EFFECT OF TEMPERATURE

ON

COMPLETE MIXING ACTIVATED SLUDGE

AERATION-ONLY SYSTEMS

Thesis

Presented to the Faculty of Engineering and Architecture
of the American University of Beirut in partial fulfillment
for the Degree of Master of Engineering (Major Sanitary)

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Beirut - Lebanon

November 1967

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ACKNOWLEDGEMENT

The writer wishes to thank Prof. Samir El-Khuri, Head of Sanitary Section at ACE for his encouragement and support in realizing this research and for his valuable and practical experience in this field. The subject of this research was originated during the design at ACE offices of a sewage disposal system in a country with hot climatic condition. The writer also wishes to thank Prof. Raja Iliya for his efforts to acquire the financial aid from the Research Committee of the School of Engineering, Prof. Aftim Acra for his endless help and effort and for putting all the Public Health Laboratory facilities at the disposal of this research, Mr. Aziz Abu Samra for his help in the erection of the apparatus and for his continual advice, Mr. Nazih Shammas for his advice on the subject, Mr. R. Milki and Miss Nora Agopian for their continuous help in the laboratory, and all the people who were concerned in realizing this research.

ABSTRACT

The Effect of Temperature on the Activated Sludge Aeration-Only Systems

Temperature is known to exert a great effect on the biological reactions. Laboratory results on units operating at 27°C, 35°C and 40°C indicated that activated sludges can withstand high temperature conditions without any serious draw-back on the efficiency of such systems.

Also it was observed that the temperature had a noticeable effect on the animal life existing in these systems, at higher temperatures approaching the 40°C the presence of animal life seemed to be adversely affected.

The effect of sudden temperature fluctuations on activated sludge systems in the temperature range of 30°C to 40°C should be further investigated before a final conclusion is taken as regards the effect of temperature on the efficiency of such systems in this part of the world.

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I- INTRODUCTION

The complete mixing activated sludge system is basically similar to the conventional activated sludge system, in as far as the basic concept of organic matter decomposition by the microbial organisms into energy and cell mass, where dissolved oxygen is supplied by means of air bubbling into the aeration tank. However, in the complete mixing process the untreated wastes in the sewage are introduced to the aeration tank at various points such as instantaneous mixing throughout the tank is expected. Hence the aeration tank mixture remains uniform all throughout which results in a uniform oxygen demand and a uniform biological growth.

Therefore it can be concluded that while in the conventional system the microbial population undergoes a continual shifting an the growth curve, the complete mixing process approaches a relatively constant equilibrium. Hence the difference in operational characteristics of the two different processes.

The complete mixing activated sludge process can be divided into three different operational methods which are shown schematically below.

A. The Aeration Only System

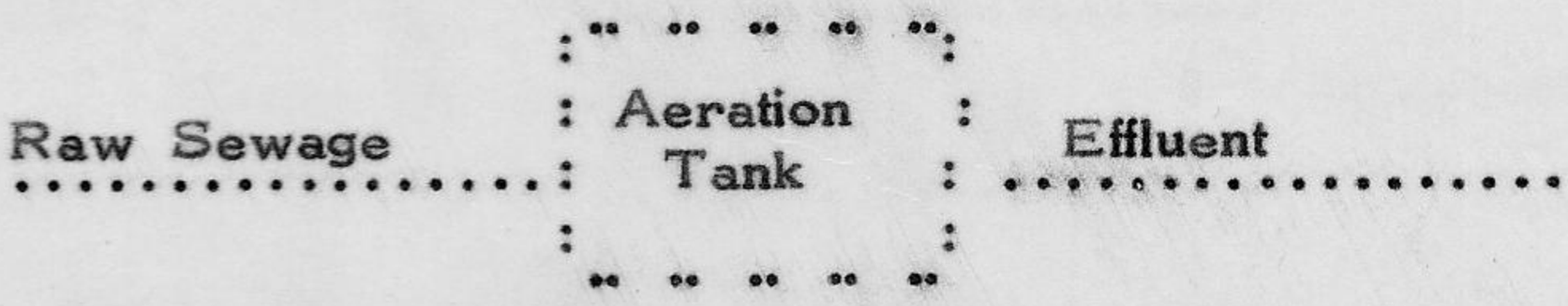


Fig (1)

It consists of an aeration tank only and hence when such system approaches equilibrium, the mixed concentration in the effluent or in the aeration tank will be a direct measure of the protoplasm synthesized.

B. <u>The Wasting of Excess Sludge in the Effluent System</u>

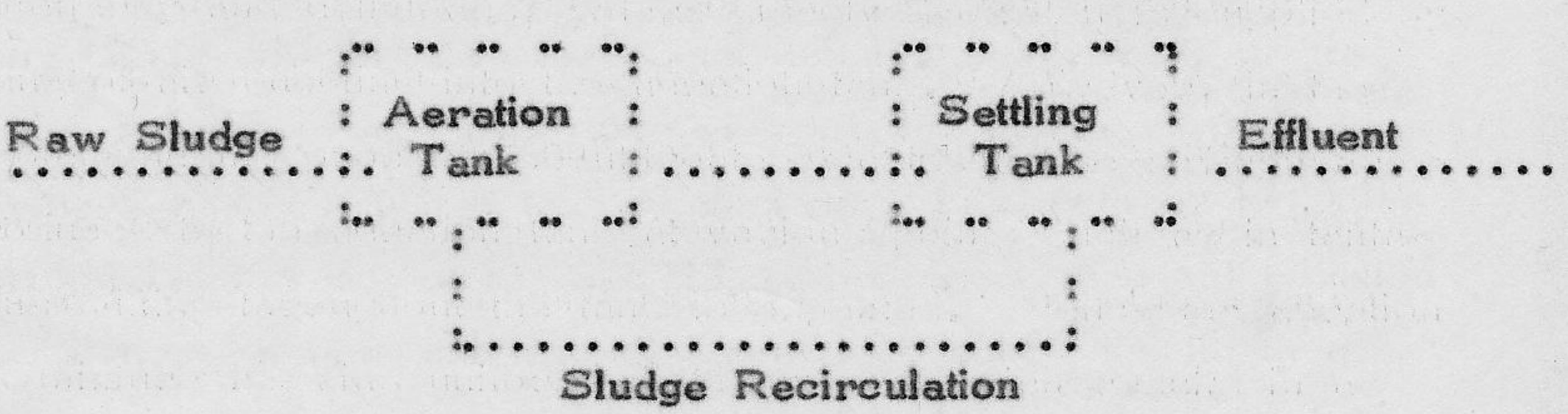


Fig (2)

In this Aeration-Sedimentation System high microbial solids are maintained in the Aeration tank by recirculatiog the settled sludge from the settling tank into the aeration tank and the excess suspended solids are lost in the effluent.

C. <u>The Separate Sludge Wasting System</u>

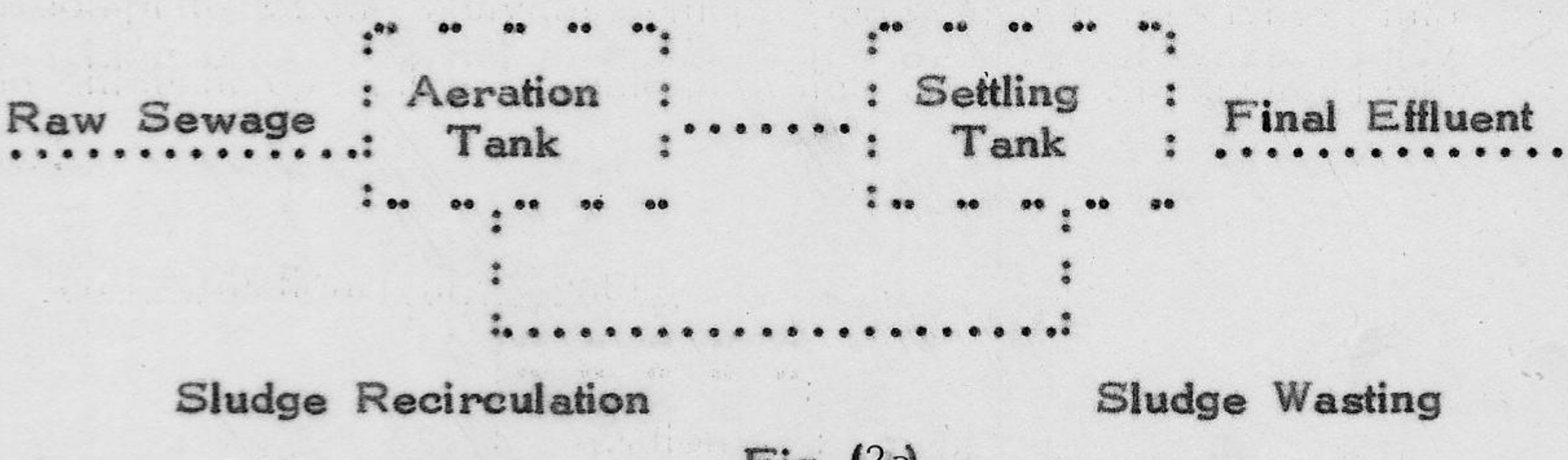


Fig (2a)

This system is also an aeration-sedimentation system, but is provided with separate sludge wasting facilities that help in maintaining a low suspended solids content in the final effluent.

The concern of sanitary engineers is to study and make recommendation on the methods that will produce the best and most economical processes for sewage treatment. Unfortunately laboratory facilities are limited for the carrying of research projects in such fields. The aeration only system is the easiest of the three methods to handle within the available facilities and since the purpose of this study is only meant to find the effect of temperature variation on the microbial organisms, it was found satisfactory to have this research on the above mentioned system. However the results will also be valid for the other two systems.

II- TEMPERATURE AND THE MICRO-ORGANISMS

A. General

Of the most important factors affecting microbial growth is temperature. It has been observed that bacteria multiply quite slowly at low temperatures but increase their rate of multiplication as the temperature increases. It has been generally stated that the rate of microbial growth doubles with every 10°C increase in temperature up to the limiting temperature. The growth reactions are normal chemical reactions which follow definite patterns. The two problems which are interposed with microorganisms are the increased rate of reaction with increased temperature and denaturation of specific proteins at definite temperatures. When these two phenomena are overlaid, we find that at low temperatures the denaturation reaction is insignificant. As the temperature approaches 35°C, the denaturation reaction becomes in most microorganisms[1]. As the temperature is increased above 35°C, the denaturation reaction soon predominates and the microorganism's rate of growth rapidly falls off to zero. There are some microorganisms which can live above the temperature where most microorganisms die off. It has been found that these heat tolerant microorganisms have proteins which resist denaturation at the lower temperature. At 60-65°C the heat resistant proteins are denatured and even the heat tolerant microorganisms soon die off. The microorganisms which grow best at the elevated temperature range between 55 and 65°C are called Thermophilic micro-organisms. Needless to say their rate of metabolism is very

high at these temperatures. The majority of microorganisms which grow best at the lower temperatures are called mesophilic microorganisms. The optimum temperature for the Mesophilic bacteria is around 35°C, they die at 40 to 45°C[1]. Most microorganisms cannot grow in low temperatures since the water which makes up of 80 percent of the cell freezes and prevents further reactions. Some few microorganisms with a minimum of water have the ability of withstanding temperatures slightly below freezing and are known as Psychrophilic microorganisms. The rate of growth of metabolic reactions of the psychrophilic microorganisms are very low.

Table I - Classes of Bacteria According to Temperature Relationship[3]

Class	Approximate Growth Temperature °C		
	Minimum	Optimum	Maximum
Psychrophilic	0°C	10°-15°C	30°C
Mesophilic	15°-25°C	25°-37°C	40°-55°C
Thermophilic	25°-45°C	50°-60°C	60°-90°C

B. Effects of Temperature on Reaction Rate

In any complex system of reactions the slowest one exerts the controlling influence, and the effect of temperature on this controlling reaction determines the influence of temperature on the entire process.

The effect of temperature on any chemical reaction within the temperature range in which the reaction can go on may be expressed by the Arrhenius equation [8].

$$\text{Log } K_T - \text{Log } K_o = \frac{U}{2.3026R} \left(\frac{1}{T} - \frac{1}{T_o}\right) \qquad \text{-1-}$$

Where K_T and K_o = Constants expressing respectively the velocity of the reaction and the absolute temperature T $(273.1 + t^oC)$ and the absolute reference temperature T_o $(273.1 + t^oC)$

R = The gas constant = 1.9885 Calories

U = The temperature constant or characteristic of the reaction.

The theory of Arrhenius was based on the assumption that not all molecules in a given system have the same kinetic energy. Some molecules through random collisions acquire more energy than others, and those energy rich molecules are the ones which are more likely to react than energy poor molecules on collision, the rate of a reaction hence is proportional to the concentration of the energy rich molecules available at a certain temperature, and not on the concentration of all molecules present.

The reactions occuring in the microorganisms seem to be governed by the physiological as well as chemical laws. The foregoing discussion was based on thermo-chemical reactions, but they seem to apply to enzyme catalized reactions.

Actually what enables biochemical reactions to occur at ordinary temperatures is the ability of the enzymes to lower the energy of activation required for the reactions. Since the rise in temperature increases the number of activated molecules by increasing their movement, it increases the rates of biochemical reactions as it would for ordinary chemical reactions.

C. Maximum and Minimum Growth Temperatures

It has been found that as the temperature varies below or above the optimum, cell activity declines and the rate of growth and multiplication slow down. The lowest and highest temperatures at which a cell can grow are called the minimum and maximum growth temperatures, this does not mean that metabolic activity ceases below or above these temperatures but merely means that the death rate is equal to or exceeds the rate of reproduction so that no net increase in the cell population occurs[3].

D. Effect of Temperature on Enzyme Activity

As mentioned earlier in this chapter, the majority of the chemical reactions brought out by living organisms occur at far lower temperatures than would be needed in their absence. For this reason catalysts that lower markedly the activation energy of the reactions are required. These catalysts are supplied by the living organisms as a part of their life process and are known as Enzymes. Hence enzymes can be defined as temperature sensitive catalysts or organic nature, elaborated by living cells and capable of action outside or inside the cell[5].

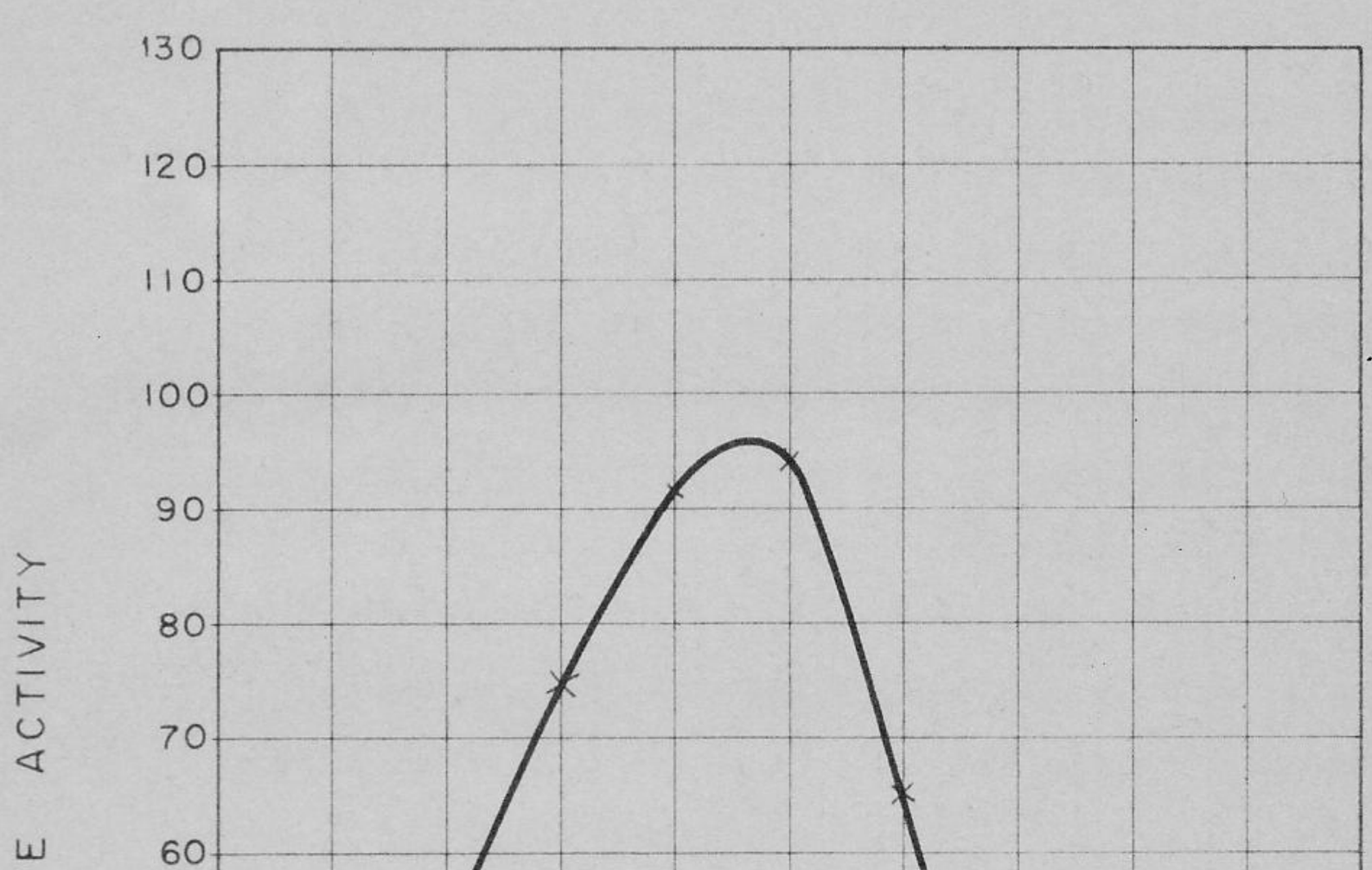
In biochemistry, temperature relationships are often referred to as Q_{10} values, which are the ratio of the reaction rate at a particular temperature to the rate at 10°C lower. A great deal of study has been given to the effect of temperature on the rate of enzyme-induced reactions.

Table II below shows the effect of temperature on the activity of Certain Enzymes.

Table II - Effect of Temperature on Activity of Certain Enzymes[5]

Enzyme	Temperature °C	Q_{10}
Amylase (starch splitters)	10-20	1.34
	15-25	1.59
	20-30	1.44
	25-35	1.27
	30-40	1.17
Pepsin (proteins)	0-10	2.60
	10-20	2.00
	20-30	1.80
	30-40	1.60
Steapsin	0-10	1.50
	10-20	1.34
	20-30	1.26

Fig (3) shows the activity of amylase at several temperatures when hydrolizing starch[5].



EFFECT OF TEMPERATURE ON THE ACTION OF MALT ANALYSE WHEN HYDROLIZING STARCH TO GLUCOSE

FIG. 3

The data in Fig (3) above illustrate the point that increasing temperature has a favorable effect upon biochemical reactions, within limits. As the temperature is increased, eventually a point is reached where the enzyme becomes less active. This change is considered to be due to denaturation of the enzyme. In systems containing living organisms, the adverse effects of high temperature may be explained by considering that the enzymes are denaturized or that the ability of the organisms to produce enzymes has been destroyed. As within a certain temperature range, there exists an equilibrium between the active and denatured enzymes which could be shifted in either direction depending on the temperature change. Since the rate of biochemical reaction is a function of the active enzyme concentration, any decrease in this active enzyme will hence lower the rate of reaction.

E. Effect of Temperature on Transport Through Cell Membrane

Osmosis is the process by which water passes in or out of the bacterial cells. This will mainly depend on the concentration of the solute which forms the environment of the bacterial cells. The bacterial protoplasm contains more dissolved matter usually than distilled water and hence if the bacteria are suspended in distilled water then this water will diffuse into the bacterial cells causing them to swell and perhaps to burst. When such process happens it is known as plasmoptysis[3]. If the cells are placed in a very concentrated solution, water will pass out of the bacterial cells into this solution and the organisms shrink. This is known as Plasmolysis[3].

When the movement of particles through the cell membrane occur either into the cell or outside the cell against a concentration gradient then the process is no more that of simple diffusion[25]. Such a movement which requires work on the port of the cell is known as active transport. The energy required for this work is derived from the metabolic processes.

The effects of temperature on diffusion rate through the cell membrane are shown in Table III including that with $10^{o}C$ rise in temperature. Since the increase in kinetic energy level is only 3 to 4% for each $10^{o}C$ rise in temperature.

Table III - Increase in Rate of Diffusion (Penetration) with $10^{o}C$ rise in Temperature[25]

Name	Q_{10}
Strong electrolytes	1.27
Sugar	1.37
Dextrin	1.41

The increase of 30 to 40% in rate of diffusion is usually attributed to both changes that occur in the viscosity of water at higher temperature and the viscosity of the cell membrane itself. Although the rate of active transport is also expected to double for each $10^{o}C$ rise in temperature, other considerations enter into the picture such as environmental factors including heavy metals, salts, pH, etc. which change this rate considerably[25].

F. High Temperature Effect on Microorganisms

If any bacterium is heated above the maximum growth temperature it will be killed. However, some organisms do grow at abnormally high temperatures, but at the expense of loosing some of their characteristic properties[3]. The time factor is very important in the killing of microorganisms at a given high temperature. The "thermal death time" is very usually a more accurate term to use than the "thermal death point". The thermal death time is defined as the length of time required to kill a certain species of microorganisms in a given medium at a stated temperature[3].

Giese[25] attributes the death of microorganisms to the inactivation of the enzymes in the cell and this inactivation at high temperatures may be due to one or more of the following phenomena:

1- The heat affects enzymes indirectly by degrading the aggregates of which they are a part, of which the denaturation of the protein particles is most significant.

2- It is also noted that dearrangements of the lipids of the cell are the cause of heat injury and the disruption of the lipids leads to death, high resistance of organisms to heat is generally correlated with a high melting point of the lipids laid down in the organisms.

3- The liberation of a coagulating enzyme by heat is suggested as a possible reason for heat injury as heat is known to liberate calcium from the outer portion of the cytoplasm and this calcium is said to liberate a clotting enzyme which gets the cell.

Giese[25] reported two types of thermophiles, the first are those thermophilic bacteria that can withstand high temperatures because they can synthesize enzymes more rapidly than the high temperature destroys them. These bacteria are resistant to heat when nutrients are available and sometimes they require vitamins and amino acids which otherwise they can make at lower temperatures. The other type of thermophilic bacteria are more resistant to heat because they possess enzymes which continue to survive and function even at high temperatures. These organisms can withstand high temperature because of their stronger hydrogen bonding proteins. Stronger hydrogen bonding of the proteins of such organisms is also a reason why such organisms cannot survive at lower temperatures, because the bonding becomes very difficult for normal catalytic action of enzymes.

G. Low Temperature Effects on the Microorganisms

Giese[25] reports that most microorganisms loose their activity as the temperature falls to the lower limits they tolerate. Many organisms will survive for weeks frozen in the ice and will grow normally again when the ice melts[3]. Such microorganisms that are cold-resistant are known as cryophilic. Some bacteria can grow slowly in ice cream at $-10^{o}C$[25].

When the temperature reaches the freezing point, the water surrounding the cell freezes thus increasing the solute concentration in the liquid medium outside the cell. Consequently water diffuses out of the cell and the result

is a concentration of solute inside the cell[25]. Such a high concentration of solute is injurious to the cell and its metabolic functions. However, many cells can endure freezing at -5°C, resuming their normal functions on thawing without apparent injury. Giese[25] explains the importance of the rate of thawing on the microorganisms, slow thawing has two lethal effects, first rapid freezing and slow thawing could enhance the growth of ice crystals inside the cell which can damage both the nucleous and the cytoplasm, second the slow melting increases the electrolyte concentration inside the cell at a higher temperature than that applied during freezing, thus allowing for more denaturing of proteins. Some microorganisms may be injured at temperatures well above the freezing point, the reason Giese[25] explains, could be deduced from the change in respiration rate that such microorganisms go through at that temperature suggesting that the cell cannot exclude certain injurious ions by the process of active transportation through its cell membrane. Arctic organisms are able to withstand cold by dehydration before the onset of winter retaining as little as 25% of their moisture content. Debris in ice allows sometimes for passage of oxygen and allows a contact space for microorganims, thus preventing physical damage of the microorganisms by disruption on freezing.

H. Adaptation of Organisms to Temperature

Temperature variations effect mostly those microorganisms that are in an active state more than those that are dormant. However, Giese[26] states that these microorganisms may gradually become adapted to lower or higher temperature if the change in temperature is small and gradual.

Giese[26] reported that the most extreme example of acclimatization is that of Dallinger who showed that over a period of 7 years flagellates were made to grow at temperatures as high as 70°C

III- EFFECT OF TEMPERATURE ON THE AEROBIC PROCESSES

A. General

Oxygen utilization is generally considered to be the best criterion for measuring the metabolic activity and expenditure of biological energy. The oxygen uptake is a function of both the hydrogen removal and carbon and nitrogen oxidation, the major elements for the production of biological energy[1]. Many investigators resorted to the oxygen utilization rate as an excellent index for determining the characteristics of activated sludges under various operating conditions.

In the following chapter the effect of temperature on oxidation rate as measured by B.O.D. reduction, Oxygen Utilization by Activated Sludges under various temperatures, the adjustment of sludges to these temperature fluctuations, the sludge growth and sludge accumulation, the volatile solids controls of activated sludges, the microbial population, and the effect of temperature on BOD removal and purification will be discussed.

B. Magnitude of the Rate of Oxidation at Different Temperatures

In this respect Gotaas[6] has studied the effect of temperature on the biochemical oxidation on sewage, and his objective was to determine the following:

1- The magnitude of the rate of oxidation at different temperatures.

2- The relationship between the temperature and the rate of oxidation including the formulation for the relationship.

The findings of Gotaas represent a very basic approach in the study of temperature on oxidation rates. Of the many different samples taken by Gotaas on Bicarbonate dilution water and phosphate dilution water and raw sewage, and incubated at temperatures varying between $5^{\circ}C$ and $40^{\circ}C$, and on which BOD tests were performed at different intervals, Fig. 4 below shows the BOD curves for different temperatures.

In investigating the mathematical formulation of the curve of best fit to the biochemical oxygen demand observations, shown on Fig. 4 below, Gotaas observed that the unimolecular equation first proposed by Phelps fit the data better than any of the other formulations studied.

$$X_t = L \quad 1 - 10 - K\ (t - t_o)$$

or $$X_t = L \quad (1 - 10^{-Kt})$$

L = Total demand of the stage

X_t = Oxygen used up at any time

K = Rate Constant for given set conditions

t_o = The value of t at the end of the lag period i.e. the value of t when $X_t = 0$

The "slope method" of Thomas was used by Gotaas to compute the rate constant K, the ultimate stage demand L and the lag period t_o .

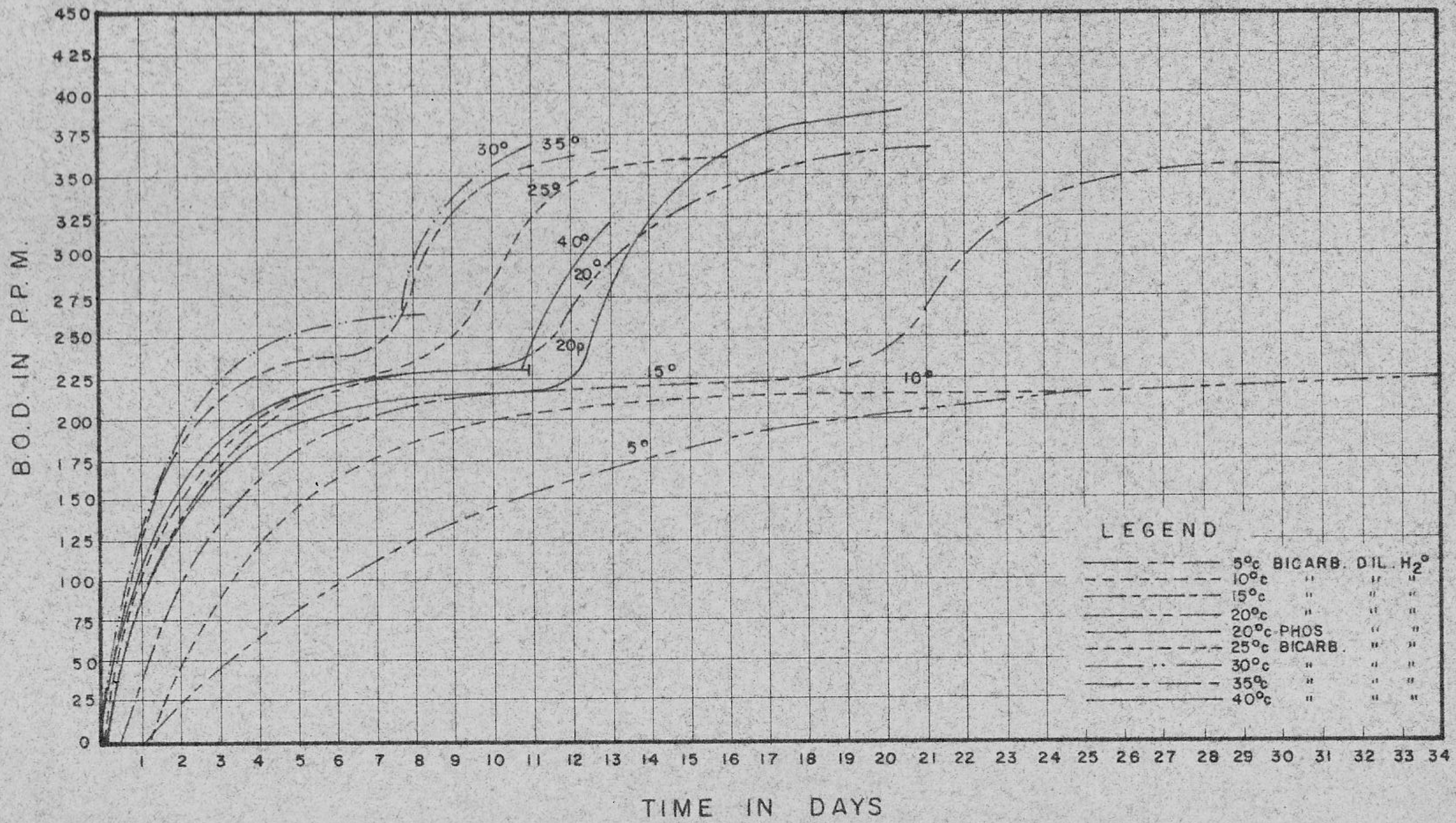

B.O.D. IN P.P.M.
450
425
400
375
350
325
300
275
250
225
200
175
150
125
100
75
50
25
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34
TIME IN DAYS
30°
35°
25°
40°
20°
20p
5°
10°
5°
LEGEND
5°c BICARB. DIL. H2°
10°c " " "
15°c " " "
20°c " " "
20°c PHOS " "
25°c BICARB. " "
30°c " " "
35°c " " "
40°c " " "

FIG. 4

The observed values of K at the different temperatures in bicarbonate and phosphate water are shown below as found by Gotaas[6].

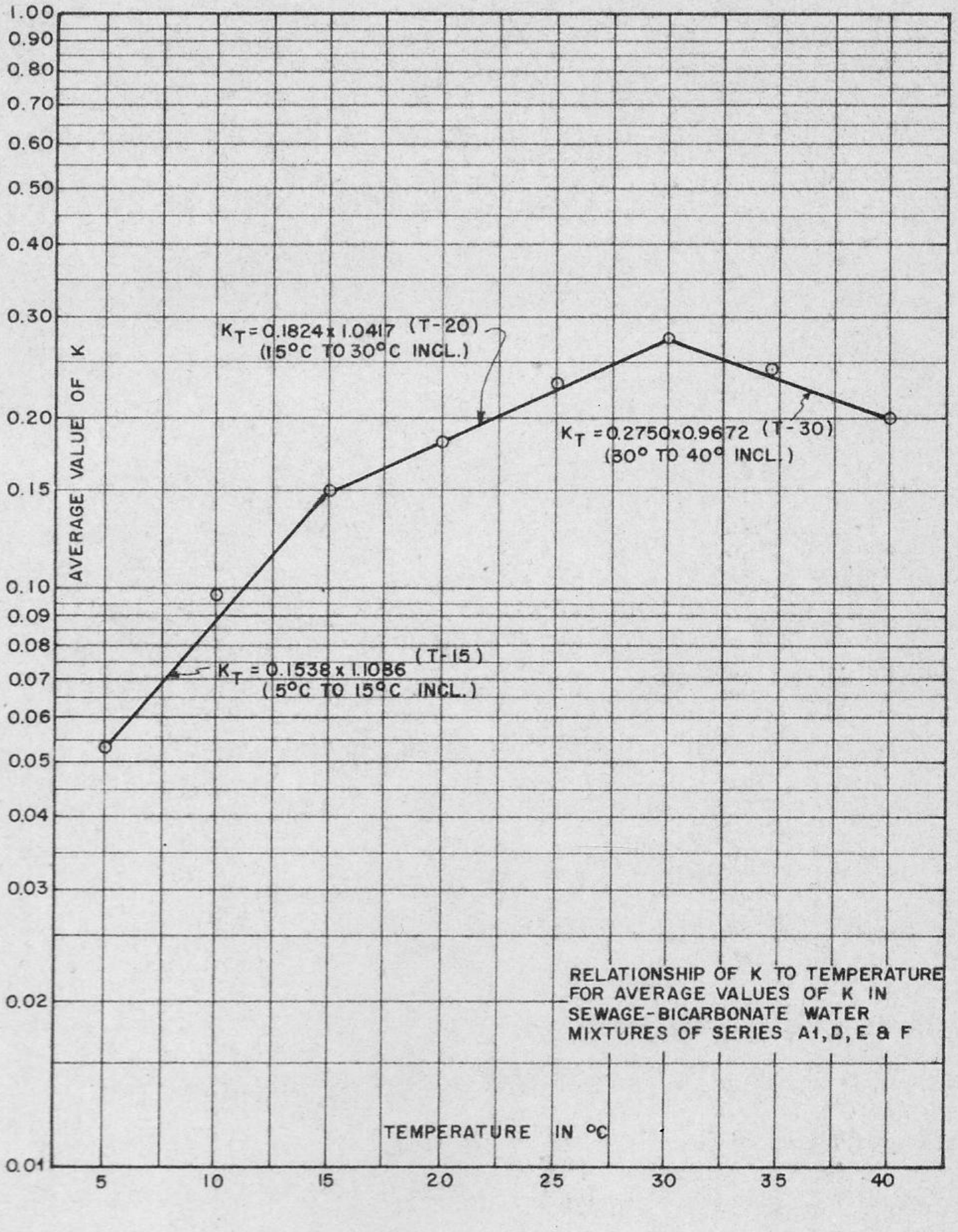
Table IV - Observed Values of K at Different Temperatures

Temp °C	series D*	series E*	series F*	Average Of K Values
10	0.125	0.06412	0.12282	0.09844
15	0.16214	0.11723	0.16090	0.14885
20	0.18718	0.16410	0.24120	0.18091
25	0.18540	0.19337	0.30294	0.22807
30	0.25506	0.25784	0.27091	0.27182
35	0.28417	-	0.22300	0.24098
40	0.21915	0.19719	0.16930	0.19521

Fig. (5) below shows the relationship of K to temperature for average values of K in sewage bicarbonate water mixtures of series D, E and F, from which Gotaas made the following observations for the value of K.

At 15°C, the average of these 15°C, K values is 0.14885, which is about twice as high as the average K of 0.075 that Greenfield and Elder found from six experiements at 14°C. However, it is in the range of magnitude of (0.1 - to 18) computed by Theriault for Adeney's experiments[6].

* Series D, E, and F are the different sewage samples used by Gotaas.



RELATIONSHIP OF k TO TEMPERATURE FOR AVERAGE VALUES OF k IN SEWAGE-BICARBONATE WATER MIXTURES OF SERIES A1, D, E & F

FIG. 5

At 20°C, the average values of K of 0.18091 are much larger than the value of 0.1 found by Phelps and Theriault and much larger than the values of 0.11 to 0.125 reported by Greenfield and Elder.

At 35°C, K values differ here for the different samples, in series E and F, K is smaller than 30°C while in series D it is a little larger.

At 40°C, the K values are all much lower than at 35°C, and in two cases lower than 30°C. This indicates that 40°C is considerably above the optimum temperature for the maximum rate of biochemical oxidation.

It is apparent that the value of K at any temperature for different sewages varies considerably. Also the value of K appears to be considerably larger than the generally accepted value of 0.1 at 20°C, and the related values at other temperatures. The magnitude of K in the temperature range 30°C to 40°C is shown to decrease from a maximum value at about 30°C as the temperature is increased[6].

Several workers investigating the activity of yeasts and bacteria have shown that the value of the energy of activation decreased with an increase in the temperature above 30°C. Hobymueller[6] studied the germination rate of spores of nine different bacilli at different temperatures, and found the rate to be greatest at about 30°C, and that it decreased as the temperature was increased above 30°C. Since biochemical oxidation is to a considerable degree, a function of the

metabolic activity of bacteria, the oxidation rate would be expected to be a maximum in the range of optimum temperature for bacteria.

Gotaas[6] concluded the relationship between the oxidation rate K and the temperature may be closely described by an equation of the form $K_t = a\ T^b$, where T is temperature in degrees C, and (a) and (b) are constants. When this equation is used, there are two temperature ranges in which the temperature effect is uniform, one from below 5°C to about 30°C, for which the average values of (a) and (b) are 0.011 and 0.932 respectively, the other from about 30°C to over 40°C for which the average values of (a) and (b) are 0.045 and 1.058.

C. Oxygen Utilization by Activated Sludges Under Various Temperatures

It seems that the sludge activity varies with temperature in the same manner as was previously shown by the Van't Hoff and Arrhenius relationships for the chemical reactions, namely that the rate of oxidation of organic matter by biological reactions is doubled for each rise of 10°C in temperature in the range of 5° to 30°C.

A study by Sawyer and Rohlich[7] on 4 different sludges and sludge sewage mixtures from four different Wisconsin Cities was conducted to determine whether or not the temperature at which the sludge was grown had any effect on the sludge respiration rate temperature relationship.

The determinations of the oxygen uptake rates were run simultaneously at 25°C, 20°C, 15°C and 10°C, for each sludge and sludge sewage mixture. The results on the oxidation studies are shown on Table V below.

Table V - Oxygen Utilization by Various Activated Sludge Mixtures

Relative rates of oxygen utilization by various activated sludge sewage mixtures expressed in percent based on value 25°C = 100 %

Source of activated sludge mixture	25°C		20°C		15°C		10°C	
	S*	W*	S	W	S	W	S	W
A	100	100	76.1	73.1	49.6	56.9	21.5	33.3
C	100	-	71.8	-	42.1	-	25.6	-
D	100	-	69.2	-	44.8	-	22.6	-
E	100	-	76.3	-	48.0	-	26.4	-
Seasonal Average	100	100	73.35	-	46.1	-	24.0	-

* S = Summer
W = Winter

Base Rate Oxygen Utilization
(i.e. with no feed)

Source of activated sludge mixture	25°C		20°C		15°C		10°C	
	S	W	S	W	S	W	S	W
A	100	100	71.6	67.1	41.9	40.0	24.0	23.5
C	100	100	69.0	71.9	45.3	46.4	25.2	26.4
D	100	100	71.8	70.9	43.3	46.2	20.2	27.8
E	100	100	72.8	74.2	48.3	50.2	26.6	30.1
Seasonal Average	100	100	71.3	71.0	44.7	45.7	24.0	26.9
Yearly Average	100		71.15		45.2		25.45	

Inspection of these results show that within the range of temperatures studied, the effect of temperature on the activity of activated sludge is approximately the same, whatever the temperature at which the sludge is grown.

Assuming that at 25°C the activity is 100% then from table V the oxidation is reported for the different temperatures 20°C, 15°C, 10°C as 73.35%, 46.1 and 24% of that at 25°C respectively, which indicates an increase in rate of oxygen utilization that varies between 2 to 3 times for each 10°C rise in temperature.

Another interesting observation that can be deduced from the above results in table V is the striking similarity between the effect of temperature on the oxygen utilization on the fed sludges and the unfed sludges, namely the effect of temperature is the same whether the sludge is fed or unfed. From which it can be said that the temperature coefficient for sludge - sewage mixtures and sludges endogenous respiration rates are the same[4].

Sawyer and Rohlich[7] computed the relationship between the relative activity of activated sludge and temperature to be $Y = 0.71\ X^{1.54}$ which is shown graphically on Fig (6).

Y = relative activity in percent of that at 25°C.

X = temperature in degrees C.

Although this table was not a final proposal by Sawyers and Rohlich[7] for interpreting temperature effects on oxygen utilization in activated sludges, but it has been arrived at from a series of tests exceeding sixty tests on 4 different sewages.

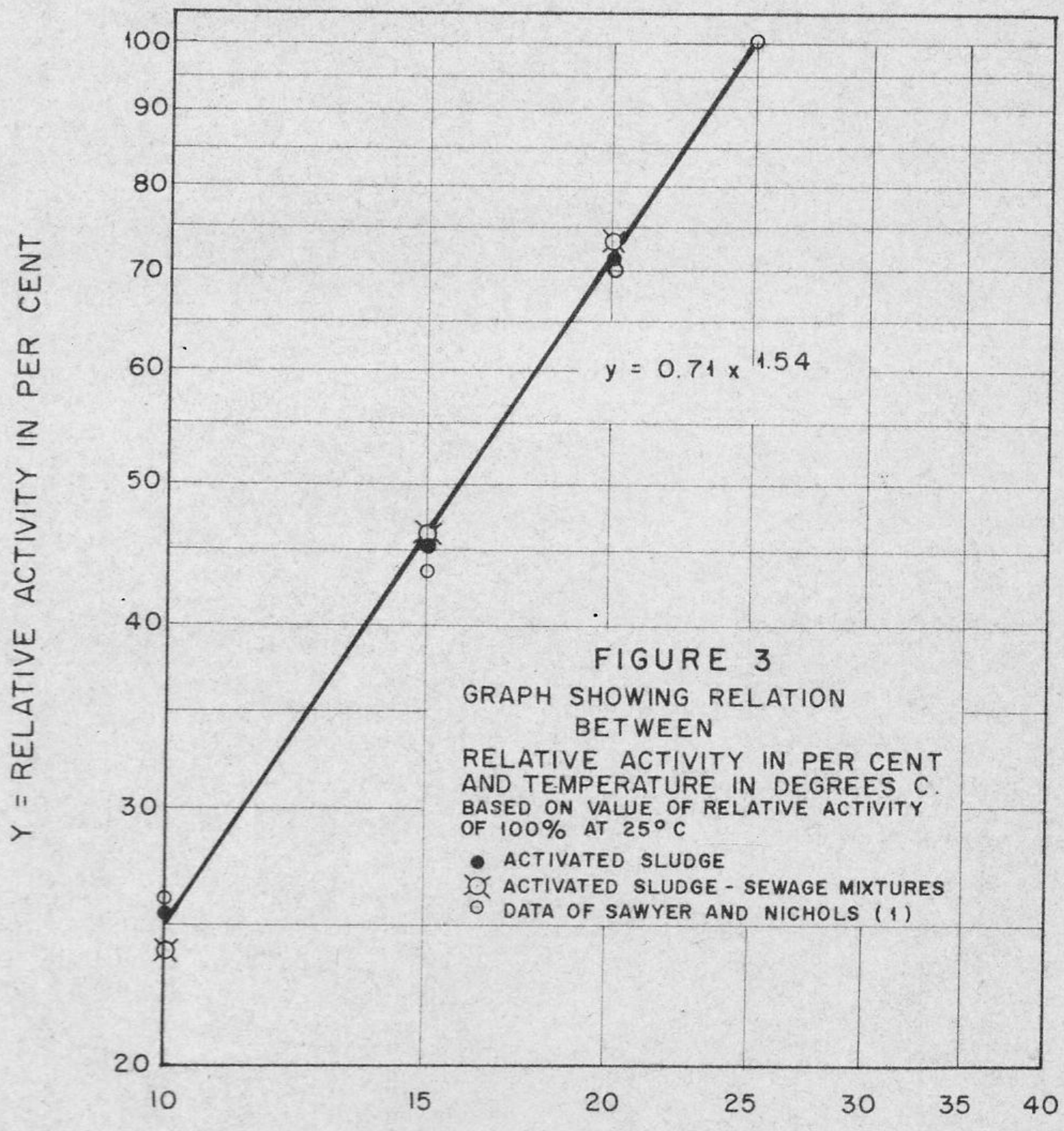

Y = RELATIVE ACTIVITY IN PER CENT
100
90
80
70
60
50
40
30
20
10
15
20
25
30
35
40
y = 0.71 x 1.54
FIGURE 3
GRAPH SHOWING RELATION
BETWEEN
RELATIVE ACTIVITY IN PER CENT
AND TEMPERATURE IN DEGREES C.
BASED ON VALUE OF RELATIVE ACTIVITY
OF 100% AT 25° C
ACTIVATED SLUDGE
ACTIVATED SLUDGE - SEWAGE MIXTURES
DATA OF SAWYER AND NICHOLS (1)
X = TEMPERATURE IN DEGREES CENTIGRADE

FIG. 6

Bloodgood[13] in his studies on activated sludge plant and Indianapolis showed that the oxygen demand was increased about 3 ppm per hour for each rise of one degree between 10°C and 30°C.

Wuhrman[14] in pilot plant studies evaluated the variation in the rate of oxygen uptake of sludges fed by domestic sewage. The oxygen uptake rate values shown on table VI indicate 100% increase in activity with each 10°C rise in temperature for sludges having different basal respirations rate.

Table VI - Rates of Oxygen Uptake of Activated Sludges of Different Basal Respiration at Various Temperatures[14]

Temperature °C	Oxygen uptake of sludge mg02/gm/1		
	Basal Respiration at 25°C =		
	15	20	25
5	3.60	4.80	6.0
10	5.15	6.85	8.57
15	7.35	9.80	12.2
20	10.6	14.15	17.7
25	15.0	20.0	25.0

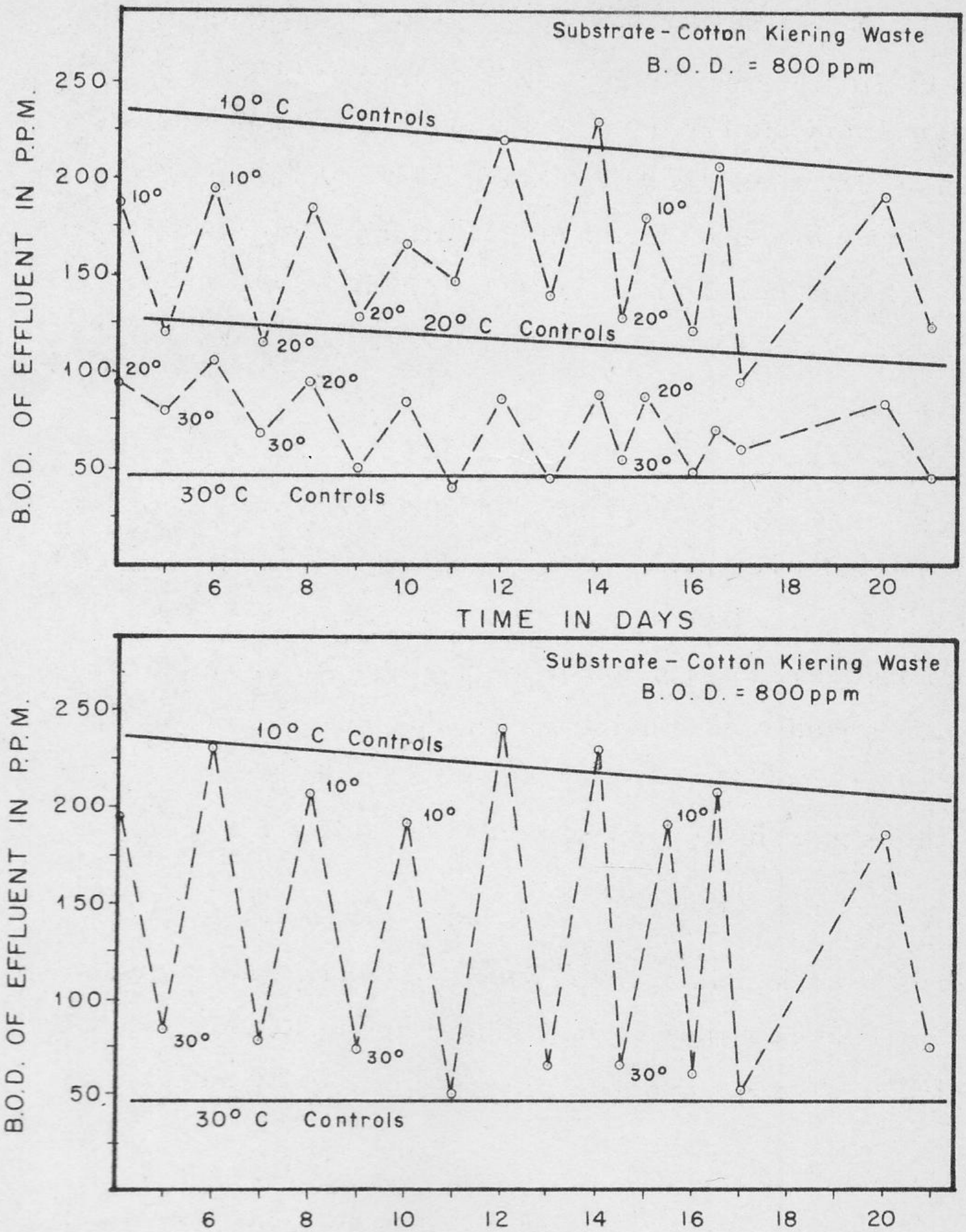
D. Adjustment of Sludges to Temperature Fluctuations

It should be noted that temperature has so far proved to be of major influence in the activated sludge process. Moreover, this importance will be examplified in the industrial wastes treatment processes which mostly operate on intermittent basis thus allowing wide variations in temperature.

The research so far has not definitely cleared this aspect. Sawyer and Wold[15] studied the effect of 12 hours temperature fluctuations between 10°C and 20°C, 20°C, 30°C and 10°C over a period of 23 days. The results shown on figure (7) indicate that the adjustment to temperature increase or decrease was immediate. The small deviations from the controls of the lower and higher temperatures were attributed to the carrying over effects as a result to the residual BOD in the sludge from the previous 12 hours Aeration Period. Following the 23 days of comparing BOD removals due to fluctuating temperatures, a study was made to determine the effect of a 20°C temperature change on the rate of BOD stabilization. The results of this study are shown in Fig (8) from which it may be seen that the rate of removal for a 10°C sludge aerated at 30°C approximated the rate of removal for a 30°C sludge and the rate of removal for 30°C sludge aerated at 10°C was similar to the rate for the 10°C sludge. These data show that the response to temperature change is immediate.

Sawyer and Nichols[16] studied the effect of temperature on the rate of oxygen utilization of activated sludges maintained at different temperatures for 12 hours prior to respiration runs.

Their results shown in Fig (9) indicate that the change in activity with change in temperature is immediate and without any time lag.



EFFECT OF TEMPERATURE VARIATION ON B.O.D. OF EFFLUENTS

FIG. 7

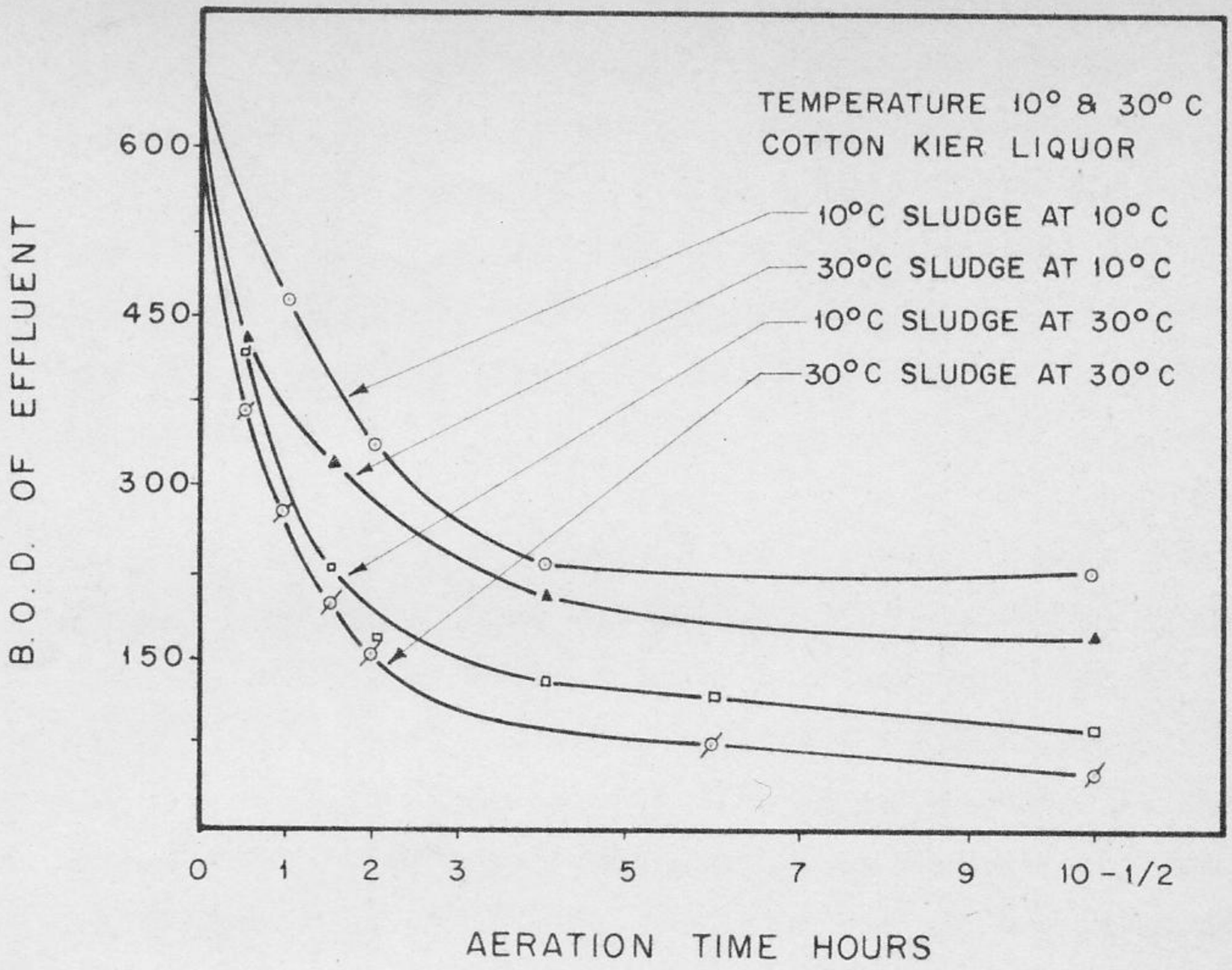


FIG. 8._ EFFECT OF TEMPERATURE FLUCTUATIONS ON RATE OF B.O.D. REMOVAL

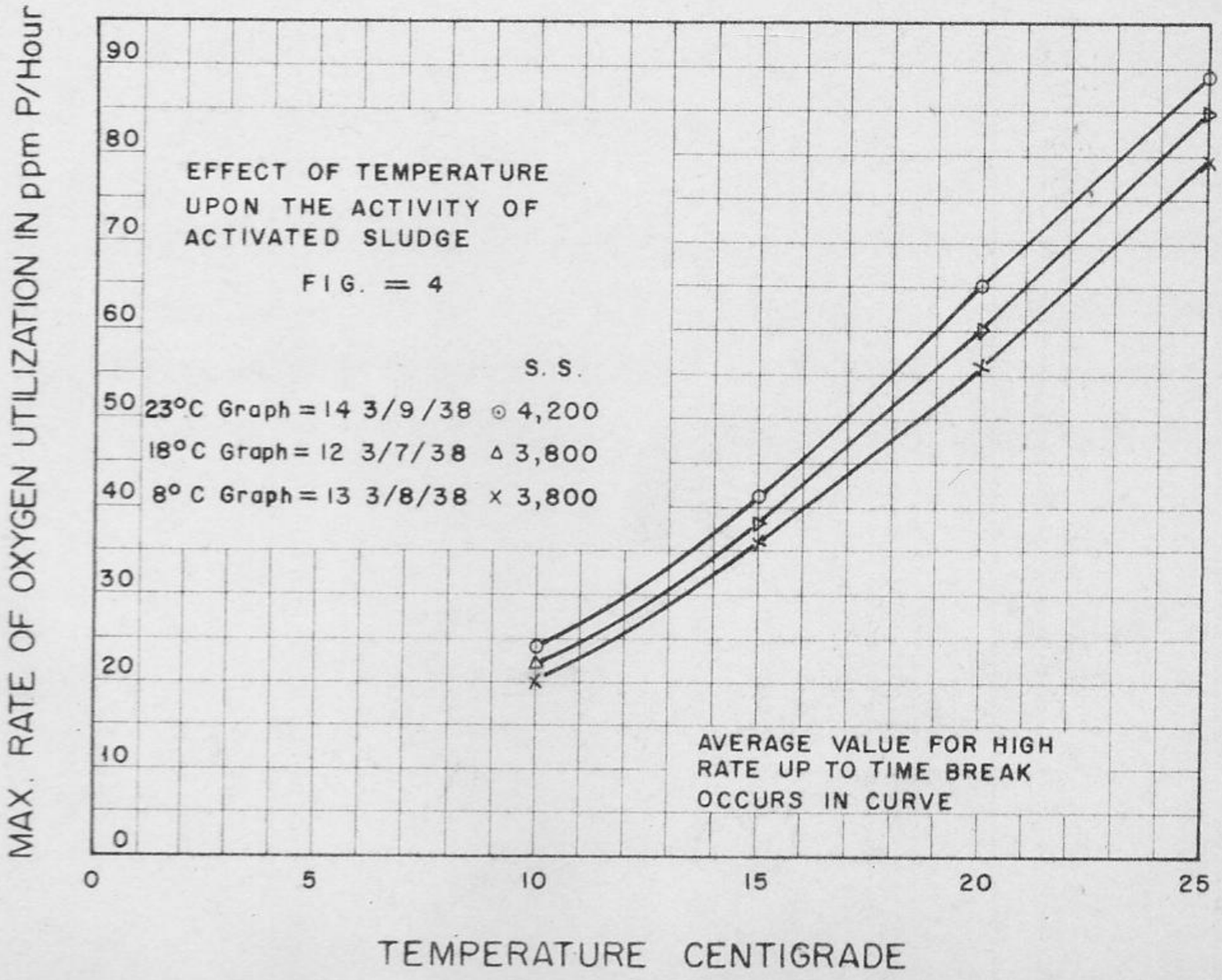


FIG. 9

Ludzack, Schaffer and Ettinger[4] studied the effect of 25°C change in temperature on sludge growth. The sludge was grown at 5°C then moved into 30°C and then the process was reversed. The studies revealed that two weeks were necessary for the sludges to adjust to their new environment, and four weeks were needed for complete adaptation of the sludges from one temperature to another.

Dougherty and McNory[18] studied the effect of a 10°C rise in temperature over a three day period. Four days were needed to get comparable COD removals after a temperature rise from 21°C to 30°C. The initial results indicated an increase in effluent COD from 5 to 230 ppm, after 4 days of maintaining the high temperature the settling characteristics improved and the effluent COD dropped back to 55 ppm. Carrying further the research, the temperature was raised at a rate of 2°C per week up to 46°C was reached, and the following conclusion was drawn from the test results:

1- An activated sludge unit could be operated at a temperature as high as 36°C with no deleterious effect to the culture or the degree of treatment.

2- If in approaching a temperature of 36°C a rapid rise in temperature of 4°C or 5°C occurred, a temporary period of unhealthy conditions was encountered but recovery took place if no further increase in temperature occurred.

3- As temperatures were increased above 36°C, the number and activity of the protozoa began to decrease until at 43°C the culture was devoid of all protozoa.

4- At a temperature of 46°C the degree of treatment was very poor and the experiment was concluded.

E. Sludge Growth and Solids Accumulation

On his study of a laboratory scale activated sludge plant with 7.5 hour detention, Viel[19] reported that most of the excess sludge accumulation occurred at moderate temperatures. At 45°C no excess sludge was formed and at 55°C that what was added was destroyed.

Ludzack[4] reported that sludges fed at high temperatures seem to accumulate less solids than those at moderate temperatures. He attributed this to the increased rate of metabolism at high temperature which results in greater conversion of feed to carbon dioxide and water and consequently less solids accumulation. The figures given were: 40% of the feed COD was converted into solids at 5°C, while only 10% were apparent as solids at 30°C.

Sawyer and Rohlich[7] compared sludges taken from the same plants during summer and winter seasons and found that in general winter sludges show higher percentages of volatile solids than summer sludges.

Sawyer[20] grew sludges at 10°C, 15°C, 20°C and 25°C in the laboratory using 2 gallons aeration tanks immersed in a water bath of various temperatures. The results of Sawyer[20] are shown in table VII below.

Table VII - Effect of Temperature on Sludge Concentration[20]

Temperature °C	10	15	20	25
Increase in suspended solids ppm.	3300	3500	3100	2800

The greater rate of growth of the sludges at 10°C and 15°C as compared to those at 20°C and 25°C can, undoubtedly, be explained by the greater oxygen requirements of the sludges maintained at the higher temperatures. Refer to Fig. 10. High oxygen requirements are probably correlated with high metabolic rates, and as the metabolic rate increases with temperature, the amount of food available for growth diminishes because of the increased amounts of food necessary to maintain the organisms already present. Also judging from the BOD removal data on the same sludges which is shown on table VIII below.

Table VIII - BOD of Effluents Produced by Activated Sludges Fed on Identical Diet at Different Temp.[20]

Temp °C	7th day	13th day	18th day	Ave. Percentage BOD Removal
10°	28.0	23.7	16.4	90.5
15°	10.0	15.4	15.5	94.3
20°	10.5	16.8	12.0	94.5
25°	14.0	13.9	11.0	94.6

CURVES SHOWING RELATION BETWEEN BASE RATE OF OXYGEN UTILIZATION & TEMPERATURE FOR VARIOUS SLUDGES

TEMPERATURE OF SLUDGE AS OBTAINED FROM PLANT

SLUDGE	SUMMER	WINTER
A	19.5°C	13° C
C	20° C	11.1°C
D	17°	9.5°
E	16°	7.5°

LEGEND

SUMMER

WINTER

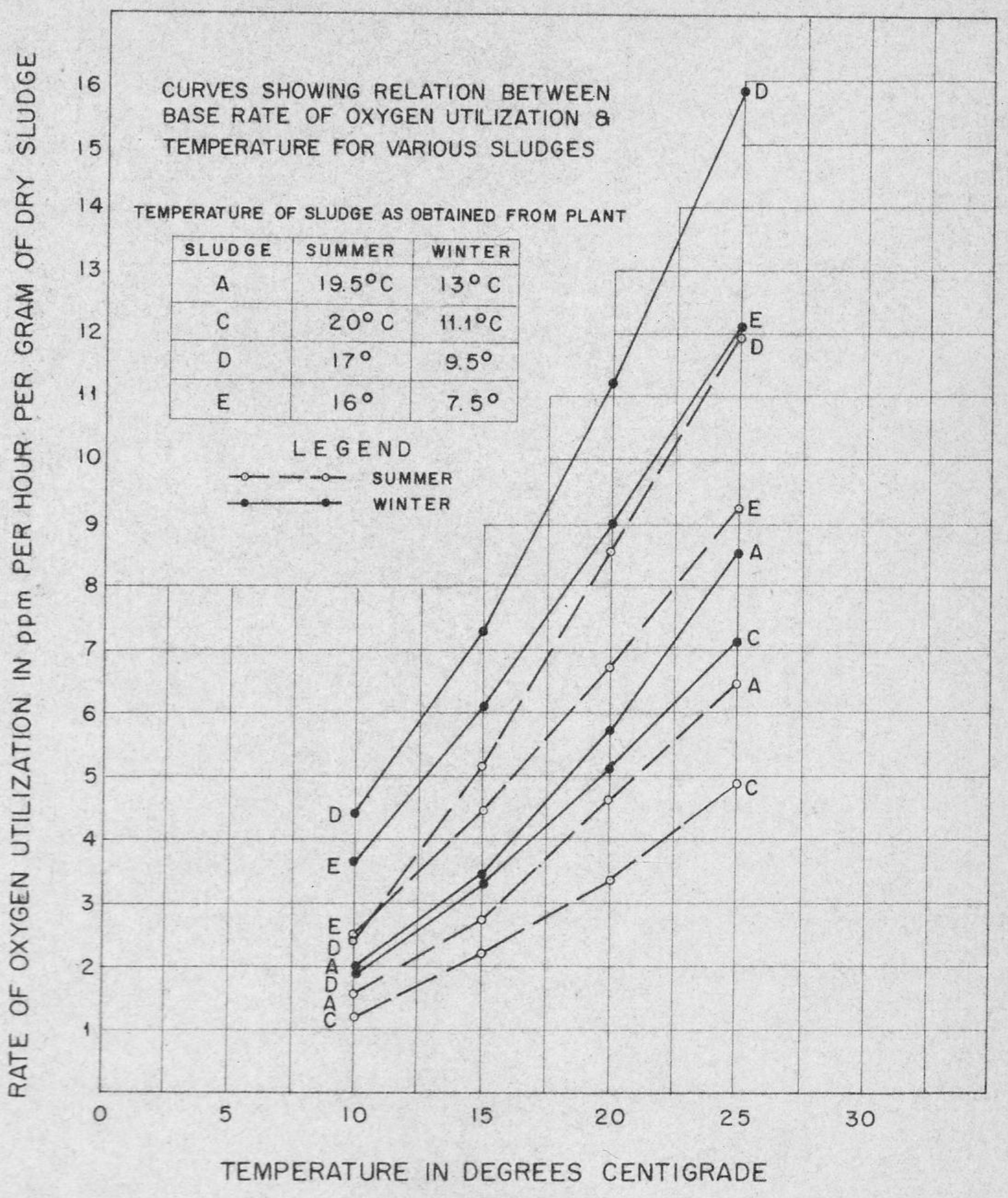


FIG. 10

Sawyer[20] concludes that the slower rate of growth of the sludge maintained at 10°C as compared to that of the sludge maintained at 15°C was due to its inability to utilize all the available food material present, and it should be noted also that the sludge maintained at 10°C, gradually lost its ability to oxidize ammonia nitrogen to nitrites and nitrates, thus, this source of energy was not utilized to its full extent and the growth obtained from it was less than in higher temperatures.

F. Volatile Solids Content of Activated Sludges

The aerobic oxidation of sewage solids or of activated sludge results in a reduction of the volatile solids content as the oxidation progresses. The end result is the development of a sludge with a lower volatile solids content and a much lower requirement for oxygen. Because of the more rapid rate of oxygen usage by activated sludges at the higher temperatures, sludges maintained at such temperatures on limited food supply will have lower volatile solids content than sludges maintained at lower temperature on identical food supplies. In a like manner when different amounts of activated sludge are used to stabilize identical amounts of food, the rate of oxidation will be greatest in case of the highest sludge concentration. Therefore the volatile solids content will be reduced most rapidly and such sludges will contain less volatile solids. These arguments are substantiated by the data on the volatile solids of the various sludges worked on by Sawyer[20] and shown on table IX below.

Table IX - Volatile Solids and Nitrogen Content of Activated Sludge Produced with Various Sludge Concentration and Temperatures

Variables											
Temp°C				Sludge Concentr. Room Temperature				Sludge Concentr. 10°C			
10°	15°	20°	25°	800	1600	2400	3200	800	1600	2400	3200
%	%	%	%	%	%	%	%	%	%	%	%
V.S.	76.8	76.6	74.8	73.0	76.3	73.7	72.6	72.5	77.6	77.6	76.9	76.6
N.	6.49	6.61	6.34	5.97	6.49	6.16	5.82	5.77	6.26	6.45	6.48	6.44

The use of low concentrations of activated sludge results in the development of sludges with high volatile solids content and high activities as measured by the base rates of oxygen utilization. Because of the high activity of such sludges they must be removed rapidly from final settling tanks and kept in contact with dissolved oxygen to keep them in condition. The chief advantage to be gained in using low activated sludge concentration is the decreased oxygen requirements to stabilize a given BOD load. This is a result of the conversion of large quantities of the available food BOD to new sludge growth and, consequently, smaller amounts are oxidized to carbon dioxide, water and nitrates. The use of high concentrations of activated sludge results in the production of sludges with lower volatile solids content and lower base rates of oxygen utilization. Such sludges may be kept for much longer periods in the absence of aeration and more compact sludges can be obtained.

Heukelekian, Orford and Manganelli[26] found a general relationship for the amounts of volatile suspended solids accumulation as a function of temperature

$A = F^{kt} B - M^{kt} S$

A = lbs of V.S.S. accumulated per day

S = lbs of V.S.S. in mixed liquor

B = lbs of BOD fed per day

M,K, and F are constants

t = temperature

This equation at 20°C becomes

$A = 0.5 B - 0.055 S$

G. Microbial Population

The above literature have indicated the possible effect of temperature on microorganisms. Viel[19] stated that the greatest number of microorganisms existed at 8°C whereas the greatest variety of microorganisms existed between 26°C and 29°C.

Dougherty and McNory[18] studied the effect of high temperature on the activated sludge process and reported that noticeable changes took place on the microbial culture as the temperature was increased.

At 21°C, the culture contained Vorticellae, Paramecium, Arcella, Peranema, and rotifers plus a larger number of bacteria. At 36°C the population and activity of the protozoa were affected adversely. At 40°C the sludge contained very few rotifers, paramecium and Arcella, and all appeared very

sluggish. At 43°C the culture was devoid of all protozoa and the bacteria population was beginning to diminish.

Ludzack, Schaffer and Ettinger[4] found that activated sludge at 5°C are full of numerous free swimming ciliates which tended to scatter the floc resulting in a greater sludge volume and settling difficulties. On the other hand they reported that sludge at 30°C contained dense floc masses with the absence of finely divided material that appeared in the low temperature sludge. Also the high temperature sludge contained nomatoid rotifers, nematodes and other varieties of stalked ciliates.

H. <u>BOD Removal and Purification</u>

The writer tried to accumulate as much as possible the findings of investigators on the effect of temperature on the different aspects of the rate of oxidation of sludges, suspended solids accumulations in activated sludges, the change in nature of these sludges with temperature and many other pertinent findings in this field. However, the main purpose is to evaluate the effect of temperature on the treatment methods by activated sludge systems and mainly the reduction in BOD by such systems. The findings of the investigators on this latter were quite variable and in most cases are not in line with the significant effect that temperature has on the rate of oxidation of organic matter and the activity of micro-organisms as has been shown.

Viel[19] reported that the data obtained from many activated sludge plants indicated little difference between winter and summer efficiencies.

Viel[19] stated that even if the purification efficiency is poor at low temperature, it ultimately improves with time. This he demonstrates on a temperature of 1.5°C at which BOD removal was 50% in the first week, in the eleventh week the efficiency has climbed up to 88%.

Wuhrman[14] did not report any significant relation between effluent quality and temperature of sewage. Sawyer[20] reported equivalent BOD removals under all conditions except at low temperatures which were accompanied with low concentration of suspended solids.

After a series of experimental results on different wastes Ludzacketel[4] reported that COD removal was increased by 5 to 10% as the temperature was increased from 5° to 30°C.

Bloodgood[21] analysed the operational data of the Indianapolis activated sludge plant and reported that the capacity of the plant more than doubles with each 10°C increase in temperature. He attributed the significant effect of temperature on the rate of purification at the Indianapolis treatment plant to the fact that the plant was always loaded to the optimum and the detention time was at a minimum,which might not have been the case with other treatment plants that other authors have obtained their results, hence the change of temperature had a significant effect on the purification rate.

Bloodgood[21] prepared the graph shown below in Fig. (11) where he correlated the rate of treatment per mg. of aerator capacity and the temperature at a chosen BOD concentration

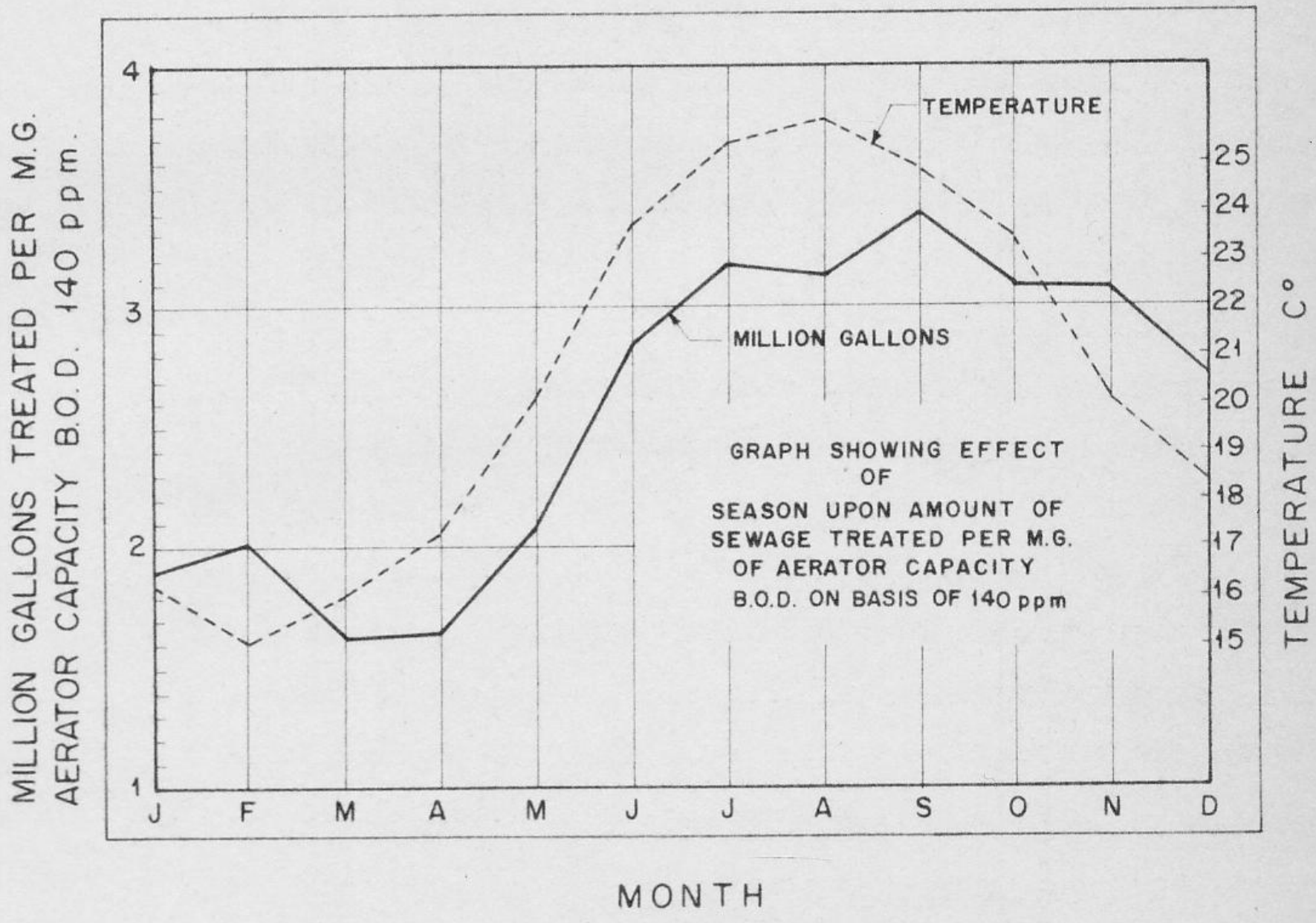

TEMPERATURE
MILLION GALLONS
GRAPH SHOWING EFFECT OF SEASON UPON AMOUNT OF SEWAGE TREATED PER M.G. OF AERATOR CAPACITY B.O.D. ON BASIS OF 140 ppm
MILLION GALLONS TREATED PER M.G. AERATOR CAPACITY B.O.D. 140 ppm.
TEMPERATURE C°
4
3
2
1
25
24
23
22
21
20
19
18
17
16
15
J F M A M J J A S O N D
MONTH

FIG. 11

of 140 ppm. It can be seen from the graph that the BOD results lagged one month behind the temperature variation but the two curves would almost coincide if shifted this lag period. Hence other things being equal, the rate of treatment in an activated sludge plant is directly related to temperature.

Howland[22] pointed out the fact that other factors such as the waste concentration, plant design, and mode of operation also have a direct effect on the oxidation rate. In heavily loaded plants Howland gave two pronounced reasons for the above effect;

a. There is less oxygen remaining in the aeration tank effluent if the tank is highly loaded and thus reducing the effect of oxygenation in it.

b. The adsorption is decreased with increase in temperature and if the plant is heavily loaded then higher temperatures would have an adverse effect on removal.

Howland[22] developed the following equation for the BOD removal as related to temperature

$$P_2 = 1 - (1-P1)^{1.035\ (T_2-T_1)}$$

where

P_2 = BOD fractional removal at T_2

P_1 = BOD fractional removal at T_1

T_1 and T_2 = temperature in ^{o}C

C = 1.035 and was obtained from operational data on activated sludge plant.

Sawyer[20] showed that at relatively high concentrations of mixed liquor the temperature was not a determining factor in BOD removal as that with low concentration of mixed liquor that are less than 1600 ppm. In this latter a marked decrease in BOD removal was noted at lower temperatures.

Sawyer and Rohlich[7] suggested that there is a compensating factor which may explain the uniform BOD removal of activated sludge plants at the various seasons of the year, although it has been demonstrated that the oxidation rate varies markedly with the temperature. They explain this compensatory factor on the basis that sludges fed identical amounts of food; those at the lower temperatures will be overfed with respect to those at the higher temperatures, because of the lower rates of stabilization of food at the lower temperatures. As a result, there is an increase in volatile solids content and activity at the lower temperatures. This increase in growth will compensate for the decrease in the oxidation rates at low temperatures.

IV. EFFECT OF TEMPERATURE ON THE REACTION RATE OF ANAEROBIC BACTERIA

So far in this literature review, only the effect of temperature on aerobic bacteria was discussed and mainly its oxidation of the organic matter in activated sludge systems. However, the anaerobic systems are important especially in sludge digestion. Although the purpose of this paper is only to investigate the effect of temperature on the aeration only systems, but a brief mention of the anaerobic system will also throw a light on the subject.

The effect of temperature on the reaction rate of anaerobic bacteria as determined by Gordon Fair and E. Moore[17] is shown on Fig (12) below.

This figure shows that from 10° - 28°C the change in rate caused by temperature appears to agree well with the law of Arrhenius, mentioned previously, as evidenced by the straightline fit of data. Calculated on this basis, the value of U in this range is approximately 12000 within this range, therefore there seems to be no disturbing factors. At about 28°C, a marked deviation from this behaviour is observed. The increase in rate becomes appreciably less than that demanded by the law of Arrhenius, and a little further on, at about 33° - 35°C, the increase in rate ceases altogether. Beyond this region a decrease in rate occurs which continuous up to about 42°C. On the range of 28° to 42°C, therefore, digestion rate for plain sedimentation sludge is apparently no longer governed directly by straight forward chemical phenomena.

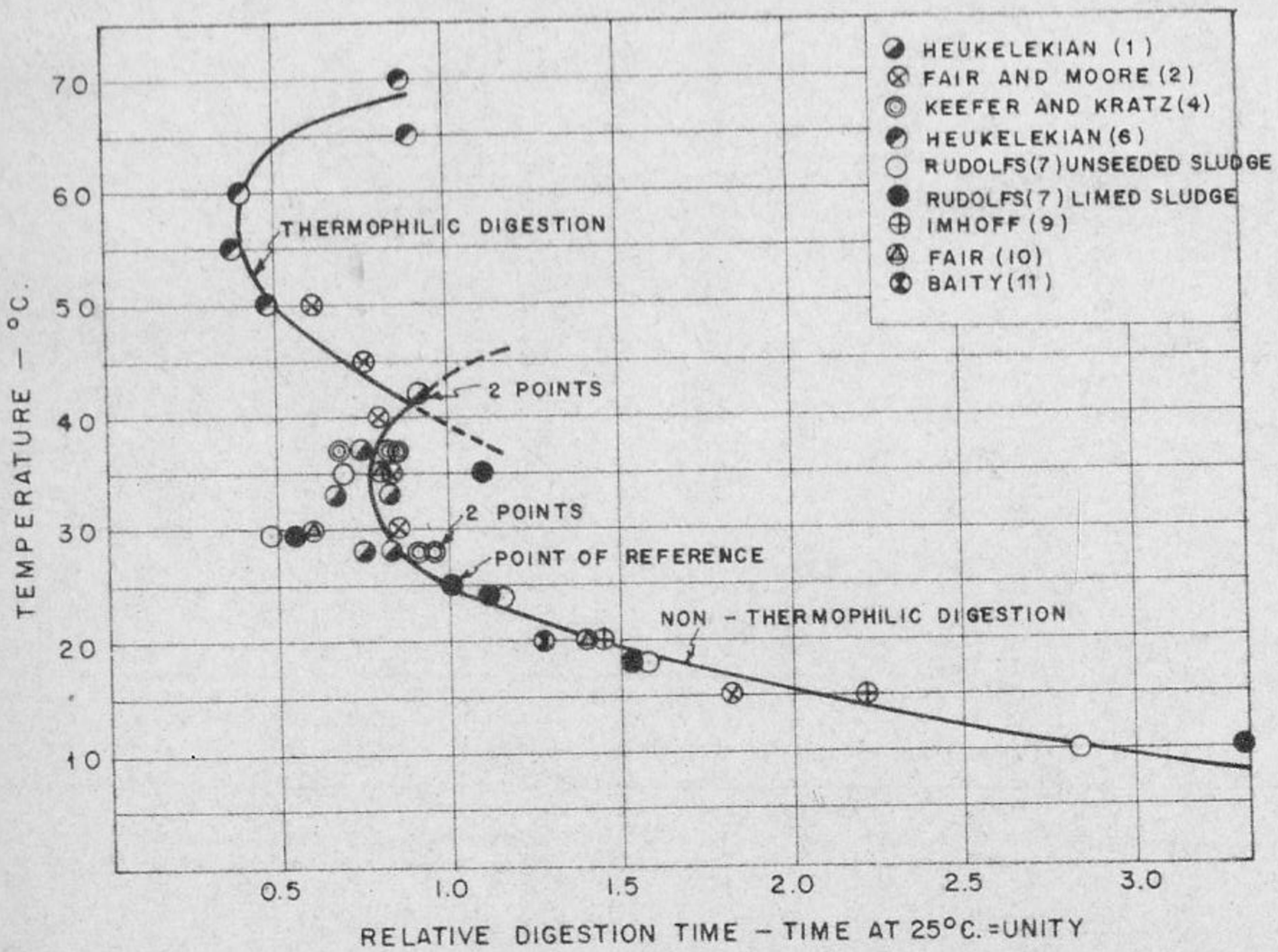


FIG. 1.—RELATIVE DIGESTION TIME OF PLAIN-SEDIMENTATION SLUDGE DIGESTED AT TEMPERATURES OF 10° TO 70° C. DIGESTION TIME IS REFERRED TO TIME REQUIRED AT 25° C.

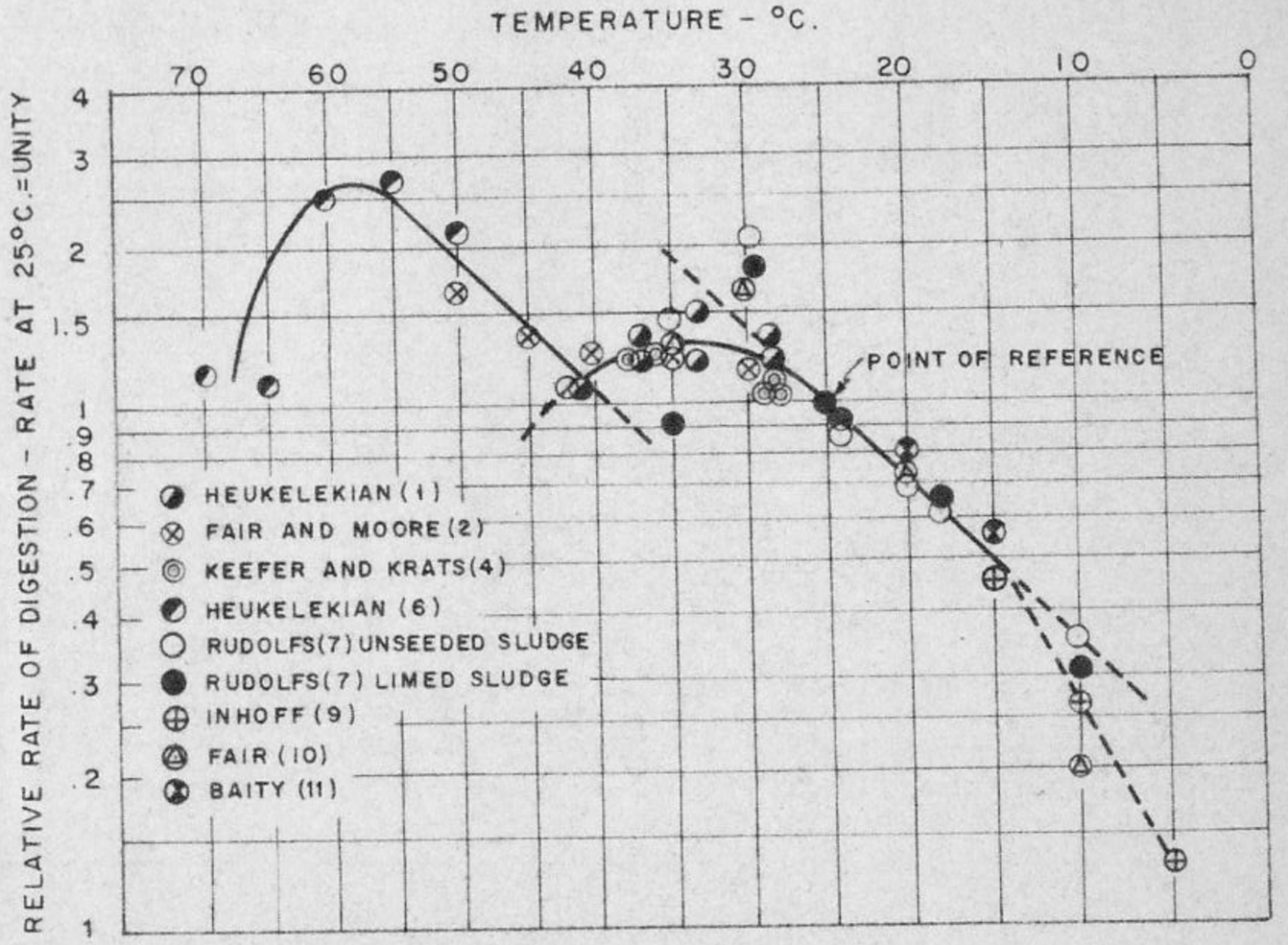


FIG. 2.—RELATIVE DIGESTION RATE OF PLAIN-SEDIMENTATION IN SLUDGE DIGESTED AT TEMPERATURES OF 5° TO 70° C. OVER-ALL RATE IS REFERRED TO OVER-ALL RATE AT 25°C. VERTICAL SCALE IS LOGARITHMIC. HORIZONTAL SCALE IS BASED ON THE RECIPROCAL OF THE ABSOLUTE TEMPERATURE (°C. + 273.1).

FIG. 12

Some other influence comes into play, disturbing the progress of the reaction and ultimately hindering it so much that the rate decreases at higher temperatures. A new factor is introduced at about 42°C, it seems that thermophilic organisms predominate at this temperature. From this point up to 55°C, the increase in rate with temperature again seems to follow Arrhenius Law, and it is interesting to note that the value of U appears to be the same within the limit of accuracy as that for non thermophilic digestion. Chemists regard the value of U as an indication of the type of chemical reaction involved, since it has been found that reactions of the same type show the same value of U.

It may be of interest to note that the observed rates for the range of 28° to 42°C lie between the rates expected according to Arrhenius Law for thermophilic and for non thermophilic digestion. At 35°C the observed rate lies almost midway between the two expected rates indicated by the dotted lines.

This zone may, therefore, represent a region of transition from non thermophilic to thermophilic digestion. Possibly both types of organisms are active within it, but operating under more or less adverse conditions. Contrary to what has been said are also the findings of Gordon Fair and Edward Moore (17) about the digestion of activated sludge which showed no drop in the intermediate range. The rate of digestion increased along the whole way from 25°C to 50°C.

V. MATHEMATICS OF THE COMPLETE MIXING AERATION ONLY SYSTEMS*

A. The Mathematical Considerations key to understanding the complete mixing activated sludge process lies in understanding the fundamental biochemistry of the aerobic biological metabolism. The stabilization of organic matter of wastes is brought about by the metabolic reactions of micro-organisms that live within the aeration tank. It has been shown that the bacteria are the primary microorganisms for the removal of organic matter in activated sludge systems. Therefore, knowledge of bacterial metabolism should permit evaluation of the metabolic reactions in the activated sludge system.

Bacteria metabolize organic matter to produce protoplasm for the creation of new bacteria. Protoplasm is not a single chemical substance but a mixture of hundred of different chemical molecules. Bacteria can produce all of these hundred of different chemical molecules from a single organic compound and simple mineral salts. To do this the bacteria must be able to break down the organic molecule being metabolized and synthesize all the molecules for protoplasm.

The synthesis reactions require energy, which the bacteria obtain by oxidizing a portion of the organic molecules being metabolized. Although protoplasm is a complex material,

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*Mathematical equations and discussions are as per McKinney's original ref. No. (12).

it is relatively uniform in its chemical composition. The energy requirements to produce a unit of protoplasm are constant regardless of the chemical materials being metabolized[12]. Thus a definite relationship exists between energy and synthesis.

Bacteria require a small amount of energy to maintain normal functions such as motion and enzyme activation. The basal energy requirements of the bacteria has been designated as endogenous respiration. It has been shown that the endogenous respiration reaction is a continuous reaction that results in the metabolism of certain components of protoplasm[12].

Even when excess nutrients are available, endogenous metabolism proceeds with the breakdown of protoplasm. The significance of this is simply that all the organic matter metabolized enters into the synthesis reactions, with the net protoplasm or sludge accumulation being the difference between the synthesis reaction and the endogenous reaction[12].

Organic matter metabolized =

Protoplasm synthesized + Energy for synthesis (1)

Net protoplasm accumulation =

Protoplasm synthesized - Endogenous respiration (2)

Mackinney[12] believes that the solution to equations (1) and (2) above lies in the selection of common units. The oxygen - equivalent scale is the best suited for these equations because the 5-day BOD test is used for a measure of the organic matter being metabolized, the oxygen uptake

is related to the energy expended for both synthesis and endogenour respiration, and the oxygen equivalent of protoplasm can be obtained from COD analysis. These basic equations can only be solved between two points in time, because a change in time is required for the reactions to progress. With a change in time, the equations can be written as rate equations

$$\frac{dFm}{dt} = \frac{dMs}{dt} + \frac{dOs}{dt} \qquad \text{- 1b -}$$

and

$$\frac{dMp}{dt} = \frac{dMs}{dt} - \frac{dOe}{dt} \qquad \text{- 2b -}$$

in which Fm is the ultimate oxygen demand of the organic matter metabolized, Ms denotes the oxygen equivalent of the protoplasm synthesized, Os refers to oxygen uptake for synthesis, t is time, Mp refers for net protoplasm accumulation as oxygen equivalent, and Oe is the endogenous oxygen uptake. Because there is a direct relationship between synthesis and energy, it is possible to equal these two factors:

$$\frac{dOs}{dt} = K_1 \frac{dMs}{dt} \qquad \text{- 3 -}$$

and here

$$\frac{dF}{dt} = (1 + K_1) \frac{dMs}{dt} \qquad \text{- 1c -}$$

which gives a direct relationship between the protoplasm synthesized and the organic matter metabolized.

The coefficient K_1 accounts for the energy expended on various physiological activities of the cells such as motion, regeneration of enzymes and the maintaining of different concentrations of solutes across the cell membranes. McKinney[12] reported a value of 0.5 for K_1, i.e. one third of the ultimate oxygen demand of the organic matter being metabolized is oxidized while the remaining two thirds is converted to protoplasm. Taking the oxygen equivalent of protoplasm as 0.7, McKinney then concluded that 1 mg of ultimate oxygen demand would produce 2/3 x 0.7 mg or 0.47 mg of protoplasm. In the absence of a sufficient outside source of energy the microorganisms will start metabolizing part of their own protoplasms, a process known as endogenous metabolism.

As the food becomes limiting, some of the bacteria start dying and thus releasing the remaining nutrients in their protoplasm to the outer environment. These released nutrients will be used as a source of food for other bacteria. A residual organic fraction of the bacteria remains, which is insoluble and not metabolized by other bacteria. The cell walls form part of this residual which is believed to be complex polysachoride. McKinney[12] stated that endogenous respiration is a function of the living or active portion of the bacterial mass.

$$\frac{dOe}{dt} = K_2 \, Ma \qquad -4-$$

Where Ma is the active or living mass of organisms, K_2 denotes the endogenous respiration constant and Oe is the endogenous oxygen utilized.

The significance of endogenous respiration lies in the reduction of cell mass with increased detention times.

Examination of the basic pattern of bacterial growth indicates that the rate of growth is either a function of the bacteria concentration or a function of the food concentration. In an unlimited supply of organic matter and with a small bacteria population, the rate of bacteria growth is limited by the bacteria's ability to process the organic matter

$$\frac{dMs}{dt} = K_3 Ma \qquad -5-$$

The rate of increase of bacterial mass continues in proportion to the mass of active bacteria until a point is reached when food becomes the limiting factor.

The ratio of food to active bacteria F/M, determines the point at which food becomes the limiting factor.

$$\frac{dMs}{dt} = K_4 F \qquad -6-$$

It is recognised that synthesis of new protoplasm is still related to the active bacteria in the system, but as long as the F/M ratio is below critical value, the food concentration is the controlling factor. Therefore synthesis can be

expressed in terms of the food remaining. The food limiting situation controls microbial growth in complete mixing activated sludge systems.

It is self evident that a batch fed system with a low initial microbial population and a high concentration of biodegradable organic matter will start with the log growth phase and then progress through the transitional phase and end up in the food limiting phase, thus following the classical growth curve. However, a continuous flow system with a definite flow and a specific concentration of substrate will operate at one point along the growth curve when it reaches equilibrium. The first basic step in the study of a continuous flow system is to be able to determine the phase of growth in which the system is operating. It is unfortunate that no sound criteria are available to determine the growth phase for continuous flow systems[8].

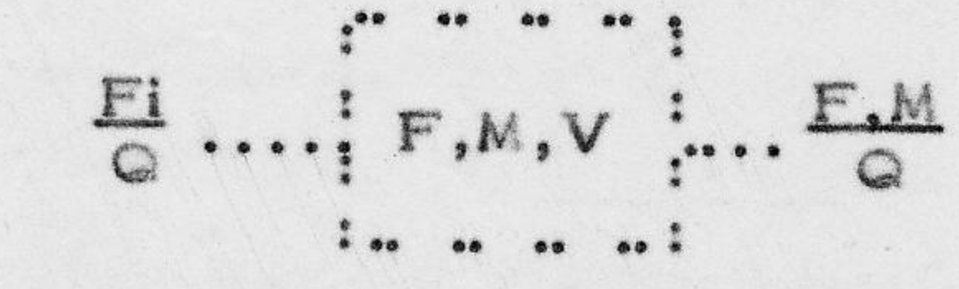
McKinney[12] stated that above a critical food microorganism ratio F/M, the rate of synthesis is related to the mass of active cells in the system, and below this value it is a function of the remaining food concentration. The critical F/M ratio suggested by McKinney[12] was 2.1, based on the ultimate oxygen demand of the food remaining unmetabolized and the weight of active microbial mass. Earlier works of McKinney suggested a value of 2.5. The F/M criteria suggested by McKinney has definite practical significance, however it is necessary to obtain more exact values of F/M as well as to investigate the range of values of F/M for which growth is in the transitional phase and to

be able to determine the factors that affect the growth in this phase.

In a system similar to that used by the writer in this study, and which consists essentially of a reaction vessel into which reactions flow at a steady flow rate and from which products emerge at the same rate, can be defined as an aeration-only form of complete mixing activated sludge. The contents of this aeration tank are continuously mixed, to approximate the ideal condition of complete mixing, so that the entire growth medium is instantaneously and uniformly dispersed throughout the vessel. In such a system the growth takes place under steady state conditions; that is, growth occurs at a constant rate and in a constant environment. Such factors are pH, concentration of nutrients, metabolic products and oxygen, which change inevitably during a normal "growth cycle" of a batch fed system, are all maintained constant in a continuous system. Moreover, these factors can be controlled by the investigator. If all the nutrients are present in excess, if the contents of the tanks are sufficiently aerated, so that the oxygen supply is always abundant, and if the organic substrate feed is kept constant, then the temperature change is the only controlling factor which differentiates the three units set up in this experiment.

B. Aeration Only Systems

If the organic matter in the metrical feed, Fi, is added continuously to the aeration tank shown in figure below



Aeration only complete mixing activated sludge system

at an average rate Q, then the organic concentration, F, in the aeration tank of volume Va, is increased by the addition of fresh organic matter and is decreased by metabolism and the displacement of mixed liquor by the incoming wastes. This can be mathematically expressed as follows:

$$Va \frac{dF}{dt} = Q\,Fi - QF - K_5\,Va\,F \qquad -7a-$$

Va = volume of aeration tank

Q = quantity of inflow

Fi = organic matter in the inflow

F = organic matter concentration in the aeration tank

t = time

If we divide equation (7a) by Va we have

$$\frac{dF}{dt} = \frac{Q}{Va} Fi - \frac{Q}{Va} F - K_5 F \qquad -7b-$$

in which

$\frac{Q}{Va}$ is the reciprocal of the aeration time, t, thus

$$\frac{dF}{dt} = \frac{1}{t} Fi - \frac{1}{t} F - K_5 F \qquad -7c-$$

In any given activated sludge system, equilibrium is reached when $\frac{dF}{dt} = O$, i.e. the concentration of the microorganisms in the aeration tank remain constant,

therefore $$O = \frac{1}{t} Fi - \frac{1}{t} F - K_5 F \qquad -7d-$$

multiplying by t gives

$$O = F_i - F - K_5 Ft \qquad -7e-$$

Solving for $$F = \frac{Fi}{K_5 t + 1} \qquad -7f-$$

McKinney[12] concludes that the organic concentration in the aeration tank as well as in the effluent when the organic concentration is limiting, will be related to the incoming organic concentration and the aeration period. The above equation hence relates the variables in a declining growth state where the food is limiting. McKinney[12] suggested a K_5 value of 15 mg/l ultimate oxygen demand removed per mg/l ultimate oxygen demand remaining per hour at 20°C.

It is important to stress the fact that for a complete mathematical solution equation -7f- should have included a term

for endogenous respiration and a term for the amount of substrate released by lysis and death. As both of these terms are function of Ma, including them would complicate the mathematics appreciably. McKinney[12] assumed that K_5 and F accounted for both endogenous respiration and lysing. The mass of the bacteria in the system may be calculated in a similar manner. The bacteria in the raw wastes are less than 1% of the bacteria in the aeration tank, so that the rate of change of bacteria in the aeration tank is equal to the bacteria synthesized less the endogenous respiration less the displaced bacteria.

$$V_a \frac{dM_a}{dt} = K_6 V_a F - K_7 V_a M_a - Q M_a \qquad -8a-$$

in which K_6 is the synthesis constant and K_7 is the endogenous respiration constant.

Dividing by V_a yields

$$\frac{dM_a}{dt} = K_6 F - K_7 M_a - \frac{Q}{V_a} M_a \qquad -8b-$$

$$\frac{dM_a}{dt} = K_6 F - K_7 M_a - \frac{1}{t} M_a \qquad -8c-$$

At equilibrium $\frac{dM_a}{dt} = 0$

$$0 = K_6 F - K_7 M_a - \frac{1}{t} M_a$$

$$M_a = \frac{K_6 F}{\frac{1}{t} + K_7} \qquad -8e-$$

This equation relates the active mass of bacteria in the system to the incoming wastes and the aeration time. K_6 is a growth coefficient having the units of mg per liter volatile active mass per mg/l ultimate oxygen demand remaining per hour. K_7 is an endogenous respiration constant having the units of mg/l decrease in active mass per mg/l active mass in the aeration tank per hour.

From equation -8c-

$$F = \frac{Fi}{1 + K_5 t}$$

or $$F = \frac{Fi - F}{K_5 t}$$

substituting this value of F in -8e-

We have $$M_a = \frac{(Fi-F)\, K_6}{K_5 (1 + K_7 t)}$$

or $$M_a = \frac{C\,(Fi - F)}{K_7 t + 1} \qquad \text{-9-}$$

where $C = \frac{K_6}{K_5} = 0.47$ when Fi and F are given in terms of ultimate oxygen demand ( ).

When the value of F is found small in comparison with the value of Fi, it can be neglected, thus reducing equation -9- to the following form

$$M_a = \frac{0.47\ Fi}{K_7 t + 1} \qquad \text{-9a-}$$

McKinney[12] suggested a K_7 value of 0.114mg/l decrease in active mass per mg/l active mass per day at 20°C.

Equation -9a- gives the active mass of bacteria in the system. However, the active mass is not the only volatile suspended solids in the aeration tank. Endogenous respiration yields an inert volatile solids mass. The total mass of volatile suspended solids, M, will be the sum of the active mass and the mass formed by endogenous metabolism[12].

$$M = M_a + M_e \qquad \text{-10-}$$

in which M_e is the volatile suspended solids formed from endogenous metabolism. However, M_e is directly related to M_a. The change in the rate of build up of endogenous mass in the aeration tank is equal to the endogenous respiration less the displaced solids

$$\frac{dM_e}{dt} = K_8 M_a - \frac{1}{t} M_e \qquad \text{-11-}$$

At equilibrium $\frac{dM_e}{dt} = O$

or $\frac{1}{t} M_e = K_8 M_a$

$$M_e = K_8 M_a t$$

Substituting in equation -10-

$$M = M_a (1 + K_8 t) \qquad \text{-11a-}$$

The constant K_8 represents the fraction of endogenous metabolism resulting in inert volatile organic matter, it has been found to have a value of 0.096 per day at 20°C.

The oxygen utilization in the aeration tank is related to the synthesis reactions and to the endogenous respiration.

$$\frac{dO}{dt} = K_9 F + K_2 M_a \qquad -12-$$

At equilibrium, the total oxygen utilized will be

$$O = (K_9 F + K_2 M_a)\, t \qquad -12a-$$

The oxygen demand of the effluent is related to the organic matter discharged in the effluent and the active mass of microbial solids. Normally, the effluent oxygen demand is measured as 5-day BOD.

$$\text{Effluent BOD} = F + K_{10} M_a \qquad -13-$$

in which F is the effluent organic matter in terms of 5-day BOD and K_{10} is the endogenous metabolism constant at 20°C over a 5-day period, given as a value of 0.6[12].

C. Evaluation of the K Constants Mentioned in the Mathematical Equations

Some of the K constants are true constants whereas others are in reality variables, dependent on temperature. The temperature dependent K values create the most problems, stated McKinney[12].

The writer mentioned previously the fact that chemical reactions indicate that the rate of these reactions doubles for each 10°C rise in temperature between certain limits. Biological reactions are affected by temperature in the same fashion as pure chemical reactions within more defined limits. McKinney[12] states that between 5°C and 35°C, the rate of biological reactions double with each 10°C temperature increase, but he concludes that additional research is necessary to clarify the temperature effect in the thermophilic range.

1. The relationship between synthesis and energy is fixed regardless of temperature. McKinney[12] gives the value of $K_1 = 0.5$ when utilizing oxygen - equivalent data for microbial mass and organic matter metabolized. Thus, 1/3 of the ultimate oxygen demand of the organic matter being metabolized is oxidized and the remaining 2/3 is converted into protoplasm. Because protoplasm in activated sludge systems is measured more often in mass units than in oxygen equivalent units, conversion can be made by multiplying the oxygen equivalent units by 0.7. Thus, the maximum quantity of protoplasm formed in activated sludge systems or in any bacterial system is 0.47. These synthesis energy relationships are based on studies with pure culture bacteria as well as with mixed bacterial cultures as occur in activated sludge.

2. The endogenous metabolism constant, K, is temperature dependent. Data obtained from Warburg studies by McKinney[12] indicated that at 20°C, K_2 is 0.007 mg/l of O_2 per liter active mass per hour, when M_a is in mass units. In activated sludge systems, nitrifying bacteria generally build up to permit complete conversion of excess ammonia nitrogen to nitrate nitrogen.

It has been found that the endogenous metabolism of bacteria releases ammonia nitrogen that the bacteria can oxidize. For this reason, most studies on endogenous respiration of activated sludge are high by the nitrifying oxygen demand. With nitrification, K_2 has an apparent value of 0.01 mg per liter of oxygen per mg per liter active mass per hour. Although the nitrification oxygen demand must be considered in calculating the total oxygen demand, it is not significant in the reduction of active mass due to endogenous respiration.

3. <u>K Constants K_3 and K_4</u>

Although the synthesis-oxidation relationship is not temperature dependent, the rate of synthesis is temperature dependent. It has been shown that above a critical food microorganisms ratio F/M, the ratio of synthesis is related to the mass of active cells in the system, and below this value it is a function of the remaining food concentration. The growth of

bacteria in a batch culture differs considerably from that of the continuously fed culture. In the batch culture, the rate of growth changes from being dependent on the mass of microorganisms to the food concentration, in the continuously fed culture, it is possible to hold the growth rate at a fixed level either dependent on the mass of the microorganisms or on the food concentrations.

McKinney[12] quotes that both Mohanrao and Von Emde operated systems for which food was the limiting factor in microbial growth. Their results indicated that K_4 for a continuously fed system would have a maximum value of 7 mg/l active mass per mg per liter ultimate oxygen demand per hour. To produce this mass would require metabolism of 15 mg/l ultimate oxygen demand per mg/l ultimate oxygen demand per hour remaining. Their results extrapolated to the log growth phase would indicate a K_3 value of 15.

4- Value of K_5 Constant

The value of K_5 by Mohanrao and Von Emde is 15 mg/l ultimate oxygen demand removed per mg/l ultimate oxygen demand remaining per hour. Usually K_5 is given in terms of daily removal instead of hourly removal, the daily value of K_5 is 360 mg/l ultimate oxygen demand removed per mg/l ultimate oxygen demand remaining per day. The value of K_5 does not change if F and F_i are given in terms of ultimate oxygen demand or 5-day BOD. The above value for K_5 is for 20°C.

5- Value of K_6 Constant

The value of K_6 at 20°C is dependent on the units for F. When F is given in terms of ultimate oxygen demand, K_6 is 0.47 K_5, 7 mg/l volatile active mass per mg/l ultimate oxygen demand remaining per hour or 168 mg/l volatile active mass per mg per liter ultimate oxygen demand remaining per day. With F given in 5-day BOD, K_6 is 250.

6- Value of K_7 Constant

The endogenous respiration constant K_7 is related to K_2, being the decrease in active mass rather than just the oxidized fraction of the active mass. The value of K_7 is 0.006 mg/l decrease in active mass per mg/l active mass in the per hour system or 0.114 per day.

7- Value of K_8 Constant

The constant K_8 is the fraction of the endogenous metabolism that results in inert volatile organic matter in the system. The value of K_8 is 0.0015 per hour or 0.036 per day at 20°C.

8- Value of K_9 Constant

The oxygenation constant, K_9, is related to both K_5 and K_6 and has a value of 5 mg/l oxygen utilization per mg/l ultimate oxygen demand remaining per hour or 7.5 mg per liter oxygen utilization per mg per 1.5 day BOD remaining per hour.

9- Value of K_{10} Constant

The oxygenation of the effluent suspended solids yields a definite oxygen utilization per unit of suspended solids. Over the 5-day incubation period at 20°C, the oxygenation constant K_{10}, has the value of 0.6 for carbonaceous metabolism or 0.9 for both carbonaceous and nitrogenous metabolism.

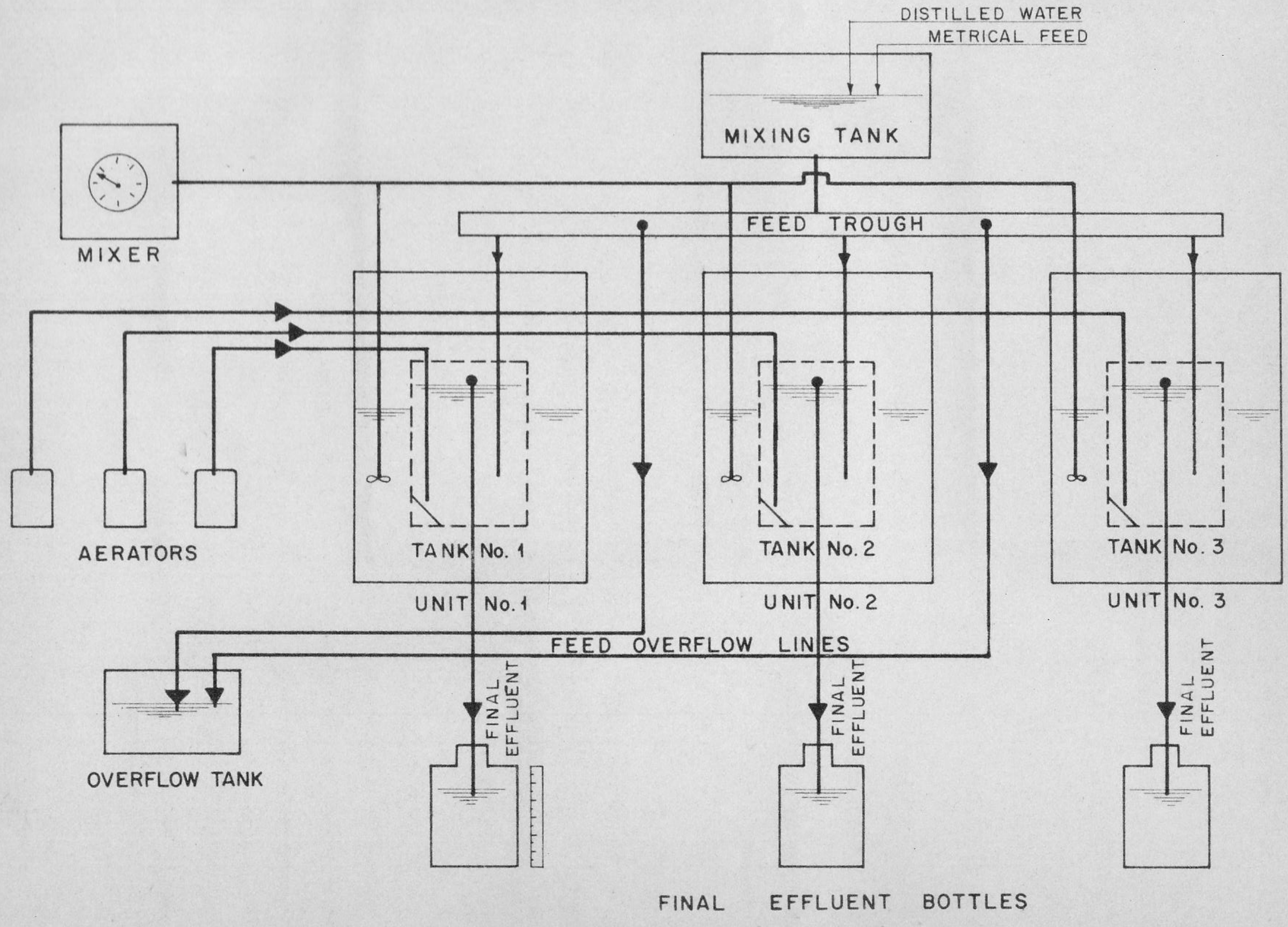
VI- LABORATORY PROCEDURES

A. Description of Apparatus

An ideal complete mixing system is one in which the contents of the culture vessel are well stirred so that the influent is instantaneously and uniformly dispersed throughout the vessel. A laboratory pilot plant was designed to approach so closely as possible these conditions. The details of this system are shown in Fig. 13.

Three units were constructed, having a liquid capacity of 7.7 liters. The exterior walls were made of 1/8 inch plexiglass while the base was made of 1/4 inch plexiglass. Each of these units had a rectangular section of 10 x 15 cms. The feed was mixed in five gallon bottles, and the effluent was collected in 4 gallon bottles, these effluent bottles were graduated in liters so that a daily record could be made of the rates of flow in and out of the units. These plexiglass units will be referred to as the aeration tanks in this paper.

Latex tubing were used for feed lines and effluent lines as well as for air lines. Porous aquarium stone diffusers were used as aerators. Two aerators were installed in each unit and were placed at different corners of the tank bottom. The air was supplied by means of air compressors of adequate capacity. The feed was supplied to the aeration tanks by gravity under the available static head. However to have a uniform quantity of flow distributed to each of the



FLOW DIAGRAM

FIG. 13

three tanks a steel trough was used with an overflow device. This trough will allow a constant head of liquid over the tanks and thus will avoid the change of rate of feed due to the change of the liquid level in the feed bottles. The feed in the aeration tanks was introduced in the opposite direction of the overflow to allow complete mixing of the contents of the tank with the feed. The air circulation in the tank created a circulatory movement which helped a lot the instantaneous mixing of the feed with the tank contents.

- Corner strips were installed in the aeration tank to minimize the possibility of having dead spots.

- Each of the three aeration tanks was submerged in another bigger steel tank containing the water bath which has a constant temperature of 27°C, 35°C and 40°C respectively. The water temperature was controlled by means of very sensitive thermostats that can control the temperature within 1/10 of a degree C. The thermostat was directly coupled to a relay which puts on and off an immersed 400 watt heater in the water bath.

- The water bath was agitated continuously by means of an electric stirrer. The surface of the water bath was covered with a layer of oil to minimize evaporation losses.

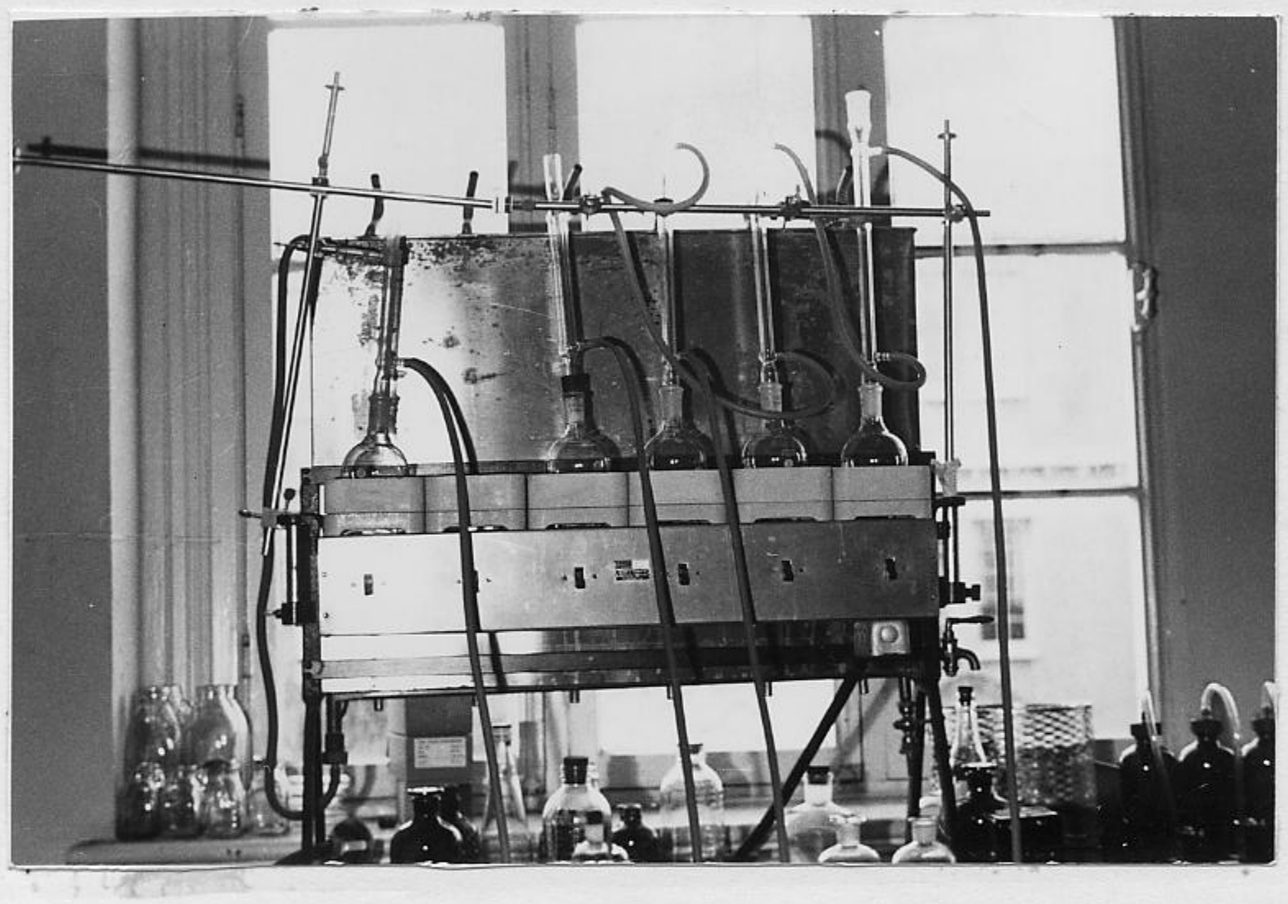
- The evaporation losses in the aeration tanks were taken care of by slight addition of distilled water at various intervals of the day.

- The slight difference of temperature between the water bath and the aeration tank contents due to aerating the contents of the later tank, was adjusted by highering the setting of the temperature in the water bath slightly thus rendering the temperature of the aeration tank exactly as desired. This calibration was always checked by taking constant temperature readings of the aeration tanks.

- Photographs of the entire set up are shown on the following pages.

- Liquid metrical was used as the feed because it represents a complex nutritionally balanced substrate. Liquid metrical which was used in this experiment contains 7.4 percent proteins, 2.1 percent fats and 11.6 percent carbohydrates, the balance being made up of water and traces of vitamins and minerals.

- Distilled water was used for mixing the feed in order to avoid any detrimental effects to the growth in the aeration tank due to uncontrolled chlorine dosages in Beirut Water. Previous experimental work on effect of substrates on the complete mixing activated sludge system by Aziz Abu Samra [8] has revealed that metrical with distilled water has yielded a satisfactory growth in the aeration tank.



COD TEST

TEMPERATURE CONTROL

TOP VIEW OF APPARATUS

PH MEASUREMENT

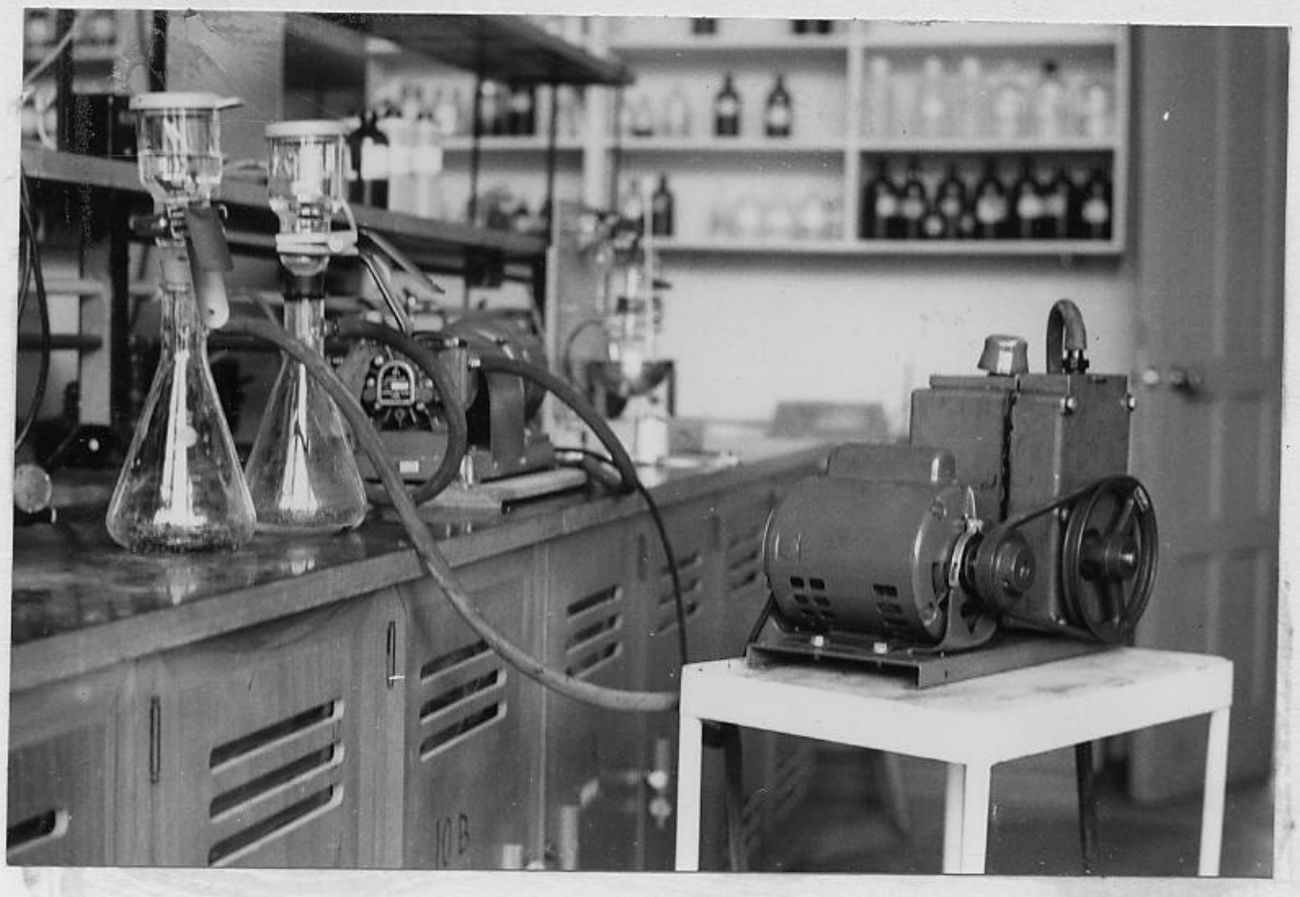
B. Start-up of Experiment

Each unit was seeded with 1.5 liters of domestic sewage obtained from the St. George sea outfall. The units were then diluted to full capacity with distilled water and aerated overnight. Regular feeding was started the next morning at a continuous flow rate of 7.7 liters in 16 hours hence allowing a period of 16 hours detention in the aeration tank. The concentration of the feed was 4 ml/l of metrical in distilled water. The pH of the feed was about 6.8 to 7.0.

Thus the units were started on April 7, 1967. The growth in the aeration tanks was checked by microscopic observations and by suspended solids tests. Measurement of pH was made at regular intervals at the start in order to keep it in the desired range of 6.8 - 7.5. After two weeks of continuous feeding the observations have shown that the units have attained equilibrium. The suspended solids were about 350 mg/l , microscopic observations have revealed a nice growth in all three tanks, of a good animal population consisting of flagellates amoeba, free swimming ciliates, rotifers, and others.

C. Testing Procedures

All tests were performed at room temperature which was about 23° to 25°C. Samples were analysed for total chemical oxygen demand (COD), soluble COD, 5-day biochemical oxygen demand (BOD), and suspended solids. .



SUSPENDED SOLIDS TEST

MEASURING EFFLUENT

MICROSCOPICAL OBSERVATIONS

COD analysis were made on the feed, and the mixed liquor total and soluble. 5-day BOD analysis were made on the feed and the mixed liquor total and soluble. Suspended solids was made on the mixed liquor. Most samples were taken 6 hours after the start of a fresh feed.

Emphasis was made on the conditions in the aeration tank rather than those in the effluent. Thus a sample of about 600 ml. was siphoned from the aeration tank of each unit whenever a run was made on this unit. The 5-day total and soluble BOD, the total and soluble COD, and the suspended solids of this sample were determined measurements of pH and dissolved oxygen were also taken.

Suspended solids samples from the aeration tank were collected all through the period of testing and two runs for volatile solids were made over them. However due to the limiting size of the sample that can be taken while the test is under run, a volatile solids test was made on the sample in the aeration tank by filtering a large sample, just before terminating the experiment, through a coarse filter.

D. Analytical Techniques*

1- Chemical Oxygen Demand

The technique used for COD determination was a modification of the method described in Standard Methods[9]. The modified method used a 10 ml. sample volume. Each sample was refluxed for two

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*The modified techniques applied were adopted from Abu Samra[8] laboratory procedure.

hours in the presence of 5 ml of N/4 potassium dichromate, 15 ml concentrated sulphuric acid and 0.2 gm. silver sulphate.

After refluxing the excess dichromate was titrated with approximately N/20 ferrous ammonium sulphate, using ferroin as indicator. A blank consisting of 10 ml. demineralized water plus the reagents was refluxed along with the sample.

The same technique was used to determine the soluble COD. The sample for the soluble COD was obtained by flocculating the microorganisms with 0.5 gms per liter of lime and one gram per liter of alum. The supernatant was then withdrawn and its pH adjusted to pH of about 7.5 with 1 N HCL or IN NAOH; after which it was filtered through a millipore filter (0.45 micron pore size). 10 ml of the filtrate were used for the determination of the soluble COD. The filtrate was also used for the determination of the soluble BOD and for a DO test to determine the initial dissolved oxygen in the BOD bottle.

It was also necessary to run soluble COD tests on samples from the aeration tank of each unit, using the filtrate of a non-flocculated sample, in order to make sure that the process of flocculation did not remove any of the remaining soluble organic matter. This was done at irregular intervals.

Because COD exerting compounds are washed from membrane filters, hence the millipore filter was prewashed with 250 ml. of demineralized water in all soluble COD determinations in order to eliminate any error that it could introduce in the value of the soluble COD or soluble BOD.

2- Biochemical Oxygen Demand

BOD tests were performed in accordance with the procedure described in Standard Methods[9]. The dilution water seed was taken from each of the units for which the run was being made. The BOD of the mixed liquor tended to yield very low values as a result of the precipitation of the solids, shaking the bottles once every day tended to yield better results. This technique was followed throughout all determinations.

3- Dissolved Oxygen (DO)

The dissolved oxygen test was performed as described in the Standard Methods[9]. The Alsterberg (Azide) Modification of the Winkler Method was used.

4- pH Determination

pH determination were made by means of glass electrodes and a Bechman # 2 model pH meter.

5- Suspended Solids

The suspended solids in the mixed liquors and effluents were determined by filtering a 20 to 40 ml. volume of

sample through a millipore filter (type HA filter having a pore size of 0.45 microns). The filter was placed in an aluminum weighing dish, dried for one hour at 103°C, dessicated for one hour exposed to the atmosphere for ten minutes and weighed to the nearest ten thousands of a gram. The filter was then placed on a ground glass filter holder. A ground glass funnel was placed on top of the filter and held with a clamp. The sample was transferred into the funnel with a volumetric pipette and a vacuum was applied to the side arm flask below the filter apparatus by means of a vacuum pump. After the liquid was extracted, the filter paper was placed back in the aluminum weighing dish. The sample was then dried at 103°C for one hour, dessicated for one hour, exposed to the atmosphere for ten minutes and weighed to the nearest ten thousands of a gram.

6- Inert Solids

Samples from the tests for suspended solids were collected all through the period of operation and two runs for inert solids were made on them. This was necessary because dispersed growth made it difficult to obtain a large enough sample for an inert solids determination in one run. A porcelain crucible with a removable lid was used in all inert solids determination. The crucible was burned at 600°C for one hour, left to cool in the muffle furnace to about 200°C dessicated for an hour, exposed to the atmosphere for ten minutes and weighed to the nearest ten thousand

of a gram. The suspended solids samples were left to cool in the muffle furnace to about 200°C dessicated for an hour, exposed to the atmosphere for ten minutes and weighed to the nearest ten thousands of a gram. The difference between the two weights gave the inert weight of the solids, while the weight of suspended solids was obtained from the summation of the weights of all the suspended samples used in the determinations.

A third run for inert solids was made by filtering a large sample of mixed liquor through a coarse filter. The microorganisms retained on the filter were scraped by a knife and transferred to a crucible which was burned at 600°C and weighed as described in the above paragraph. The crucible and its contents were then dried at 103°C, dessicated for one hour, exposed to the atmosphere for ten minutes and weighed to the nearest ten thousands of a gram. After this the crucible and its contents were burned at 600°C for the inert weight determination as described above.

7- Analytical Errors (adopted from Abu Samra ref. No.8)

a. Chemical Oxygen Demand (COD) Test: The COD test described in Standard Method gave a standard deviation of 0.07 ml. on distillery wastes and an average of 0.095 ml. on miscellaneous wastes ranging from 350 to 57,500 mg/1. The U.S. Public Health Service using a

mixture of 150 mg/l glucose and 150 mg/l glutanic acid reported the precision of the COD to be within ± 8% of the accepted COD value. A study by Washington [9] on the precision of the modified COD test, using acetic acid, yielded a standard deviation of 19 mg/l for a sample with a mean COD = 363 mg/l. This is equivalent to a standard deviation of ± 5.2 %. Hence the standard deviation of the modified method used in this study can be excepted to be of the same order as those mentioned above.

b. Biochemical Oxygen Demand: A study of the precision of the 5-day BOD test by the U.S. Public Health Service [9] concluded that the values obtained were valid within ± 20%. This error resulted from a statistical evaluation of the values obtained by 33 analysts working on a synthetic waste composed of 150 mg/l glucose and 150 mg/l glutanic acid. The Standard Methods reportsthat the standard deviation for BOD tests on sewages and effluents may range from 0.07 to 0.11 ml oxygen demand titrated. The Standard Methods further states that the above deviation should hold true for wastes from food processing industries or other organic non toxic wastes. The standard deviation could be larger in the case of soluble BOD in the aeration tank when

its value is low as that which is encountered in this study.

c. Suspended Solids: Engelbrecht and MacKinney[11] using the membrane filter, technique reported a standard deviation of 1.6 percent for activated sludge suspended solids ranging from 276 to 4,746 mg/l. However, the authors reported a standard deviation of 2.8 percent for the 276 mg/l sample. As the level of solids in this study was always near to 400 mg/l the standard deviation will be expected to be closer to the latter value.

d. Inert Solids: No report on the precision of the inert solids determination by the membrane technique has been published. As the sample in this study is subjected to more weighing than in the case of suspended solids, the standard deviation would be expected to be slightly higher than 2.8 %.

VII- MICROSCOPICAL OBSERVATIONS

A. General

Microscopical observations were carried daily on the three units. Observations were carried by the optical microscope which had three magnifying powers 10 x 43 x and 97 x. For the 97 x times oil was used between the lens and the specimens. Staining slides by methylene blue helped in observing the various types of bacteria present.

B. Tank No.1

In this tank the activated sludge was immersed in a water bath at 27°C. Continuous observation on activated sludge samples taken from the mixed liquor displayed a great variety of microorganisms of which the following were noticed clearly.

1- Bacteria: The basic group of microorganisms of importance to sanitary engineers are the bacteria. They are the simplest of plant life. They exist mainly in three forms, rod shape, spherical shape, and spiral shape. Observations on stained samples from tank No.1 displayed the existence of the three above mentioned forms of bacteria.

2- Algae: The algae are aquatic plants and they differ from the funji and bacteria in their ability to carry out photo synthesis. A great variety of this plant were noticed under the microscope, its apparent color makes this plant very easy to identify.

3- <u>Protozoa:</u> The protozoa are not easily defined, however, as sanitary engineers it suffices to say that the protozoa are single cells animals which reproduce by binary fission. The protozoa are usually divided into five groups:

a. Sarcodina - false foot
b. Mastigophora - flagella
c. Sporozoa - sporeformer
d. Ciliata - cilia
e. Suctoria - tentacles

Most of the protozoa are strict aerobes. The metabolic activities of the protozoa lead to the production of protoplasm. The protozoa survive in the dilute organic wastes by living off the bacteria. They can utilize soluble organic compounds for their food but this is not possible unless the food concentration exceeds 5000 mg/liter.

The most noticeable group in tank No.1 were the ciliata group of which the paramecium, and the colpoda were predominant.

4- <u>Rotifers:</u> The rotifer is the simplest of the multicell animals, they are strict aerobes and normally are found in environments which contain at least several milligrams per liter of dissolved oxygen.

Rotifers were sited occasionally in tank No.1 and the dicranophorus forcipatus was the most common.

C. Tank No. 2

In this tank the apparent life of microorganisms was much less noticeable than that in tank No.1. Of the protozoa only the paramecium was apparent in great number while no rotifers or other form of ciliates were apparent.

D. Tank No. 3

This tank was immersed in a water bath at 45°C. No trace of rotifers were noticed in this tank. The existence of protozoa was limited to extremely few parameciums that were spotted occasionally. On the whole animal life was not a dominant feature in this tank.

VIII- EXPERIMENTAL RESULTS

A. COD Tests

1. COD tests were run on the metrical feed, by taking fresh samples from the mixing tank and samples 20 hours old. Average results are shown on table X. These results were plotted on simple probability paper to determine the most fit straight line between them as shown on Fig. 14. The 50% value was determined to be as 1140 mg/l, which for the purposes of this experiment will be referred to as the total COD of the feed. The rate of feed to the tanks was kept constant, however the variation in the feed COD was due to the biogradation of the feed in the feed tank which the writer tried to eliminate by keeping the feed as fresh as possible.

2. Samples for COD tests were taken from the mixed liquor of the three units and both the total COD test and the dissolved COD tests were run on these samples simultaneously. The results are shown on table X.

   The values of the different runs made on the units for the total COD test are shown on Fig. 15. The curve in thick line represents the three average values for the different tests. These average results were obtained by plotting the different results on probability paper and the 50% value was taken as the average value. Fig. 16 shows these average values.

   The values for the dissolved COD tests are shown plotted on figure 17. The thick curve also indicates

Table X - Chemical Oxygen Demand Tests (COD)

Date of Sampling	COD of feed in mg/l	Total COD in mg/l			Dissolved COD in mg/l		
		27°C tank No.1	35°C tank No.2	40°C tank No.3	27°C tank No.1	35°C tank No.2	40°C tank No.3
29/6/67	1220	776	640	656	16	20	24
4/7/67	905	768	648	792	20	24	28
10/7/67	1256	718	710	669	20	32	42
19/7/67	984	760	653	805	23.8	28.5	45.6
25/7/67	992	632	600	744	22.8	84	8
30/7/67	1200	720	700	580	18	37	47
2/8/67	1108	731	680	663	22	30.6	31.4
5/8/67	1169	720	810	675	34.4	88	68
9/8/67	1000	658	616	707	28	34.4	28.8
11/8/67	1215	626	792	784	20	18	35

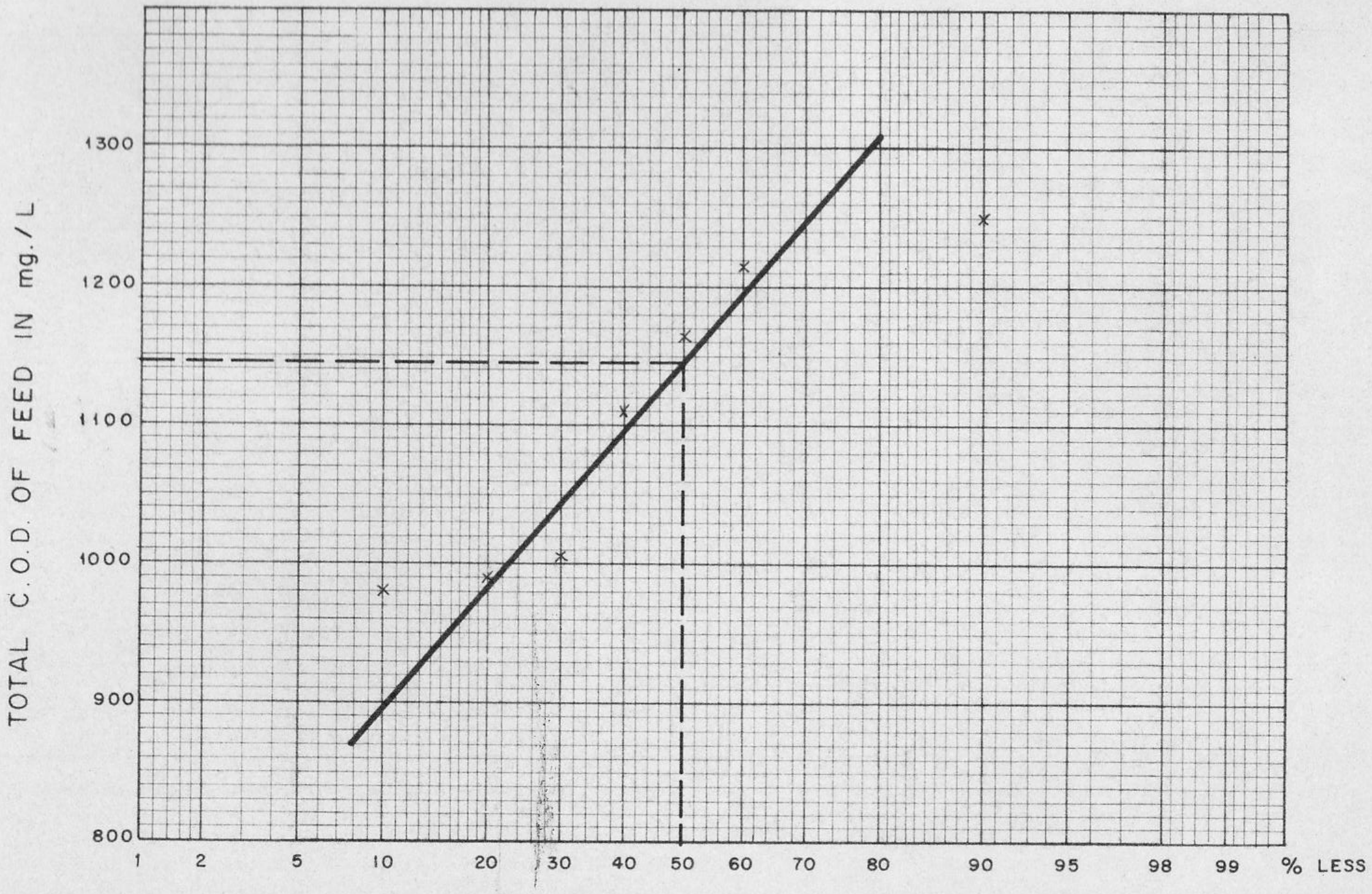

TOTAL C.O.D. OF FEED IN mg./L
1300
1200
1100
1000
900
800
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
% LESS

FIG. 14

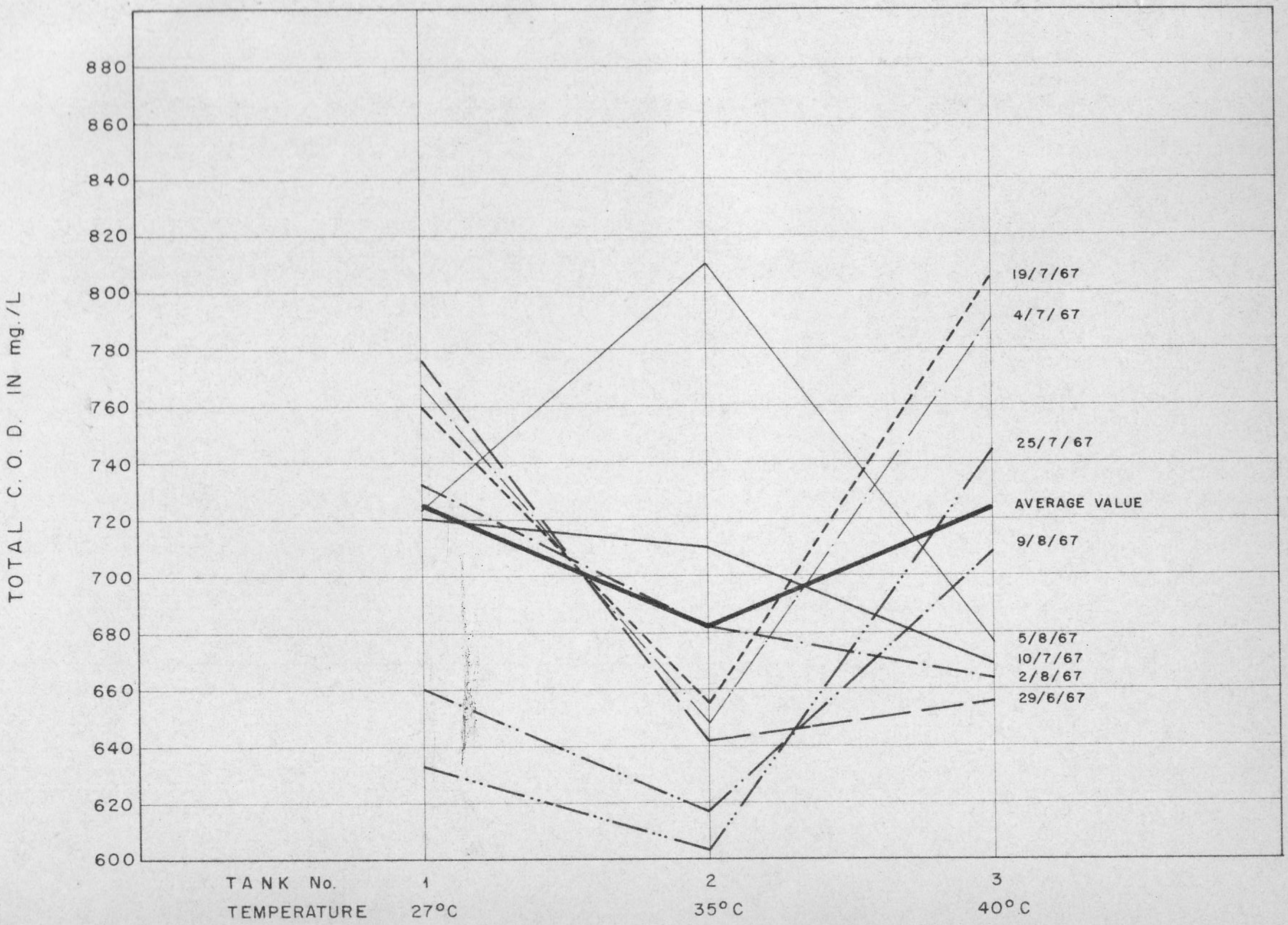

TOTAL C.O.D. IN mg./L
880
860
840
820
800
780
760
740
720
700
680
660
640
620
600
19/7/67
4/7/67
25/7/67
AVERAGE VALUE
9/8/67
5/8/67
10/7/67
2/8/67
29/6/67
TANK No.
1
2
3
TEMPERATURE
27°C
35°C
40°C

FIG. 15

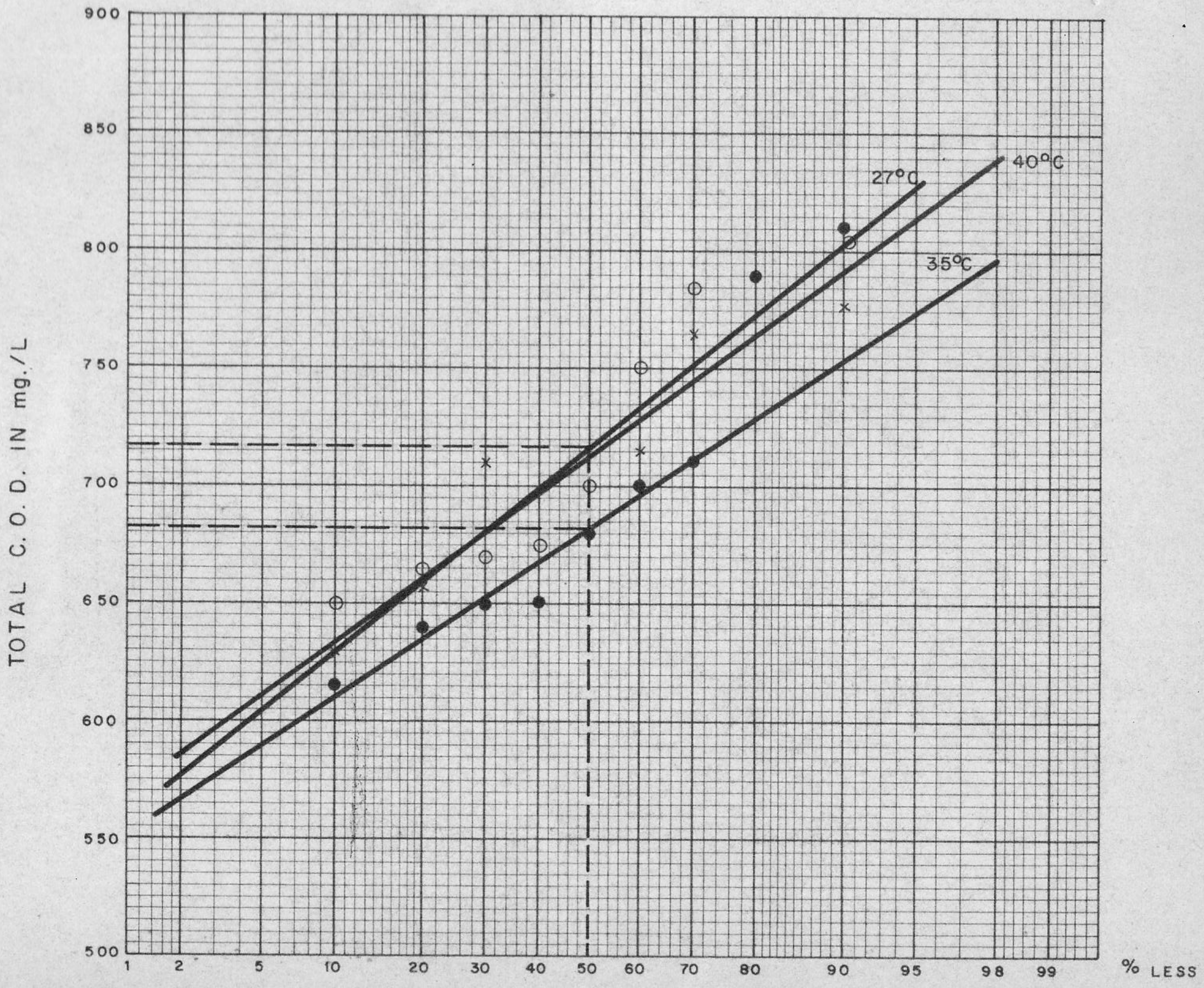

900
850
800
750
700
650
600
550
500
TOTAL C. O. D. IN mg./L
27°C
40°C
35°C
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
% LESS

FIG. 16

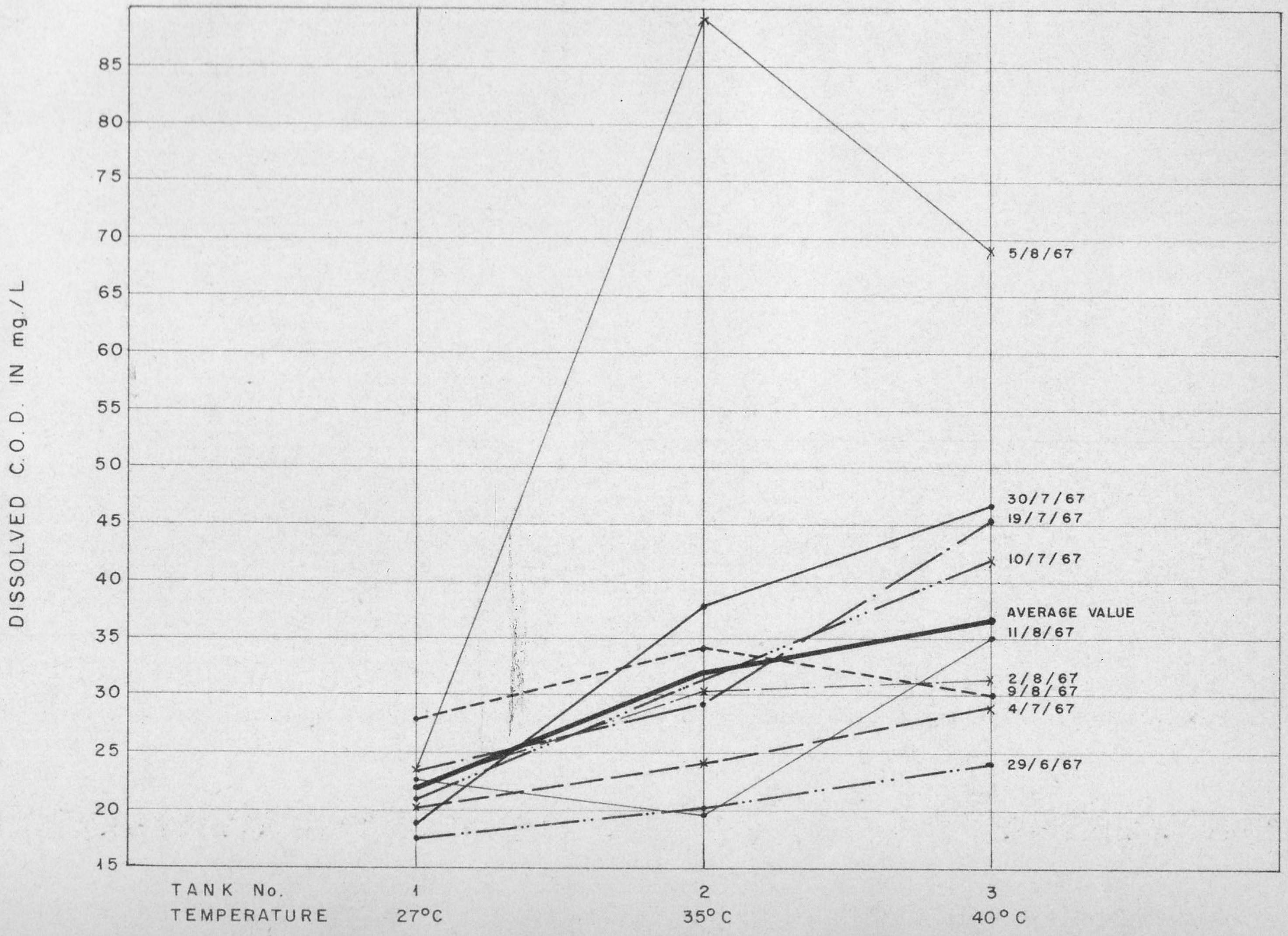

DISSOLVED C.O.D. IN mg./L
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
5/8/67
30/7/67
19/7/67
10/7/67
AVERAGE VALUE
11/8/67
2/8/67
9/8/67
4/7/67
29/6/67
TANK No.
1
2
3
TEMPERATURE
27°C
35° C
40° C

FIG. 17

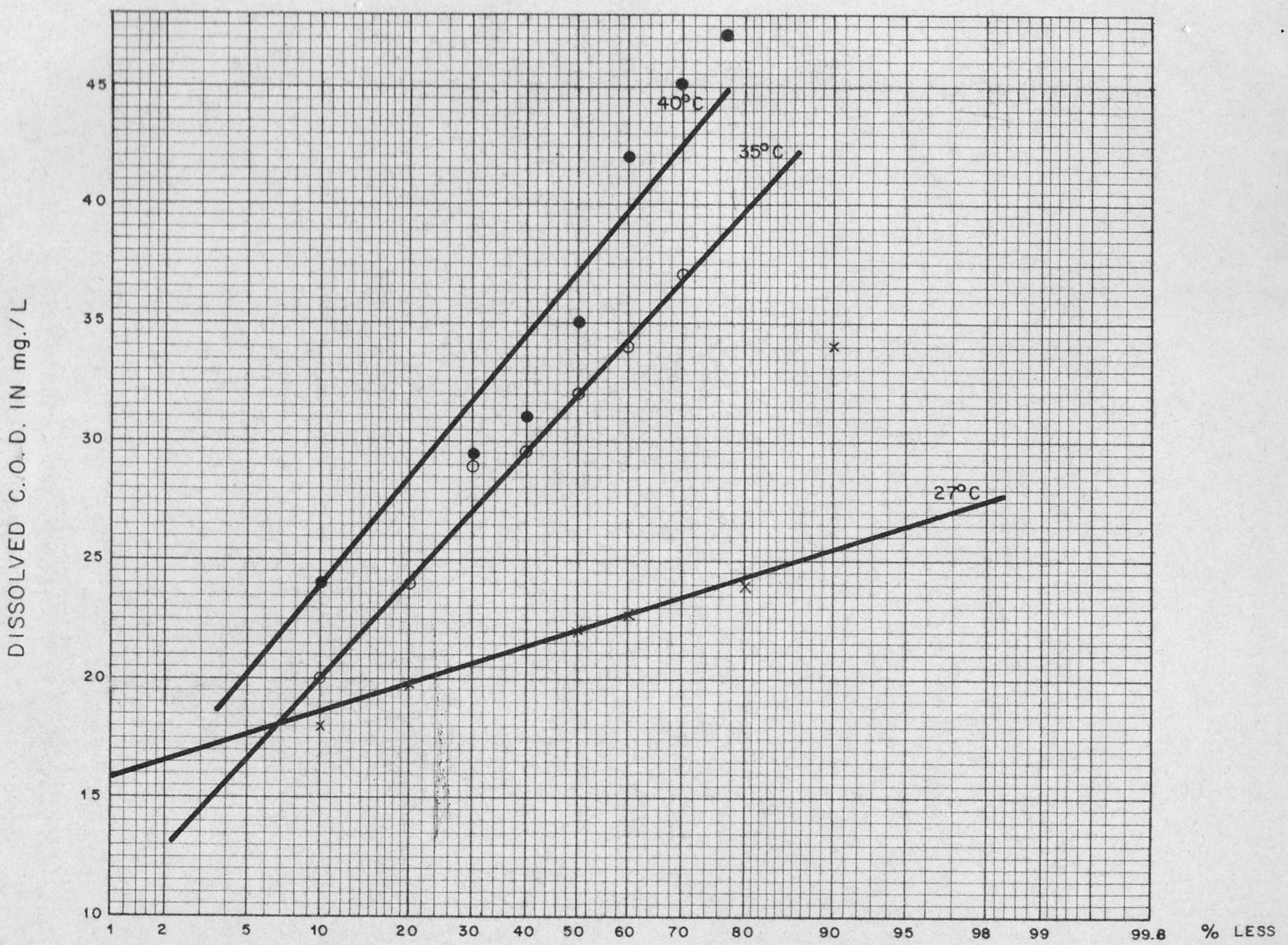

DISSOLVED C.O.D. IN mg./L
45
40
35
30
25
20
15
10
40°C
35°C
27°C
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
% LESS

FIG. 18

the average conditions as discussed above and Fig. 18 shows these average values.

B. BOD Tests

1. 5-day BOD tests were run on the feed in a similar manner to that of the COD tests.

The results are shown on table XI. The 50 % most probable value was determined as 640 mg/l which will be referred to as the 5-day BOD value for the feed and is shown on Fig. 19.

2. Samples were also taken from the three different units mixed liquor, and the 5-day BOD tests were made on these samples for the total BOD and dissolved BOD determinations.

The results of these tests are shown on table XI.

The results of each run were plotted on figure 20 for the total BOD, and on figure 21 for the dissolved BOD. Average results for both total and dissolved BOD tests are shown in thick lines on both of the above figures. The 50 % average values were obtained from Fig. 22 and Fig. 23.

C. Suspended Solids Tests

1. Suspended solids tests were made on each of the three units, together with the other tests mentioned above.

Table XI - Biochemical Oxygen Demand Tests (BOD)

Date of Sampling	BOD of feed in mg/l	Total BOD mg/l			Dissolved BOD mg/l		
		27°C tank No.1	35°C tank No.2	40°C tank No.3	27°C tank No.1	35°C tank No.2	40°C tank No.3
29/6/67	675	180	138	150	5	8	8
4/7/67	600	240	227	156	4.3	5.6	5.3
10/7/67	630	390	222	210	5	10	20
19/7/67	600	390	192	174	6	5.2	15
25/7/67	600	240	204	192	3	6	11
30/7/67	620	415	285	270	9	25	34
2/8/67	710	400	290	270	3.8	7.3	9.7
5/8/67	580	370	370	285	7	31	12.2
9/8/67	560	330	320	225	6	3	6
11/8/67	630	270	250	240	2	3.3	4.7

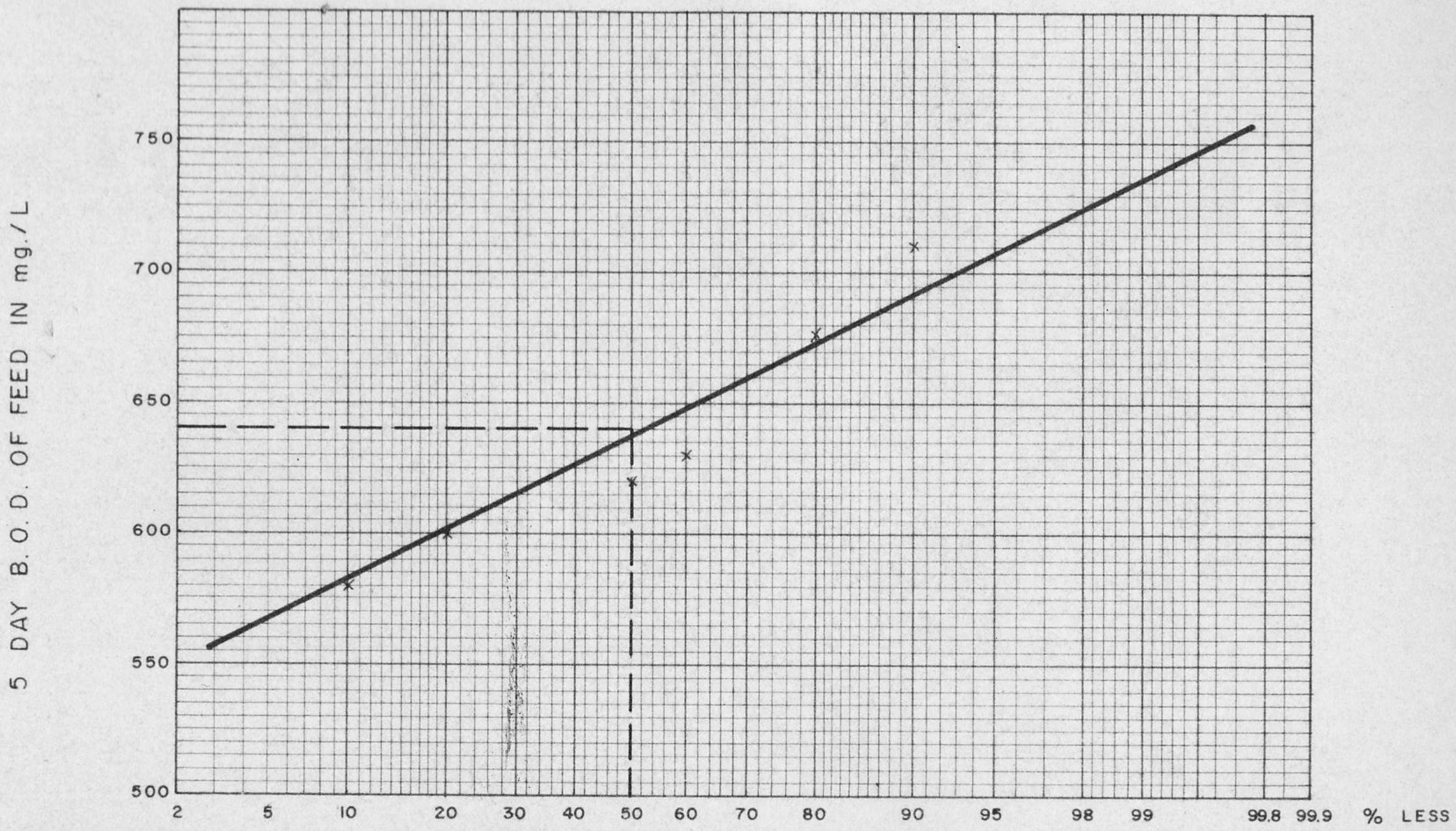

5 DAY B.O.D. OF FEED IN mg./L
750
700
650
600
550
500
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
% LESS

FIG. 19

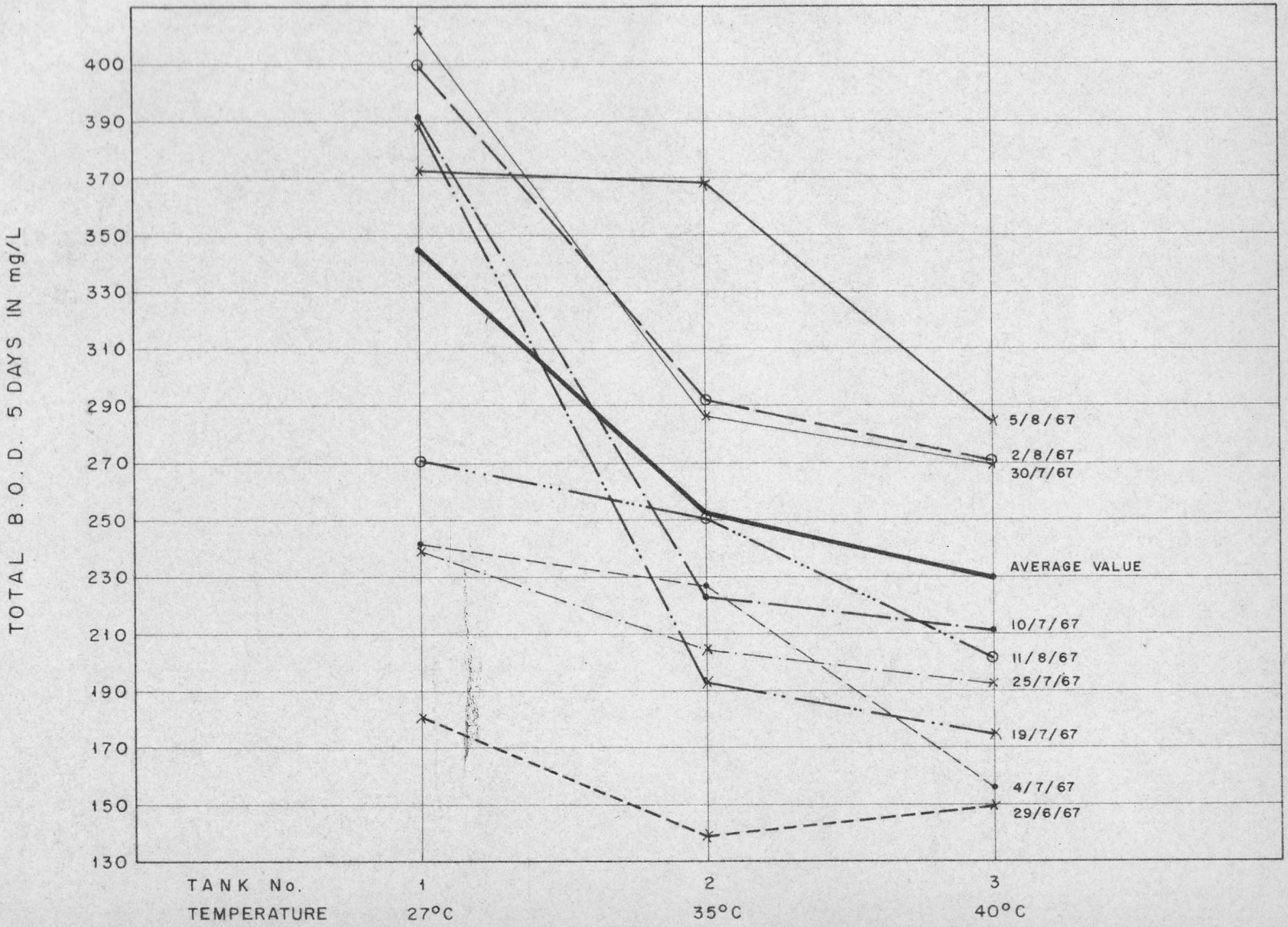

TOTAL B.O.D. 5 DAYS IN mg/L
400
390
370
350
330
310
290
270
250
230
210
190
170
150
130
5/8/67
2/8/67
30/7/67
AVERAGE VALUE
10/7/67
11/8/67
25/7/67
19/7/67
4/7/67
29/6/67
TANK No.
1
2
3
TEMPERATURE
27°C
35°C
40°C

FIG. 20

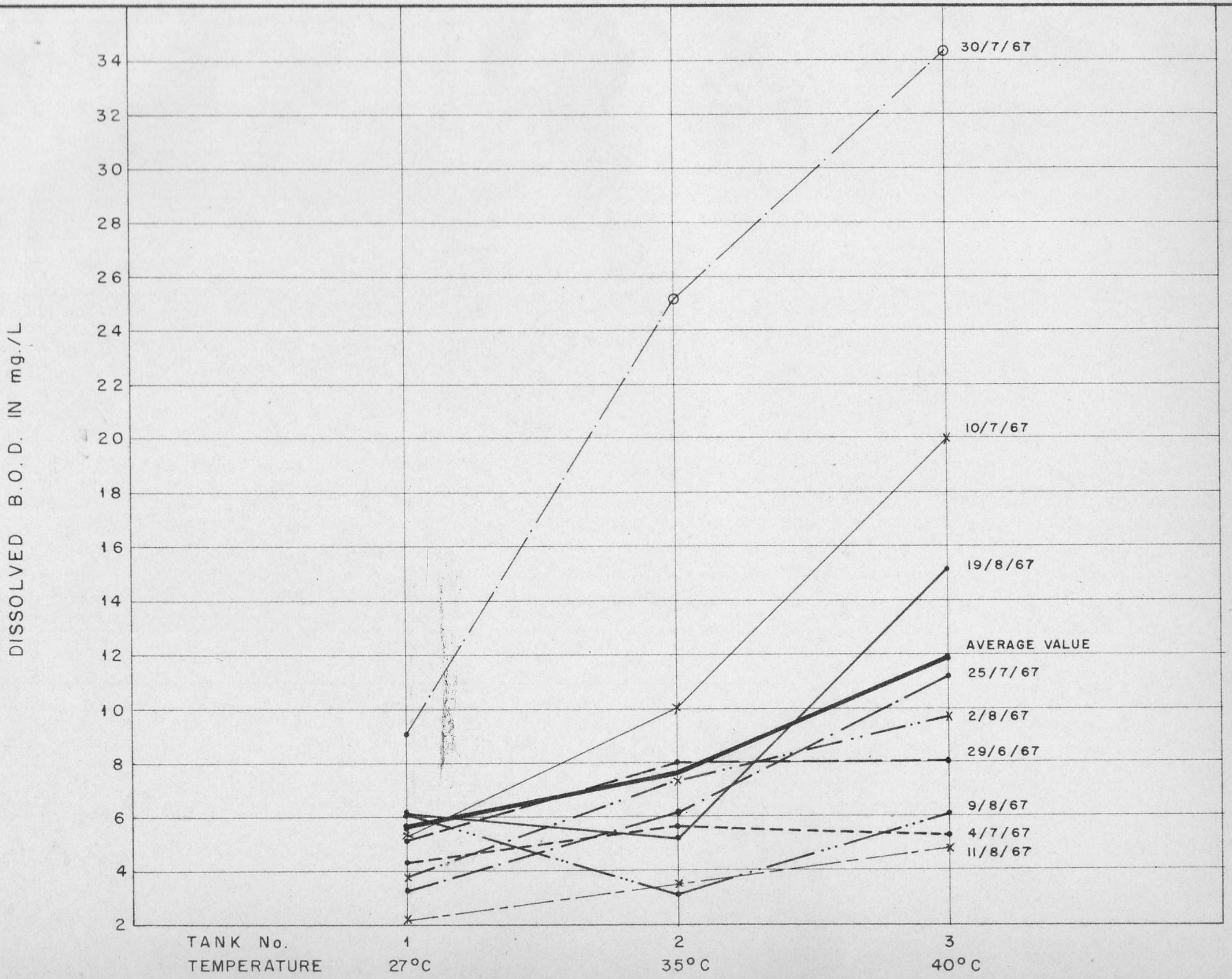

DISSOLVED B.O.D. IN mg./L
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
30/7/67
10/7/67
19/8/67
AVERAGE VALUE
25/7/67
2/8/67
29/6/67
9/8/67
4/7/67
11/8/67
TANK No.
1
2
3
TEMPERATURE
27°C
35°C
40°C

FIG. 21

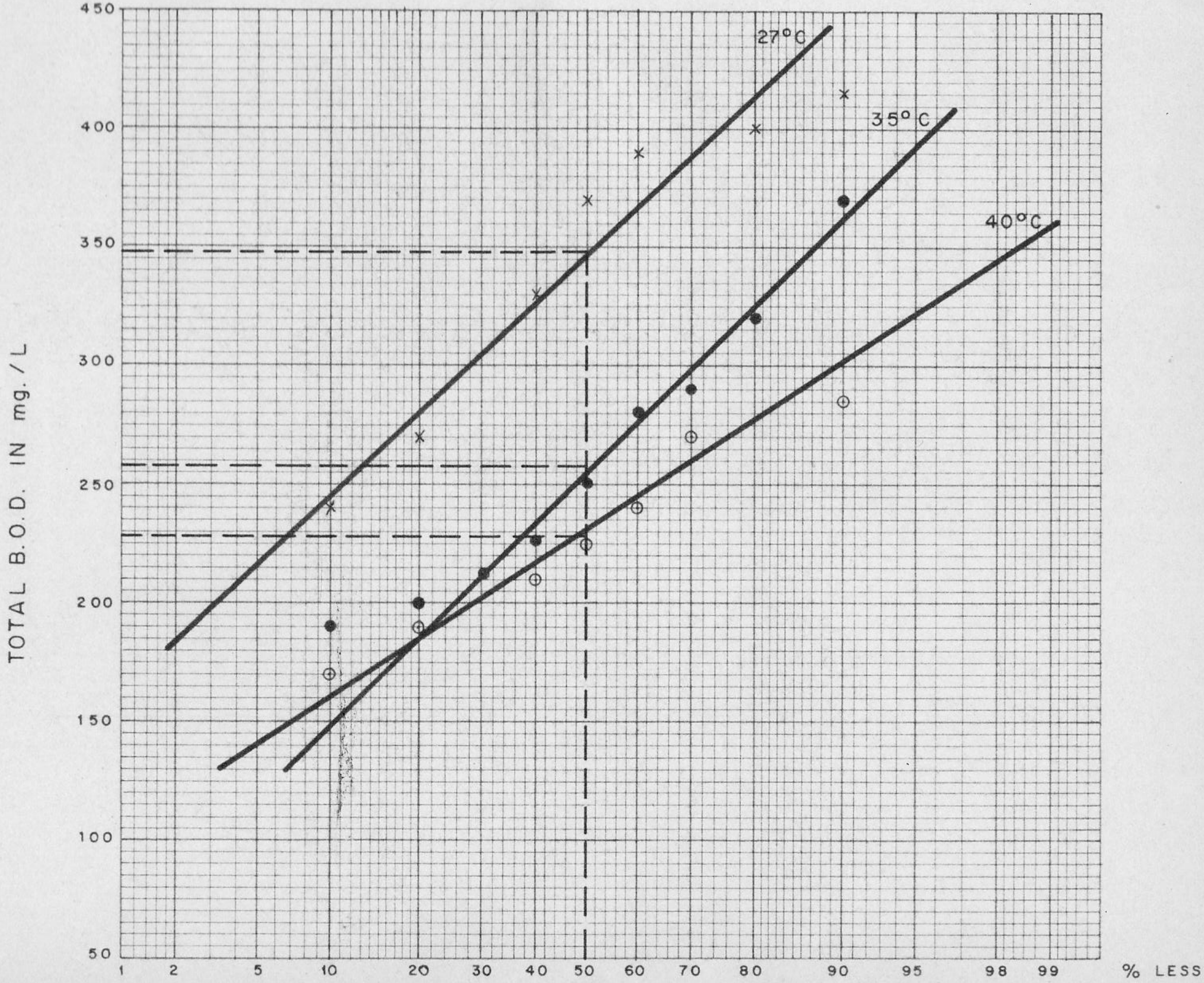

27°C
35°C
40°C
TOTAL B.O.D. IN mg./L
450
400
350
300
250
200
150
100
50
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
% LESS

FIG. 22

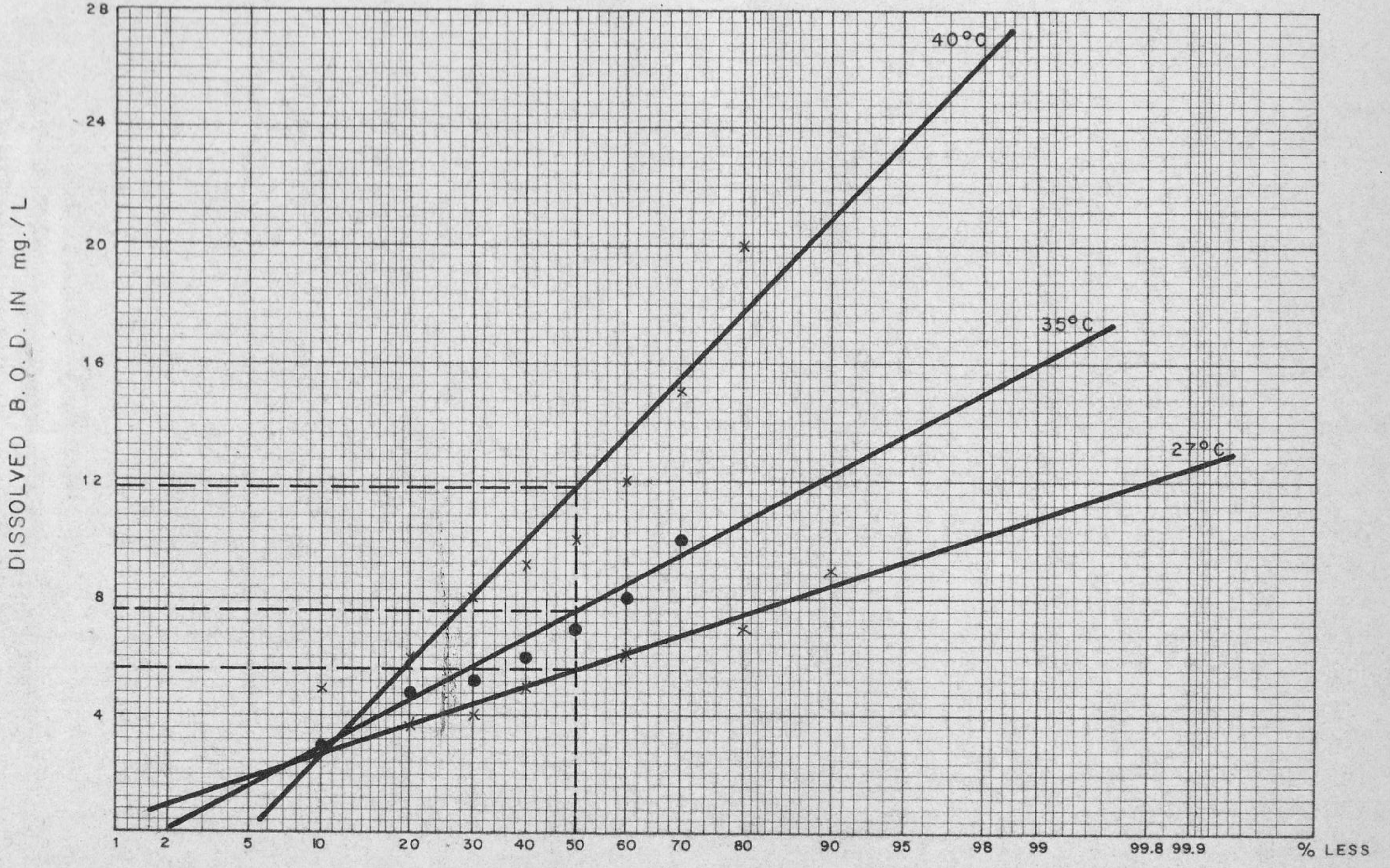

DISSOLVED B.O.D. IN mg./L
28
24
20
16
12
8
4
40°C
35°C
27°C
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.8
99.9
% LESS

FIG. 23

The values for the different tests are shown on table XII.

The results of each run were plotted on Fig. 24, and the line shown in thick represents the average conditions as obtained from Fig. 25.

2. The volatile suspended solids were obtained by collecting the suspended solids milli-pore filters over the period of the experiment and one run was made on them to determine the V.S.S. The results are shown on table XII.

D. <u>pH Tests</u>

pH determinations were carried occasionally on the units activated sludge mixed liquor. The value of the pH was almost invariably constant at a value of about 7 in all the three units.

pH measurement was carried also on the feed. The value of the pH of the fresh feed was equal to that of the distilled water with which it was mixed, namely about 6.8. However the value of the pH of the feed used to drop to about 6.3 at the end of the feed day due to the start of fermentation in the Metrical.

E. <u>Dissolved Oxygen Tests</u>

Dissolved oxygen determinations were carried on the three units and very frequently. The value of the dissolved oxygen was always maintained above 3 ppm in the three units.

Table XII - Total Suspended Solids Tests (SS)

Date of Sampling	Total Suspended Solids 27°C tank No.1	35°C tank No.2	40°C tank No.3	Volatile Suspended Solids Test 27°C tank No.1	35°C tank No.2	40°C Tank No.3
29/6/67	430	310	320			
4/7/67	400	305	316			
10/7/67	432	416	382			
19/7/67	450	280	220			
25/7/67	404	377	315	88 %	88 %	90 %
30/7/67	411	378	355			
2/8/67	498	418	358			
5/8/67	397	454	450			
9/8/67	463	492	475			
11/8/67	396	519	481.5			

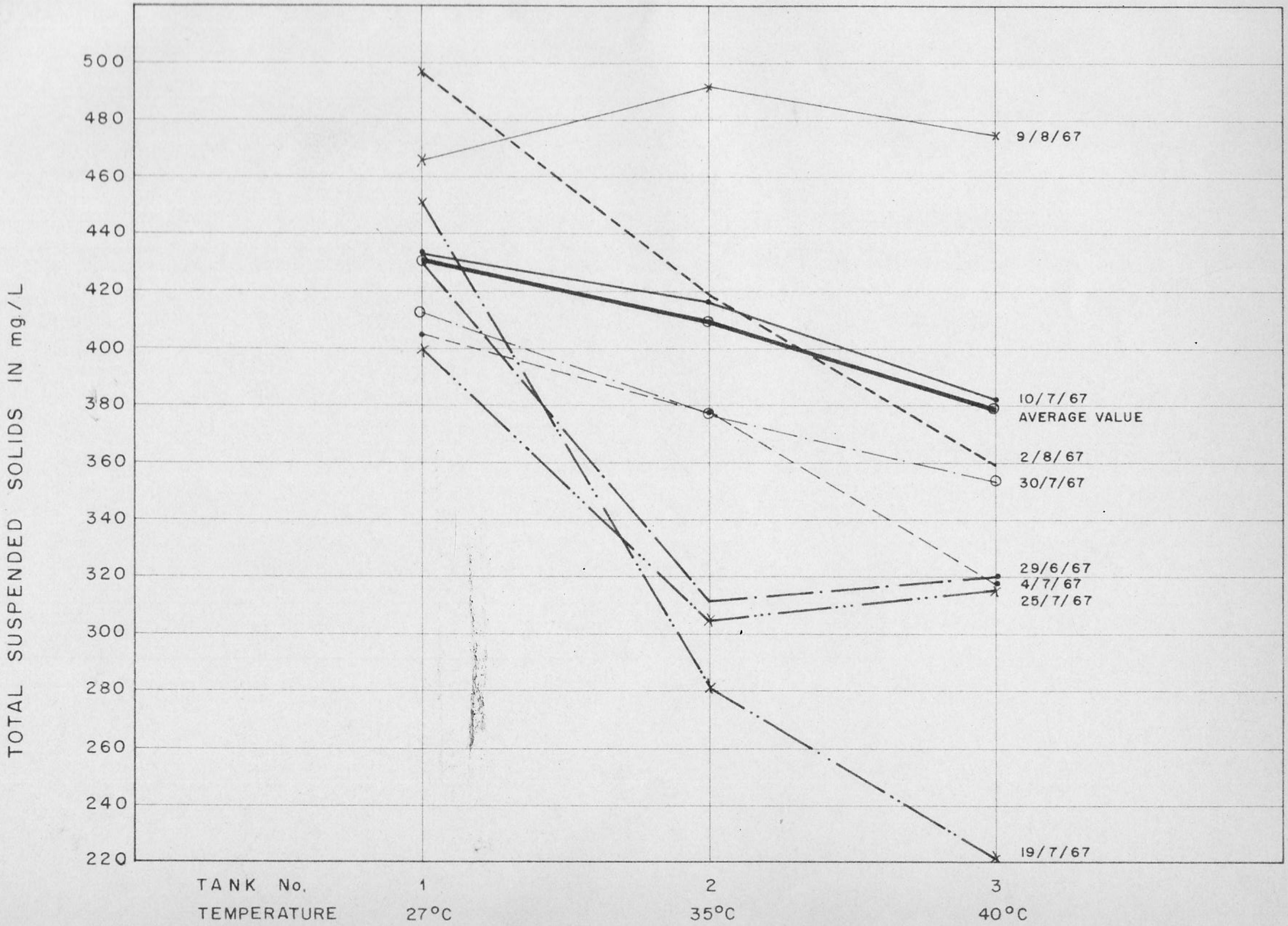

TOTAL SUSPENDED SOLIDS IN mg/L
500
480
460
440
420
400
380
360
340
320
300
280
260
240
220
9/8/67
10/7/67
AVERAGE VALUE
2/8/67
30/7/67
29/6/67
4/7/67
25/7/67
19/7/67
TANK No.
1
2
3
TEMPERATURE
27°C
35°C
40°C

FIG.(24)

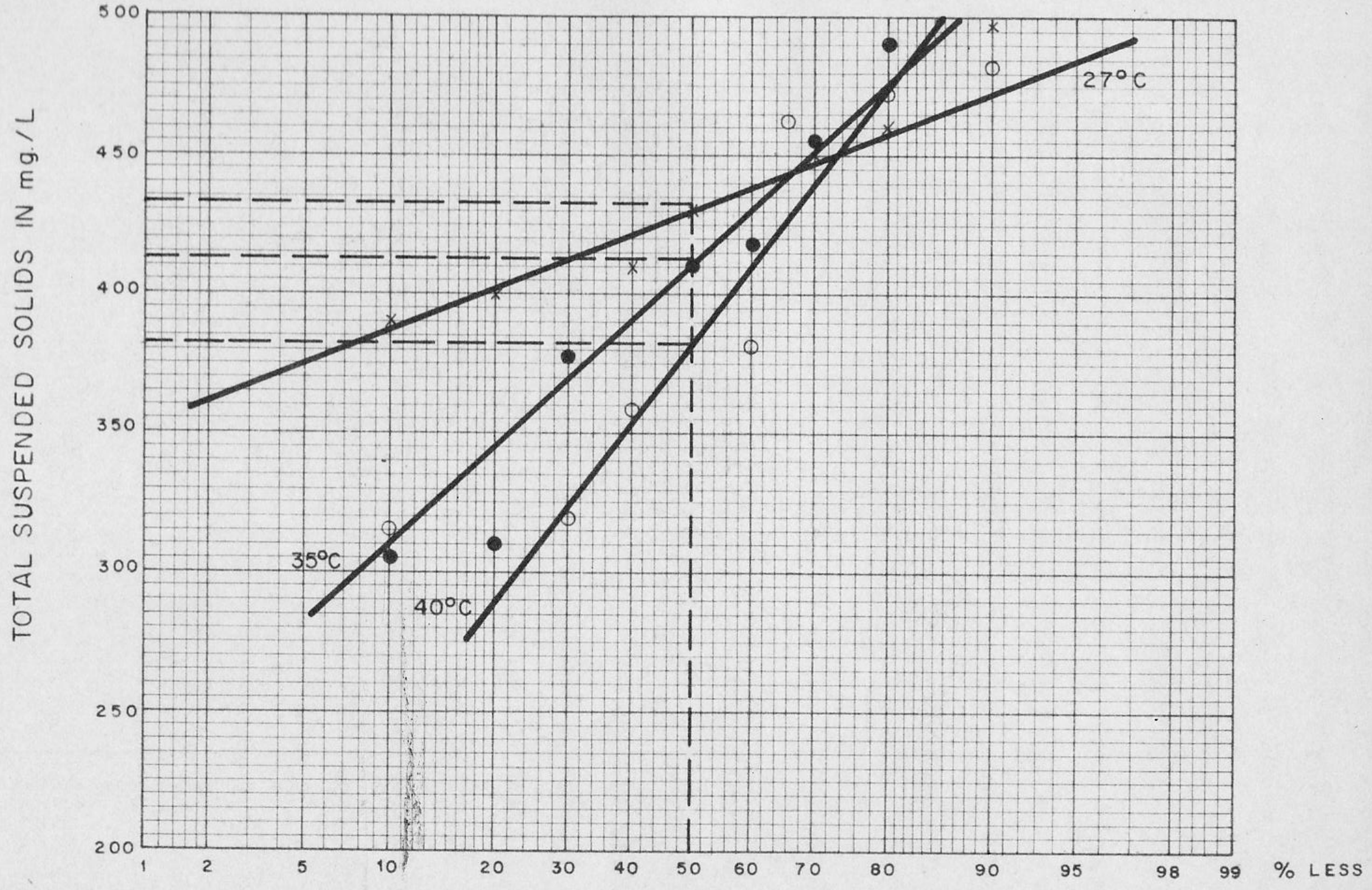

TOTAL SUSPENDED SOLIDS IN mg./L
500
450
400
350
300
250
200
27°C
35°C
40°C
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
% LESS

FIG. 25

However one interesting observation was noted in tank No.2 with the 35°C temperature, the dissolved oxygen value was invariably lower than that in tanks No.1 and No.3. All through, the writer exchanged more than once the aerator units just to detect whether this was a cause of the aeration system. Apparently it was a characteristic of the sludge respiration at that temperature. As the experiment was not intended to measure the oxygen utilized or the quantity of air supplied, this phenomenon remains to be cleared by further investigations.

F. Detention Time

The detention time of the units was maintained at 16 hours. The writer ran the test on the units, with specific attention to keep the detention time as constant as possible within the practicable means of the experimental set up. Mention should be made here that this was of considerable difficulty due to blockage of the feed lines by growth and colloidal matter in the feed which was not easy to avoid in a simple set up as was possible to erect for this experiment.

IX- ANALYSIS OF TEST RESULTS

A. General

It can be seen from the results shown on table XI that the microorganisms that are of main interest to the sanitary engineer can carry their metabolic reactions at temperature conditions of 27°C, 35°C and 40°C without any major handicap on the net result mainly the efficiency of the activated sludge units.

Starting with this concluding statement the writer will, based on the experimental results, try to outline the effect of the temperature on the aeration-only activated sludge systems.

B. Cell Yield

This is defined as the net protoplasm accumulation and is measured by the total suspended solids in the aeration units. The total suspended solids is a direct measure of the cell mass which is the net product of the metabolic reactions. As we have seen before bacteria metabolize organic matter to produce protoplasm for the creation of new bacteria. The metabolism of the organic matter in this process results in the removal of organic matter from the mixed liquor. This organic matter removal is measured in BOD and COD tests. The energy requirements to produce a unit of protoplasm are constant regardless of the chemical materials being metabolized[12]. However

the rate at which this organic matter is metabolized is a function of temperature. Besides the normal function of the bacteria to metabolize the organic matter and build protoplasm, and consequently new cell mass, the bacteria require a small amount of energy to maintain normal functions such as motion and enzyme activation. The basal energy requirements of the bacteria has been designated as endogenous respiration[1]. This basal energy requirement is also a function of temperature.

Energy uptake by the microorganisms remains to be the most difficult problem to determine as the conventional concepts of thermodynamics cannot be applied. In thermodynamics the oxidation of organic or inorganic compounds releases heat energy, but microorganisms are not heat engines and cannot utilize heat energy[1]. McKinney concludes that the organisms are forced to prevent the loss of the chemical energy in the form of heat, and hence energy is given up from one compound to another compound with only a very minor heat loss. The Coenzymes ADP and ATP are high energy compounds and contain high energy phosphate bondings. As the chemical reactions release energy, inorganic phosphate is added to ADP to form ATP, in this, the energy is stored in the ATP rather than lost as heat. As the microorganisms require the energy, the ATP is reduced back to AOP with the transfer of energy to the chemical reaction needing it.

Substrate energy = End product energy
+ Heat energy
+ Energy in cellular protoplasm

It should be interesting to note here that the works of Fair and Moore[24] on the heat energy relations in the digestion of sewage solid had proved that this process could be potentially and endo-thermic as well as an exo-thermic process.

It should be noted here that bacteria and other microorganisms in waste stabilizing systems do not oxidize matter by the direct addition of oxygen, but rather by the indirect scheme of hydrogen removal and addition of water, the hydrogen eventually reacts with oxygen, carbon nitrogen or sulphur. Strict aerobes as those present in this experimental system utilize "free" dissolved oxygen for their ultimate hydrogen acceptor, while anaerobes such as those in digestion tanks use "chemically bound" oxygen, carbon, nitrogen or sulphur as their hydrogen acceptor.

As is obvious in all microorganisms, enzymes are formed and regenerated in every biological reaction. The enzymes formed within the cell are known as intracellular enzymes and those that are excreted outside the cell are known as extracellular enzymes. Enzymes are known to be specific in their reactions and each act on a specific substance. The enzymes can be classified into two major groups, the hydrolytic enzymes and the oxidation reduction enzymes. The hydrolytic enzymes are those responsible for reactions

involving the hydrolysis of large molecules, whereby the molecule is split up into two or more components and water or elements of water H^+ and OH are added to the point of breakage. These enzymes are generally found outside the cell and are extra cellular enzymes. The intra cellular enzymes exist inside the cell and they are either oxidazes or reductazes. The first group are for the oxidation reactions, i.e. they remove the hydrogen from the compound such as occurs in aerobic bacteria, where oxygen is the hydrogen acceptor. Other hydrogen acceptors include oxygen containing substances like nitrates, nitrites and sulphates, which accept the hydrogen and are themselves reduced by the hydrogen, such reactions occur with anaerobic bacteria.

The action of aerobic bacteria on the organic matter hence can be summarized as follows:

a. The hydrolysis of big particles such as protein molecules, carbohydrates, polysaccharides, fats, into smaller particles.

b. The adsorption of these molecules through the cell wall membrane of the bacteria.

c. Further hydrolysis of the molecules that are still large inside the cell.

d. The small molecules undergo a process of oxidation forming end products of carbon dioxide and water.

The growth pattern based on a mass of microorganisms is shown on Fig 26 and it has three phases. Log growth starts as soon as the microorganisms come into contact with the substrate. The mass of the cells increases before numerical division occurs, then the declining growth phase follows, with the endogenous phase.

a. Log Phase: In this stage excess food is present and the rate of metabolism and growth is limited only by the microorganisms ability to process the substrate. Hence at this stage there exists maximum growth and hence maximum removal of organic matter from the mixed liquor. The use of the log growth phase for stabilizing wastes is limited by the fact that the organic concentration in the liquid surrounding the microorganisms must be high if the log growth phase is to be maintained. This means that it is impossible to produce a stable effluent as long as the microorganisms are in log growth.

b. Declining Growth: The limitation of food causes the rate of growth to decrease, hence the food concentration starts to decrease and the rate of growth starts to decrease also.

c. Endogenous Phase: In this stage growth ceases and the food concentration becomes minimum. The small quantity of organic matter still in solution is in equilibrium with the microorganisms. As the organisms demand more food, they are forced to metabolize their own protoplasm, as well as slowly decreasing the food

concentration in solution. The mass of microorganisms and the food concentration ratio remains constant during the endogenous phase. As the microbial mass decreases, the rate of metabolism decreases.

As was mentioned earlier in the works of McKinney[12] there are certain values at which the food concentration to cell mass ratio F/M becomes limiting however, there is no definite way of establishing exactly the growth phase of a flow system.

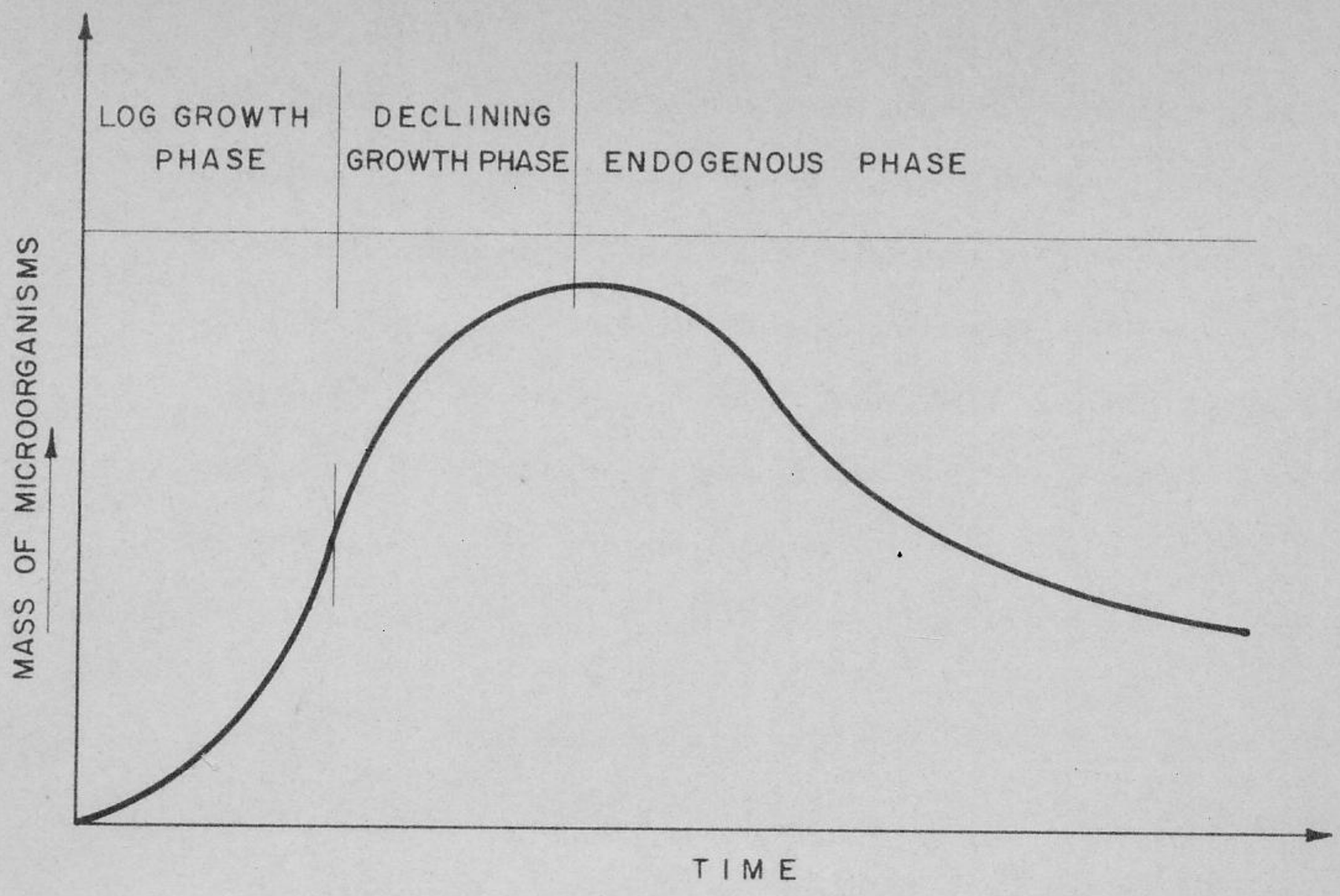
It is obvious that in a complete mixing activated sludge system such as the one we are concerned about in this experiment, the food to microorganisms ratio is so limiting and the situation is that between the declining growth phase and the endogenous phase.

Another source of cell yield in the system is the animal life namely protozoa. The bacteria which are classified as plants process the soluble food while the animals can process solids food. Therefore in a mixed system plants and animals do not compete for the same food but rather the animals lives on the plant as food. The free swimming ciliates are the most predominant protozoa in the activated sludge systems as they can live on bacteria as food, microscopical observations in this experiment has confirmed the predominancy of this type of protozoa. As the ciliates process the bacteria for food the bacterial population decrease, as the free swimming ciliates demand a lot of energy to survive, they give way to the

stalked ciliates. The stalked ciliates can attach themselves to solid particles in suspension and draw food to them by moving their cilia. Their lower energy demand allows them to survive at very low bacterial population. Eventually, as the food available in bacterial form diminishes, the protozoa cannot have enough energy to survive and hence give way to the rotifers. The rotifers are a higher animals and have the ability to utilize the non soluble fraction of the dead bacteria as well as other solid organic particles. McKinney [1] has best expressed this sort of cyclic growth pattern in Fig 27. This figure summarizes the possible life cycle occurring in mixed liquor activated sludge system.

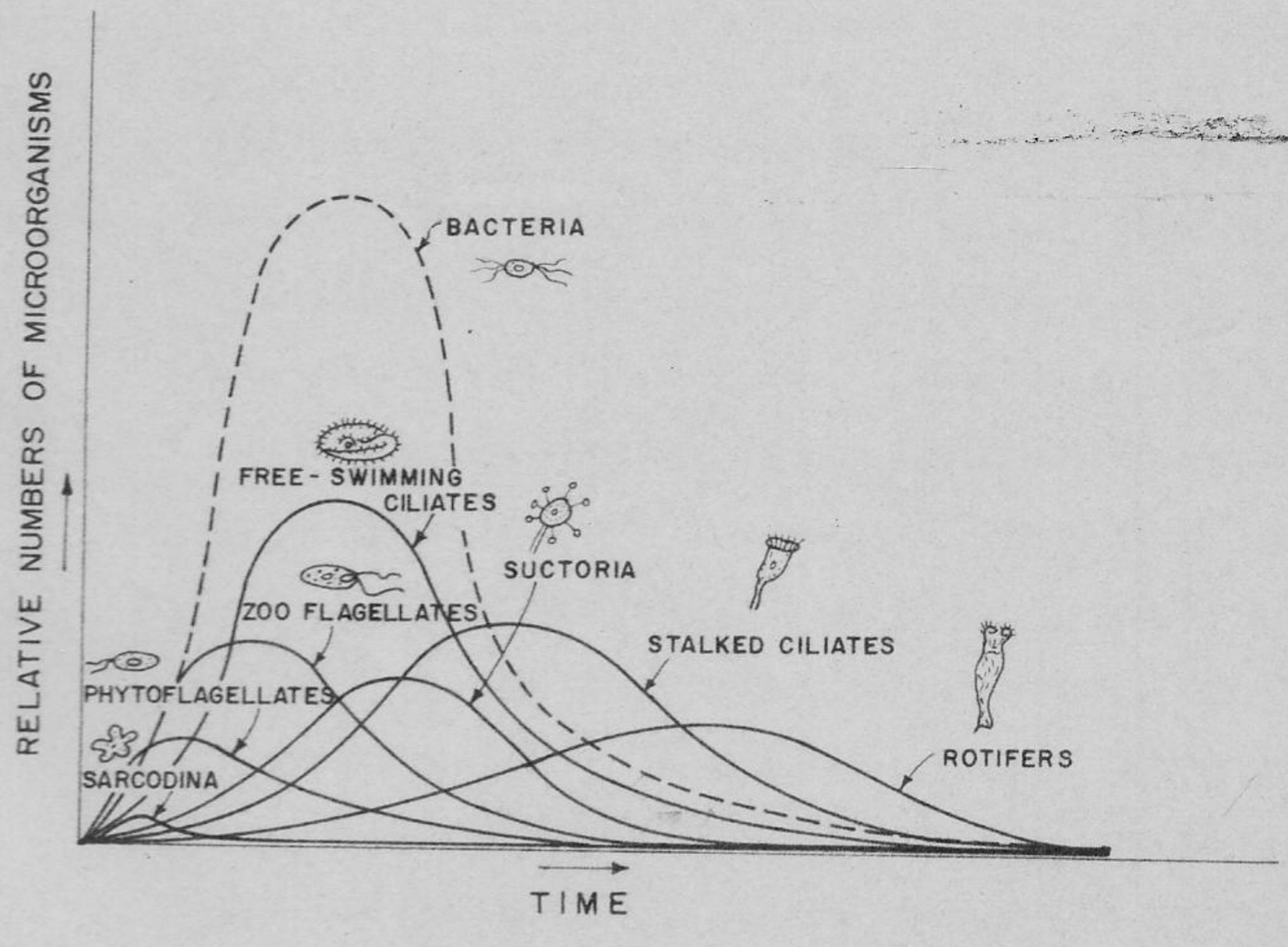
Continuous observations of the units have displayed the following observations. In unit No.1 at 27°C minor variations on the number of protozoa were noticed. In unit No.2 at 35°C the paramecium used to appear in large numbers then it used to disappear in another observation. Rotifers were cited in large numbers sometimes and then disappeared in the following observations. In unit No.3 at 40°C the protozoa were cited only occasionally. The suspended solids results in Fig 21 show a marked increase in the suspended solids content of tank No.1 than on those of tank No.2 and tank No.3. Average results are 430 mg/l in tank No.1, 410 mg/l in tank No.2 and 380 mg/l in tank No.3.

This increase in suspended solids between tank No.1 and tank No.2 seems to be a small difference not exceeding 4.6%.



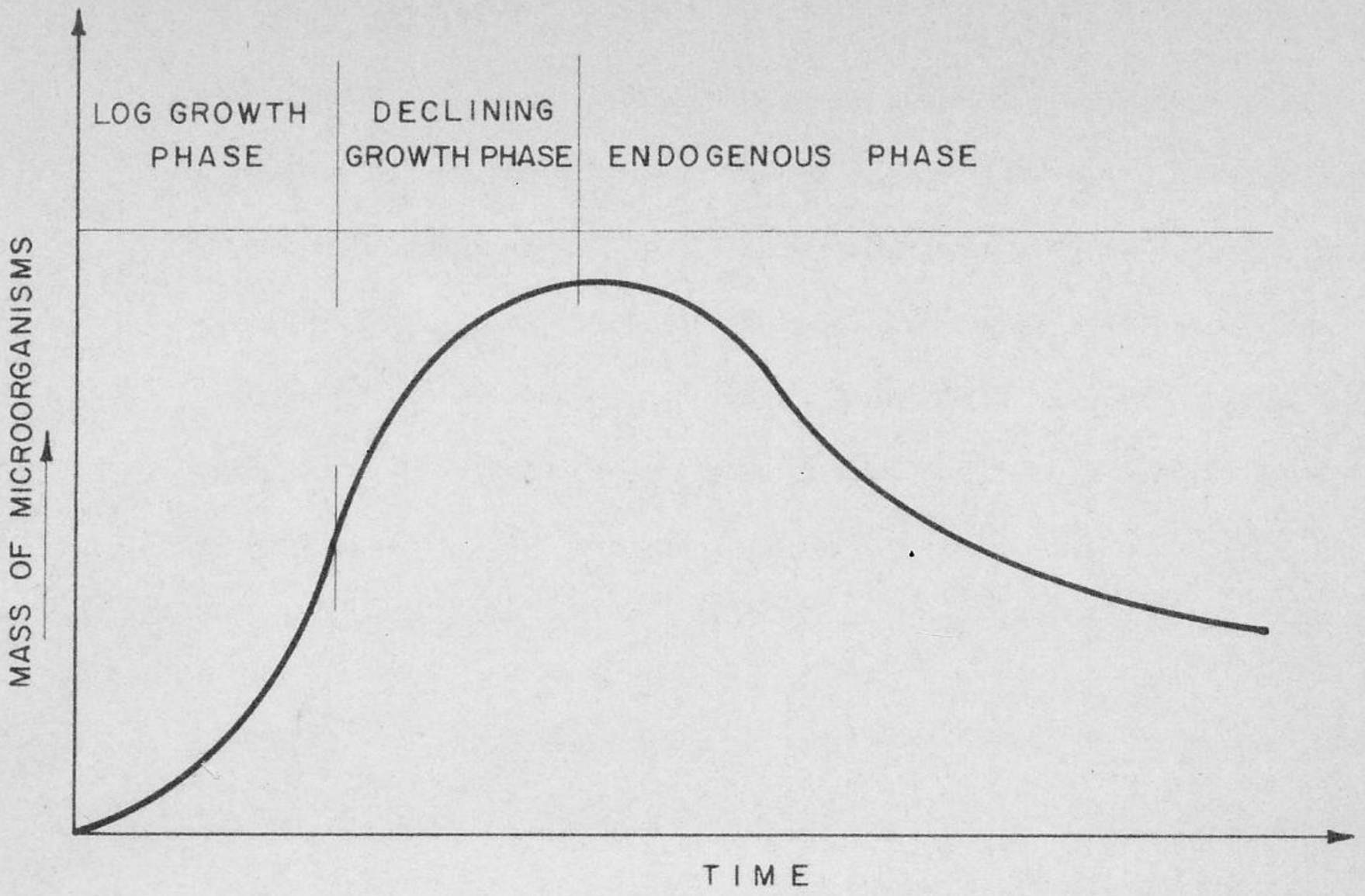
GROWTH PATTERN BASED ON MASS OF MICROORGANISM

FIG. 26



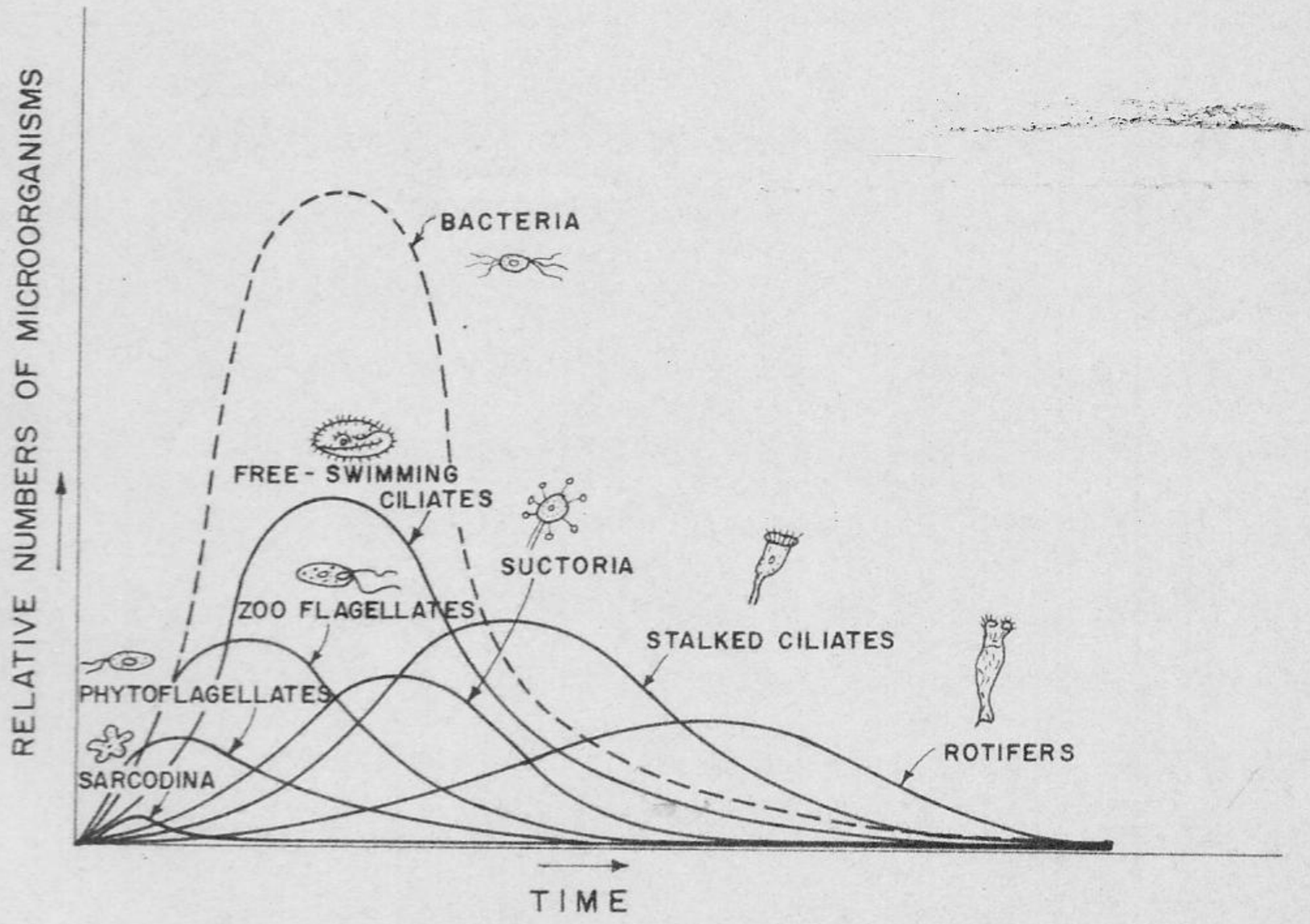
RELATIVE GROWTH OF MICROORGANISMS IN STABILIZATION OF LIQUID ORGANIC WASTES

FIG. 27



GROWTH PATTERN BASED ON MASS OF MICROORGANISM

FIG. 26



RELATIVE GROWTH OF MICROORGANISMS IN STABILIZATION OF LIQUID ORGANIC WASTES

FIG. 27

if compared to a difference of 10-15% obtained by Sawyer[20] for each 5°C of increase in temperature. However the results of the volatile solids test show almost an equal percentage of volatile solids in the mixed liquor in both tanks. The decrease in the suspended solids in units No. 2 and 3 indicate a higher activity in these two units, if we consider that the total BOD removal as the criteria by which the efficiency of the units is measured.

Ludzack[4] concluded that sludges fed at higher temperatures seem to accumulate less solids than those at moderate temperatures, however, the temperature range in which Ludzack[4] was concerned was below 30°C. Sawyer[20] also concluded that the increased rate of metabolism at higher temperatures lead to a greater conversion of the feed to carbon dioxide and water with a net result of decreased solids accumulation at higher temperatures.

Microscopical observation show that tank No. 2 has experienced a less dispersed growth than in tank No. 1. Fluctuations in the suspended solids indicate most probably a cyclic animal life growth in this unit. Figure 28 shows this fluctuation in the suspended solids contents of the three units. It is interesting to notice that readings Nos. 6, 7, 8 and 9 for tanks No. 2 and 3 show an increased tendency in the suspended solids contents of the unit. This sludge accumulation was observed microscopically and yielded thick undispersed growth in the units which later started to disperse and disappear. It should be

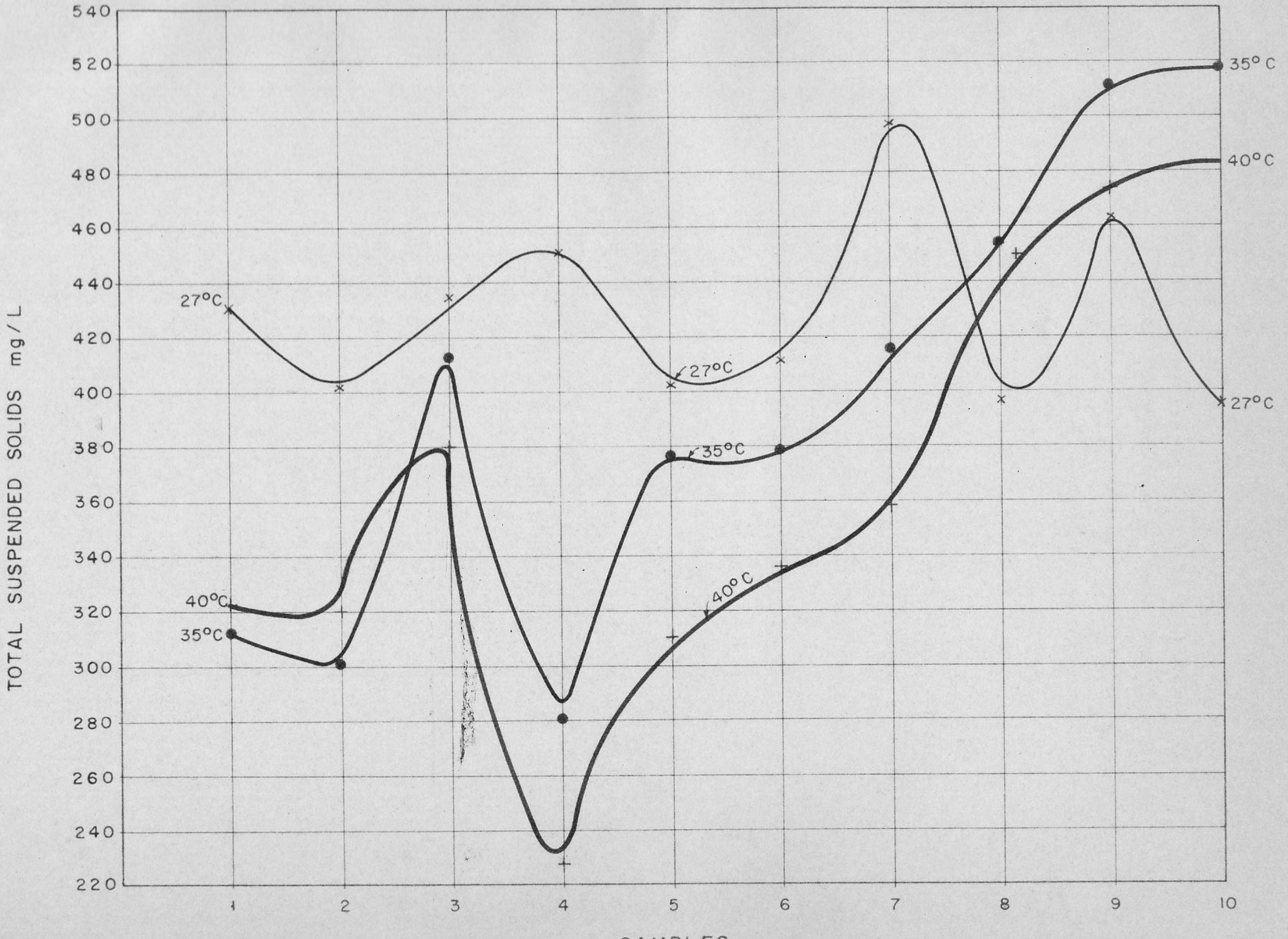

TOTAL SUSPENDED SOLIDS mg/L
540
520
500
480
460
440
420
400
380
360
340
320
300
280
260
240
220
1
2
3
4
5
6
7
8
9
10
SAMPLES
27°C
27°C
27°C
35°C
35°C
35°C
40°C
40°C
40°C

FIG. 28

mentioned here that for the units at temperatures 35°C and 40°C the suspended solids concentration do not reflect the same harmonious coexistence of the plant and animal life as in unit No. 1 at 27°C which shows more or less a cyclic trend.

C. BOD and COD Results

The BOD tests show the amount of biogradable material in both the feed and the aeration units. The COD tests almost show all of the oxidizable amount of organic material available regardless of it can be metabolized or not by the bacteria in the system. The total BOD and COD tests reflect the value of the total organic matter available in the units including the soluble and non soluble part.

The dissolved BOD tests show the amount of dissolved biogradable organic matter remaining in the system. The dissolved COD tests show the total amount of organic matter available including the part remaining from the feed and the part resulting from lysing of dead cells.

The overall efficiency of the units can be conceived as the total COD remaining in the system in proportion to the initial COD of the feed. The efficiency of the different units determined as such were found to be 36.5% for unit No.1, 41% for unit No.2, and 36.5% for unit No.3, namely the total COD removal was greatest at the 35°C temperature. However, if this is analysed in conjunction with the dissolved COD removals the picture is slightly changed as higher removals occured at 27°C than at 40°C. The amounts of organic matter removal in the three units were 98% for unit No.1, 97.1% for

unit No.2 and 97% for unit No.3. However, one can say that complete removal of dissolved organic matter was incurred, which is normal in complete mixing aeration systems. The dissolved BOD results are well in conformity with the dissolved COD results.

A remarkable observation in the results is the low total BOD to total COD ratio which is 0.48 for unit No.1, 0.37 for unit No.2 and 0.32 for unit No.3, while such ratio is usually in the order of 0.7 as determined by McKinney and others. The writer explains these low BOD values by the fact that the samples were seeded from the units themselves and not from a separate seed, hence the lag period in the 5-Day BOD curve which could have yielded an erroneous interpretation of the 5-Day BOD values. This was also very specifically significant in the case of the $40^{o}C$ unit where the seed at $40^{o}C$ did not adjust to the incubation temperature of $20^{o}C$ in a short period and hence the enormous difference between the total COD and total BOD values for this unit.

This interesting finding although it was not intended but reveals a very important phenomena which is that of the period of acclamitization necessary for the micro-organisms. The findings of Sawyer and Wold[15] indicated immediate adjustment of sludges between 10^{o} and $30^{o}C$, while Ludzacketel[4] reported that 2 weeks were necessary for the sludge to adjust for a $25^{o}C$ temperature change.

Hence the units will be compared on the basis of COD values and not on BOD values which are for the purposes of this experiment not indicative.

Fig. 15 shows a remarkable drop in the COD value at the 35°C temperature, if the COD is taken as the criteria for efficiency, then it can be said that the optimum temperature was around 35°C.

Eckenfelder[2] states that variation in temperature affect all biological processes, and the rate of biological reaction will increase with temperature to an optimum value, approximately 30°C for most aerobic waste systems. Further increases in temperature result in a decrease in rate for mesophilic organisms. Eckenfelder[2] concludes that the magnitude of the temperature effect depends in a great measure on the nature of the process. Eckenfelder[2] mentions that a plant performance data a temperature of 32°C indicated BOD removals of 88% while at 49°C it indicated BOD removals of 75% only. The installation of a cooling tower which maintained the aeration tank temperature below 35°C resulted in maintaining BOD removal efficiencies in excess of 85%.

The works of Gotaas[16], Hobymueller[6] also indicated a maximum oxygen utilization rate at 30°C which started to decrease as the temperature was increased.

D. Mathematical Considerations

1- Organic Matter Removal: McKinney[12] suggested that in a completely mixed activated sludge system the removal of soluble organic matter can be determined by the following equation:

$$F = \frac{Fi}{K_5 t + 1}$$

Fi = Concentration of organic matter in the influent

F = Concentration of soluble organic material in the aeration tank

t = Detention time in days

The values of K_5 for the different units are shown in table XIII below.

Table XIII - Evaluation of the K_5 Constant

Item	F	Fi	Detention time in days	K_5	Temperature
Unit No.1	5.8	640	0.665	164	27°C
Unit No.2	7.8	640	0.665	124	35°C
Unit No.3	11.8	640	0.665	80	40°C

The value K_5 suggested by McKinney was 360 mg/l at 20°C. This value seems to be rather high.

Abu Samra[8] determined a value of K_5 = 250 at 23.5°C for metrical substrate with distilled water, and 18 hours detention time. The writer shares the opinion of Abu Samra[8] that McKinney's values do not take into consideration the detention time which could be a major factor besides temperature that will effect the value of K_5. The decrease in the value of K_5 as the temperature was increased above 27°C is quite a remarkable finding in this research.

2- Bacterial Mass: McKinney[12] has indicated that one third of the ultimate oxygen demand COD of a substrate is used for energy and that two thirds results in synthesis. Using an oxygen to cellular volatile solids conversion of 0.7g VSS/g O_2, 0.47 mg VSS (volatile suspended solids will be synthesized for each gram of COD removed. Variations in this value have been attributed to endogenous respiration effects.

Sawyer and Coellman and Henkelekian[2] have shown that for sewage and several industrial wastes 0.5 g VSS is synthesized per gram of BOD_5 removed.

Recently Servizi and Bogan[2] showed that synthesis is proportional to the change in free energy of oxidation. Since the free energy for most organic compounds is the same (-3160 cal/g COD) to (-3587 cal/g COD), it follows that synthesis will be proportional to the COD

of the substrate. Data for a wide variety of substrates yielded the following relationship:

$$g\ VSS = 0.39\ g\ COD\ removed$$

Sludge accumulation from biological oxidation of various wastes has been summarized by Eckenfelder[2] and shows a variation of 0.38 to 0.93 g VSS/g BOD_5 removed.

The reason as established by Eckenfelder is that the K rate of BOD test vary with the substrate and that the VSS present in most wastes will influence the calculated sludge yield.

McKinney suggested the following equation for the determination of the active mass of microorganisms

$$Ma = \frac{K_6 F}{\frac{1}{t} + K_7}$$

for which we showed previously that

$$Ma = \frac{c\,(Fi-F)}{K_7\ t+1}$$

The total volatile suspended solids M was expressed by McKinney by the following equation

$$M = Ma\ (1 + K_8\ t)$$

where the concentration of the suspended solids M in the mixed liquor is equal to the active mass plus the

inert volatile solid resulting from endogenous respiration. The value of K_8 is estimated as 30% of K_7 by McKinney. Eckenfelder reports a value of about 35% for domestic sewage.

From the above equation we have

$$M = \frac{c(Fi-F)}{K_7 t+1} \quad (1+0.3 K_7 t)$$

Hence solving the value K_7 from the results obtained in the three units we have the following results:

Table XIV - Evaluation of the K_7 Constant

Temperature	F	Fi	Detention time in days	K_7
27°C	24	1140	0.665	1.46
35°C	33	1140	0.665	1.68
40°C	37	1140	0.665	1.50

The total volatile solids contents was about 346 mg/l for unit No.1, 328 mg/l for unit No.2, and 340 mg/l for unit No.3. Starting with these values of M, the K_7 Constants were calculated and are shown in the above table. The value of K_7 represents the endogenous respiration constant having the units of mg/l decrease in active mass per mg/l active mass in the aeration tank per hour. It is interesting to note that the 35°C unit

had a lesser volatile solids content than the other 2 units which is another indication that unit No.2 had a more active sludge than the other two units.

The total COD value of this unit was the least of the three also. This is in conformity with Sawyer's[20] findings about the effect of temperature on sludge concentrations and the high respiration rates that he obtained and are shown on Fig. 10. This increase in the endogenous rate K_7 is explained by the fact that as the metabolic rate increases with temperature, the amount of food available for growth diminishes because of the increased amounts of food necessary to maintain the organisms already present. The high oxygen requirements in tank No.2 are also correlated with the high activity of this unit.

X- CONCLUSIONS

1- Temperatures as high as 40°C produced no deleterious effect on the efficiency of complete mixing activated sludge system under the experimental conditions involved.

2- At 27°C the microorganisms seemed to exist in a great variety including both plant and animal life, and the 35°C temperature appeared to be very close to the maximum temperature at which this great variety of microorganisms can survive. At 40°C animal life diminished considerably and appeared only occasionally.

3- The highest COD removal was that of the 35°C unit which also had the highest endogenous rate and the lowest volatile solids content. More than 98% of the soluble BOD was removed in all the three units.

4- At 35°C and 40°C temperatures the units showed some varying trends which are described below:

   a. Color changes were always noticed in the 35°C and 40°C units from time to time.

   b. The growth was sometimes in dispersed form and at other times in floculated form.

   c. Higher divergence were noted in the test results of these 2 units.

5- Between 5°C and 40°C existing literature indicates that increasing temperatures increase the activity of the micro-organisms until an optimum temperature beyond which this activity starts to decrease, the results of this research indicate the value of 35°C as being the optimum temperature. However, further studies should be carried on the temperature range between 25°C and 40°C but with smaller intervals of temperatures so as to be able to spot this optimum temperature more accurately.

6- The response of the microorganisms to sudden variations of temperature will have to be further investigated especially in the range between 30°C and 40°C.

7- The writer would like to emphasize the fact that the conditions and limitations of the laboratory equipment made it extremely difficult to create the best conditions for aeration and feed control. Any further research on the subject shall need more elaborate equipment.

XI- PRACTICAL APPLICATION

The results of this experiment are enough to indicate that even with the high temperatures prevailing in this part of the wprld, the complete mixing activated sludge aeration only systems together with other processes utilizing the same principle, can function satisfactorily, provided that further research can prove that the microorganisms can adjust to the daily temperature fluctuations without displaying an erratic behaviour.

Previous work indicate that at temperatures below 30°C adaption to temperature is immediate and that rapid fluctuations do not cause a deterioration of activated sludge with respect to its physical characteristics. However, for temperatures above 36°C the microorganisms did not show an immediate adaption to temperature fluctuations.

The aeration only systems will produce total BOD reductions up to 75% depending on the temperature range and detention time. These systems can be constructed as simple earthen ditches, or lined concrete tanks and aeration could be affected either mechanically or by diffused air.

This system has been used to treat domestic sewage in the so called "aerated lagoons".

Application of this process in the United States have shown that the low concentrations of microbial solids in the effluent makds it difficult to remove them by simple settling, hence the practice of

combining such systems with secondary oxidation ponds that can remove and stabilize these effluents up to 99% BOD reduction.

The aeration system with sludge return and loss of excess sludge in the effluent have gained the name of Extended Aeration Units and are very popular now for the treatment of domestic sewage and industrial wastes. One such designed treatment plant by the Associated Consulting Engineers will be put into effect in the near future for the treatment of domestic sewage for a 6000 population, in the Lebanon, another one will be put into operation in the Kuwait, which apparently will both cover a temperature range of operation between 5°C and 40°C. Field results from both these plants is expected to yield very valuable information.

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