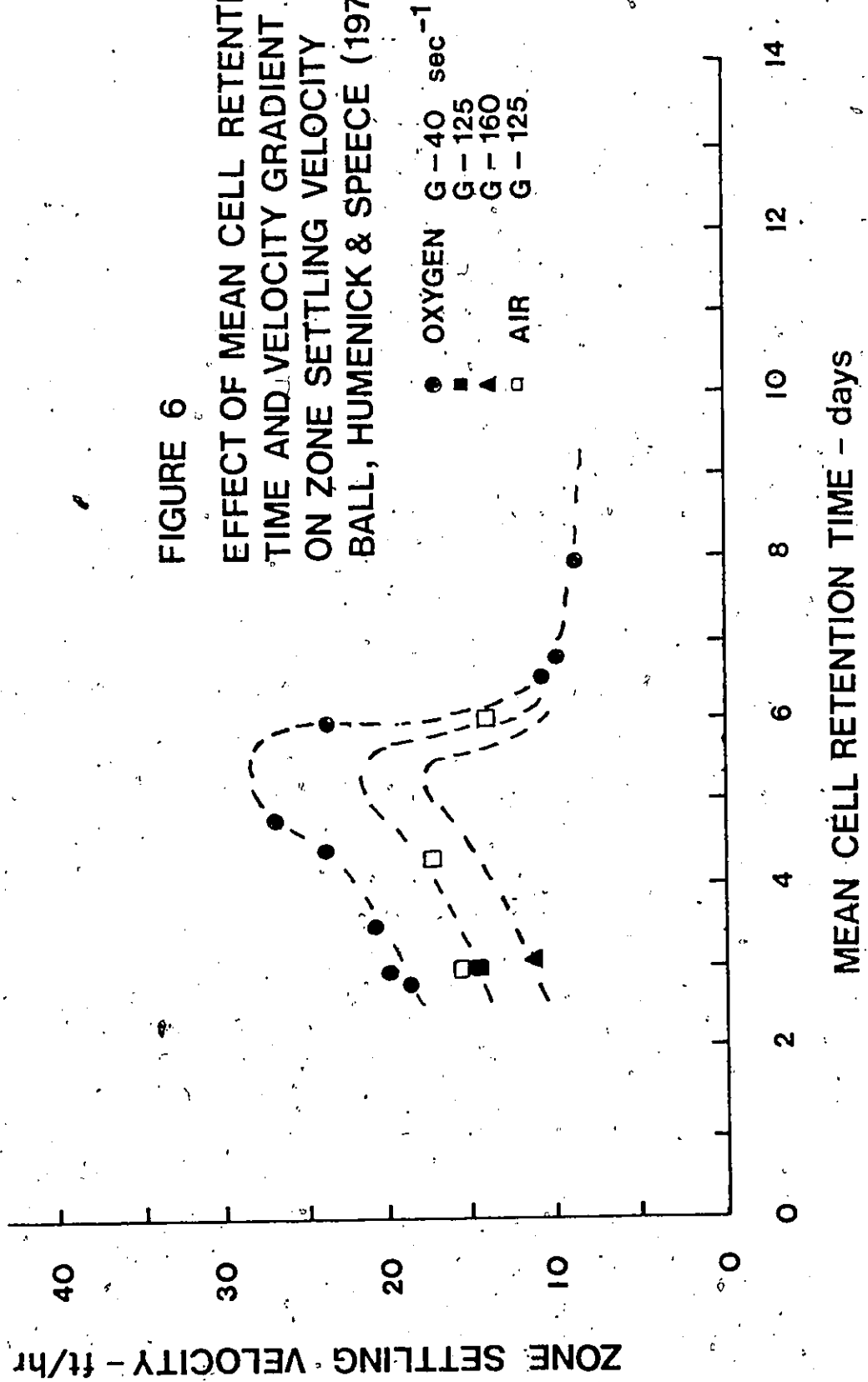
In summary, a considerable number of sources have suggested that a biomass generated under pure oxygen conditions is both rapidly settleable and readily compactable. There is little substantiation, however, that settling characteristics will differ from air generated sludges under the same operating conditions (i.e. F/M, concentration, mixing intensity). Inherent to oxygen systems however, are two important factors:

TABLE 3

COMPARATIVE SETTLEABILITY IN THE ZONE SETTLING RANGE
BALL, HUMENICK AND SPEECE (1972)

Run	Unit	Mean Cell Retention Time - Days	Root Mean Square Velocity Gradient sec ⁻¹	Oxygen Tension mg/l	Initial Settling Velocity ft/hr
1	diffused oxygen	6.6	40	2	11
	absorbed oxygen	8.0	40	2	9
2	diffused oxygen	6.8	40	3	10
	absorbed oxygen	4.8	40	3	27
3	diffused oxygen	3.5	40	3	21
	absorbed oxygen	2.9	40	3	19
9	diffused oxygen	4.5	40	8	24
	diffused air	4.3	125	4	18
10	diffused oxygen	3.0	40	7	20
	diffused oxygen	3.0	125	7	15
	diffused oxygen	3.0	160	8	12
	diffused air	3.0	125	3	16
11	diffused oxygen	6.0	40	7	24
	diffused air	6.0	125	3	14

FIGURE 6
EFFECT OF MEAN CELL RETENTION
TIME AND VELOCITY GRADIENT
ON ZONE SETTLING VELOCITY
BALL, HUMENICK & SPEECE (1972)



MEAN CELL RETENTION TIME - days

- 1) there is a greater force for dissolution of oxygen, and a resulting reduction in mixing intensity through reduced gas flows, and
- 2) there is a capability for maintaining a higher concentration of micro-organisms aerobic.

Questions related to settling properties which are yet to be answered are:

- 1) what, if any, are the effects of the reduced mixing intensity,
- 2) what, if any, are the effects of oxygen tension, and,
- 3) do the above two effects, justify recent recommendations for operation of oxygen systems at two-fold higher solids levels without affecting the size of solids separation equipment?

2.1.4 Biological Nitrification

In recent years increasing attention has been given to means of controlling the amount of nitrogenous matter in sewage effluents because of the contribution to the oxygen demand, toxicity (Ball, 1967), chlorine demand, and nutrient enrichment. In order to affect the removal of

nitrogenous matter in sewage, the problem is two-fold:

- 1) to fully oxidize all nitrogenous matter (nitrification) and
- 2) to reduce as much oxidized matter to elemental nitrogen as possible (denitrification).

Although step one may be performed in existing facilities, biological treatment processes designed for carbonaceous and solids removal are generally both inefficient and unreliable for nitrification.

In a comprehensive review of parameters affecting the extent of nitrification, Downing et al (1964) indicated that,

"values for the level of dissolved oxygen at which the effect becomes independent of concentration vary to some extent from about 0.3 to above 1.0 ppm."

Wuhrman (1960) has reported, in studies with three identical high-rate activated sludge units, that only 10 percent of the effluent inorganic nitrogen was in the form of nitrite or nitrate in the unit containing 1 ppm dissolved oxygen, whereas the corresponding figures were 90 percent in the other units at 4 and 7 ppm.

In activated sludge studies, Kiff (1972) has concluded that nitrification is curtailed at dissolved oxygen saturation levels of less than 20 percent (i.e. approximately 1.8 ppm at 20°C). The author states further

that,

"organic matter appears to be inhibitory at lower levels of dissolved oxygen indicating more complex interactions."

Stankewich (1972) has also proposed the necessity of providing higher dissolved oxygen concentrations to achieve greater nitrification rates. The author presents data from two Union Carbide pilot plant studies indicating reductions of Total Kjeldahl and Ammonia Nitrogen in excess of 80 percent.

The removals of Ammonia and Total Kjeldahl Nitrogen observed by Albertsson et al (1970), in the Batavia Study were found to be "essentially equivalent". Dissolved oxygen levels in the air system averaged slightly greater than 1.0 ppm with the oxygen system in excess of 6 ppm. Overall removals of 37 percent were observed in both instances.

In summary, it is apparent that critical dissolved oxygen levels expressed in terms of nitrification are variable from system to system and probably lies in the range of 0.3 to approximately 2.0 ppm.

2.2 SLUDGE AGE

The fundamental biological design parameter in the activated sludge process for many years has been the organic loading or food to mass ratio, (i.e. lbs BOD/Day/lb MLVSS). The mean cell residence time or sludge age, however, has been promoted as a more rational basis for design, control and operation of activated sludge treatment plants (Lawrence and McCarty, 1970; Jenkins and Garrison, 1968; Walker, 1971). Sludge age is considered to be a more realistic parameter because of its direct relationship to the growth of the biomass. Sludge age describes the mean residence time of a cell in the system and hence is a measure of the age of the sludge.

Although the food to mass ratio has had wide application in aerobic biological processes, its general usage is limited in the difficulty of reasonably determining a measure of the active biomass. This is often approximated by the mixed liquor volatile suspended solids. Lawrence and McCarty (1970) claim that this may be reasonable for a soluble waste but for cases such as domestic sewage, the estimate may be high by a factor of two to five because of a large nonactive volatile suspended solids contributed by the waste.

In contrast, if the mixed liquor suspended solids are homogeneously distributed, and the retention time of total suspended solids and microbial solids are the same, then even for systems where the active microbial

mass is only a fraction of the total MLSS, the sludge age is the same.

The sludge age and food to mass ratio can be mathematically related. The biological growth and substrate utilization has been formulated (Lawrence and McCarty, 1970; Walker, 1971) in the following expression:

$$\frac{dx}{dt} = Y \frac{df}{dt} - bx$$

where: $\frac{dx}{dt}$ is the net production of volatile solids

$\frac{df}{dt}$ is the available substrate per unit time

Y is the weight of volatile solids produced per unit weight of substrate

x is the mass of volatile solids

b is the decay coefficient

Dividing both sides of the expression by the volatile suspended solids concentration yields the equation:

$$\frac{1}{x} \frac{dx}{dt} = \frac{1}{\theta} = Y \frac{1}{x} \frac{df}{dt} - b$$

The growth rate of bacterial cultures in a given substrate is also expressed as the unit rate of cell concentration or;

$$\frac{1}{x} \frac{dx}{dt}$$

The term,

$$\frac{1}{x} \frac{df}{dt}$$

is more familiarly expressed as the food to mass ratio or the organic loading per unit mass of solids.

In addition to its direct relationship to the metabolic activity level of activated sludge, Bisogni and Lawrence (1971) have published data indicating the existence of a relationship between biological solids retention time and sludge settleability and also the extent of bio-flocculation.

2.2.1 Solids Production

The relationship between sludge age and solids production was expressed previously as a mass balance, whereby the net growth rate was given as a function of the rate of sludge synthesis minus the rate of sludge loss by decay processes,

$$\frac{1}{\theta} = Y \frac{1}{x} \frac{df}{dt} - b$$

and in terms of flowrate and substrate removal,

$$\frac{1}{\theta} = Y \frac{Q(C_0 - C)}{xV} - b$$

This is conveniently utilized by plotting the net growth rate, $(1/\theta)$, versus food to mass to determine the yield and decay coefficients.

It is evident that as the sludge age is decreased, there is less substrate removed per pound volatile solids and as a result less solids produced per pound volatile solids.

An important limitation arises in the application of the above relationship when organic solids are present in the influent. If influent suspended solids are not reduced to soluble substances and subsequently metabolized by the biomass, an abnormally high yield coefficient will be observed. At the same time, a contribution to the organic loading by the influent solids is highly probable, (Jenkins and Garrison, 1968) and hence must be considered. The extent of metabolism of influent solids is not well defined and is subject to several variables. The contribution to the organic loading is more easily determined by comparing filtered versus unfiltered samples (usually 0.45 μ membrane filters are employed).

Without primary treatment, difficulty has arisen in yield determinations directly as a result of incomplete metabolism of the higher solids levels. Ball and Humenick (1972) question the conclusions of the Batavia study (Albertsson et al, 1970) which relate to reduced sludge yields produced by the oxygenation through an apparent misinterpretation

of this effect.

The Batavia Municipal Treatment Plant did not include primary treatment. Volatile solids concentrations in excess of 100 mg/l were typical, with weekly averages as high as 557 mg/l. The authors suggested that higher sludge ages inherent to the oxygenation system conditions, resulted in a greater degree of aerobic digestion of the influent solids. The net result was exhibited in terms of lower calculated yields relative to the aeration system.

2.2.2 Oxygen Uptake

In the activated sludge process oxygen is required specifically for conversion of organic carbon to cell material and carbon dioxide, for auto-oxidation of cells and in some cases for nitrification of inorganic and organic compounds.

The total oxygen required has been estimated by Eckenfelder (1956) from the relationship:

$$\frac{dO_2}{dt} = a \frac{df}{dt} + b'X$$

or in terms of oxygen uptake per unit weight of volatile suspended solids,

$$\frac{1}{X} \frac{dO_2}{dt} = a \frac{1}{X} \frac{df}{dt} + b'$$

One would then expect oxygen to bear a similar relationship to the food

to mass ratio as the net specific growth rate. Simultaneous increases in both the oxygen uptake and the net growth would occur with an increase in the food to mass ratio.

It is of some interest that the activity of activated sludge as measured by the dissolved oxygen uptake rate has been found to be independent of the net growth rate when expressed on a viable cell basis. (Weddle and Jenkins, 1971). In the net growth rate range from 0.03 to 6 days⁻¹, Weddle and Jenkins have found both the dehydrogenase enzyme activity and dissolved oxygen uptake rates per viable cell to be constant. At the same time, the authors noted that the viable cell count per gram of volatile solids was a function of the net growth rate. Thus the oxygen uptake was found to vary with growth rate when expressed on a volatile solids basis.

For conventional activated sludge operation, Downing (1968) has reported that dissolved oxygen uptake rates are generally in the range 15-35 mg D.O. per hour per gram of suspended solids, with higher values associated with nitrifying sludges. Weddle and Jenkins (1971) reported between 7.6 and 37 mg D.O. per hour per gram volatile suspended solids for conventional activated. For activated sludge operation, on synthetic wastes Bisogni and Lawrence (1971) have obtained uptake rates of 15 to 25 mg D.O. per hour per gram volatile solids.

2.2.3 Settling Characteristics

Factors affecting settling and clarification properties are generally divided into two categories. The first is associated with changes in the biological population's physical or biochemical character. The second involves population shifts, involving changes in bacterial predominance from non-filamentous to filamentous forms, as well as the presence or absence of higher order protozoan and metazoan populations.

The prerequisite for efficient solid-liquid separation is the flocculation of micro-organisms and other suspended or colloidal components into a readily settleable mass. Bio-flocculation alone, however, does not necessarily result in a good settling floc. It may also be characterized by a poorly compactable or bulked sludge.

Several distinct theories of bacterial flocculation have been supported throughout the last sixty years. Recent reviews of early flocculation theories, have been made by Pavoni et al (1972) and Ball et al (1972).

The polymer bridging model of cell aggregation is generally supported as the most plausible flocculation theory. In this model, flocculation is viewed as the result of the interaction of naturally produced, high molecular weight, exocellular polymers. The long chain polymers are composed of an extracellular polysaccharide-lipid protein complex which has an affinity for polyvalent cations. The resulting slime layer has a net

positive charge, and hence shows an affinity for the negatively charged dispersed cells.

The extent of slime accumulation and biological accumulation, has been found in batch studies to only occur in later stages of growth (Pavoni et al, 1972; Tenney et al, 1970). Thus systems with long mean cell retention times would naturally accumulate a greater bulk of slime per unit mass of organisms than a system approaching washout.

Tenney and Stumm (1965) believe dispersed growth, which occurs at low sludge ages, is the result of natural polymers which are not excreted fast enough by the cells to provide a proper polyelectrolyte dose for flocculation. The authors suggest that optimum conditions for bio-flocculation exist under long aeration times such as extended aeration, where sludge age is very long and dispersed solids are a minimum.

A second effect involving the physical character of the sludge, has been termed zooglear bulking by Heukelekian and Weisberg (1956). The authors attempted to quantify the relationship between bound water and free water in various activated sludges. Bound water was termed as adsorbed water, bound to the sludge cells by colloid micelles and having lost all its colligative properties. Free or interstitial water could be forced from the sludge flocs by slight pressure and it retained all its inherent properties.

7

Under conditions of high food to mass ratio, when easily degradable substrates are available in excess, the organisms were found by the authors to have a higher bound water content. Heukelekian and Weisberg postulated that the increased affinity resulted from the increased production of capsular material during high growth rate conditions (log growth phase) which is polysaccharide in nature and highly hydrated. Simultaneous increases in SVI were then noted. Ford (1967) has found the amount of bound water to also increase with loading. SVI and zone settling velocity were also dependent in part on the bound water content. Somewhat in contradiction to Heukelekian and Weisberg (1956), bound water was found to contribute to filamentous sludge bulking.)

Ball, Humenick and Speece (1972) have observed no variation in bound water levels with sludge age and, in fact, have questioned the dilatometric bound water monitoring technique. It is apparent that bound water measurements are seldom employed in activated sludge studies and, in addition to their relationship with non-filamentous bulking sludge, are open to further study.

Population shifts in both bacterial and higher forms of microbial life have been found to affect settling properties and effluent clarity. The most evident shift in population, is witnessed by the emergence of a dominant population of filamentous organisms growing as a diffuse floc. When the filamentous organisms constitute a significant percentage of

the total biomass, they are known to cause a marked decrease in settling velocity and increase in SVI.

Sphaerotilus natans is most commonly reported as being the dominant filamentous organism in bulking sludge (Eckenfelder, 1973). Geotrichum candidum (Jones, 1964), Escherichia coli (Pasveer, 1969), Leucothrix cohaerens, Lineola longa and Spirulina albiba (Cyrus and Sladka, 1970) have also been cited as the filamentous organisms responsible, (the fungi are not truly filamentous, but rather exhibit somewhat similar mycelial growth).

Filamentous bulking has been found to be primarily a function of organic loading (food to mass ratio). The loading at which it occurs, appears to be related to the complexity of the organic waste, occurring at lower loadings with more readily available carbohydrates (Pipes, 1969). Hence, low sludge ages and high growth rates are conducive to both types of bulking.

The effect of filamentous bacteria and fungi on effluent clarity is rather unclear. Pasveer (1969) and Chubdova (1973) note that many sources have found a better quality effluent under bulking conditions. Bisogni and Lawrence (1971), on the other hand claim, that both types of bulking usually exist as dispersed growth.

The general effects of washout on bacterial forms, as sludge age is

decreased (and wastage increased because of higher solid production levels) is unknown. As would be expected, definition of all forms present is a difficult task, in itself, without the addition of further process variables.

However, the effects on higher order forms of protozoa, and metazoa (predominantly rotifera, flat worms, and crustaceans) are more evident because they are characteristically an order of magnitude, or more, larger than bacteria and readily distinguishable under a microscope. Three major groups of protozoa are evident in sewage treatment plants: ciliates, flagellates and amoebae. The latter two groups generally occur only in small numbers (United Kingdom, Ministry of Technology, 1968). Ciliates probably play no significant role in the oxidation process but there is evidence suggesting that these organisms play a major part in final effluent clarification (Butterfield, 1935; Curds *et al*, 1968). Results of Curds *et al* (1968) are presented in Table 4. Ciliates, when present in activated sludge were found to reduce rather large numbers of non-settling bacteria by predation. The authors also make reference to pure culture studies indicating the ability of protozoa to flocculate suspended matter and bacteria. In the study by Watson (1945), a mucus material secreted by the ciliates was found to act as a flocculating agent.

The role of metazoa and specifically rotifera are more poorly defined.

TABLE 4

EFFECT OF THE PRESENCE OF
PROTOZOA ON EFFLUENT COMPOSITION

	<u>Ciliates Absent</u>	<u>Ciliates Present</u>
COD (mg/l)	198 - 254	124 - 142
Organic Nitrogen (mg/l)	14.2 - 20.7	7.0 - 10.0
Suspended Solids (mg/l)	86 - 118	26 - 34
Optical Density at 600 m μ	0.95 - 1.42	0.23 - 0.34
Total Bacterial Count (millions/ml)	292 - 422	90 - 121

Reference: Curds et al (1968)

Calaway (1968) states that rotifera also act as predators. Active rotifera are not as durable as are the ciliates, however and require longer time periods to become established.

In general, the presence of rotifera as well as both stalked and crawling ciliates normally indicates a healthy sludge (Curds et al, 1970; Calaway, 1968; United Kingdom, Ministry of Technology, 1968). Growth rates of the multicellular metazoa, and to a lesser extent, the protozoa are much slower than that of bacteria and hence are more subject to wash-out at low sludge ages. Sherrard and Schroeder (1972) noted that although both protozoa and rotifers were present at a sludge age of 2 days, higher concentrations were present at 11.8 days.

In summary, the above factors influencing settling and clarification properties would indicate that:

- 1) at low sludge ages or high F/M ratios, bulking and/or dispersed growth is probable and
- 2) at high sludge ages or low F/M ratios, well flocculated, readily settleable and compactable sludge is probable.

Unfortunately observations of settling properties as a function of sludge age or food to mass ratio have been only in partial agreement.

Sherrard and Schroeder (1972) have observed an improvement in settling velocity and compactability as sludge age was increased from 2 days to 11.8 days. Supernatant clarity was good over the full range of 2 to 18 days.

As shown in Figures 7, 8 and 9 similar results were observed by Bisogni and Lawrence (1971). It is worthy of note that sludge volume index declined at sludge retention times less than 2 days. This presumably was the result of an over-riding effect of very highly dispersed floc conditions (which prevented measurement of the zone settling velocity).

In a study of three differing wastewaters, Ford (1967) noted a reduction in zone settling velocity at both high and low loading conditions. Filamentous growth conditions were responsible for high load bulking and reduced zone settling velocity. Poor settleability at the low loadings was thought to be due to break-up of unoxidized fragments of the floc.

Based on later data presented by Eckenfelder (1973) it is apparent that the range of sludge ages studied by Ford was greater. This may explain some of the conflict in results at high sludge ages. This condition was also characterized by a lesser increase in SVI (see Figure 10).

Although not evident in their data, Bisogni and Lawrence (1971) predicted the occurrence of pin-point or deflocculated particles at corresponding

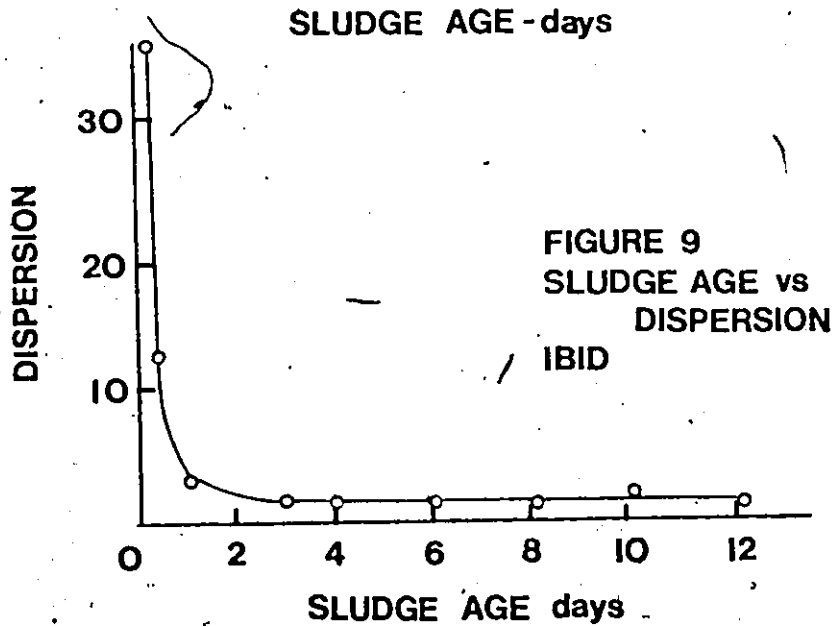
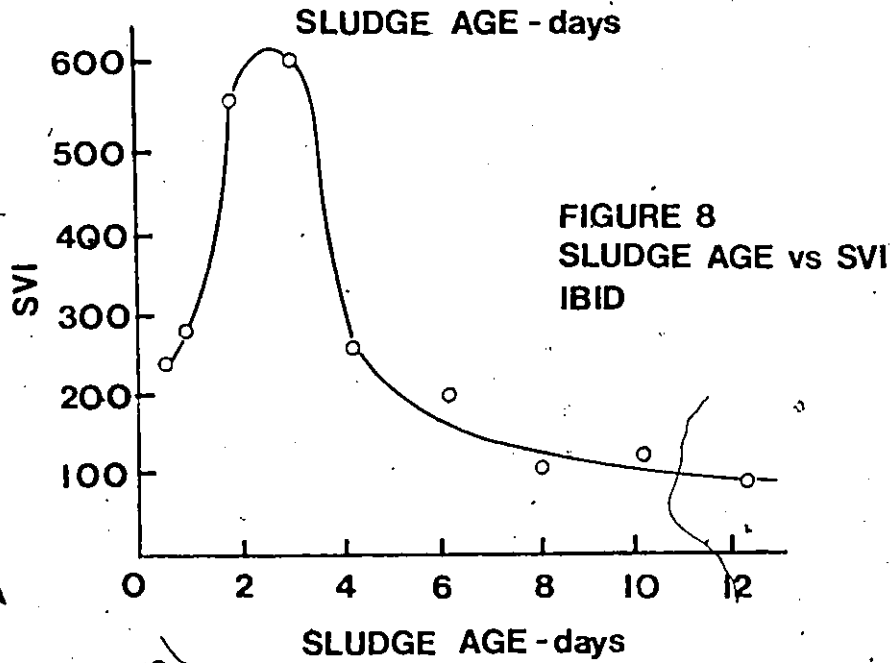
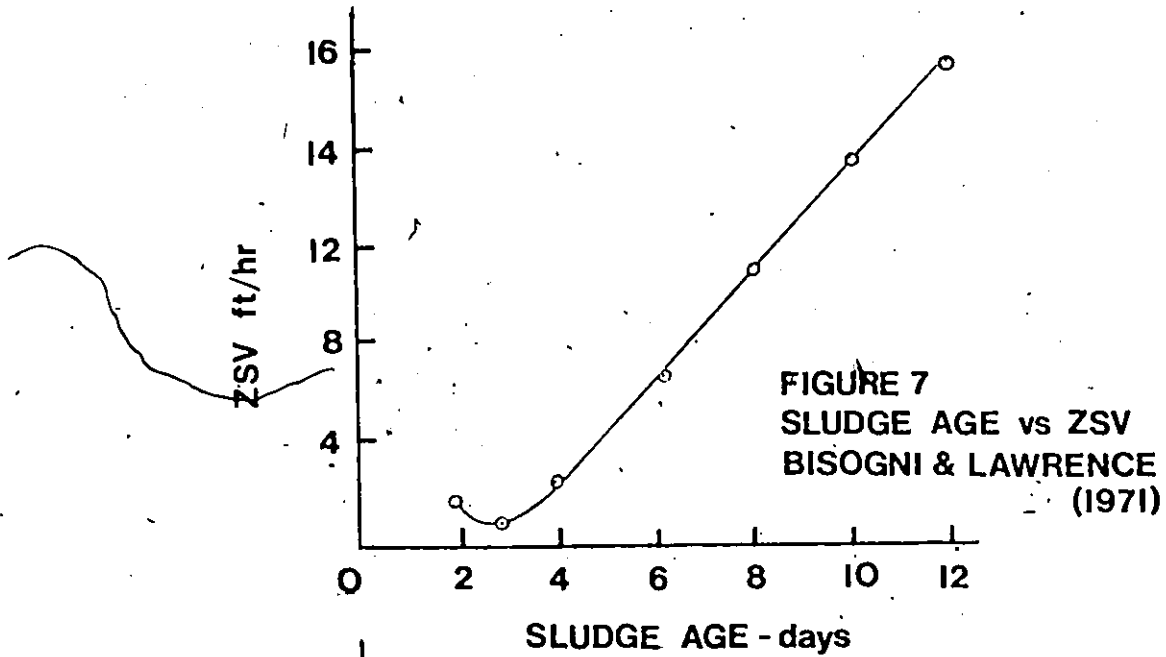
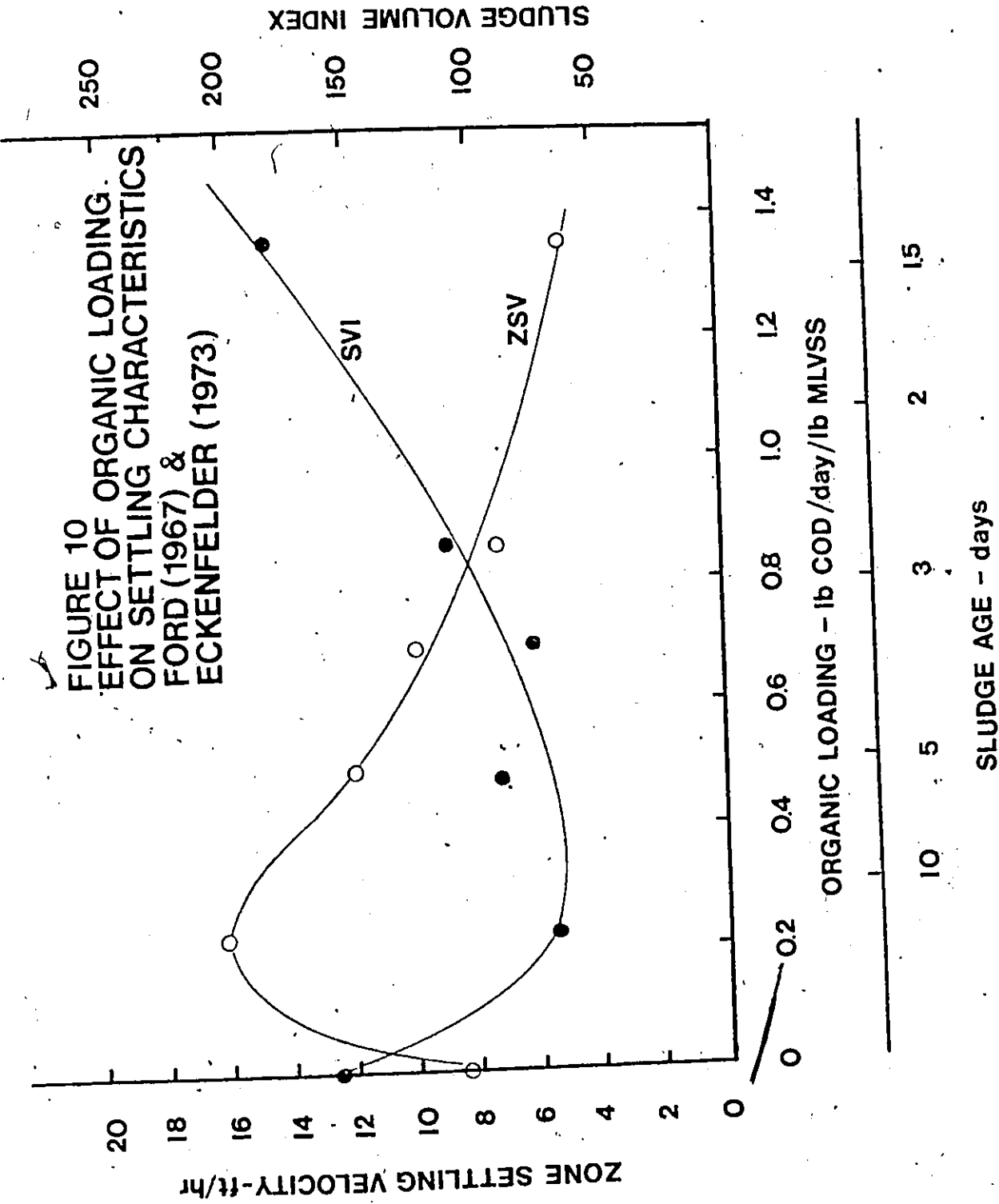


FIGURE 10
EFFECT OF ORGANIC LOADING.
ON SETTLING CHARACTERISTICS
FORD (1967) &
ECKENFELDER (1973)



low loadings (or high sludge ages) in agreement with Ford's data. Reductions in sludge volume index, however, are predicted by both Bisogni and Lawrence (1971) and Pipes (1969) under the above conditions.

As shown previously, the results of Ball et al (1972), Figure 6, support the results of Ford, with optimal zone settling velocities occurring at approximate mean cell retention times of five days.

From the above survey, it is evident that the requirements for the most rapid substrate utilization are generally incompatible with the requirements for optimum bio-flocculation.

Although there is a tendency for improved settling properties at high sludge ages, an increased susceptibility towards deflocculation and pin point floc has been observed. The presence of pin point floc has not been explained and at present there is no solution to the problem other than reduction of sludge age. Well conditioned sludges have been observed in intermediate ranges from 5 days to in excess of 18 days.

2.2.4 Biological Nitrification

Nitrifying organisms have relatively long generation times and low yield coefficients compared to the predominant heterotrophic population found in biological treatment processes. Since they are intimately mixed with all other micro-organisms common to activated sludge, the sludge retention time will be decisive in their existence within the process.

High growth rates or rather low sludge ages will necessitate greater wastage of excess sludge and hence a greater loss of nitrifiers. Nitrification is therefore bound to operating conditions leading to a minimum of excess sludge production. Consistent with the concept of maintaining long sludge ages are findings by Downing and co-workers (1964).

Improved nitrification was achieved by increasing the concentration of suspended solids. This acts to reduce the food mass ratio and hence reduces the growth rate or increases the sludge age.

Ford (1967) concluded that total Kjeldahl nitrogen reduction and subsequent nitrite and nitrate concentrations decreased significantly with organic loading. In a later application of the sludge age concept to Ford's data, Eckenfelder (1973) predicted a minimum of 3 days sludge age would be required for nitrification at 20°C.

This work has been reinforced in current investigations with multi-stage nitrification-denitrification systems. Barth et al (1968) and Mulbarger (1971) have reported that by reducing the carbon levels in a first stage high rate activated sludge unit, reduced cellular synthesis in the second stage and consequently minimal wastage permits growth of an enriched culture of nitrifiers in the second stage. Typical mean cell retention periods reported by Mulbarger (1971) are 1 to 3 days in stage one and 10 to 15 days in stage two.

2.3 MIXING INTENSITY.

The energy of mixing commonly occurring in activated sludge systems is high. Fair et al (1968) have indicated a two-fold greater mixing intensity than present-day chemical coagulation systems.

The power applied functions to:

- 1) supply oxygen to the biological flocs,
- 2) transfer substrate to the biomass,
- 3) maintain the biomass in suspension and hence maintain a high floc-fluid interface for efficient mass transfer,
- 4) remove waste products from the sludge, and
- 5) flocculate or produce flocs of size and density allowing separation by normal gravitational sedimentation.

The mechanical energy input to flocculation systems is commonly expressed in terms of the mean velocity gradient introduced by Camp and Stein (1943). The velocity gradient is defined as:

$$G = \sqrt{P/\mu V}$$

where P = power consumption-ft-lbs/sec

V = volume of the flocculator - cu.ft.

μ = absolute viscosity of the fluid - lbs/sec-sq.ft.

In a study of 20 American water treatment plants, Camp (1955) has found the mean velocity gradient to be in the range of 20 to 74 seconds⁻¹. Parker et al (1970) confirmed the two-fold difference suggested by Fair et al, with a range of 88 to 220 seconds⁻¹ found in a study of fourteen American activated sludge plants. Further substantiation can be found in other sources (Rickard and Gaudy, 1968; Ball et al, 1972).

As an operating variable, mixing intensity is seldom if ever considered and is generally a function solely of the oxygen requirements of the biomass to metabolize a given waste, the type and efficiency of transfer of aeration equipment, and tank depth and volume. Variation in the air flow rate to diffused air systems may be possible, but generally the air flow rate is necessarily set to maintain a given dissolved oxygen level rather than to maintain a given mixing intensity.

In recent years, however, mixing intensity has been shown to have an effect on:

- 1) sludge yield,
- 2) oxygen uptake rate,
- 3) zone settling velocity and floc characteristics, and
- 4) the development of filamentous organisms.

2.3.1 Sludge Yield

In a biological system, one would expect the yield, itself, to be a

function of the species of organisms and enzymes present, the metabolic pathway by which the substrate is degraded, the composition or free energy of the substrate, and the detention time. In the later case, this may be the result of a sorting or washout process whereby organisms of short generation time will predominate as detention time is decreased.

Recent work by Rickard and Gaudy (1968) has shown a rather surprising variation of yield with mean velocity gradient. The reduction of yield with increasing velocity gradient was accomplished with no deterioration in effluent quality. The authors have also found that the decrease occurred primarily at the expense of cellular carbohydrates (as opposed to protein, RNA or DNA content). They have proposed a mechanism whereby there is a reduction in synthesis of stored material rather than a reduction in the viable population produced.

It is of some note that Ball et al (1972) found no difference in yield when mixing intensities were varied from 40 to 160 seconds⁻¹. This is not necessarily in opposition to Rickard and Gaudy however, with their work extending from approximately 300 to 1350 seconds⁻¹.

2.3.2 Oxygen Uptake Rate

The mixing energy imparted to a liquid bacterial culture has been shown by several workers (Zahradka, 1966; Rickard and Gaudy, 1968; Bennett and Kempe, 1965) to affect the activity of bacterial cells. The activity

may be expressed in terms of increased oxygen uptake or substrate utilization per unit mass of biological organisms. Tsao and Kempe (1960) have observed increases in oxygen uptake of Pseudomonas ovalis as the turbulence of the system was increased by adjustment of the mechanical stirring rate. Zahradka (1966) has concluded that the mixing intensity can improve the aerated space activity substantially while the food to mass ratio is of less significance. Zahradka suggests that the BOD loading per unit of mechanical energy is a better parameter than is the BOD to solids ratio.

McKinney (1956) concluded that maintenance of a high energy to micro-organism level produced a dispersed non-flocculent growth. Continued lowering of the ratio produced better flocculation but at the same time reduced microbial activity. He further states, however, that excess aeration (i.e. very high turbulence) resulted also in a loss of micro-organism activity, and reduction in effluent quality.

In a study into the effect of mixing energy on activity, Rickard and Gaudy (1968) cited five possible mechanisms to explain the increase in oxygen uptake (and decreasing yield) observed with increasing velocity gradient:

- 1) changes in microbial predominance,
- 2) increased frequency of contact between cells and substrate,

- 3) production of smaller floc particles with resultant improved penetration of substrate and oxygen,
- 4) increases in the rate of oxygen transfer across the cell-liquid interface, and
- 5) maintenance of a higher D.O. concentration with increasing turbulence.

Although none of the mechanisms have been eliminated by the authors, it was felt that the increase in oxygen uptake resulted from reductions in the cell-liquid interfacial resistance to oxygen transfer as mixing energy was increased.

Pasveer (1953), on the other hand has attributed the observed effects to a reduction in floc size by mechanical shear and a resulting increase in interfacial area for mass transfer of both oxygen and substrate.

Rincke (1967) attributes the improved performance to a combined effect also due to an improved frequency of contact between cells and substrate.

Despite the fact that Zahradka (1966) has noted changes in bacterial predominance, he also is in support of the mechanism proposed by Pasveer.

2.3.3 Settling and Floc Characteristics

Separation of mixed liquor solids for return to the aeration tank is one

of the most critical steps in the activated sludge process. Maximum thickening is favoured by the economy of returning a smaller flow to the aeration tank and maximum clarification is necessitated by the increasingly stringent water quality standards.

The separation of particles from suspension has been shown to be enhanced by the agglomeration of particles into aggregates (Bradley and Krone, 1971). Activated sludge particles exhibit cohesive properties under normal operating conditions and can be aggregated into larger particles by facilitating repeated collisions. However these aggregates may be broken up if the shear stress on the particle resulting from local velocity gradient exceeds some minimum level.

According to Parker et al (1971) the highly turbulent conditions common to the aeration tank results in the occurrence of excessive floc break up rather than inadequate floc aggregation. The result is a high level of dispersed solids which can effect both settling velocity and effluent turbidity.

The occurrence of a reduction in aggregate size with increased velocity gradient is well documented. Ganczarçyk (1967) has reported that activated sludge from a number of locations had mean floc sizes ranging from 140 to 290 microns while those plants with "intense mixing" had floc sizes as low as 60 to 70 microns.

Parker (1970) has confirmed, in studies of five field installations, present practice does not yield maximum incorporation of dispersed materials into the floc. In later work, Parker et al (1971) concluded that addition of a mildly stirred flocculation stage between the aeration basin and the secondary clarifier should provide an environment more conducive to aggregation and resulting in an effluent with significantly less suspended solids.

The mixing history has also been shown to influence the particle properties of both size and density. Lagvankar and Gemell (1968) have found that flocculation with higher temporal mean velocity gradients produce more dense Fe (III) flocs. The density however, was found to be characteristic of the floc size with small flocs being more dense and as suggested by Bradley and Krone (1971) possessing greater shear strength as a result.

In qualitative terms, the effects of mean velocity gradient, or shearing rate, on zone settling velocity is not well defined. With a controlled shear apparatus, Bradley and Krone found for dilute suspensions (300 mg/l), large aggregates formed at low shearing rates settled faster than smaller aggregates formed at higher shearing rates. For concentrated sludges (2000 mg/l), the variation in settling rate was less pronounced. As found by Parker et al (1971), aggregation during uniform low-rate shearing yielded better clarification than the random aggregation following shear at high rate. The range of experimental coverage was from 15 to 75

seconds⁻¹.

Ball et al (1972) have found that more intense mixing produced lower settling velocities at concentrations of 1500 to 2000 mg/l. Their data, plotted previously in Figure 6 illustrates the effects on the initial settling rate of both the mean velocity gradient and mean cell retention time. Their data suggest that perhaps Bradley and Krone restricted their work to a rather overly limited range of velocity gradients or indeed the wall effects on the Couette type device utilized were significant.

The influence of mixing intensity on floc morphology is not restricted solely to floc size. Recent evidence has indicated that the hydraulic regime or degree of mixing can act to suppress filamentous forms of micro-organisms (Rickard and Gaudy, 1968; Zahradka, 1966; Chubdova et al, 1973).

Rickard and Gaudy (1968) have found for conditions that produced filamentous organisms at 310 seconds⁻¹ there appeared to be a complete absence at 1010 seconds⁻¹. The practicality of applying such a means of control, however, may well be limited by deterioration of effluent quality through shearing of the flocs.

Chubdova et al (1973) have observed that aeration systems with a low degree of axial mixing (i.e. with a low dispersion number or approaching

plug-flow) tend to favour non-filamentous micro-organisms and suppress the growth of filamentous forms, in relation to complete mix systems. They have related this to the maintenance of a concentration gradient along the aeration system and hence a decreasing organic loading rate through the system.

It is apparent that the mixing requirements of biological substrate uptake and yield are contrary to those of settling velocity and effluent clarity. In design of a system, both aspects should be given consideration, and conditions appear suitable for process optimization. Other alternatives include:

- 1) inclusion of a flocculating tank between the aerator and thickener (Parker et al, 1971),
- 2) coagulant addition with or without flocculation facilities,
- 3) oxygenation systems (which require 1/5th the horsepower to supply oxygen requirements) and
- 4) longer aeration detention for reduced power input per unit volume.

2.4 SUMMARY

Despite considerable differences in opinion, and an abundance of weakly supported claims, there are several important inherent characteristics of pure oxygen systems.

- 1) There is a greater driving force for the dissolution of oxygen and a resulting reduction in mixing intensity through reduced gas flow,
 - which may act to produce a better conditioned sludge.

- 2) There is a capability for maintaining a higher concentration of micro-organisms aerobic which permits longer sludge ages to be obtained in equivalent tankage to conventional air systems,
 - which may act to produce less excess solids,
 - which may act to produce a more readily settleable and compactable sludge,
 - which may act to produce a more highly nitrified effluent,
 - which may also be conducive towards the growth of protozoa and metazoa, which may reduce effluent solids levels by predation.

- 3) There is a capability for providing higher effluent dissolved oxygen levels.

- 4) Economic considerations have shown the process to be competitive with conventional systems.

The above characteristics offer in themselves a realistic alternative to conventional activated sludge systems. Claims of directly related effects of oxygen tension on sludge, metabolic activity and settling characteristics are yet to be conclusively substantiated. Such claims are most probably the cause of most present day skepticism towards this process.

3. EQUIPMENT AND EXPERIMENTAL PROCEDURES

3.1 SAMPLING PROCEDURES

The feed source consisted of domestic sewage which was continuously pumped into the Wastewater Technology Centre, Canada Centre for Inland Waters, from the Burlington Skyway Treatment Plant. Sewage was screened and degritted at the Skyway Plant prior to being pumped to the Centre.

The feed was collected daily in a 75 gallon polyethylene container. The vessel was filled in mid-afternoon and allowed to settle for approximately two hours. When required, the sewage was supplemented with yeast extract to control the soluble organic carbon level to be fed to the reactors. Grab samples were taken prior to start-up of each new batch and periodically the following day to check for any degradation of the soluble organic level.

Grab samples of the reactors were taken daily to monitor total and volatile suspended solids. The entire contents of the absorption columns were wasted daily and both solids and TOC analyses were run on the contents of this sample. Discharge samples of the reactors were composited over a period of approximately three hours each morning.

In general, sampling was performed at the same time each day to maintain uniformity for both control of the system and purposes of data comparison.

3.2 WASTEWATER CHARACTERISTICS

The sewage, previously screened and degrittied, was allowed to settle for at least two hours before the supernatant was fed to the reactors, to ensure a uniform substrate.

The contribution of settleable solids to the influent COD is illustrated in Figure 11. The two hour settling time represented a practical minimum time period to maintain reasonably constant influent solids and COD levels. This was also consistent with conventional retention times for primary clarification.

Although further clarification was observed, with decreases commonly to less than 50% of the two hour level, the poorly settleable solids were found to be predominantly non-volatile (Figure 12). Depression of COD values through both sedimentation and biodegradation were in the order of 10 to 20 percent. Breakdowns in soluble TOC were measureable only with yeast extract addition and generally varied up to 10 percent.

The day to day variation in raw sewage pH, TOC, and settled COD are shown in the probability plots, Figures 13, 14 and 15. The settled COD - soluble TOC ratio was found to have a mean value of approximately 2.68.

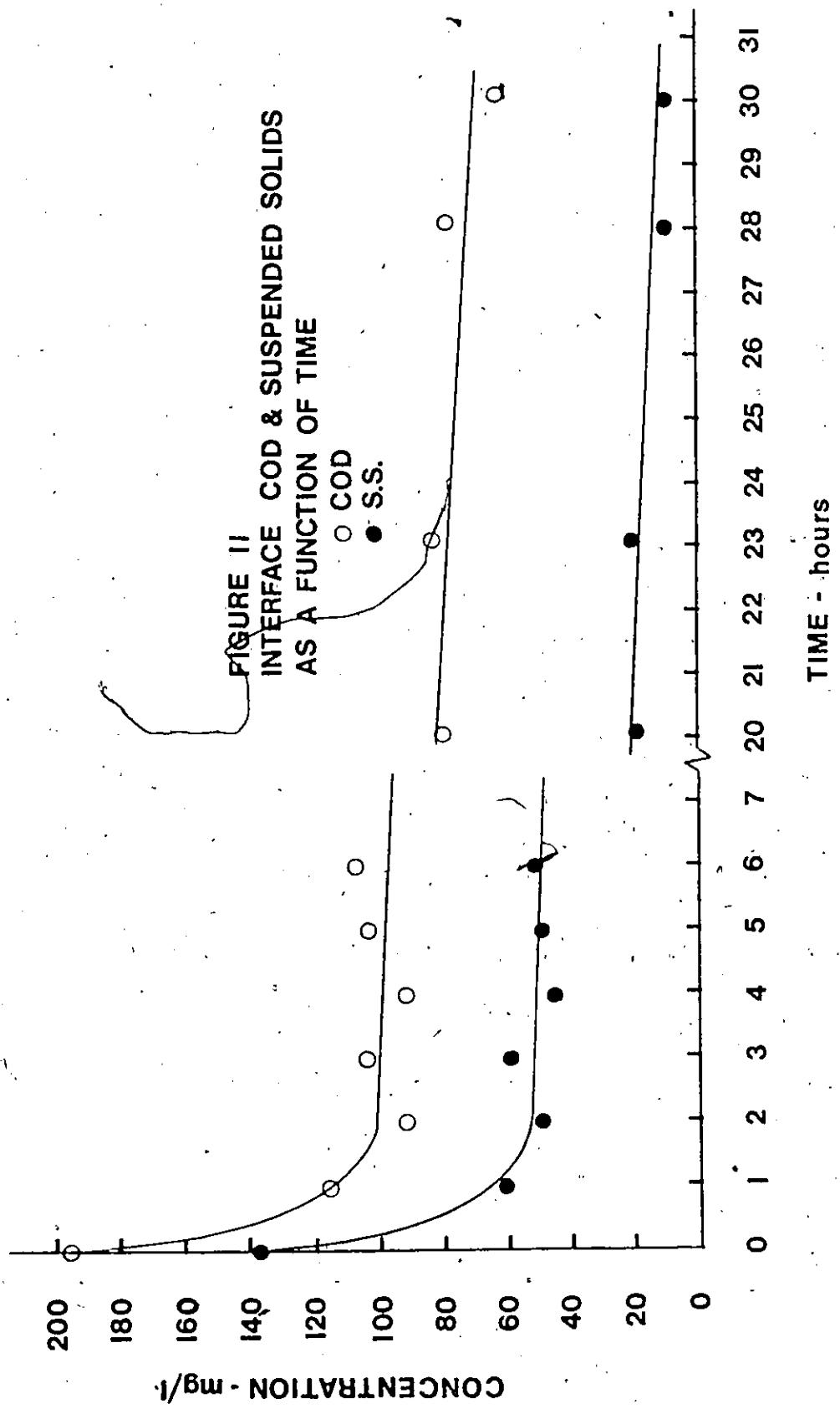
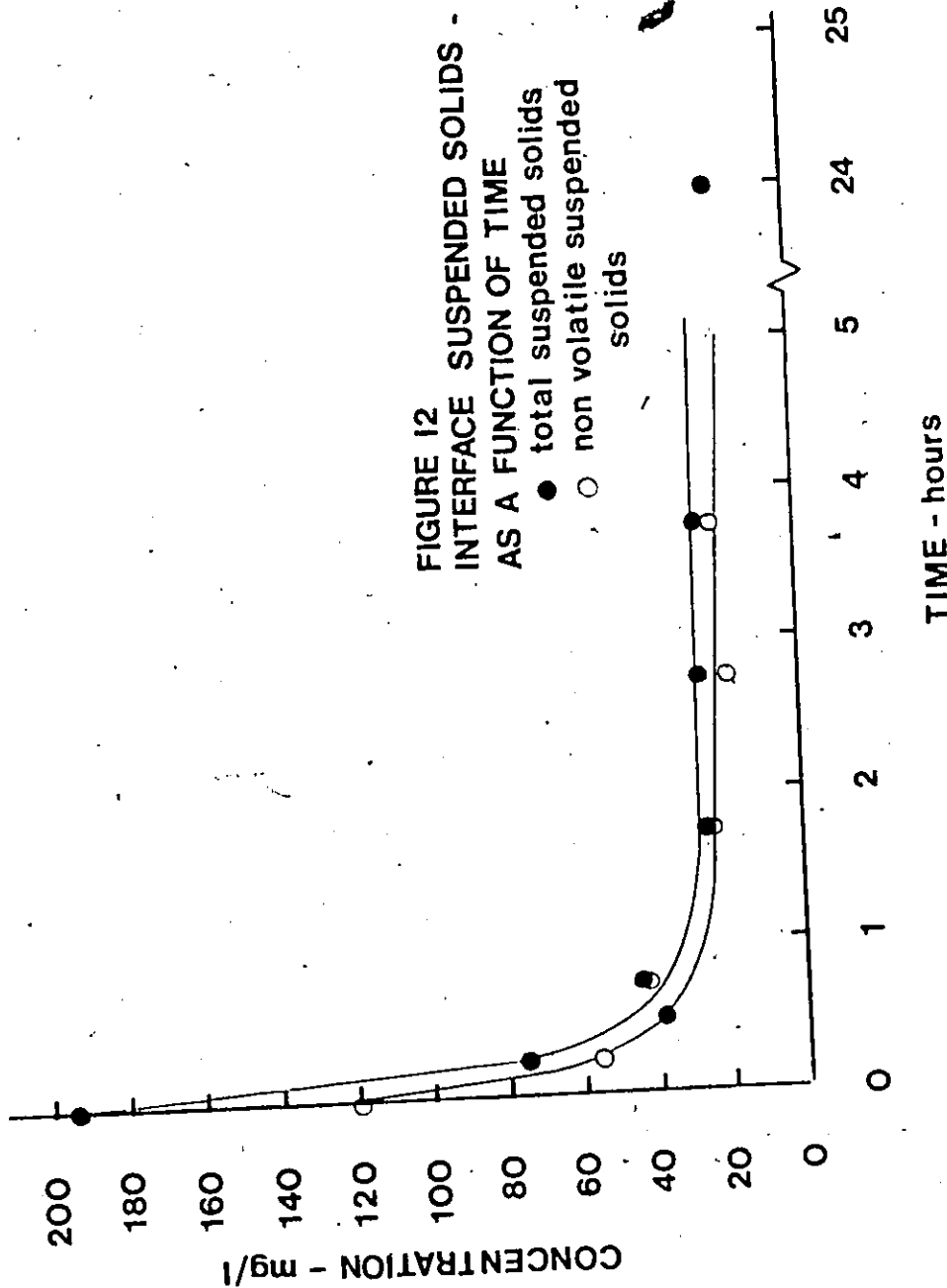


FIGURE 12
INTERFACE SUSPENDED SOLIDS -
AS A FUNCTION OF TIME
● total suspended solids
○ non volatile suspended
solids



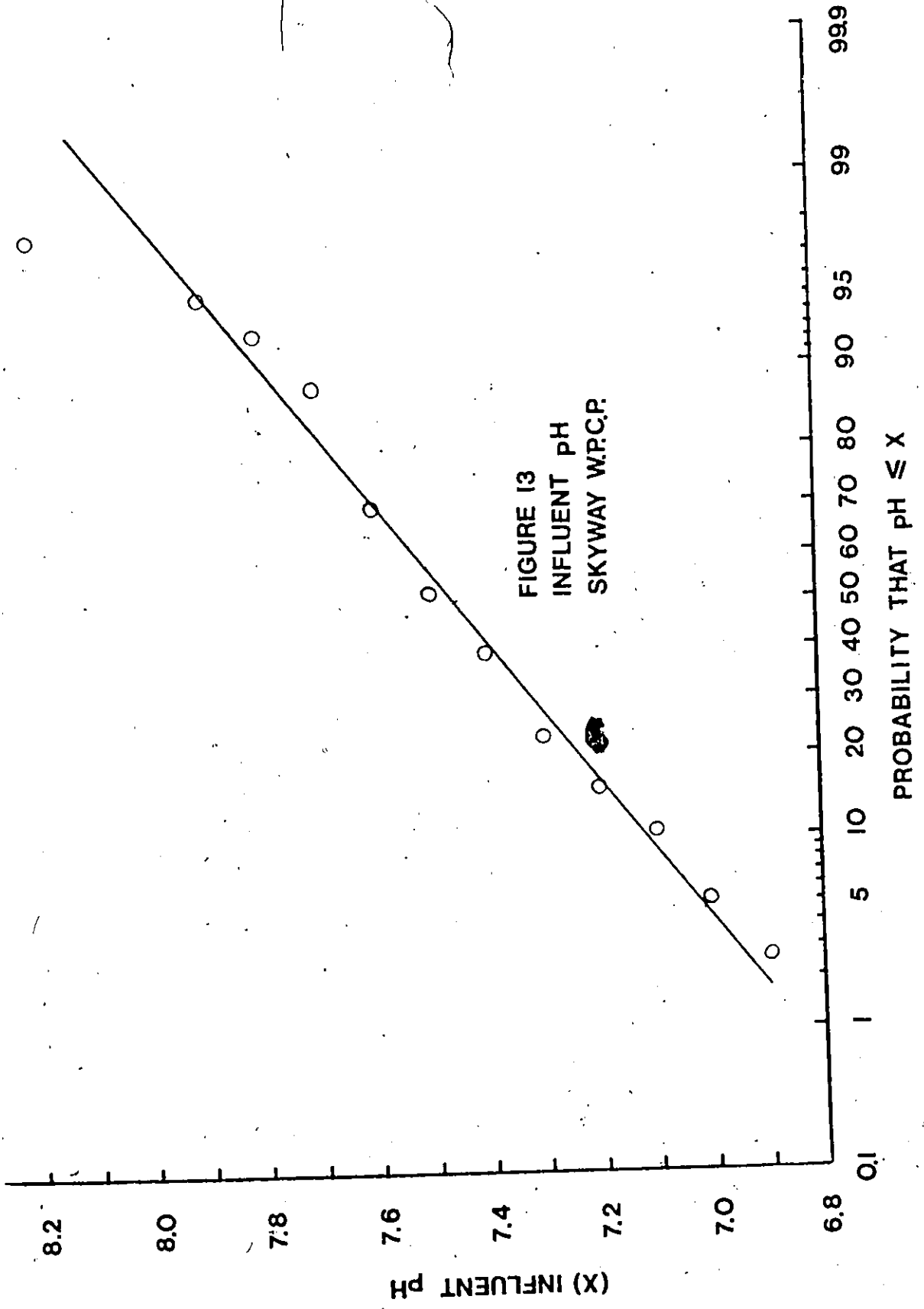
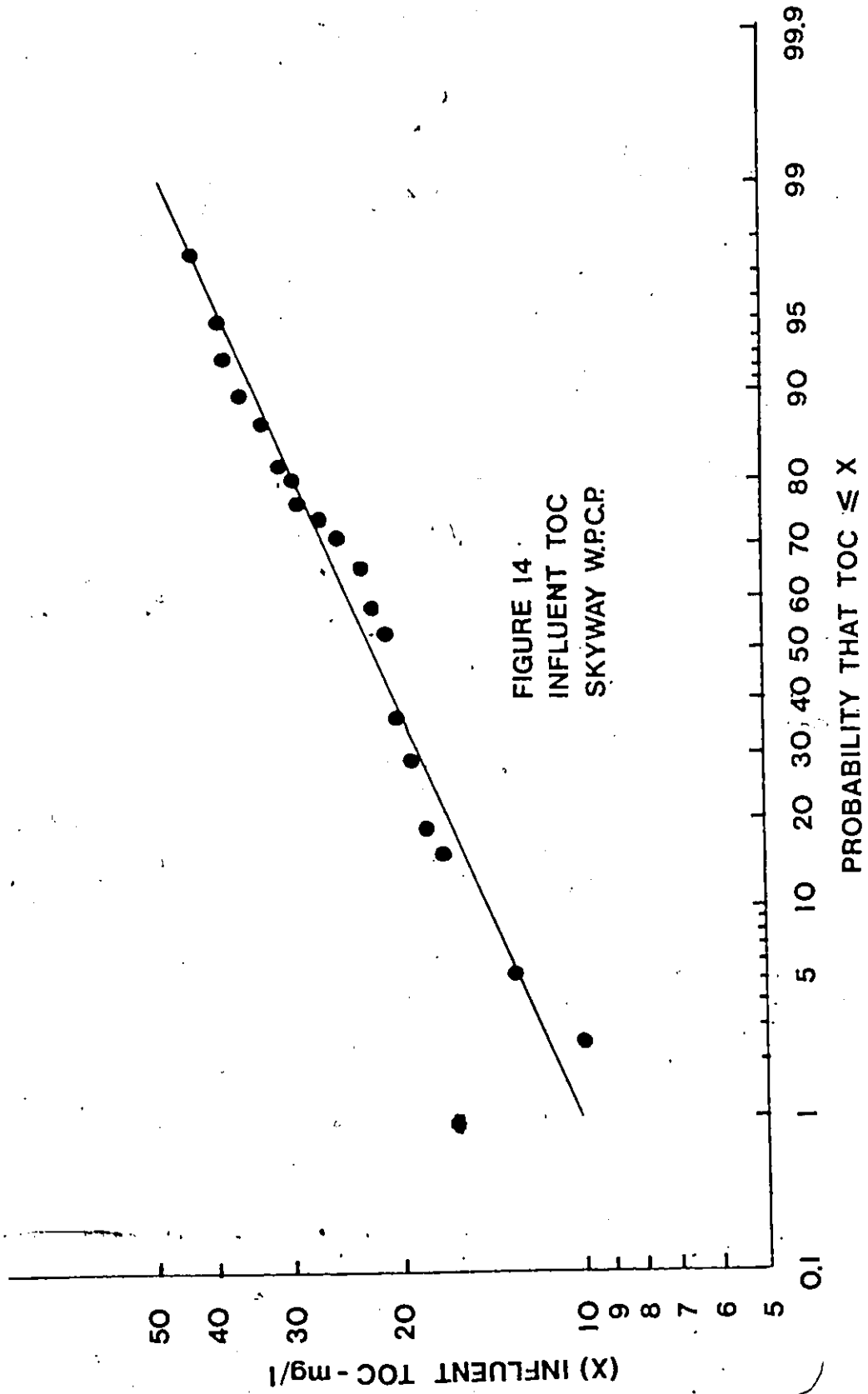


FIGURE 13
INFLUENT PH
SKYWAY W.P.C.P.



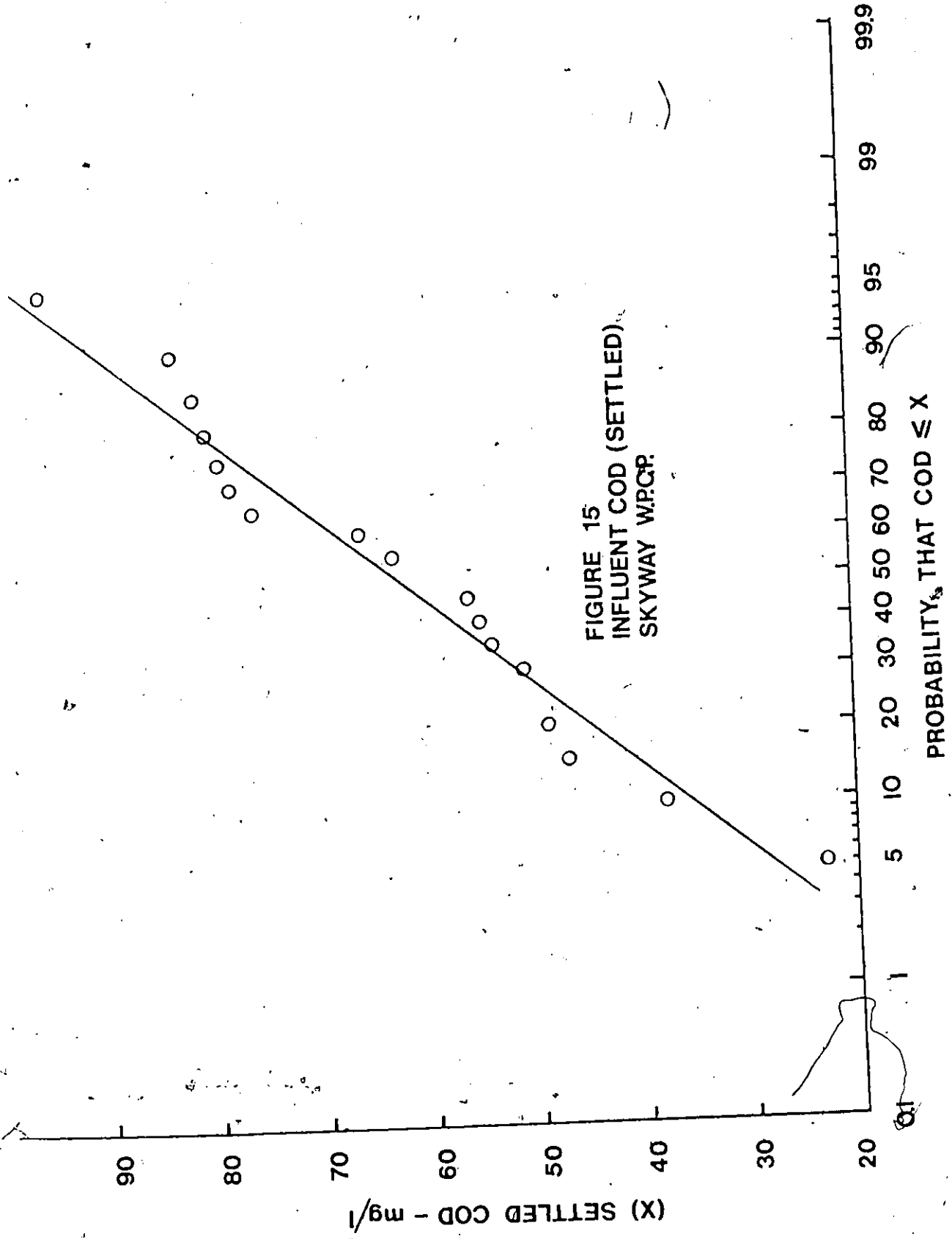


FIGURE 15
INFLUENT COD (SETTLED)
SKYWAY W.P.C.P.

PROBABILITY THAT COD ≤ X

3.3 AERATION UNITS - DESIGN AND METHODOLOGY

Continuous biological reactors styled after the "Bio-precipitation" unit of Okun (1948) were used. As shown in Figure 16, the reactor featured a preoxygenation of the influent in an absorption column. The feed was then contacted with biological solids in an agitated contact vessel. Solids separation prior to discharge was accomplished by an internal baffled clarification zone (see also photographs, Figure 17).

The Okun system was selected because it offered the following benefits:

- 1) it permits, in situ, settling tests and alleviates any effects due to sludge handling,
- 2) it enables the control of velocity gradient without interfering with oxygen transfer,
- 3) it eliminates the need for external clarification units and solids recirculation, and
- 4) it facilitates oxygen uptake measurements, in situ, or out of vessel.

In the original Okun reactor (illustrated previously in Figure 1) the influent and recirculated effluent flowed down through the absorber, counter-current to gas flow, and was pumped to the bottom of the reactor. The effluent passed up through the sludge blanket and was either recycled to the absorber or discharged. Stagnant areas were prevented by impellers spaced incrementally up the column.

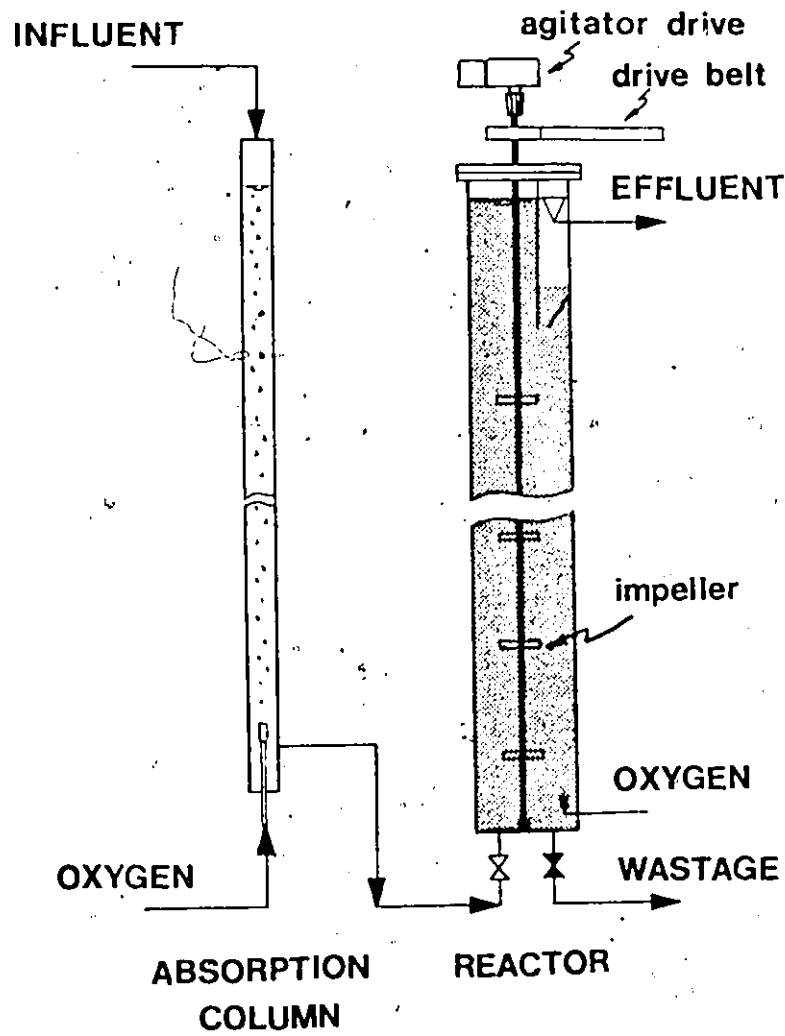


FIGURE 16
EXPERIMENTAL EQUIPMENT

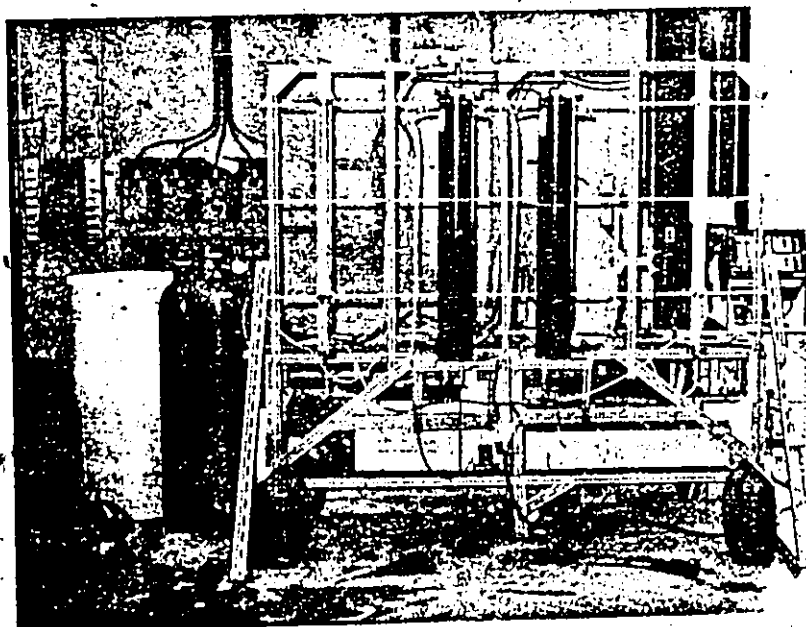
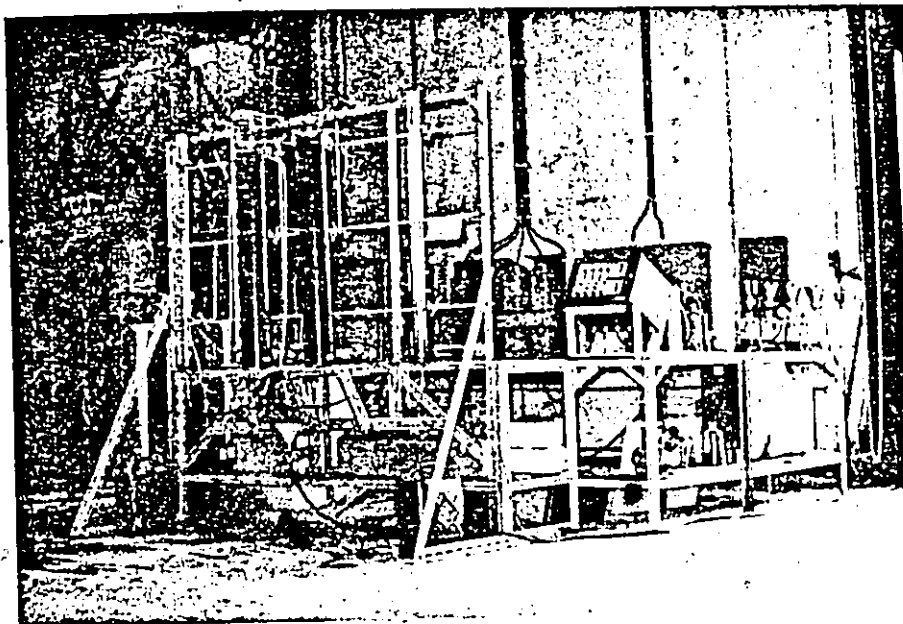


FIGURE 17
EXPERIMENTAL EQUIPMENT

Insufficient oxygen was provided in the absorption columns to satisfy the full oxygen demand and as a result Okun found it necessary to recycle approximately five times as much clarified effluent as influent wastewater. In the modified reactor, recirculation of effluent was not employed but rather supplemental oxygen was added to the reactor. With the very high oxygen deficit, between saturation and reactor dissolved oxygen levels, oxygen addition was minimal. Direct addition, also permitted a finer control of dissolved oxygen levels.

The experimental set-up featured two plexiglass units, operated in parallel and each four feet tall. The absorption columns were two inches in diameter and operated with a liquid volume of 2.42 litres. The agitated reactors were six inch diameter columns, with liquid volume of 21.5 litres.

The units were fed by a Cole-Parmer variable speed peristaltic pump which permitted detention times of twenty to forty minutes in the absorption columns and approximately three to six hours in the agitated reactors. Influent oxygen levels to the reactors were typically 25 to 30 mg/l.

Agitation was provided by a Canlab, model RZR1, heavy duty variable speed laboratory stirrer. Both units were driven from the common drive by a belt and pulley arrangement. Agitation speeds of 45 to 220 rpm were available from the high torque arm of the stirrer. Each agitator shaft

was guided on bearings at the top and bottom of the reactor and was equipped with five four-bladed impellers (and total blade area of ten square inches).

Operational control of both units was based on the maintenance of a fixed level of mixed liquor suspended solids. The effects of suspended solids levels on settling characteristics has been well documented (Kynch, 1952; Eckenfelder, 1966; and Dick, 1970) and hence this was a major constraint on this study. Conventional solids levels of $2000 \text{ mg/l} \pm 100 \text{ mg/l}$ were chosen in line with this constraint.

The capability for varying sludge age was then restricted to the control of the influent substrate concentration or the detention time. In the latter case, two levels of approximately three hours and six hours were utilized. In the former case, organic carbon levels in the sewage were supplemented with yeast extract. Lower concentration levels were determined by the soluble TOC of the sewage, and upper levels by bulking and washout of solids.

Yeast extract represented both a readily soluble and biodegradable growth medium. It is commonly employed as a substituent of synthetic wastes (Ball et al, (1972) and Bisogni and Lawrence (1971),) and is known to be a good source of organic carbon, nitrogen and biological growth factors.

Organic Carbon was chosen as a measure of substrate concentration. The short analysis time enabled rapid adjustment and control of organic carbon levels in the feed vessel. The major limitation of Total Organic Carbon monitoring was the failure to include the organic carbon content of influent suspended solids. The microlitre samples utilized must generally be free of solids prior to injection. Accurate yield coefficient determinations were of secondary interest to this study and hence no attempt was made to determine the substrate contributions of influent solids. Reduction of particulate size by sonification, however is a viable alternative for future studies (Emery et al (1971)). Hence the yield coefficients and food to mass ratios differ from actual values according to the mean relationship between soluble and settled TOC.

The undefined relationship between loading condition and net solids production did not enable the usage of sludge age as a primary operational variable. The sludge age was determined according to the effect of substrate concentration, detention time and mixed liquor solids concentration on the net growth rate. Hence, the primary variables were adjusted, and the resulting sludge age was determined based on the solids produced.

Oxygen tension was controlled manually by the variation of gas flowrate to the reactors, according to periodic concentration checks. Variations in oxygen uptake from day to day, prevented close control of dissolved oxygen concentration and normally ranges of operation varied from 1 to 2.

mg/l in the low level reactor and from 8 to 12 mg/l in the high level reactor. This served as a comparison between conventional oxygen tensions and the higher concentrations possible with oxygenation systems. This also ensured the concentration distributions would be sufficiently separated in the two levels of operation.

To eliminate any effects due strictly to differences in reactors, oxygen tension levels were alternated between the units.

3.3.1 Detention Time Determination

To ensure that the units approximated a completely mixed reactor, dilute-out curves were determined for two levels of mixing intensity. The two agitation speeds represented the maximum velocity available and the minimum velocity which would keep the solids completely suspended in the upper portion of the reactors.

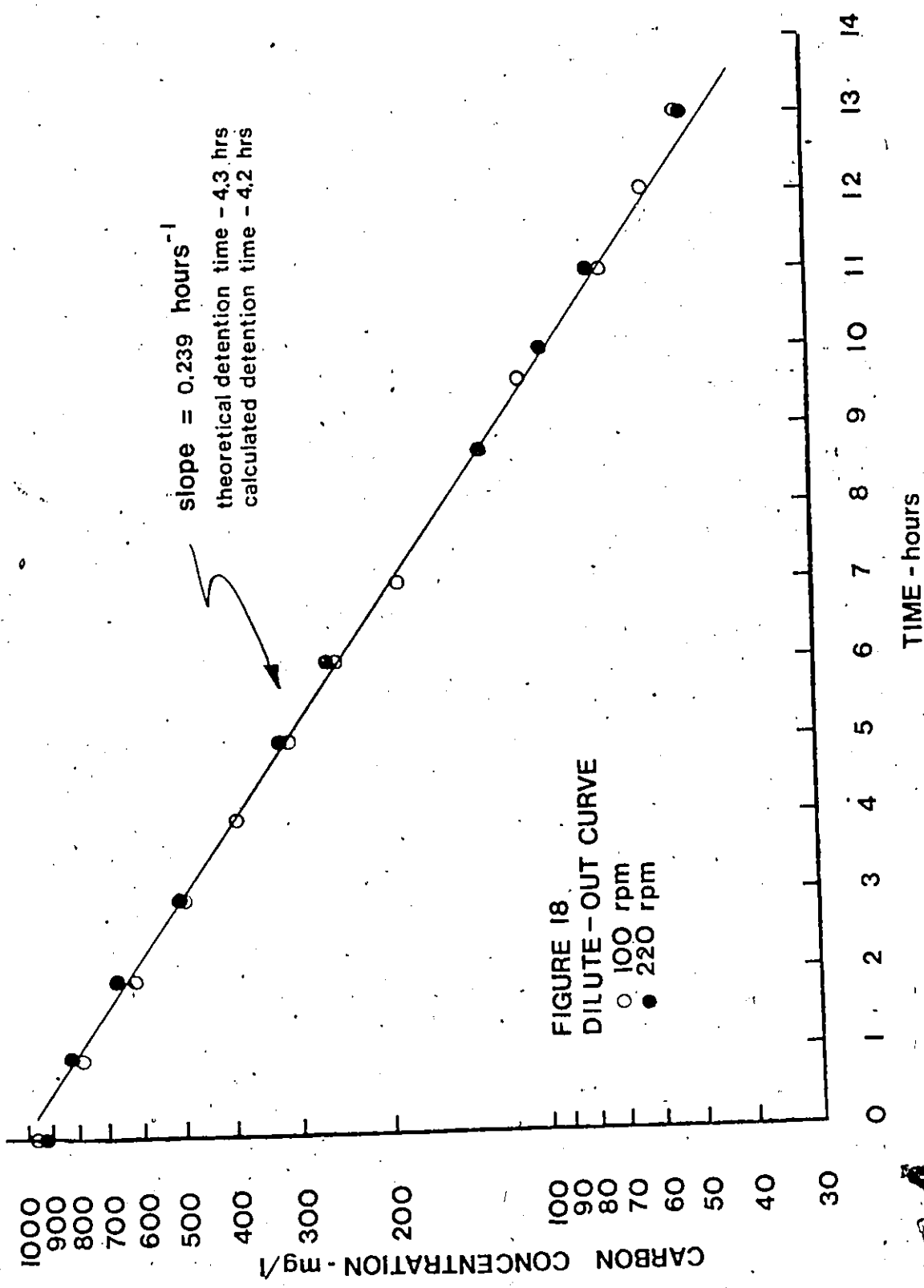
This procedure was accomplished by filling the reactor with tap water containing glutamic acid at approximately 1000 mg/l as Total Organic Carbon (TOC). This concentration was then diluted out with tap water at fixed flowrate and samples were taken at various time increments. Experimental results could then be compared with the integrated form of mass balance:

$$\frac{dm}{dt} = V \frac{dC}{dt} = QC$$

$$\text{or } \ln (C/C_0) = \frac{Qt}{V} = Dt$$

where D = dilute-out rate - hours⁻¹
 C = initial TOC - mg/l
 C = TOC at any time t - hours
 Q = flowrate of influent - litres/hour
 V = reactor volume - litres

The dilute-out curves for operation at 120 and 220 rpm are given in Figure 18. Experimental results were within a few percent of theoretical predictions of the slope and hence the reactors were assumed to be completely mixed.



3.4 PHASE CONTRAST MICROSCOPY

Activated sludge flocs, protozoa and metazoa were observed under phase contrast microscopy. A Leitz Laboulux stereo microscope was provided by the Wastewater Technology Centre for use in this study. The nose-piece featured four objectives of 3.5, 10, 40 and 100 power magnification. The eyepiece magnification was 6.3 power. The microscope was equipped with a Leica MDa 35 mm rangefinder camera and microflash attachment.

Kodak Panatomic X film, a fine grain panchromatic film (32 ASA) was employed.

4. LABORATORY ANALYSES

4.1 TOTAL ORGANIC CARBON

Organic carbon levels were determined using a Beckman Total Organic Carbon Analyzer. Inorganic carbon was removed by acidification and purging of the carbon dioxide produced, with nitrogen. The remaining organic carbon was then oxidized at 950°C, and measured by an infrared analyzer.

Samples were filtered through a 0.45 μ membrane filter paper prior to injection.

4.2 CHEMICAL OXYGEN DEMAND

The Chemical Oxygen Demand was determined by both manual and instrumental methods. The COD probability plot, Figure 15, was determined instrumentally by the Analytical Section of Wastewater Technology Centre from mid-day composite samples. The procedure was utilized for settled COD (two hour) and employed a Technicon Auto-Analyzer. The interface COD-time relationship, Figure 11, was determined using the manual reflux procedure as presented in Standard Methods (1971).

4.3 SOLIDS ANALYSES

Suspended solids analyses were run in general compliance with the procedure outlined in Standard Methods (1971). Samples were filtered through 0.45 μ

Gelman Membrane Filters using a Fisher Filtrator filtering apparatus. The residue and filter were then dried in an oven at 103°C for two hours.

Volatile solids were determined by combusting the residue and filter in a muffle furnace at 550°C, for 15 minutes.

4.4 SLUDGE SETTLING PROPERTIES

The reactors were designed to permit in situ measurement of settling properties. Tests were performed by turning off the feed pump, lowering the mixed liquor level below the settling zone, and finally, shutting down the agitator drive. Interface position was monitored as a function of time from an initial depth of 90 cm. SVI numbers were based on the thirty minute settled volume within the reactors and the initial MLSS concentration.

Periodic checks of the thirty minute supernatant clarity were determined by measurement of suspended solids levels.

4.5 DISSOLVED OXYGEN CONCENTRATION

Oxygen levels were monitored by a YSI Model 51 dissolved oxygen meter. The meter was calibrated periodically by the Azide Modification to the

standard Winkler Procedure (Standard Methods, 1971). Periodic checks of dissolved oxygen levels in the absorption columns were beyond the range of the YSI meter and were also determined by the above method.

4.6 OXYGEN UPTAKE RATE

The YSI meter was also employed to monitor oxygen uptake rates. Uptake rates were determined both within the reactors and in a BOD bottle containing a sample of mixed liquor. However, to ensure uniformity in results and avoid the possibility of inconsistent mixing effects, all reported results were measured by the latter procedure. In so doing, a probe with attached stirrer (YSI model 2420A BOD Probe) was inserted into the bottle, and oxygen depletion was monitored with time. This procedure gave almost identical results to the in situ method, and was generally more convenient. Transient loading and dissolved oxygen levels were minimized for both reactors and faster checks of reproducibility of results were possible.

Oxygen tension was increased in the low D.O. reactor to corresponding levels in the high D.O. reactor, a sample was taken and the rate of decrease in oxygen tension was monitored immediately.

4.7 NITROGEN ANALYSES

Instrumental techniques were also employed to monitor nitrate, nitrite,

Total Kjeldahl and ammonia nitrogen, using a Technicon Auto Analyzer. Analyses were performed by the Analytical Section of the Wastewater Technology Centre.

4.8 ACTIVITY MEASUREMENTS

In conjunction with this study, simultaneous biological activity studies were undertaken by Nutt (1974). Samples provided from both reactors under varying loading conditions, were analyzed for DNA, RNA, ATP, viable cell count, oxygen uptake rate, solids and dehydrogenase activity. In all cases reported the samples were taken after an operating period of at least one full sludge age. Measurement techniques are documented in the report of Nutt.

4.9 PHYSICAL PARAMETERS

As a comparison of physical characteristics between the sludges generated in both systems, an evaluation was made of floc size and appearance, floc density and Capillary Suction Time.

Flocs were observed under phase contrast microscopy after enclosure of a drop of mixed liquor between a slide and coverglass. Photographs were taken of the biomass. Floc sizes were determined by calibrating the internal scale, built into the microscope barrel, with a micrometer plate (for each objective). The maximum floc dimension was then measured

from the photograph.

Floc density was monitored utilizing a buoyancy procedure developed by Zaloum (1973). Sludge was pipetted with an open mouth disposable pipet into a series of standard density solutions, prepared in increments of 0.005 gm/cc. The glucose solutions were regularly checked with density bottles. The floc sample was inserted into the solutions below the meniscus and the density was established by the solution in which the flocs remained in suspension, a few seconds.

Capillary Suction Time was measured utilizing the patented instrument introduced by Baskerville and Gale (1968). The CST is proposed as a measure of the sludge filterability and the value of the CST has been related to the specific resistance of the sludge to filtration.

5. EXPERIMENTAL RESULTS AND DISCUSSION

5.1 EQUIPMENT DESIGN AND DEVELOPMENT

The prime objective in equipment selection was the development of a continuous biological reactor which would facilitate in situ settling tests. This would alleviate any possible effects of physical handling or transportation on the sludge settling characteristics.

Domestic sewage was chosen as a feed source primarily because of the considerable quantity of previous work with synthetic wastes (Bisogni and Lawrence, 1971 ; Ball et al, 1972 ; and Rickard and Gaudy, 1968). It was also believed that the constant bacterial seed available with domestic sewage would reduce the possibility of bacterial changes through occasional upset conditions. This factor may prevent the re-development of some strains in a synthetic feed-system and thus affect results.

The selection of sewage as a feed source indirectly dictated the capacity of the reactors. Consideration had to be given to solids accumulation and plugging in the process tubing. Tubing diameters of 3/16 to 1/4 inch determined the peristaltic pumping capacity and hence the reactor volume required to satisfy conventional activated sludge detention times. Selection of a four foot settling column then specified all reactor dimensions.

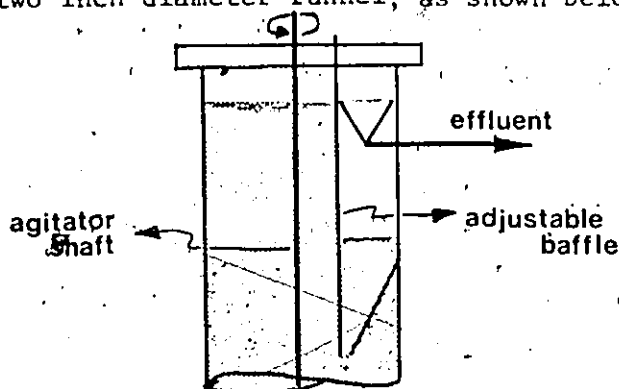
Mixing requirements were provided by a Canlab laboratory stirrer. The transverse shaft provided a speed range from 45 to 220 rpm. As shown in Appendix B, this theoretically covered the normal range of velocity gradients observed in activated sludge operations (Parker, 1970). Later measurements of the power transferred to the mixed liquor, indicated that the theoretical velocity gradient determination provided a reasonable estimate of actual conditions.

Checks were also made on both mixed liquor suspended solids concentrations and dissolved oxygen concentrations as a function of depth. No variation with depth was observed at agitation rates above 100 rpm.

It was important that the units provided good solids separation over the range of experimental conditions to be studied. Efficient separation was critical to the maintenance of mixed liquor suspended solids levels and to the determination of the solids produced.

Design of a baffled, quiescent zone within the reactor proved to be the greatest operational problem to be overcome. It was necessary to damp the upward axial velocity imparted by the impellers at high mixing intensities and yet prevent sludge bridging at lower mixing velocities. The final arrangement included baffling of a segment of the cylindrical vessel. As shown below, the base of the settling zone was affixed to the vessel walls and sloped downwards towards the bottom of

the baffle at an angle of 60° from the horizontal. Bridging was prevented by allowing the baffle to be raised or lowered and the cutting of a rectangular notch in the bottom-centre of the baffle where axial velocities were a minimum. The clarified effluent overflowed from the reactors into a two inch diameter funnel, as shown below.



One of the major disadvantages of the Okun reactor was the necessity of maintaining high internal recirculation of clarified effluent to the absorption column in order to transfer sufficient oxygen for the oxidation process. The only means of oxygen tension control was by way of varying the recirculation rate and hence the upflow rate within the reactor. For parallel systems operating at different oxygen tensions, internal upflow rates within the reactors would differ and consequently affect the solid separation functions. This also represented a rather coarse control procedure for oxygen tension with a comparatively slow response time. Inefficient separation in the clarification zone could also present a further problem with the absorption column becoming a biological reactor.

Direct addition of oxygen to the reactors as a supplement to the 25-30

mg/l D.O. in the influent was found to be a more attractive alternative. With lower oxygen tensions in the agitated vessel, the driving force for mass transfer was considerably higher with a deficit of approximately 35 mg/l as compared to somewhat less than 15 mg/l in the absorption columns. The supplemental gas flow rates were, therefore lower than the rates employed in the absorption column.

Oxygen requirements generally were less than 40 mg O_2 /hr/gm VSS. This however, represented a demand of 1120 mg O_2 /hr. To maintain the high D.O. reactor at 10 mg/l would have necessitated a feed rate of approximately 56 l/hr. Detention time limitations, restricted influent flowrates to 7.0 l/hr maximum. Hence using the "Bio-precipitation" unit of Okun (1948), an internal recirculation of approximately eight times the feed flowrate would be necessary. Operation at 2 mg/l dissolved oxygen would correspondingly require an internal recirculation rate of five times the feed rate.

The oxygen supplied by the absorption columns generally represented less than one half of the total oxygen transferred and, in the case of the high D.O. reactor, as little as one eighth to one tenth of the total. As a result any extension of this work, would best be served by elimination of the absorption columns as a separate unit and their incorporation into the reactor as an affixed air-lift tube. In this configuration, the mixed liquor would pass into the bottom of the tube, and be lifted

by the rising oxygen bubbles (diffusing into the tube as at present) and overflow back into the reactor. This modification would generally satisfy the experimental requirements with the exception of velocity gradient control.

As previously mentioned supplemental oxygen was supplied directly to the reactors and thus rising bubbles contribute to the mean velocity gradient. The experimental conditions within the reactors would not be identical as the different dissolved oxygen levels dictated that different gas rates be applied. Approximately five times as much oxygen had to be transferred in the high D.O. system under lower driving forces (i.e. lower oxygen deficit). Fortunately the mean contribution of the oxygen bubbles to the overall velocity gradient is low. Differences in mean velocity gradient attributable to differing gas flow rates were generally less than 50 seconds^{-1} at a level of $115 \text{ to } 150 \text{ seconds}^{-1}$.

One further limitation was the biological degradation occurring in the absorption columns. The natural bacterial seed inherent to sewage, under aerobic conditions resulted in an active biological culture. It was necessary, as a form of control to waste the contents each morning to prevent excessive growth. Operation over a twenty-four hour period generally resulted in wastage concentrations in excess of 500 mg/l . This naturally produced a variable loading condition on the stirred reactors. Removals in soluble TOC of up to 20% of the feed vessel concentration

were observed. It was necessary to include this wastage figure in the total solids production estimate and sludge age determinations. This, of course, resulted in a small inconsistency in conventional food to mass ratio or sludge age concepts:

Oxygen uptakes and sludge activity measurements were taken after wastage of the absorption column contents, when food to mass ratio's were more truly representative of the stirred reactor loading. The two units were scheduled to operate in parallel each at a different oxygen tension. The experimental design was based initially on operation at two levels of influent TOC and two levels of detention time. With centrepoints this would have provided four to five differing food to mass ratios or sludge ages. Unfortunately planned upper levels of influent TOC (in excess of 75 mg/l) caused rapid bulking of the sludge. Lower levels of influent TOC were determined by the theoretical sludge age and hence the necessary run duration. To utilize the sludge age concept it was necessary to operate for a minimum of one sludge age before acquiring settling or activity data. This constraint proved to be a major factor, in the determination of the number of conditions that could be studied in the time available. Influent concentrations levels of 50 mg/l and 150 mg/l were initially selected in the hope of providing an estimated sludge age range of 2 to 10 days. Initial estimates indicated a sludge age in excess of 12 days when the influent TOC's were 25 mg/l, at both levels of detention time. Unfortunately sludge bulking prevented operation below

3 days, and 75 mg/l was the maximum concentration level obtainable in continuous operation without serious loss of solids. The detention times of 3 hours and 6 hours were selected, both being consistent with the conventional range of activated sludge operation.

The experimental runs were randomized and two repeats were selected. Operation at a centre point was eliminated because of difficulty in maintaining distinct levels of influent TOC at 62.5 mg/l from 50 or 75 mg/l. This is attributed to degradation in the batch feed vessel over a twenty-four hour period (up to 10%) and biodegradation in the absorption columns (up to 20%).

A trend toward improved settling characteristics at the higher sludge ages prompted a final run at a lower food to mass ratio, as a more practical alternate.

5.2 EXPERIMENTAL RESULTS

5.2.1 Sludge Production

One of the primary objectives of the study was to determine whether there was any fundamental difference in solids production or substrate removal between systems operating under conventional dissolved oxygen levels and the levels common to oxygenation systems.

Solids production data are summarized in Figure 19. As previously stated, only the soluble substrate loading was monitored and hence the actual value of the yield coefficients are not meaningful. However, the comparative solids production data are meaningful through parallel operation of both systems from a common feed source. The abnormal positive intercept is attributed to the contribution of non-settleable solids to the total substrate loading value. The addition of this contribution would tend to shift the ordinate axis to the right and most probably result in a negative intercept, normally representative of the bacterial auto-oxidation rate. No discernable difference in the net solids production is evident in Figure 19, for operation at the differing oxygen tensions.

No attempt was made to fit by Linear Least Squares each set of data independently, because of the high relative errors in both the dependent and independent variable. One can test whether the differences in the net solids produced are significantly different from zero. In so doing,

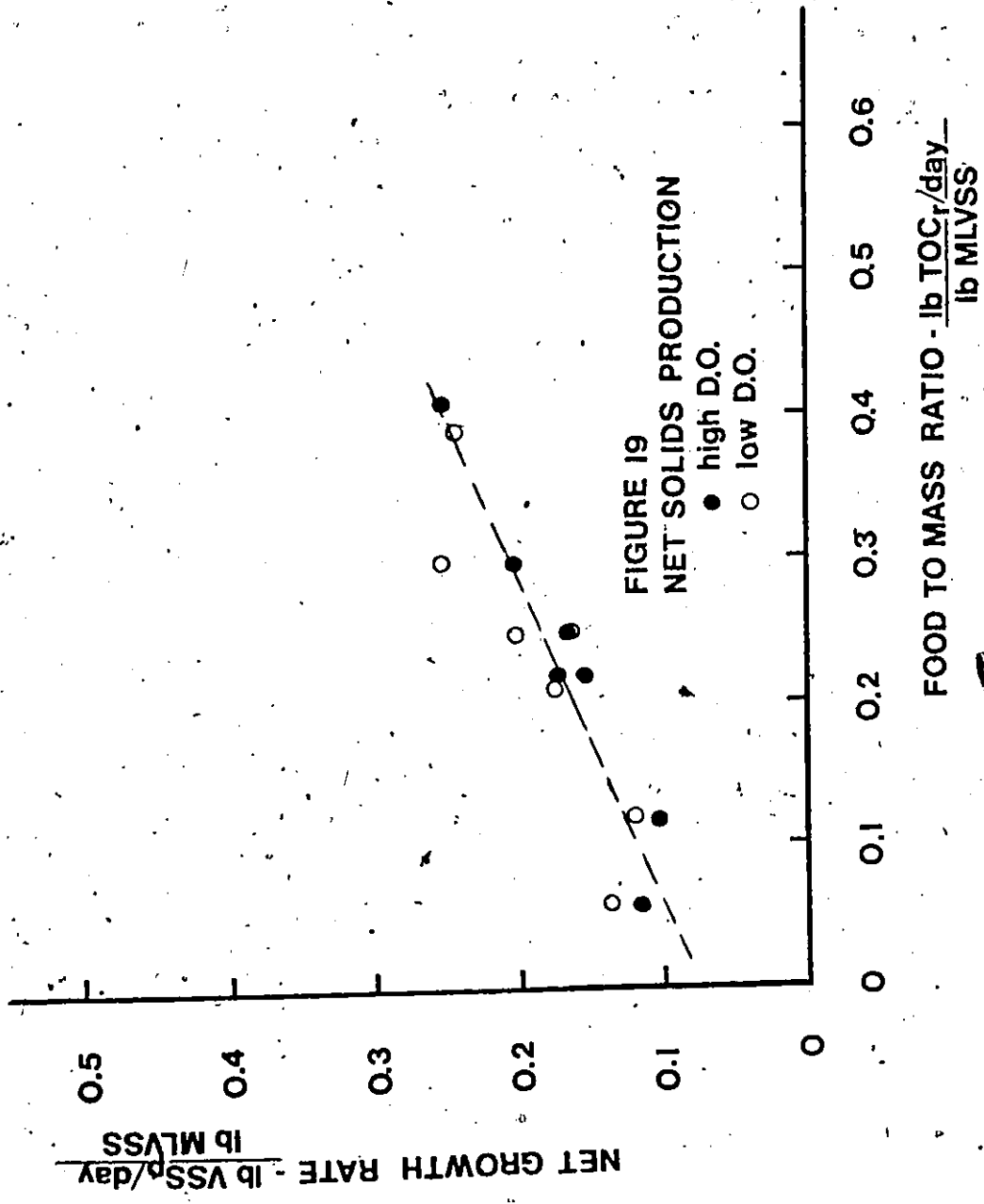


FIGURE 19
NET SOLIDS PRODUCTION

● high D.O.
○ low D.O.

it is assumed that for each run operating conditions were identical in each reactor. Based on the comparative food to mass ratios applied to each reactor, as listed in Table 5, this assumption appears reasonable, although minor differences in substrate removal, velocity gradient and volatile solids concentrations did occur.

At the 95 percent level of confidence, the hypothesis that the difference in net solids production was zero at the two levels of oxygen tension was rejected. (i.e. versus the null hypothesis that the difference is greater than zero). In all but one run, the net solids produced at high oxygen tension levels was less than at conventional oxygen levels. At the same time the maximum difference for any run was a 20 percent reduction at high oxygen tensions. Reproduceability between runs at similar loadings, was in the same order of magnitude and hence it is not surprising that other sources (Rickard and Gaudy, 1968; Ball and Humenick, 1972) have found no major differences in solids production.

The nature of these differences, should they be real, may be the result of differences in the yield or auto-oxidation rates. The reason why one or both factors should be affected is unknown.

Minor and yet consistent differences in both substrate removal and effluent clarity were also observed. Effluent suspended solids levels were found to be consistently lower under operation at the higher level of oxygen tension. Alternating high oxygen levels in the reactors

TABLE 5

COMPARATIVE SOLIDS PRODUCTION

Run	Oxygen Tension	Food to Mass Ratio	Net Solids Production	difference d
#1	1-2	0.25	0.162	+0.007
	8-12	0.22	0.155	
#2	1-2	0.12	0.121	+0.017
	8-12	0.12	0.104	
#3	1-2	0.21	0.175	+0.002
	8-12	0.22	0.173	
#4	1-2	0.39	0.241	- 0.013
	8-12	0.41	0.254	
#5	1-2	0.25	0.203	+0.039
	8-12	0.25	0.164	
#6	1-2	0.06	0.136	+0.018
	8-12	0.06	0.118	
#7	1-2	0.30	0.254	+0.051
	8-12	0.30	0.203	

$$\bar{d} = 0.0173$$

$$s = 4.947 \times 10^{-4}$$

$$H \quad d_1 - d_2 = 0$$

$$\text{vs } H_0 \quad d_1 - d_2 > 0$$

$$\text{test } t = \frac{\bar{d} - 0}{s/\sqrt{n}} \quad \text{cf } t_{.95}(\gamma=6)$$

eliminated the effects of any differences in the clarification function.

A summary of the effluent quality observed are presented in Table 6.

Based on a total of approximately 45 sampling days, the difference in effluent suspended solids (and Total Organic Carbon) at the two levels of oxygen tension is significantly different from zero at the 95% confidence level. Occurrences of better effluent quality at conventional dissolved oxygen levels was infrequent. (see Table A-4, Appendix A).

Effluent suspended solids were generally 20 to 120% higher when operating at conventional dissolved oxygen levels. The direct consequence of this occurrence, was that a large fraction of the daily wastage passed over the effluent weir. In most cases, the amount of solids that had to be manually wasted was greater in the high D.O. reactor.

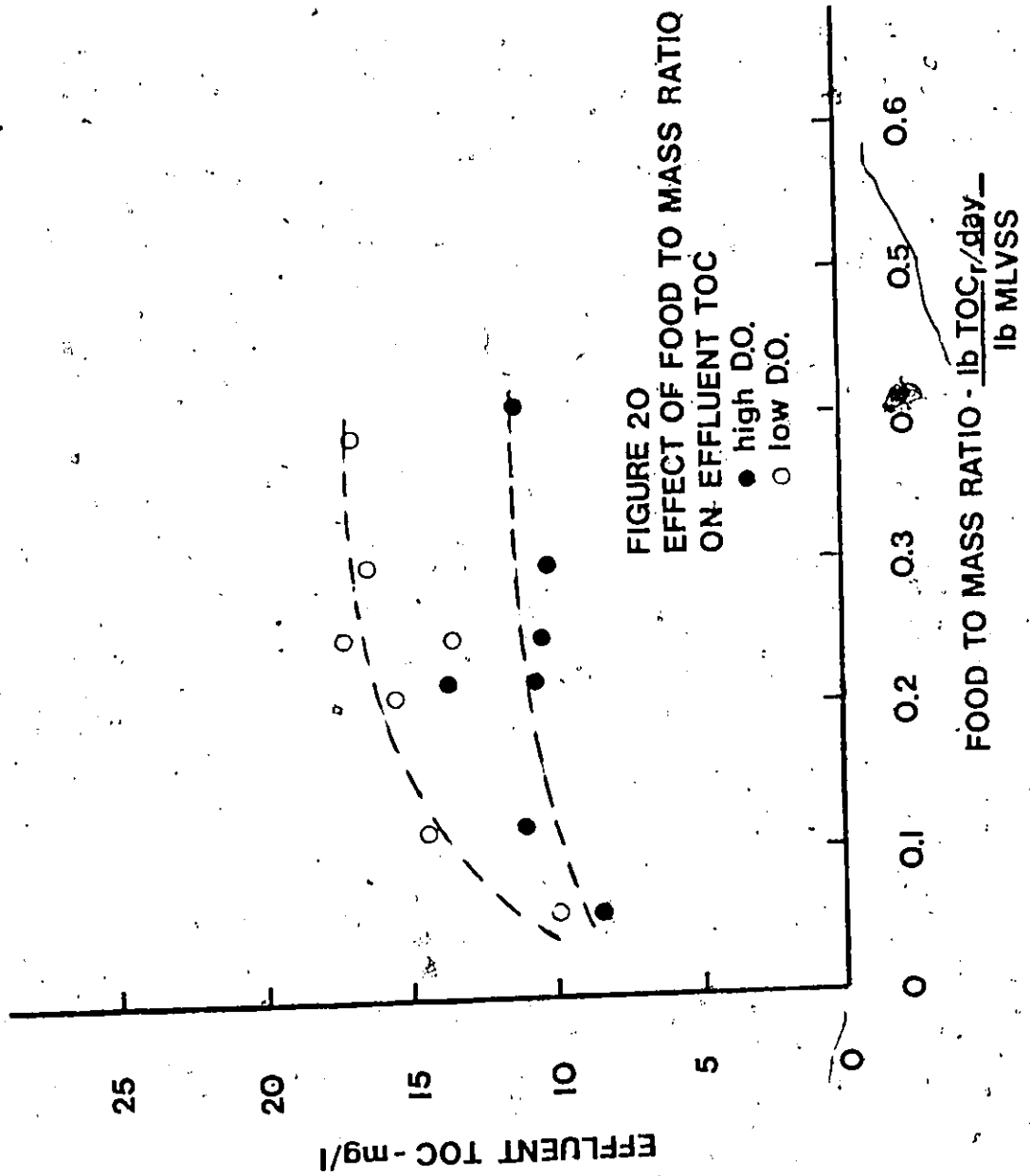
The effluent substrate concentration did not bear a direct proportionality to the food to mass ratio as Eckenfelder (1966) has suggested. However, as shown in Figure 20, a slight downward trend in effluent carbon was observed as the food to mass ratio was decreased. This trend was also observed with effluent suspended solids, Figure 21.

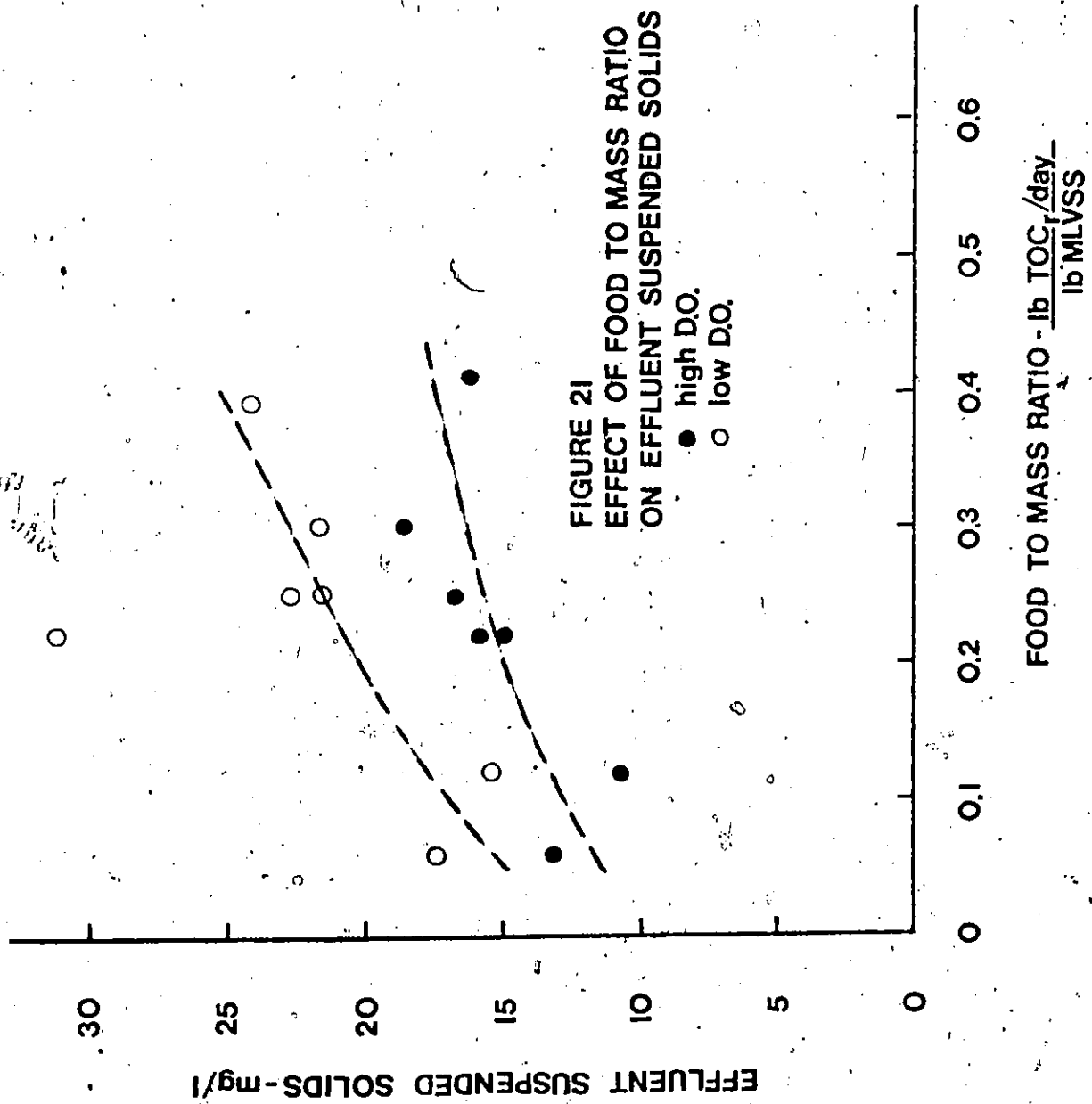
Improvement in effluent substrate concentration with decreasing food to mass ratio (or decreasing growth rate) is consistent with most sources. (Lawrence and McCarty, 1970; Eckenfelder, 1966; and Jenkins and Garrison, 1968) including the Michaelis Menton model (Aiba et al, 1965).

TABLE 6

COMPARATIVE EFFLUENT QUALITY

Run	Suspended Solids mg/l		Total Organic Carbon mg/l		TOC Removal %	
	Low D.O.	High D.O.	Low D.O.	High D.O.	Low D.O.	High D.O.
#1	21.5	15.8	17.1	13.7	66.9	72.7
#2	15.3	10.7	14.4	11.0	71.0	77.8
#3	22.2	14.8	15.4	10.7	80.0	86.1
#4	24.0	16.2	17.0	11.2	77.5	85.0
#5	22.7	16.7	13.4	10.4	73.2	79.2
#6	17.4	13.2	9.9	8.4	66.3	70.5
#7	21.6	18.6	16.3	10.2	77.9	86.2





At the same time, the improvement in effluent clarity as the food to mass ratio is reduced (or sludge age is increased) supports the findings of Bisogni and Lawrence (1971) and Sherrard and Schroeder (1972).

5.2.2 Sludge Activity

Concurrent with the oxygen tension studies were investigations by Nutt (1974) into the biological activity of both pure cultures and activated sludges. Samples were supplied from the biological reactors throughout this study and monitored for DNA, ATP, plate counts, dehydrogenase activity, and oxygen uptake. The data represent grab samples taken after operation for at least one sludge age. Two sampling days were selected during each run.

Table 7 is a summary of the results obtained. An attempt was made to determine whether the difference in any parameter at the two levels of oxygen tension was significantly different from zero. It was necessary to reject the hypothesis (that the difference in value at the two levels of dissolved oxygen concentration was zero) for both ATP and plate count. Surprisingly a higher plate count was observed at conventional oxygen tensions on all but one sampling. This could not be related to any minor differences in mixed liquor volatile solids levels. This observation warrants further study and could be indicative of the selectivity of the plate count medium. There seems to be little, if any justification for the biological activity under high oxygen tensions to be less than at

TABLE 7

BIOLOGICAL ACTIVITY RESULTS

Run	Oxygen Tension mg/l	DNA ug/ml	ATP ug/ml	Dehydrogenase Activity u mole TF prod.	Plate Count no. x 10 ⁻⁸ ml	Oxygen Uptake mg O ₂ /hr g VSS
1	1-2	35.4	0.65	0.0173	1.06	-
		40.0	0.61	0.0203	0.67	-
2	8-12	59.1	1.02	0.0309	0.69	73.8
		63.0	1.05	0.0334	0.77	
3	1-2	56.8	0.50	0.0482	1.83	54.5
		56.2	0.81	0.0148	1.49	23.4
4	8-12	31.5	0.71	0.0129	0.58	31.5
		32.8	0.54	0.0207	0.31	38.4
5	1-2	26.6	0.56	0.0344	1.45	25.5
		47.1	0.52	0.0445	2.88	39.0
6	8-12	19.7	0.96	0.0116	0.24	17.9
		44.0	1.42	0.0326	0.68	44.5
7	1-2	44.1	0.62	0.0370	2.92	26.4
8	8-12	30.5	1.77	0.0174	1.66	25.8
		51.6	3.28	0.0324	0.59	42.0
9	1-2	34.5	0.39	0.0306	1.40	39.6
		50.0	0.92	0.0071	0.51	69.0
10	8-12	55.4	1.33	0.0290	0.70	42.9
		54.8	1.00	0.0090	0.42	63.9

conventional levels. The ATP concentrations monitored exhibited the opposite result, with higher concentrations observed in the culture acclimated to the higher oxygen tension on all but one occasion. ATP levels suggest a greater viable cell fraction for the biomass generated at the higher oxygen tension. ATP is a cell constituent, thought to be nonconservative and present in approximately constant amounts in viable microbial cells of different species and growth rates (Weddle and Jenkins, 1971). This parameter may provide some explanation for the greater effluent quality observed at the higher oxygen tension and is worthy of further investigation.

To evaluate whether a dependency between any of the activity parameters and growth rate or settling characteristics existed, the correlation coefficients were determined. Since both variables were essentially observational data, and not directly controlled the coefficient of correlation was selected as the best means of determining whether an association in occurrence existed.

Tables 8 and 9 are summaries of the correlation coefficients between the above mentioned parameters. To evaluate the significance of the correlation, it was necessary to determine the probability that the correlation could occur by a random sampling of two uncorrelated populations. Values of the correlation coefficient which are just significant at a given level of probability are presented in Table 10.

TABLE 8

CORRELATION COEFFICIENTS
BETWEEN ACTIVITY PARAMETERS
AND NET GROWTH RATE

	<u>Oxygen Tension</u>	
	1-2 mg/l	8-12 mg/l
DNA n	-0.404 9	+0.052 10
ATP n	-0.033 9	+0.852 10
Dehydrogenase n	-0.016 9	+0.291 10
Plate Count n	+0.307 9	+0.581 10
Oxygen Uptake n	+0.005 7	-0.148 9

nb: n = number of paired observations

TABLE 9

CORRELATION COEFFICIENTS
BETWEEN ACTIVITY PARAMETERS
AND ZONE SETTLING VELOCITY

	<u>Oxygen Tension</u>	
	1-2 mg/l	8-12 mg/l
DNA n	-0.599 9	-0.575 10
ATP n	-0.556 9	-0.741 10
Dehydrogenase n	-0.193 9	-0.468 10
Plate Count n	-0.383 9	+0.073 10
Oxygen Uptake n	-0.170 7	-0.308 9

nb: n = number of paired observations

TABLE 10

SIGNIFICANT LEVELS OF THE CORRELATION

COEFFICIENT, r_{xy}

n	J_2	P=95%		P=97.5%		P=99%	
		Z	r_{xy}	Z	r_{xy}	Z	r_{xy}
7	0.5000	0.8225	0.6764	0.9800	0.7530	1.163	0.8220
8	0.4472	0.7353	0.6263	0.8761	0.7044	1.040	0.7778
9	0.4082	0.6712	0.5857	0.7997	0.6638	0.949	0.7393
10	0.3780	0.6218	0.5523	0.7409	0.6296	0.879	0.7059

The correlation coefficient is not normally distributed and hence the numbers presented in the table were developed through a normalizing transformation, as discussed by Fisher (1970). It is evident that for a sample size of 10 paired observations, there is a 95% confidence that the parameters are not independent if the correlation coefficient is greater than 0.552.

The determination of correlation coefficients between growth rate and the various activity parameters resulted in a limited number of significant correlations. At the 95% confidence level there was no indication of a dependency between growth rate and D.N.A., dehydrogenase activity or oxygen uptake, at both levels of oxygen tension. There was, however, a significant positive correlation, at the 95% level between growth rate and both ATP and plate count, at the higher level of oxygen tension. For ten pairs of observations, the correlation coefficient between ATP and growth rate was 0.852, which is also significant at the 99% confidence level. Weddle and Jenkins (1971), also noted a positive increase in ATP concentration with an increase in growth rate. The authors related the result to an increase in the viable fraction of the volatile solids present. As indicated above, a positive correlation between plate count and growth rate was significant at the 95% confidence level. The apparent zero correlation between ATP and growth rate at the lower dissolved oxygen level may well be the result of the low correlation between plate count and growth rate.

At the 95% confidence level, significant negative correlations were found between zone settling velocity and both DNA and ATP. With the later, however, the correlation was significant only at the higher D.O. The fact that both DNA and ATP are cell constituents, may be indicative of the effects of changing cell composition on the settling characteristics of the biomass. No substantiation for a possible dependency between zone settling velocity and dehydrogenase activity, plate count or oxygen uptake was found.

Further investigations appear to be warranted into the effects of growth rate on ATP concentration with respect to the viable cell concentration at both levels of oxygen tension, and secondly, into the possible relationship of cell composition and settling characteristics, as influenced by variation in growth rate.

Oxygen uptake rates were observed to fluctuate considerably from day to day, within the range of approximately 18 to 75 mgO₂/hr/gm VSS. The results were found to vary only slightly greater than reported ranges of approximately 15-35 mgO₂/hr/gr VSS by Downing (1968), Weddle and Jenkins (1971) etc. The apparent zero correlation with growth rate, is not in agreement with the data of Weddle and Jenkins who found a positive increase in uptake with growth rate. They did, however, relate the increase to an increase in the viable cell count.

5.2.3 Sludge Settleability

The settling characteristics of the sludges within each reactor were monitored by determination of the zone settling velocity and sludge volume index. The above measurements were collected following operation for at least one sludge age and generally were measured daily over the following two to three day period.

The mean settling characteristics are summarized in Table 11, and presented graphically in Figure 22 as a function of sludge age. No major trend was observed in terms of improved settling properties resulting from operation at high dissolved oxygen levels. A statistical comparison of mean settling velocities, resulted in acceptance of the hypothesis that the difference in zone settling velocities was zero at the two levels of operation (versus the null hypothesis that the difference was greater than zero) at the 95% confidence level.

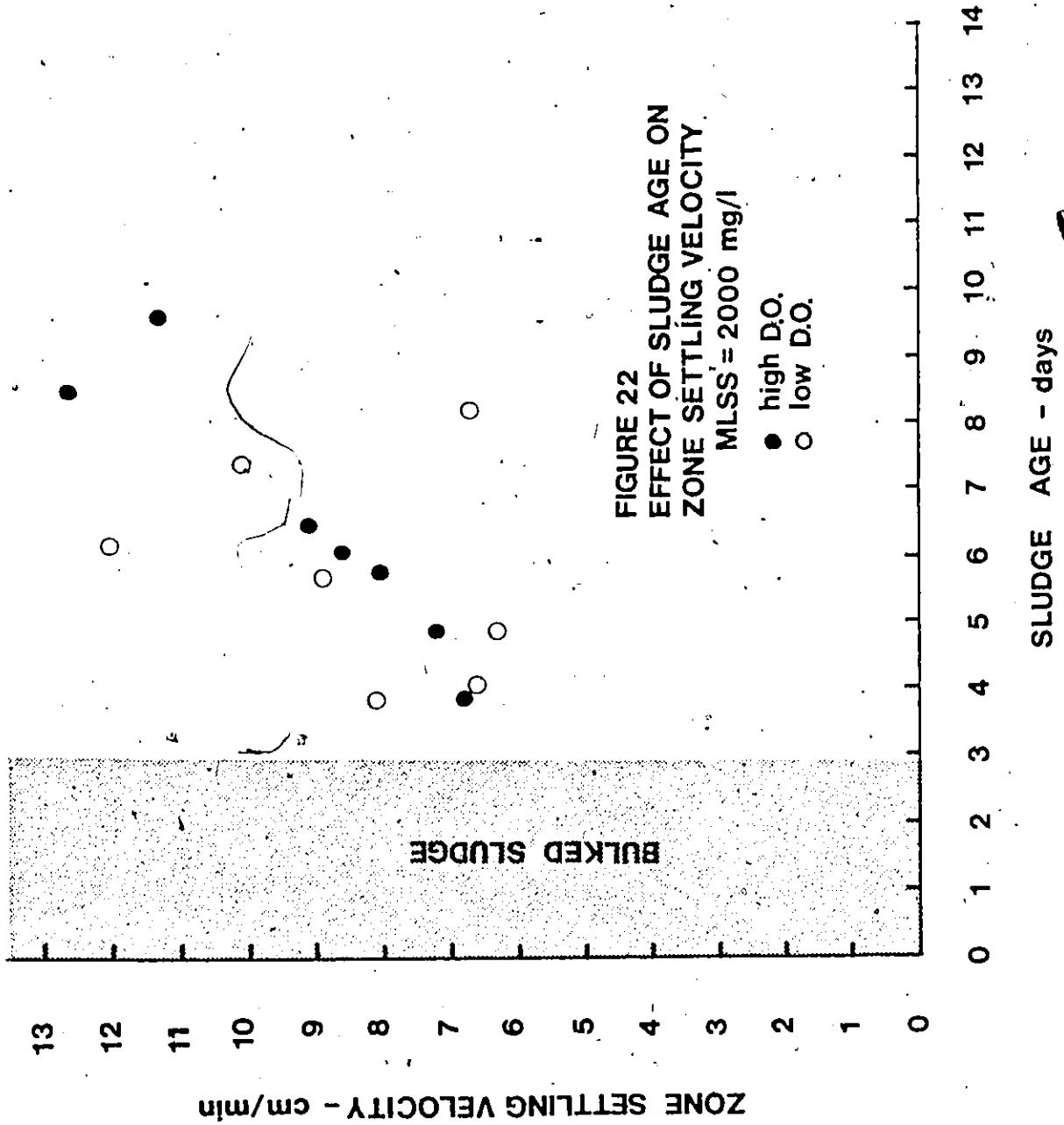
The sludge settling characteristics at the lower oxygen tension exhibited considerably more scatter in terms of any consistent relationship with sludge age. This suggests that operation is probably less stable and shows greater variation at lower oxygen tensions, and the system is more subject to upset. Hence, this may negate the statistical analysis.

It is evident, particularly with the sludge generated at high oxygen tensions that zone settling velocity improved as sludge age increased.

TABLE 11

COMPARATIVE SETTLING CHARACTERISTICS

Run	Oxygen Tension mg/l	Zone Settling Velocity cm/min	Sludge Volume Index
1	1-2	12.0	43
	8-12	9.1	97
2	1-2	6.7	118
	8-12	11.3	70
3	1-2	8.9	86
	8-12	8.0	90
4	1-2	6.6	72
	8-12	6.8	99
5	1-2	6.3	114
	8-12	8.6	99
6	1-2	10.1	64
	8-12	12.6	50
7	1-2	8.1	92
	8-12	7.2	103



This is consistent with findings of Bisogni and Lawrence (1971) and Sherrard and Schroeder (1972). The data plotted in Figure 22, also illustrates that the results are not not necessarily inconsistent with the results of Ford (1967). Ford observed a subsequent reduction in zone settling velocity and increase in SVI, as sludge age was further increased (i.e. as organic loading was decreased). This occurrence was attributed to the formation of a dispersed floc.

At lower sludge ages representing high growth rates, a deterioration in settling characteristics was observed in both systems. This occurrence has been noted by several sources and has been attributed to the propagation of filamentous organisms or the growth of a diffuse bacterial floc. The influence of both factors were evident in operation of the reactors and will be discussed further in the following section.

At sludge ages of less than approximately three days, solids were lost from the system and most of the reactor contents were often lost overnight.

Consistant with the low bacterial generation times, the biological solids did not behave as a conservative material. As opposed to 2 or 3 retention times required for a conservative material in a fully mixed system, a stabilization in settling characteristics was observed within one sludge

age. The physical response in growth rate to a change in operating conditions was evident almost immediately. Although sludge age is a convenient means of establishing a growth rate in systems where feed rate and substrate concentration are fixed, under the operating conditions of this study, extended runs were judged unnecessary (see Bisogni and Lawrence, 1971).

As a non-conservative material, the ability of the micro-organisms to adapt to changing conditions (within certain limitations) should be expected to occur more rapidly than might be implied by the inverse of the growth rate. The establishment of maximum growth rates for acclimated bacteria in the presence of readily biodegradable substrates is commonly measured in batch experiments in terms of hours rather than days. Settling characteristics were monitored over a period of approximately two sludge ages in run number five and results are presented in Figure 23. Little change in zone settling velocity was noted from the fourth to the tenth day.

The effects of velocity gradient on zone settling velocity have been observed by Ball et al (1972) and Bradley and Krone (1971). Time restrictions prevented operation of the units at a second level of agitation. However, an attempt was made to determine whether short terms increases in mixing intensity had any affect on settling velocity.

Settling characteristics were observed at normal agitation rates of approximately 120 rpm throughout this study. In addition, settling

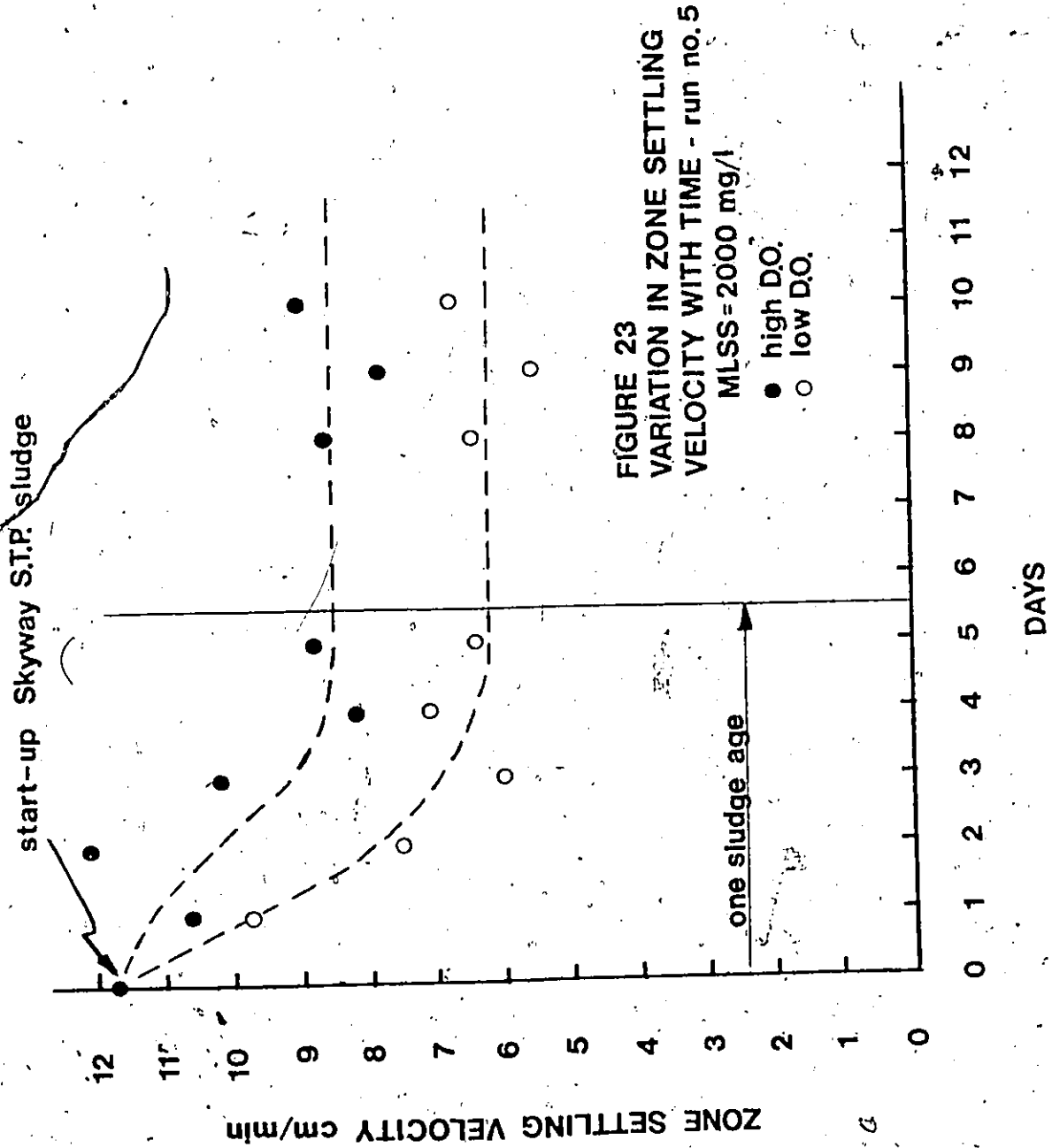


FIGURE 23
VARIATION IN ZONE SETTLING
VELOCITY WITH TIME - run no.5
MLSS = 2000 mg/l

curves were obtained following a two hour period of agitation at 220 rpm. Including the contribution of the oxygen bubbles within the reactors, this effectively doubled the mean velocity gradient.

As shown in Table 12, there were no major changes in either zone settling velocity or sludge volume index. All differences are accountable by measurement error. This suggests that any effect of velocity gradient should it occur is not attributable to short term shearing of flocs under the mixing conditions studied.

5.2.4 Sludge Bulking

Under almost all operating conditions studied, filamentous organisms were observed. The presence of these organisms were noticeable at the higher growth rates occurring when food to mass ratios were a maximum. Bulking became progressively more severe as the sludge age approached three days or the food to mass ratio approached 0.5 mg TOC/day/mg VSS. Solids levels could not be maintained in either reactor beyond the above limits. The sludge produced at approximately 0.5 mg TOC/day/mg VSS was light, fluffy and exhibited limited settling in thirty minutes (see Figure 24). The bulked sludge tended to be lighter brown in colour than the sludge generated at lower loading rates.

Bulked sludge was qualitatively defined in this work as sludge that would not settle in the baffled zone of each reactor. The arbitrary criterion

TABLE 12
EFFECT OF SHORT TERM INCREASES
IN VELOCITY GRADIENT
RUNS 1 and 2

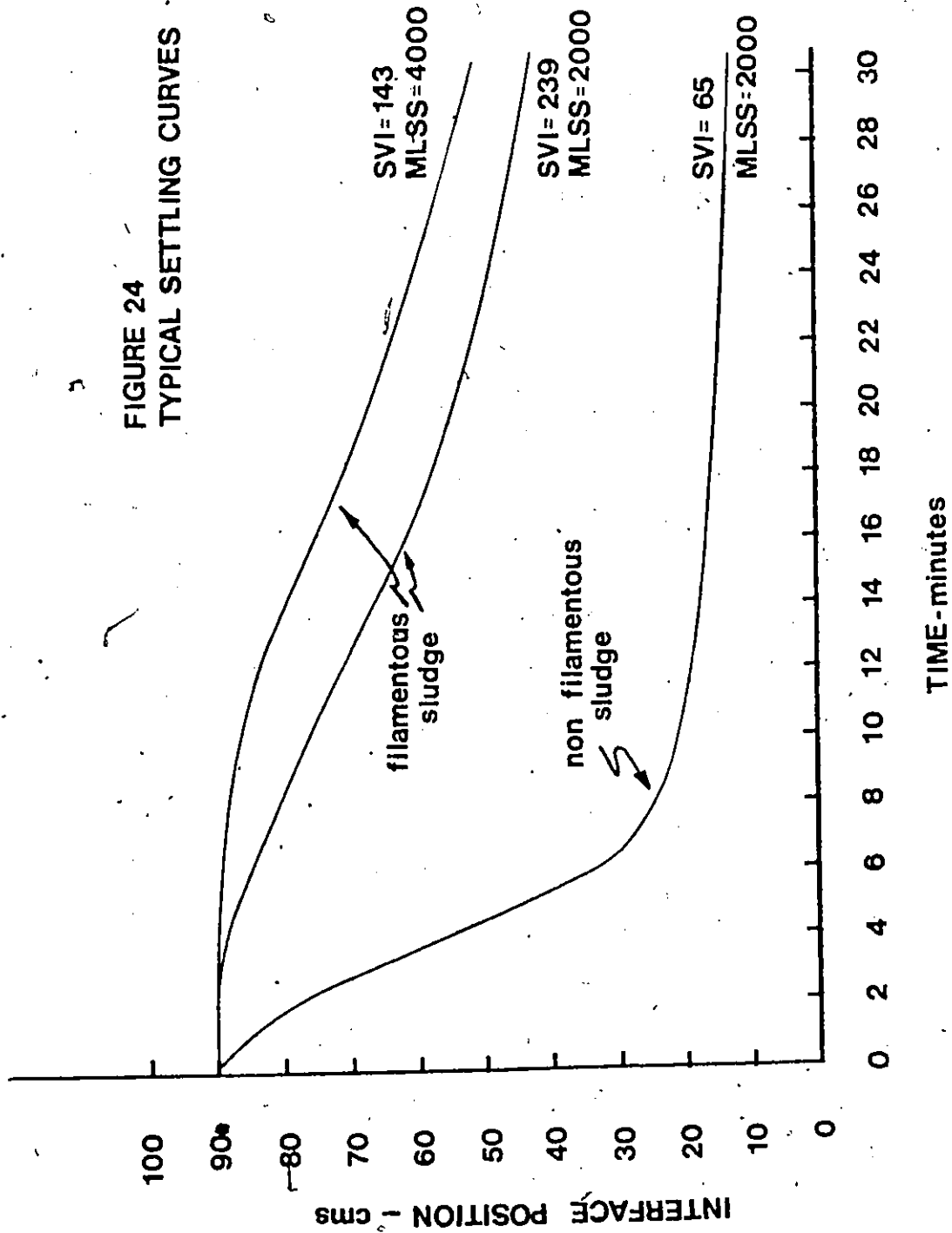
Oxygen Tension	Rpm	Zone Settling Velocity cm/min	Sludge Volume Index
low	120	12.5	36
	220	12.4	35
high	120	8.9	94
	220	9.1	94
low	120	11.5	50
	220	11.6	50
high	120	9.2	100
	220	9.2	102
low	120	6.2	119
	220	5.8	122
high	120	10.8	61
	220	10.5	60
low	120	7.1	116
	220	6.9	116
high	120	11.7	78
	220	11.5	78

of an SVI in excess of 200 (Pipes, 1969) was not meaningful at higher mixed liquor solids levels. As shown in Figure 24, at suspended solids levels of 4000 mg/l, sludge which only settled four centimeters in ten minutes, exhibited an SVI of 143.

Initial attempts to establish the upper bound on the food to mass ratio where bulking restricted operation, resulted in overnight bulking of the high D.O. reactor. The low D.O. reactor generally followed a day or so later. It later became apparent that the high growth rates and the correspondingly high oxygen demand reduced dissolved oxygen levels in the low D.O. reactor below 1 mg/l. Eckenfelder (1973) has indicated that filamentous growths are obligatory aerobes and hence will be affected under anaerobic or very low oxygen tensions. Hence, it is suspected that the rather loose manual adjustment of dissolved oxygen levels was responsible for early bulking differences. As a result, it was necessary to adjust new feed conditions early in the day to have sufficient time to monitor the changing responses within the system and regulate the oxygen supply accordingly.

When the low D.O. system was maintained above 1 mg/l filamentous bacteria were generally more predominant, than in the high D.O. system. Okun (1963) has suggested that the higher relative surface area to filament volume enables the filamentous forms to successfully compete for available oxygen at low dissolved oxygen conditions. At higher oxygen tensions

FIGURE 24
TYPICAL SETTLING CURVES



the capability for oxygen penetration into the floc is increased and hence floc-forming bacteria are able to predominate.

In any event, neither system was observed microscopically to be free of filamentous forms especially at low sludge ages. There also seems to be a delicate balance of conditions which determine whether one form will predominate. A better method of dissolved oxygen control would be advised in any further investigations into this phenomenon.

The relative absence of filamentous forms was noted only at sludge ages in excess of seven days. Their absence is attributed to the limited carbon source available (Pipes, 1969). Comparative photographs are shown in Figure 25, illustrating the differences in appearance of normal and bulked sludge flocs.

Investigations into the effects of long aeration periods in the absence of a food source has indicated that the observed bulking may also be due to high bound water content. Substantial improvement in settling velocity and SVI were noted as a function of time on Figure 26. This is not a consistent occurrence, however, and could be observed only when the sludge had been exposed to very high influent organic carbon concentrations (i.e. greater than 150 mg/l). Although filamentous growth was observed, the results corresponded to earlier findings of Heukelekian and Weisberg (1956). The authors observed that rapid growth rates in the presence of high substrate concentration



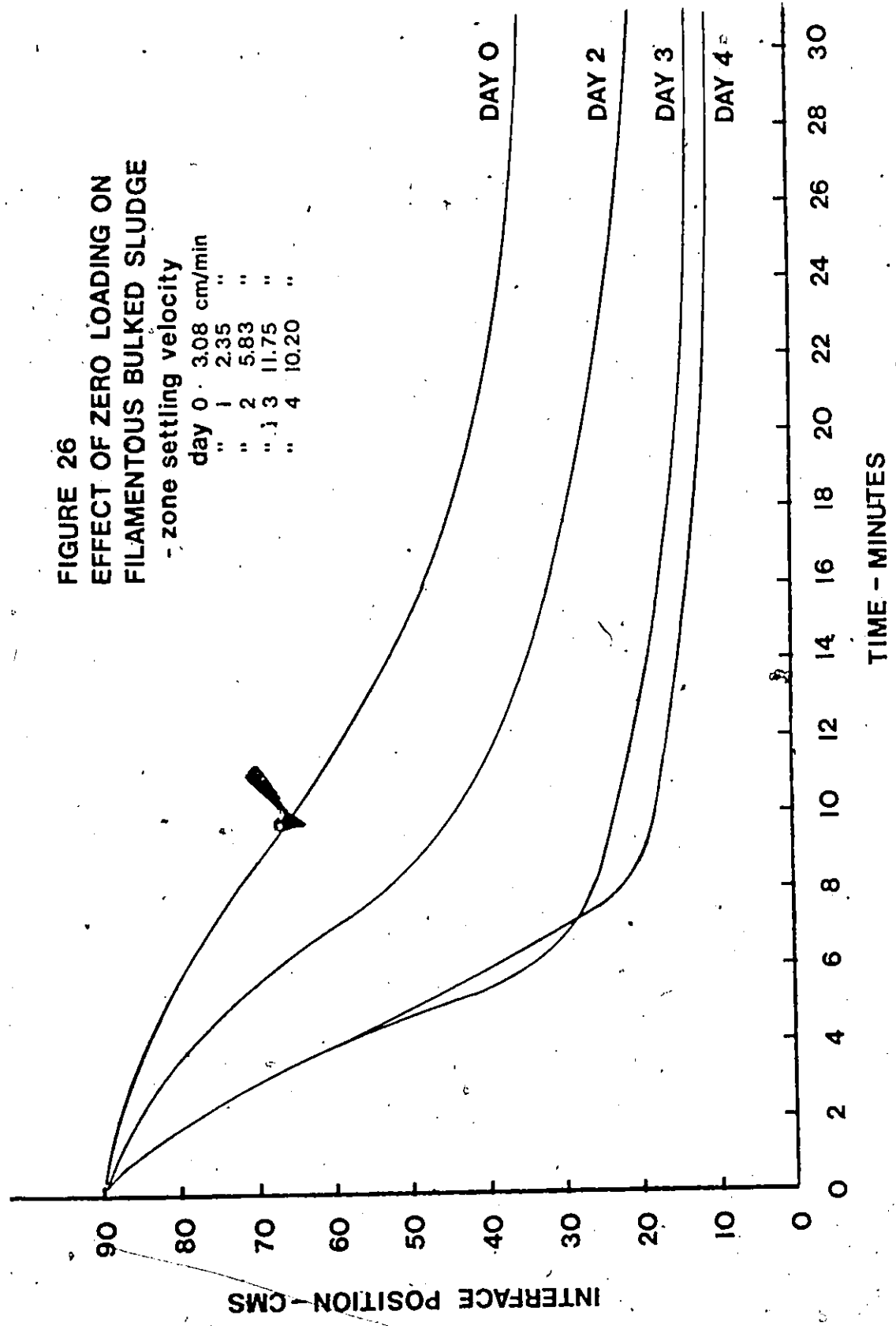
FIGURE 25a
FILAMENTOUS FLOCS



FIGURE 25b
NON-FILAMENTOUS FLOCS

FIGURE 26
EFFECT OF ZERO LOADING ON
FILAMENTOUS BULKED SLUDGE

- zone settling velocity
day 0 3.08 cm/min
" 1 2.35 "
" 2 5.83 "
" 3 11.75 "
" 4 10.20 "



yielded a microbial structure containing considerable bound water and resulting low specific gravity. Long aeration periods without a food source was found to convert the floc to a more dense form.

The results suggest that a physical change in the existing cell or floc structure such as reduction in bound water content may be occurring. The growth rate was minimal, with the bacterial culture existing in the stationary or possibly the death phase of growth. No visual reductions in filamentous forms were evident in microscopic analysis although this represents a rather rough monitoring approach. Hence changes in predominance away from filamentous forms is perhaps less likely.

It is also worthy of some note, that supernatant clarity was noticeably reduced after four to five days without feeding. This observation is also consistent with the findings of Eckenfelder (1973) who observed the presence of unoxidized fragments of floc remaining in suspension at very low organic loadings (from over oxidation of the biomass).

5.2.5 Physical Measurements

As a further means of establishing whether there was any physical differences between sludges generated at high oxygen tensions relative to conventional dissolved oxygen levels several physical parameters including floc size and appearance, floc density, and capillary suction

time were monitored along with sludge settling characteristics.

The biological floc was viewed microscopically throughout the study. No major visual difference in two-dimensional floc size or appearance was noted between the two sludges. Attached or stalked ciliates were observed in both systems over the full range of sludge ages studied. However, the numbers were found to increase as sludge age increased. This was also true of free swimming ciliates and rotifera. Crawling ciliates were noted only during run number 6, at a sludge age of approximately 8 days, and in very limited numbers. The above findings are generally consistent with the findings of Sherrard and Schroeder (1972) and consistent with the longer relative generation times of both protozoa and rotifera.

Populations of both rotifers and stalked ciliates were noticeably greater at the higher oxygen tension for sludge ages generally above six days. However, it is difficult to conclude whether the populations reflect the better effluent quality observed in the high D:O system or whether the effluent quality is the result of bacterial predation by the higher forms. Several sources (Curds et al, 1970; Calaway, 1968; etc) have noted that the presence of rotifera and stalked ciliates are characteristic of a healthy sludge. The U.K. Ministry of Technology (1968) in a review of several articles, including the work of Curds et al (1968), indicates considerable support for the action of protozoa

to reduce the bacterial content of a clarified effluent (and hence reduce turbidity) and secondly, to flocculate suspended matter and bacteria, by mucus secretion. Calaway (1968) contends that rotifers are also responsible for reductions of non-settleable bacteria by predation as well as bacterial flocculation through secretion of a flocculating agent. The observed settling characteristics and effluent clarity of the high D.O. system are generally compatible with the above.

The extent to which the higher dissolved oxygen concentration will influence the populations of protozoa or rotifera in the activated sludge processes is not well defined. Calaway (1968) reports that metazoan presence in anaerobic environments is excluded, because of their oxygen dependent metabolic process. McKinney (1962) also states,

"the rotifer is a strict aerobe and normally is found when the environment contains at least several milligrams per litre of dissolved oxygen."

Cürds et al (1968), in a discussion following the paper, reported that,

"it was reasonable to expect a healthy ciliate population in an activated sludge plant if the D.O. was maintained at 1-2 mg/l."

The authors also indicated that although certain ciliates would flourish at low D.O.'s, others such as Vorticella (a stalked ciliate) required "higher levels". Hence there is some qualitative support for the observations reported. Figure 27 illustrates the profuse growth of



stalked ciliates

rotifer & free swimming ciliate

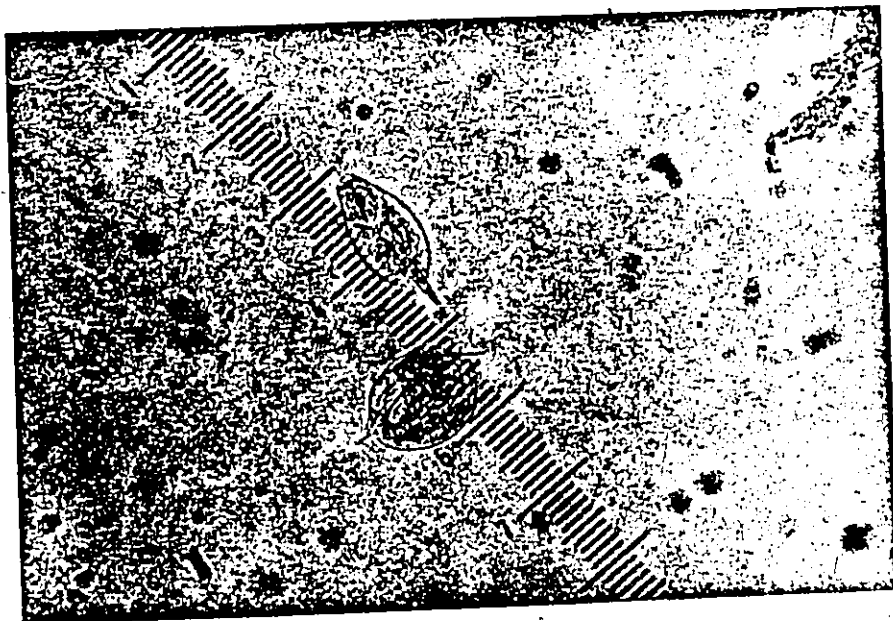


FIGURE 27a
COMMON CILIATES & ROTIFERA



FIGURE 27b
COMMON CILIATES

Vorticella which was typical of the higher oxygen tension system in addition to photographs of the rotifers and ciliates present.

An attempt was also made to establish whether there was any measureable difference in floc density between the two systems. On the basis of work, undertaken by Zaloom (1973), at the E.P.S. Wastewater Technology Centre, Burlington, Ontario, density measurements were made by buoyancy tests in solutions of known density. Sludge was pipetted, with a disposable pipet into a series of standard density solutions, prepared in increments of 0.005 gm/cc. The density of the aggregates or flocs was that of the solution in which the flocs remained in suspension a few seconds. The method was based on the assumption that in the time allowed for the sample to remain in suspension, little or no mass transfer of solution would occur through the aggregate and that at the same time the water surrounding the aggregate dispersed in the upper layers of the medium.

The test was found to be insensitive to any variation in control parameters during the study period. Flocs were observed to remain suspended in a glucose solution of density 1.005 grams/cc. The flocs remained suspended for a short period and eventually fell to the bottom.

As defined by Mueller et al (1967), the wet density may include water in any or all of the following forms:

1. water adsorbed on the surface,
2. interstitial water, or water absorbed within the floc, and
3. bound water (i.e. bound by colloid micelles).

The interchange of the above forms with the glucose solution, by diffusion is likely responsible for the observed increase in density.

The results obtained were also considerably lower than a range of 1.08 to 1.10 grams/c.c. reported by Mueller et al. This suggests that this procedure may not adequately distinguish between the above forms of water, and external water entering the solution with the floc particles.

In addition to the floc density measurements, a comparison of floc size was also undertaken, by photographic measurement of the maximal particle dimensions. No visual differences in floc dimensions were noted. Floc samples were collected with an open-mouth pipette, and a drop was deposited on a glass slide. A cover glass was then placed over the drop, and the slide was photographed under low power magnification. The scale included in the microscope eye piece, was calibrated with a micrometer plate. Flocs were found to vary in size from less than 10 microns to approximately 400 - 500 microns. Although several very small particles were observed on the photographs, the readily distinguishable particles, had a maximum dimension, normally in the range of 50 to 200 microns.

In relation to the mean floc size range of 140 to 290 microns observed

by Ganczarzyk (1967) the flocs in this study appear to be somewhat smaller.

An evaluation of floc filterability, by means of the Capillary Suction Time also showed the parameter to be somewhat insensitive. The solids concentration were generally too dilute to give a significant filtration time for differences to be observed. Capillary Suction Time for both sludges was typically 5 to 7 seconds. Hence a brief look at some of the physical characteristics of the sludges generated at the two levels of oxygen tension, has indicated little differences. The high dissolved oxygen sludge generally was observed to consist of greater numbers of rotifera and stalked ciliates. It is difficult, to conclude however, whether they were present as the result of a slightly better quality effluent, or whether the slight improvement in effluent quality was the result of their presence. There does appear to be some support in the literature for the later, and some support indicating the preference of both forms for higher oxygen tensions.

5.2.6. Biological Nitrification

As a preliminary evaluation of any possible effects of oxygen tension on the extent of nitrification, influent and effluent samples of both reactors were monitored for total Kjeldahl, ammonia, nitrite, and nitrate nitrogen. Samples were collected during each run and submitted for analysis to the Analytical Section of the Wastewater Technology Centre.

Samples were generally representative of conditions within the reactor after operation for one sludge age.

The extent of nitrification was observed to be dependent on both sludge age and oxygen tension. At sludge ages of less than seven days the reduction in ammonia or Kjeldahl nitrogen varied from zero to approximately fifty percent (see Table 13). A corresponding increase in nitrate nitrogen was observed but with no appreciable increase in nitrite. In general, results were highly variable and often inconsistent in terms of appreciable reductions in TKN with little or no gain in nitrate or nitrite nitrogen and vice versa. However, a trend towards a greater extent of nitrification was observed at the higher level of dissolved oxygen.

The use of yeast extract at the lower sludge ages contributed to the concentration of ammonia nitrogen in the feed (see run No. 7, Table 13). Whether the yeast extract exerted any influence on the nitrifying capacity of the sludge is unknown but it is thought to be unlikely.

At a sludge age in excess of seven days, the reduction in ammonia nitrogen averaged as high as 86% at the higher level of oxygen tension. For the data shown in Table 14, a comparative reduction of approximately 64% was found at the lower dissolved oxygen level. At the 95% confidence level, the hypothesis that the difference in the two effluent ammonia

TABLE 13
COMPARATIVE NITROGEN LEVELS - mg/l

Run	Sample	NO ₂ /N	NO ₃ /N	NH ₃ /N	TKN
1	Influent	nil	0.6	20.8	21.4
	Effluent				
	low D.O.	nil	0.2	21.1	22.3
	high D.O.	nil	17.9	4.9	5.1
	Influent	nil	0.7	17.0	17.2
	Effluent				
	low D.O.	0.5	9.6	9.8	10.5
	high D.O.	0.1	5.5	13.2	13.6
5	Influent	nil	nil	26.2	26.3
	Effluent				
	low D.O.	0.1	0.8	29.8	29.9
	high D.O.	0.1	2.3	16.4	16.8
	Influent	0.1	0.2	29.1	29.5
	Effluent				
	low D.O.	0.2	0.2	27.0	27.1
	high D.O.	0.2	7.9	20.2	21.1
7	Influent	nil	nil	99.3	103.0
	Effluent				
	low D.O.	nil	0.7	90.5	91.2
	high D.O.	0.1	8.8	73.0	76.5
	Influent	nil	nil	130.0	132.1
	Effluent				
	low D.O.	0.1	0.7	126.0	132.0
	high D.O.	0.5	9.9	74.5	76.0

TABLE 14

COMPARATIVE NITROGEN LEVELS - mg/l

RUN #6

Date	Sample	NO ₂ /N	NO ₃ /N	NH ₃ /N	TKN
September 15	Influent	0.1	0.9	29.4	29.5
	Effluent				
	low D.O.	0.2	17.2	2.1	2.6
	high D.O.	0.7	17.7	2.2	3.1
16	Influent	0.1	0.3	29.1	29.1
	Effluent				
	low D.O.	0.1	7.5	24.0	24.0
	high D.O.	0.8	15.7	2.6	3.8
17	Influent	nil	0.2	29.2	29.2
	Effluent				
	low D.O.	0.8	18.2	8.4	8.4
	high D.O.	0.7	20.8	1.1	2.3
19	Influent	0.1	0.1	26.3	26.6
	Effluent				
	low D.O.	0.1	22.3	2.7	2.7
	high D.O.	0.2	21.2	0.6	2.8
20	Influent	nil	nil	31.6	32.0
	Effluent				
	low D.O.	0.9	14.5	21.4	21.4
	high D.O.	0.4	16.0	14.8	15.1
21	Influent	nil	nil	16.4	16.9
	Effluent				
	low D.O.	0.1	3.3	14.2	14.2
	high D.O.	0.1	11.1	0.8	3.1

nitrogen (or TKN) concentrations was zero, was rejected. The above results generally support the findings of both Wahrman (1960) and Kiff (1972). Current understanding of this phenomenon is rather limited, but it may be dependent on possible inhibitory effects of organic matter at low dissolved oxygen levels as suggested by Kiff.

The data presented in Table 14, was accumulated over a period of operation extending from the fourth to the eleventh day of operation. The sludge age was approximately eight days. The system, once again, appears to be capable of achieving some stability or uniformity in a period of operation less than one sludge age. Any dependency, then might be best viewed as a relationship with the growth rate of the heterogenous culture and not necessarily requiring a full changeover of vessel contents to observe the resulting effects.

6. SUMMARY AND CONCLUSIONS

1. Several inherent process advantages appear to be available with the use of pure oxygen in the activated sludge process, which are not necessarily a function of the higher oxygen tension. These include the higher driving force for oxygen dissolution, allowing reduced mixing energy and the potential for a better conditioned sludge and secondly, the ability to operate at higher sludge ages (i.e. lower growth rates) by maintenance of greater concentrations of bacteria aerobic, in a given volume. Operation at a longer sludge age allows the potential for a reduction in the excess solids produced, a more settleable and compactable sludge, a greater nitrifying capability and a greater population of higher order predatory organisms (to possibly assist in effluent turbidity reduction).

2. Possible effects of oxygen tension, acting independently of sludge age were noted on the following parameters:
 1. the net solids production,
 2. the effluent suspended solids,
 3. the effluent organic carbon levels,
 4. the biological nitrification,
 5. the ATP concentration,
 6. the plate count, and
 7. the populations of rotifera and stalked ciliates.

The effects of oxygen tension on the following sludge parameters were not evident:

1. the settling characteristics (i.e. Z.S.V.),
2. the dehydrogenase activity,
3. the DNA content,
4. the oxygen uptake,
5. the floc size or appearance,
6. the floc density, and
7. the Capillary Suction Time

3. No improvement in settling characteristics was noted as the result of operation at the higher level of oxygen tension, relative to conventional levels. However, it was evident, particularly with the sludge generated at the higher dissolved oxygen concentration that zone settling velocity improved as sludge age increased.

This increase was exhibited with greater uniformity at the higher level of oxygen tension. No effect on settling characteristics was noted as the result of short term increases in velocity gradient.

4. A small but consistently lower production of excess solids was found with operation at the higher oxygen tension. The net solids production decreased as sludge age was increased (i.e. as growth rate decreased).

5. Higher effluent quality was also observed, in terms of both lower organic carbon and suspended solids concentrations for operation

- at the higher level of dissolved oxygen.
6. At sludge ages in excess of seven days, a greater conversion of ammonia nitrogen to nitrate/nitrite nitrogen was indicated in the high D.O. system. Less than 50% reductions in ammonia nitrogen were found for sludge ages under seven days in both systems.
 7. Filamentous bacterial forms were predominant in both systems at low sludge ages (i.e. 3-4 days) and were generally believed to be responsible for the poor settling characteristics exhibited. Pre-dominance of a filamentous bacterial culture appears to occur more rapidly at the lower oxygen tension except when D.O. concentrations fell well below 1 mg/l.
 8. Rotifera and ciliates (including stalked, free swimming and crawling types) were observed in both systems, with their numbers gradually increasing as sludge age increased. The number of rotifers and stalked ciliates appeared to be normally greater, in the sludges generated at the higher oxygen tension.
 9. With the exception of ATP, no evidence was gained supporting an improvement in bacterial activity through operation above conventional levels of oxygen tension. On all but one occasion, ATP concentrations were observed to be higher in the high D.O. sludges. Conversely, plate counts were greater on all but one occasion for the low D.O. sludge.

10. At the 95% level of confidence, there was no indication of a dependency between growth rate and either DNA, dehydrogenase activity or oxygen uptake at both levels of oxygen tension. A significant positive correlation at the 95% level was obtained between growth rate and both ATP and plate count at the higher oxygen tension. Also at the 95% confidence level, a significant negative correlation was observed between zone settling velocity and DNA at both levels of oxygen concentration.
11. No differences in floc size or appearance, floc density or Capillary Suction Time were observed between the two systems. The latter procedures were generally felt to be insensitive to any process variations.
12. Observations of settling characteristics, solids production data and ammonia nitrogen reductions, has indicated that the biological system does not require a full sludge age to reach a condition of reasonable uniformity in response to a change in process variables.

LIST OF ABBREVIATIONS

a	-	oxygen uptake coefficient
ATP	-	adenosine tri-phosphate
b	-	bacterial decay coefficient
b'	-	endogenous respiration coefficient
BOD	-	biochemical oxygen demand
C, C ₀	-	organic carbon concentration (subscript denotes time equal to zero)
COD	-	chemical oxygen demand
D	-	dilute-out rate
D.O.	-	dissolved oxygen
f	-	mass of substrate
F/M	-	food to (bio-) mass ratio
G	-	velocity gradient
hr	-	hour
l	-	litre
m	-	mass of carbon
mg/l	-	concentration - milligrams per litre
MLSS	-	mixed liquor suspended solids
MLVSS	-	mixed liquor volatile suspended solids
ppm	-	concentration - parts per million
P	-	power consumption
Q	-	flowrate
SVI	-	sludge volume index

LIST OF ABBREVIATIONS (cont'd)

t	-	time
TOC	-	total organic carbon
V	-	reactor volume
VSS	-	volatile suspended solids
X	-	mass of volatile suspended solids
Y	-	yield coefficient
ZSV	-	zone settling velocity
θ	-	sludge age
μ	-	absolute viscosity (also microns)

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APPENDIX A

DATA SUMMARY

TABLE A-1

OPERATING SCHEDULE

Run	Run Duration	Flowrate l/hr	Influent TOC mg/l
1	July 19-27	7.0	50
2	July 28-Aug. 7	3.5	50
3	Aug. 13-21	3.5	75
4	Aug. 22-27	7.0	75
5	Aug. 28-Sept. 6	7.0	50
6	Sept. 11-21	3.5	25
7	Sept. 22-30	7.0	75

TABLE A-2

SOLIDS PRODUCTION

Run	Oxygen Tension e mg/l	Food To Mass Rate mg TOC _r /D/mg VSS	Net Solids Production mg VSS _p /D/mg VSS	Sludge Age days
1	1-2 8-12	0.25 0.22	0.162 0.155	6.2 6.5
2	1-2 8-12	0.12 0.12	0.121 0.104	8.3 9.6
3	1-2 8-12	0.21 0.22	0.175 0.173	5.7 5.8
4	1-2 8-12	0.39 0.41	0.241 0.254	4.1 3.9
5	1-2 8-12	0.25 0.25	0.203 0.164	4.9 6.1
6	1-2 8-12	0.06 0.06	0.136 0.118	7.4 8.5
7	1-2 8-12	0.30 0.30	0.254 0.203	3.9 4.9

TABLE A-3
GRAMS OF VOLATILE SOLIDS (PRODUCED) PER DAY

Oxygen Tension mg/l	Sludge Age days	Solids Lost In Effluent gms	Solids Wasted From Absorption Column gms	Solids Wasted From Reactor gms	Total Solids Removed gms
1-2	6.2	1.86	0.89	0.88	3.63
8-12	6.5	1.58	0.89	1.96	4.43
1-2	8.3	1.29	0.76	0.84	2.89
8-12	9.6	0.58	0.76	1.47	2.81
1-2	5.7	1.43	0.62	2.25	4.30
8-12	5.8	0.64	0.62	3.15	4.41
1-2	4.1	2.35	0.94	2.73	6.02
8-12	3.9	1.56	0.94	4.10	6.60
1-2	4.9	2.43	1.08	1.53	5.04
8-12	6.1	1.83	1.08	1.56	4.44
1-2	7.4	0.89	0.61	2.15	3.65
8-12	8.5	0.70	0.61	1.96	3.27
1-2	3.9	2.46	0.89	4.73	8.08
8-12	4.9	2.19	0.89	4.24	7.32

TABLE A-4

DAILY EFFLUENT CHARACTERISTICS

Date	Suspended Solids mg/l		Total Organic Carbon mg/l	
	Low D.O.	High D.O.	Low D.O.	High D.O.
<u>Run 1</u>				
July 19	19	18	20	18
22	24	14	12	12
23	20	22	19	12
24	18	15	17	13
25	14	6	18	12
26	34	20	18	15
27	-	-	16	14
<u>Run 2</u>				
July 29	-	-	22	19
30	13	10	-	-
31	6	3	13	9
Aug. 1	4	4	13	9
2	26	13	-	-
3	24	7	14	9
4	23	28	12	10
5	11	10	12	10
<u>Run 3</u>				
Aug. 15	40	36	6	6
16	20	16	18	9
17	24	12	14	11
18	37	16	25	13
19	36	15	14	14
20	36	4	16	11
21	-	-	15	11
<u>Run 4</u>				
Aug. 22	42	42	22	16
24	16	16	17	10
25	19	19	14	9
26	17	17	15	11
27	26	26	-	10

TABLE A-4 cont'd

DAILY EFFLUENT CHARACTERISTICS

Date	Suspended Solids mg/l		Total Organic Carbon mg/l	
	Low D.O.	High D.O.	Low D.O.	High D.O.
<u>Run 5</u>				
Aug. 29	-	-	16	14
30	25	16	13	14
31	18	6	17	11
Sept. 2	41	23	13	9
3	18	7	11	7
4	31	18	11	10
5	17	26	-	-
6	19	21	13	8
<u>Run 6</u>				
Sept 11	17	13	-	-
13	22	20	12	9
14	-	19	11	10
15	22	7	13	10
16	7	3	13	7
17	5	2	7	7
18	16	-	8	7
19	23	24	9	9
20	28	16	8	7
21	17	15	8	10
<u>Run 7</u>				
Sept 23	4	8	14	12
25	23	18	13	12
26	10	20	11	7
27	35	26	23	11
29	36	21	21	9
30	-	-	16	10

TABLE A-5

SETTLING CHARACTERISTICS

Run	Date	Oxygen Tension mg/l	ZSV cm/min	SVI
1	July 26*	1-2	12.5	36
		8-12	8.9	94
	July 27*	1-2	11.5	50
		8-12	9.2	100
2	Aug. 3*	1-2	6.7	108
		8-12	9.5	81
	Aug. 6*	1-2	6.2	119
		8-12	10.8	61
	Aug. 7	1-2	7.1	116
		8-12	11.7	78
3	Aug. 17*	1-2	10.1	70
		8-12	9.8	72
	Aug. 19	1-2	9.9	94
		8-12	8.0	94
	Aug. 20	1-2	7.8	86
		8-12	8.0	86
	Aug. 21	1-2	8.9	84
		8-12	8.1	90
4	Aug. 24*	1-2	5.3	117
		8-12	10.1	69
	Aug. 26	1-2	6.6	72
		8-12	6.5	105
	Aug. 27*	1-2	-	-
		8-12	6.8	92

* settling tests run to coincide with activity measurements by Nutt (1974)

cont'd

TABLE A-5 cont'd
SETTLING CHARACTERISTICS

Run	Date	Oxygen Tension mg/l	ZSV cm/min	SVI
5	Aug. 31*	1-2	7.2	96
		8-12	8.3	67
	Sept. 4*	1-2	6.5	103
		8-12	8.7	102
	Sept. 5	1-2	5.6	116
		8-12	7.9	111
	Sept. 6	1-2	6.8	111
		8-12	9.1	86
6	Sept. 19	1-2	11.0	56
		8-12	11.3	44
	Sept. 20	1-2	8.6	67
		8-12	13.6	50
	Sept. 21	1-2	10.7	69
		8-12	13.0	56
7	Sept. 27	1-2	7.8	96
		8-12	7.4	100
	Sept. 28	1-2	8.4	88
		8-12	6.9	105

* settling tests run to coincide with activity measurements by Nutt (1974)

APPENDIX B

ESTIMATION OF VELOCITY GRADIENT

APPENDIX B

Estimation of Velocity Gradient

To determine whether the mixing conditions within the reactors were representative of the velocity gradient common to conventional activated sludge units, an attempt was made to estimate the mean velocity gradient within the reactors. Both theoretical equations and physical measurement were used for this purpose.

The mean velocity gradient imparted to a fluid mass is a function of the power dissipation in the system, the viscosity of the medium and the volume of the fluid involved. For a stirred system the velocity gradient is given by,

$$G = \left[\frac{C_d \rho A (1-\alpha) v^3}{2\mu V} \right]^{1/2} \quad (B-1)$$

where C_d is the drag coefficient,

A is the total impellor area,

μ is the absolute viscosity,

V is the volume of fluid,

v is the impellor tip velocity,

ρ is the fluid density, and

α is the correction factor for the relative velocity between fluid and impellor.

Assuming the drag coefficient to be 1.2 (Rickard and Gaudy, 1968), α to be 0.25 (Camp, 1955) and a viscosity equal to that of water at 20 C, the equation can be reduced to the form,

$$G = 5.993 \times 10^{-2} n^{3/2} \quad (B-2)$$

This relationship is plotted in Figure B-1.

The most convenient means of evaluating this estimate was by the direct determination of the power drawn by the agitator drive. Power was determined from the A.C. relationship:

$$P = VI\cos\theta \quad (B-3)$$

where: V is the voltage (volts),

I is the drawn current (amps), and

$\cos\theta$ is the power factor.

The current drawn by the agitator drive was measured as a function of rpm for both an empty reactor and one containing mixed liquor. The resulting relationship between current and agitator rpm (for a single unit) is shown in Figure B-2. It was evident that the resistance of the bearings, internal windings, etc., consume a great proportion of the input power. It was assumed that air creates no appreciable drag and that the difference in drawn power between the two conditions is the power transferred to the mixed liquor.

Unfortunately the difference in amperage drawn under both conditions only becomes appreciable at high rotational speeds. As rpm is decreased, differences in drawn current approach the magnitude of the measurement error. At the same time, the absolute value of the power input is limited by the uncertainty in the power factor, (assumed to be 0.9).

However, it is evident from the data below that both estimates are within the same order of magnitude and both are consistent in their relationship with rpm. The velocity gradients also cover the range observed by Parker (1970).

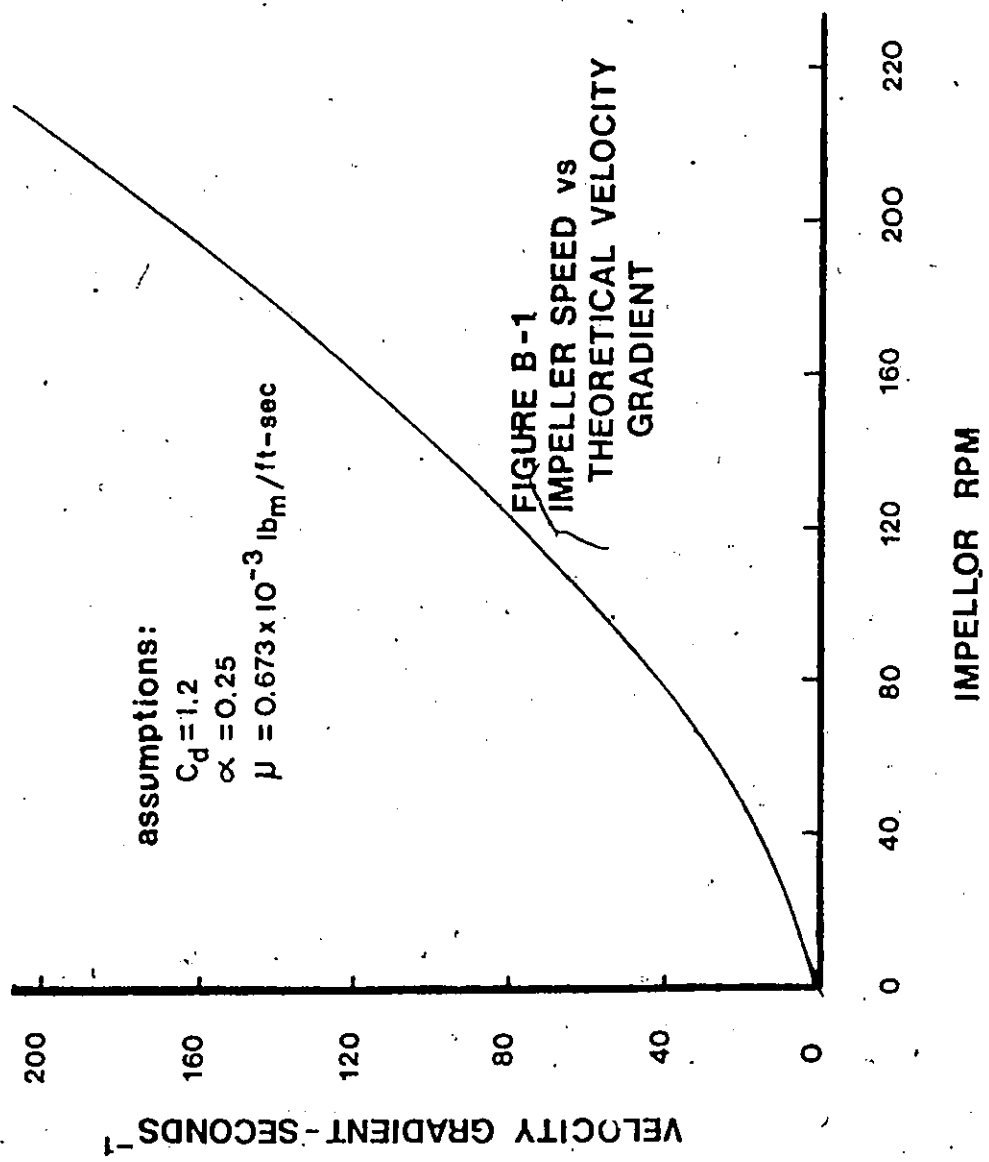


FIGURE B-1
IMPELLER SPEED vs
THEORETICAL VELOCITY
GRADIENT



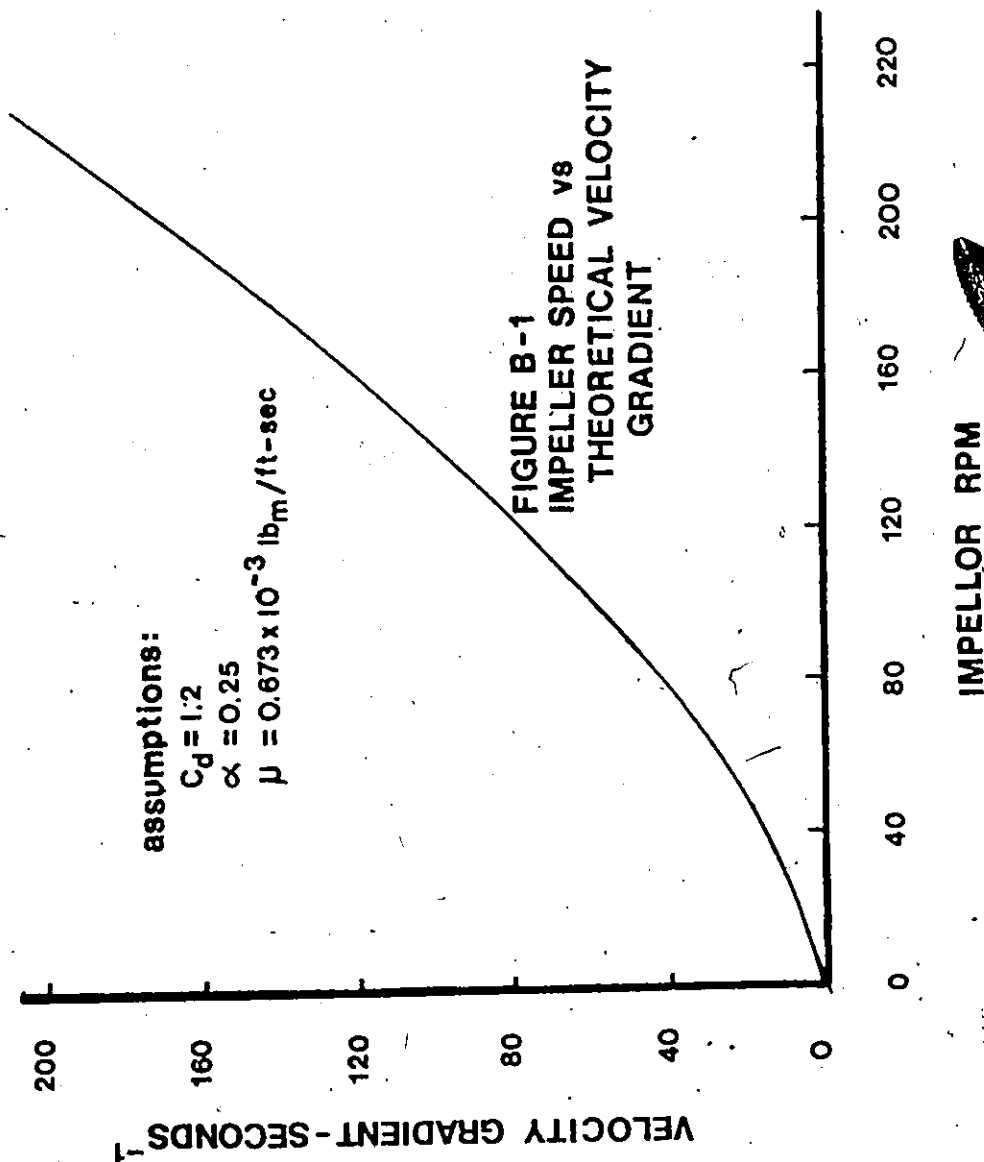


FIGURE B-1
IMPELLER SPEED VS
THEORETICAL VELOCITY
GRADIENT



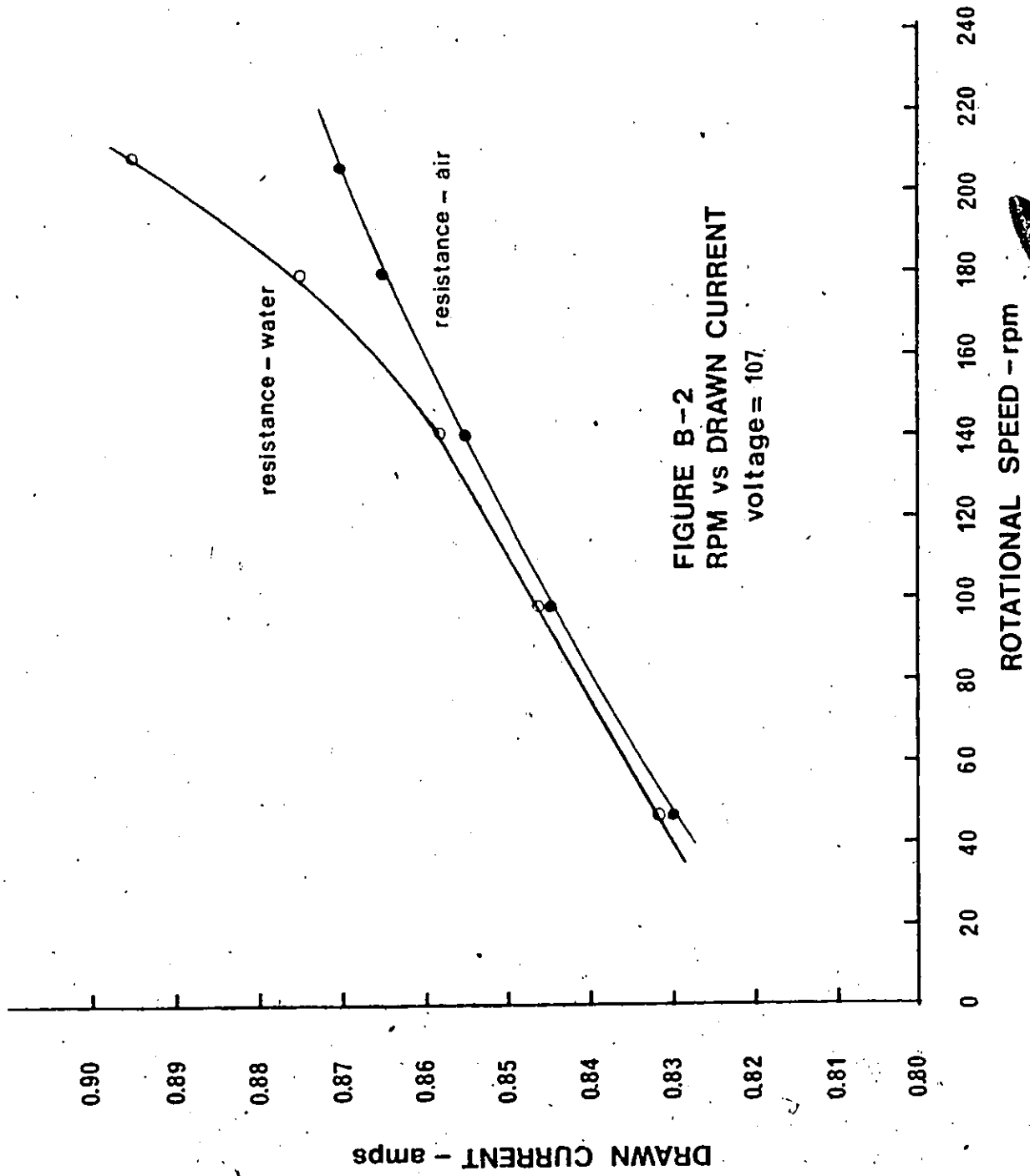


TABLE B-1

Estimate of Velocity Gradient

Controller Setting	RPM	Difference in Amps Drawn	Velocity Gradient sec ⁻¹	
			exp.	calc.
0	47	0.002	86	19
2	98	0.002	86	58
4	140	0.003	106	99
6	179	0.010	188	144
8	207	0.025	310	178

The experimentally determined velocity gradient increased somewhat more rapidly than predicted theoretically. This suggests that the relative velocities of the fluid and impellor did not remain directly proportional over the whole range of tip velocities.

It is recommended that internal baffling of the reactor be considered in future work to help reduce the effect of this phenomenon. Because of the limited utilization of the velocity gradient concept in this stage of the work, the approach undertaken was suited to our purposes despite the several weaknesses noted. A more intensive evaluation of other procedures such as shaft torque measurements is warranted should studies into the effects of velocity gradient be intended.

As indicated previously, oxygen was introduced into the reactors and hence a contribution to the mixing intensity was made by the rising bubbles. Camp (1943) has related velocity gradient to the upward gas flow in the following two equations.

$$G^2 = \frac{Q}{\mu V} \left[4890 \log \frac{H + 34}{34} \right] \quad (B-4)$$

$$G^2 = \frac{Q}{\mu V} \left[2120 \frac{H}{H/2 + 34} \right] \quad (B-5)$$

where Q is the gas flow, cfs

H is the liquid depth, feet

μ is the viscosity, pound-seconds/foot²

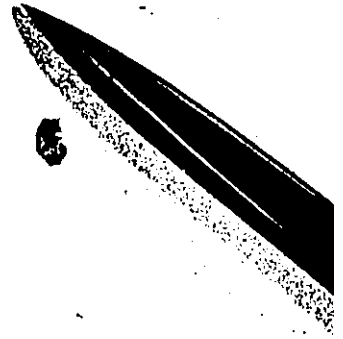
V is the volume of fluid, cubic feet

The approximate air flow rates varied from 0.004 to 0.02 cubic feet per minute for respective sludge ages of approximately 9 days down to 4 days. According to equation B-5, this represents a range in velocity gradient of approximately 31 to 70 seconds⁻¹.

Hence operation was generally maintained at a mean velocity gradient of 115 to 150 seconds⁻¹. This is within the range found by Parker (1970) of 88 to 220 seconds⁻¹ in a study of fourteen American activated sludge plants.

APPENDIX C

COD - TOC RELATIONSHIP



APPENDIX C

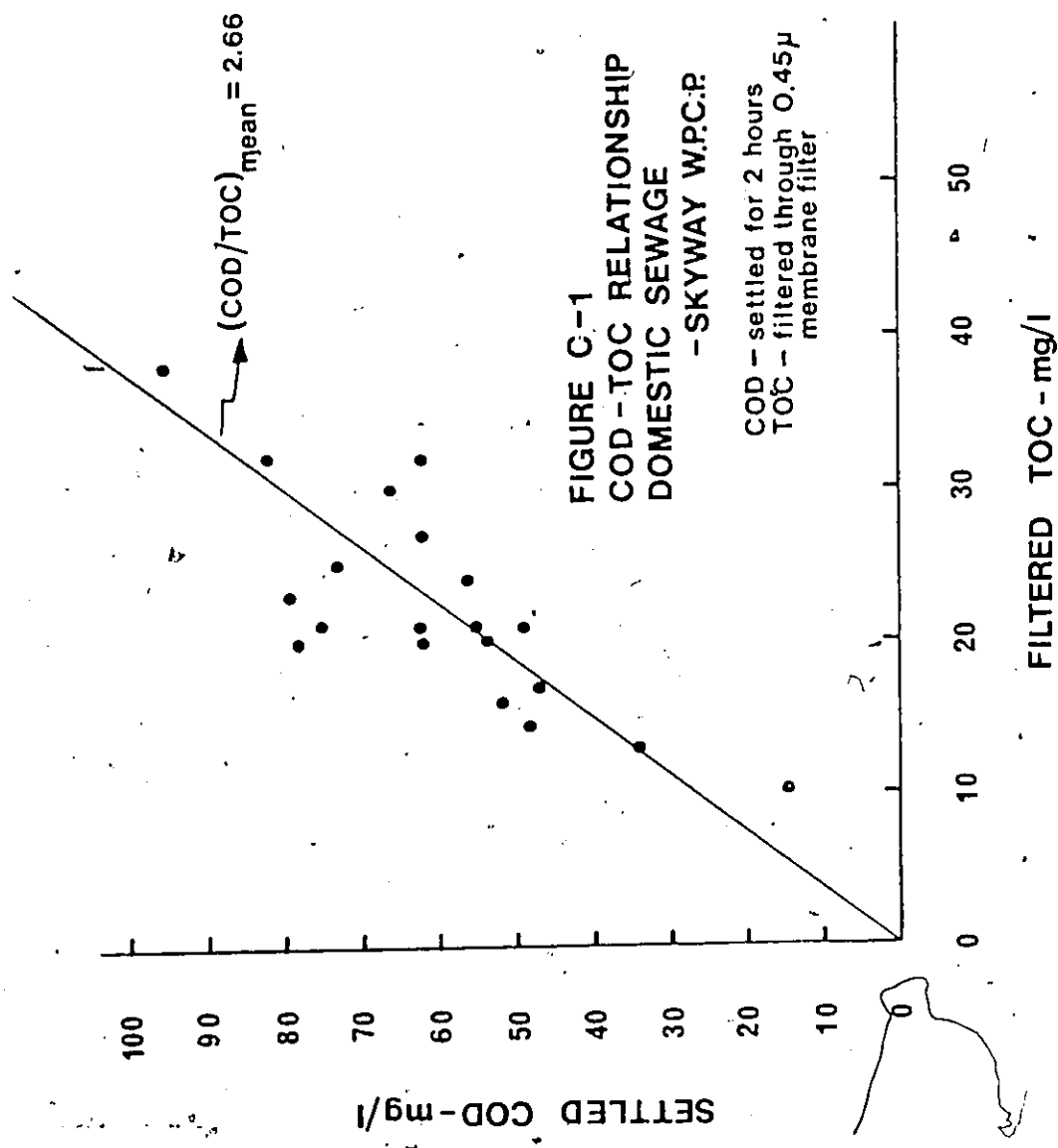
COD - TOC Relationships

Although the time and facilities were not available to run daily COD values, an attempt was made to determine the approximate COD loading rates applied to the reactors. The two hour settled raw sewage COD value is plotted as a function of the filtered TOC, in Figure C-1.

The data was not suitable for application of Least Squares fitting techniques since both independent and dependent variables are random variables. However, the data can be conveniently fitted by eye or the mean value of the COD-TOC ratio can be determined (which applies a further constraint that the fitted line pass through the origin). The application of a mean ratio has been employed by Eckenfelder and Ford (1970) and is the basis for the "fitted" line in Figure C-1.

An approximate relationship of settled COD to soluble TOC can then be determined for the yeast extract supplemented substrate based on a knowledge of the amount of yeast extract added and the COD contributed per gram. Figure C-2 summarizes the COD, BOD, and TOC available as a function of the concentration of yeast extract in a water solution. It is evident that the COD-TOC ratio for yeast extract is less than that of domestic sewage at 1.76 compared to 2.66.

The approximate influent settled COD levels for each run are presented below, in Table C-1.



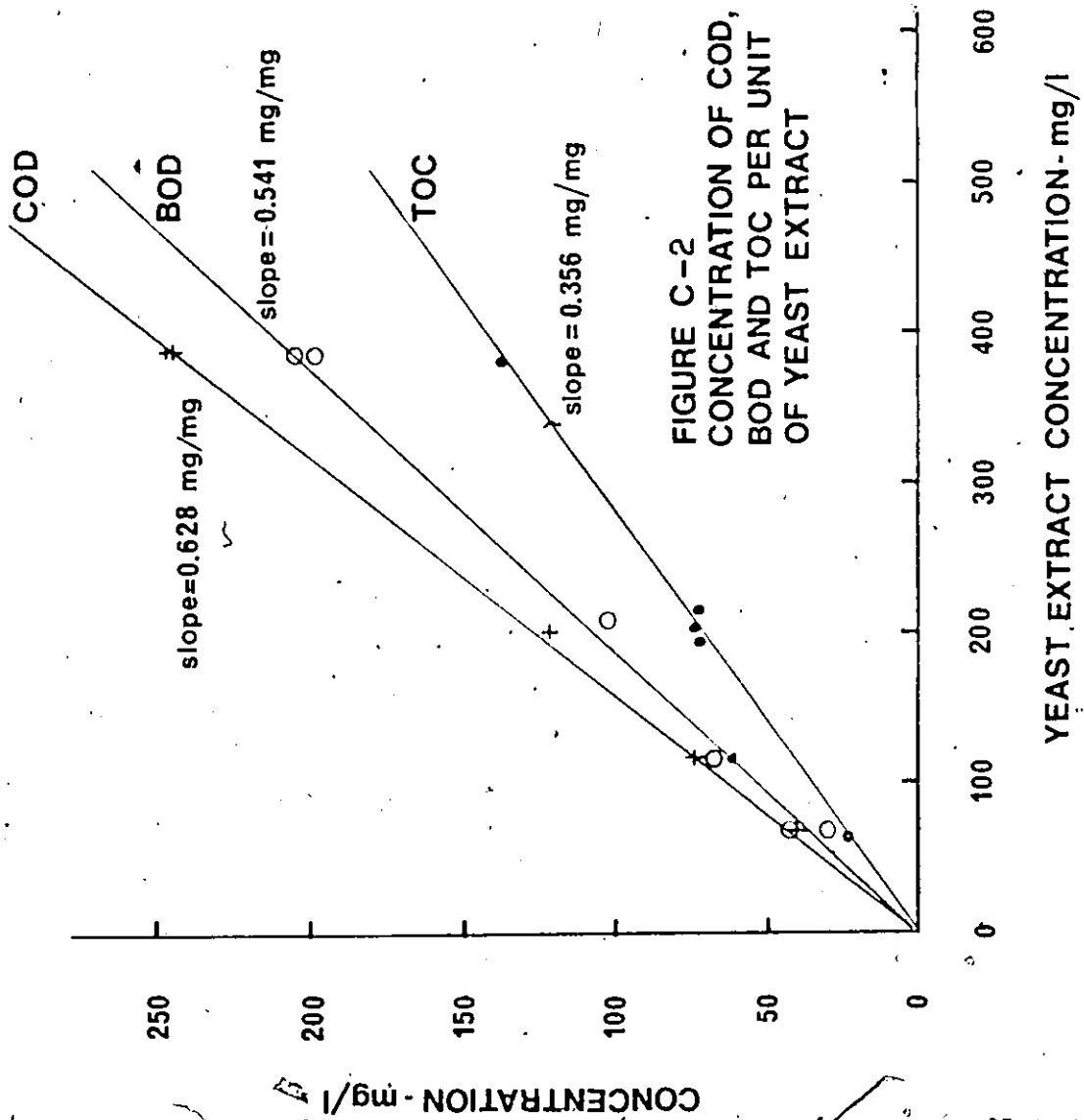


FIGURE C-2
CONCENTRATION OF COD,
BOD AND TOC PER UNIT
OF YEAST EXTRACT

TABLE C-1

INFLUENT COD-TOC RELATIONSHIP

Run	TOC mg/l	COD mg/l	COD/TOC
1	50	126	2.52
2	50	126	2.52
3	77	155	2.02
4	76	154	2.02
5	50	126	2.52
6	29	78	2.66
7	74	150	2.03

Estimates of the COD loading were then obtained by applying the above ratios to the food to mass ratio which was based on TOC. The results are plotted in Figure C-3, in comparison with earlier fitted lines reported in the literature. The data obtained bear a reasonably close similarity to the results of previous studies. The plot also suggests that the positive intercept may be due to the influence of biodegradable influent solids. The high solids production in Run 6 (ie. with an approximate food to mass ratio of 0.155 gms COD/D/gm VSS) also suggests that the loading rate was higher than that predicted by the mean settled COD to soluble TOC ratio.

In any event, this exercise was undertaken to provide some comparison with previous work, in an attempt to show that reactor operation was not atypical. This route was necessitated because of the limited information available based on Total Organic Carbon. Classically yield has been determined based on COD or BOD removal and the available literature appears reluctant to alter this approach.

