STUDIES ON TOTAL OXIDATION PROCESS WITH INTERNAL AND EXTERNAL SLUDGE RECYCLE

By

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To My Beloved Parents

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c - Sludge recycle concentration factor, equal to the ratio between the recycle solids concentration, X_R, and the biological solids concentration in the reactor, X

D - Dilution rate. Ratio of the rate of flow, F, and the volume of liquor in the aeration tank, V. It is equal to the reciprocal of the mean hydraulic residence time, $\bar{t}$, in a completely mixed reactor, hr^{-1}

k_d - Maintenance energy coefficient, day^{-1}

K_s - A biological "constant" used in the hyperbolic expression relating specific growth rate to substrate concentration. It is known as the saturation constant. It is numerically equal to the substrate concentration at which specific growth rate is equal to half the maximum specific growth rate for the system, mg/l

S - Substrate concentration, measured as COD, mg/l

S_i - Concentration of substrate in the inflowing feed in continuous flow operation, measured as COD, mg/l

S_o - Initial substrate concentration used in batch growth studies measured as COD, mg/l

S_e - Concentration of substrate in the effluent filtrate measured as COD, mg/l

$\bar{S}_e$ - Steady state concentration of substrate in the effluent filtrate measured as COD, mg/l

S_t - Concentration of COD in the clarifier effluent, supernatant including non-settled biological solids, mg/l

$\bar{S}_t$ - Steady state concentration of COD in the clarifier effluent, supernatant including non-settled biological solids, mg/l

$\bar{t}$ - Mean hydraulic detention time, hrs

U - Specific substrate utilization rate, day^{-1}

V - Volume of liquor in aerator #1, liters

X - Biological solids concentration, mg/l

$\bar{X}$ - Steady state biological solids concentration in the reactor, mg/l

X_e - Biological solids concentration in the clarifier effluent, mg/l

$\bar{X}_e$ - Steady state biological solids concentration in the clarifier effluent, mg/l

X_R - Biological solids concentration in the recycle flow to the reactor, mg/l

$\bar{X}_R$ - Steady state biological solids concentration in the recycle flow to the reactor, mg/l

X_W - Excess biological solids (sludge wasted), mg/day

$\bar{X}_W$ - Steady state excess biological solids (sludge wasted), mg/day

Y_{t_B} - True mean cell yield obtained during growth at specific growth rate at or near μ_{max} (batch system)

Y_o - Observed mean cell yield obtained during growth at specific growth rate (continuous system with cell recycle)

Y_t - True cell yield

μ_n - Net specific growth rate in continuous system with cell feedback, hr^{-1}

μ_{max} - Maximum specific growth rate for a system in exponential growth, hr^{-1}

α - Recycle flow ratio

Θ_c - Sludge retention time, days

CHAPTER I

INTRODUCTION

World-wide awakening to environmental pollution problems has encouraged the passing of anti-pollution legislation. The continuous debate over the pollution problem without giving much credence to the views of professional people in the field resulted in legislation with environmental goals which are in all probability unattainable within the prescribed time limit. One of those goals in the water pollution field is achieving "zero discharge" of pollutants by 1985. Even though "zero discharge" of pollution may be an ideal goal, the cost to society of achieving it will in all probability be more than it can pay. Thus, in assessing environmental conditions objectively, it is wise for the environmental engineer not to overlook the assimilation capacity of the receiving streams. This capacity may be defined as the ability of the stream to degrade waste material entering it without lowering the dissolved oxygen (DO) concentration below 50 percent of the saturation level. There are four major factors which determine the assimilation capacity of a stream. They are stream runoff, time of passage down the stream, water temperature, and reaeration coefficient. Based on the assimilation capacity of a stream, a limit can be set for the residues in wastewater effluents. This limit, in turn, would indicate a particular degree of required treatment prior to discharging the wastewater into the stream. It is obvious that simple primary treatment cannot deliver effluent of the required quality. Secondary (biological) treatment and sometimes chemical-physical treatment, or combinations of both, have the capability of delivering effluents of the required quality. Economic considerations have always favored biological treatment over chemical treatment. Unlike other engineering processes, the material employed in the biological process is a living material, i.e., it is composed of microorganisms. Although the biochemical mechanism for control of metabolism of heterogeneous microbial populations which exist in treatment facilities is not fully understood, many process modifications have been developed, and it is possible to achieve a high degree of purification.

There are various biological treatment processes, and they can be placed, broadly, in two general categories; viz., fluidized bed systems and fixed bed systems. An example of a fluidized process is activated sludge, and an example of a fixed bed process is trickling filtration. The activated sludge process is widely used because of its versatility in design and operation. Since its inception, the process has undergone several modifications. Some examples of such modifications of the conventional activated sludge process are "tapered aeration," "step aeration," biosorption," "complete mixing," and "extended aeration" or "total oxidation" processes. All of the above mentioned modifications were initiated for treatment of a particular kind of waste or in order to overcome a particular problem.

A major problem in activated sludge processes is disposal of excess sludge. Some of the methods used for the disposal of excess sludge are sludge digestion--either aerobic or anaerobic, incineration, and wet oxidation. The residues from these processes are generally disposed of through landfill operations. Sludge disposal constitutes a major portion of the cost of an activated sludge treatment plant. A process that includes both purification of the waste and disposal of sludge is the extended aeration process. This process has been widely used over the past 25 years, but only for rather small wastewater flows. The principle of the extended aeration process is total oxidation of the organic sludge produced in the purification process to carbon dioxide (CO_2) and water. The validity of this principle has come under constant debate in the research field. Much of the controversy has been resolved by the long-term investigations conducted at Oklahoma State University. A modification to the regular extended aeration process has been proposed for the engineering control of the biological solids concentration in extended aeration processes. This modification has been termed the "hydrolytically-assisted extended aeration process." The modified process was operated successfully in laboratory-scale pilot plant studies. It was also found that the "hydrolytic-assist" was useful in treating wastes containing a high ash content; there was no buildup of unreasonably high ash content in the activated sludge.

In all previous work on the extended aeration process, there were not many engineering controls except the detention time and permissible substrate concentrations, i.e., loadings. One characteristic of this process is unsteadiness with respect to biological solids concentration. This situation exists even for the "hydrolytic-assist" modification.

Based on the general theory of continuous culture, various models for the design of activated sludge processes have been advanced over the years. These mathematical models provide reliable design and operational data for the biological systems, but all are based upon the premise that the system is operating under steady state conditions; i.e., the system parameters such as dilution rate, influent substrate concentration, cell yield, microbial concentration, and effluent substrate concentration, remain constant. The model proposed by Gaudy has an added advantage over many of the proposed models in that it uses as a system constant the recycle sludge concentration, X_R. This mode of operation has been shown to make the system fit the assumed steady state condition of the model more effectively than do other modes of operation. In this mode of operation, with strict control of all engineering parameters involved, there could conceivably be a situation, as hypothesized originally by Porges, in which a steady state with respect to biological solids concentration exists for a particular organic loading under a specific detention time. In such a situation, the sludge produced would be just sufficient to recycle in constant concentration, i.e., there would be no excess sludge.

In the present investigation, there are two phases, both of which involve the principle of total oxidation. The first phase of the investigation was to test the operational feasibility of using the hydrolytically-assisted extended aeration process for a waste of high ash content at a higher organic loading than previously tested. The second phase of the investigation was aimed at determining if, using the model of Gaudy and his co-workers (constant recycle sludge concentration), there exists any possibility of achieving steady state conditions at which there would be no excess sludge.

CHAPTER II

LITERATURE REVIEW

Many of the previous investigators in this laboratory who employed the extended aeration process in their research, described it in sufficient detail in the literature review in their theses (1)(2)(3)(4)(5). In this thesis, only a brief account of the literature is needed, since there has not been much reported since the investigation of Roach in this laboratory (3).

Porges and his co-workers in the early '50s (6)(7)(8)(9) concluded that an activated sludge could be operated at an equilibrium wherein the net increase in biological solids due to assimilation of exogenous substrate would be counterbalanced by the decrease in biomass due to endogenous respiration or autodigestion in the system. This could be achieved when a long detention time in the order of 18-24 hours was employed, and when a proper food-to-microorganisms ratio was adopted. Kountz (10) supported this concept, based upon a one-year pilot plant study during which no wastage of sludge was needed. Later, in association with Forney, Kountz (11) reported an accumulation of sludge at the rate of 0.122 lbs/day. They also reported that the actual endogenous loss was two percent per day of the total weight of the activated sludge in the unit, and there was an accumulation of non-oxidizable sludge of 0.6 percent per day of the total weight of the activated sludge.

Symons and McKinney (12) in their studies on soluble organic substrates concluded that the total oxidation system would not work, and there would be a continuous buildup of sludge. It was felt that the system was theoretically unsound because of synthesis of nonbiodegradable extracellular polysaccharides, and thus there was a continuous buildup of inert organic fraction if no sludge wastage was practiced.

In 1958, Tapleshay (13) in his investigations on the performance of extended aeration units in the field, reported that total oxidation of organic wastes could be accomplished. He reported BOD reduction between 80 to 90 percent and effluent BOD of less than 20 ppm for the treatment of domestic sewage. The volatile solids in the system were as low as 50 percent. The solids concentration, in general, was maintained at relatively fixed levels over extended periods of time with no necessity of wasting any sludge.

In an attempt to determine the limitations of the "total oxidation" process, Busch and Myrick (14) conducted both continuous flow and batch experiments for a period of one year. They concluded that total oxidation is neither theoretically sound nor practically attainable; some buildup of biological solids is inevitable unless carryover of solids in the effluent is sufficient for balance. They also reported cyclic fluctuations in concentration of biological solids in continuous systems without complementing fluctuations in effluent quality. This find provides some indication of autodigestion of microorganisms.

Studies of Washington, Hetling, and Rao (15) showed that the system did not reach any steady state condition, but demonstrated periods of increasing as well as decreasing biological solids concentrations, which was another evidence for some autodigestion and/or lysis of the microorganisms in the system.

Washington and Symons (16) in their studies on volatile solids accumulation in extended aeration systems reported that there was a continuous buildup of biologically inactive mass which was mainly extracellular polysaccharides.

Ludzack (17) reported in his studies on the extended aeration process that 20 percent solids wastage per week yielded a volatile solids content of 75-80 percent in the sludge, whereas when wastage was decreased to five percent per week, the volatile solids content of the sludge decreased to 60 percent. Finally, when no sludge wastage was practiced, the volatile content dropped further--from 60 to 55 percent.

McCarthy and Broderson (18) in their report suggested that solids accumulation must be considered in the design of extended aeration systems. They concluded that the system will accumulate solids and discharge the excess suspended solids in the effluent if no facilities for disposal of excess sludge are provided.

Sawyer (19) presented some guidelines for the satisfactory operation of the extended aeration process. The guidelines included an aeration time of 24 hours, loading of 15 lbs BOD/day/1000 cu ft, and 5000-8000 mg/l biological solids concentration.

In the midst of controversial views regarding total oxidation, Gaudy and his co-workers began long-term systematic studies in the mid-1960s. Thabaraj and Gaudy (20) in 1971 showed sufficient proof in favor of the concept of total oxidation according to results of batch experiments. They stated that prolonged endogenous metabolism of biological solids developed under balanced growth conditions in some cases resulted in oxidation of an amount of solids essentially equal to the total solids synthesized during the substrate removal period.

In their long-term pilot plant studies in the Oklahoma State University bioenvironmental engineering laboratories, all of the investigators who worked on the extended aeration process obtained evidence for no steady state of biological solids level, but found evidence for periods of solids accumulation and periods of solids de-accumulation due to autodigestion of the biological solids in the reactor. Since one of the foremost problems encountered by many of the previous investigators with the process was inadvertent loss of biological solids over the weir of the final clarifier, Gaudy and his co-workers centrifuged all of the effluent, assuring return of all biological solids to the aeration tank. The experimental results of a two-year study by Gaudy, Ramanathan, Yang, and DeGeare (21) indicated conclusively that an extended aeration activated sludge system without sludge wastage could be operated with good biological efficiency and without continuous solids accumulation or unacceptable buildup of biologically inactive portions of the sludge. It was also observed, however, that the steady state with respect to biomass reported by Porges, failed to materialize. For the periods of solids accumulation and periods of de-accumulation, Gaudy concluded that the complex and dynamic ecosystem found in the heterogeneous population was capable of altering predominance ratios in order to allow for specific assimilation of virtually all cellular constituents.

It became apparent from many investigations that biological solids in the extended aeration system would not increase indefinitely, but it was impossible to predict the occurrence of the irregular cycles of solids accumulation and de-accumulation. The solids level at times was so high as to impair their separation in the clarifier. It became essential, therefore, to initiate an engineering assist to the process for the control of solids. Gaudy, Yang, and Obayashi (22) initiated the procedure of withdrawing some of the sludge periodically and breaking down the macromolecules by chemical hydrolysis, then recycling the liquefied cells. This process was termed the "hydrolytic-assist." They concluded that an extended aeration process assisted by chemical hydrolysis to aid the autodigestive process could be operated successfully for concurrent treatment of the organic waste and for sludge disposal. The "hydrolytic-assist" made it possible for the system to do chemically what is difficult to do biologically, and to do biologically what is difficult to do chemically. Through recycling the hydrolysate, the system has an added advantage of supplying nitrogen (and possibly phosphorous), useful in treating nutrient-deficient wastes.

Yang and Gaudy (23)(24) showed further proof in favor of the operational feasibility of the "hydrolytic-assist" extended aeration process through long-term pilot plant studies. They concluded the "hydrolytic-assist" process made the system independent of the natural periods of accumulation and de-accumulation of biological solids. They also reported that the system possessed a good ability to accept shock loading. They found that the "hydrolytic-assist" would not impair the production of highly nitrified effluent to any extent, and that the effluent was as nitrified as that from the normal extended aeration process. These studies demonstrated conclusively that microbial cells do serve as substrates. In order to ascertain the relative availability of the various cell components, Obayashi and Gaudy (25) used five microorganisms to produce heteropolysaccharide, and fed it as sole source of carbon to microorganisms of sewage origin. They concluded that extracellular polysaccharide cannot be classified as biologically inert material, as reported by Washington, Symons, and McKinney (12), and consequently, buildup of extracellular polysacchardies cannot be validly cited as evidence against the concept of total oxidation.

Further studies were conducted by Saidi (1), Murthy (2), and Roach (3) concerning the operational stability of the modified extended aeration process at higher organic loadings. The investigation conducted by Saidi provided a definite indication of the capability of the "hydrolytic-assist" system to function at loadings of 500 mg/l to 1000 mg/l, which are considered rather high for the system in comparison to the recommendations of Sawyer (19). Further, it was reported that highly nitrified effluent was produced at the loading of 1000 mg/l. It was also reported by Saidi that the "hydrolytic-assist" system was extremely stable with respect to substrate leakage under quantitative shock loading conditions.

The investigation conducted by Murthy showed that nitrified effluent could be obtained at an organic loading of 1500 mg/l, but at 2000 mg/l, nitrification in the system eventually ceased and all of the ammonia in the feed came out in the effluent. This, as Murthy concluded, was added evidence for the correlation between organic loading and degree of nitrification. Furthermore, his suggestions to use partial unit hydrolysis as an expedient for the removal of filamentous bulking sludge in the extended aeration system agrees with the suggestions of Yang and Scott (4)(5).

Roach (3) in his investigation reported that the extended aeration system showed no apparent upset in purification efficiency even at a five-fold increase shock load (1000-5000 mg/l glucose and hydrolysate). He also concluded that increases in hydrolysate concentration in the feed of 2800 mg/l caused a high degree of leakage of filtrate COD.

The concept of total oxidation has been proven valid with respect to sound microbiological theory by the results of the above investigations (1)(2)(3)(4)(5)(21)(22)(23)(24)(25). The waste used in nearly all of the studies was synthetic waste consisting of a buffer salts medium using glucose as the carbon source and ammonium ion as a source of nitrogen. In an attempt to study the application of the process to the wastes containing a high ash content, Gaudy, et al. (26) conducted an investigation using trickling filter sludge from the municipal sewage treatment plant of Stillwater, Oklahoma. The waste used in previous studies had little or no suspended organic solids. The sludge from the trickling filter plant was hydrolyzed before feeding. The laboratory pilot plant ran initially at 500 mg/l COD for about 440 days. During this period, the solids concentration varied between 5000 mg/l and 15,000 mg/l; the average was 12,200 mg/l. The biological solids concentration was almost in a balanced steady condition during the period of 310-440 days. Throughout the studies, both the purification efficiency and nitrification characteristics were reported to be excellent. The ash content in the sludge before hydrolysis was 34.2 percent, and after hydrolysis, 66.9 percent. It was reported that biomass concentration in the system had an ash content of 49 percent, which was unusually high. Even at this percentage of ash content, the protein content was reported as 49 percent on volatile solids basis, and 25 percent on a suspended solids basis, which indicates a healthy active mass. For the next 83 days, the system was operated at an average influent COD of 1096 mg/l. During this period, the average solids concentration was 20,200 mg/l while the ash content and protein content in the system were 55 percent and 35 percent, respectively. Gaudy, et al. (26) concluded that high ash content in wastewater can be expected to result in higher ash contents in the avtivated sludge, but ash content would not continue to build up in the sludge.

Singh and Patterson (27), studying the improvement of aerobic digestion rates of wastes, reported that acid hydrolysis plus autoclaving at pH 1 yielded a soluble COD approximately 65 percent of the original volatile suspended solids. He also reported that uptake of soluble organics, measured as COD in the aerobic digester was extremely rapid, with the rate of uptake being proportional to the substrate added. This investigation supported the finding of Gaudy and his co-workers that the "hydrolytic assist" can make it easy for the organisms to metabolize cell components.

From the foregoing review, it can be seen that the majority of the early research workers concluded that the concept of total oxidation of organic sludge was erroneous. They argued that there would be a build-up of biologically inert organic material; such inert material included extracellular polysaccharides. Assuming this conclusion to be correct, no one really seems to have studied the system over a sufficiently long period of time to determine the time required for failure of the system. Also, these workers did not show any reasonable experimental verification of their conclusions regarding inertness of biological materials. There was practical objection to the concept of total oxidation because it was thought that there would always be a loss of biological solids in the effluent. These two reasons were proven conclusively to be incorrect in later investigations. Since the validity of the concept has now been proved beyond doubt, it was important to apply the principle of treatment of a more complicated waste. It was possible that the system might fail when treating waste of high ash content, because continuous accumulation of ash in the sludge could slowly decrease the efficiency and cause ultimate failure. The investigation on high ash waste conducted just prior to the present investigation indicated that the above concern was unwarranted, and the first phase of the present investigation was undertaken to determine how the system would function at a higher organic loading.

Even though the theory of total oxidation was proven to be valid, all of the investigations in support of it showed that there was no steady state in the biological solids concentration. Gaudy, et al. (28) in presenting computational analysis for their design and operational model of the activated sludge, showed that there could be a situation of zero excess sludge and a steady state for the biological solids in the reactor; that is to say, the mathematical model predicted zero excess sludge in accordance with the boundaries of the model and the assumption that the biological constants were, indeed, constant. Before discussing further the factors involved in achieving steady state, it is important to describe the theory and development of Gaudy's model of activated sludge.

Gaudy and his co-workers (29)(30) made extensive investigations to comprehend the growth characteristics of the continuous culture of heterogeneous microbial populations in completely mixed reactors in once-through and with cell feedback-type operations. These studies were undertaken to determine whether the theory of continuous culture developed for pure cultures (31)(32)(33)(34) was applicable to heterogeneous populations. It was found that the Monod equation

$$\mu = \frac{\mu_{max} S}{K_s + S}$$

for pure cultures was also applicable to heterogeneous cultures. It was also concluded that growth constants, viz., maximum specific growth rate constant, μ_{max}, saturation constant, K_s, and cell yield, Y, were variable because of heterogeneity of the microbial populations. For these constants, a useable range has been defined through many investigations (35)(36)(37). The equations of Herbert for continuous growth in once-through reactors were useful in describing the effluent substrate and biomass concentrations (29)(30). However, the equations for steady state concentration of effluent substrate and cell or biomass concentration, $\bar{S}$ and $\bar{X}$, for cell recycle systems, were not entirely useful (shown in Table I). There are three biological constants, μ_{max}, K_s, and Y, and two hydraulic parameters, α and c, in these equations. At a selected dilution rate, these five parameters exert control of $\bar{X}$ and $\bar{S}$. The primary operational parameter in Herbert's model was the recycle concentration factor, c, which is the ratio between the recycle sludge concentration, X_R, and aeration tank suspended solids concentration, $\bar{X}$. The growth rate in the system can be controlled by selection of c for a particular α, and D $\left[\mu = D(1 + \alpha - \alpha c)\right]$. Attempts to operate using this parameter caused severe fluctuation in the "steady state" values of $\bar{X}$ and $\bar{S}$ when heterogeneous populations were employed. In order to keep c

TABLE I

COMPARISON OF STEADY STATE EQUATIONS ACCORDING TO MODELS OF HERBERT AND OF RAMANATHAN AND GAUDY*

Herbert Constant c $\left(c = \frac{X_R}{X}\right)$		Ramanathan & Gaudy Constant X_R	
$\bar{X} = \frac{Y}{1+\alpha-\alpha c}\left(S_i-\bar{S}_e\right)$	(1a)	$\bar{X} = \frac{Y\left[S_i-(1+\alpha)\bar{S}_e\right]+\alpha X_R}{1+\alpha}$	(1)
$\bar{S}_e = \frac{K_s D(1+\alpha-\alpha c)}{\mu_{max}-D(1+\alpha-\alpha c)}$	(2a)	$\bar{S}_e = \frac{-b\pm\sqrt{b^2-4ac}}{2a}$ $a = \mu_{max}-(1+\alpha)D$ $b = D\left[S_i-(1+\alpha)K_s\right]-\frac{\mu_{max}}{1+\alpha}\left[S_i+\frac{\alpha X_R}{Y}\right]$ $c = K_s D S_i$	(2)
$\mu = D(1+\alpha-\alpha c)$	(3)	$\mu = D\left(1+\alpha-\alpha\frac{X_R}{\bar{X}}\right)$	(3)

*Source: (38)

constant, X_R has to be adjusted for every change in $\bar{X}$, and when X_R was increased for an increase in $\bar{X}$ to keep c constant, $\bar{X}$ was increased further, causing the system to drift further away from steady state. Even though it was not in agreement with principles of the theory of continuous culture, it was decided to hold the recycle sludge concentration, X_R, constant instead of holding c as a constant. The model equations with constant X_R derived from $\bar{X}$ and $\bar{S}$ are shown in Table I. In deriving these equations, the concentration of S in the recycle solids was assumed to be negligible (30).

Behavior of the kinetic equations developed for this model was determined by setting up a computational program varying all of the parameters such as biological constants, maximum specific growth rate, μ_{max}, saturation constant, K_s, and cell yield, Y, and engineering parameters, recycle flow rate, α, recycle solids concentration, X_R. The mathematical ramifications of maintaining X_R as a system constant have been discussed, and the relationships between the operational parameters have been delineated (38). The model using X_R as a system parameter for design and operation proved to be less sensitive to high dilution rates than did Herbert's model (38).

Srinivasaraghavan and Gaudy ran pilot plant studies employing X_R as a design and operational constant (39). They found the equation to be highly successful in predicting $\bar{S}$ and $\bar{X}$, but they were less accurate as predictors of excess sludge production, X_W. They added a fourth biological constant, the decay coefficient, k_d. With inclusion of the decay coefficient, their model provided excellent prediction of X_W as well as S and X for the system under various operational conditions (40). The modified equations, including the decay coefficient, are shown in

Table II.

It is of interest to include a review of literature on the decay coefficient or, as it is sometimes called, the maintenance coefficient.

The earliest microbiologist to distinguish between energy required for synthesis and energy for maintenance of cells was Duclaux (1898). He reported that for yeast, the energy of maintenance was 0.25 gms of sugar/gm yeast/hr.

The explanation of variability of cell yield has been formulated around the concepts of endogenous metabolism and maintenance. Monod (41) has postulated that a minimum substrate concentration should exist which would allow only survival and maintenance of the cells. He was not successful in measuring it quantitatively, and as a result, many subsequent workers discarded the theory of maintenance. Dawes and Ribbons (42) reviewed the aspects of the endogenous metabolism and defined it as "the total metabolic reactions that occur within the living cell when it is held in the absence of compounds or elements which may serve as specific exogenous substrates." According to these authors, in providing energy for its maintenance, a cell must utilize an endogenous substrate in the absence of an exogenous substrate, and when endogenous substrate is all utilized, the cell would lyse if no exogenous substrate is provided.

Marr, et al. (43) suggested that respiration of cells in limiting substrate media includes (i) occurrence of substrate oxidation proportional to growth rate, and (ii) a constant rate of oxidation of endogenous material that occurs at all growth rates. Mallete and McGrew (44) recognized the need for the metabolic energy meeting the demand of physical and chemical wear and tear during the cellular

TABLE II

STEADY STATE EQUATIONS INCLUDING MAINTENANCE ENERGY COEFFICIENT FOR THE MODEL EMPLOYING CONSTANT X_R*

$$\bar{X} = \frac{Y_t\left[S_i - (1+\alpha)S_e\right] + \alpha X_R}{1+\alpha+k_d/D} \qquad (4)$$

$$\bar{S}_e = \frac{-b \pm \sqrt{b^2-4ac}}{2a}$$

$$a = \mu_{max} - (1+\alpha)D - k_d$$

$$b = D\left[S_i-(1+\alpha)K_s\right] - \frac{\mu_{max}}{1+\alpha}\left[S_i + \frac{\alpha X_R}{Y_t}\right] + k_d\left[\frac{S_i}{1+\alpha} - K_s\right] \qquad (5)$$

$$c = K_s\, S_i\left(D + \frac{k_d}{1+\alpha}\right)$$

$$X_W = V\bar{X}\,\mu_n \text{ mg/day} \qquad (6)$$

$$\mu = \mu_n\bar{X}/D \text{ mg/l (to convert to mg/day multiply Eq. (7) by F)} \qquad (7)$$

$$\mu_n = \frac{X_W}{V\bar{X}} = \frac{1}{\text{sludge age}} = \frac{1}{\Theta_c} \quad \text{(where } X_W \text{ is given in mg/day)} \qquad (8)$$

$$= \frac{X_W \cdot D}{\bar{X}} = \frac{1}{\text{sludge age}} \quad \text{(where } X_W \text{ is given in mg/l)} \qquad (9)$$

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*Source: (40)

processes. Mallette and McGrew (44) and Mallete (45), studying the maintenance requirement, E. coli, found that small amounts of glucose provided as exogenous substrate would provide energy to maintain the cell without allowing growth to occur.

Pirt (46) reviewed the equations of Marr, et al. (43), and Schulze and Lipe (47), and presented his own descriptive equations for determining the maintenance coefficient. Marr, et al. plotted the straight line relationship given as: $\frac{1}{X} = \frac{a}{X_{max}} \cdot \frac{1}{D} + \frac{1}{X_{max}}$ where X is the steady state concentration of cells, D is the dilution rate, X_{max} is the maximum concentration of cells where the maintenance energy is zero, and 'a' is the specific maintenance rate. Pirt terms this as an approximation which is nearly true provided growth rate is low enough for the utilization of energy substrate to be nearly complete. Pirt's equation for maintenance was derived from material balance of substrate; he used the expression: $\frac{1}{Y} = \frac{m}{\mu} + \frac{1}{Y_G}$ where Y is the observed yield, m is the maintenance coefficient, and Y_G is the true yield. Pirt concluded from his data that maintenance energy is a significant factor at low growth rates.

Sherrard and Schroeder (48)(49)(50) developed a mathematical model for completely mixed biological systems, utilizing a variable microorganism yield coefficient in conjunction with microbial continuous culture theory. They have shown that the observed cell yield is maximum at high specific growth rates and minimum at low specific growth rates. The primary reasons attributed to the variations in yield were predation activities of higher life forms and increased microorganism maintenance energy requirements at lower specific growth rate. The other model which incorporated the maintenance coefficient was due to

Lawrence and McCarthy (51).

It is interesting to know the reported values of the maintenance coefficient obtained by many of the researchers. Using the organism Aerobacter cloacae with glucose as substrate under aerobic conditions, Pirt (46) calculated a maintenance coefficient of 0.094 gms glucose/gm dry wt/hr. Using the same organism under anaerobic conditions, he obtained a maintenance coefficient of 0.473 gms glucose/gm dry wt/hr. Schulze and Lipe (47), using E. coli, calculated a maintenance coefficient of 0.055 gms glucose/gm dry wt/hr at 30°C under aerobic conditions. Pirt (46), using Marr's data for E. coli at 30°C, has calculated a maintenance coefficient of 0.07 gm glucose/gm dry wt/hr. McGrew and Mallette (44) made direct attempts to determine maintenance requirements on E. coli by adding glucose to the culture until a threshold level was obtained so that a particular turbidity was maintained which neither increased nor decreased. It was concluded that this level of glucose was specifically utilized for maintenance without growth. An amount of 0.1 mg of glucose was needed to maintain 1.5 mg of cells. This gives a maintenance coefficient of 0.067 gm glucose/gm dry wt/hr. Srinivasaraghavan and Gaudy (52) calculated a maintenance coefficient for heterogeneous populations of 0.14 $days^{-1}$ using the plot of specific substrate utilization rate (U) and net specific growth rate (μ). Saleh (53) in his studies on the behavior of the activated sludge process under shock load conditions calculated a maintenance coefficient of 0.16 day^{-1}.

Chiu, et al. (54)(55) reported a value of k_d ranging between 0.0064 hr^{-1} and 0.0244 hr^{-1} for mixed microbial populations. The data used was from batch cultures grown with the seed from continuous systems at different dilution rates. Stall (56) obtained a value of 0.09 days^{-1} in his studies on phosphorous removal in the activated sludge process.

From the above review on the model and maintenance coefficient it seems that Porge's hypothesis of steady state for biological solids might possibly be obtained. His idea of proper food-to-microorganisms ratio can be explained in conjunction with the minimum amount of substrate required for maintenance of cell populations. Although, to the author's knowledge, no one in the basic microbiology field specifically mentions autodigestion, it is generally considered that decreased yield is also because of higher amount of autodigestion at lower growth rates. Thus, the maintenance coefficient includes both autodigestion rate and cell maintenance requirement rate. When the biological solids attain a steady state without production of any excess sludge, it indicates for all purposes that growth rate equals the maintenance coefficient or autodigestion coefficient, i.e., net specific growth rate equals zero.

A portion of the present investigation was devoted to determining whether the above described condition of steady state could be achieved.

CHAPTER III

MATERIALS AND METHODS

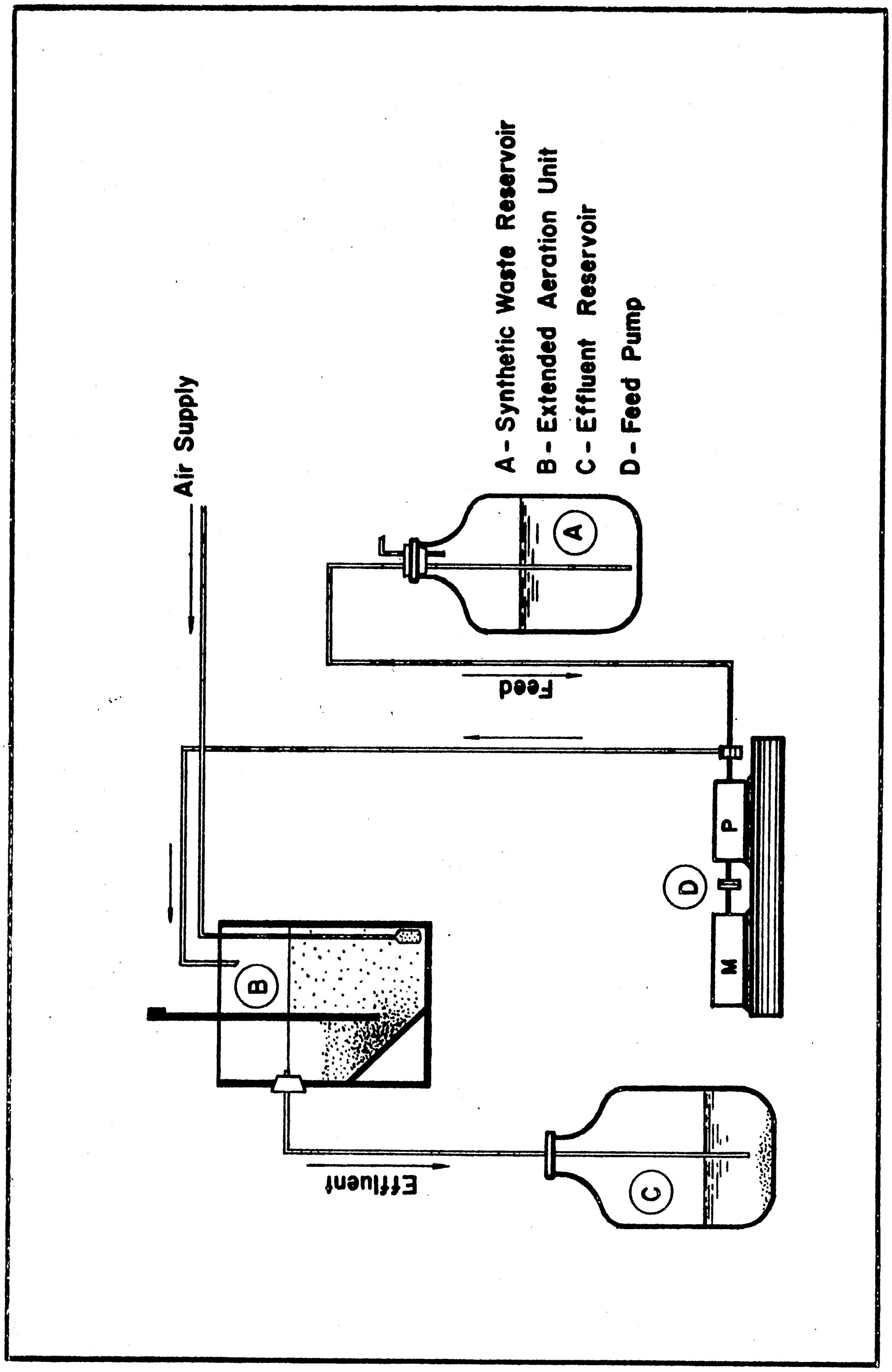
Studies on the "Hydrolytic-assist" Extended Aeration Process for Wastes of High Ash Content

The pilot plant employed to study the performance of the extended aeration process with "hydrolytic-assist" for wastes of high ash content was placed in operation by Saidi (1) in October, 1973, and later, Reddy and Manickam continued at different levels of organic loading (26).

Experimental Apparatus

Figure 1 shows the experimental setup employed in this investigation. The apparatus consisted of a plexiglass unit with a 6.2-liter aeration basin and a 3.2-liter settling chamber, making a total volume of 9.4 liters. A movable baffle was provided to separate the two compartments. The baffle was placed just above the tank bottom, leaving a small gap so that the mixed liquor could pass to the settling tank and sludge could recycle to the aeration chamber. The feed flow rate was 10 liters/day, yielding a mean hydraulic detention time of approximately 16 hours in the aeration chamber, and eight hours in the settling chamber, with a total detention time of 24 hours. The pump used for pumping feed was a peristaltic pump. The temperature was monitored

Figure 1. Schematic Flow Diagram of a Laboratory-scale Continuous Flow Extended Aeration System


A - Synthetic Waste Reservoir
B - Extended Aeration Unit
C - Effluent Reservoir
D - Feed Pump
Air Supply
Feed
Effluent
A
B
C
D
M
P

throughout the study and was 24 $\pm$ 2^{o}C. The pH of the system was adjusted at 7.0 as needed by adding a few drops of 10N potassium hydroxide solution.

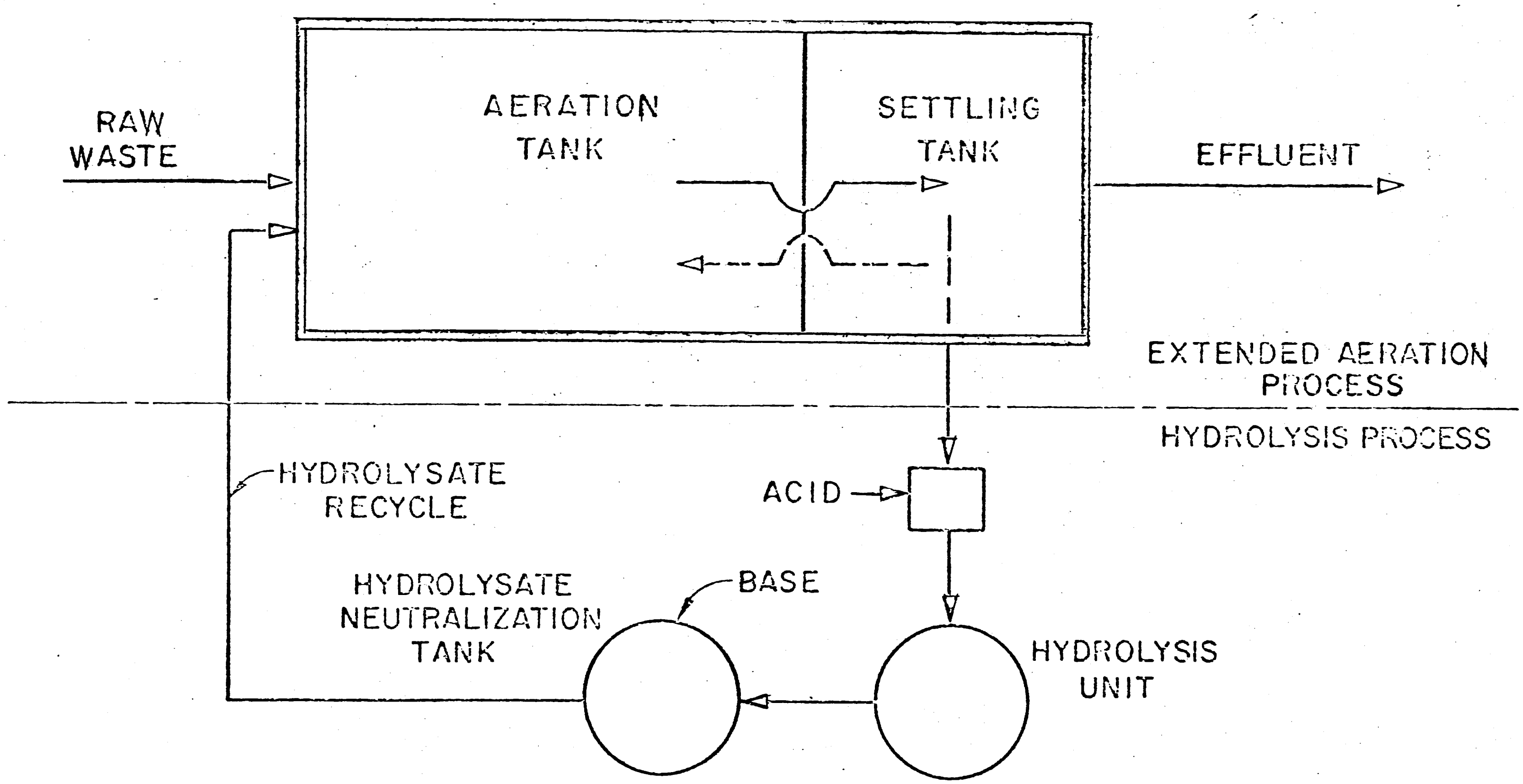
Feed Preparation

The feed used was prepared from the sludge withdrawn from the underflow of the secondary clarifier of the municipal treatment plant. The trickling filter sludge was acidified to pH 1 with concentrated H_2SO_4, autoclaved for five hours at 15 psi, 121^{o}C, and neutralized to pH 7 with 10N KOH. The chemical oxygen demand (COD) of the sludge was determined before and after hydrolysis. Since the COD of the sludge was very high, small portions sufficient for making 20 liters of feed at approximately 2000 mg/l COD were made and stored in the freezer to deter microbial growth until the feed was used. As a part of the operation of the unit, 1800 ml of sludge was withdrawn from the clarifier once every two weeks until day 689, after which the same amount was withdrawn once every week. The withdrawn sludge was hydrolyzed, as described earlier, then was divided into equal portions for subsequent feedings and was fed to the aeration chamber along with the trickling filter sludge. This material was not considered as feed material in calculating the loadings to the system, but was considered simply as a part of the return sludge. An example of a flow diagram showing the incorporation of the "hydrolytic-assist" process is given in Figure 2.

Experimental Procedure

On alternate days, the stock solution of the hydrolyzed trickling filter sludge was thawed, and 20 liters of feed at concentration 2000

Figure 2. Flow Diagram Showing the Incorporation of the "Hydrolytic-assist" Into the Extended Aeration Activated Sludge Process (57)


RAW WASTE
AERATION TANK
SETTLING TANK
EFFLUENT
EXTENDED AERATION PROCESS
HYDROLYSIS PROCESS
HYDROLYSATE RECYCLE
ACID
BASE
HYDROLYSATE NEUTRALIZATION TANK
HYDROLYSIS UNIT

mg/l COD prepared. The measured concentrated sludge was checked for neutral pH and final adjustment to exactly pH 7.0 was made by adding base or acid. Before preparing the new feed, the feed bottle was cleaned with dichromate cleaning solution and rinsed thoroughly with tap water. The concentrated feed (trickling filter sludge) was poured into the feed bottle which was then filled with tap water to slightly less than 20 liters so that the hydrolyzed mixed liquor portion would complete the 20-liter volume. Meanwhile, the baffle separating the aeration chamber and clarifier was removed to mix all of the contents. The pH of the system was checked, and whenever it was less than pH 7 it was adjusted with a few drops of 10N KOH. The feed line was disinfected by pumping a one percent Clorox solution in tap water for one hour. This was followed by a thorough rinsing with tap water. The baffle was re-inserted after an hour's aeration. The flow rate was checked daily at regular intervals.

The following parameters were monitored during the study period:

1. Feed (excluding recycle hydrolysate mixed liquor)

   a. Unfiltered sample

      1) COD (alternate days)
      2) suspended solids (alternate days)
      3) total solids and volatile solids (weekly)
      4) organic nitrogen (a few times)
      5) BOD (once each two weeks)

   b. Filtrate

      1) COD (alternate days)
      2) NH_3-N (alternate days)

2. Feed (including hydrolysate mixed liquor)

   a. Unfiltered sample

      1) COD (alternate days)
      2) suspended solids (alternate days)

3) total solids and volatile solids (weekly)
4) organic nitrogen (a few times)

3. Effluent

a. Supernatant

1) COD (alternate days)
2) suspended solids (alternate days)
3) total solids and volatile solids (weekly)
4) BOD (each two weeks)

b. Filtrate

1) COD (alternate days)
2) NH_3-N (alternate days)
3) NO_3-N (alternate days)
4) BOD (once each two weeks)

4. Mixed Liquor

a. Total sample

1) suspended solids (alternate days)
2) total solids and volatile solids (alternate days)
3) organic nitrogen (a few times)

b. Filtrate sample

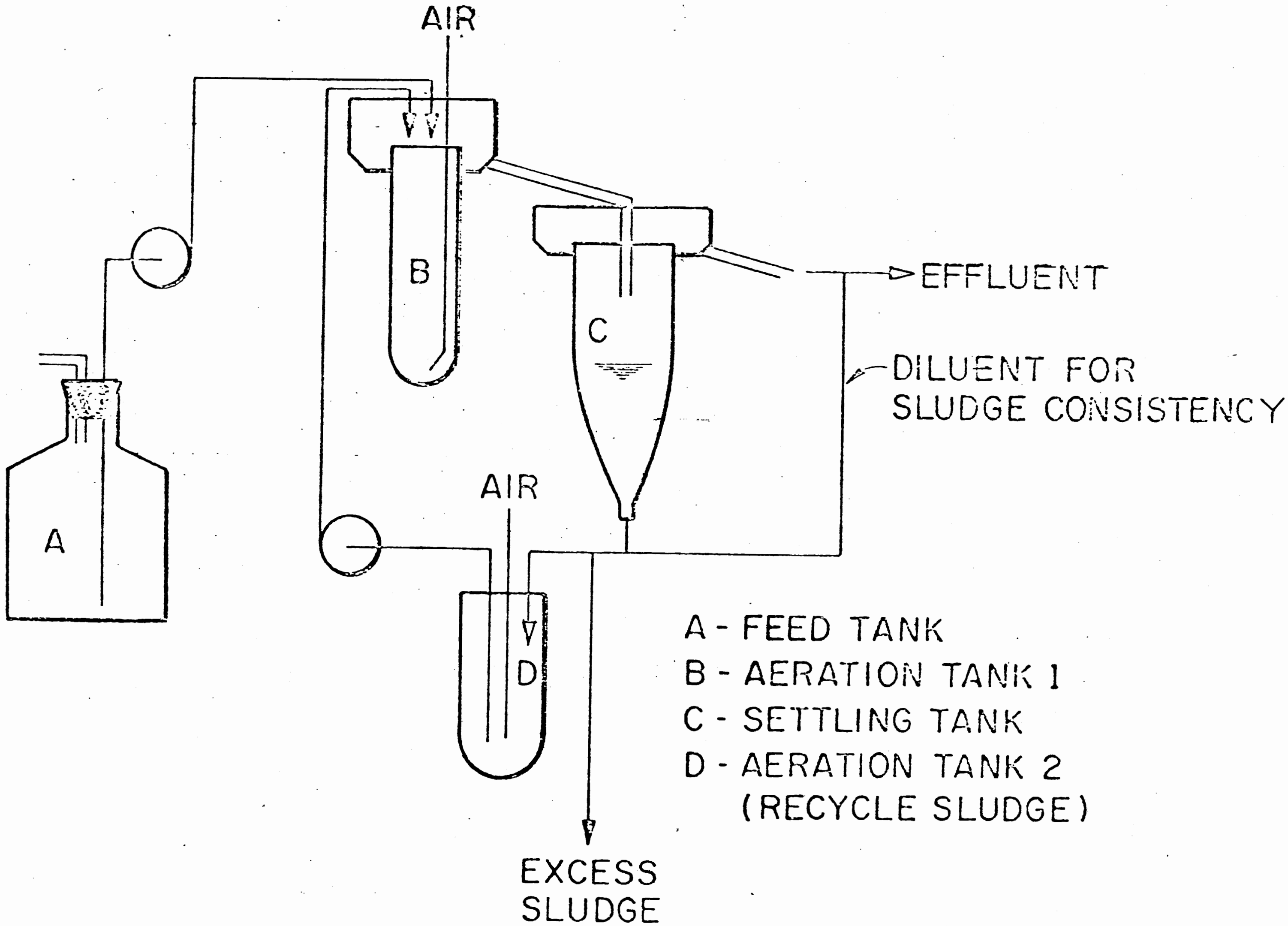
1) dissolved solids and volatile solids (alternate days)

During the entire study period, only one growth rate study in batch experiments was performed. The procedure used was the same as described later. A settling test was conducted using 1000 ml graduated cylinders for 25, 50, 75, and 100 percent biological solids concentrations.

Studies on the "Total Oxidation" Process Employing a Mathematical Model of Activated Sludge With Constant Sludge Feedback

The laboratory pilot plant operated for this study was begun by Saleh (53) for the study of shock loads. The experimental setup used is shown in Figure 3. The volume of aeration tank #1 was two liters, and the volume of the settling tank was five liters. A sludge consistency tank (aeration tank #2) with a total capacity of two liters was used for sludge recycling. The air supply was adequate to mix the contents of the tanks as adjudged by checks for complete mixing, i.e., such as optical densities in the reactor and reactor effluent. The composition of the feed is shown in Table III. For detention periods of eight hours and 18 hours, a dual positive displacement pump (Milton Roy Model MM1-B-96R) was used to pump the feed to reactor #1, but for a detention period of 24 hours, a peristaltic pump was used because of the inability of the Milton Roy model pump to discharge such low flow rates. Throughout the study, a peristaltic pump was used to pump recycle sludge from the sludge consistency tank (aerator tank #2) into aerator #1. The feed lines were cleaned by pumping one percent Clorox solution in distilled water. In these experiments, alternate feed lines were employed; one was being chemically disinfected while the other was in use. This was done to prevent any growth in the feed line and consequently in the feed bottle. The system was checked often for complete mixing, using optical density techniques on mixed liquor and effluent of aerator #1. The mixed liquor from the reactor overflowed into the settling tank. The settled sludge was withdrawn from the clarifier bottom either at 12- or 24-hour intervals. One ml sample of the withdrawn sludge was diluted to 50 ml, and the optical density was read. From a previously prepared standard curve for solids concentration versus optical density, the sludge concentration was estimated for the sample. The withdrawn thickened sludge was diluted to give the required concentration of recycle sludge, X_R. The required

Figure 3. Activated Sludge Pilot Plant for Operation With Constant X_R (38)


AIR
B
A
EFFLUENT
C
DILUENT FOR
SLUDGE CONSISTENCY
AIR
D
A - FEED TANK
B - AERATION TANK 1
C - SETTLING TANK
D - AERATION TANK 2
(RECYCLE SLUDGE)
EXCESS
SLUDGE

volume of returned sludge was placed in the sludge consistency tank (aeration tank #2), from which it was pumped at the predetermined flow rate.

TABLE III

COMPOSITION OF GROWTH MEDIUM PER 600 mg/l GLUCOSE

Constituents	Amount
Glucose	600 mg/l
Ammonium sulfate $(NH_4)_2\ SO_4$	300 mg/l
Magnesium sulfate, $MgSO_4 \cdot 7H_2O$	60 mg/l
Ferric chloride, $FeCl_3 \cdot 6H_2O$	0.30 mg/l
Manganous sulfate, $MnSO_4 \cdot H_2O$	6.0 mg/l
Calcium chloride, $CaCl_2$	4.5 mg/l
1.0 M phosphate buffer solution, pH 7.0	6 ml/l
Tap water	60 ml/l

The recycle sludge was either aerated or stirred to keep it aerobic and properly mixing. The sludge that remained after placing the required amount in the sludge consistency tank was the excess sludge produced as a result of substrate removal. The parameters monitored during the study period are given below:

1. Feed

    a. COD (alternate days)

b. NH_3-N (a few determinations)

2. Effluent

a. Filtrate

1) COD (daily)
2) NH_3-N (a few determinations)
3) NO_3-N (a few determinations)

b. Supernatant

1) COD (daily)
2) suspended solids (daily)
3) BOD (a few determinations)

3. Aeration tank mixed liquor

a. Biological solids (daily)
b. pH (daily)

4. Sludge consistency tank

a. Suspended solids (daily)

During each steady state, cells from aeration tank #1 were employed as initial inoculum for batch experiments to determine μ_{max}, K_s, and Y_{t_B}, using methodologies described previously (29)(35)(57). The medium used for batch experiments was the same as that employed in continuous flow studies. The cells were grown in 250-ml Erlenmeyer flasks with glucose concentrations ranging from 100 to 1000 mg/l as the limiting nutrient. The initial inoculum concentration was approximately the same in all flasks; the initial optical density was approximately 0.0605 (percent transmission = 87). The total volume of sample per flask was 40 ml. These flasks were placed on an oscillating shaker (Eberbach), which was adjusted to give approximately 100 osc/min. Growth curves were obtained by measuring optical density at frequent intervals. Initial and final suspended solids and substrate concentrations were measured (58). Based on this, the batch yield, Y_{t_B}. was determined.

The μ_{max} and K_s were determined from the plot of the experimental data obtained.

Analytical Methods

Chemical oxygen demand (COD), suspended solids concentration employing membrane filter technique (Millipore Corp., Bedford, Mass., HA 0.45 μm), total solids, volatile solids, NO_3-N (Brucine Method), organic nitrogen (Kjeldahl Method), and biochemical oxygen demand (Winkler's Azide Modification Method for DO) were run in accordance with the recommendations set forth in Standard Methods for the Treatment of Water and Wastewater (58). NH_3-N was measured, using the method of Ecker and Lockhart (59). pH was determined regularly, using a digital pH meter (Orion Research, Model 701).

CHAPTER IV

RESULTS

Studies on the "Hydrolytic-assist" Extended Aeration Process for Wastes of High Ash Content

The aim of this phase of investigation was to test the ability of the "hydrolytically-assisted" extended aeration process to treat a waste containing a high ash content at an organic loading of 2000 mg/l COD. The unit employed for this investigation was already in operation and was tested successfully to treat the same waste at lower loadings of 500 mg/l and 1000 mg/l COD. The unit had been operated for 441 days at a loading of 500 mg/l COD and for 82 days at a loading of 1000 mg/l COD. The operational characteristics of the unit for these loadings are shown in reference 26.

Before presenting the results of the performance of the system, analytical results showing the characteristics of the feed are presented.

Characteristics of Feed

Table IV shows the significant characteristics of trickling filter sludge of the municipal treatment plant at Stillwater, Oklahoma. The table contains analyses of the sludge before and after hydrolysis during different times of the investigation. The values in parentheses

TABLE IV

CHARACTERISTICS OF THE TRICKLING FILTER SLUDGE BEFORE AND AFTER HYDROLYSIS

		Total Solids			Suspended Solids			Dissolved Solids			COD		BOD	
Description of Sample	Date	1 Total mg/l	2 Volatile mg/l / % of 1	3 Ash mg/l / % of 1	4 Total mg/l / % of 1	5 Volatile mg/l / % of 4	6 Ash mg/l / % of 4	7 Total mg/l / % of 1	8 Volatile mg/l / % of 7	9 Ash mg/l / % of 7	10 Total mg/l	11 Soluble mg/l / % of 10	12 Total mg/l / BOD_5/COD	13 Soluble mg/l / % of 12
Trickling Filter Sludge Before Hydrolysis	1975 4-20	37,000	19,000 (51.4)	18,000 (48.6)	33,900 (91.6)	16,600 (49.0	17,300 (51.0)	3,100 (8.4)	2,400 (77.4)	700 (22.6)	34,600	5,100 (14.7)	-	-
Trickling Filter After Hydrolysis		73,400	18,800 (25.6)	54,600 (74.4)	27,700 (37.7)	10,200 (36.8)	17,500 (63.2)	45,700 (62.3)	8,600 (18.8)	37,100 (81.2)	33,800	12,600 (37.3)	-	-
Trickling Filter Sludge Before Hydrolysis	6-12	32,400	18,900 (58.3)	13,500 (41.7)	30,100 (92.9)	17,900 (59.4)	12,200 (40.6)	2,300 (7.1)	1,870 (81.3)	430 (18.7)	31,400	4,000 (12.7)	-	-
Trickling Filter After Hydrolysis		66,200	18,800 (28.9)	47,400 (71.6)	27,100 (40.9)	12,000 (44.3)	15,100 (55.7)	38,400 (58.0)	7,600 (19.8)	30,800 (80.2)	30,600	12,300 (40.2)	-	-
Trickling Filter Sludge Before Hydrolysis	7-17	52,000	34,200 (65.8)	17,800 (34.2)	48,200 (92.6)	31,100 (64.5)	17,100 (35.5)	3,840 (7.4)	3,110 (80.9	730 (19.1)	52,100	7,300 (14.0)	21,800 (0.42)	3,400 (15.5)
Trickling Filter After Hydrolysis		103,000	34,100 (33.1)	68,900 (66.9)	42,200 (41.0)	21,800 (51.8)	20,400 (48.2)	60,800 (59.0)	12,300 (20.2)	48,500 (79.8)	47,900	18,800 (39.1)	24,000 (0.5)	9,900 (41.2)

show the percent composition of the total for the absolute value directly above. The data indicate how much variation exists from time to time. The main reason for variations could be the degree of thickening of sludge in the secondary clarifier.

The total solids concentration of the sludge before hydrolysis varied from 32,000 to 52,000 mg/l during the study period. Suspended solids comprised about 90 percent of the total solids, and the ash content was 34 to 49 percent of the total solids. The suspended solids contained 35 to 51 percent ash, whereas the dissolved solids ranged between 18 to 22 percent ash. The total chemical oxygen demand of the sludge was variable from 31,000 to 52,000 mg/l. The 5-day biochemical oxygen demand was determined for only one sample and was 21,800 mg/l. The soluble COD and BOD_5 constituted about 14-15 percent of the total COD and total BOD_5, respectively.

The analyses after hydrolysis showed that hydrolysis increased the ash content of the waste significantly. It varied from 66.9 to 74.4 percent during the study period. Hydrolysis also solubilized a significant portion of the volatile suspended solids. From the table, it is seen that the reduction in volatile suspended solids was comparable to the increase in dissolved volatile solids. The result of solubilization of VSS was clearly observed in the increase of soluble chemical oxygen demand (COD) and 5-day biochemical oxygen demand (BOD_5). There was no significant change in the total chemical oxygen demand (COD) after hydrolysis.

Operational Performance Characteristics of the Process

The total number of days of operation of the process was 247 days (day 524 to day 771). The beginning day for this report is day 524.

Figures 4, 5, 6, and 7 show the influent characteristics, effluent characteristics, concentrations of suspended solids, and volatile solids in the reactor. The arrows along the plot of suspended solids indicate the days of withdrawal of 1800 ml of mixed liquor for hydrolysis and subsequent recycling of equal fractional portions for succeeding feeding days. The influent COD plotted in Figures 5 and 7 is the COD of the hydrolyzed trickling filter sludge. Although it is true that the hydrolysate of mixed liquor will have some COD, this was considered simply as a portion of the recycle sludge.

The reactor solids concentration before increasing the organic loading, i.e., when it was operated at 1000 mg/l COD, was about 19,000 mg/l. This was the peak concentration during 1000 mg/l COD feeding. On day 524, withdrawal of 1800 ml of mixed liquor for subsequent recycling decreased the solids concentration to approximately 15,500 mg/l. This could be considered as the initial solids concentration for the new phase of investigation. At this time, the volatile fraction of the biomass was 43 percent of the total solids in the reactor. It can be seen that some experience was required before it was possible to arrive at the proper dilution of trickling filter hydrolysate to yield a feed concentration of 2000 mg/l.

Between day 524 and day 538 (days of withdrawal of mixed liquor), solids in the reactor increased to 28,500 mg/l. The average chemical

Figure 4. Operational Performance of Extended Aeration Pilot Plant Showing Influent and Effluent Characteristics for Days 524 to 649

COD_1 Indicates Normal Trickling Filter Sludge COD fed to the System

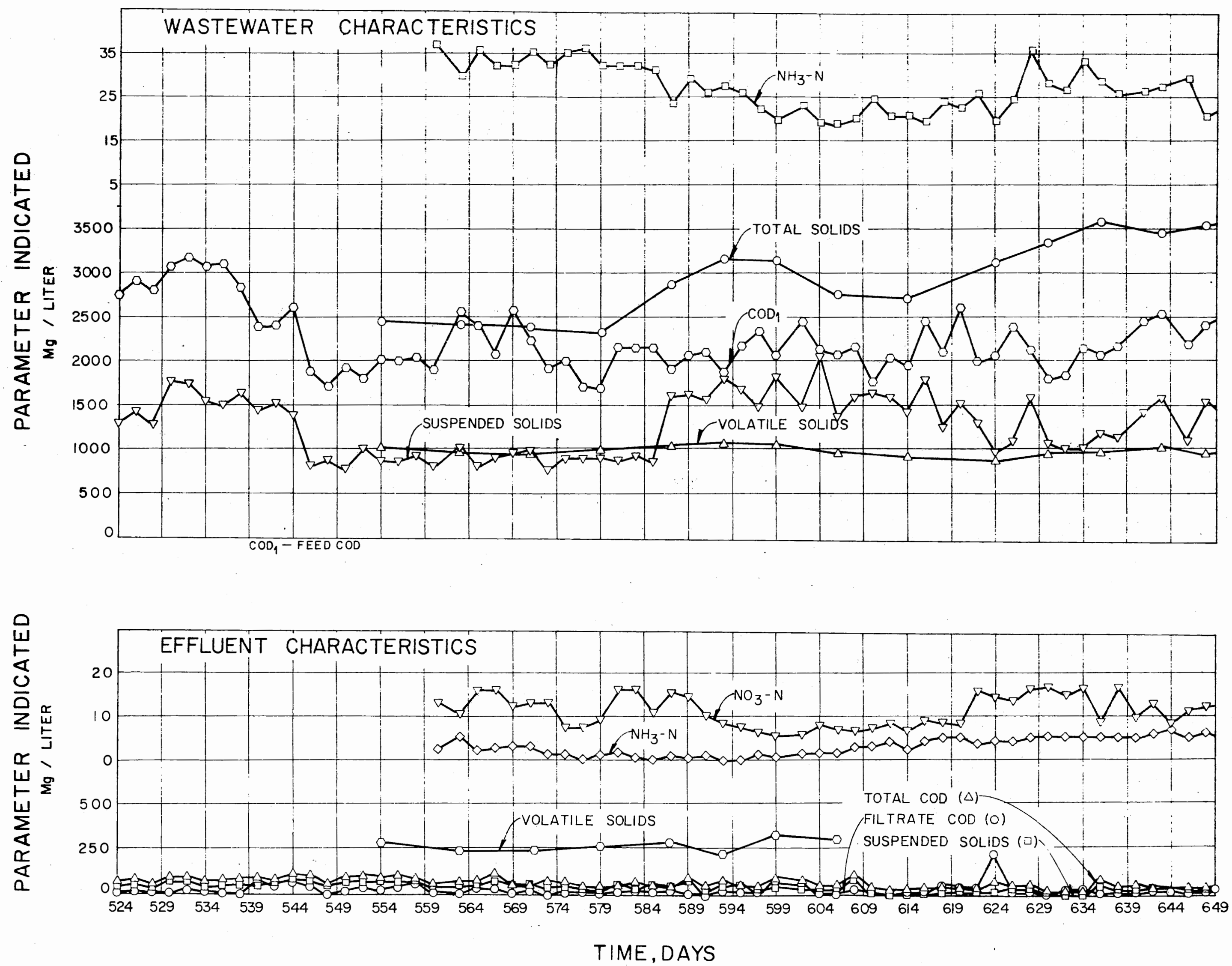

WASTEWATER CHARACTERISTICS
PARAMETER INDICATED
Mg / LITER
35
25
15
5
3500
3000
2500
2000
1500
1000
500
0
NH_3-N
TOTAL SOLIDS
COD_1
SUSPENDED SOLIDS
VOLATILE SOLIDS
COD_1 — FEED COD
EFFLUENT CHARACTERISTICS
PARAMETER INDICATED
Mg / LITER
20
10
0
500
250
0
NO_3-N
NH_3-N
VOLATILE SOLIDS
TOTAL COD (△)
FILTRATE COD (○)
SUSPENDED SOLIDS (□)
524 529 534 539 544 549 554 559 564 569 574 579 584 589 594 599 604 609 614 619 624 629 634 639 644 649
TIME, DAYS

Figure 5. Operational Performance of Extended Aeration Pilot Plant Showing Biomass Characteristics for Days 524 to 649

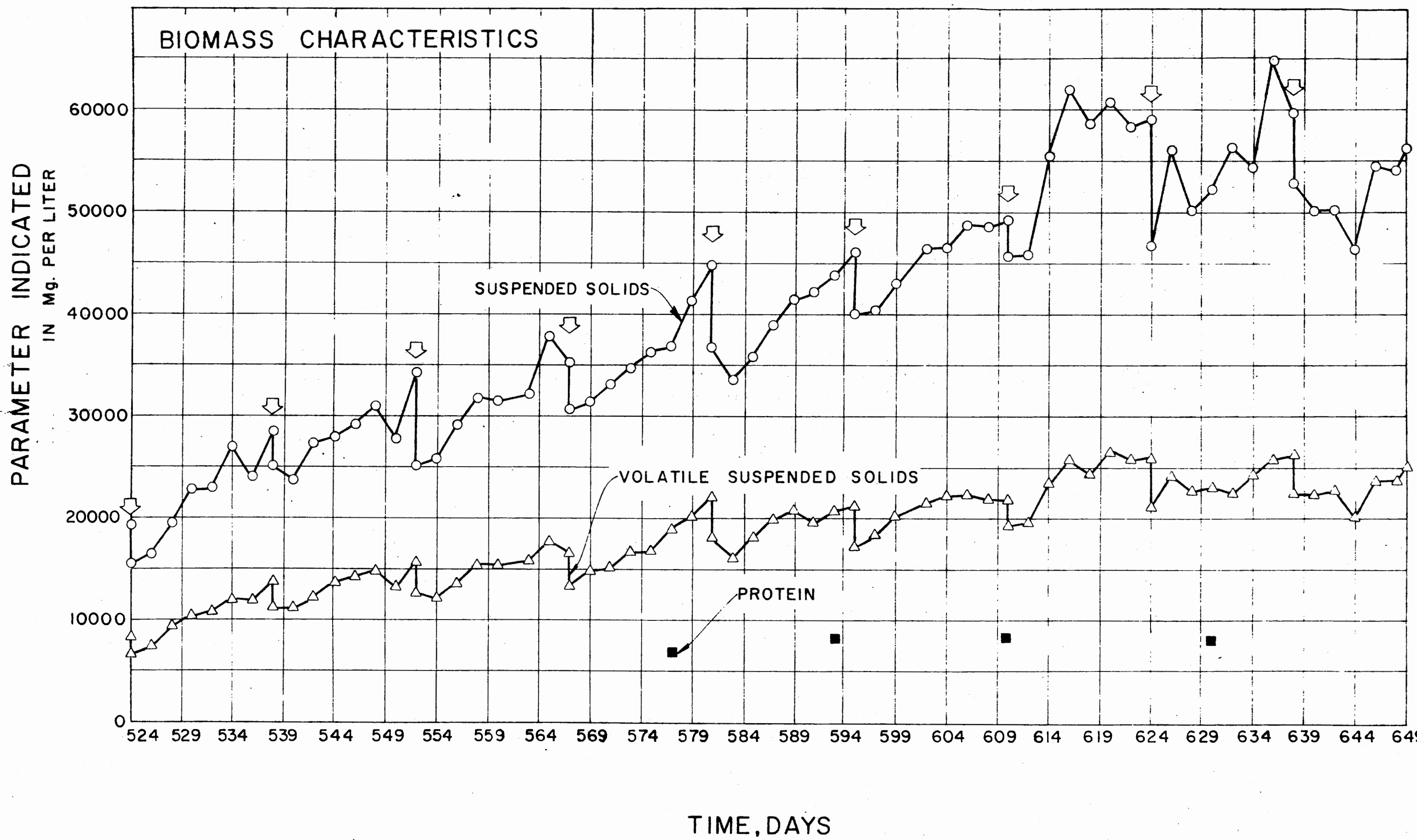

BIOMASS CHARACTERISTICS
SUSPENDED SOLIDS
VOLATILE SUSPENDED SOLIDS
PROTEIN
PARAMETER INDICATED
IN Mg. PER LITER
0
10000
20000
30000
40000
50000
60000
524 529 534 539 544 549 554 559 564 569 574 579 584 589 594 599 604 609 614 619 624 629 634 639 644 649
TIME, DAYS

Figure 6. Operational Performance of Extended Aeration Pilot Plant Showing Influent and Effluent Characteristics for Days 649 to 771

COD_1 Indicates Normal Trickling Filter Sludge COD fed to the System

COD_2 Indicates COD due to Internal Sludge Hydrolysate Which was the Only Organic Feed After Day 729

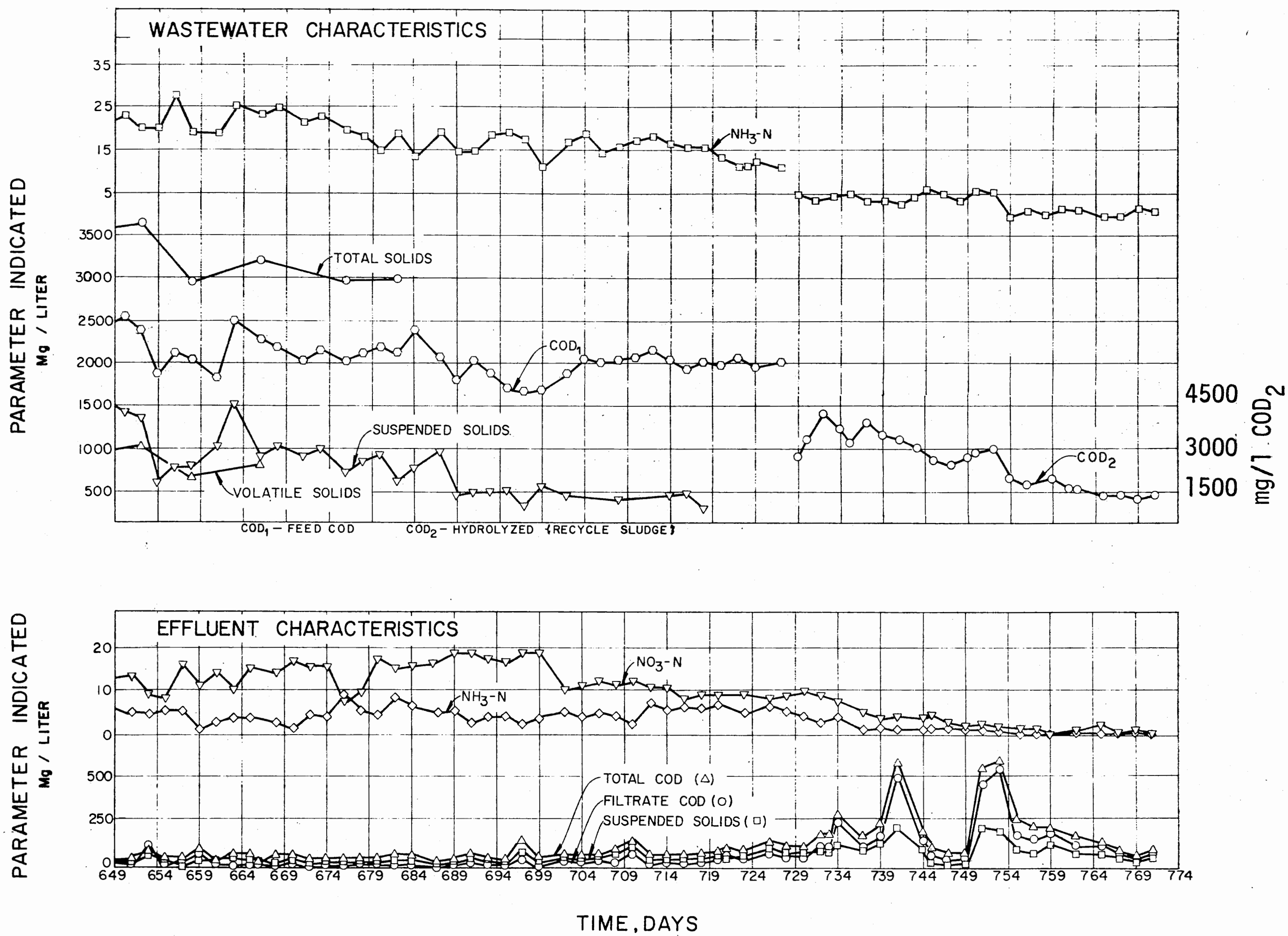
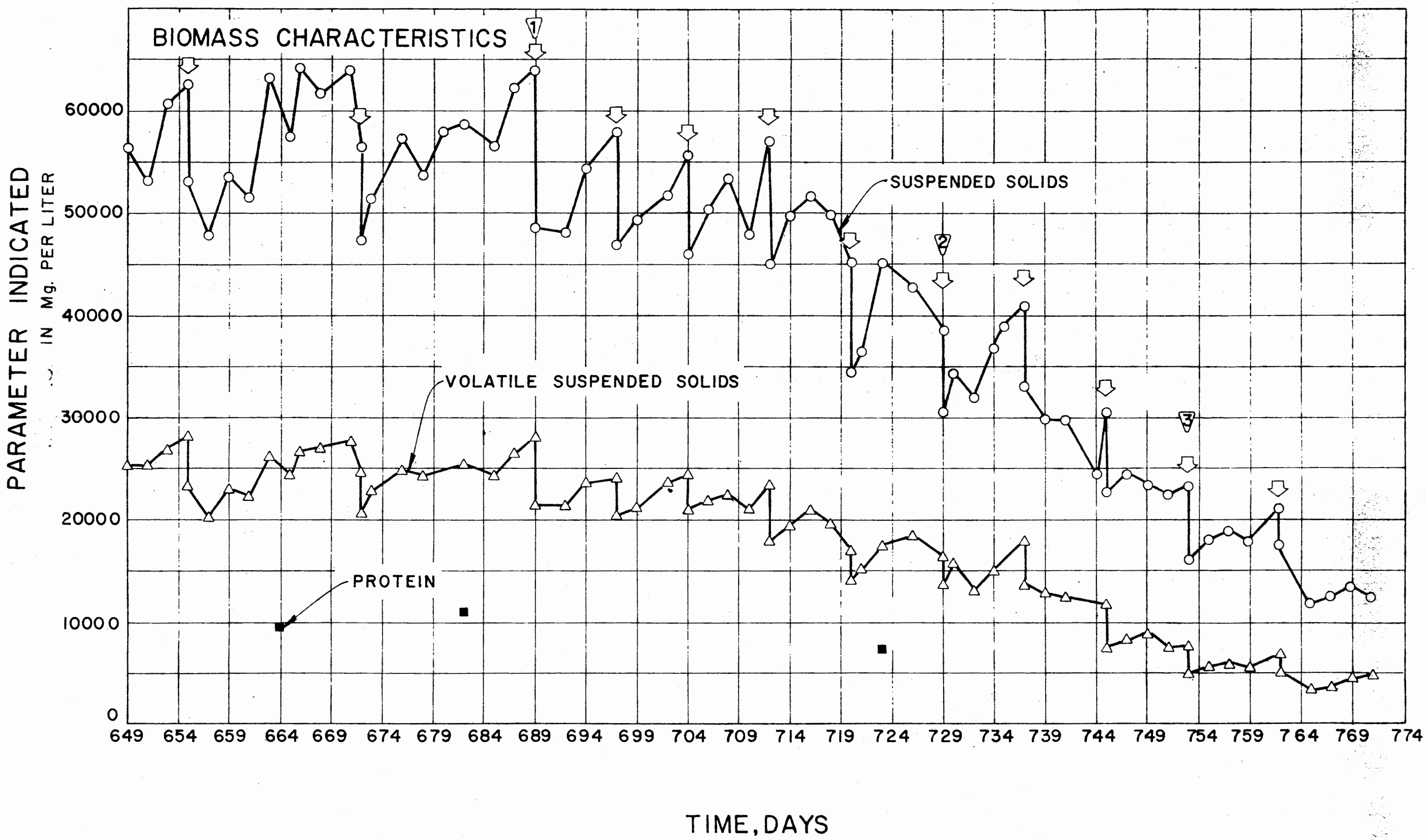

WASTEWATER CHARACTERISTICS
35
25
15
5
3500
3000
2500
2000
1500
1000
500
NH3-N
TOTAL SOLIDS
COD1
SUSPENDED SOLIDS
VOLATILE SOLIDS
4500
3000
1500
mg/l COD2
COD2
COD1 – FEED COD
COD2 – HYDROLYZED {RECYCLE SLUDGE}
PARAMETER INDICATED
Mg / LITER
EFFLUENT CHARACTERISTICS
20
10
0
500
250
0
NO3-N
NH3-N
TOTAL COD (△)
FILTRATE COD (○)
SUSPENDED SOLIDS (□)
PARAMETER INDICATED
Mg / LITER
649
654
659
664
669
674
679
684
689
694
699
704
709
714
719
724
729
734
739
744
749
754
759
764
769
774
TIME, DAYS

Figure 7. Operational Performance of Extended Aeration Pilot Plant Showing Biomass Characteristics for Days 649 to 771


BIOMASS CHARACTERISTICS
PARAMETER INDICATED
IN Mg. PER LITER
SUSPENDED SOLIDS
VOLATILE SUSPENDED SOLIDS
PROTEIN
TIME, DAYS
0
10000
20000
30000
40000
50000
60000
649 654 659 664 669 674 679 684 689 694 699 704 709 714 719 724 729 734 739 744 749 754 759 764 769 774
1
2
3

oxygen demand of the feed supplied was 2988 mg/l. The average observed yield during this period was 0.63. The yield was estimated by calculating the average increase in mass of solids per day divided by the average of substrate COD utilized per day. The average increase of the solids per day was calculated on the basis of the difference of final and initial solids during this period. The effluent quality was excellent with the average efficiency of solids removal being 98 percent, and COD removal being 97.4 percent on supernatant COD basis and 98 percent on filtrate COD basis. The volatile portion of the biomass increased to 49 percent. The dissolved solids in the reactor contained 84-87 percent ash content. No nitrogen determinations were made during this period.

The solids level which decreased on withdrawal at the end of two weeks began to rise at a steady rate during the subsequent weeks. Between days 538 and 624, sludge was withdrawn six times at regular intervals of two weeks. The solids concentration on day 538 was 25,150 mg/l and increased to nearly 60,000 mg/l by day 624 in spite of regular withdrawal of sludge. The yield, i.e., biomass accumulation ratio, during this period varied from 0.3 to 0.6. These values are the ones at the end of every two-week sludge withdrawal period. During this rapid solids increasing period, the efficiency of the system for solids removal and substrate removal remained always as high as 96 percent. The feed concentration during this period averaged about 2000 mg/l COD. This average COD relates only to trickling filter sludge and does not include COD due to hydrolysate mixed liquor. The volatile portion of the mixed liquor was 47 percent on average. The effluent characteristics indicate low suspended solids and an average supernatant COD of 75 mg/l and a filtrate COD of 50 mg/l. Nitrogen determinations were started from day 560. There was always leakage of ammonia nitrogen in small quantities, varying from three to five percent of the influent ammonia nitrogen. At the same time, the nitrate nitrogen in the effluent varied from 36 to 55 percent of the NH_3-N available for nitrification in the influent. The organic nitrogen contents of the feed and the mixed liquor were monitored only a few times. The protein content of the sludge was estimated to be the protein content of the mixed liquor. The protein content of the mixed liquor was taken as 6.25 times the organic nitrogen. The protein content of the biomass was thus estimated to be about 39 percent of volatile solids and 19 percent of total solids. This indicates that the sludge was healthy and active. The ash content of the feed and effluent were monitored from day 554. The ash content of the feed was about 65 percent, and that of the effluent was 86 percent. This gives a clear indication that most of the ash content fed was coming out in the effluent and was not building up in the reactor.

The steady rise in the solids level in the reactor for such a long time gave doubt whether the system would ever reach any degree of steadiness. At day 616, the system appeared to have reached a peak concentration. The withdrawal of sludge on day 624 decreased the solids to 47,000 mg/l, and by day 638, the solids reached the previous peak concentration; upon subsequent removal of sludge for hydrolysis, the cycle was repeated. It appeared the system reached pseudo-steady state condition wherein the mixed liquor suspended solids could be expected to cycle between 46,000 to 65,000 mg/l under the "hydrolytic-assist" adapted. The system was run under the same conditions until day 689.

During this period, the effluent quality was excellent with suspended solids being as low as 5 mg/l and the COD of the supernatant and filtrate being as low as 27 mg/l and 20 mg/l, respectively. There were still small amounts of ammonia present in the effluent, and nitrate nitrogen varied from 50 to 100 percent of the influent ammonia nitrogen. The protein content of the sludge increased to 43 percent of the volatile solids. The volatile fraction of the mixed liquor decreased to 42 percent, and the ash content in the effluent increased to 90 percent and above.

One peculiarity noted in the functioning of the system during the steady condition was that there were more days (14 days in 65) of "natural" decreasing solids than during the early portions of the study when solids were increasing (7 days in 100). It appears that the "hydrolytic-assist" enhanced natural decay more effectively during the later part of the study when the system was in a pseudo-balance state.

Except for the fact that the suspended solids level was extremely high, the overall function of the system was as excellent as it was at lower loadings of 500 mg/l and 1000 mg/l COD. It was decided to bring the solids level down by withdrawing larger amounts of solids from the system for hydrolysis and subsequent recycling. First it was decided to withdraw more volume of mixed liquor from the reactor, but it was feared that the solids level might decrease so much it could affect the system performance. As an alternative, it was decided to withdraw the same volume as before out of the reactor once each week, but from the settling tank alone (before pulling the baffle used) instead of from the mixed liquor immediately after pulling the baffle. The settling tank contained about one to two times higher sludge concentration than the aerator before mixing each day. The system was run under these conditions of operation from day 689 (see marker number 1 on Figure 7) to day 724, and the solids level was brought down successfully from 65,000-40,000 mg/l. During this period, the volatile portion of the sludge decreased as low as 39 percent of total solids. The protein content of the biomass decreased to 35 percent of the of the volatile solids. During this period, the effluent quality still remained satisfactory. The efficiency of removal of suspended solids and supernatant COD was about 88 percent. On the basis of filtrate COD, the efficiency remained above 95 percent. The nitrification efficiency was reduced from almost 100 percent to 70 percent.

After successfully lowering the solids level, it was decided to stop feeding the unit the trickling filter sludge COD, but other operations were continued, i.e., the feed bottle volume was replenished with tap water and internal hydrolysate. This was done to study how long the system would last in a strictly endogenous phase. This was done from day 729 (see marker number 2 on Figure 7) to day 753. During this period, solids decreased from 30,000 mg/l to 25,000 mg/l. The volatile portion of the mixed liquor decreased to 33 percent. The effluent quality deteriorated. There was no ammonia nitrogen supply, and whatever ammonia was found in the effluent was because of the hydrolysate recycle which had some small quantity of ammonia.

From day 753 (see marker number 3 on Figure 7), the amount of mixed liquor for withdrawal was reduced to 900 ml so that solids would not decrease rapidly. However, it was observed that solids decreased more rapidly than before. The biomass concentration decreased from 25,000 to 11,000 mg/l before the unit was shut off on day 771.

Growth Studies

The batch experiment conducted on day 729 using glucose as substrate, yielded comparable values for biological constants as obtained in many of the experiments for other heterogeneous populations. There was a lag period of eight hours before any growth could be noted (optical density). Plotting the substrate concentrations (S_o) against specific growth rates (μ) yielded a hyperbolic relation. The plotting of straight-line relationships of Monod's equation yielded a maximum specific growth rate, μ_{max} = 0.43 hr^{-1}, a saturation constant, K_s = 258 mg/l, and a batch yield, Y_{t_B} = 0.57.

Settling Test

The concentration of the mixed liquor suspended solids on day 729 was 42,000 mg/l. The sludge volume indices for different concentrations varied from 23.4 to 37. The concentrations used were 100 percent, 75 percent, 50 percent, and 25 percent. The highest SVI was for 25 percent concentration.

Studies on the "Total Oxidation" Process Employing a Mathematical Model With Constant Sludge Feedback

The pilot plant used for these studies was operated for 146 days at different hydraulic detention times. The pilot plant was operated with 8-hour detention time for the first 46 days and a $\bar{t}$ of 18 hours for the next 36 days. This was done to determine whether the heterogeneous populations employed retained the same values for biological parameters which had been previously obtained by Srinivasaraghavan and Saleh in their studies using the same pilot plant and synthetic waste (39)(40)(52)(53). Calculations using the model equations of Srinivasaraghavan and Gaudy indicated that if the biological parameters μ_{max}, K_s, Y_t, and particularly k_d, were approximately the same as for previous studies, there should be no excess sludge at a $\bar{t}$ of 24 hours for α and X_R of 0.25 and 10,000 mg/l, respectively (28). On day 83, the system was operated at a mean hydraulic retention time of 24 hours. The major parameters indicating performance characteristics of the system are plotted in Figures 8, 9, and 10 for the entire study period. Since there were relatively fewer determinations of NH_3-N and NO_3-N in the filtrate of the effluent, these analyses are not plotted. The same is true for BOD_5 in the supernatant. The author had never operated a system in accordance with the constant X_R model, and the first 21 days were considered as a "break-in" period.

The data between days 24 and 46 (see Figure 8) indicated that the system was in a relatively steady condition, although a slight rising tendency in effluent COD and suspended solids can be observed during this period; the influent COD ranged from 534 mg/l to 641 mg/l, with an average of 608 mg/l. The effluent character as measured by the filtrate COD, S_e, was excellent; the average filtrate COD, S_e, was 20 mg/l, providing 96.7 percent removal of COD. The average suspended solids concentration in the effluent during this steady state run was 29 mg/l. The average total COD of the effluent was 40 mg/l, providing a removal efficiency of 93.4 percent. The filtrate COD, S_e, varied from 11 mg/l to 32 mg/l, and the suspended solids varied from 10 mg/l to 55 mg/l.

Figure 8. Operational Performance of the Total Oxidation Process With Constant X_R for Days 1 to 51

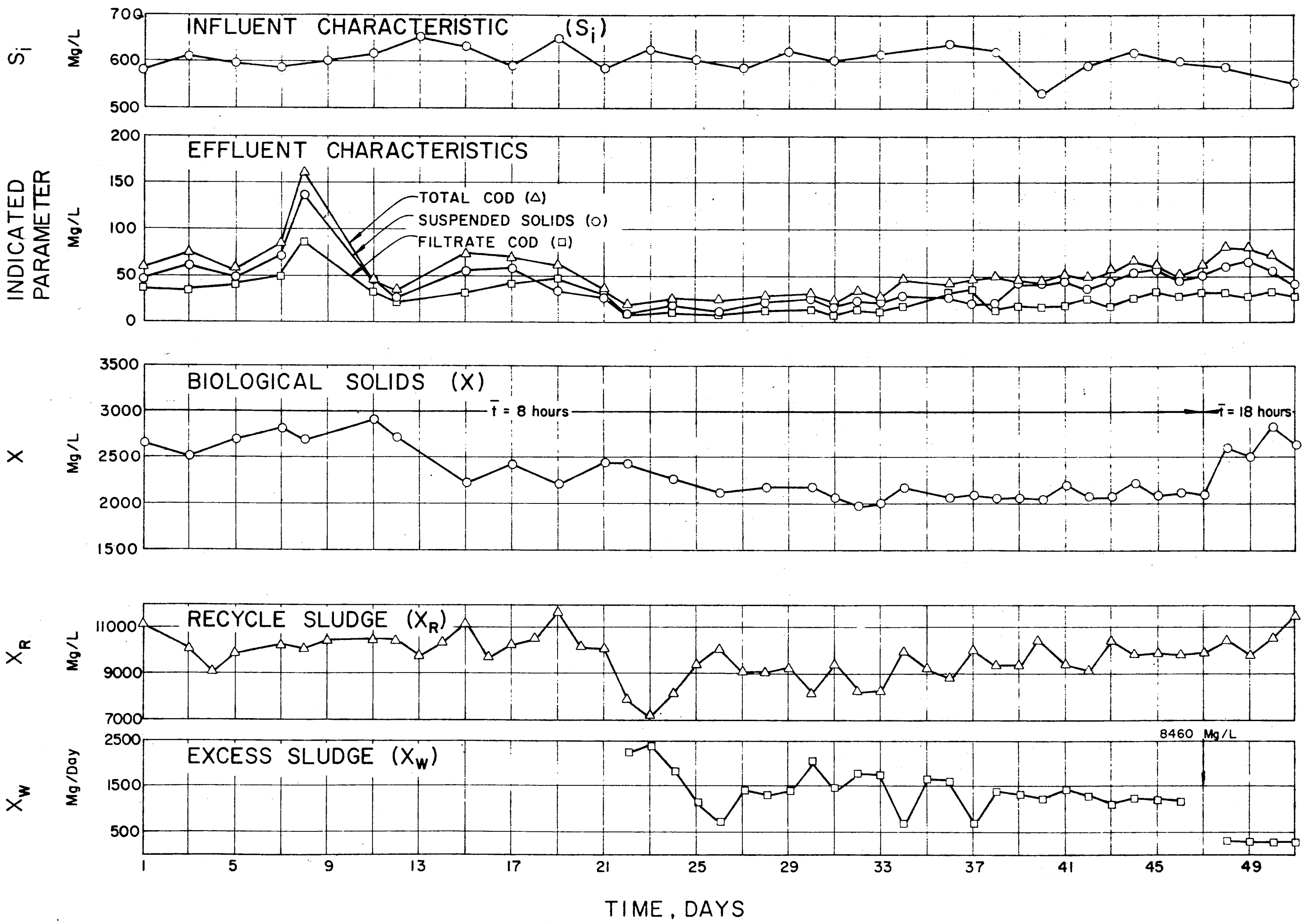

INFLUENT CHARACTERISTIC (S_i)
EFFLUENT CHARACTERISTICS
TOTAL COD (△)
SUSPENDED SOLIDS (○)
FILTRATE COD (□)
BIOLOGICAL SOLIDS (X)
t̄ = 8 hours
t̄ = 18 hours
RECYCLE SLUDGE (X_R)
EXCESS SLUDGE (X_W)
8460 Mg/L
S_i
INDICATED PARAMETER
X
X_R
X_W
Mg/L
Mg/Day
700
600
500
200
150
100
50
0
3500
3000
2500
2000
1500
11000
9000
7000
2500
1500
500
1
5
9
13
17
21
25
29
33
37
41
45
49
TIME, DAYS

Figure 9. Operational Performance of the Total Oxidation Process With Constant X_R for Days 51 to 101

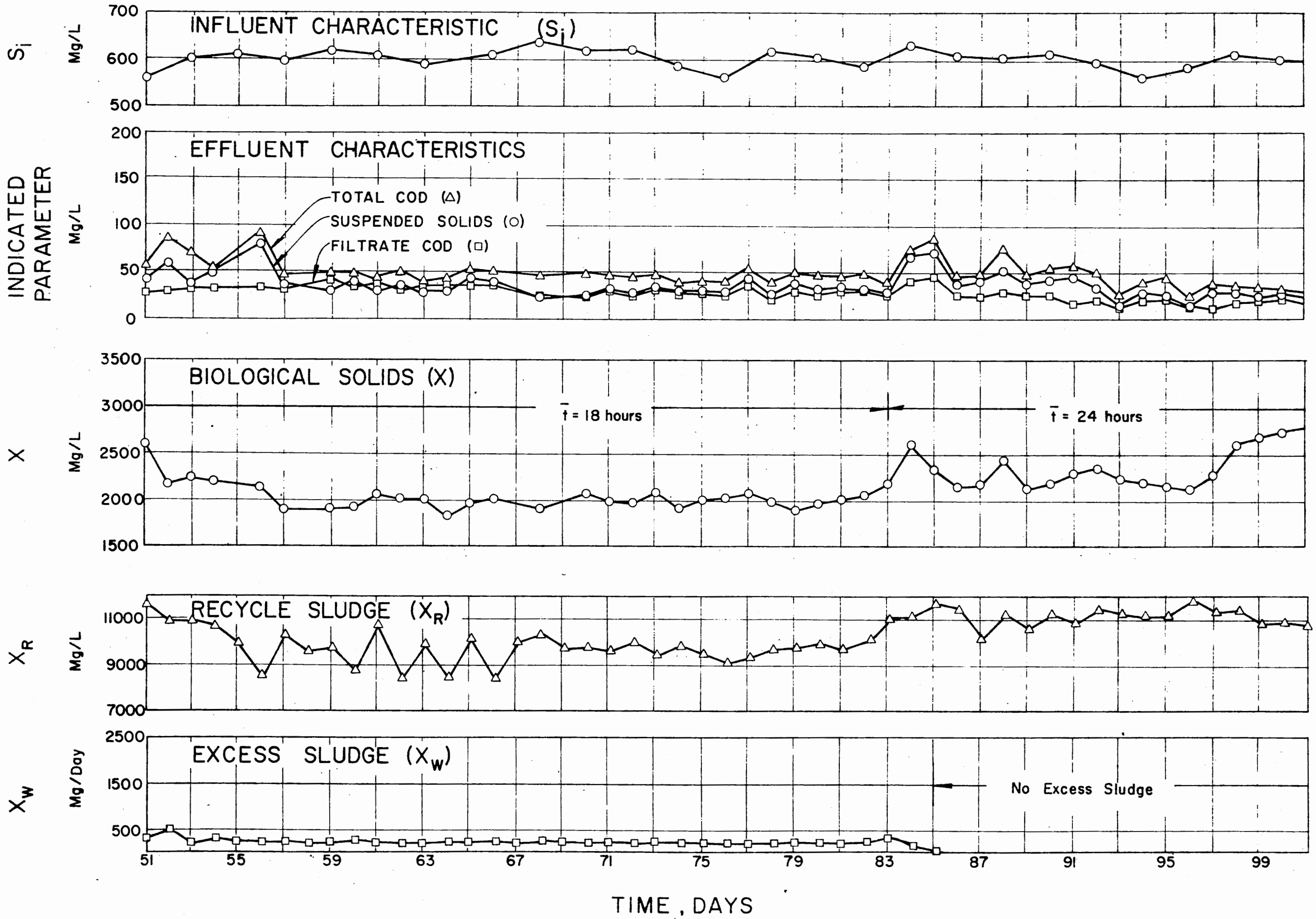
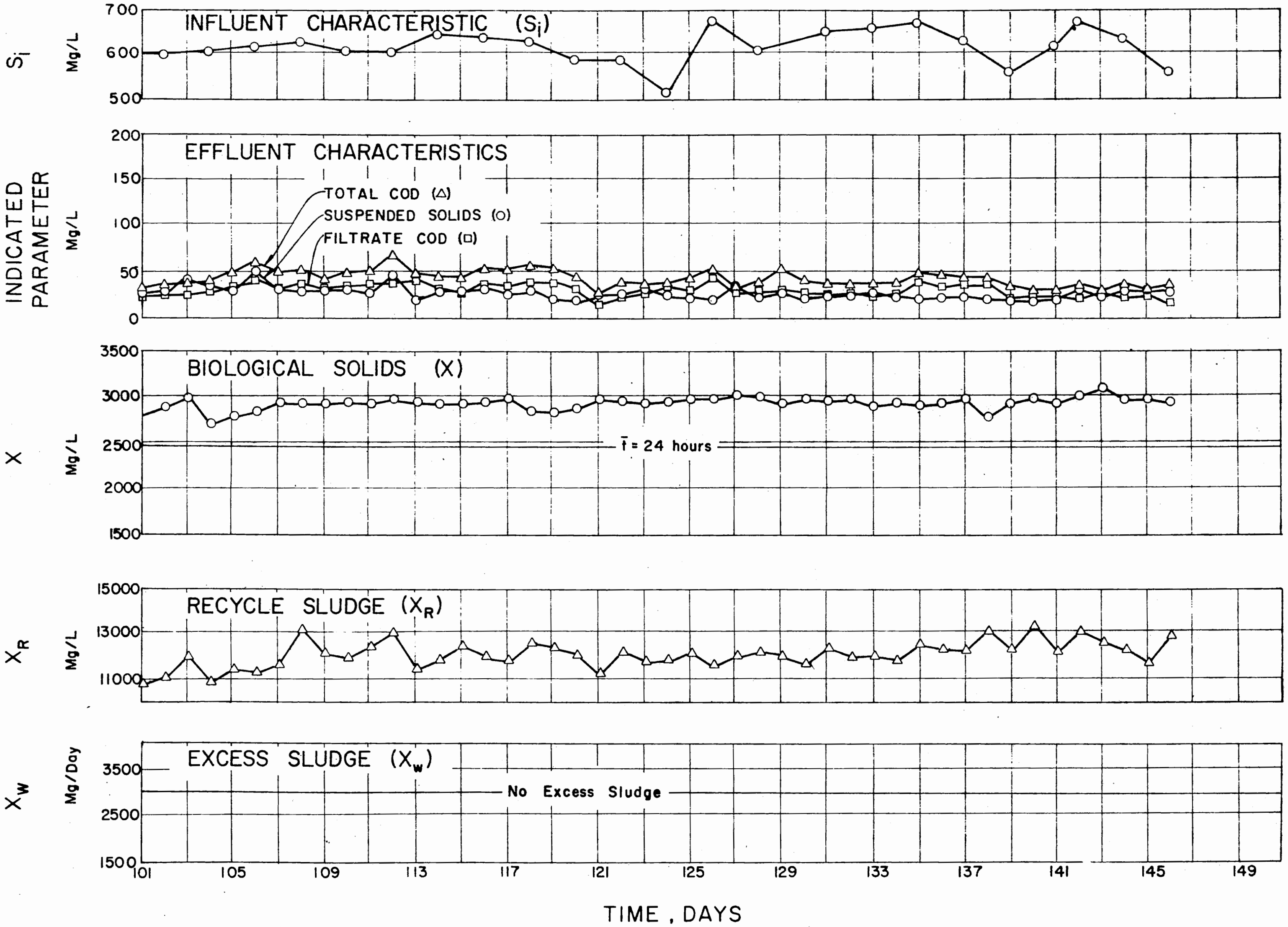

INFLUENT CHARACTERISTIC (S_i)
S_i
Mg/L
700
600
500
EFFLUENT CHARACTERISTICS
INDICATED PARAMETER
Mg/L
200
150
100
50
0
TOTAL COD (△)
SUSPENDED SOLIDS (○)
FILTRATE COD (□)
BIOLOGICAL SOLIDS (X)
X
Mg/L
3500
3000
2500
2000
1500
t̄ = 18 hours
t̄ = 24 hours
RECYCLE SLUDGE (X_R)
X_R
Mg/L
11000
9000
7000
EXCESS SLUDGE (X_W)
X_W
Mg/Day
2500
1500
500
No Excess Sludge
51
55
59
63
67
71
75
79
83
87
91
95
99
TIME, DAYS

Figure 10. Operational Performance of the Total Oxidation Process With Constant X_R for Days 101 to 146



INFLUENT CHARACTERISTIC (S_i)
S_i
Mg/L
700
600
500
EFFLUENT CHARACTERISTICS
TOTAL COD (△)
SUSPENDED SOLIDS (○)
FILTRATE COD (□)
INDICATED PARAMETER
Mg/L
200
150
100
50
0
BIOLOGICAL SOLIDS (X)
X
Mg/L
3500
3000
2500
2000
1500
$\bar{t}$ = 24 hours
RECYCLE SLUDGE (X_R)
X_R
Mg/L
15000
13000
11000
EXCESS SLUDGE (X_w)
X_W
Mg/Day
3500
2500
1500
No Excess Sludge
101
105
109
113
117
121
125
129
133
137
141
145
149
TIME, DAYS

In general, during this period the system provided very satisfactory treatment and delivered high quality effluent. The biological solids concentration in reactor #1 varied from 1956 mg/l to 2243 mg/l, with an average of 2097 mg/l. From the figure, it can be seen that the system was rather steady with respect to X. X_R varied from 8130 mg/l to 10,530 mg/l, with an average of 9389 mg/l. Few determinations of filtrate COD in the recycle sludge (not plotted in the figure) showed only traces of COD. Thus, little or no carbon source was being recycled to reactor #1. This observation justifies one of the basic assumptions made in deriving the steady state equations for the model. The bottom graph in Figure 8 shows the excess sludge production. The values generally varied from 624 mg/day to 1745 mg/day, with an average of 1353 mg/day, but the daily sludge production during this run remained relatively steady.

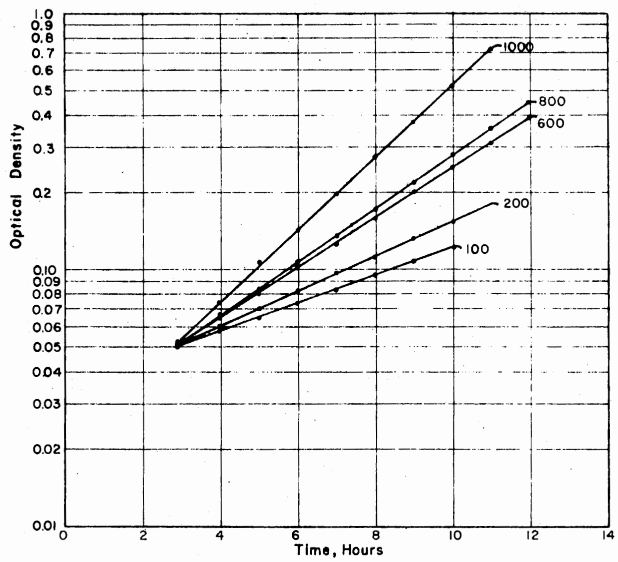
Figures 11 and 12 show the growth curves obtained from batch experiments conducted on days 34 and 43 during this continuous flow period. The data are shown as a semilogarithmic plot of optical density vs. time during the growth period. At the end of each curve, the initial substrate concentration, S_o, is shown. The other plot shows the experimentally determined values of μ at the various S_o values. The curve was plotted on the basis of calculations using the equation:

$$\mu = \frac{\mu_{max} S_o}{K_s + S_o} \tag{10}$$

The values for μ_{max} and K_s in the above equation were obtained from the double reciprocal plot of $1/S_o$ vs. $1/\mu$, and also from the plot of S_o vs. S_o/μ. Both plots gave approximately the same values for μ_{max} and

Figure 11. Batch Growth Curves at Various Initial Substrate Concentrations, and Relationship Between μ and S_o for Cells Harvested From the Total Oxidation Pilot Plant Operating at an S_i of 600 mg/l, $\bar{X}_R$ of 10,000 mg/l, and a Detention Time, $\bar{t}$, of Eight Hours (on Day 34)

The μ_{max} and K_s Values Obtained From the Plot of $1/\mu$ vs. $1/S_o$ are 0.3 hr^{-1} and 182 mg/l, Respectively


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
Optical Density
0
2
4
6
8
10
12
14
Time, Hours
1000
800
600
200
100

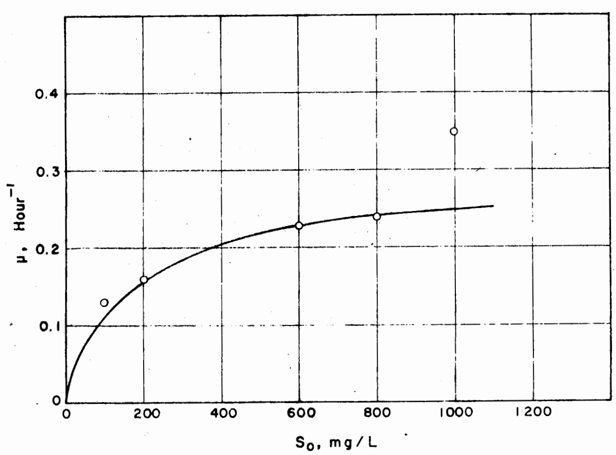
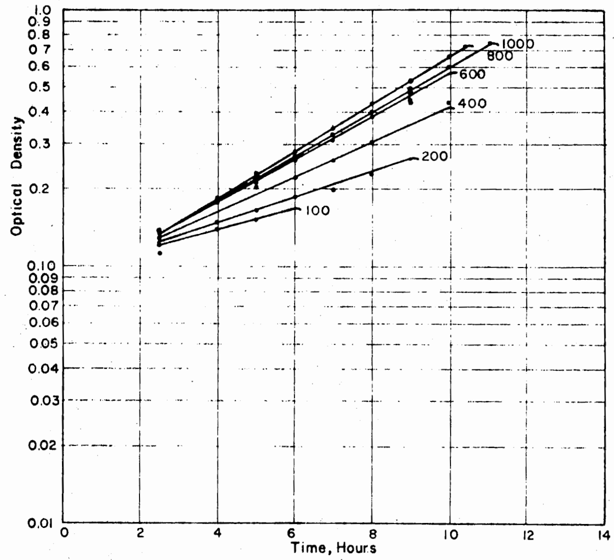
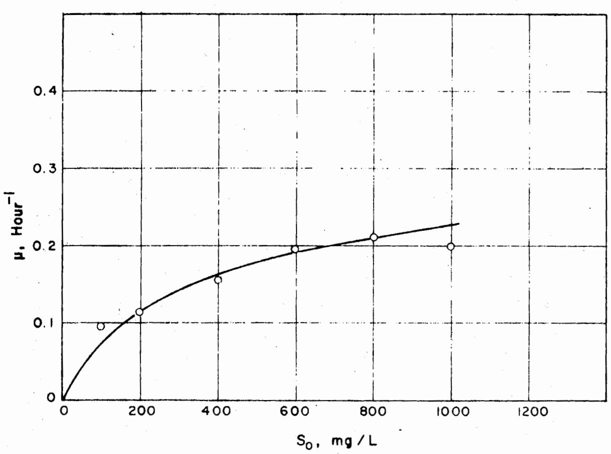

0.4
0.3
0.2
0.1
0
μ, Hour⁻¹
0
200
400
600
800
1000
1200
S₀, mg/L

Figure 12. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Total Oxidation Pilot Plant Operating at an S_i of 600 mg/l, X_R of 10,000 mg/l, and $\bar{t}$ of eight hours (on Day 43)

The μ_{max} and K_s Values Obtained From the Plot of $1/\mu$ vs. S_o are 0.31 hr^{-1} and 333 mg/l


Optical Density
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
2
4
6
8
10
12
14
Time, Hours
1000
800
600
400
200
100


μ, Hour⁻¹
0.4
0.3
0.2
0.1
0
0
200
400
600
800
1000
1200
S₀, mg/L

and K_s. It can be noted that the experimental values of μ compare favorably with the curve which was calculated using the values of μ_{max} and K_s obtained from the data. The plots used for determining the μ_{max} and K_s values were based on the straight-line relationships of Monod's equation. The following are the two forms employed:

$$\frac{1}{\mu} = \frac{K_s}{\mu_{max}} \frac{1}{S_o} + \frac{1}{\mu_{max}} \tag{11}$$

$$\frac{S_o}{\mu} = \frac{K_s}{\mu_{max}} + \frac{S_o}{\mu_{max}} \tag{12}$$

The values for maximum specific growth rates, μ_{max}, observed in two batch experiments conducted during the run were 0.3 hr^{-1} and 0.31 hr^{-1}, and shape factors, K_s, were 182 mg/l and 333 mg/l. The values of the biological constants obtained for this sludge which was originally grown with t = 8 hours were in close agreement with those obtained by Srinivasaraghavan and Saleh (40)(53).

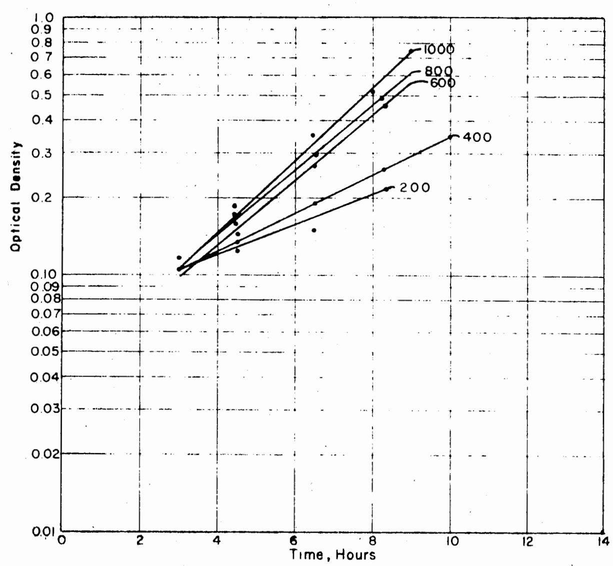
It was now desirable to lower μ_n in continuous flow operation to determine if X_W would be reduced and a new steady state condition established. Accordingly, $\bar{t}$ was increased to 18 hours on day 47. It is noted that there is a break in the plot of X_W betweem days 46 and 48; the reason for this is explained below. It should be understood that the immediate increase of $\bar{t}$ caused a large decrease in throughput and caused an immediate pileup of excess sludge. This excess was discarded, since it would have been an unfair test to require the system at the new operational conditions to dispose of sludge which had been produced under the former conditions.

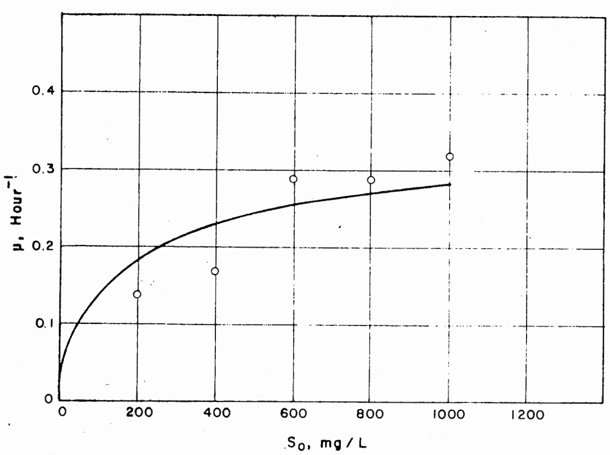
The performance data from day 47 to day 83 in Figures 8 and 9 depict the system behavior for a $\bar{t}$ of 18 hours. Day 48 to day 56 was assumed to be a transition stage which developed as a result of the negative hydraulic shock load. During the period from day 57 to day 82, the system operated in a relatively steady condition. The average influent substrate concentration, S_i, was 603 mg/l. Based on the effluent filtrate COD of 31 mg/l, the COD removal efficiency during this time was 94.9 percent. Based on total COD of the effluent of 48 mg/l, the COD removal efficiency was 92.5 percent. The average biological solids concentration, X, in reactor #1 was 1971 mg/l, while the recycle solids concentration, X_R, was 9515 mg/l. Comparing these results with those of the previous run at the 8-hour detention period, the solids concentration in reactor #1 decreased by about 125 mg/l even though the recycle solids concentration during this period was approximately 125 mg/l higher than those at the 8-hour detention time. The effluent solids concentration, effluent COD, and effluent filtrate COD were slightly higher than in the previous run. The excess sludge production, X_W, was only 262 mg/day, about one-sixth of the excess sludge produced in the previous run.

The batch-grown curves made on day 79 and the hyperbolic plot, μ vs. S_o, are shown in Figure 13. The values of maximum specific growth rate, μ_{max}, shape factor, K_s, and batch yield, Y_t, were 0.33 hr^{-1}, 165 mg/l, and 0.40 respectively. The values of μ_{max} and K_s were rather close to those observed at the lower $\bar{t}$. From the experimental pilot plant data for COD removal and waste sludge production at the 8-hour and 18-hour detention times, the net specific growth rate, μ_n, and observed yield, Y_o, were calculated. The reciprocal of μ_n and Y_o

Figure 13. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Total Oxidation Pilot Plant Operating at an S_i of 600 mg/l, X_R of 10,000 mg/l, and $\bar{t}$ of 18 Hours (on Day 79)

The μ_{max} and K_s Values Obtained From the Plot of $1/\mu$ and $1/S_o$ are 0.33 hr^{-1} and 165 mg/l, Respectively


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
Optical Density
1000
800
600
400
200
0
2
4
6
8
10
12
14
Time, Hours


0.4
0.3
0.2
0.1
0
μ, Hour⁻¹
0
200
400
600
800
1000
1200
S₀, mg/L

values were plotted on the maintenance coefficient plot prepared in the earlier studies of Saleh (see Figure 34 of Reference 50). These points plotted along the straight line through those data, thus the values of decay coefficient, k_d, and true cell yield, Y_t, remained essentially the same as they were in the investigations of Srinivasaraghavan (40) and Saleh (53). Since the other biological parameters μ_{max} and K_s remained the same as before, it was decided to increase the detention time from 18 to 24 hours. At this detention time, as per the computational analyses for the model, the sludge produced should have been approximately that needed for recycle at the concentration of 10,000 mg/l, the recycle ratio, α, remaining the same.

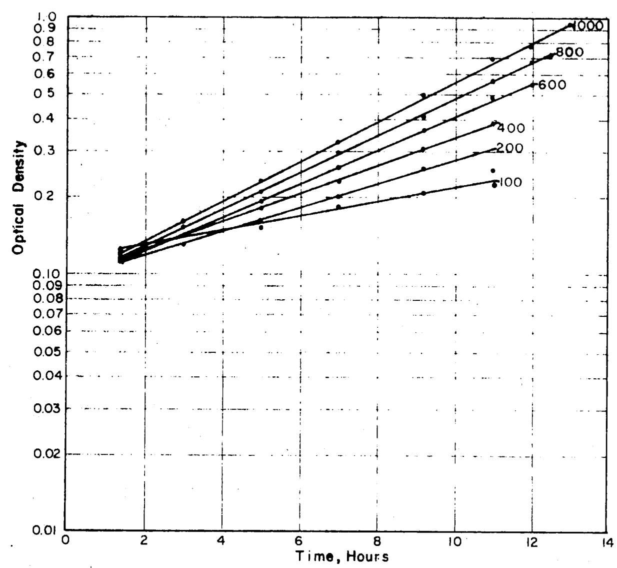
On days 84 and 85 there was a very minimal excess sludge, and starting from day 86, there was no excess sludge although it is noted that X_R was 11,000 rather than 10,000 mg/l. Between days 86 and 97 (see Figure 9), the system operated under relatively steady state conditions with respect to biological solids concentration, recycle solids concentration, and effluent characteristics. During this period, the effluent was checked a few times for the presence of nitrates, but no traces were observed. It was thought that in all probability the system lacked nitrifiers, thus about 20 ml of nitrifying population from a unit being operated by a colleague, A. Esfandi, was added on day 97. This addition coincided with a change in the performance of the system with respect to biological solids. For the steady state conditions before the addition of nitrifiers, the average influent substrate concentration was 596 mg/l. The biological solids concentration was 2214 mg/l, and the recycle solids concentration was 10,970 mg/l. The effluent characteristics indicate that the average total COD was 45 mg/l, and filtrate was 22 mg/l. The solids concentration in the effluent was 34 mg/l. There was no excess sludge. The only sludge lost was through effluent solids and sampling. Usually, the sample amount was one ml for recycle solids concentration, but now and then this was checked with a five ml sample. The variation in biomass concentration obtained with these two sample values was negligible (0.5-1.0 percent). Compared to the previous two runs, the solids concentration in reactor #1 and the recycle tank were higher while effluent quality remained the same. The COD removal efficiency on the basis of filtrate COD was 96.3 percent, while on the basis of total COD it was 92.4 percent. There existed a reasonably steady level for both solids concentrations in reactor #1 and the recycle sludge tank.

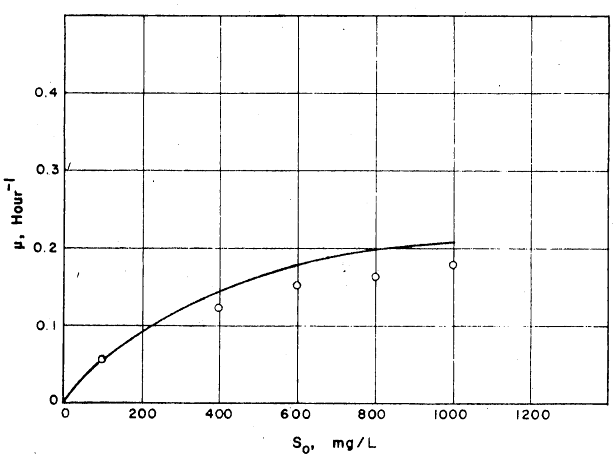
Figure 14 shows the results of the batch growth studies conducted during the run at $\bar{t}$ = 24 hrs, but before addition of the nitrifying seed (day 89). The maximum specific growth rate, μ_{max}, shape factor, K_s, and batch yield were 0.32 hr^{-1}, 450 mg/l, and 0.44, respectively. These values were in the same range as those obtained previously.

Introduction of the nitrifying seed on day 97 may have disrupted the steady state behavior of the system. The solids concentration started to increase enormously from 2200 mg/l until it reached about 2900 mg/l. The system did begin to nitrify about 30-40 percent of the influent NH_3-N. This verifies the earlier doubt of non-existence of nitrifiers. From day 102 to day 146, biological solids concentration in reactor #1 remained rather steady at 2900 mg/l, while the recycle sludge concentration varied from 10,860 to 13,200 mg/l, with an average of 12,037 mg/l. The steadiness in solids concentration in reactor #1 prompted the investigator to recycle all of the sludge produced after

Figure 14. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Total Oxidation Pilot Plant Operating at an S_i of 600 mg/l, X_R of 11,000 mg/l, and $\bar{t}$ of 24 Hours (on Day 89)

The μ_{max} and K_s Values Obtained From the Plot of $1/\mu$ vs. $1/S_o$ are 0.32 hr^{-1} and 450 mg/l


Optical Density
Time, Hours
1000
800
600
400
200
100

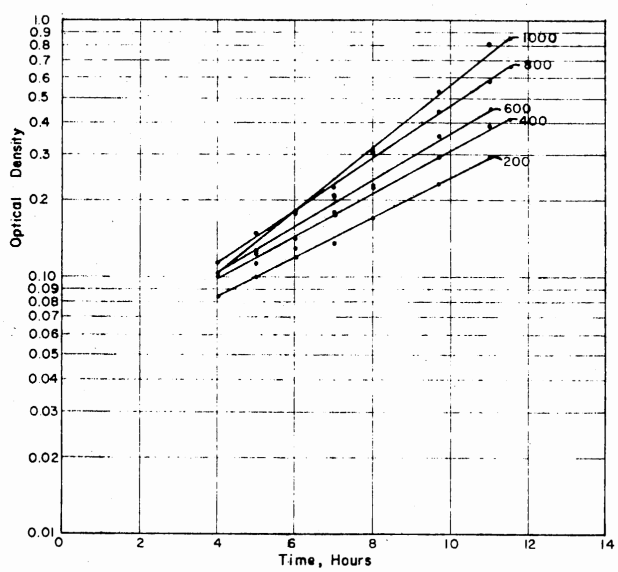

μ, Hour⁻¹
S₀, mg/L

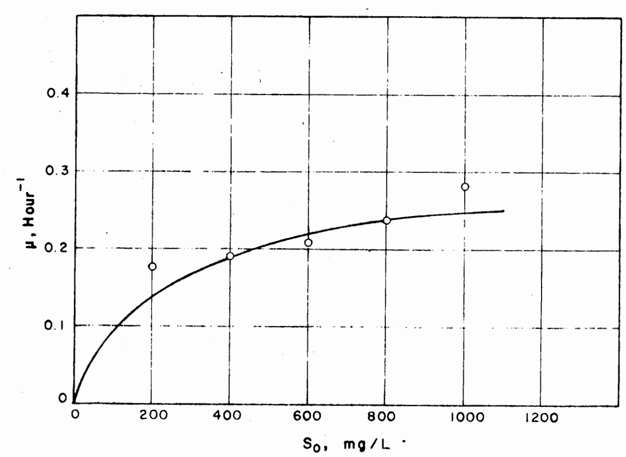
making it up to the required volume. Thus, the X_R of 10,000 mg/l was not maintained. It was felt at this stage of the work that it was more important to see if a steady X and S with total recycle could be maintained regardless of holding to the previous design constant. The effluent characteristics indicate that the system still functioned as efficiently as before. The average solids concentration in the effluent was 21 mg/l; the lowest in the entire period of investigation. The average influent substrate concentration, S_i, during this period was 614 mg/l, and the COD removal efficiency based on effluent filtrate COD of 24 mg/l was 96.1 percent, while based on total effluent COD of 38 mg/l, it was 93.8 percent. The nitrification efficiency improved further during the later days of the run until it reached 70 percent. Comparing the biological solids concentration, X, with that at previous runs, it is considerably higher. Probable reasons for this are explained in the next chapter.

The batch growth studies data which are shown in Figure 15 yielded values for μ_{max} and K_s as 0.31 hr^{-1} and 253 mg/l, respectively.

Figure 15. Batch Growth Curves at Various Initial Substrate Concentrations and Relationship Between μ and S_o for Cells Harvested From the Total Oxidation Pilot Plant Operating at an S_i of 600 mg/l, X_R of 12,000 mg/l, and $\bar{t}$ of 24 Hours (on Day 120)

The μ_{max} and K_s Values Obtained From the Plot of $1/\mu$ vs. $1/S_o$ are 31 hr^{-1} and 253 mg/l, Respectively


Optical Density
Time, Hours
1000
800
600
400
200


μ, Hour⁻¹
S₀, mg/L

CHAPTER V

DISCUSSION

The process of extended aeration has been in use since the early 1950s. Even though many of the researchers concluded that the process was theoretically unsound, its simplicity of operation, low cost, and ability to withstand environmental changes placed it in a favorable position for application in the field. The later research at Oklahoma State University clarified many of the objections to the process and provided sound theoretical and experimental explanations, and even suggested and demonstrated in laboratory scale some engineering modifications to the process to ensure its successful operation. Such a modification to the process was the "hydrolytic-assist" for controlling solids concentration in the aerator. It was thought that the suggested "hydrolytic-assist" process could be used to treat a waste containing high ash content, but there was always a chance that the high ash content of the waste might result in buildup of large amounts of ash in the system causing eventual biochemical failure. The aim of first phase investigation was to determine whether the sludge would accumulate ash content.

Without engineering modification, there exists a unanimous opinion among researchers that an extended aeration process could not be maintained in a steady state with respect to biological solids as Porges hypothesized. On the basis of computational analyses of the experimental data of an activated sludge process employing a constant X_R, it was thought that, stoichiometrically, the system could reach a steady state provided certain engineering controls were applied and provided the biological parameters for the populations to remain constant for a considerable period. The second phase of the present study of the extended aeration process was made to determine if any such steady state condition would develop using this mode of operation for which the engineering control parameters are constant recycle sludge concentration, X_R, recycle flow rate constant, α, and dilution rate, D.

Performance of the "Hydrolytic-assist" Extended Aeration Process to Treat High Ash Content Waste

The entire study period is discussed in four phases based on the behavior and operation of the system. The period from day 524 to day 624 represents a phase during which the solids were increasing steadily in spite of regular withdrawal of sludge for hydrolsis. The period from day 624 to day 689 represents a regular cyclic phase which can be termed a steady phase in that the mode of cycling was essentially constant. During this period, solids fluctuated between 46,000 mg/l and 63,000 mg/l as a result of withdrawal for hydrolysis and refeeding. The period from day 689 to day 724 represents the phase during which there was an increase of solids recycle through hydrolysis. The last phase, i.e., from day 724 to day 771, represents strictly an endogenous phase wherein no exogenous substrate except hydrolysate recycle was supplied. Table V shows the average values for the various parameters for each of the first three periods and also the average performance

TABLE V

SYSTEM PERFORMANCE AT ORGANIC LOADING OF 2000 mg/l NOMINAL COD
(From Day 524 to Day 727)

	Day 524 to Day 624			Day 624 to Day 689			Day 689 to Day 727			Average Day 524 to Day 727		
	Feed mg/l	Effl. mg/l	Effic. %	Feed mg/l	Effl. mg/l	Effic. %	Feed mg/l	Effl. mg/l	Effic. %	Feed mg/l	Effl. mg/l	Effic. %
Total COD	1175	73	96.8	2209	53	97.6	2209	84	95.8	2164	70	96.8
Filtrate COD	-	54	97.6	655	38	98.3	670	54	97.3	662	49	97.7
% Soluble	-	74.0	-	-	71.7	-	-	-	-	-	-	-
BOD_5	1107	15	98.6	1108	17.0	98.5	988	30	97.0	1081	19.4	98.2
BOD_5 Soluble	-	11	-	-	10.6	-	-	13.5	-	-	11.3	-
% Soluble	-	73.3	-	-	62.3	-	-	45	-	-	58.2	-
BOD_5/COD	0.49	0.21	-	0.5	0.32	-	0.49	0.36	-	0.50	0.28	-
Suspended Solids	1280	35	97.3	1099	35	96.8	540	80.0	85.2	1148	42	96.3
Sol. Solids	1481	2209	-	2223	3178	-	2995	3920	-	1931	2635	-
Organic N_2	12.7	-	-	16.3	0	-	16.5	-	-	15.5	-	-
NH_3-N_2	27.6	3.0	-	23.8	5.9	-	17.0	5.7	-	23.8	4.6	-
NO_3-N_2	-	11.2	-	0	14.5	-	-	15.5	-	-	13.1	-

for the entire study period (excluding the endogenous phase).

From the table, it is observed that the overall performance of the "hydrolytic-assist" extended aeration at a nominal COD loading of 2000 mg/l was exceptionally good. The effluent quality compared favorably with that at lower loadings (26). The percent efficiencies of the system for suspended solids removal, for COD and BOD removal, remained nearly the same at different solids levels, except in the endogenous phase. The average influent COD for the period from day 524 to day 624 was 2275 mg/l. Based on the supernatant and filtrate, the efficiencies of COD removal during the same period were 96.8 percent and 97.6 percent, respectively. On the basis of BOD_5, the average strength of the influent waste was 1107 mg/l, and efficiency of BOD removal was 98.6 percent. The efficiency of suspended solids removal was 97.3. Looking at the nitrogen figures in the influent and effluent, only 40 percent of ammonia fed appeared as nitrates, and there was always a small leakage of ammonia in the effluent. The balance of the nitrogen was used, presumably, for synthesis between hydrolysis period. During these 100 days of operation, there were only seven days on which a decrease of solids due to natural autodigestion was observed. The hydrolysis schedule employed in these studies did not seem to keep suspended solids in the aerator tank at low levels. The average biomass concentration during this phase was 38,400 mg/l, out of which 17,820 mg/l was volatile solids. Thus, on average, the activated sludge exhibited a rather high ash content of 53.6 percent. The protein content was 39.2 percent of volatile solids. It is interesting to observe during this period the occurrence of increasing and decreasing ash content. The cycling of ash content was also observed in the previous study (26).

The reason for the decrease in ash content at times was due to release of soluble inorganic solids during natural autodigestion and chemical hydrolysis.

After 100 days of operation, the system had reached a peak solids concentration. The regular cyclic fluctuations of the solids from day 624 to day 689 indicates that the system was indeed at a pseudo-steady condition. The performance of the system at enormously high concentration of solids was good. The average biomass concentration during this period was 56,180 mg/l, of which 24,550 mg/l were volatile solids; thus, the ash content averaged 56.3 percent. During this period, the amount of inorganic solids remaining in the system increased slowly, and by day 689 the ash content was 57.5 percent compared to 55.5 percent on day 624. The protein content of the sludge was 41 percent of the volatile solids. The average efficiency for COD removal, BOD removal, and suspended solids removal were 97.6 percent, 98.5 percent, and 96.8 percent, respectively. There was an increase in the ammonia concentration in the effluent, but on average, 60 percent of ammonia fed was nitrified and appeared as nitrates in the effluent.

Even though the performance of the system was excellent insofar as purification was concerned, the high suspended solids concentration posed a problem for internal recycling of sludge from the settling tank. Since the sludge blanket formed in the settling chamber was very thick as a result of improper "internal" recycling, the upward flow forced the sludge to raise upward at times. When the surface of the sludge blanket reached the outlet level, some solids escaped into the effluent. This problem was alleviated by removing the baffle wall each day and aerating the entire contents of the system for approximately one hour.

From day 689 to day 724, the effect of increased solids withdrawal and subsequent recycle after hydrolysis was studied. It was observed that increased solids withdrawal had no adverse effect on COD removal. The biomass level in the system decreased from 60,000 mg/l to 40,000 mg/l. The ash content in the system increased to 62 percent as a result of higher ash content in the recycled hydrolysate. The average suspended solids concentration during this period increased from 35 to 80 mg/l, due primarily to the escape of higher than usual concentrations of solids on days 690, 697, and 710. The reason for this was the same as explained in the above paragraph. During this period, the system was producing well-nitrified effluent but still there was some leakage of ammonia in the effluent.

On comparing the overall performance of the process from day 524 to day 724 at 2000 mg/l COD loading with its performance at 1000 mg/l and 500 mg/l COD loadings (26), it can be stated that the system was able to work as efficiently as at 1000 mg/l and 500 mg/l COD loadings. The average COD removal efficiency was 96.8 percent, whereas it was 89.7 percent and 94.9 percent at 500 mg/l and 1000 mg/l COD, respectively. The suspended solids removal efficiency was 96.3 percent, which was comparable to the 92.6 percent and 98.1 percent for 500 mg/l and 1000 mg/l COD, respectively. The average biomass concentration during this period was 49,360 mg/l as compared to 20,200 mg/l at 1000 mg/l COD. Volatile solids constituted about 44 percent of the total suspended solids. Even at this low volatile solids content, the system performed well. It is interesting to note that in field studies, Tapleshay observed good removal efficiency from an extended aeration plant for which the volatile content of the sludge was approximately 50 percent or lower (13). The nitrification characteristics were satisfactory, but this differs with the conclusion of Murthy (2) that nitrification cannot be easily attained at waste strength of 2000 mg/l COD. The solids concentration in Murthy's investigation for a feed COD of 2000 mg/l was only about 10,500 mg/l, but in the present investigation the solids were much higher. This result agrees with the idea that decreased unit organic loadings lead to nitrification; in other words, it is the ratio of organic loading to cell concentration in the system which determines the nitrification characteristics.

In the present and previous studies, the ash content of the sludge exhibited cyclic increases and decreases. The important conclusion that can be drawn here is that there would not be any continuous increase in the ash content of the system to cause a biochemical failure. The ash can be expected to pass through the system as soluble inorganic material in the effluent.

The period from day 729 to day 771 indicates that the system can survive for a considerable period in an endogenous phase, but continued withdrawal of mixed liquor and subsequent recycle after hydrolysis increased the ash content of the system up to 67 percent. If the same were continued beyond day 771 there would have been, in all probability, continued increase of ash content as the organic material in the system decreased, i.e., as it approached total oxidation.

It would have been interesting to study growth characteristics of populations in the system using the filtrate of trickling filter sludge. However, the coloration and optical density of this feed prevented such study. The biological parameters obtained, using synthetic medium consisting of glucose as carbon source, were reasonably close to those for heterogeneous populations grown originally on less complicated carbon sources than trickling filter hydrolysate. The low sludge volume indices obtained are attributable to high inorganic (weighting factors) fraction in the sludge.

Performance of the Total Oxidation Process Employing a Mathematical Model With Constant Sludge Feedback

This phase of the work was initiated largely because in making computational analyses using the active model equations of Gaudy and his co-workers it becomes apparent that if the biological constants remain constant, especially the decay constant, k_d, it should be possible to select the engineering constants, α, X_R, and D (or $\bar{t}$) so as to produce no excess sludge, X_W. Thus, a condition of total oxidation, the original concept of the extended aeration process, could be calculated. The effect of k_d and D on X_W in accordance with this model is shown in Figure 16. Since the k_d values obtained by the previous operators of the pilot plant herein used remained in the range of 0.14 to 0.16 days^{-1} for a rather long period, it seemed that by operating with increased $\bar{t}$ (decreased D) one could obtain a condition of zero X_W.

The operational and performance characteristics at the various dilution rates are summarized in Table VI. These data indicate that the system delivered well-treated effluent with respect to filtrate COD and total COD and biological solids concentration, X_e. Also, the relatively few determinations for BOD_5 indicate high purification efficiency. The COD removal efficiency based on effluent filtrate COD at

Figure 16. Effect of k_d and $\bar{t}$ on X_W at an S_i of 600 mg/l (μ_{max} = 0.5 hr^{-1}, Y_t = 0.5, α = 0.25, X_R = 10,000 mg/l)

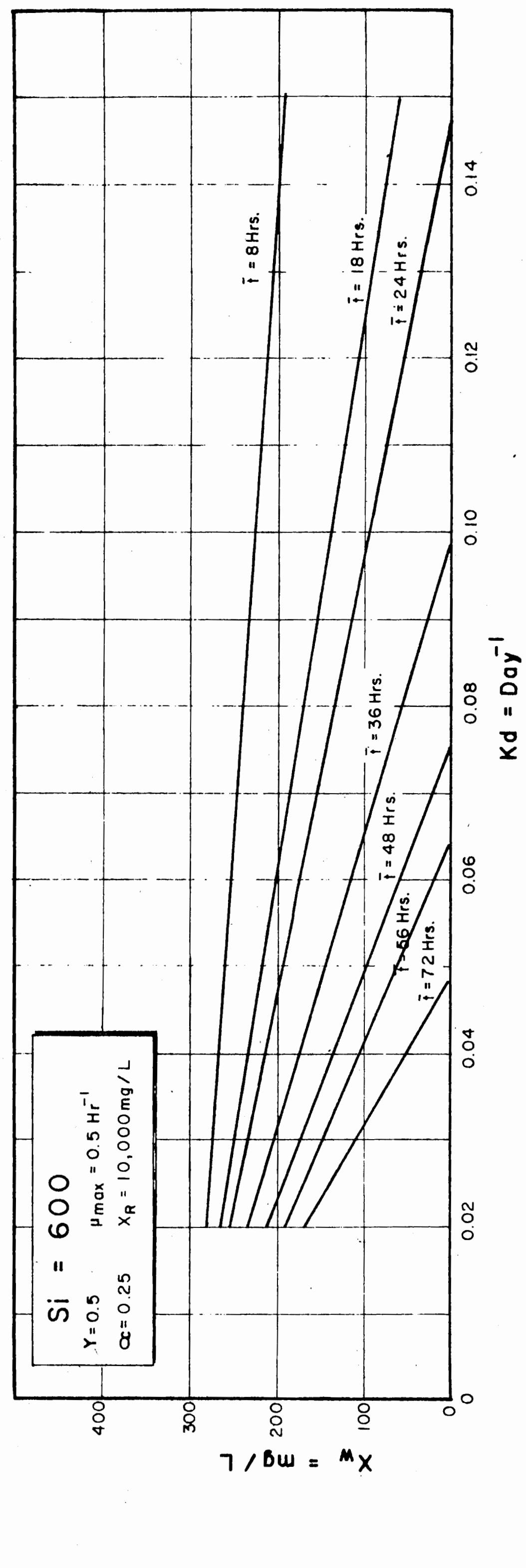

Si = 600
Y = 0.5
μmax = 0.5 Hr^-1
α = 0.25
X_R = 10,000 mg/L
t̄ = 8 Hrs.
t̄ = 18 Hrs.
t̄ = 24 Hrs.
t̄ = 36 Hrs.
t̄ = 48 Hrs.
t̄ = 56 Hrs.
t̄ = 72 Hrs.
0
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Kd = Day^-1
0
100
200
300
400
Xw = mg/L

TABLE VI

AVERAGE STEADY STATE VALUES AT DIFFERENT DILUTION RATE PERIODS

Period (days)	Sampling (# days)	S_i mg/l COD	S_t mg/l COD	S_e mg/l COD	$\bar{X}$ mg/l	$\bar{X}_e$ mg/l	$\bar{X}_R$ mg/l	$\bar{X}_W$ mg/day	$\bar{X}_W$ incl. X_e mg/day	NH_3 effluent mg/l	NH_3 effluent mg/l	NO_3 effluent mg/l	BOD_5 mg/l
24-46	23	608	40	20	2097	29	9389	1353	1527				
57-82	26	603	45	31	1971	42	9515	180	262				
86-97	12	596	45	22	2214	34	10970	-	61	62	55	0	10
107-146	44	614	38	24	2923	21	12037	-	38	66	24	33	9

all three detention times was 94 percent or greater, and based on total COD, it was 92 percent or greater. There were a few occasions during the transient stage wherein there was escape of somewhat higher concentration of biological solids in the effluent. Also, it is interesting to note, although difficult to explain, that the biological solids concentration in the aeration tank experienced an increase followed by a decrease to a new steady level when $\bar{t}$ was changed from eight to 18 hours. It is noted that the recycle sludge concentration, X_R, was inadvertently increased to approximately 11,000 mg/l at this time. However, this would account for an increase of only about 250 mg/l $\left(\text{i.e., } 1000 \times \left[\frac{\alpha}{1+\alpha}\right]\right)$. The observed increase was about 700 mg/l before X returned to its former level. It may be that the abrupt change in dilution rate affected the metabolism of the predator population, causing a temporary decrease in the decay coefficient.

It is interesting that the system attained a reasonably steady condition in S and X with no excess sludge between days 86 and 97 after changing $\bar{t}$ from 18 to 24 hours. At this $\bar{t}$, the excess sludge averaged 262 mg/day (see Table VI), and X_R was allowed to migrate from an average of 9515 to 10,970 mg/l. The increase of 1455 mg/l in X_R could be expected to cause an increased X of no more than 1/5th of this value, i.e., 291 mg/l, and on average it caused an increase of 243 mg/l. In retrospect, it may have been better to hold X_R at 10,000 mg/l to see if zero excess sludge could be attained by manipulation of $\bar{t}$ alone. However, the author felt that the system was so close to "total oxidation" that the increase in X_R was warranted, and this departure from the original experimental plan was made. The results during this period do give a positive indication that it is possible to obtain a steady state for biological solids, X, in the aeration tank with return of solids at a selected concentration and flow without production of excess sludge. The system would have been maintained at this level of X_R and possibly again eventually reduced to 10,000 mg/l had it not been for the event which began on day 97. Spot sampling for NO_3^- in the effluent revealed no nitrification. It must be remembered that the sludge was taken over by the author after it had undergone a long period of experimentation at growth rates which select against nitrifying organisms, so it may not be too surprising that nitrification was not manifested at the low growth rates in the present study. Thus, it was thought to add a seed of nitrifying organisms.

After the introduction of new seed on day 97, the solids rose to a very high value--approximately 2900 mg/l. In order not to waste any sludge, the X_R was increased, i.e., all of the daily sludge production was contained in the volume of sludge recycled. However, the value of X_R concentrations did not account for all of the increase in X. In discussing this aspect, it is advisable to introduce the maintenance plots and the values of the parameters employed in estimating k_d and Y_t from such a plot. The maintenance coefficient and true cell yield were estimated from a plot of reciprocal values of observed cell yield, Y_o, and net or observed specific growth rate, μ_n. Pertinent data and the formulae from which they were calculated are given in Table VII. The values of specific substrate utilization rates, U, are also given, although the alternate procedure for making cell maintenance plots using this parameter was not employed because it was found to not provide the spread of plotting points needed for making a semi-graphical calculation of k_d and Y_t. The maintenance plot is shown in Figure 17.

TABLE VII

DATA EMPLOYED FOR MAINTENANCE PLOT

$\bar{t}_d$ (hrs)	S_i glucose (mg/l)	(1) μ_n	(2) μ_n	(3) Θ_c	(4) U	(5) Y_o	(6) Y_o	(7) $1/Y_o$
8	600	0.3800	0.3640	2.75	0.84	0.460	0.430	2.33
18	600	0.0615	0.0665	15.04	0.39	0.174	0.172	5.81
24	600	0.0113	0.0138	72.50	0.26	0.044	0.050	20.00
24	600	0.22	0.0065	154.00	0.20	0.0325	0.032	31.25

(1) $\mu_n = D\left(1+\alpha-\alpha \frac{\bar{X}_R}{\bar{X}}\right) \frac{1}{\text{day}}$

(2) $\mu_n = \frac{\bar{X}_W}{V\bar{X}} \frac{1}{\text{day}}$

(3) $\Theta_c = \frac{1}{\mu_n(2)}$ day

(4) $U = \frac{D(S_i-\bar{S}_e}{\bar{X}} \frac{1}{\text{day}}$

(5) $Y_o = \frac{\mu_n \bar{X}}{D(S_i-(1+\alpha)\ \bar{S}_e}$ mg/mg μ_n was calculated from Eq. 2.

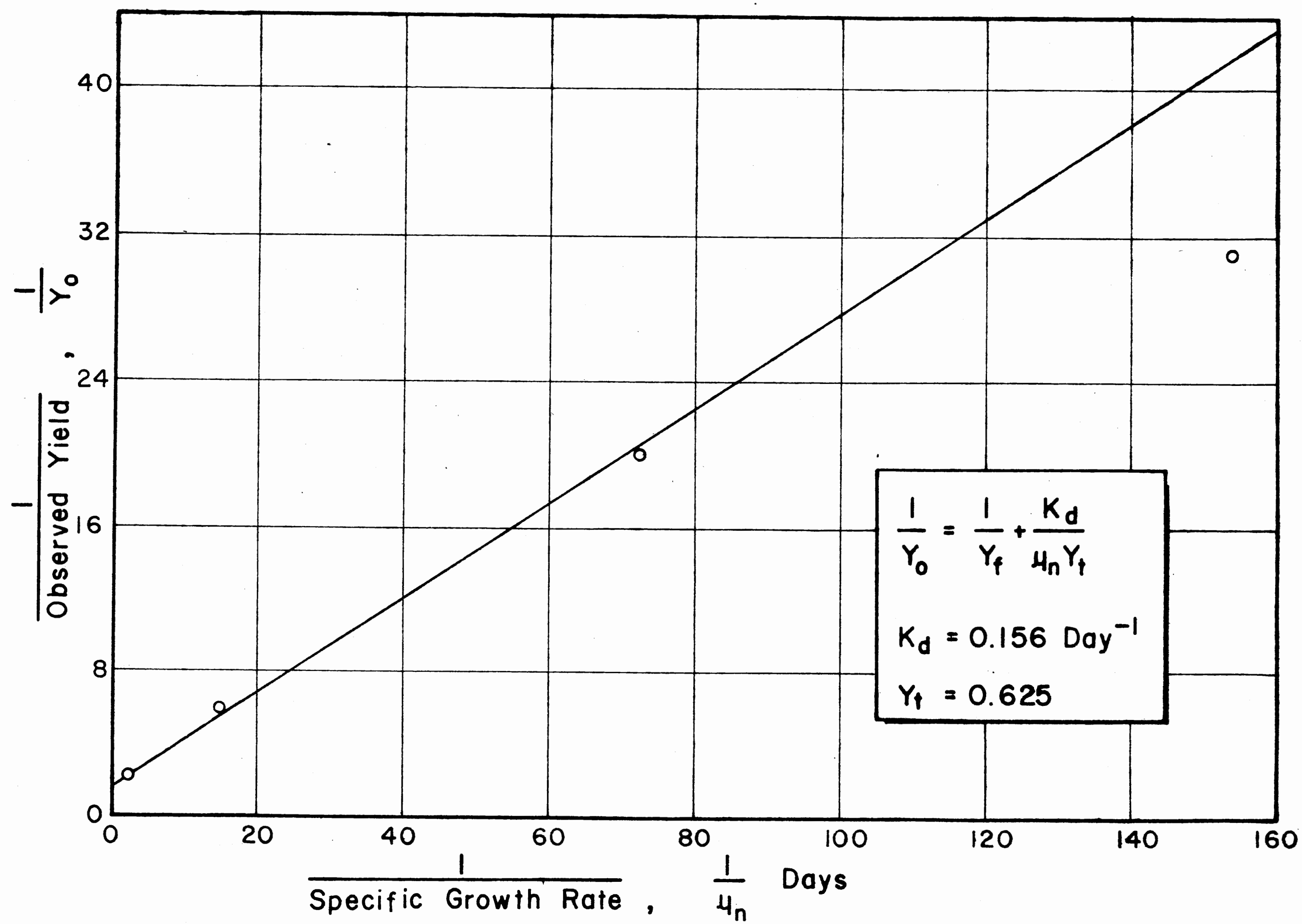
(6) $Y_o = \frac{\bar{X}_W}{F(S_i-\bar{S}_e)}$ mg/mg

(7) $\frac{1}{Y_o(6)}$

$\bar{X}$, $\bar{X}_R$, $\bar{X}_W$, S_i, and $\bar{S}_e$ are mean steady state values

Note: Columns (2) and (6) were used in making the maintenance plot of Figure 17

Figure 17. Plot of Maintenance Energy Equations to Determine True Cell Yield, Y_t, and Maintenance Coefficient, k_d



1/Observed Yield , 1/Yo
0
8
16
24
32
40
0
20
40
60
80
100
120
140
160
1/Specific Growth Rate , 1/μn Days
1/Yo = 1/Yf + Kd/μnYt
Kd = 0.156 Day^-1
Yt = 0.625

This plot was made using the values in columns (2) and (6) of Table VII. It is seen that, excluding the last run at $\bar{t}$ = 24 hours, i.e., the data obtained after adding a small seed of nitrifying sludge, the k_d and Y_t values of 0.15 day^{-1} and 0.63, respectively, are in fairly close agreement with those reported by Saleh (53). After nitrification began, the k_d value decreased as evidenced by the fact that the point plots below the line drawn through the first three points. Another change which occurred after nitrification began was that the values of μ_n in columns (1) and (2) of Table VII no longer agree. All of the data of Srinivasaraghavan and of Saleh, as well as the first three steady state runs in the current study yielded comparable values of μ_n when either formula was employed. Calculations of μ_n were not made during the experimental runs. Thus, the author was not alerted to the problem with calculation of μ_n. Had this knowledge been apparent, even closer check on the values of μ, D, X_R, and X, which determine μ_n, would have been made. In any event, frequent checks on the hydraulic factors (except check for complete mixing during this period) were made and X_R and X were carefully determined. It is not easily explained why presence of nitrifying organisms should or could cause this discrepancy. Both formulae employ the actual experimental data, and there is no reason why an increase in X should not have caused a proportional increase in X_R, since the recycle sludge volume was constant at 0.5 liters and all sludge was recycled. While it is true that a decrease in k_d as well as presence of nitrifiers should increase X, calculation of X using the equations of Srinivasaraghavan and Gaudy and the experimental values for X_R with Y_t and k_d values existing prior to nitrification indicated an $\bar{X}$ of 2400. Even a decrease in k_d to zero would raise X to only 2700 mg/l. Biomass contribution from the autotrophic metabolism of the nitrifiers could also account for an increase in biomass. However, only 33 mg/l of ammonia was converted to NO_3^-. Assuming the value of 3.1 mg/l cells per mg of ammonia used as reported by Stover (60), the biomass could have been increased by approximately 100 mg/l. However, neither of these plausible explanations for an increase in biomass provides explanation as to why the increase in reactor solids, X, was not also reflected in a proportionate increase in X_R. It is clear from examination of the equation used to calculate μ_n in column (2) of Table VII that with D and α at the same values as before this increase in X (and assuming the X value to be correct), the X_R value needed to give a μ_n of 0.0065 day^{-1} is approximately 12,850 mg/l (as compared to the average of 12,037 mg/l which was observed). This represents an approximate difference of only six percent. On the other hand, holding X_R at 12,037 mg/l, an X of 2750 mg/l would be required to obtain a μ_n of 0.0065 day^{-1}. This biomass concentration is within 10 percent of the recorded value. Thus, it can be seen that what seems like a small different in percent using larger numerical values can lead to larger differences in small numerical values such as those involved at the minute in μ_n herein employed.

Be this as it may, the μ_n values calculated by either formula have always provided like results. The major difference between this pilot plant run and the others was the existence of nitrification. It is also possible that X in the reactor could be proportionally higher than that which should have been in the recycle sludge because of non-complete mixing in the aerator tank, i.e., a higher concentration in the reactor than in the reactor effluent during the period between day 98 and day 146. Regrettably, the unit was not checked for complete mixing during this 7-week period. This is rather ironic, because the unit was checked routinely for optical density in and out of the reactor rather frequently prior to this. The fact that it had always been found to be completely mixed lulled the investigator into assuming that it would always be completely mixed. It was not realized during the data-taking phase that the inconsistency in the value of μ_n would occur. As can be seen from the calculation made previously, the reactor would not have to be too far out of complete mix to give an enormously high X.

Although the above problem could be resolved and the μ_n values as per the model equation do not check for the last seven weeks of the study, the results leave little doubt that during those seven weeks the process was operated under a steady condition with no excess sludge production, and it provided excellent purification efficiency as well as a rather high degree of nitrification. Whether the process could be operated over a sufficiently long time under steady conditions using this mode of operation cannot be assumed.

It is interesting to check the amount of agreement between the observed values of S, X, and X_w and those predicted by the model equations. In calculating the predicted values, the biological constants for μ_{max} and K_s were those determined during each steady state period, and the values for k_d and Y_t were those obtained for the data using the maintenance plot of Figure 17. The effect of the maintenance coefficient on X_w is of special interest to the extended aeration process, and the values of the parameters with and without use of the maintenance coefficient are compared in Table VIII.

The rather large differences between predicted and observed S have been previously discussed by Srinivasaraghavan and Gaudy (40). They

TABLE VII

EFFECT OF MAINTENANCE COEFFICIENT, k_d, ON PREDICTED VALUES OF S, X, AND X_W

	$\bar{t}$	S_i Glucose (mg/l)	Obs.	Effluent Substrate, $\bar{S}$, mg/l (predicted) $Y_t = 0.625$ $k_d = 0.156$	Effluent Substrate, $\bar{S}$, mg/l (predicted) $Y_t = 0.625$ $k_d = 0$	Obs.	Biological Solids, X, mg/l (predicted) $Y_t = 0.625$ $k_d = 0.156$	Biological Solids, X, mg/l (predicted) $Y_t = 0.625$ $k_d = 0$	Obs.	Excess Sludge, X, mg/day (predicted) $Y_t = 0.625$ $k_d = 0.156$	Excess Sludge, X, mg/day (predicted) $Y_t = 0.625$ $k_d = 0$
1.	8	600	20	14.4	13.8	2097	2082	2169	1527	1594	2325
2.	18	600	31	5.3	4.8	1971	1998	2185	262	286	976
3.	24	600	22	10.2	8.5	2214	2197	2478	61	61	842
4.	24	600	24	5.4	4.6	2923	2400	2699	38	31	877

come about because of the use of COD as a measure of S, and because in the effluent there is residual COD other than original substrate. In general, this table shows the same trends as were shown in previous work at higher growth rates. The inclusion or non-inclusion of k_d in the model does not have much effect on the predicted values of S and X, but does have a significant effect on the predicted values of X_W. Furthermore, inclusion of k_d is necessary to obtain close agreement between observed and predicted values of X_W. It is obviously an important parameter in the extended aeration process. The results of run 4 with respect to prediction of X are in obvious error, partially because of a change in k_d and other possible causes previously discussed.

CHAPTER VI

CONCLUSIONS

Results of the first phase of the investigation on the "hydrolytic-assist" extended aeration process support the following conclusions:

1. The "hydrolytic-assist" extended aeration process will treat a waste of high ash content efficiently at organic loadings of 2000 mg/l COD.

2. A low volatile solids concentration of the biomass of about 40 percent does not adversely affect the efficiency of purification in a hydrolytically-assisted extended aeration process.

3. A high concentration of dissolved inorganic solids in the influent will not be expected to cause a continuing buildup of ash content in the sludge to the point of system failure. The inorganic materials can be expected to pass through the system as dissolved solids in the effluent.

4. The increased withdrawal of sludge and subsequent recycle after hydrolysis during the period of very high solids concentration will help to reduce the solids level without affecting the efficient performance of the system.

5. Since the organic loading was rather high (218 lbs COD/1000 ft^3 aeration capacity), it is concluded that low unit organic loadings, i.e., low F/M ratio and not simply low organic loadings, seem to determine the nitrification characteristics.

The following conclusions are made from the results of the second phase of the investigation on the total oxidation process using the model with constant X_R:

The event which occurred after seeding the unit with the nitrifying population, whether due to this addition or not, make it difficult to draw sharp conclusions regarding this phase of the study. The reason for the above statement is given in the discussion. However, it is clear that the system was behaving in accordance with the model and was approaching total oxidation prior to the abnormal increase in X. It is also clear that even with this unexplained abnormality, the system was operated in a steady condition with respect to X and S with total cell recycle.

CHAPTER VII

SUGGESTIONS FOR FUTURE STUDY

Based on the findings of this study, the following suggestions are made for future investigations on the "hydrolytic-assist" extended aeration process and on the extended aeration process employing constant X_R:

1. Study the stability of the "hydrolytic-assist" extended aeration process for treatment of high ash trickling filter sludge waste at organic loadings higher than 2000 mg/l COD and, ultimately, without any dilution of trickling filter sludge, i.e., study "hydrolytically-assisted" aerobic sludge digestion as a separate unit process.

2. Investigate the extended aeration process with continuous external recycle of sludge instead of internal recycle by providing separate aeration and settling tanks.

3. More intense investigation of already explored physical and chemical methods to remove the dissolved inorganic solids should be undertaken.

4. Experiments of the second phase using the constant X_R model should be repeated. The recycle sludge concentration, X_R, should be held close to 10,000 mg/l, and total oxidation should be approached by elongating $\bar{t}$, as was the original plan in the second phase. In other experiments one could hold $\bar{t}$ at a constant level to see if total oxidation could be achieved by increasing X_R.

5. Investigate possible methods of automatic measurement and control of X_R, possibly employing a more rapid method of analysis for biological solids concentration.

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