STUDIES ON THE BEHAVIOR OF A NEW ACTIVATED SLUDGE PROCESS UNDER SHOCK LOADING CONDITIONS

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Dedicated to my wife and daughter

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LIST OF SYMBOLS

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}
F	- Rate of flow of incoming substrate or wastewater, l/hr
F_w	- Amount of waste sludge flow, l/day
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 ½ 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_e	- Concentration of substrate in the effluent, filtrate COD, mg/l
$\bar{S}_e$	- Steady state concentration of substrate in the effluent, filtrate 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

S_{R_1} - Concentration of substrate in the effluent of aerator #1, filtrate COD, mg/l

S_R - Filtrate COD in the recycle sludge, mg/l

$\bar{S}_R$ - Steady state filtrate COD in the recycle sludge, mg/l

t - 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

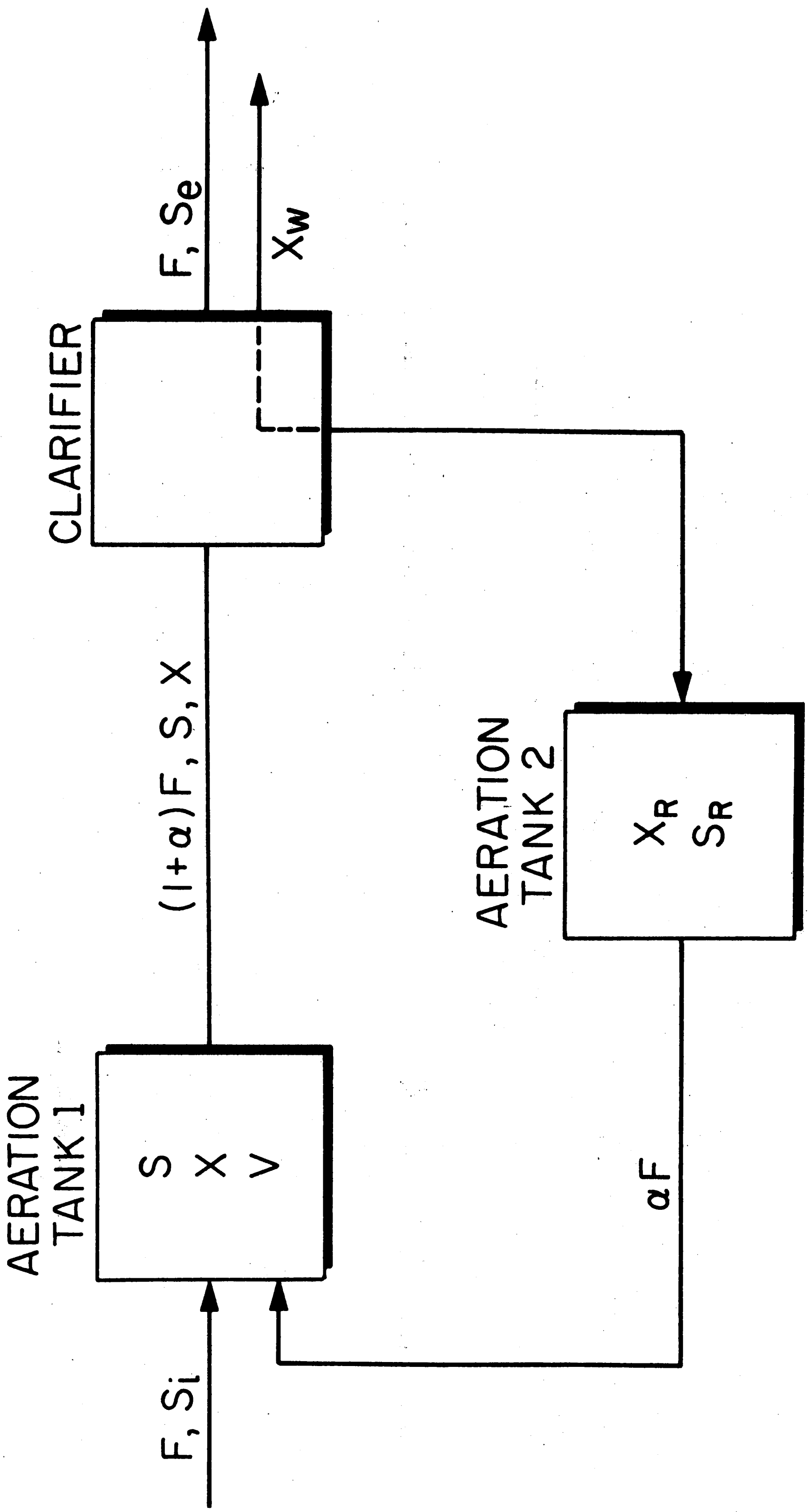
INTRODUCTION

Biological processes have long been used to treat the waste effluent of society. In the past, the efficiency of these processes was of less concern to society, because few streams and rivers were seriously damaged by pollution. As waste discharges increased because of continued growth and industrialization, more and more streams became low in dissolved oxygen, and fish kills became apparent. To rescue the aesthetic and economical resources of water bodies and conserve these resources which have not yet been ruined, users will be required to produce effluents of increasing quality. For many industries, waste treatment costs have become a significant item of economic analysis in manufacturing. As this trend continues, more effective waste treatment systems will become mandatory.

Primary sedimentation, a simple and cheap method for separating settleable solids from liquids, and microbial processes, or secondary treatment, have become the most widely used methods of waste treatment. The advantages of "secondary" biological treatment systems relate to their natural place in the decay portion of the carbon cycle. Waste organic matter is oxidized to carbon dioxide, and microorganisms are produced to maintain the process. The only major energy requirement is that needed to keep the system well mixed and aerobic. A significant cause for concern with these processes is characterization and control of response to environmental change. Practically all municipal and many industrial waste treatment systems have no provision for control over the quantity and quality of the waste entering the process; thus, the biota are constantly responding to changes in the influent waste stream. These changes can upset process performance and cause variation in biochemical oxygen demand (BOD) removals over a wide range.

Control measures and improvements in the process have come slowly, resulting predominantly from work done in field installations. However, over the past decade, large amounts of data on continuous flow activated sludge systems have been amassed by various researchers. It was found by Srinivasaraghavan and Gaudy that under relatively steady operating conditions, an activated sludge system employing constant cell feedback concentration, X_R (Figure 1), was extremely useful in steadying the inherent dynamic (unsteady) nature of this heterogeneous biomass (1)(2)(3). However, little is known of the response of such an activated sludge model to severe changes in the external environment, i.e., shock loading conditions. Based upon past work in the author's laboratory, some guidelines are emerging with respect to the ability of continuous culture systems to accommodate change, but more work is needed. The long-range objective of this thesis was to examine the stability of an activated sludge process operated with constant solids recycle concentration. The general plan was to operate a laboratory scale pilot plant similar to that run by Srinivasaraghavan and assess steady state performance of this system at various growth rates prior to applying various environmental perturbances. In the current studies, the steady state was disrupted by administering various changes in hydraulic inflow rate (hydraulic shock loadings) and in substrate concentration

Figure 1. Flow Diagram for Model Employing Constant Recycle Sludge Concentration, X_R


F, Si
AERATION
TANK 1
S
X
V
(1+α) F, S, X
CLARIFIER
F, Se
Xw
AERATION
TANK 2
XR
SR
αF

(quantitative shock loadings). After characterizing the transient response to the step change, the system was run until it attained a new steady state. The major aim of this study was to characterize the nature of the transient response in going from initial to final steady state. However, another important phase of the study involved subjecting the system to various pulsing hydraulic shock loads and quantitative shock loads. The aim of this part of the study was to determine if steadiness in effluent substrate concentration could be maintained under continuous transient loading conditions, and to gain scientific insight into the causative mechanisms for the response.

CHAPTER II

LITERATURE REVIEW

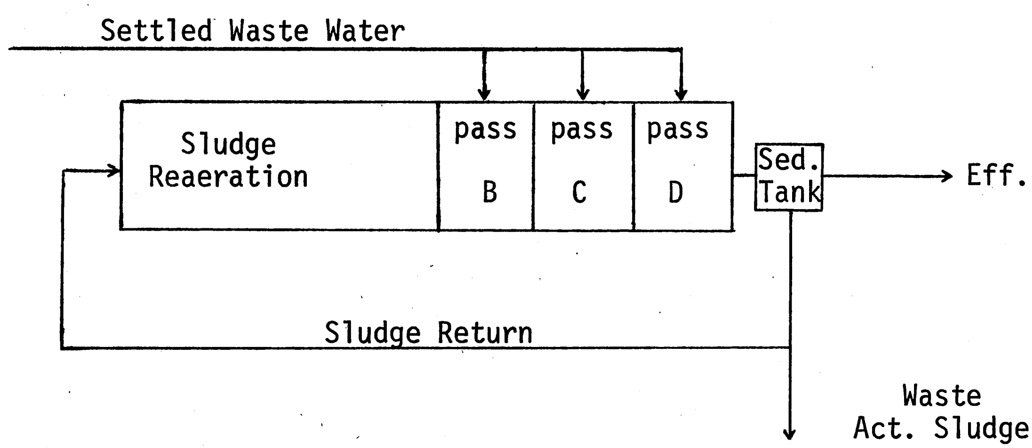
A. Activated Sludge Process: Review and Development

The activated sludge method has been widely emplyed for over half a century. This process enjoys ever-increasing popularity as a major means of biological treatment. Various researchers have shown the process to be extremely adaptable, and many process modifications have been proposed to meet specific requirements and conditions.

The activated sludge process can be considered as having been spawned by blowing air through wastewater. Among recorded incidents are those of Dr. Angus Smith (1882), Dupré and Didbin (1884), and Hartland and Kaye-Perry (1888) in Europe, and Dr. Drawn (1891), Mason and Hine (1891), and Col. Waring (1892-94) in the United States (4).

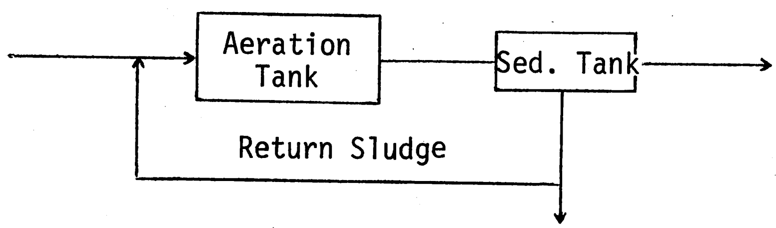
By 1917, the Manchester Corporation had brought a 250,000 gpd (946,000 l/day) continuous flow plant into operation in Washington. The next step was the evolution of a satisfactory theory to explain its unusual characteristics. By 1930, a theory of action based on biological considerations was well established. The studies of Seizer (5) in Germany and Buswell and Long (6) provided very convincing data. Studies on oxygen requirements can be considered as important landmarks in the development of the process. New knowledge concerning oxygen requirements in relation to sludge concentration, temperature, substrate, nutrition, and bacterial growth response served as a base for the following activated sludge methods:

Tapered aeration based on the rapidly diminishing oxygen requirements as the treatment progresses was considered by Kessler, Rohlich, and Smart (7). In order to save aeration tank capacity, Gould (8) proposed a system of operation referred to as "step aeration." This system is best adapted to multiple-pass tanks, with three or four channels. The first pass is reserved for reaeration of the returned sludge. Sewage is added stepwise--usually one-third in the beginning of each of the second, third, and fourth passes in a four-pass system.

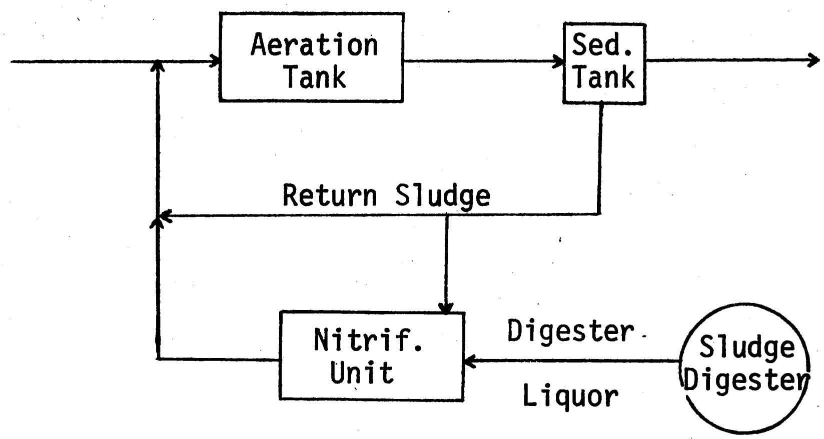


Attempts are made in this method to keep the oxygen demand at fairly uniform levels. In this scheme of treatment, much of the ammonia nitrogen escapes in the final effluent (9). Step aeration has been applied widely in spite of its having been a proprietary process until recently.

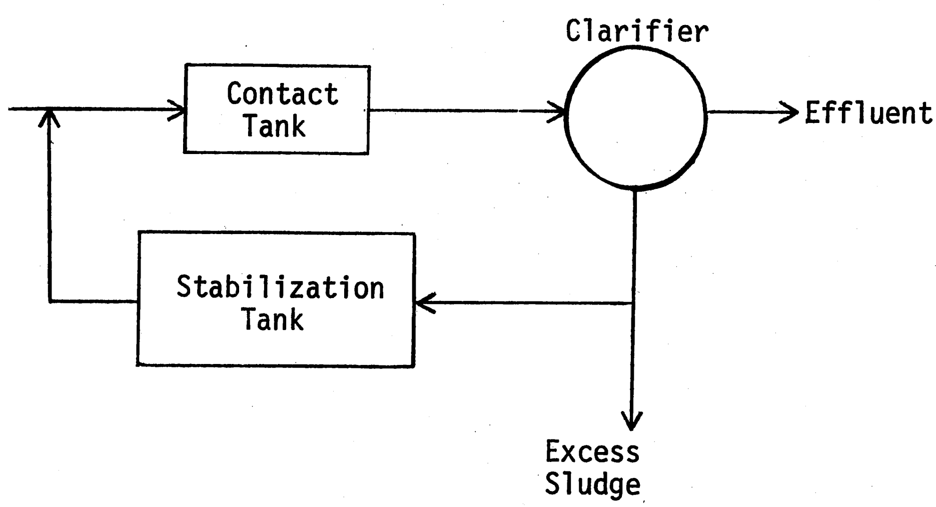
It is reported to produce well settling sludges as well as savings in tank volume (9). Studies by Setter and Edwards (10) in New York City showed that an activated sludge process could be operated to produce an intermediate degree of treatment in a reliable manner if the aeration solids were restricted to low levels of 300 to 600 mg/l with aeration periods in the range of 1.2 to 2 hours. This new scheme of treatment was referred to as "modified aeration." It accomplishes a degree of BOD and suspended solids removals in the range of 65 to 75 percent. Sludges compact well and are readily digestible; the flow pattern is the same as for a conventional system. Aeration tankage is almost one-third of that for conventional activated sludge.



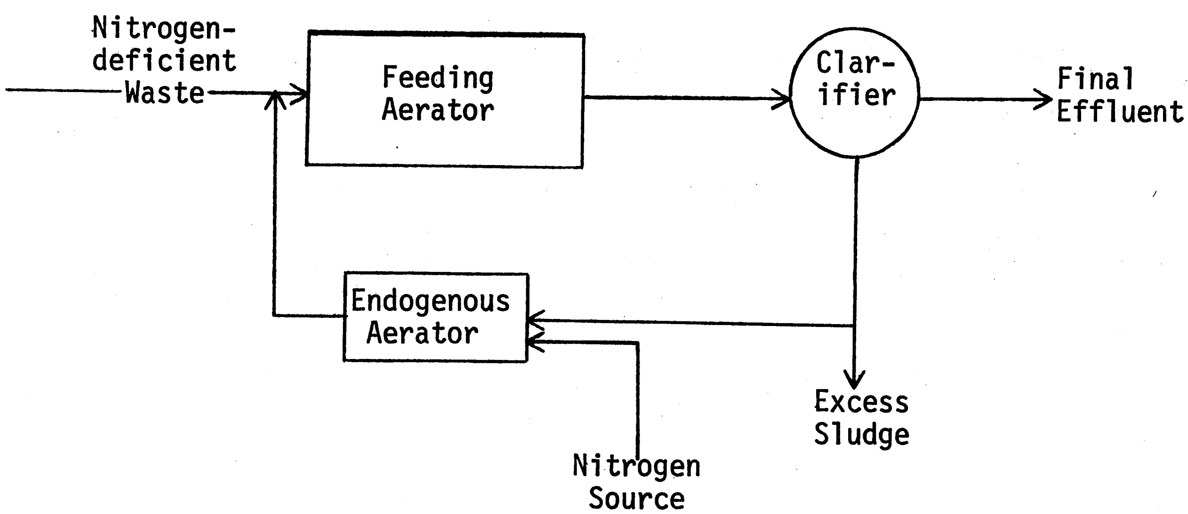
In 1945, Kraus (11) reported on the use of aerobically conditioned sludge mixed with digester overflow liquor as a means of controlling bulking of activated sludges. Digester overflow liquor, digested sludge, and activated sludge are aerated for many hours under aerobic conditions. The resultant mixture is highly nitrified and contains biologically active sludge with low volatile solids and good settling properties. By adding this mixture in proper proportions to the returned activated sludge and modifying the method of aeration, Kraus (12) has been able to control sludge bulking and to maintain a high degree of purification while handling BOD_5 loadings in the range of 100 to 175 lbs/day/1000 cu ft of aeration tank capacity.



The biosorption process, which is characterized by using the supposed adsorptive properties of a well conditioned activated sludge, was not widely known until 1951. Ulrich and Smith (13) established the flow diagram shown below in which the activated sludge, well conditioned by reaeration, is brought into contact with the unsettled wastewater under intense aeration for a period of about 30 minutes. BOD_5 loadings in the range of 150 lbs/day/1000 cu ft of aeration tank capacity have been treated with purification efficiency in excess of 90 percent. It has been stated that the process produces sludges that are difficult to concentrate in excess of 2-5 percent solids by gravity. This modification is referred to as "contact stabilization application" (9). Contact stabilization, wherein settled wastes are treated, has been used successfully in many plants (14)(15). It has been claimed that such modification has provided a greater flexibility of operation and better protection against shock loadings imposed by industrial waste discharges (16). The rapid removal of waste (as BOD) was attributed to adsorption, as it was considered unlikely that biological purification could proceed so rapidly. However, Gaudy and Engelbrecht (17) have shown that rapid purification of soluble wastes by activated sludge is biochemical in nature rather than adsorptive.



In 1967, a process flow sheet shown below, which utilizes two aerators, was proposed for treatment of nitrogen-deficient industrial wastes. In the first, or feeding, aerator nitrogen-free effluent is produced since no nitrogen is added to the waste and the waste is removed by non-proteinaceous oxidative assimilation. The sludge to be recycled is regenerated by addition of ammonia nitrogen in a second (endogenous) aerator. A considerable savings in the cost of nitrogen has been realized since a COD:N ratio much higher than that used in traditional methods of treatment can be employed (18). Laboratory scale pilot plant studies using several synthetic wastes and sugar refinery waste have demonstrated the feasibility of the proposed continuous oxidative assimilation process for the treatment of nitrogen-deficient industrial wastes (19)(20).



Many workers have concluded that activated sludge processes could perform more efficiently than they are usually run in the field. Wuhrman (21), Pasveer (22), and many others demonstrated in pilot plant operation that BOD_5 loadings of 190 lbs/day/1000 cu ft could be treated with removals on the order of 80 percent. Pasveer, in laboratory studies, demonstrated that it is possible to accomplish complete nitrification at BOD_5 loadings of 112 lbs/day/1000 cu ft, and that BOD removals as great as 93 percent can be accomplished at BOD_5 loadings as high as 375 lbs/day/1000 cu ft if adequate oxygen is supplied. Aeration solids were maintained in the range of 4000 to 10,000 mg/l. The process is essentially the same as conventional activated sludge except that completely mixed aeration systems are used with high aeration solids and aeration periods of 1 to 1.5 hr. In practice, activated sludge is designed and operated with BOD_5 loadings up to 35-40 lbs/day/1000 cu ft of aeration tank capacity.

The large amount of waste sludge that must be disposed of is one of the major problems of nearly all activated sludge systems. The extended aeration system was conceived as a means of alleviating the sludge disposal problem while producing a highly purified effluent. It has made the activated sludge process a practical system of treatment for many small communities. In general, it functions best at BOD_5 loadings of less than 15 lbs/day/1000 cu ft of aeration capacity or less than 0.1 lb of BOD_5/lb mixed liquor solids.

Aerated lagoons as treatment devices have shown that biologically active systems can be maintained with detention periods in the range of three to five days. Such systems are capable of producing biological floc that can be settled with reasonable detention times and will produce BOD removals in the range of 80 to 90 percent.

In spite of all of the processes that have been advanced to overcome some of the shortcomings of the conventional activated sludge process, the main drawback of all of these modifications is that the organisms are not subjected to constant loading during the entire aeration period. Busch and Kalinske (23) have indicated that certain conditions have to be satisfied for the best operation of the activated sludge process. These are: young flocculent sludge in the logarithmic stage of growth; maintenance of the log growth state by controlled sludge wasting; continuous organic loading to the organisms, and elimination of anaerobic conditions at any point in the oxidative treatment.

The process known as "complete mixing" activated sludge can meet most of the above mentioned requirements; however, a "complete mixing" system can be operated on the basis of high synthesis of sludge with controlled wasting of sludge, or on the total oxidation principle with no intentional wastage of sludge. McKinney (24) defines complete mixing as a basic process in which the incoming wastes are completely mixed with the entire contents of the aeration tank. He considered that the aeration tank acts as a surge tank and tends to level out wide fluctuation in the organic load and that the use of the entire mass of activated sludge to stabilize the organic load distributes the load uniformly over the entire aeration tank and permits better utilization of the air blown into the mixed liquor. Eidness (25) was the first to report on the significance of intense mixing in activated sludge plants. Pilot plant studies indicated that with complete mixing it was possible to produce an effluent of 25 mg/l BOD in a 2.5-hour contact time with domestic sewage.

A process proposed by McKinney (26) to overcome the shortcomings of conventional activated sludge processes is called "hi-lo" activated sludge; the wastes are introduced along the entire length of the aeration tank. Biological solids are allowed to build up to 20,000 mg/l. This process also serves to absorb various organic contents of the waste, and effects dilution on mixing with the contents of the aeration tank. Hence, no high initial oxygen demand is exerted. The high solids concentration also serves as a buffer against incoming wastes with a pH below 6.5 and above pH 9.0. This process closely approximates the more general present day concept of completely mixed systems. Intense aeration and/or agitation serves the dual purpose of supplying oxygen to the growing organisms and effecting complete mixing in the aerator. Grieves, et al. (27) studied the effect of shortcircuiting in the completely mixed activated sludge process. They indicated that the effect of a stagnant zone is equivalent to that of an increase in loading which increases the effluent BOD by an amount proportional to the amount of shortcircuiting.

The use of completely mixed activated sludge processes has made possible the treatment of many industrial wastes which could not be treated in a conventional activated sludge process without some form of pre-treatment. The following few references will show the importance of this process for the treatment of industrial wastes:

McKinney, et al. (28) have reported on the treatment of highly alkaline textile wastes without pre-neutralization in a completely mixed system. Effluent with less than 50 mg/l BOD could be produced and variations in organic loading did not upset the process as severely as they do a conventional activated sludge system.

Haterfield and Strong (20) used complete mixing in preference to a conventional activated sludge process for the treatment of toxic wastes. They indicated that higher organic loadings could be handled by this system.

Busch and Kalinske (23) have reported an average treatment efficiency of 89 percent with BOD loadings up to 350 lbs/1000 cu ft aerator volume per day in an "aero-accelerator" pilot plant. The aero-accelerator is an aeration tank manufactured by the Infilco Company.

Coe (30) studied the treatment of petroleum wastes in a laboratory-size activated sludge unit. His results indicate BOD reduction of 90-95 percent at organic loadings up to 140 lbs BOD/1000 cu ft aerator volume/day.

Ross and Sheppard (31) made use of an aero-accelerator to remove phenol from petroleum waste. Their results indicate that this plant can successfully treat up to 600 lbs phenol/day with an efficiency of 99.9 percent. They indicated that phenol was oxidized to CO_2 and water.

Gehm (32) has indicated the desirability of using a commercial fermentor for the treatment of wastes high in BOD. He reported that it is possible to treat boardmill wastes up to BOD loadings of 400 lbs/1000 cu ft aeration volume/day at an efficiency of over 90 percent using these aerators. Completely mixed systems have been used extensively to obtain design data for the treatment of industrial wastes containing aniline, nitrobenzol, phenol, and 2,4-dichlorophenol, chemical wastes containing antibiotics, synthetic vitamins, cortisone, and pharmaceutical wastes (33)(34)(35)(36). The great advantage of the complete mixing system lies in the fact that the size of the unit is not a factor in getting useful information for design purposes. The only criterion to be satisfied either in a laboratory scale unit or full scale treatment plant is that of complete mixing. Once this condition is satisfied, the shape and size of the pilot plant unit are of little consequence.

Tenney, et al. (37) have used a completely mixed system to study the effect of high organic loading, and they varied loadings from 60 lbs to 1690 lbs COD/1000 cu ft aerator volume/day. They indicated that 88 percent of the influent COD was biologically processed either to CO_2

and H_2O or resultant solids. Of the COD utilized, 48 percent was lost from the system, and the remainder converted to solids. Solids yield was found to be independent of loading.

Data from batch operated activated sludge processes have been used to design completely mixed systems. Weston and Stack (38) have indicated that batch data can be used for the prediction of the behavior or completely mixed systems by calculating the apparent BOD transfer coefficient.

Busch (39)(40)(41) has indicated that the design of a complete mixing system on the basis of batch grown solids is hazardous. He has indicated that batch experiments using cells grown in continuous flow units will yield information on the rate of waste purification and that the settling characteristics of batch grown cells are a function of solids age, while in the continuous system the applied surface loading determines the settling characteristics of the solids. Gaudy (42) has used cells grown in a completely mixed system to evaluate the effect of qualitative shock loading under batch aeration.

One of the modifications of the completely mixed activated sludge process which has been mentioned previously is the so-called total oxidation system. Kountz and Forney (43) stated that solids balance could be reached when some wastage was practiced, whereas for total recycle, solids balance could not be reached within a reasonable time period because of solids accumulation of 20 percent by weight of the solids produced.

McCarty and Broderson (44) indicated that total oxidation of sludge is not feasible. They studied the effect of three different loadings--40, 80, and 120 lbs BOD/1000 cu ft/day on the performance of total oxidation systems over a period of 48 days. Their results indicated that a total oxidation system operates satisfactorily at a loading of 40 lbs BOD/1000 cu ft aerator volume/day. The problem of rising sludge due to denitrification in the secondary settling tank was also indicated by their work. In batch systems, evidence in favor of the concept of total oxidation was presented in 1971 by Thabaraj and Gaudy (45). Long-term continuous flow pilot plant studies were undertaken in which there was obtained evidence for periods of biological solids accumulation and periods of de-accumulation due to autodigestion of the biological solids in the reactor (46)(47).

Deindoerfer and Humphrey (48) and Herbert (49) have presented types of classification of continuous flow biological processes based on (a) biochemical, and (b) chemical engineering principles. The biochemical approach to classification takes into account the fact that biochemical transformation can be brought about either with accompanying growth of microorganisms or in the absence of growth. They are referred to as (a) growth, and (b) non-growth systems. In the process which involves growth, the biocatalytic activity is a function of limiting nutrient concentration attained as well as the amount of limiting nutrient utilized. In the non-growth process, the suspended cell concentration provides the enzyme to convert substrate to extracellular products in a manner analogous to the chemical reactions carried out by solid catalysts. Even resting cells can bring about the chemical transformation, provided the necessary enzymes are present. The latter process is also referred to as a "catabolic" process, or breakdown to simpler molecules, and an example would be the breakdown of glucose to ethanol. The process is exergonic and can be brought about even by resting cells. The growth process has been termed as a "biosynthetic" process, and an example would be the production of penicillin (49).

The chemical engineering classification offers several different criteria. One important distinction is between homogeneous and heterogeneous systems. In a homogeneous system, the composition of reactor liquid is uniform throughout. In the heterogeneous system, there may exist a concentration gradient of cells, or substrates, or any other or all of the system parameters. Microorganisms passing through a heterogeneous reactor will undergo something akin to the growth cycle of a batch culture.

All continuous flow systems can be classified as either single phase or multiphase systems. In the single phase system, the biochemical transformation takes place in one phase--generally the liquid phase. Single phase systems can be either homogeneous or heterogeneous. The multiphase system, as the name implies, involves more than one phase. A typical example of a multiphase system is the trickling filter. The operation of trickling filters involves a solid and a liquid phase. The waste is passed through a filter bed during which time the microorganisms attached to the bed metabolize the organic substrates present in the waste. Multiphase reactors are necessarily heterogeneous systems.

Classifications such as "open" and "closed" systems have been presented by Herbert (49). In the closed system, the microorganisms never leave the reactor and may be retained by means of a semi-permeable membrane. Such a system is formally analogous to the so-called total oxidation or "total recirculation" system employed in wastewater treatment in which there is no sludge wasting. Thus, the continuous flow process provides much flexibility in operation with uniform quality of end products over an indefinite period. Because of the uniformity of reaction products and reaction rates in continuous flow completely mixed reactors, they are more suitable for the study of biochemical reactions than fill-and draw or batch processes. In the fill-and-draw or batch process, the overall operational conditions are selected empirically for optimizing the various steps such as energy transfer, catalyst synthesis, and product formation. This can result in the inefficient operation of the process, since each of the above steps might require quite different optimum conditions. Continuous flow processes offer a striking advantage in this aspect, since a series of reactors can be used for optimizing each of the above steps.

Even though the continuous flow process appears to be far superior to batch systems, it does have disadvantages. The major disadvantage is that failure in any one of the unit operations will result in total failure of the system. When the process involves the use of pure cultures, contamination or generation of mutants will also result in the shutdown of the process. However, in the main, continuous flow processes are more promising than fill-and-draw operations for nearly all bioengineering systems and in particular for wastewater treatment.

Extensive investigation was done by Gaudy and co-workers to gain insight into growth characteristics of heterogeneous microbial populations cultivated continuously in completely mixed reactors of the once-through type and with cell feedback-type operations (50)(51). These studies were undertaken for the purpose of assessing the applicability of various models relating values of kinetic growth parameters to concentrations of limiting nutrients, and for the purpose of determining whether steady state operation with respect to biological solids concentration, X, and substrate concentration, S, could be approached for heterogeneous populations. It was found that the Monod equation was applicable.

$$\mu = \frac{\mu_{max} \cdot S}{K_s + S} \tag{1}$$

It was found also due to the heterogeneity of the population, that some variation in the maximum logarithmic growth rate constant, μ_{max}, and saturation constant, K_s, was to be expected. It was also found that the value of cell yield, Y_t, could be expected to vary. The kinetic concepts could be employed, but a usable range of values rather than a precise numerical value should be employed. Concerning the attainment of a steady state with respect to S and X, it was found that a steady state could be approached rather closely for S and less closely for X.

One such model that has an inherent operational control parameter is that of Herbert (49). The steady state equations for S and X, according to this model, are shown in Table I. There are three biological "constants," μ_{max}, K_s, and Y, and two hydraulic parameters, α and c. These five parameters control S and X at any selected dilution rate, D. An operational system constant is the ratio of recycle solids concentration to the aeration tank solids concentration ($X_R/X = c$). The requirement of this model is that c should be held constant. The growth rate in the system can be controlled by selection of c for a particular α and D. Since $\mu = D(1 + \alpha - \alpha c)$, it is seen that a relationship between μ and c can be developed for various combinations of α and D. Thus, the system can be run at desired growth rates or cell ages by proper choice of α, D, and 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	
$\bar{X} = \frac{Y}{1+\alpha-\alpha c}\left(S_i-\bar{S}\right)$	(2a)	$\bar{X} = \frac{Y\left[S_i-(1+\alpha)\bar{S}\right]+\alpha X_R}{1+\alpha}$	(2)
$\bar{S} = \frac{K_s D(1+\alpha-\alpha c)}{\mu_{max}-D(1+\alpha-\alpha c)}$	(3a)	$S = \frac{-b\pm\sqrt{b^2-4ac}}{2a}$ $a = \mu_{max}-(1+\alpha)D$ $b = D\left[S_i-(1+\alpha)K_s\right] - \frac{\mu_{max}}{1+\alpha}\left[S_i+\frac{\alpha X_R}{Y}\right]$ $c = K_s DS_i$	(3)
$\mu = D(1+\alpha-\alpha c)$	(4a)	$\mu = D\left(1+\alpha-\alpha\frac{X_R}{\bar{X}}\right)$	(4)

Here the model failed insofar as its use with heterogeneous populations is concerned. It is realized from the equation for growth rate that μ is very sensitive to the value of c. Thus, it is essential that c be maintained constant at the desired value. In order to keep c constant, X_R should be adjusted for every change in X. Operating such a laboratory pilot plant causes problems when dealing with heterogeneous populations. The value of X fluctuates within practical limits, and any alteration in X_R to maintain constant c will disrupt the system. This was observed experimentally by Ramanathan and Gaudy (51). When X_R was increased for an increase in X to keep c constant, X was increased further and pushed the system further away from steady state, acting directly against the purpose of the control procedure. Therefore, operation with constant X_R, rather than a constant value of c, might exert a steadying influence on the biological solids concentration.

Writing materials balances for $\bar{X}$ and $\bar{S}$ in the steady state, holding X_R constant and assuming that the concentration of S in the recycle solids was negligible, led to the equations shown in Table I. These equations are those evolved as a consequence of an operational decision to employ X_R rather than c as a constant in the kinetic model. Another difference between this model and Herbert's theoretical analysis of continuous culture systems of the completely mixed type in the steady state was the assumption of neglecting S in the recycle flow. Herbert developed his model to depict the behavior of X and S as D was varied. The main purpose of the model developed by Ramanathan and Gaudy was to obtain a workable system at dilution rates one might reasonably consider for activated sludge processes. From a theoretical standpoint, as a consequence of assuming zero substrate concentration in the recycle rather than $\bar{S}$, the value of $\bar{S}$ cannot approach S_i as D approaches very high values. Instead, it approaches the value of $S_i\left(\frac{1}{1+\alpha}\right)$. It is realized that this is an unrealistic assumption at the extreme upper boundary of D values. Concerning the assumption of constant X_R at very high dilution rates, the value of $\bar{X}$ would approach $X_R\left(\frac{\alpha}{1+\alpha}\right)$; there would be no new growth, and the only cells in the aeration tank would be those due to recycle flow. High dilution rates would result in inefficient clarification due to lack of flocculation as well as low biochemical efficiency at higher loading (S_i) conditions. Such high dilution rates would also make the system very unstable even under mild shock load situations, either quantitative or hydraulic. A computational program was set up to determine the behavior of the kinetic equations for $\bar{S}$ and $\bar{X}$ of this model as the biological parameters, maximum specific growth rate, μ_{max}, saturation constant, K_s, and cell or sludge yield, Y, as well as the engineering constants, hydraulic recycle rate, α, and recycle solids concentration, X_R, were varied. These results have been reported and the kinetic consequences and ramifications of the equations discussed (52).

In order to account for the variability in cell yield in the past, two methods have been adopted by various investigators. Either a yield constant and a decay coefficient are included in materials balance equations, or cell yield is considered as a variable of the system, depending on the operating conditions. The use of a yield constant and a decay coefficient is a more practical approach as well as one more closely associated with the theory of continuous culture. It allows one to retain the "true cell yield," Y_t, as a property of the biomass rather than a joint property of the biomass and the operational conditions.

A study of the effect of this additional biological constant, i.e., the maintenance energy coefficient, a decay coefficient, on the steady state equations for $\bar{X}$ and $\bar{S}$ in the model employing constant X_R has been made by Gaudy and Srinivasaraghavan (1)(3). The modified model equations employing constant X_R are shown in Table II.

The main advantage of this model over others used for design and operation is that operational parameters for the control of the process are inherent in the design model. It provides for control over selectable variables to aid in operating the system steadily. The parameter X_R in this model is more easily measured or estimated in a short time than are other parameters in other models (e.g., F/M or Θ_c). In practice, it is assumed that solids concentration in the clarifier underflow remains constant. From field experience in treatment plants, it is known that this assumption is not valid, because the compacted sludge concentration in the clarifier depends on the characteristics of the particular sludge and the blanket level. This may vary if the wastage rate is varied. Thus, an increase in the volume of sludge wasted will not ensure a proportional increase in total wastage. The independent control of α without control of X_R is ineffective. An increase or decrease of pumping rate of sludge will not ensure a proportional change in the total amount of cells being recycled to the aeration basin. Thus, when X_R is maintained constant in a sludge consistency tank, there will be three available independent hydraulic parameters for control: α, X_R, and D. These parameters provide the designer with an opportunity to consider the economic and operational aspects without having to sacrifice the efficiency of treatment. The

TABLE II

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

$$\bar{X} = \frac{Y_t\left[S_i - (1+\alpha)\bar{S}\right] + \alpha X_R}{1+\alpha+k_d/D} \tag{5}$$

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

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

$$b = D\left[S_i-(1+\alpha)K_s\right] - \frac{\mu_{max}}{1+\alpha}\left[S_i + \frac{\alpha X_R}{Y_t}\right] + k_d\left[\frac{S_i}{1+\alpha} - K_s\right] \tag{6}$$

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

$$X_W = V\bar{X}\,\mu_n \text{ mg/day} \tag{7}$$

$$= \mu_n\bar{X}/D \text{ mg/l (to convert to mg/day multiply Eq. (8) by F)} \tag{8}$$

$$\mu_n = \frac{X_W}{V\bar{X}} = \frac{1}{\text{sludge age}} = \frac{1}{\Theta_c} \text{ (where } X_W \text{ is given in mg/day)} \tag{9}$$

$$= \frac{X_W \cdot D}{\bar{X}} = \frac{1}{\text{sludge age}} \text{ (where } X_W \text{ is given in mg/l)} \tag{10}$$

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equations tabulated previously concerning this model consider all of the biochemical aspects, μ_{max}, K_s, Y, and k_d, and all of the hydraulic and loading aspects, α, X_R, D, and S_i. This model is an engineering adaptation of continuous culture theory, and it is closer to the theory than are other models.

So far as F/M ratio is concerned, this model can control this ratio by adjusting X_R or α, which brings about an increase or decrease in X which, in turn, controls F/M. Thus, X_R has a direct control on X as opposed to the Θ_c method, which provides an indirect method of arriving at steady state by sludge wastage control. In other words, the Θ_c technique controls the solids in the system by wastage rate which requires measurement of suspended solids concentration. An increase in organics would mean a higher wastage rate to maintain the same Θ_c, and vice versa. This would require rather frequent monitoring of solids concentration in the underflow.

B. Transient State, Prediction, and Behavior

As pointed out by Gaudy and Englebrecht (53), four types of transients are possible in activated sludge systems. These are quantitative shifts in the concentration of nutrients in the influent; qualitative shock loads caused by changes in the chemical composition of the waste; hydraulic loads caused by changes in the inflow rates, and toxic shock produced by the addition of substances inhibitory to biological growth. Quantitative transients have the greatest potential for producing oxygen stress, which could result in new metabolic and physical characteristics for the mixed liquor of a system, because the culture is acclimated to the substrate and can react rapidly to increases in the influent nutrient. Completely mixed processes with sludge recycle provide maximum hydraulic protection from all types of shock loading because the aeration basin functions as a surge basin to dampen the effect of changes in the influent.

The early work in continuous cultures was achieved by microbiologists who were interested primarily in growth in steady state systems. The classical kinetic model used to describe these systems was developed by Monod (54) and by Novick and Szilard (55). The model is based upon two postulates:

1) the cell yield factor is constant, and

2) the relation between specific growth rate for a culture and concentration of growth-limiting nutrient can be defined by a single continuous function.

Considerable controversy has been generated over these postulates. Herbert, et al. (56) reported a varying yield factor when the dilution rate was increased. Rickard and Gaudy (57) observed decreasing cell yield with increasing liquid turbulence. Hetling and Washington (58) demonstrated that cell yield varied with substrate, organism, and detention time. Gaudy and Gaudy (59) in reviewing the literature, reported cell yield was not constant, but for engineering purposes a usable range of values was suitable.

In the activated sludge process, hydraulic detention time and sludge recycle are used to control growth. The yield factor observed in a particular installation might, therefore, be expected to be a function of these two process variables. The Monod relationship (see Equation 1) is an empirical equation which best described, for Monod, the growth rate observed in batch systems. Modifications to the relationship have been proposed by Teissier (60), Schulze (61), and Contois (62). However, the Monod equation has remained dominant in the field because it is relatively simple and because a great deal of experimental data can be fitted to this relationship. Also, there are no points of discontinuity in a plot of μ vs. limiting nutrient concentration. This latter feature is especially appealing from the standpoint of mathematical model development.

Various techniques used for prediction of transient response of continuous cultures have been based on the functional relationship derived for steady state systems (63)(64), and the Monod equation for specific growth rate substrate concentration dependence (65)(66) has been used in their development.

Predictions of the continuous fermentation performance from batch data based on the assumption that the continuous system is physiologically identical in growth rates and metabolic activities with the organisms of the corresponding batch fermentation at the same population have been made (67). However, it has proven very difficult to predict performance of continuous flow systems solely from batch data.

Mateles and Goldthwaite (67) investigated a product-limited continuous culture of *Saccharomyces carlsbergensis* and *Pseudomonas ovalis*. There were no oscillations in S and X resulting from changes in glucose concentrations. "Overshoot" phenomena on approach to near steady state conditions did occur upon changes from one steady state dilution rate to another. This finding agrees with the transient prediction model of Luedeking and Piret (64). An experiment in which step changes in ammonium sulfate concentration and dilution rate were imposed gave non-oscialIatory transient responses for the yeast *S. cerevisiae* growing on dilute, chemically defined media in continuous culture with either glucose or ammonium sulfate as the growth-limiting ingredient (68).

Another technique combining continuous culture with continuous indirect measurement of the cell mass concentration has permitted accurate estimation of unsteady state growth rates (69). A steady state was maintained for 15 hours, then an increase in dilution rate was made. Nitrogen was used as the limiting nutrient. The results indicated that protein and RNA biosynthetic activities in the cell increased immediately when the feed rate of the limiting nutrient was increased. However, the increase in growth was not great enough to match that predicted by the Monod equation. The authors indicate that, contrary to the views of Herbert, et al. (56), a significant lag in adjustment of growth rate to dilution rate does exist, and that this lag should be taken into account in experimenting with single or multi-stage continuous culture systems.

Eckhoff and Jenkins (70) proposed a mathematical model for continuous flow systems subjected to transient loading. They proposed an equation for calculating the effluent COD due to transient loading. In their formulation they assumed that solids concentration remains constant. Having observed that the experimental data did not fit their theoretical equation, they modified their equation by introducing a coefficient for adsorption. Including a coefficient of adsorption did not bring the calculated values closer to the experimental data.

A formal discussion by Gaudy (71) of the Eckhoff model (70) accurately points out many of the inconsistencies and misconceptions regarding the Monod equation as a transient model.

Storer and Gaudy (72) found that accurate prediction of transient behavior by use of the Monod equation and constant yield factor is not possible. Characteristic behavior of the system during step increases could best be found by observation of a variety of systems and interpretation of the data to delineate and quantitatively describe the general properties. Examination of the biochemical structure was needed to describe the kinetic properties of the transient state. It was determined experimentally that during a quantitative increase in influent substrate, the "growth rate hysteresis" phenomenon previously described by Piret was observed to occur. This made it theoretically impossible to use the Monod relationship, since instantaneous changes in growth rate to changes in substrate would be required. It was further indicated that the cell yield may not be constant during the transient phase.

Ierusalimskii, et al. (73) ascribed the delay in change of specific growth rate (μ) due to change in the substrate concentration to the time needed for synthesis of ribosomes. They also felt that oscillatory effects were possible, but emphasized that they do not always appear. They developed a mathematical model to describe the oscillatory state employing some specific biochemical and physiological parameters; however, there was no experimental verification of this model.

Mor and Fiechter (74) used continuous cultures of *S. cerevisiae* to study the effect of changes in dilution rate on the behavior of cells.

Adams and Eckenfelder (75) fed an internal recycle activated sludge system industrial and/or domestic wastes, and they recorded transient substrate and oxygen uptake responses to quantitative shock loadings. In evaluating the substrate response to the shock load, biochemical parameters peculiar to Eckenfelder's design equation obtained in steady operational conditions were applied to the steady state. Oxygen uptake rates were shown to increase immediately after increasing the substrate loading. They investigated the effect of step increases in dilution rate for various magnitudes of increase in D, starting from various initial dilution rates. When the dilution rate was rather low, e.g., 0.011 hr^{-1}, a step change to D = 0.102 hr^{-1} caused a damped oscillation in X as the new steady state was approached. The biological solids concentration overshot the new steady state concentration, then reversed, and eventually levelled out as the new steady state was approached. On the other hand, when the dilution rate was changed from 0.066 hr^{-1} to 0.127 hr^{-1}, there were no oscillations in X and the new steady state was approached in a smooth transition curve.

Schaezler, et al. (76) used mixed cultures in a chemostat and an internal recycle system in an investigation of growth rate interactions and transient response. They hypothesized that the specific growth rate coefficient was independent of reactor substrate concentration for values greater than 5 mg/l, and that the controlling factor was the substrate flux rather than the substrate concentration as predicted by Monod-type equations. They found that slower growing cultures responded more rapidly to increases in influent substrate concentration, S, and dilution rate, D, than did faster growing cultures.

Thabaraj and Gaudy (77) showed that there could be immediate successful response to 100 percent increase in substrate concentration, but it could be followed by severe disruption due to predominance changes. In a more severe shock, there was an immediate leakage of substrate which was attributed to release of metabolic intermediate products by the existing population. In this case it was reasoned that these metabolic intermediates could have shifted the population and caused a secondary response.

Grady (78) performed a modeling study of activated sludge shock load response using an analog computer. It was concluded that the biochemical response to quantitative shock load is primarily a function of the change in the mass rate of substrate input to the reactor and is relatively independent of the manner in which it is applied. It was further concluded that at a given hydraulic retention time, the biochemical response to a shock load is strongly dependent upon the steady state specific growth rate constant prior to the shock, and the lower the growth rate constant prior to the shock, and the lower the growth rate, the better the response. It is significant to note that in the recent report on thermal shock loading by George and Gaudy (79) in which the step increase in temperature was applied at the same rate independently of dilution rate, D, or specific growth rate, μ, systems growing at slower values of μ responsed more favorably, i.e., showed less leakage of carbon source during the transient state. Also, studies on quantitative shock loading by Krishnan and Gaudy (80) for both once-through and cell recycle systems using different values of hydraulic retention time ($\bar{t}$) led to the conclusion that the higher the $\bar{t}$, the less leakage of substrate as the shock loading was increased. They indicated that the cell recycle had some beneficial effect with regard to transient substrate leakage and will smooth out the fluctuations in the effluent substrate curve during the transient state.

Sterkin, et al. (81) studied transitional stages occurring in continuous cultures of *Escherichia coli* and *Pseudomonas fluorescens* with rapid changes of temperature, dilution rate, growth-limiting substrate, and also with a delta-type of pulse in growth-limiting substrate. The delta-type shock was recurring pulses of equal amounts of glucose. It was concluded that transitional states are affected by the age of the population and conditions of cultivation at the moment of sudden change.

The steady state model suggested by Ramanathan and Gaudy for operation of heterogeneous biomass systems with cell feedback has proven to be useful in steadying the inherent or internal dynamics of the system which result simply because of the heterogeneity of the population regardless of the steadiness or unsteadiness of the external environment (51)(52).

From their studies on shock loading, Gaudy and his co-workers have generally concluded that under conditions of severe change in external environment (i.e., shock loading conditions), some guidelines are emerging with respect to the ability of continuous culture systems to accommodate to change (82). The results of the once-through chemostat studies (79)(83) gave tentative guidelines which were conservative for systems with cell feedback. Systems operating at dilution rates commonly employed in field processes for wastewater treatment can be expected to accommodate without serious disruption a change in D or in S_i of 100 percent. In general, the growth history prior to the shock may play a significant role in determining the nature of the response. The system growing at the slower growth rate prior to the shock responds more successfully (79). It also seems reasonable that the more biomass in the reactor, the less will be the leakage of substrate during the shock. Cell recycle systems should thus be particularly advantageous, since they both lower the specific growth rate and increase $\bar{X}$ compared to once-through systems.

For recycle models with constant recycled sludge, the following expression is applicable.

$$\mu_n = \mu - k_d = D\left(1+\alpha-\alpha\frac{X_R}{X}\right) \tag{11}$$

Thus, it can be seen that in addition to the hydraulic control imparted by D and α, the recycle solids concentration, X_R, plays a significant role in determining μ_n as well as providing a high concentration of biomass to resist change. Also, S_i can affect μ_n since it affects $\bar{X}$. Also, the cell or biomass age, Θ_c, may have a separate effect on response. For example, less deleterious blockage of one substrate by introduction of another for populations of greater cell or biomass age have been reported (84). Since $\mu_n = \frac{1}{\Theta_c}$, the role of the net specific growth rate in determining the response to change may be of considerable significance. Also, from an ecological point of view, slower growth rate enhances the opportunity for greater diversity and co-existence of bacteria and higher forms of microorganisms and, thus, stability in the ecosystem. Thus, there are possible relations between some of the controllable variables which may enhance ultimate control over the dynamics of biological response to change.

CHAPTER III

SHOCK LOADINGS - GENERAL THEORETICAL CONSIDERATIONS

Activated sludge systems have been designed primarily on data collected from mixed liquor acclimated to a certain waste and to various conditions of operation, i.e., substrate, temperature, pH, and flow rate (detention time). However, sometimes for combined treatment purposes, multi-wastes may have to be treated, resulting in various shock conditions in regard to composition and flow. One of the major types of shock load that could occur is an increase in BOD loading. However, there are several different types of waste stream changes which can be classified as shock loads. Generally, any sudden change in the physical or chemical environment in a biological system can be classified as a system shock or shock load. The major types of shock loads which may impair plant efficiency are as follows:

A. Quantitative Shock Loads

This type involves generally an increase (or sometimes decrease) in the concentration of the biologically degradable organic matter or BOD in the effluent. This type of shock load occurs in all treatment plants, whether or not they treat one or multiple types of wastes.

B. Qualitative Shock Loads

This type of shock loading involves a change in the chemical structure of the carbon source. This concept of a shock load was originally described by Gaudy (42). He theorized that a successful response to such a shock load depended upon changes in predominance, shifts to different metabolic pathways, and the induction of necessary enzymes.

C. Hydraulic Shock Loads

This involves a change in the rate of flow of the influent waste stream, which causes a change in detention time in the aerator. This type of shock load may or may not be accompanied by a concurrent change of organic matter in the influent. Thus, a hydraulic shock load may frequently be accompanied by a quantitative shock load and the system response may be adversely affected. The occurrence of a hydraulic shock load is incidental to variations in waste flow caused by hourly variations of water usage, both domestic and industrial, and is of considerable importance where combined sewers are in use.

D. pH Shock Loads

This is a change in pH of the incoming waste due, for example, to a change in industrial processes. The change in pH is very important biochemically, as all enzymatic reactions are pH-dependent.

E. Temperature Shock Loads

This type of shock load occurs by sudden change in temperature of the influent waste stream or reactor. Cooling or heating processes in industries may result in changes in waste streams which will affect enzymatic activities in the reactor.

F. Toxic Shock Loads

This type of shock involves an influx of wastes which contain certain toxic components, e.g., heavy metals, which disrupt the established metabolic reactions in the activated sludge.

Generally, response to any type of shock load may depend upon the type and severity of the change in the environment and the immediate past growth history of the system. Physical properties of the activated sludge may also change in response to shock. Therefore, successful response may depend on several factors, summarized as follows:

1) severity of the shock load
2) dilution rate prior to the shock
3) biochemical and physical characteristics of the sludge
4) solids concentration in the returned sludge
5) degree of heterogeneity in the microbial populations, and
6) amount of oxygen in the reactor.

In general, activated sludge may be defined as a continuous culture of mixed populations. They operate in a dynamic steady state, converting the reactants (organic matter) into products (cells and metabolic products), but never at an equilibrium with regard to number of each species present. Several control mechanisms are set in motion during the shock load, so that the population adjusts to the environment. Analysis of the effects of shock loads on sludge and substrate removal efficiency as well as a discussion of the mechanistic aspects may lead to analysis of the observed responses. The response of a mixed population may be classified as either intracellular or intercellular. The first deals with changes in the types, activity, and concentration of enzymes, the rate of chemical reactions, and the different biochemical components in the cell, whereas the latter deals with the different species present in the biological population making up the activated sludge. The intracellular response involves biochemical acclimation of all or a portion of the population, whereas the intercellular response involves adaptation of the population resulting in a natural selection of the organisms best suited for the new environment.

Intracellular response may be the result of two separate responses, i.e., a response controlled by enzyme synthesis or repression of synthesis; a response due to an effect on the activity level of synthesis, and a response due to an effect on the activity level of the enzymes existing in the system. Both responses will lead to changes in the efficiency of the microorganisms. Bacterial mass will change according to changes in the amount of intracellular constituents, i.e., protein, carbohydrates, lipids, RNA, and DNA. One can affect growth rate of microorganisms in a completely mixed reactor by hydraulic dilution rate, and a number of other parameters, e.g., α, X_R. To translate these external controls into biochemical action, a period of adjustment is needed before reaching a new steady state. This period is called a "transient" period, and it is an aim of this thesis to investigate the ramifications of the transient state to effluent quality when a system operating under the model of "constant X_R" is subjected to various changes in inflowing waste. In studying the response to shock, it is also necessary to characterize the steady state before and after shock. The steady state data are valuable in continuing assessment of the kinetic behavioral patterns of the model.

CHAPTER IV

MATERIALS AND METHODS

A. Experimental Apparatus

The experimental apparatus (pilot reactor) used in these studies is shown in Figure 2. The aeration vessel (aeration tank #1) was made of Pyrex glass; the volume of reaction fluid was two liters. The capacity of the settling vessel was five liters. A sludge consistency tank (aeration tank #2) with a capacity of two liters was used in the recycle line. The air supply was adjusted to provide adequate mixing of the reactor contents and maintenance of a dissolved oxygen concentration level of 90 percent of the saturation value. Cells were first grown in batch operation, using primary effluent from the municipal waste treatment plant at Stillwater, Oklahoma, as initial inoculum. After growing sufficient cells, continuous flow operation was begun. The composition of the feeds employed in this study is shown in Tables III, IV, and V. The synthetic waste was pumped to aeration tank #1 by a dual positive displacement pump. The pump and motor unit employed for pumping the waste was manufactured by the Milton Roy Company (Model MM1-B-96R). The detention time was controlled by varying the rate of inflow of the synthetic waste, at a pre-determined rate, to give the desired mean hydraulic retention time, $\bar{t}$ ($\bar{t} = \frac{V}{F}$). Alternately, each of the feed lines was cleaned by pumping a one percent solution of Clorox in distilled water. Thus, one of the lines was being disinfected

Figure 2. Activated Sludge Pilot Plant for Operation With Constant X_R

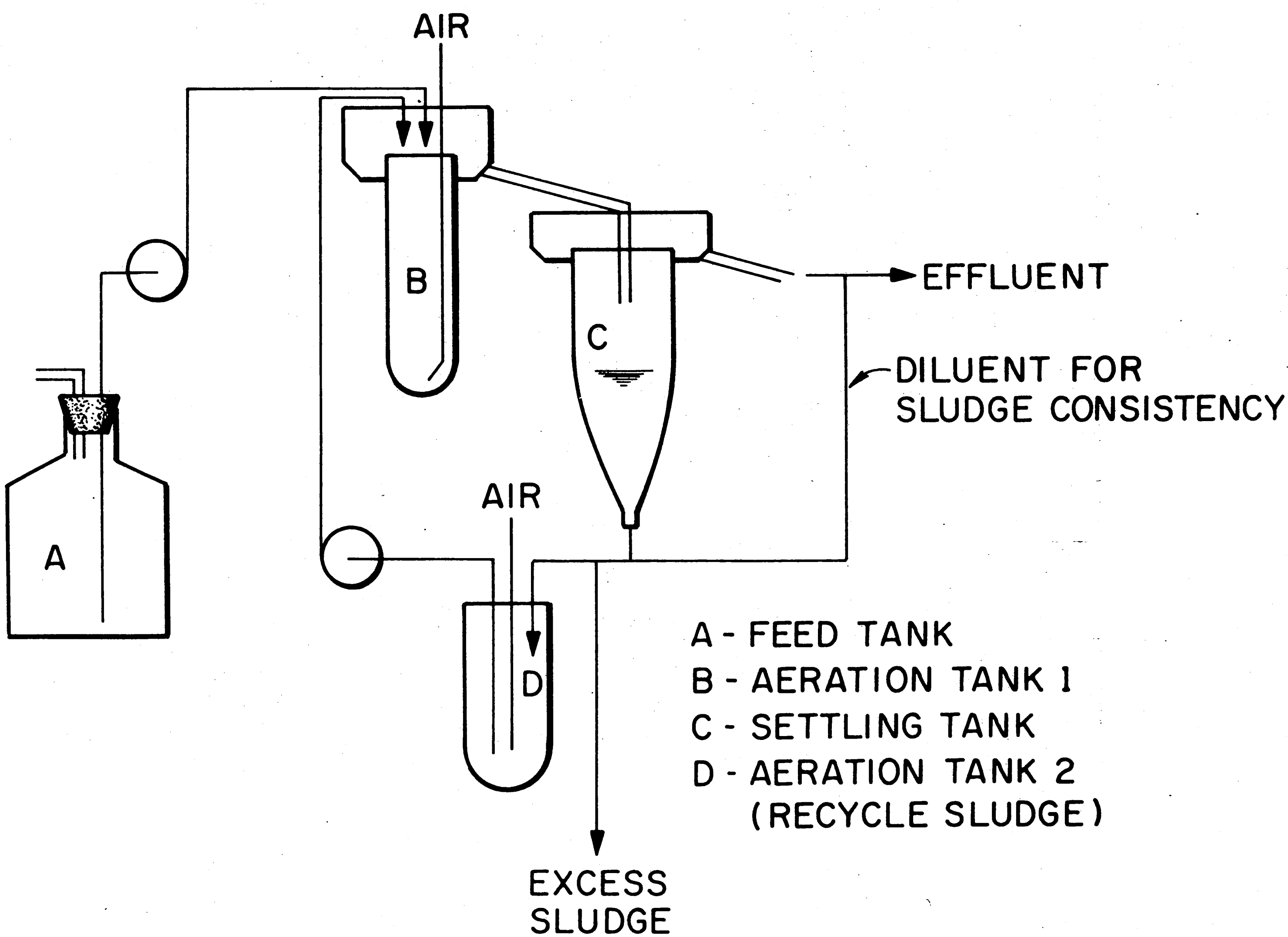

AIR
B
EFFLUENT
C
DILUENT FOR
SLUDGE CONSISTENCY
A
AIR
D
A - FEED TANK
B - AERATION TANK 1
C - SETTLING TANK
D - AERATION TANK 2
(RECYCLE SLUDGE)
EXCESS
SLUDGE

TABLE III

COMPOSITION OF GROWTH MEDIUM PER 500 mg/l GLUCOSE

Constituents	Amount
Glucose	500 mg/l
Ammonium sulfate $(NH_4)_2SO_4$	250 mg/l
Magnesium sulfate, $MgSO_4 \cdot 7H_2O$	50 mg/l
Ferric chloride, $FeCl_3 \cdot 6H_2O$	0.25 mg/l
Manganous sulfate, $MnSO_4 \cdot H_2O$	5.0 mg/l
Calcium chloride, $CaCl_2$	3.75 mg/l
1M phosphate buffer solution, pH 7.0	5 ml/l
Tap water	50 ml/l

TABLE IV

COMPOSITION OF GROWTH MEDIUM PER 1500 mg/l GLUCOSE

Constituents	Amount
Glucose	1500 mg/l
Ammonium sulfate $(NH_4)_2SO_4$	750 mg/l
Magnesium sulfate, $MgSO_4 \cdot 7H_2O$	150 mg/l
Ferric chloride, $FeCl_3 \cdot 6H_2O$	0.75 mg/l
Manganous sulfate, $MnSO_4 \cdot H_2O$	15.0 mg/l
Calcium chloride, $CaCl_2$	11.25 mg/l
1M phosphate buffer solution, pH 7.0	15.00 ml/l
Tap water	150 ml/l

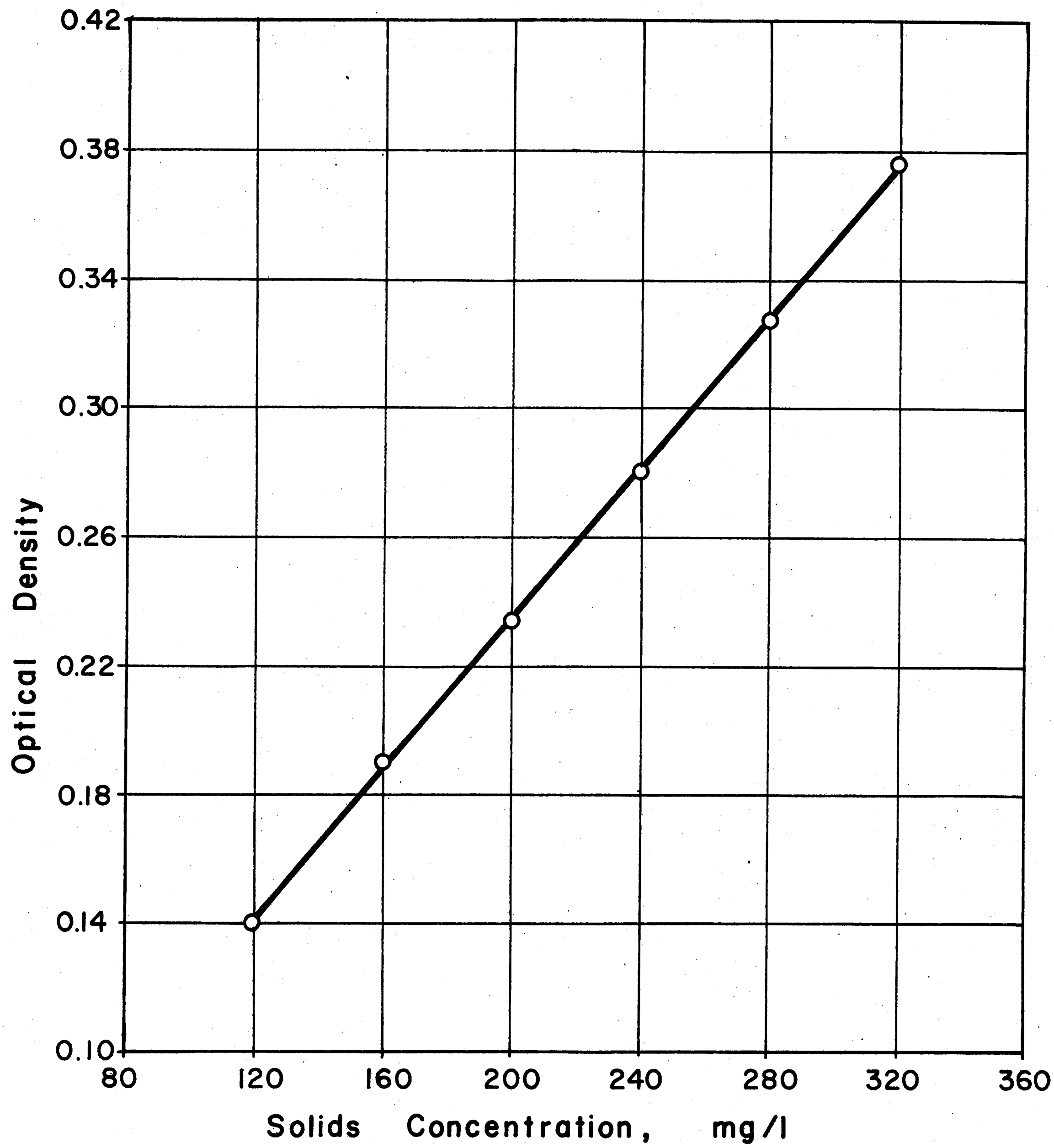
TABLE V

COMPOSITION OF GROWTH MEDIUM PER 3000 mg/l GLUCOSE

Constituents	Amount
Glucose	3000 mg/l
Ammonium sulfate $(NH_4)_2SO_4$	1500 mg/l
Magnesium sulfate, $MgSO_4 \cdot 7H_2O$	300 mg/l
Ferric chloride, $FeCl_3 \cdot 6H_2O$	1.50 mg/l
Manganous sulfate, $MnSO_4 \cdot H_2O$	30.0 mg/l
Calcium chloride, $CaCl_2$	22.50 mg/l
1M phosphate buffer solution, pH 7.0	30.0 ml/l
Tap water	300 ml/l

while the other was being used. This procedure adequately prevented growth in the feed line. The system was checked for complete mixing, using procedures described by Komolrit and Gaudy (85). The mixed liquor from the reactor overflowed into the settling tank. The settled sludge in the settling tank was withdrawn from the bottom at either 12- or 24-hour intervals. A concentrated sample of sludge was diluted to a range in which optical density was directly proportional to solids concentration in mg/l, and the OD values were compared to the previously prepared standard curve. The standard curve was obtained by preparing samples of various solids concentrations and measuring the optical density on the spectrophotometer. These samples were analyzed for solids concentration by the membrane filter technique (86). The suspended solids in mg/l were plotted against the optical density. A typical plot of this type is shown in Figure 3. The spectrophotometer reading is linear and most reliable between 120 mg/l and 320 mg/l suspended solids concentration. This curve was checked several times for its reliability at different intervals by repeating the same procedure mentioned above. Using the optical density reading of the diluted sample, the suspended solids concentration of the thickened sludge was calculated. According to the desired X_R concentration, the thickened sludge was then diluted. The required volume of the returned sludge was poured into the sludge consistency tank (aeration tank #2), from where it was pumped at the desired flow rate. The pump used for returning sludge from the consistency tank to aeration tank #1 was a Sigmamotor "finger" pump, Model T-8. Aeration was used in the consistency tank to keep the sludge mixed and aerobic. The excess volume of the diluted sludge used in preparing X_R represents the major portion of excess

Figure 3. Relation Between Optical Density and Solids Concentration



0.42
0.38
0.34
0.30
0.26
0.22
0.18
0.14
0.10
Optical Density
80
120
160
200
240
280
320
360
Solids Concentration, mg/l

sludge, X_W, produced due to the substrate utilization. In calculating X_W, the solids in the effluent, X_e, as well as those removed for various samples were included in the total amount of X_W.

B. Batch Experiment Studies

During each steady state continuous run, 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 (50)(87)(88). 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. Initial inoculum concentration was the same in all flasks with an initial optical density of approximately 0.036 (percent transmission = 92 percent). The total volume of reaction fluid per flask in these experiments was 40 ml. These flasks were placed on an oscillating shaker (Eberbach), which was adjusted to 100-110 oscillations/min. The growth curve was obtained by measuring OD at frequent intervals. The initial and final suspended solids and substrate concentration were measured (86), which allowed determination of the batch cell yield, Y_B. The μ_{max} and K_s were calculated by plotting the data obtained from batch growth experiments.

C. Development of the System in Steady State Prior to Administering the Shock Loads

Each experiment was initiated by seeding the synthetic waste with sewage from the primary clarifier of the sewage treatment plant, Stillwater, Oklahoma. The sewage was aerated under batch conditions for a period long enough to build up sufficient microbial growth concentration to supply the consistency tank with recycle sludge, X_R. The system was then fed with synthetic waste by continuous pumping from a feed reservoir along with recycled sludge from aeration tank #2 until a steady state was ensured. Steady state conditions were checked by periodic measurement of the mixed liquor solids concentration, substrate concentration in the effluent, and the excess sludge produced per day.

D. Shock Loading Procedures

After the system had remained in a steady state condition for 7 to 10 days, shock load procedures were initiated.

1. Quantitative Shock Loads

In this study, shock loading was administered by changing the glucose concentration in the feed to a value greater than that employed at the previous steady state condition. This type of shock loading was administered without changing the flow rate.

2. Hydraulic Shock Loads

In the hydraulic shock loading, the conditions studied were termed as shock loads with "constant organic concentration." In this type of experiment, the glucose concentration in the feed was maintained constant (500 mg/l) at all times, and the flow rate (detention period) was varied by increasing the dilution rate from that which would yield an 8-hour detention time, $\frac{V}{F}$. The concentration of returned sludge was changed for each run along with dilution rate in order to establish different net growth rates. It can be seen that under conditions of constant concentration of carbon source in the inflow, the daily organic loading increased in proportion to the increase of flow rate. The steady state flow rate maintained before applying any shock load was one which provided an 8-hour detention time in the aerator, i.e., the 8-hour detention time was used as a base value for flow rate. Any other base flow could have been chosen, but the 8-hour detention time is one commonly employed in the field.

3. Pulsing Shock Loads

These experiments involved subjecting the system to various pulsing hydraulic shock loads and quantitative shock loads. The main point of interest was in determining if the system approached a new steady state between the cyclic changes in inflow rate and/or substrate concentration. Determination of conditions which provided steadiness in substrate concentration in the effluent was the main aim of this study. Four runs were conducted.

a. Cyclic Hydraulic Shock Load With Constant α. The system was run at steady state for almost 12 days, after which a cyclic hydraulic loading was maintained over the 24 hours of each day. The detention period was changed three times daily. Starting from 12 midnight to 12 noon, $\bar{t}$ was eight hours; it was then changed to four hours until 6 P.M., at which time it was changed to 16 hours. It was held at 16 hours until midnight, at which time the cycle was repeated. The feed concentration was maintained constant at 500 mg/l. Cyclic loading continued for 17 days.

b. Cyclic Hydraulic Shock Load With Varying α. Previous to pulsing the load, a steady state was maintained for eight days. The load was then pulsed hydraulically as before, except that α was changed. The aim of this run was to study the effect of the ratio α (the ratio between the sludge recycle and the inflow rates) on the behavior of the model while loading was changing over the 24 hours of each day. The feed was maintained at 500 mg/l.

c. Cyclic Quantitative Shock Load With Constant α. The system operated in a steady state for 12 days with an 8-hour $\bar{t}$ and α equal to 0.25. S_i during this time was 500 mg/l. A triple increase in substrate was then made for 12 hours, beginning at 12 noon. At midnight the concentration of S_i was returned to 500 mg/l, and at noon a new cycle was begun. This cyclic quantitative shock was repeated for 17 days. Finally, the system was again operated under steady conditions at 500 mg/l glucose.

d. Cyclic Quantitative-Hydraulic Shock Loading With Constant α. Starting with a steady state as before (S_i = 500 mg/l; $\bar{t}$ = 8 hrs), a combined hydraulic and quantitative shock load was imposed at noon; S_i was increased to 1500 mg/l, and $\bar{t}$ was decreased to four hours. This triple increase in substrate concentration along with the doubling in hydraulic flow rate resulted in a six-fold increase in mass loading rate. At midnight the S_i and $\bar{t}$ were returned to 500 mg/l and 8 hours, respectively. At noon another cycle was begun. The system was operated in this cyclic manner for 16 days and then returned to the initial steady state condition.

In order to accomplish these types of shock it was desirable to employ a number of pumps which had been pre-adjusted and calibrated to the desired flow ratio rather than attempting to change the flow rate of a single pump. Thus for the cyclic hydraulic shock, three pumps were employed and an additional one was held in standby.

E. Analytical Procedures

From the foregoing text it can be seen that, in general, shock loading experiments were accomplished in three stages:

1) Steady state was examined for 7-12 days at $\bar{t}$ = 8 hours.

2) Transient state in response to shock load (either quantitative, hydraulic, or cyclic) was examined. In cases of step changes, the system was examined in the new steady state.

3) Transient state during return to the initial condition was examined.

4) The final steady state was compared to the initial steady state.

During all stages, samples were collected to determine the behavior of the system.

During the transient state, solids concentration in reactor #1 as well as effluent characteristics were determined at short time intervals in order to facilitate graphical representations of response in the transient state. The following analyses were run:

1) Feed:
   - a) COD (daily)
   - b) NH_3-N (periodically)

2) Effluent:
   - a) filtrate
      - 1) COD (daily)

2) NH_3-N (periodically)

3) NO_3-N (periodically)

4) anthrone (periodically)

b) supernatant

1) COD (daily)

2) suspended solids (daily)

3) BOD (periodically)

4) total organic carbon (in only one experiment)

3) Aeration tank mixed liquor:

a) biological solids (daily)

b) dissolved oxygen (daily)

c) pH (daily)

4) Sludge consistency tank:

a) suspended solids (twice daily)

b) filtrate COD (daily)

c) protein (periodically)

d) carbohydrate (periodically)

e) endogenous oxygen uptake (only twice)

A summary of the analytical methods follows:

1. Chemical Oxygen Demand

The COD test was performed to measure the total organic concentration in various samples. The procedure adopted was as described in Standard Methods (86). Silver sulfate and mercuric sulfate were used for all COD determinations.

2. Suspended Solids Concentration

This test was performed to measure the cell concentration in various samples. The pore size of the filters was 0.45 μm (Millipore Filter Corp., Bedford, Mass.). Samples with high cell concentration were first centrifuged and then filtered for more rapid determinations. The general procedure was as given in Standard Methods (86).

3. Nitrogen

Ammonia nitrogen, NH_3-N concentration in the influent and effluent was determined by a method developed by Niss and described by Ecker and Lockhart (89). Nitrate-nitrogen determinations were in accordance with Standard Methods (86).

4. Biochemical Oxygen Demand

The azide modification of the Winkler Method (86) was employed for periodic determination of BOD of the effluent supernatant from the pilot plant.

5. Protein and Carbohydrate

Periodic analyses of sludge for protein and carbohydrate content were performed, as outlined by Gaudy (90).

6. Anthrone Test for Carbohydrate

Spot checks for carbohydrate concentration in the effluent filtrate were made using anthone reagent, adopting the procedures described by Ramanathan, Gaudy, and Cook (91).

7. Oxygen Uptake

The oxygen uptake rate of the sludge from the recycle tank was measured during continuous runs using the Warburg apparatus by employing the method outlined in "Manometric Techniques," by Umbreit, et al. (92).

8. Total Organic Carbon

At times during steady state operation, samples from the effluent were taken for analysis of total organic carbon (TOC). After the COD sample was taken from the filtrate, the remaining filtrate was placed in a small sampling bottle, capped, and kept in a freezer for later TOC analysis. The TOC sample bottles were covered and sent to the Oklahoma State University Zoology Department for analysis using a Model 915 Beckman total organic carbon analyzer.

In addition to the above mentioned analyses, regular microscopic examinations of mixed liquor from the reactor and aeration tank #2 were performed to follow changes in predominance and morphological form of microbes. The pH was measured by a Beckman Expandomatic SS-2 pH meter. Dissolved oxygen of the mixed liquor in aerator #1 was measured periodically using a DO meter (Weston and Stack Model No. 300). Temperature was measured throughout the study; it averaged $23 \pm 0.5^{o}C$. The pH was monitored two to three times daily in aerator #1. The synthetic waste was designed to hold the pH near 7.0. The daily determination indicated it ranged from 6.9 to 7.3.

CHAPTER V

RESULTS

The experimental data will be presented in three major sections dealing with (1) hydraulic, (2) quantitative, and (3) cyclic shock loads. In general, the results of each experiment are presented in one figure, except those for the cyclic shock load, in which case each run is presented in two separate figures. In general, each figure gives such parameters as the influent characteristics, effluent characteristics, biological solids, cell protein, cell carbohydrate, recycled sludge, filtrate COD in aerator #1, filtrate COD in aerator #2, and excess sludge production. For all figures, the data to the left of the indicating arrow show steady state conditions prior to the initiation of a shock. The vertical line to which the arrowhead points indicates time at which shock loading was initiated, and the data to the right of that line show the post-shock conditions. The termination of the transient state is indicated by another arrow, after which a new steady state is established. In all cases, the system was operated in the new steady state for several days. The steady state was terminated by the initiation of another shock, and this is indicated by an arrow. In all cases, the experimental run was ended by operation under steady state conditions.

The units along the abscissa are in days. At times, an expanded scale is employed in order to provide enough space for plotting the data which were taken at short intervals during the transient state. In Table VI are summarized all parameters measured during all steady state periods for all experiments. These average steady state results are listed chronologically and are referred to each figure.

A. Hydraulic Shock Loads With Constant Influent Organic Concentration

In this series of experiments, the responses to stepwise increases in dilution rate when the feed consisted of constant influent organic concentration were studied.

1. Response to an Increase in Dilution Rate of 300 Percent With X_R = 10,000 mg/l

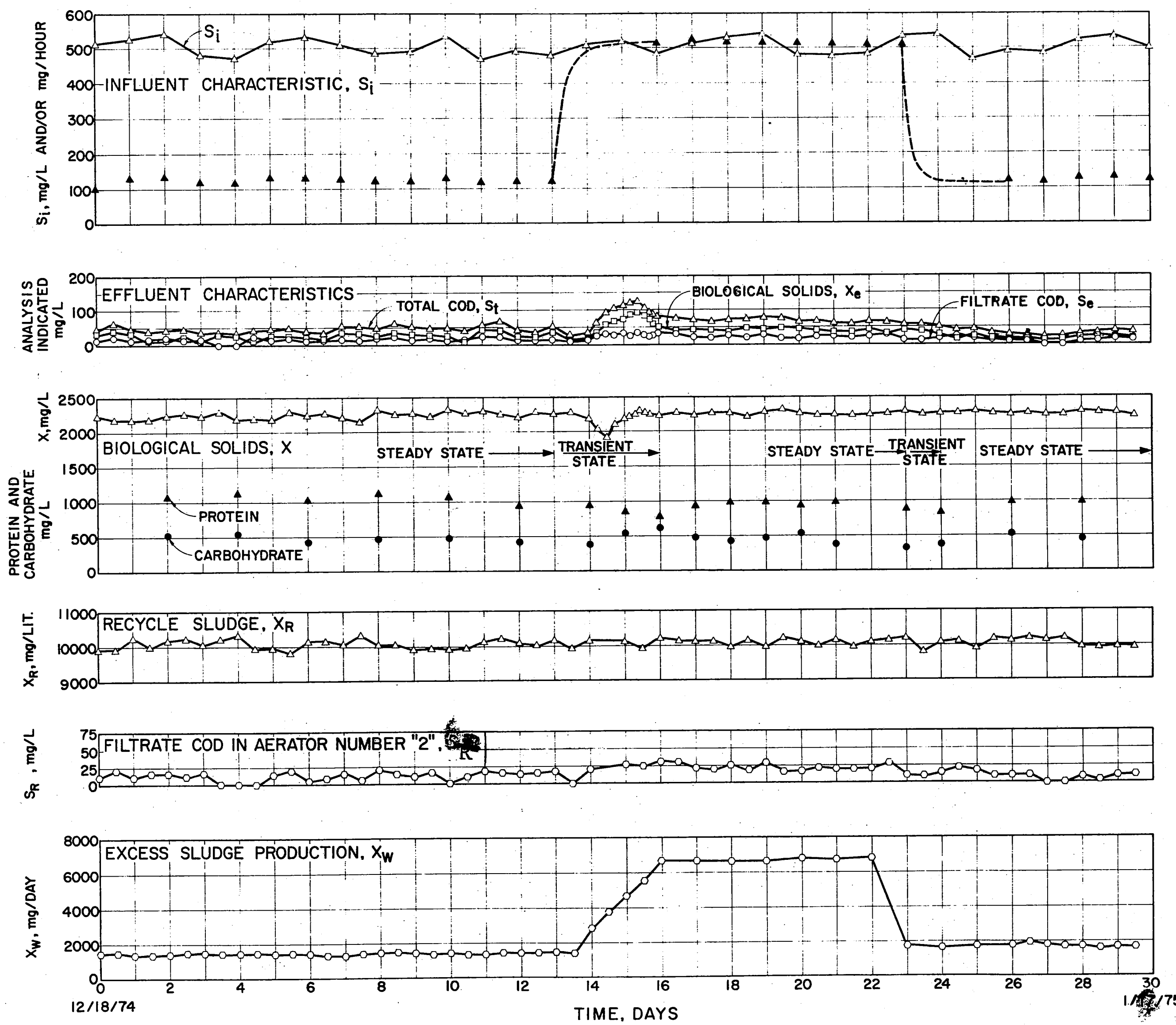
It was decided to test the model under severe hydraulic shock load conditions by increasing the dilution rate 300 percent while the recycle sludge concentration was kept as close as possible to 10,000 mg/l. The organic feed concentration was kept constant while changing the inflow feed rate. In Figure 4 the different parameters monitored during the experiment are shown. The feed concentration, S_i, was kept very close to 500 mg/l. The solid triangles represent loading rate in mg/hr before and after the shock. The transitional change in loading is shown by a dilute-in curve, while the reverse change is shown by a dilute-out curve. The average steady state conditions for the first steady period shown in Figure 4 are given in line 21 of Table VI. For this 10-day period with nominal S_i = 530 mg/l glucose COD and X_R = 10,000 mg/l, the average biological solids concentration was 2200 mg/l, and it is seen in Figure 4 that the system was rather steady with respect to X. The

TABLE VI

MEAN STEADY STATE VALUES OF FEED, EFFLUENT, AND BIOLOGICAL SOLIDS FOR THE ACTIVATED SLUDGE PROCESS WITH CONSTANT X_R

							Effluent							Biological Solids					
							Filtrate			Supernatant					Recycle		Sludge		
Line #	From	To	Fig. #	μ_n hr^{-1}	Dilution Rate, D hr^{-1}	Feed Obs. COD mg/l	Carbo. Anthrone mg/l	COD mg/l	Eff. %	COD mg/l	Eff. %	BOD mg/l	X_e mg/l	X mg/l	X_R mg/l	S_R mg/l	Protein %	Carbo. %	X_W mg/day
1	3-21-74	3-31-74	-	0.0145	0.125	517	-	22	96	35	93	-	20	1766	8012	-	-	-	1290
2	4- 7	4-24	-	.0149	0.125	527	-	28	95	36	93	-	15	1788	8088	-	-	-	1302
3	5-10	5-31	10	.0166	0.125	503	12	24	95	33	93	-	27	1776	7935	10	51	21	1416
4	6-10	6-17	10	.0445	0.125	1496	10	19	99	34	98	-	22	2237	7998	13	48	18	4850
5	6-20	6-25	10	.0153	0.125	509	9	15	97	32	94	-	18	1774	7996	11	51	21	1302
6	6-28	7- 5	11	.0148	0.125	545	8	14	98	38	93	10	28	1782	8064	7	48	18	1330
7	7-14	7-20	11	.0742	0.125	3062	14	30	99	46	98	8	28	3095	8047	14	52	24	10272
8	7-21	7-27	11	.0165	0.125	514	9	14	97	33	94	11	19	1777	7946	9	51	2[illegible]	1398
9	8-15	8-31	8	.0066	0.125	500	6	12	98	48	90	7	37	2513	12033	7	48	17	1140
10	9- 5	9-11	8	.0213	0.25	521	17	6	99	30	94	-	21	2554	11899	15	42	26	2697
11	9-12	9-23	8	.0086	0.125	505	11	9	98	37	93	3	24	2553	12060	10	47	18	1137
12	9-24	10- 5	7	.0142	0.125	539	11	22	95	36	93	-	23	1775	8075	12	42	21	1422
13	10-11	10-15	7	.0299	0.25	497	12	15	97	31	94	8	16	1794	8113	12	45	26	2502
14	10-16	10-24	7	.0146	0.125	512	9	13	97	38	93	-	23	1760	7983	11	46	22	1420
15	10-25	11- 3	6	.0240	0.125	506	15	18	96	57	89	11	39	1421	6014	18	46	20	1430
16	11- 9	11-14	6	.0554	0.25	540	15	33	94	72	87	14	38	1450	5969	14	49	22	3558
17	11-15	11-21	6	.0214	0.125	502	20	22	96	57	89	-	35	1399	6037	16	43	21	1495
18	11-22	11-30	9	.0063	0.125	495	11	16	97	39	92	10	23	3115	14963	12	50	18	1120
19	12- 7	12-14	9	.0220	0.25	518	7	20	96	46	91	12	24	3224	14983	10	52	20	3167
20	12-14	12-21	9	.0079	0.125	530	6	10	98	32	94	10	19	3170	15026	8	49	18	1087
21	12-18	12-31	4	.0131	0.125	504	8	15	97	45	91	-	28	2200	10075	12	47	22	1280
22	1- 3-75	1- 9-75	4	.0629	0.5	511	18	25	95	69	87	-	43	2249	10116	22	42	22	6724
23	1-10	1-17	4	.0146	0.125	506	0	13	97	37	93	9	23	2220	10069	7	41	19	1237
24	1-27	2- 7	-	.0138	0.125	527	-	10	98	33	94	10	21	2210	10071	8	53	22	1291
25	3- 1	3-10	-	.0129	0.125	519	-	17	97	33	94	-	14	2205	10121	15	-	-	1205
26	3-11	3-19	-	.0417	0.125	1552	-	13	99	40	97	10	26	2187	8015	10	-	-	4368
27	3-20	3-27	-	.0675	0.125	3084	-	15	99	47	98	12	31	2818	8005	12	-	-	9129
28	3-28	4- 4	18	.0138	0.125	508	-	12	97	42	92	-	27	2210	10075	7	41	24	1222
29	4-20	5- 1	-	.0143	0.125	525	0	10	98	29	94	8	17	2204	10008	9	40	23	1316
30	5-20	5-28	24	.0163	0.125	526	-	9	98	32	94	8	22	2247	10052	9	51	20	1288
31	9-26	10- 7	12	.0171	0.125	527	8	11	98	50	91	16	33	1820	8107	8	48	20	1419
32	10-10	10-17	12	.0729	0.125	3023	28	45	99	87	97	27	39	3018	8047	22	41	26	10630
33	10-21	10-30	12,13	.0163	0.125	518	11	42	92	57	89	21	10	1799	8055	18	47	17	1428
34	11- 2	11- 9	13	.0492	0.125	1522	12	31	98	64	96	23	36	2359	8090	15	49	18	4683
35	11-13	11-18	13	.0154	0.125	526	11	24	95	44	92	17	25	1804	8142	17	49	16	1342
36	11-19	11-24	5	.0096	0.125	535	14	20	96	61	89	16	43	2132	10000	14	51	17	1209
37	11-27	12- 3	5	.0575	0.5	513	13	16	97	70	83	14	63	2240	10172	8	48	19	6221
38	12- 7	12-14	5	.0146	0.125	525	12	20	96	59	89	25	39	2210	10028	14	49	17	1260

Figure 4. Operational Characteristics for an Activated Sludge Process With Constant X_R of 10,000 mg/l at an S_i of 500 mg/l Hydraulically Shock Loaded by Change in Dilution Rate From 0.125 hr^{-1} to 0.50 hr^{-1} and From a Dilution Rate of 0.5 hr^{-1} to 0.125 hr^{-1} (from 12-18-74 to 1-17-75)


INFLUENT CHARACTERISTIC, S_i
S_i
S_i, mg/L AND/OR mg/HOUR
EFFLUENT CHARACTERISTICS
TOTAL COD, S_t
BIOLOGICAL SOLIDS, X_e
FILTRATE COD, S_e
ANALYSIS INDICATED mg/L
BIOLOGICAL SOLIDS, X
X, mg/L
STEADY STATE
TRANSIENT STATE
STEADY STATE
TRANSIENT STATE
STEADY STATE
PROTEIN
CARBOHYDRATE
PROTEIN AND CARBOHYDRATE mg/L
RECYCLE SLUDGE, X_R
X_R, mg/LIT.
FILTRATE COD IN AERATOR NUMBER "2", S_R
S_R, mg/L
EXCESS SLUDGE PRODUCTION, X_W
X_W, mg/DAY
12/18/74
TIME, DAYS
1/17/75

X_R values ranged from 9,847 to 10,312 mg/l, and the average was 10,075 mg/l. The COD values for recycle sludge filtrate, S_R, indicate very little substrate, with an average value of 12 mg/l. Determination of protein and carbohydrate content of the sludge indicated values in the expected range, i.e., protein 47 percent, and carbohydrate 22 percent. The bottom graph in Figure 4 shows the daily production of excess sludge. The values varied between 1210 and 1481, with an average of 1280 mg/day, and it is seen that excess sludge production remained relatively steady. The mean effluent filtrate COD, S_e, was 15 mg/l, yielding a substrate removal efficiency of 97 percent. The suspended solids concentration in the effluent in this steady state run was 28 mg/l. The range of values for filtrate COD, S_e, was zero mg/l to 24 mg/l, while X_e varied between 14 mg/l and 48 mg/l.

After running the system for almost thirteen days, the hydraulic loading was increased by 300 percent; i.e., D was increased from 0.125 hr^{-1} to 0.5 hr^{-1}. The first noticeable effect was a slight washout of reactor solids. A drop in solids concentration of about 17 percent was recorded on the second day of the shock. After the middle of the second day after application of the shock, the biological solids concentration increased to a value of 2264 mg/l. Then it decreased slightly to 2228 mg/l, after which a steady state was maintained. During the transient state there were some changes in effluent characteristics. The total substrate in the effluent, S_t, as measured by COD, reached 125 mg/l. Although a rather high COD value was recorded in the clarifier, total effluent filtrate COD, S_e, did not rise significantly. The maximum S_e during transient was 34 mg/l. The physical properties of the sludge flocs had changed and effluent biological solids concentration, X_e, rose to 91 mg/l. The total COD, S_t, started to decrease during the third day of transient. The excess sludge produced per day increased by approximately 400 percent. A new steady state was established three days after initiating the shock loading. An average value of the biological solids concentration, $\bar{X}$, in the reactor during the six days of new steady state was 2249 mg/l (see line 22 of Table VI). There was a small increase in biological solids concentration from the previous steady state. The total COD, S_t, from the effluent clarifier was, in this new steady state, relatively high. The average value of S_t was 69 mg/l. Most of this COD was due to leakage of cells since the filtrate COD, S_e, was 25 mg/l, i.e., a biochemical efficiency of 95 percent was observed. The average biological solids concentration in the effluent was 43 mg/l and the excess sludge produced per day attained a steady state value of 6724 mg/day. The recycle sludge, X_R, was very close to 10,000 mg/l, having a range from 9,912 to 10,212 mg/l. The dilution rate was returned to its original value of 0.125 hr^{-1}. Another new steady state was rapidly attained without any significant transient response. The average steady state data obtained during the new steady state are given in line 23 of Table VI. The main parameters indicating the performance characteristics are plotted in the right portion of Figure 4 for this period. The COD of the influent ranged from 484 to 541 mg/l, with an average of 506 mg/l. The effluent characteristics as measured by filtrate COD, S_e, were excellent; the mean S_e was 13 mg/l, providing 97 percent removal of the substrate. The S_e value varied from zero to 25 mg/l, while X_e varied between 14 and 41 mg/l. In general, the system provided very satisfactory steady state performance as well as very fast recovery from the shock.

Growth studies were made during all operational periods, and results are summarized in Table VII. The table shows the values for the biological constants, μ_{max}, K_s, and Y_B. Values shown on lines 21 and 23 were obtained from batch growth studies during the beginning and final steady states, when D was 0.125 hr^{-1}, while on line 22 are given the biological parameters, K_s, μ_{max}, and Y_B during a batch growth study when D increased to 0.5 hr^{-1}. The value of μ_{max} varied in the range from 0.49 to 0.54, while Y_B ranged from 0.55 to 0.59. The values of μ_{max} and K_s were determined by plotting $\frac{1}{S_o}$ vs. $\frac{1}{\mu}$, and employing the equation

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

2. Repeat of the Previous Experiment After 10 Months

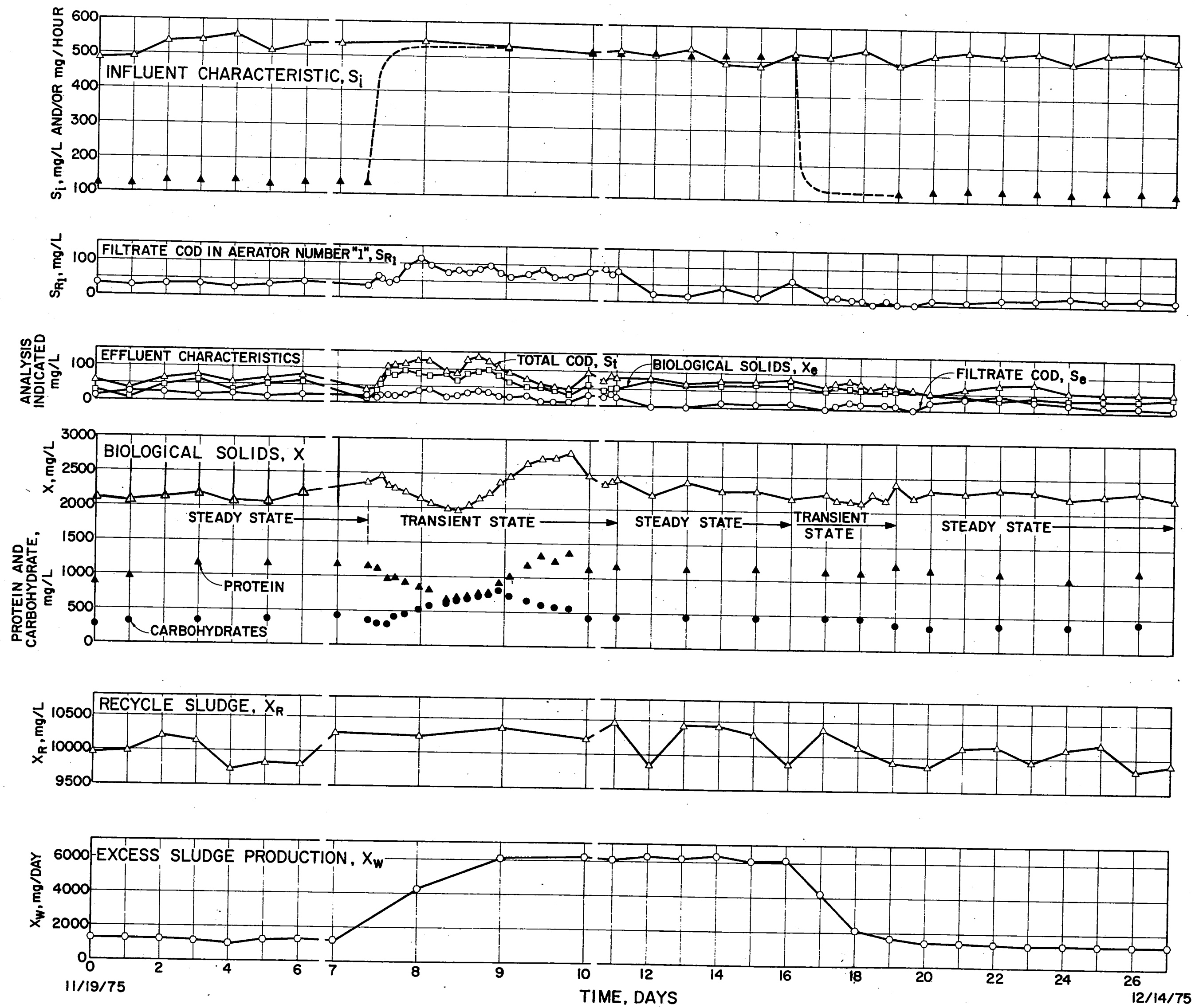
It was interesting to determine the reproducibility of the response to the 300 percent increase in dilution rate after a reasonable period of time had elapsed. New seeding material obtained from the Stillwater sewage treatment plant was used to develop the activated sludge. The experiment was run under the same conditions as the previous run; however, one additional parameter was measured--the filtrate COD in reactor #1. The results are shown in Figure 5 and lines 36 through 38 of Table VI. Prior to shock, the feed concentration ranged from 511 to 553, with an average of 535 mg/l, and the feed loading rate averaged 134 mg/hr. The filtrate COD in aerator #1, S_{R_1}, was fairly low. The observed filtrate COD in the clarifier effluent varied from

TABLE VII

VALUES OF THE BIOLOGICAL CONSTANTS, MAXIMUM SPECIFIC GROWTH RATE, μ_{max}, SATURATION CONSTANT, K_S, AND CELL YIELD, Y, OBTAINED IN BATCH EXPERIMENTS USING CELLS HARVESTED FROM THE COMPLETELY MIXED REACTOR DURING CONTINUOUS FLOW STEADY STATE RUNS

Exp. #	Feed Glucose mg/l	Dilution Rate D hr^{-1}	μ_n hr^{-1}	Maximum Specific Growth Rate μ_{max}, hr^{-1}	Saturation Constant K_s, mg/l	Batch Yield Y_{t_B} mg/mg
1	500	0.125	0.0145	--	--	--
2	500	0.125	.0149	--	--	--
3	500	0.125	.0166	0.50	110	0.46
4	1500	0.125	.0445	0.55	181	0.49
5	500	0.125	.0153	0.45	161	0.43
6	500	0.125	.0148	0.46	123	0.45
7	3000	0.125	.0742	0.58	108	0.56
8	500	0.125	.0165	0.49	115	0.42
9	500	0.125	.0066	0.54	164	0.38
10	500	0.25	.0213	0.47	125	0.45
11	500	0.125	.0086	0.43	140	0.38
12	500	0.125	.0142	0.42	208	0.53
13	500	0.25	.0299	0.47	94	0.58
14	500	0.125	.0146	0.49	110	0.56
15	500	0.125	.0240	0.50	177	0.56
16	500	0.25	.0554	0.51	214	0.60
17	500	0.125	.0214	0.53	204	0.54
18	500	0.125	.0063	0.35	63	0.38
19	500	0.25	.0220	0.34	144	0.60
20	500	0.125	.0079	0.37	185	0.40
21	500	0.125	.0131	0.49	112	0.58
22	500	0.50	.0629	0.53	176	0.59
23	500	0.125	.0146	0.54	145	0.55
24	500	0.125	.0138	0.50	217	0.50
25	500	0.125	.0129	0.45	115	0.42
26	1500	0.125	.0417	0.54	196	0.52
27	3000	0.125	.0675	0.62	131	0.52
28	500	0.125	.0138	0.44	110	0.45
29	500	0.125	.0143	0.46	270	0.49
30	500	0.125	.0163	--	--	--
31	500	0.125	.0171	0.45	141	0.50
32	3000	0.125	.0729	0.61	87	0.59
33	500	0.125	.0163	0.46	129	0.49
34	1500	0.125	.0492	0.52	110	0.55
35	500	0.125	.0154	0.51	140	0.46
36	500	0.125	.0096	0.47	131	0.49
37	500	0.5	.0575	0.51	85	0.53
38	500	0.125	.0146	0.48	141	0.46
Average				0.50	145	.50

Figure 5. Operational Characteristics for an Activated Sludge Process With Constant X_R of 10,000 mg/l at an S_i of 500 mg/l Hydraulically Shock Loaded by an Increase in Dilution Rate From 0.125 hr^{-1} to 0.5 hr^{-1}, and a Decrease in Dilution Rate From 0.5 hr^{-1} to 0.125 hr^{-1} (from 11-19-75 to 12-14-75)



INFLUENT CHARACTERISTIC, S_i
S_i, mg/L AND/OR mg/HOUR
FILTRATE COD IN AERATOR NUMBER "1", S_{R_1}
S_{R_1}, mg/L
EFFLUENT CHARACTERISTICS
TOTAL COD, S_t
BIOLOGICAL SOLIDS, X_e
FILTRATE COD, S_e
ANALYSIS INDICATED mg/L
BIOLOGICAL SOLIDS, X
X, mg/L
STEADY STATE
TRANSIENT STATE
STEADY STATE
TRANSIENT STATE
STEADY STATE
PROTEIN
CARBOHYDRATES
PROTEIN AND CARBOHYDRATE, mg/L
RECYCLE SLUDGE, X_R
X_R, mg/L
EXCESS SLUDGE PRODUCTION, X_w
X_w, mg/DAY
11/19/75
TIME, DAYS
12/14/75

15 to 26 mg/l, with an average $\bar{S}$ of 20 mg/l COD. Thus, the effluent was, on the average, very good; efficiency of substrate removal was 96 percent, and the value of S was relatively steady. Similarly, the biological solids concentration, $\bar{X}$, remained rather steady, ranging from 2110 to 2410, with an average value of 2132 mg/l (line 36, Table VI). It is interesting to note that the average recycle sludge concentration was exactly 10,000 mg/l. The range observed was from 9,810 to 10,270. One cannot expect to be able to make up the X_R concentration with this accuracy at all times; however, these results attest to the applicability of the optical density technique for estimating the recycle sludge concentration.

COD concentration in the filtrate of the recycle, S_R, was considerably lower than $\bar{S}_e$; the average COD was 14 mg/l. Thus, the assumption that S_R is low enough to be neglected (i.e., $S_R = 0$), seems justified. Excess sludge, X_W, produced at this loading level, varied from 1185 to 1231 mg/day, with an average of 1209 mg/day. This value included the amount taken for analysis as well as biological solids in the effluent.

After six days of steady operation, the shock load was applied. COD determinations of filtrate in aerator #1 (S_{R_1}) showed a gradual increase. The maximum value was 114 mg/l and was attained 12 hours after beginning the shock. At the same time the filtrate effluent COD, S_e, was only 35 mg/l. Filtrate COD from aerator #1 continued to "leak" in the range from 63 to 96 mg/l until the end of the transient period, which took two and a half days. The total effluent COD, S_t, was in the range from 46 to 132 mg/l, which was due to an increase in the biological solids in the effluent, X_e.

It was interesting to note the decrease in biological solids concentration in aerator #1. There was a washout phase for 22 hours in which the concentration decreased at a rate of 20 mg/hr (an approximation was made by drawing a straight line through the decreasing leg of the biological solids curve). Biological solids started to increase after reaching a minimum level of 1970 mg/l. This increasing rate, measured as previously indicated, was 35 mg/hr. Excess sludge production, X_W, was remarkably increased to five times or more the amount produced during the previous steady state.

A new steady state was established at the high loading rate. The new steady state was accompanied by a decrease in the filtrate COD, S_{R_1}, which was, on the average, 25 mg/l. The effluent characteristics improved as a result of a decrease in the biological solids in the effluent, X_e. The total COD, S_t, was in the range from 64 to 95 mg/l, with an average of 70 mg/l. The filtrate COD, S_e, was in the range from 10 to 34 mg/l. Biological solids, X_e, was, on the average, 63 mg/l. Carbohydrate concentration in the clarifier filtrate effluent was 13 mg/l.

Biological solids concentration in aerator #1 was fairly steady, with an average of 2240 mg/l, which was slightly higher than the average value in the previous steady state. Excess sludge production, X_W, was in the range from 6098 to 6391, with an average of 6221 mg/day.

After six days of steady state operation under this high loading rate, it was interesting to determine the effect of a decrease shock loading on the behavior of the system. There was no drastic change in the filtrate COD from aerator #1, S_{R_1}, or in the effluent characteristics from the clarifier. A noticeable and predictable change was a drop in excess sludge production, X_W. Biological solids concentration in aerator #1, X, was fairly steady during the transient state, and returned to approximately the same concentration as in the first steady state. Transient state in X_W lasted for approximately two and a half days.

The feed COD during the last steady state varied from 504 to 539 mg/l, with an average S_i of 525 mg/l. The observed filtrate COD of the effluent varied from 10 to 33 mg/l, with an average $\bar{S}$ of 20 mg/l COD. The efficiency of substrate removal was 96 percent, and the value of S was relatively steady. Similarly, the biological solids concentration, X, remained rather steady, ranging from 2112 to 2340 mg/l, with an average value of 2210 mg/l. The sludge recycle concentration was kept very close to 10,000 mg/l, averaging 10,028 mg/l.

Average excess sludge production, X_W, was slightly higher than that observed in the starting steady state. The values ranged from 1191 to 1368, with an agerage of 1260 mg/day, whereas previous X_W averaged 1209 mg/day.

Microscopic examination of the biomass in aerator #1 during the first transient state, i.e., the increase in loading rate, showed a significant change in the number and type of protozoa present in the system. Before the shock, high numbers of rather large protozoa were present; however, very small-size protozoa were in the system during the transient. These small-size protozoa persisted during the high loading steady state period. There was also an increase in filamentous growth during the high loading steady state; however, settling characteristics of the biomass remained rather good. Although the biomass showed a sludge volume index (SVI) of 230, which is higher than the recommended values (50-150), there was no problem in obtaining the required concentration for recirculated sludge.

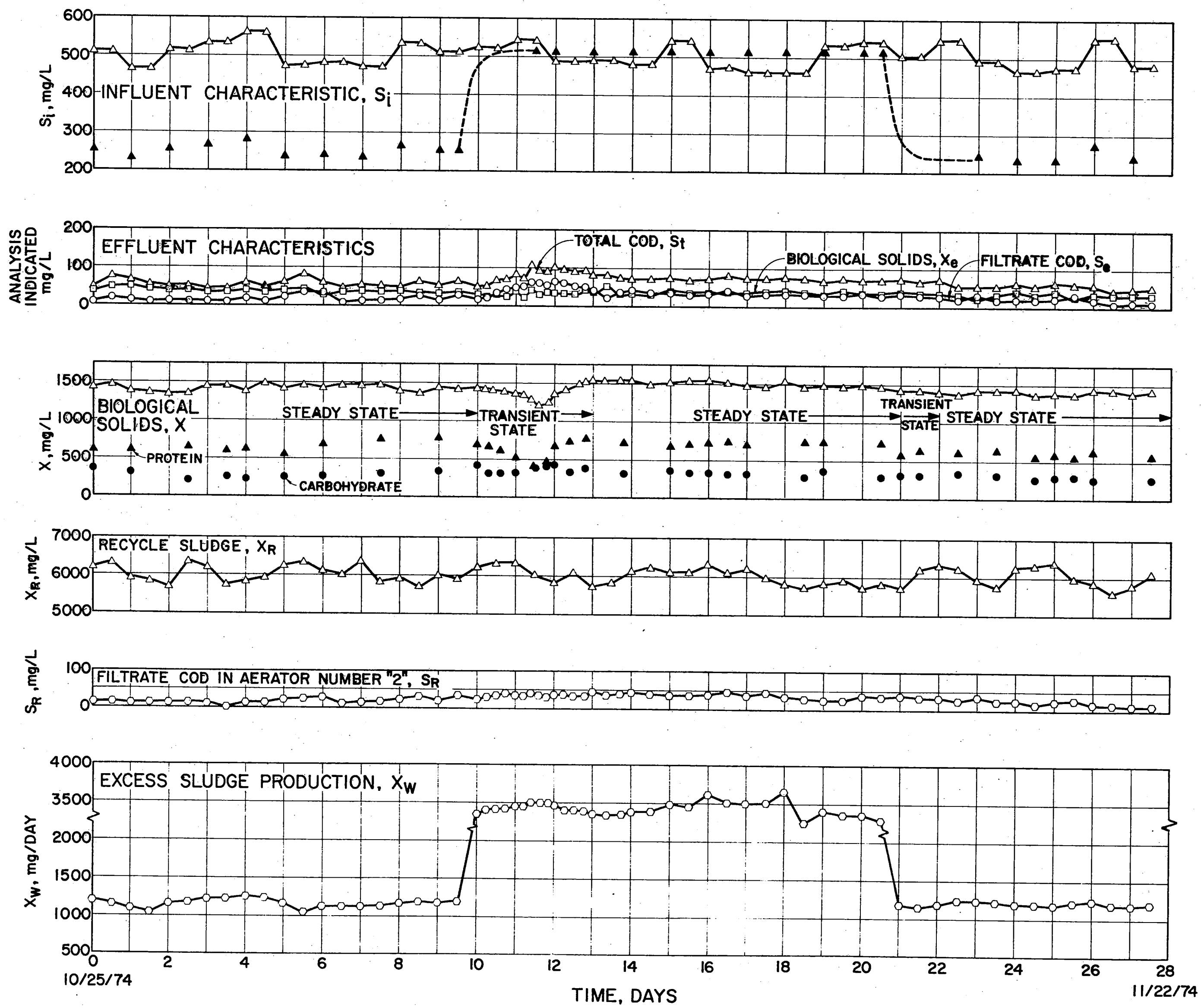
During each steady state period, samples of cells from aerator #1 were employed in batch growth studies to determine μ_{max}, K_s, and Y_t. The values of the biological constants for each batch experiment during each steady state run are given in Table VII (see lines 36, 37, and 38). The value of μ_{max} in both steady states in experiments 36 and 38 agreed rather closely (0.47 and 0.48 hr^{-1}). The saturation constants, K_s, were 131 and 141 mg/l, respectively, while the true yield values were 0.49 and 0.46, respectively. During the high loading steady state (see line 37), the biological constants determined from the batch experiment were 0.51 hr^{-1} for μ_{max}, 85 mg/l for K_s, and 0.53 for the yield.

3. Response to an Increase in Dilution Rate of 100 percent With X_R = 6000 mg/l

Since it had been shown that a system operated using the model with constant concentration of recycle solids, X_R, was capable of withstanding a 300 percent increase in hydraulic loading at a reasonable X_R concentration of 10,000 mg/l, it was of interest to determine the effect of X_R on ability of the system to accommodate hydraulic shock. The next four series of results show the response obtained for X_R values of 6000, 8000, 12,000, and 15,000 mg/l. The same procedure was applied, i.e., developing a steady state with D = 0.125 hr^{-1} for ten days using S_i = 500 mg/l, but X_R was 6000 mg/l instead of 10,000 mg/l. In Table VI, the average performance characteristics of the pilot plant with an S_i loading which ranged from 465 to 561 mg/l COD, with an average recycle solids concentration of 6014 mg/l are shown in line 15. The steadiness of the system is exhibited by the effluent characteristics as well as by the biological solids concentration, X, as shown in Figure 6. The effluent filtrate COD varied from 8 to 39 mg/l, while anthrone samples indicate lower values. The average X value for this steady state run was 1421 mg/l. The effect of X_R on X when α is held constant can be readily seen by comparing the steady state values for solids concentration in aerator #1 at different recycle solids concentrations (see Table VI). The ratio X/X_R ranges from 1:5 to 1:4 throughout the study. Thus, it is seen that X_R exerts a controlling effect on X. The range of solids concentration in the aerator in this run was 1348 to 1488 mg/l. The excess sludge production, X_W, in this case was 1430 mg/day on the average, and was relatively steady throughout the run.

On the ninth day, the system was subjected to a change in dilution rate from 0.125 hr^{-1} to 0.25 hr^{-1}, which resulted in a change in loading rate from 253 mg/2 hrs to 503 mg/2 hrs. In that day, a slight decrease in solids concentration in the reactor from 1425 mg/l to 1399 mg/l was observed. On the second day of the shock, the reactor showed a faster decreasing rate in solids concentration, and the solids reached a value of 1210 mg/l. During the second half of the second day, biological solids in the reactor started to build up rapidly and reached a value of 1540 mg/l at the end of the third day of the transient. In the transient state, effluent characteristics on the second day indicated COD, S_t, of 110 mg/l, which indicates only 80 percent removal efficiency. On the basis of S_e (filtrate COD), 88 percent

Figure 6. Operational Characteristics for an Activated Sludge Process With Constant X_R of 6000 mg/l at an S_i of 500 mg/l Hydraulically Shock Loaded by Change in Dilution Rate From 0.125 hr^{-1} to 0.25 hr^{-1} and From a Dilution Rate of 0.25 hr^{-1} to 0.125 hr^{-1} (from 10-25-74 to 11-22-74)


INFLUENT CHARACTERISTIC, Si
Si, mg/L
600
500
400
300
200
EFFLUENT CHARACTERISTICS
TOTAL COD, St
BIOLOGICAL SOLIDS, Xe
FILTRATE COD, Se
ANALYSIS INDICATED mg/L
200
100
0
BIOLOGICAL SOLIDS, X
X, mg/L
1500
1000
500
0
STEADY STATE
TRANSIENT STATE
STEADY STATE
TRANSIENT STATE
STEADY STATE
PROTEIN
CARBOHYDRATE
RECYCLE SLUDGE, XR
XR, mg/L
7000
6000
5000
FILTRATE COD IN AERATOR NUMBER "2", SR
SR, mg/L
100
0
EXCESS SLUDGE PRODUCTION, XW
XW, mg/DAY
4000
3500
2000
1500
1000
500
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
10/25/74
TIME, DAYS
11/22/74

removal efficiency was recorded. The system did not recover rapidly, and S_t values remained rather high. It was interesting to note that S_e concentration was more than the X_e concentration during the transient state. The filtrate COD, S_e, was approximately 67 mg/l, while X_e was 45 mg/l; i.e., the increase in dilution rate did not disrupt the effluent characteristics with respect to biological solids as much as in respect to filtrate COD, S_e.

At the lowest solids concentration in aerator #1, protein and carbohydrate solids content were approximately the same. As the solids recovered during the third day of the transient, the protein and carbohydrate content exhibited more normal composition ratios. After the end of the fourth day, the system behaved steadily with respect to effluent characteristics and solids concentration in the reactor. Although S_t was somewhat high (72 mg/l on the average), it exhibited considerable steadiness during the new steady state ($D = 0.25\ hr^{-1}$). The values of S_e and X_e during the new steady state averaged 33 and 38 mg/l, respectively. Average biological solids concentration in the reactor was 1450 mg/l, showing a very small difference from the average during operation at the previous dilution rate; i.e., solids concentration did not change significantly when dilution rate changed since S_i and X_R were kept constant. High loading steady state continued for seven days, and solids concentration in the reactor as well as effluent characteristics showed marked steadiness (Figure 6, middle portion). In addition to the characteristics shown, spot checks were made for carbohydrate in the filtrate effluent, S_e. The overall biochemical efficiency based on the average feed COD of 540 mg/l and effluent filtrate of 33 mg/l was 94 percent. The anthrone test indicated nearly all of the carbohydrate feed was removed; the maximum amount of carbohydrate was 43 mg/l with an average of 15 mg/l. However, since the effluent COD averaged 33 mg/l, it can be seen that carbohydrate comprised approximately 50 percent of the effluent COD in the filtrate. The biological solids concentration in the aerator was slightly higher than at the lower dilution rate (only 29 mg/l greater). The recycle solids concentration, X_R, was controlled within 300 mg/l of the desired 6000 mg/l. The average amount of excess sludge produced was 3558 mg/day (Table VI, line 16). The dilution rate was then returned to 0.125 hr^{-1}, while X_R was kept at 6000 mg/l and S_i at 500 mg/l. There was a noticeable drop in average solids concentration in the reactor. About 50 mg/l reduction in solids concentration was observed. There was also a decrease in total effluent COD, S_t. Although there was a noticeable transient disturbance as evidenced by an increase in effluent COD, the system was observed to withstand the shock rather well.

The average solids concentration in the effluent during the steady state stayed almost the same as before, but a reduction in S_e COD was recorded. There was a slight decrease in average protein content. An average of 43 percent was recorded for protein, and 21 percent for carbohydrates, whereas in the steady state of the higher loading, protein and carbohydrate content averaged 49 and 22 percent.

Steady state operation was continued for seven days (Figure 6). The average excess sludge production was less than half the average in the previous steady state (compare lines 16 and 17 in Table VI).

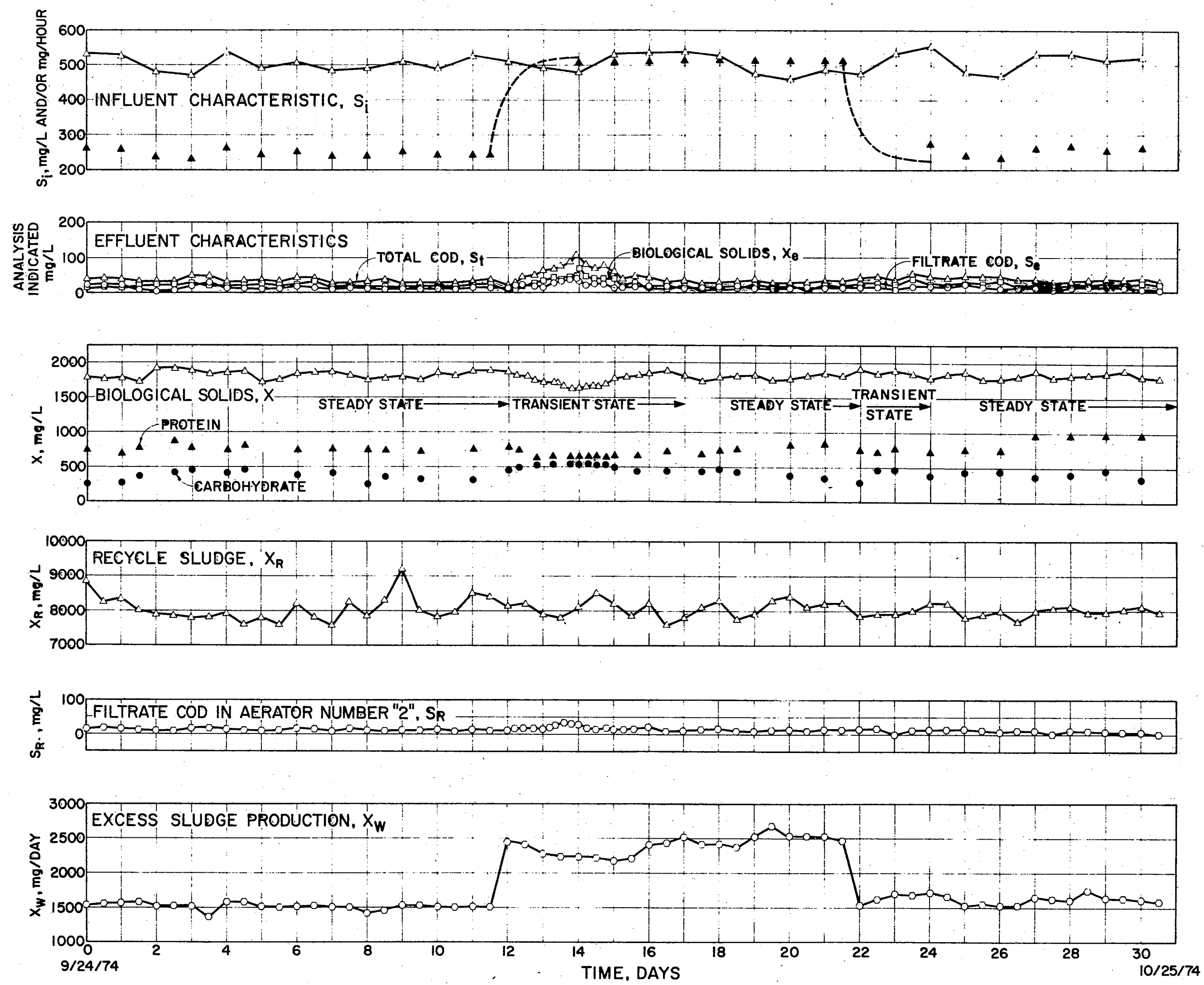
The batch growth pattern and relationship between μ and S_o during the three steady states were determined from shaker experiments. The μ_{max} values for the two steady states at D = 0.125 hr^{-1} were 0.5 and

0.53, and for D = 0.25 hr^{-1}, it was 0.51. The K_s values were somewhat higher than those usually observed, although they were not abnormally high. These values were 177 and 204 mg/l for cells harvested with D at 0.125 hr^{-1}, and 214 mg/l for the run at 0.25 hr^{-1} (see lines 15, 16, and 17 in Table VII).

4. Response to an Increase in Dilution Rate of 100 Percent With X_R = 8000 mg/l

A hydraulic shock study with recycle solids concentration, X_R, of 8000 mg/l was made. The pilot plant was operated at the same nominal S_i concentration, 500 mg/l. The actual range of values was from 469 to 534 mg/l COD with an average recycle solids concentration of 8075 mg/l. In Table VI, the average performance characteristics of the pilot plant during these periods are shown in line 12. The steadiness of the operational model is exhibited by the effluent characteristics as well as by the biological solids concentration, X, as shown in Figure 7 (left portion). The effluent filtrate COD varied from 6 to 30 mg/l; the carbohydrate concentration as measured by the anthrone test was 4 to 21 (not plotted in Figure 7). The values for S_R were in the range 8 to 18 mg/l COD. The average X value for this steady state run was 1775 mg/l. The effect of X_R on X can be readily seen by comparing the steady state values of X_R of 8000 mg/l in this steady state, and X_R of 6000 mg/l in the previous experiment (i.e., compare lines 12 and 15). It is evident, therefore, that X is controlled mainly by X_R, which is itself a controllable parameter in this model. The recycle sludge, X_R, in this run ranged from 7584 to 8850 mg/l. The excess sludge production in this case was 1422 mg/day compared to 1430 at the same S_i

Figure 7. Operational Characteristics for an Activated Sludge Process With Constant X_R of 8000 mg/l at an S_i of 500 mg/l Hydraulically Shock Loaded by Change in Dilution Rate From 0.125 hr^{-1} to 0.25 hr^{-1} and From a Dilution Rate of 0.25 hr^{-1} to 0.125 hr^{-1} (from 9-24-74 to 10-25-74)


INFLUENT CHARACTERISTIC, Si
Si, mg/L AND/OR mg/HOUR
EFFLUENT CHARACTERISTICS
TOTAL COD, St
BIOLOGICAL SOLIDS, Xe
FILTRATE COD, Se
ANALYSIS INDICATED mg/L
BIOLOGICAL SOLIDS, X
STEADY STATE
TRANSIENT STATE
STEADY STATE
TRANSIENT STATE
STEADY STATE
PROTEIN
CARBOHYDRATE
X, mg/L
RECYCLE SLUDGE, XR
XR, mg/L
FILTRATE COD IN AERATOR NUMBER "2", SR
SR, mg/L
EXCESS SLUDGE PRODUCTION, XW
XW, mg/DAY
9/24/74
TIME, DAYS
10/25/74

concentration, but with X_R of 6000 mg/l. This will be discussed later. The excess sludge production in this case was relatively steady. Determination of protein and carbohydrate content of the sludge indicated values in the expected range, i.e., protein 42 percent, and carbohydrate 21 percent. During the eleventh day, the hydraulic rate of feed was doubled in order to increase dilution rate from 0.125 hr^{-1} to 0.25 hr^{-1}. Recycle flow, F_R, was also doubled in order to keep α constant. Biological solids concentration decreased through the second day and reached a value of 1630 mg/l. On the third day, solids in the reactor started to build up, and by the end of the fourth day reached 1840 mg/l. After the fifth day, the system was adjudged to be in the steady state. During the transient, protein content of the biological solids decreased and the carbohydrate content increased. The protein and carbohydrate content of the lower solids concentration during the transient were 36 and 34 percent, respectively. Two days after starting the shock, the total effluent COD rose to a high value of 108 mg/l. During these few days, the effluent COD rose steadily. It is interesting to note that during the transient response, unlike the previous experiment, the major contribution to S_t was due to effluent solids, X_e, rather than to soluble COD, S_e.

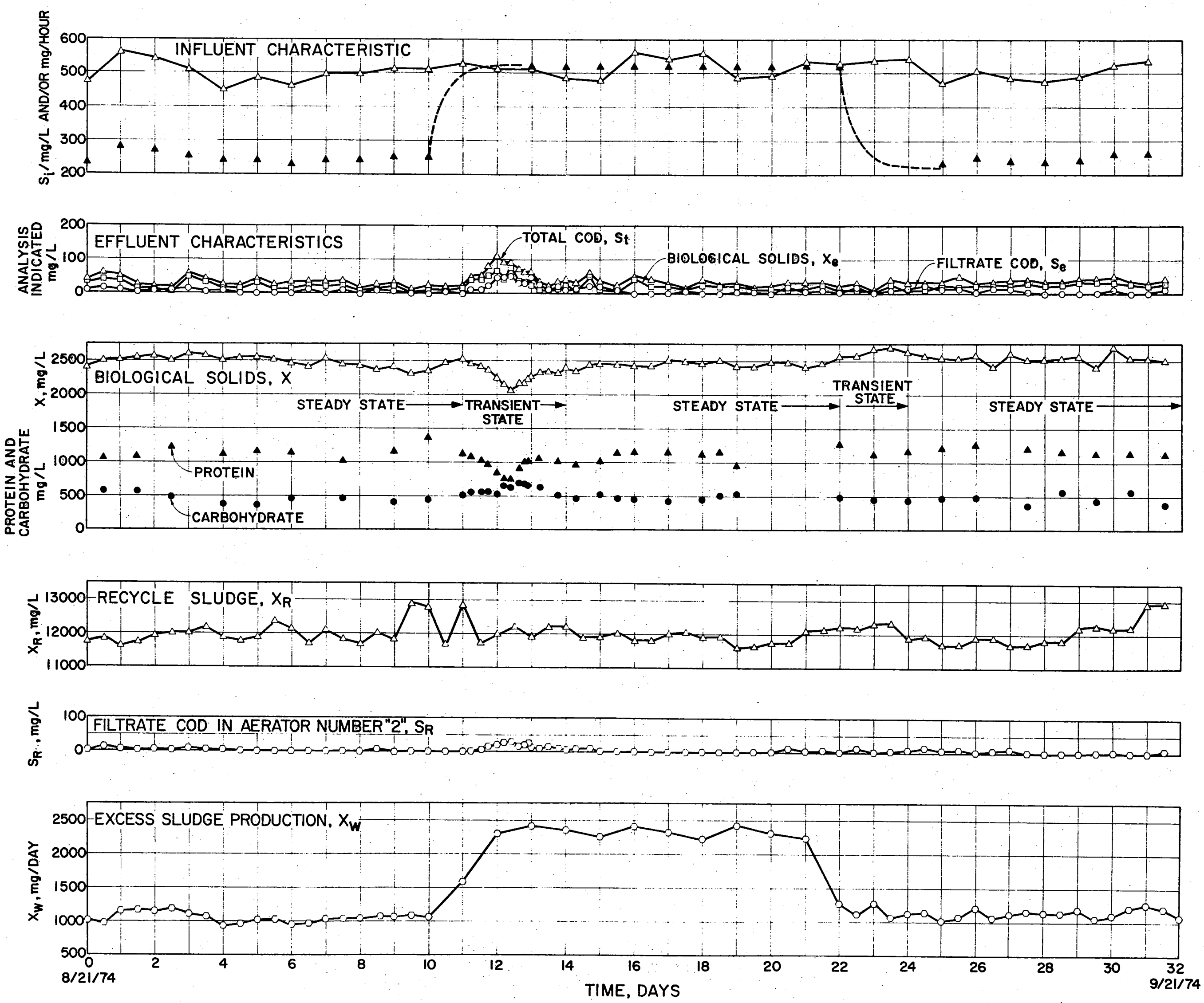
Excess sludge production, X_W, rose to 2450 mg/day. Over the next three days there was a 10 percent reduction in excess sludge production. Excess sludge production, X_W, then increased and appeared to reach a steady state on day 17. Between days 17 and 22, X_W averaged 2502 mg/day. All steady state data obtained at the new dilution rate are shown on line 13 of Table VI. The protein and carbohydrate content of the cells rose slightly to 45 and 26 percent, respectively. The carbohydrate in the effluent showed an average value of 12 mg/l. The biochemical efficiency based on the average feed COD, S_i, of 497 mg/l and effluent filtrate COD of 15 mg/l, was 97 percent. The average biological solids concentration in the reactor was clsoe to the average in the previous steady state period. The average biological solids concentration, $\bar{X}$, was 1794 mg/l compared to 1775 mg/l for the previous steady state (line 12). The system exhibited a very high degree of steadiness with respect to aerator solids concentration, as well as effluent characteristics. The recycle solids concentration, X_R, was controlled within 500 mg/l of the desired 8000 mg/l. The excess sludge production during this period was more than one and a half times the previous value. After determining the steady state condition, the dilution rate was again returned to its original value, 0.125 hr^{-1}. There was no significant change in biological solids concentration in aerator #1 during transient; the only change was a decrease in excess sludge production, X_W. A new steady state was maintained for seven days, then the experiment was terminated. The average biological solids concentration in the reactor was 1760 mg/l compared to 1775 mg/l in the first steady state, and 1794 mg/l in the steady state for the high dilution rate. Thus, it can be seen that the change in D did not change significantly the biological solids concentration, X, during the entire experiment. After returning D to 0.125 hr^{-1}, the system still exhibited a high degree of steadiness with respect to aerator solids concentration as well as effluent characteristics. The recycle solids concentration, X_R, was controlled within 300 mg/l of the desired 8000 mg/l. The COD of the recycle sludge, S_R, was 11 mg/l. The biochemical efficiency based on the average feed of 512 mg/l and effluent filtrate COD of 13 mg/l was

97 percent (see line 14, Table VI). The anthrone test indicated very little of the carbohydrate remained in the effluent; the maximum amount found was 14 mg/l, with an average of 9 mg/l. The batch studies during each steady state were made to determine the biological constants. The μ_{max} values obtained from the three individual growth studies were very similar, i.e., 0.42, 0.47, and 0.49 hr^{-1}, and K_s values were 208, 94, and 110 mg/l. The yield values were 0.53, 0.58, and 0.56, respectively (see experiments 12, 13, and 14 in Table VII).

5. Response to an Increase in Dilution Rate of 100 Percent With X_R = 12,000 mg/l

The system was operated at a steady state for eleven days at an S_i loading of 500 mg/l and X_R of 12,000 mg/l. The average data obtained during this run are shown in Table VI (lines 9, 10, and 11). The performance characteristics are plotted in Figure 8. The biochemical efficiency based on the average feed COD, S_i, of 500 mg/l, and effluent filtrate COD, S_e, of 12 mg/l, was 98 percent. Carbohydrate concentration in the filtrate clarifier overflow ranged between zero and 14 mg/l. The biological solids concentration in aerator #1, $\bar{X}$, was 2513 mg/l on average, with a range from 2318 to 2601 mg/l. The recycle solids concentration, X_R, was controlled within 500 mg/l of the desired 12,000 mg/l. The recycle sludge filtrate, S_R, was only 7 mg/l COD on average. The excess sludge production during this run was 1140 mg/day on average. Determination of protein and carbohydrate content of the sludge indicated values in the expected range, i.e., protein 48 percent, and carbohydrate 17 percent. After operating the system for eleven days under steady state conditions, it was subjected to a 100 percent

Figure 8. Operational Characteristics for an Activated Sludge Process With Constant X_R of 12,000 mg/l at an S_i of 500 mg/l Hydraulically Shock Loaded by a Change in Dilution Rate From 0.125 hr^{-1} to 0.25 hr^{-1} and From a Dilution Rate of 0.25 hr^{-1} to 0.125 hr^{-1} (from 8-21-74 to 9-21-74)



INFLUENT CHARACTERISTIC
S_i, mg/L AND/OR mg/HOUR
EFFLUENT CHARACTERISTICS
ANALYSIS INDICATED mg/L
TOTAL COD, S_t
BIOLOGICAL SOLIDS, X_e
FILTRATE COD, S_e
BIOLOGICAL SOLIDS, X
X, mg/L
STEADY STATE
TRANSIENT STATE
STEADY STATE
TRANSIENT STATE
STEADY STATE
PROTEIN
CARBOHYDRATE
PROTEIN AND CARBOHYDRATE mg/L
RECYCLE SLUDGE, X_R
X_R, mg/L
FILTRATE COD IN AERATOR NUMBER "2", S_R
S_R, mg/L
EXCESS SLUDGE PRODUCTION, X_W
X_W, mg/DAY
8/21/74
9/21/74
TIME, DAYS

increase in flow rate (D changed from 0.125 to 0.25 hr^{-1}). There was a decrease in biological solids concentration, X, in aerator #1. Solids decreased rapidly from a value of 2524 mg/l to 2173 mg/l in about 29 hours. After this period, there was a slight increase in biological solids concentration for a period of seven hours, after which a sustained increase was maintained for 30 hours. The decrease in the biological solids concentration in aerator #1 during transient was accompanied by an increase in the total effluent COD concentration, S_t. Total COD, S_t, rose to a value of 114 mg/l twenty-four hours after applying the shock. The filtrate COD, S_e, rose to 50 mg/l. The total effluent COD, S_t, decreased rapidly, indicating speedy recovery in overall purification efficiency in the system. The system returned to a new steady state within three days after applying the shock. Protein and carbohydrate content of the biological solids at the lowest biological solids concentration, X, during the transient state were 38 and 35 percent, respectively. Thus, it is seen that during the transient there was a decrease in protein and an increase in carbohydrate content of the biomass. As the system approached the new steady state, there was an increase in protein and a decrease in the carbohydrate content. The new steady state at D = 0.25 hr^{-1} was monitored for eight days, and the average biological solids concentration in the reactor was 2554 mg/l. The recycle sludge concentration, X_R, was maintained very close to 12,000 mg/l. The average excess sludge production, X_W, during the new steady state was 2697 mg/day (see Table VI, line 10). Determination of protein and carbohydrate content of the sludge indicated values in the range of 42 and 26 percent, respectively. The biochemical efficiency based on the average feed concentration, S_i, of 521 mg/l and effluent filtrate COD, S_e, of 6 mg/l was 99 percent. After assessing the new steady state, a 50 percent decrease in dilution rate was applied (D was decreased to 0.125 hr^{-1}). There was a slight increase in biological solids concentration and a value of 2704 mg/l was attained two and one-half days after administering the shock. The protein and carbohydrate content of the cells did not vary. There was no change in effluent characteristics during the shock. The system was operated seven days to assess the new steady state. The effluent quality remained excellent, yielding 93 percent efficiency based on supernatant COD, S_t, and 98 percent based on filtrate COD, S_e. The mean effluent solids concentration during this period was 24 mg/l (see Table VI, line 11). The average carbohydrate content in the effluent was 11 mg/l, and some of the anthrone analyses indicated zero concentration. The difference between the high and low values of X_R was only 260 mg/l, with an average of 12,060 mg/l. The average biological solids concentration was 2553 mg/l. With this experiment, as with all preceding pilot plant runs, the filtrate COD in the recycle sludge was very low, and in some cases, zero COD was recorded. The amount of excess sludge produced during the final steady state was 1137 mg/day on average.

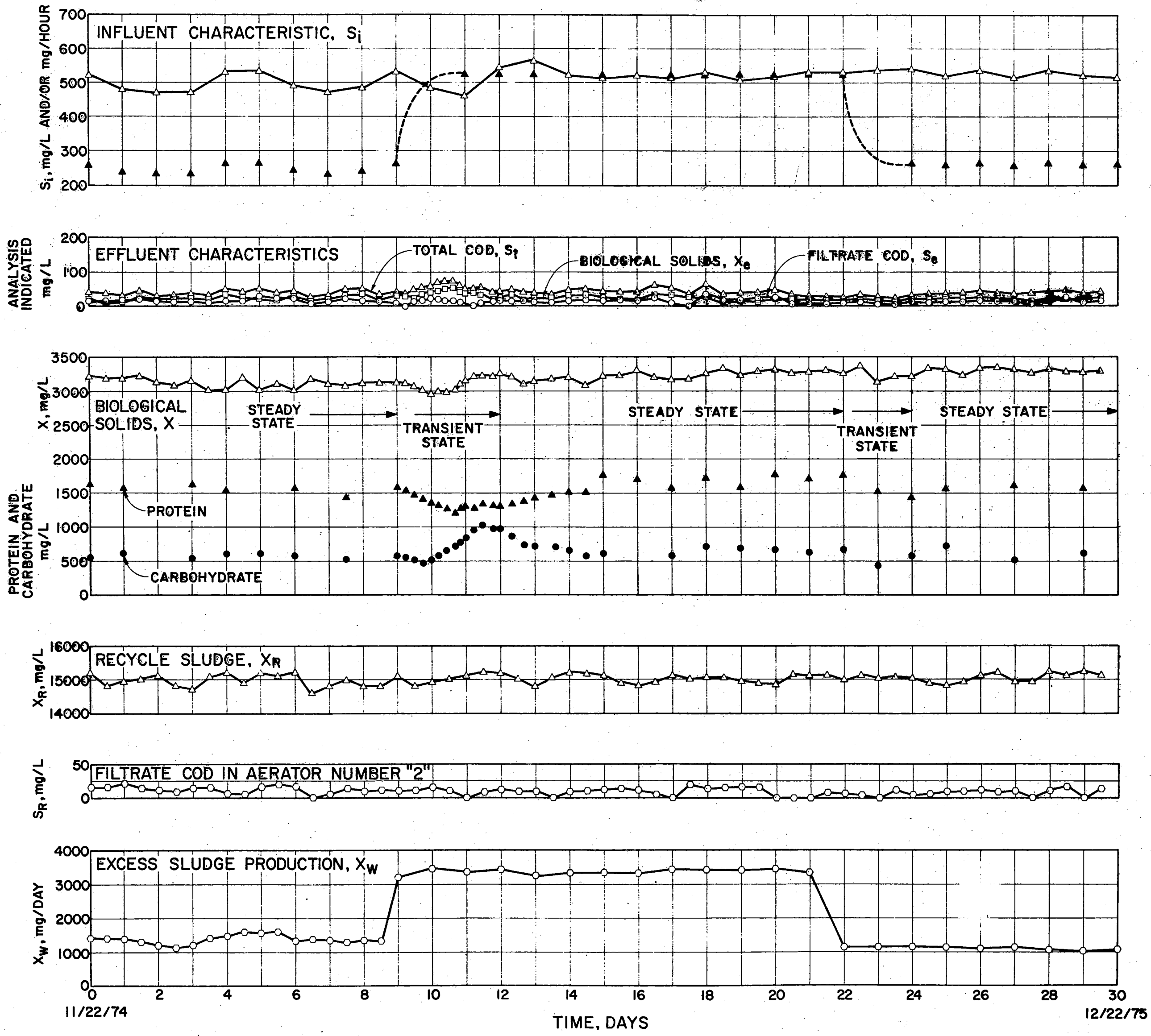
Values of the biological constants, μ_{max}, K_s, and Y_B are recorded in Table VII, lines 9, 10, and 11. The maximum specific growth rates, μ_{max}, observed in these experiments ranged between 0.43 and 0.54 hr^{-1}, and K_s varied between 126 and 164 mg/l; the Y_B values ranged between 0.38 and 0.45.

6. Response to an Increase in Dilution Rate of 100 Percent With X_R = 15,000 mg/l

Responses to the three previous shocks indicated a less deleterious response as X_R was increased from 6000 to 12,000 mg/l; i.e., the higher the X_R, the more rapid was the recovery. Therefore, it was decided to study the response to the same percent increase in dilution rate, but with even higher recycle solids concentration, i.e., 15,000 mg/l. Figure 9 shows the biochemical response of the system before, during, and after the hydraulic shock. The system, as before, was operated under steady state for nine days. The average feed COD was 495 mg/l. The effluent quality was excellent, yielding better than 92 percent efficiency based on supernatant COD, S_t, and 97 percent efficiency based on filtrate COD, S_e (see Table VI, line 18). The mean effluent solids concentration during this period was 23 mg/l. The biological solids concentration, X, varied over a very narrow range during this period. The difference between the high and low values of X_R was only 600 mg/l, with an average of 14,963 mg/l. The average biological solids concentration, $\bar{X}$, was 3115 mg/l. The filtrate COD of the recycle sludge, S_R, was low, with an average of 12 mg/l. The average amount of excess sludge produced, X_W, was 1120 mg/day.

After maintaining the system at steady state for nine days, the shock load was applied. There was a small decrease in biological solids concentration in reactor #1. The biological solids, X, decreased from 3124 to 2980 in about twenty hours and statyed fairly steady for almost eight hours, after which it started to increase. Biological solids concentration, X, in reactor #1 continued to increase during

Figure 9. Operational Characteristics for an Activated Sludge Process With Constant X_R of 15,000 mg/l at an S_i of 500 mg/l Hydraulically Shock Loaded by a Change in Dilution Rate From 0.125 hr^{-1} to 0.25 hr^{-1} and From a Dilution Rate of 0.25 hr^{-1} to 0.125 hr^{-1} (from 11-22-74 to 12-22-74)



INFLUENT CHARACTERISTIC, S_i
S_i, mg/L AND/OR mg/HOUR
700
600
500
400
300
200
EFFLUENT CHARACTERISTICS
ANALYSIS INDICATED mg/L
200
100
0
TOTAL COD, S_t
BIOLOGICAL SOLIDS, X_e
FILTRATE COD, S_e
3500
3000
2500
2000
1500
1000
500
0
X, mg/L
BIOLOGICAL SOLIDS, X
STEADY STATE
TRANSIENT STATE
STEADY STATE
TRANSIENT STATE
STEADY STATE
PROTEIN AND CARBOHYDRATE mg/L
PROTEIN
CARBOHYDRATE
16000
15000
14000
X_R, mg/L
RECYCLE SLUDGE, X_R
50
0
S_R, mg/L
FILTRATE COD IN AERATOR NUMBER "2"
4000
3000
2000
1000
0
X_W, mg/DAY
EXCESS SLUDGE PRODUCTION, X_W
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
11/22/74
TIME, DAYS
12/22/75

the second and third days after the shock. Biological solids rose to 3264 mg/l at the end of the third day. Effluent characteristics were monitored by total COD, S_t, biological solids, X_e, and filtrate COD, S_e, indicating little leakage of substrate from the unit. Effluent COD, S_t, rose to 75 mg/l in the second day of shock load, while filtrate COD, S_e, did not show any rise. The biochemical efficiency based on the filtrate COD, S_e, was 97 percent. The anthrone test indicated nearly all of the carbohydrate was removed. During the transient state, excess sludge production nearly tripled. A new steady state was established after three days. Average values are shown in Table VI, line 19. The average biological solids concentration in the reactor was 3224 mg/l. The biochemical efficiency was 91 percent based on the total COD, S_t, and 96 percent based on the filtrate COD, S_e. The anthrone test indicated very low values for carbohydrate in the effluent. After maintaining the new steady state for ten days, the feed dilution rate was returned to the previous level. There was no significant response to the decrease in dilution rate. The only response was a decrease in the excess sludge production (50 percent). The system was operated for six days, and a high degree of steadiness in the biological solids concentration in the reactor as well as in the effluent characteristics was observed (see Table VI, line 20). The biological solids concentration, X, averaged 3170 mg/l compared to 3115 mg/l in the previous steady state (Table VI, line 18). The effluent quality remained excellent, yielding better than 94 percent based on supernatant COD, S_t, and 98 percent efficiency based on filtrate COD, S_e. The mean effluent solids concentration, X_e, was 19 mg/l on average. Excess sludge produced, X_W, was 1087 mg/day on average.

The values of the biological constants obtained from the batch growth plots made during the three runs, D = 0.125, 0.25, and 0.125 hr^{-1}, are reported in Table VII, experiments 18, 19, and 20). The maximum specific growth rate, μ_{max}, observed in these experiments, were 0.35, 0.34, and 0.37, respectively, and K_s varied from 63.0 mg/l to 185 mg/l.

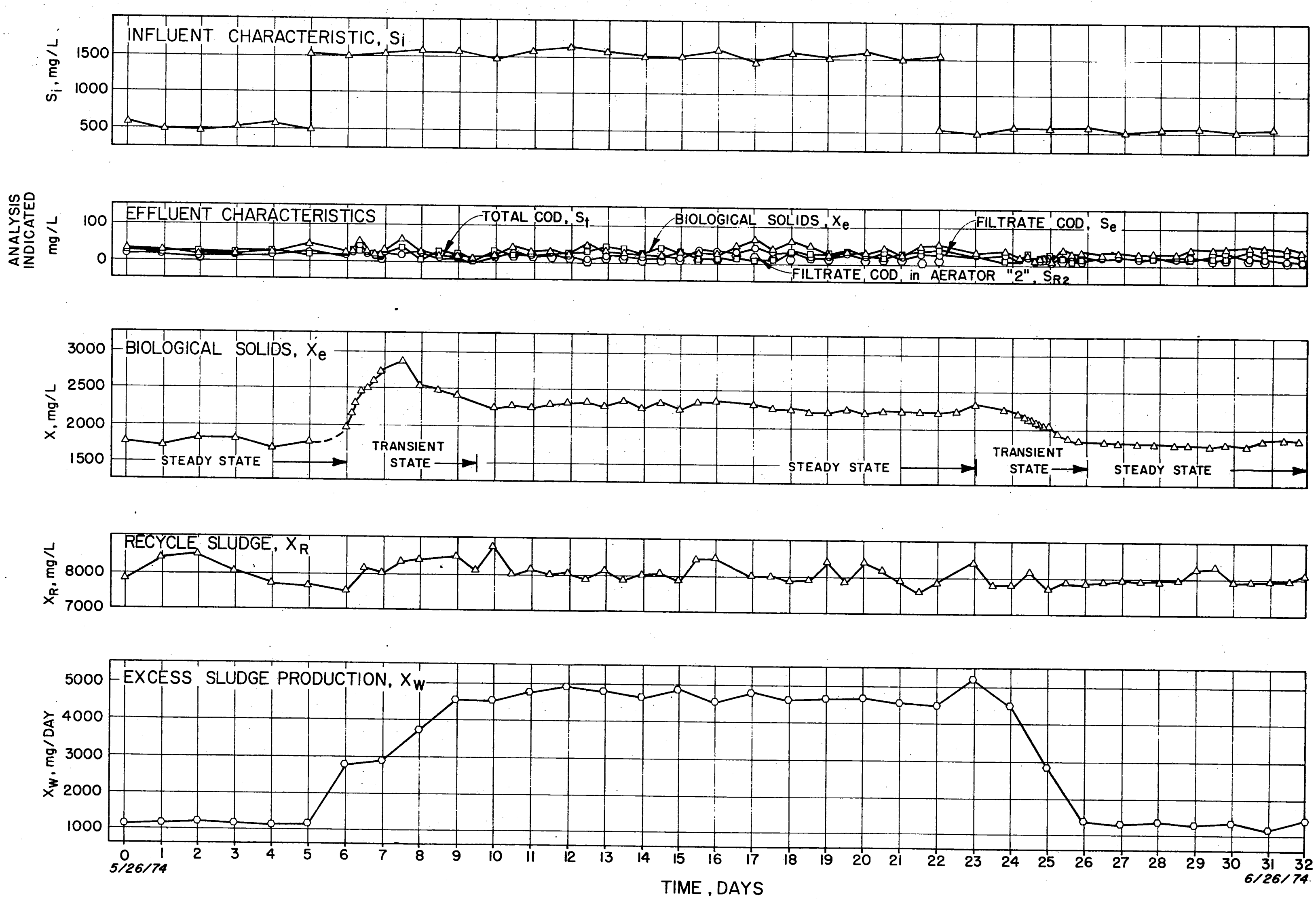
B. Quantitative Shock Loads

To evaluate the overall system response of an activated sludge to quantitative shock loads, step changes in substrate loadings were studied. Responses to three-fold and to six-fold increases in S_i were examined. Each shock was repeated in order to determine the repeatability of the general response.

1. Three-fold Substrate Increase

Prior to increasing substrate concentration from 500 to 1500 mg/l, the pilot plant was operated in the steady state. The average steady state values obtained during the continuous flow run with S_i of 500 mg/l glucose and 8000 mg/l X_R are given in Table VI, line 3. The performance characteristics are plotted in Figure 10. Also shown in Table VI line 3 are the averages of the relatively few determinations of the filtrate carbohydrate of the clarifier supernatant (not plotted in Figure 10). The COD of the influent ranged from 456 to 588 mg/l, with an average of 503 mg/l. The effluent quality as measured by filtrate COD, S_e, was excellent; the mean S_e was 24 mg/l, providing 95 percent removal of the substrate. The biological solids concentration in the effluent, X_e, in this steady state was 27 mg/l, and this resulted in 93 percent efficiency

Figure 10. Operational Characteristics for an Activated Sludge Process With Constant X_R of 8000 mg/l at an S_i of 500 mg/l Quantitatively Shock Loaded by a Change in S_i of 500 mg/l to 1500 mg/l and from an S_i of 1500 mg/l to 500 mg/l (from 5-26-74 to 6=26-74)



INFLUENT CHARACTERISTIC, S_i
S_i, mg/L
1500
1000
500
ANALYSIS INDICATED mg/L
EFFLUENT CHARACTERISTICS
TOTAL COD, S_t
BIOLOGICAL SOLIDS, X_e
FILTRATE COD, S_e
FILTRATE COD in AERATOR "2", S_{R2}
100
0
BIOLOGICAL SOLIDS, X_e
X, mg/L
3000
2500
2000
1500
STEADY STATE
TRANSIENT STATE
STEADY STATE
TRANSIENT STATE
STEADY STATE
RECYCLE SLUDGE, X_R
X_R, mg/L
8000
7000
EXCESS SLUDGE PRODUCTION, X_W
X_W, mg/DAY
5000
4000
3000
2000
1000
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32
5/26/74
6/26/74
TIME, DAYS

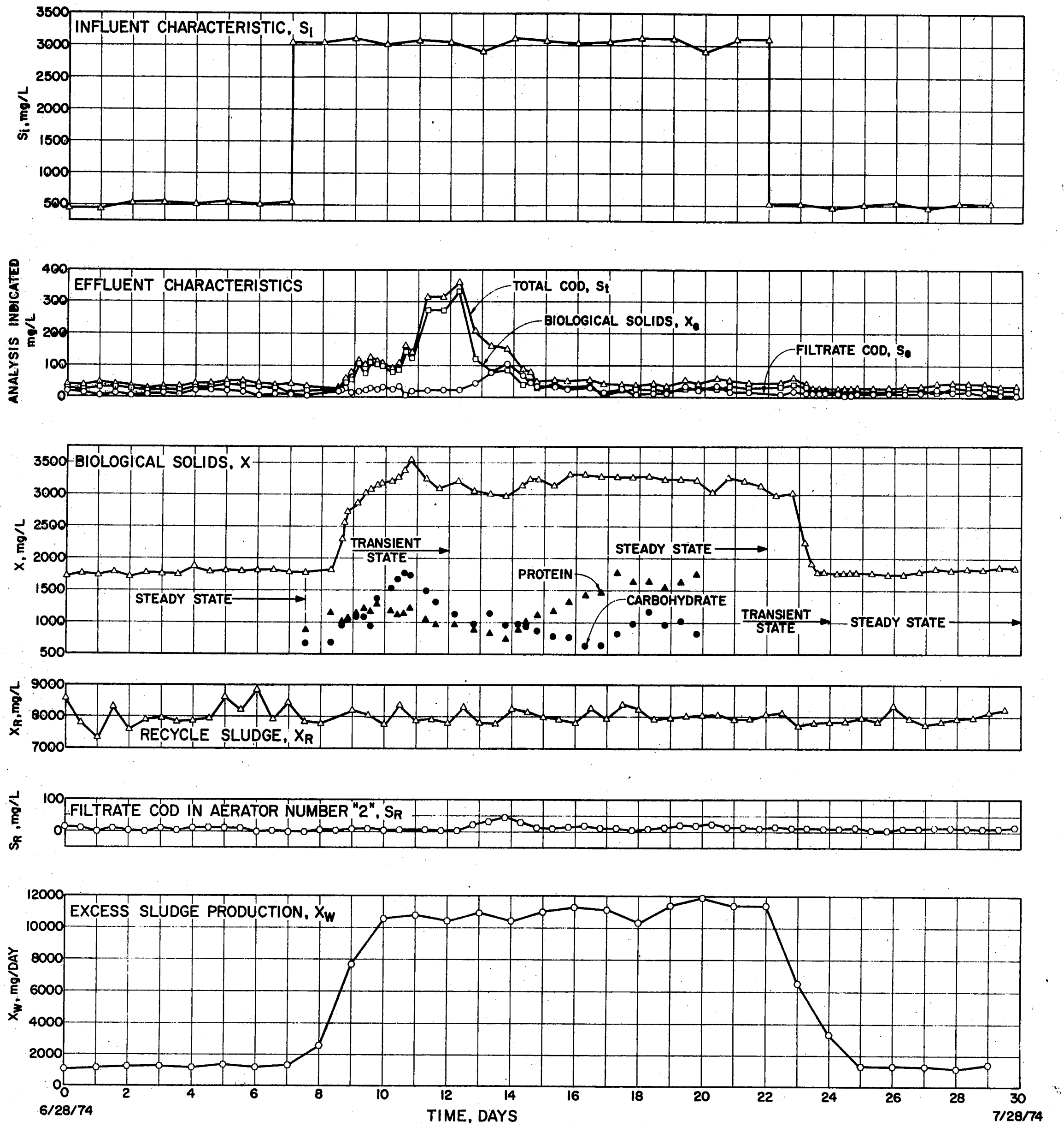
on the basis of total COD, S_t, in the effluent. The range of values for filtrate COD, S_e, was 12 mg/l to 36 mg/l, while X_e varied between 12 and 43 mg/l. In general, the system provided very satisfactory treatment and delivered effluent of high quality. The biological solids concentration in aerator #1 varied between 1677 and 1860, with a mean of 1776 mg/l. The X_R values ranged from 7443 to 8510 mg/l, and the average was 7935 mg/l. The COD for recycle sludge filtrate, S_R, indicates very little substrate was being returned to the aerator with recycle sludge, justifying the basic assumption made in the derivation of the steady state equation (1).

The bottom graph of Figure 10 shows the daily production of excess sludge. The values varied between 1305 and 1430 mg/day; it is seen that X_W remained relatively steady. Six days of steady state data were recorded before starting the shock. The increase in influent substrate concentration is represented by a vertical line (see top portion of Figure 10). Mixed liquor biological solids concentration in the aeration tank rose to a value of 2840 mg/l at the end of 28 hours. Daily production of excess sludge increased to 4136 mg/day after three days from application of the shock. Total COD, S_t, ranged from 28 mg/l to 65 mg/l, and filtrate COD, S_e, ranged from 8 mg/l to 46 mg/l; i.e., the system recorded a successful total as well as biochemical response recovery during the transient stage. The biological solids concentration in aerator #1 gradually decreased after a maximum concentration of 2840 mg/l. The biological solids kept decreasing for four days and reached a value of 2270 mg/l. A new steady state was established with regard to biological solids concentration, X, and effluent characteristics (see Table VI, line 4). Biological solids concentration ranged from 2170 to 2338 mg/l, with an average of 2237 mg/l. Recycle sludge concentration, X_R, ranged from 7600 to 8470, with an average of 7998 mg/l. Influent substrate concentration, S_i, was kept close to the nominal glucose concentration, i.e., 1500 mg/l, with an average of 1496 mg/l. The filtrate effluent COD, S_e, attained an average of 19 mg/l, providing a 99 percent removal efficiency. Excess sludge production, X_W, in this new steady state rose to 4850 mg/day. The sludge settling properties remained very good, and there was essentially no change in the apparent color of the biomass. After maintaining the system in the new steady state for almost twelve days, the influent substrate was returned to 500 mg/l. This step decrease in influent substrate concentration did not change the effluent characteristics. The biological solids concentration in aerator #1 decreased steadily for almost two days. During this time, the solids concentration decreased from 2300 mg/l to 1710 mg/l. The filtrate COD, S_e, as well as total COD, S_t, concentrations were very low, and the excess sludge production, X_W, decreased by 75 percent. A steady state was attained after three days. The biological concentration, X, in aerator #1 varied in the range from 1740 mg/l to 1832 mg/l, with an average of 1774 mg/l. This average value was very close to that for the previous steady state at the same S_i (compare lines 3 and 5 in Table VI). The effluent characteristics as measured by filtrate COD, S_e, were still excellent; the mean filtrate COD, S_e, was 15 mg/l, providing 97 percent removal of the substrate. The average biological solids concentration in the effluent in this steady state run was 18 mg/l. Carbohydrate in the filtrate effluent as measured by anthrone ranged from zero mg/l to 16 mg/l. The biological constants for the three steady state runs are reported in Table VII (experiments 3, 4, and 5). Values of μ_{max} ranged from 0.45 to 0.55 hr^{-1}, K_s from 110 to 181, and Y_B from 0.43 to 0.49.

2. Six-fold Step Substrate Increase

A steady state was maintained for almost eight days with a nominal S_i loading of 500 mg/l glucose concentration at the same recycle sludge concentration, X_R (8000 mg/l), as the previous run. The average data obtained during this run are shown in Table VI, line 6. The performance characteristics before, during, and after the shock are plotted in Figure 11. Effluent characteristics were monitored in terms of clarifier effluent COD, S_t, filtrate COD, S_e, and supernatant solids concentration, X_e. Also, spot checks were made for anthrone tests on the clarifier filtrate supernatant, S_e, to determine the amount of carbohydrate in the effluent (not plotted in Figure 11). The chemical oxygen demand removal efficiency based on the average feed COD of 545 mg/l and effluent filtrate COD of 14 mg/l was 98.0 percent. The anthrone test indicated that there was very little carbohydrate in the effluent. The maximum amount of carbohydrate found was 16 mg/l, with an average of 8 mg/l. The biological solids concentration in aerator #1 was almost the same in average as the previous steady state runs (compare lines 3 and 5 with line 6). The average biological solids concentration, $\bar{X}$, was 1782 mg/l. The system exhibited a very high degree of steadiness through the 8-day pre-shock period with respect to all parameters. The recycle solids concentration, X_R, was controlled within 800 mg/l of the desired 8000 mg/l. It is interesting to note that the COD in the recycle sludge filtrate was only 7 mg/l compared to the effluent filtrate COD of 14 mg/l. The average amount of excess sludge produced, X_W,

Figure 11. Operational Characteristics for an Activated Sludge Process With Constant X_R of 8000 mg/l at an S_i of 500 mg/l Quantitatively Shock Loaded by a Change in S_i From 500 to 3000 mg/l and From an S_i of 3000 mg/l to 500 mg/l (from 6-28-74 to 7-28-74)



INFLUENT CHARACTERISTIC, S_i
S_i, mg/L
EFFLUENT CHARACTERISTICS
ANALYSIS INDICATED mg/L
TOTAL COD, S_t
BIOLOGICAL SOLIDS, X_e
FILTRATE COD, S_e
BIOLOGICAL SOLIDS, X
X, mg/L
TRANSIENT STATE
STEADY STATE
PROTEIN
CARBOHYDRATE
RECYCLE SLUDGE, X_R
X_R, mg/L
FILTRATE COD IN AERATOR NUMBER "2", S_R
S_R, mg/L
EXCESS SLUDGE PRODUCTION, X_W
X_W, mg/DAY
TIME, DAYS
6/28/74
7/28/74

was 1330 mg/day. Cell protein and carbohydrate contents were 48 and 18 percent, respectively.

After administering the shock (500 to 3000 mg/l glucose COD), the biological solids concentration in aerator #1 increased sharply from approximately 1820 to 3093 mg/l within about fifty-two hours and stayed approximately constant for five hours; then it rose again to a maximum value of 3550 mg/l sixty-two hours after administering the shock. After this peak, biological solids concentration decreased steadily until it reached a level of 2975 mg/l after approximately three days. A new steady state was maintained for seven days (Table VI, line 7), with an average biological solids concentration of 3095 mg/l. In the transient stage, the effluent characteristics changed significantly one and one-half days after applying the shock. The total COD, S_t, increased due to an increase in biological solids, X_e. The filtrate COD, S_e, did not rise for almost five days. The biological solids, X_e, increased to 276 mg/l, while S_e was only 12 mg/l. The biochemical removal efficiency for the system remained very high for five days while the total efficiency was low due to leakage of cells. The filtrate COD, S_e, increased after the fifth day and continued to increase to a value of 106 mg/l. On the seventh day, the biochemical removal efficiency was 96 percent based on filtrate COD, S_e, and the total removal efficiency was 95 percent based on the effluent COD, S_t. The highest value of S_t recorded during the transient was 360 mg/l, yielding an efficiency of 90 percent. Excess sludge production, X_W, rose to an average value of 10,272 mg/day. The system was adjudged to have attained a new steady state on day 15. The biological solids concentration in aerator #1 averaged 3095 mg/l, with a range of 2980 to 3304 mg/l. The average values for effluent quality were as follows: St, 46 mg/l, X_e, 28 mg/l, and S_e, 30 mg/l (see Table VI, line 7). Carbohydrate and protein contents of the sludge were determined at three- to six-hour intervals during the transient state. The cell carbohydrate rose to 53 percent, and cell protein decreased to 35 percent by the fourth day after applying the shock. Thereafter, carbohydrate content decreased and protein increased. Protein and carbohydrate contents fluctuated during the steady state period in X and S, but an average was 52 and 24 percent, respectively. After eight days of steady state operations at S_i of 3000 mg/l, the substrate concentration was decreased to 500 mg/l. There was no significant change in effluent characteristics. The only change was a decrease in both the biomass in aerator #1 and the excess sludge production, X_W. The biomass in aerator #1 was reduced by 43 percent, and the excess sludge, X_W, was reduced by 36 percent.

In Table VI, line 8, the performance characteristics of the pilot plant in the new steady state are given. The S_i loading ranged from 483 to 535 mg/l COD, with an average value of 514 mg/l. Recycle solids concentration ranged from 7704 to 8241, with an average of 7946 mg/l. The steadiness of operation is exhibited by the effluent characteristics, as well as by the biological solids concentration, X, as shown in Figure 11 (right portion). There was no transient leakage of substrate. The effluent filtrate COD, S_e, varied from 6 to 25 mg/l. The anthrone samples indicate lower values; they ranged from 0 to 14 mg/l, with an average of 9 mg/l. The filtrate COD in aerator #2, S_R, was low, ranging from 4 to 14 mg/l. The average X value for this steady state run was 1777 mg/l. Thus, it is readily apparent that the system returned to the previous steady state conditions (compare lines 6 and 8 in Table VI).

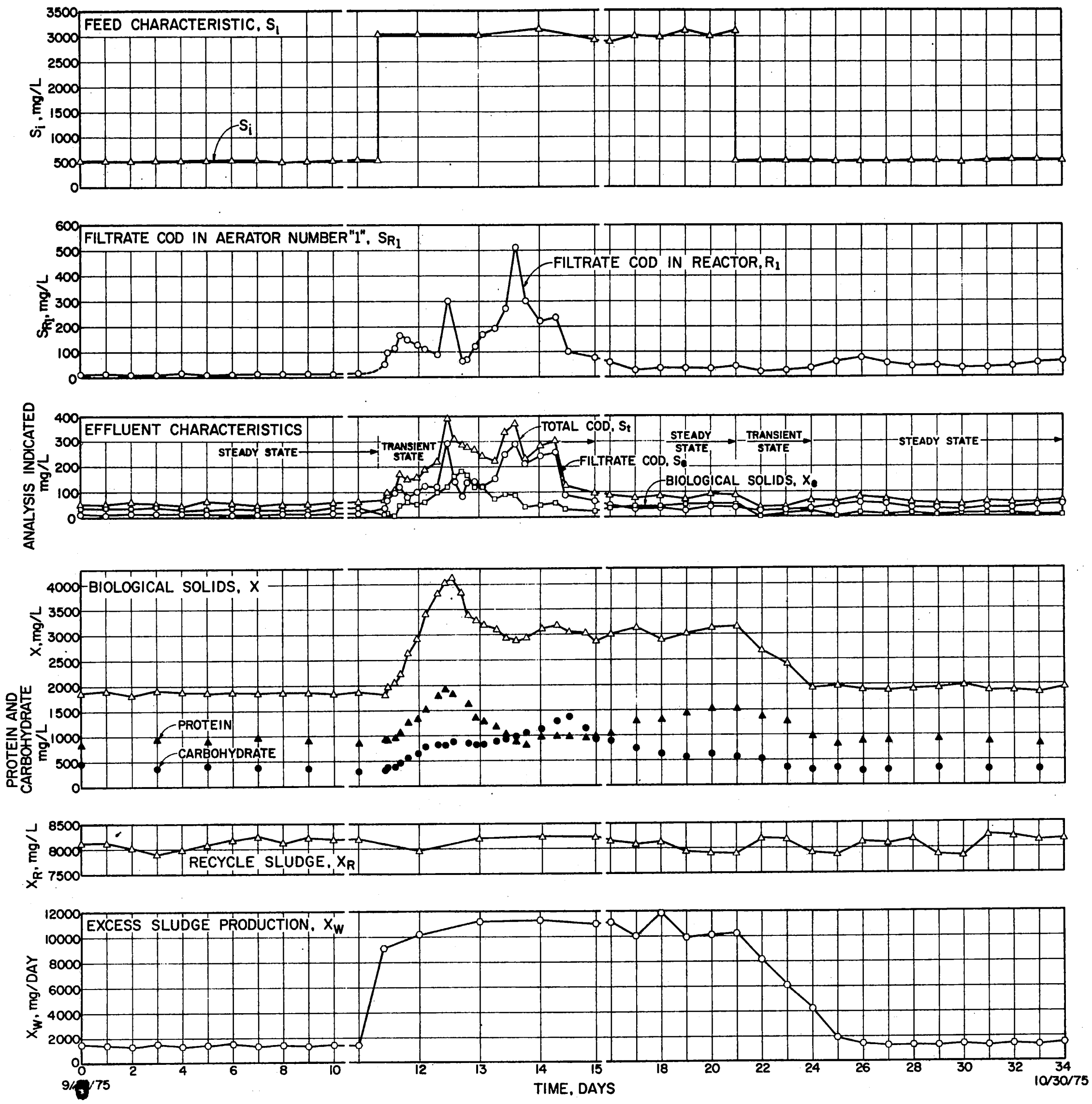
It is also apparent that the system needed little or no time to recover from a step decrease in S_i. It is interesting to note that, at the low loading, X consists mainly of sludge which is recycled, whereas, at the higher loading, one-half of the biological solids in the reactor were due to new growth. Biological solids concentration in aerator #2 (sludge consistency tank) was measured at the beginning and end of each 12-hour period (and often at more frequent intervals). There was no evidence for autodigestive decrease in biological solids concentration in this tank. The average beginning concentration was 7929 mg/l, and the average ending concentration was 7958 mg/l.

The biological constants for the biomass during the three steady state periods were determined by batch growth experiments and are recorded in Table VII (experiments 6, 7, and 8). The maximum specific growth rate, μ_{max}, ranged between 0.46 and 0.58 hr^{-1}. The saturation constants, K_s, were in the range 108 to 123 mg/l. It is interesting to note a significant increase in Y_B during the high loading steady state. A value of 0.56 was recorded, compared to 0.42 and 0.45 in the low loading state.

3. Repeat of the Three- and Six-fold Shocks After 13 Months of Operation of the Pilot Plant

Thirteen months after performing the previously described experiments, it was decided to repeat the three- and six-fold quantitative shocks. The main idea of repeating these experiments was to test the reproducibility of response using an entirely different heterogeneous population. It was also interesting to gain more insight into the kinetics of the response during the transient state by determining the filtrate COD in the mixed liquor exiting from aerator #1, as well as filtrate COD in the clarifier effluent. Also, it was decided to start with the severe shock, i.e., increase the feed concentration from 500 mg/l to 3000 mg/l. Figure 12 shows the results of the complete shock load experiment. Steady state was monitored for almost twelve days. The heterogeneous microbial population comprising the activated sludge was one newly developed from municipal sewage. Again, it is seen that rather steady operational results were achieved; that the system delivered an excellent effluent, and that the values for each parameter are approximately the same as those previously shown in line 6, Table VI (compare lines 6 and 31). The theoretical COD of 500 mg/l glucose is approximately 530 mg/l, and the feed concentration in these studies varied from 498 to 545 mg/l, with an average S_i COD of 527 mg/l. The total effluent COD, S_t, ranged from 41 to 59 mg/l, with an average of 50 mg/l. The observed filtrate COD of the effluent varied from 8 to 14 mg/l, with an average COD, S_e, of 11 mg/l, while X_e varied between 26 and 39 mg/l. Thus, the effluent was, on the average, very good; efficiency of substrate removal was 98 percent, and the value of S_e was relatively steady. The filtrate COD in aerator #1 ranged from 8 to 14 mg/l, with an average of 11 mg/l. Similarly, the biological solids concentration, X, remained rather steady, ranging from 1714 to 1904 mg/l, with an average value of 1820 mg/l. It can also be seen in this figure that it was possible to control the sludge recycle concentration at a value of approximately 8000 mg/l. The range observed was from 7889 to 8241 mg/l, with an average of 8107 mg/l. It is important also to note in this run that the filtrate of the recycle sludge, S_R, was considerably lower than S_e. The average COD, S_R, was 8 mg/l.

Figure 12. Operational Characteristics for an Activated Sludge Process With Constant X_R of 8000 mg/l at an S_i of 500 mg/l Quantitatively Shock Loaded by a Change in S_i From 500 to 3000 mg/l and From 3000 mg/l to 500 mg/l (from 9-26-75 to 10-30-75)



FEED CHARACTERISTIC, S_i
S_i, mg/L
FILTRATE COD IN AERATOR NUMBER "1", S_{R_1}
FILTRATE COD IN REACTOR, R_1
S_{R_1}, mg/L
EFFLUENT CHARACTERISTICS
ANALYSIS INDICATED mg/L
STEADY STATE
TRANSIENT STATE
TOTAL COD, S_t
FILTRATE COD, S_e
BIOLOGICAL SOLIDS, X_e
BIOLOGICAL SOLIDS, X
X, mg/L
PROTEIN AND CARBOHYDRATE mg/L
PROTEIN
CARBOHYDRATE
X_R, mg/L
RECYCLE SLUDGE, X_R
EXCESS SLUDGE PRODUCTION, X_W
X_W, mg/DAY
TIME, DAYS
10/30/75

Excess sludge, X_W, produced at this loading level varied from 1321 to 1561, with an average of 1419 mg/day.

When feed substrate was increased to 3000 mg/l, the response was a rapid increase in biomass concentration in aerator #1. The maximum concentration of biological solids reached a value of 4130 mg/l after one and one-half days, approximately. The solids in aerator #1, after reaching this high level of concentration, decreased and in one day reached a value of 2862 mg/l. Analysis for filtrate COD in aerator #1 during the transient indicated considerable leakage of soluble COD. A value of 164 mg/l was recorded six hours after beginning the shock. The filtrate COD in reactor #1 reached a maximum of 512 mg/l. The filtrate COD, S_e, in the clarifier reached a maximum of 288 mg/l approximately two days after applying the shock. This difference may be attributed to biological activity in the sedimentation tank. There was a considerable disruption in effluent characteristics. Total COD, S_t, showed high values due to an increase in both biological solids and filtrate COD in the clarifier effluent, S_e. Fluctuations in the filtrate COD in aerator #1, S_{R_1}, followed the same trend as did the filtrate COD of the clarifier supernatant, S_e, except at the first half of the third day of shock when the filtrate COD in aerator #1 was 200 mg/l COD more than the filtrate COD, S_e. There was a noticeable change in color as well as change in the size of floc as revealed by microscopic examination. Filamentous growth increased and became predominant in the sludge. Protozoa seemed to disappear during the transient state and in the first days of the steady state at the higher loading. Six days after the shock, both filtrate COD in aerator #1 and the filtrate COD in the effluent clarifier decreased to 55 and 45 mg/l on average, respectively.

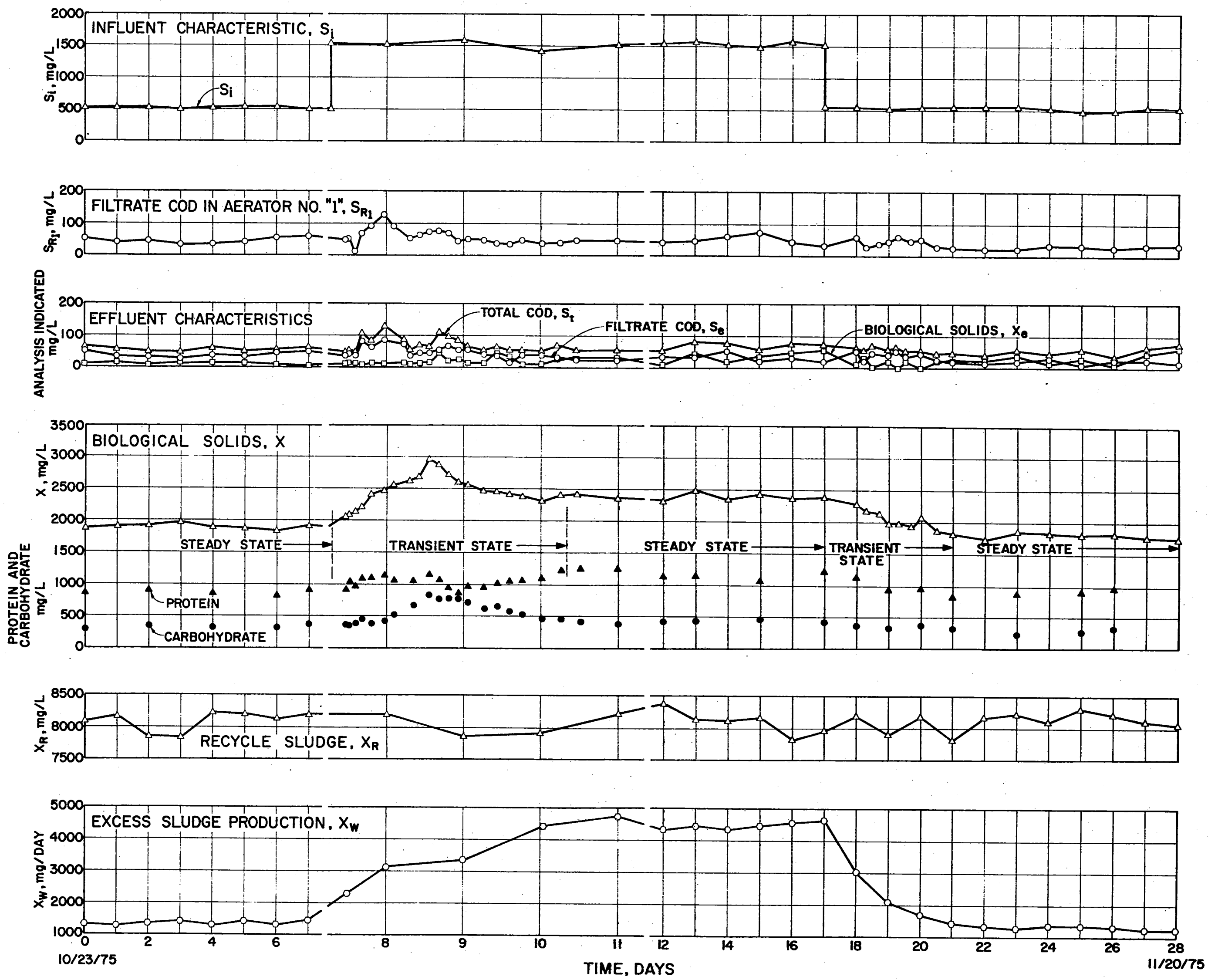
The color, after maintaining steady state at the feed concentration of 3000 mg/l, changed from milky to yellowish-brown. The performance of the system at S_i of 3000 mg/l is shown in Figure 12 (middle portion). The mean steady state values are recorded in TAble VI, line 32. The effluent filtrate COD varied from 25 to 85 mg/l, with an average of 45 mg/l. It is interesting to point out that BOD_5 analyses were made during the steady state run on a regular basis. An average value of 27 mg/l BOD_5 was recorded for the clarifier effluent. It is interesting also to note again that values of S_R were relatively smaller than $\bar{S}_e$ (average S_R = 22 mg/l). This observation attests to the fact that the residual COD in the effluent is subject to further removal. The biological solids concentration in aerator #1 ranged from 2856 to 3148 mg/l, with an average of 3018 mg/l, which is very close to the average observed previously under the same conditions ($\bar{X}$ = 3095 mg/l, Table VI, line 7). Settling tests were conducted and showed a sludge volume index (SVI) of 210, which is higher than that usually considered to be desirable, but the biomass was still showing fair settling results. Excess sludge production, X_W, ranged from 9980 to 11,220 mg/day, with an average of 10,630 mg/day.

After monitoring the system for steady state for about six days, the system was shocked again by decreasing the feed concentration to 500 mg/l. This type of shock did not produce any deleterious effect on either the clarifier supernatant or on the filtrate COD in aerator #1. The only change was a decrease in the biological solids concentration in aerator #1 as well as decrease in the amount of excess sludge production. A new steady state was monitored for ten days, and the average of the steady state data is recorded in Table VI, line 33. The biological solids concentration in aerator #1 ranged from 1738 to 1970 mg/l, with an average of 1799 mg/l. Filtrate COD in aerator #1 ranged from 22 to 78 mg/l, with an average of 30 mg/l. Recycle sludge was kept very close to 8000 mg/l, with an average of 8055 mg/l. Excess sludge production, X_W, was in the range of 1288 to 1660 mg/day, with an average of 1428 mg/day. As before, filtrate COD in aerator #2 showed an average value of 18 mg/l, which was much lower than the filtrate COD in the clarifier effluent (S_e = 42 mg/l).

It is interesting to note the behavior of protein and carbohydrate content during the transient and at the high loading steady state. Both the concentration of protein and carbohydrate increased after application of the shock. The protein concentration increased more rapidly than did the carbohydrate content. This trend changed one day after applying the shock. The protein concentration after reaching a value of 2000 mg/l, started to decrease while the carbohydrate concentration was constant for almost a day. However, carbohydrate concentration continued to increase and soon was higher than protein. It remained higher for a period of 35 hours, after which the protein concentration started to increase again and carbohydrate decreased. After returning the loading to 500 mg/l, the carbohydrate and protein concentrations of the cell returned to approximately 400 and 900 mg/l, respectively. It was close to the concentration observed at the previous feed of 500 mg/l (compare lines 31 and 33, Table VI).

After ten days of steady state at S_i = 500 mg/l (Table VI, line 33), the feed concentration was increased to 1500 mg/l. The first noticeable effect was an increase in the biomass concentration in aerator #1 (Figure 13). The biomass increased steadily for two days after

Figure 13. Operational Characteristics for an Activated Sludge Process With Constant X_R of 8000 mg/l at an S_i of 500 mg/l Quantitatively Shock Loaded by a Change in S_i From 500 to 1500 mg/l and From 1500 mg/l to 500 mg/l (from 10-23-75 to 11-20-75)



INFLUENT CHARACTERISTIC, S_i
S_i, mg/L
FILTRATE COD IN AERATOR NO. "1", S_{R1}
S_{R1}, mg/L
EFFLUENT CHARACTERISTICS
TOTAL COD, S_t
FILTRATE COD, S_e
BIOLOGICAL SOLIDS, X_e
ANALYSIS INDICATED mg/L
BIOLOGICAL SOLIDS, X
X, mg/L
STEADY STATE
TRANSIENT STATE
STEADY STATE
TRANSIENT STATE
STEADY STATE
PROTEIN
CARBOHYDRATE
PROTEIN AND CARBOHYDRATE mg/L
RECYCLE SLUDGE, X_R
X_R, mg/L
EXCESS SLUDGE PRODUCTION, X_W
X_W, mg/DAY
10/23/75
TIME, DAYS
11/20/75

applying the shock, attaining a maximum value of almost 3000 mg/l. It was interesting to compare both biomass responses to the six- and three-fold increases in feed substrate concentration. If the rate of increase in the biological solids is approximated with linear kinetics, the rate of the biomass increase was 100 and 32 mg/l/hr, respectively. It was also noticed that the biolgical solids concentration took less time to reach the peak concentration when the high shock was applied.

After the biomass reached a concentration of 3000 mg/l, it decreased steadily. The highest value recorded for the filtrate COD in aerator #1, S_{R_1}, was 128 mg/l. The system recovered rapidly. Total COD in the clarifier effluent showed two peaks, 129 and 110 mg/l, while the filtrate COD, S_e, did not rise to more than 88 mg/l. The biological solids concentration, X_e, was in the range from 8 to 45 mg/l. The filtrate COD in the recycle sludge for aerator #2 averaged only 11 mg/l during the three-day transient period. Also, the carbohydrate concentration in the clarifier filtrate averaged only 11 mg/l during the transient period. The carbohydrate concentration of the cells followed the same pattern as the biomass; i.e., it increased for half a day and then decreased for one day while protein did not change significantly. Protein concentration dipped to 875 mg/l, and recovered rapidly to a value of 1400 mg/l. The average excess sludge production, X_W, changed significantly from 1428 mg/day to 4683 mg/day. This increase required almost three days.

The system was operated in the steady state for seven days at the loading of 1500 mg/l (Table VI, line 34). The biological solids concentration, X, ranged from 2310 to 2482, with an average of 2,359 mg/l.

The BOD test was used to characterize the filtrate substrate in aerator #1, S_{R_1}, the effluent filtrate, S_e, and total clarifier effluent, S_t. The average BOD values were 15, 8, and 28, respectively. The filtrate COD in aerator #1 was in the range from 32 to 72 mg/l, with an average of 46 mg/l. In regard to the clarifier, the filtrate COD, S_e, was 31 mg/l, and the total COD, S_t, was 64 mg/l, with an average of 36 mg/l biological solids concentration, X_e. The filtrate in the recycle line for aerator #2, S_R, was 15 mg/l, again justifying the assumption that $S_R = 0$ in the model. The biological solids concentration in the consistency tank was in the range from 7913 to 8380, with an average of 8090 mg/l. Excess sludge production, X_W, ranged from 4310 to 4716 mg/day, with an average of 4683 mg/day. Protein and carbohydrate were both in the normal concentration with respect to the total cell mass. Averages of 49 and 18 percent for protein and carbohydrate content were recorded.

The feed concentration was decreased to 500 mg/l. The response of the system to this decrease in feed concentration was characterized by a decrease in biological solids concentration in aerator #1 as well as a decrease in excess biomass production, X_W. A new steady state ensued without any disruption in effluent characteristics. The average steady state values are recorded in Table VI (line 35). The filtrate COD in aerator #1, S_{R_1}, did not rise, but ranged from 12 to 45, with an average of 28 mg/l. The biological solids in aerator #1 varied from 1724 to 1860 mg/l, with an average value of 1804 mg/l. The total COD in the effluent, S_t, ranged from 34 to 54 mg/l, with an average of 44 mg/l, while filtrate COD, S_e, was in the range from 10 to 30 mg/l, with an average of 24 mg/l. Biological solids, X_e, was

25 mg/l, on average, with a range from 15 to 34 mg/l. The average carbohydrate content in the effluent filtrate as measured by the anthrone test was 11 mg/l. The recycle sludge concentration, X_R, was kept very close to 8000 mg/l, with an average of 8142 mg/l. Excess sludge production, X_W, varied in the range from 1291 to 1361 mg/day, with an average of 1342 mg/day.

During each steady state period, samples of cells from aeration tank #1 were employed in batch growth studies to determine μ_{max}, K_s, and Y_{t_B}. The sludge yield was determined as the ratio of the weight of the biological solids produced, ΔX, and the substrate removed, ΔCOD, at the end of the removal period. The values of the biological constants for batch experiments during each steady state are given in Table VII (experiments 33, 34, and 35). The maximum specific growth rate values, μ_{max}, ranged from 0.46 to 0.52 hr^{-1}, and the saturation constants ranged from 110 to 140 mg/l. The batch yields recorded were 0.55 in experiment 34, and values of 0.49 and 0.46 for experiments 33 and 35, respectively.

C. Pulsing Shock Loads

1. Cyclic Hydraulic Shock Loads With Constant α

The aim of this experiment was to study the cyclic effect of fluctuation in hydraulic loading during each 24-hour period. The mode of hydraulic cycling to which the system was subjected is outlined in Table VIII. Three separate hydraulic flows were employed, $\bar{t}$ was changed from 8 to 4 to 16 hrs. In the laboratory pilot plant these

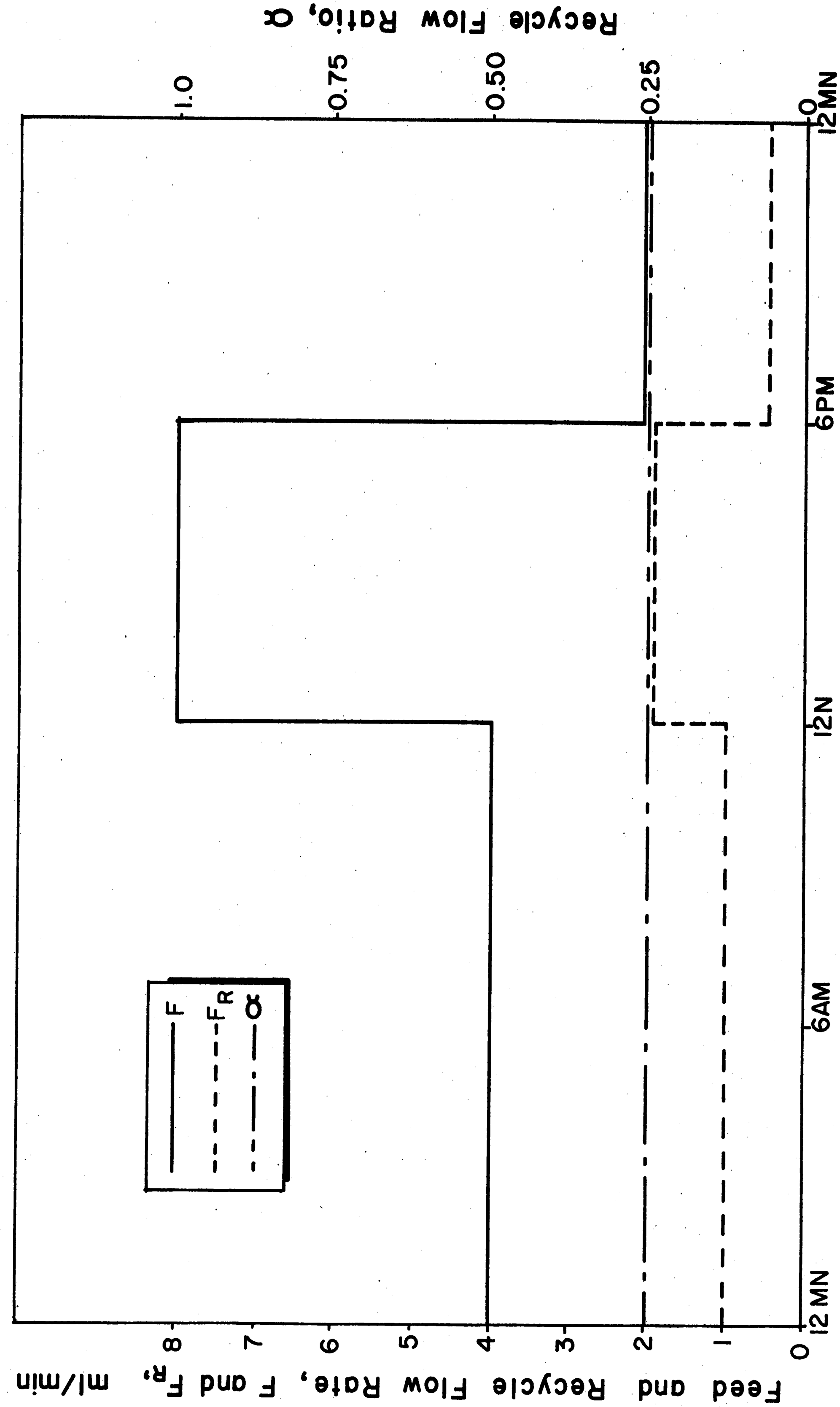
TABLE VIII

RELATION BETWEEN MEAN HYDRAULIC RETENTION TIME, $\bar{t}$, DILUTION RATE, D, REACTOR DILUTION RATE, D_1, RECYCLE FLOW RATIO, α, AND REACTOR VOLUME, V (20-day run)

Time	$\bar{t}$	D	D_1	α	V
	hours	hr^{-1}	hr^{-1}	$\frac{F_R}{F}$	liters
12M-12N	8	0.1250	0.156	0.25	1.92
12N-6PM	4	0.250	0.313	0.25	1.92
6PM-12M	16	0.0625	0.080	0.25	1.92

corresponded to flow rates F, of 4, 8, and 2 ml/min, and they were maintained in the system for durations of 12, 6, and 6 hours, respectively (Figure 14). Thus, the system was exposed to three different mass loading rates: 3000, 6000, and 1500 mg/day of glucose during each 24-hour period. At the same time, recycle sludge flow rate, F_R, was varied in order to keep the ratio between recycle flow rate and the influent flow rate, α, constant at 0.25. Steady state data prior to shock loading are not shown in Figure 15, but during the 12-day steady state period, the average steady state data obtained with 500 mg/l glucose as feed and 10,000 mg/l X_R are given in Table VI, line 24. The biochemical efficiency based on the average feed COD of 527 mg/l and effluent filtrate COD of 10 mg/l was 98 percent. During this run, volatile suspended solids determinations (VSS) were added to those usually run. However, they were run each two days rather than daily. During the pre-shock steady state, VSS ranged between 71 and 79 percent. The filtrate COD in the recycle sludge was only 8 mg/l. The biological solids concentration in aerator #1 ranged from 2041 to 2418 mg/l, with an average of 2210 mg/l. The recycle solids concentration, X_R, was controlled within 200 mg/l of the desired 10,000 mg/l, with an average value of 10,071 mg/l. The average amount of excess sludge produced, X_W, was 1291 mg/day. The batch growth curves were plotted to obtain the biological constants. The μ_{max} value obtained was 0.5 hr^{-1}, and the K_s value was 217 mg/l (Table VII, experiment 24). It was interesting to determine the endogenous rate of oxygen uptake of the biological solids in aerator #1 as well as in aerator #2. Sludge concentrations of 135 mg/l were placed in the Warburg apparatus. The endogenous O_2 uptake of sludge in reactor #1 was 11 mg O_2/hr/gm solids, while the endogenous O_2

Figure 14. Mode of Operation During Cyclic Hydraulic Shock Load With Constant α


Feed and Recycle Flow Rate, F and F_R, ml/min
Recycle Flow Ratio, α
0
1
2
3
4
5
6
7
8
0
0.25
0.50
0.75
1.0
12 MN
6AM
12N
6PM
12MN
F
F_R
α

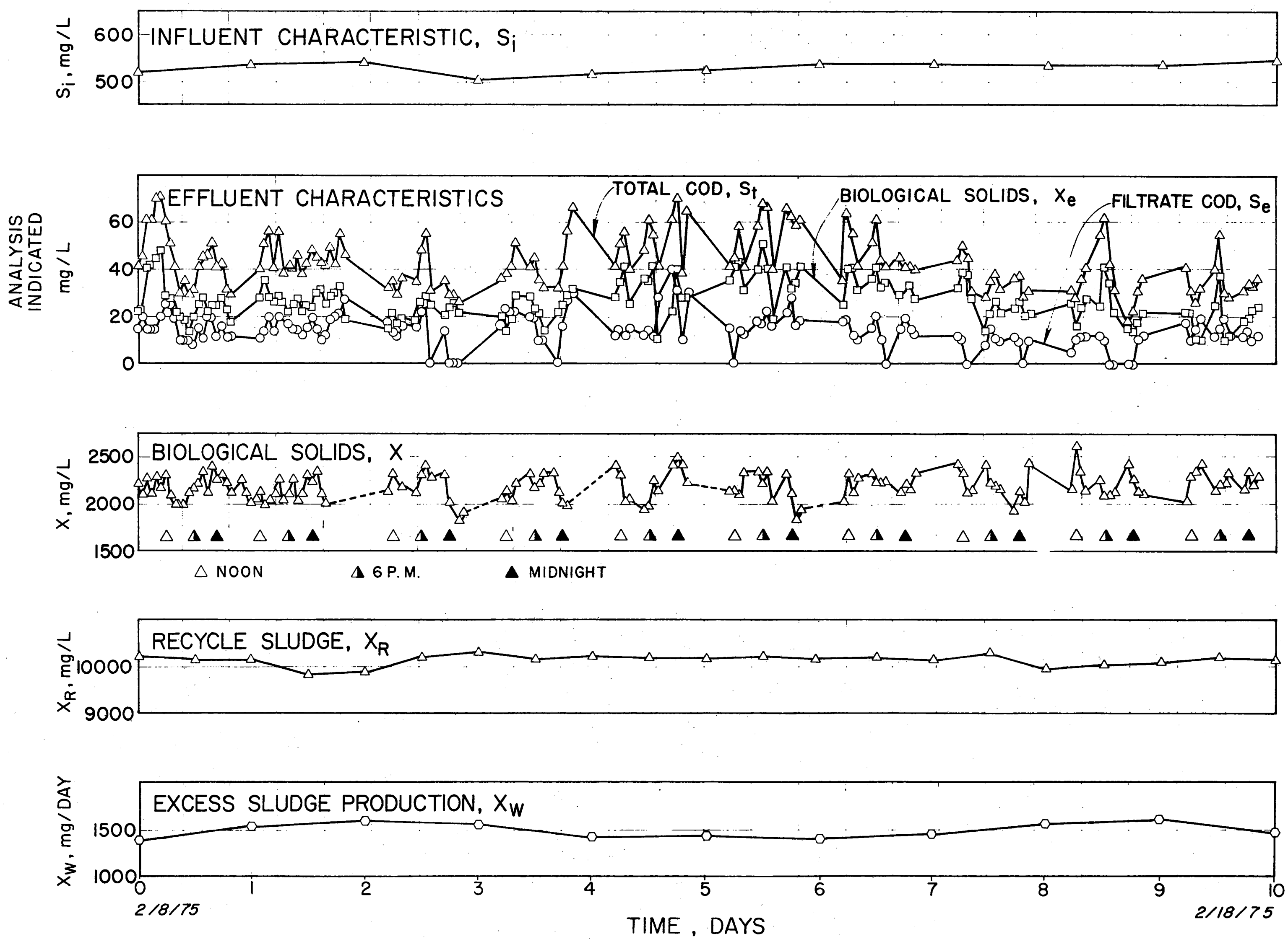
uptake in aerator #2 was 7 mg O_2/hr/gm solids. In another experiment during this steady state, values of endogenous O_2 uptake in reactors #1 and #2 were 11 and 4 mg O_2/hr/gm solids, respectively.

Figure 15 shows the behavior of the system under the cyclic shock load condition. It can be seen that when the dilution rate was increased at noon ($\bar{t}$ was changed from 8 to 4 hrs), the biological solids in aerator #1 decreased slightly, while at 6 PM, when the dilution rate was decreased ($\bar{t}$ was changed from 4 to 16 hrs), the solids concentration increased in the reactor, and when the dilution again increased at 12M ($\bar{t}$ was changed from 16 to 8 hrs), the biological solids decreased slightly. The cyclic behavior of the biological solids concentration in aerator #1 was recorded until the ninth day, after which a greater steadiness in biological solids concentration developed and continued until the end of the experimental run (see Figure 16).

In Table IX, the average biomass in aerator #1, the effluent characteristics, recycle sludge and excess sludge production are tabulated for each cyclic period in the 24-hour day for the whole experiment. Average values for all parameters remained approximately the same regardless of the change in hydraulic flow. However, as seen in Figures 15 and 16, there was considerable variation during each day. A maximum of 70 mg/l was recorded for the total effluent substrate COD, S_t. The settling characteristics of the sludge did not change drastically, and the solids concentration in the effluent, X_e, varied in the range of 25 mg/l, with a maximum value of 50 mg/l.

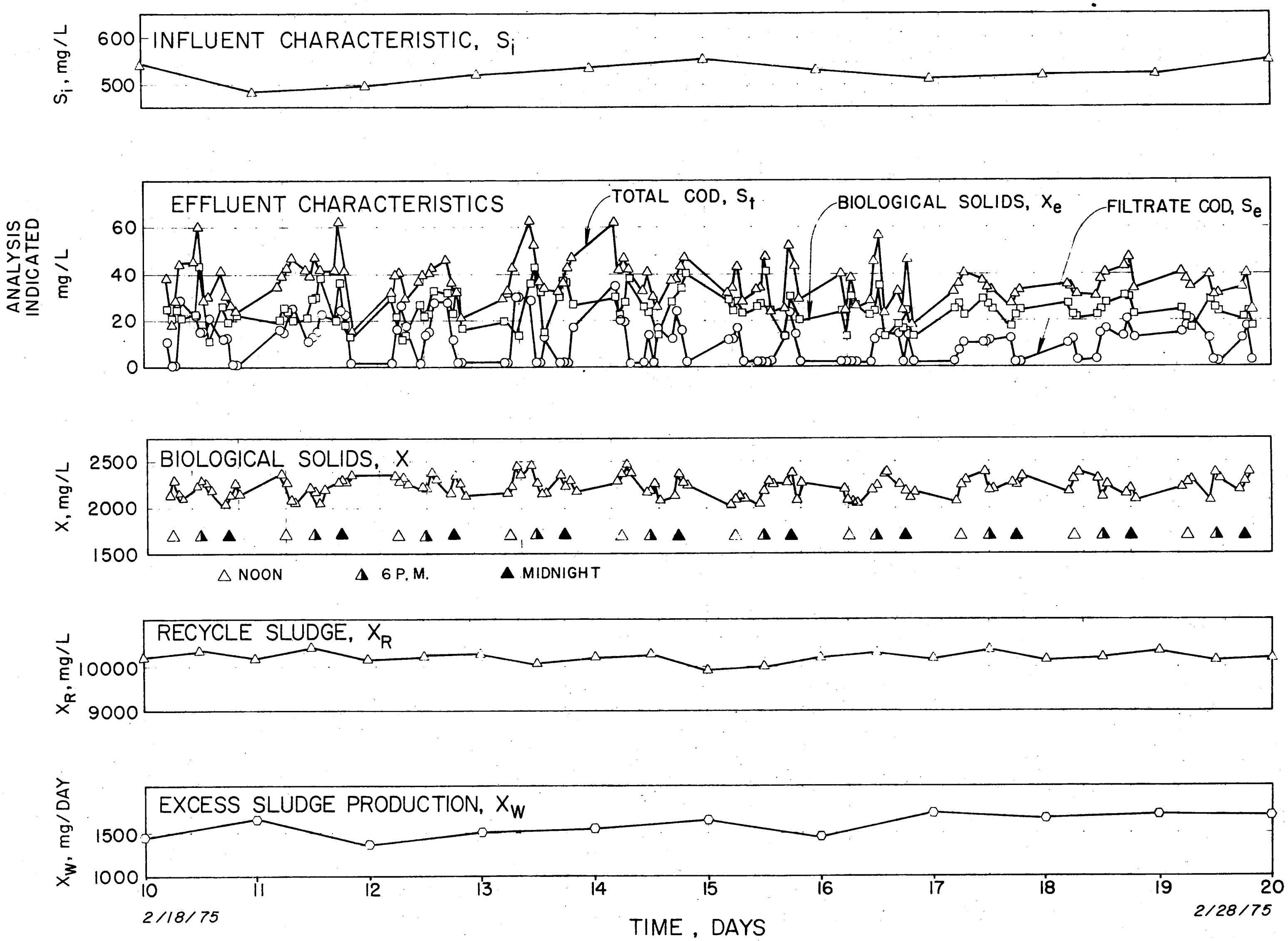
Insofar as steadiness of the system is concerned, biological solids concentration, X, in the reactor was kept in the range between 2000 and 2500 mg/l, and total effluent substrate, S_t, ranged between 16 and

Figure 15. Operational Characteristics for an Activated Sludge Process With Constant X_R of 10,000 mg/l at an S_i of 500 mg/l Subjected to Cyclic Hydraulic Shock Loading at Dilution Rates of 0.125, 0.25, and 0.0625 hr^{-1} Every 24-hour Period (from 2-8-75 to 2-18-75)



INFLUENT CHARACTERISTIC, S_i
S_i, mg/L
600
500
EFFLUENT CHARACTERISTICS
TOTAL COD, S_t
BIOLOGICAL SOLIDS, X_e
FILTRATE COD, S_e
ANALYSIS INDICATED mg/L
60
40
20
0
BIOLOGICAL SOLIDS, X
X, mg/L
2500
2000
1500
△ NOON
▲ 6 P.M.
▲ MIDNIGHT
RECYCLE SLUDGE, X_R
X_R, mg/L
10000
9000
EXCESS SLUDGE PRODUCTION, X_W
X_W, mg/DAY
1500
1000
0
1
2
3
4
5
6
7
8
9
10
2/8/75
2/18/75
TIME , DAYS

Figure 16. Operational Characteristics for an Activated Sludge Process With Constant X_R of 10,000 mg/l at an S_i of 500 mg/l Subjected to Cyclic Hydraulic Shock Loading at Dilution Rates of 0.125, 0.25, and 0.0625 hr^{-1} Every 24-hour Period (from 2-18-75 to 2-28-75)



INFLUENT CHARACTERISTIC, S_i
S_i, mg/L
600
500
EFFLUENT CHARACTERISTICS
TOTAL COD, S_t
BIOLOGICAL SOLIDS, X_e
FILTRATE COD, S_e
ANALYSIS INDICATED mg/L
60
40
20
0
BIOLOGICAL SOLIDS, X
X, mg/L
2500
2000
1500
NOON
6 P.M.
MIDNIGHT
RECYCLE SLUDGE, X_R
X_R, mg/L
10000
9000
EXCESS SLUDGE PRODUCTION, X_W
X_W, mg/DAY
1500
1000
10
11
12
13
14
15
16
17
18
19
20
2/18/75
2/28/75
TIME , DAYS

TABLE IX

AVERAGE CYCLIC HYDRAULIC SHOCK LOAD DATA AT S_i = 500 mg/l GLUCOSE
X_R = 10,000 mg/l AND α = 0.25 (20-day run)

Time	S_i mg/l	S_t mg/l	S_e mg/l	X_e mg/l	X mg/l	X_R mg/l	X_W mg/day
12M-12N		39.0	12.0	24.0	2176.0	10,175	
12N-6PM	524	39.0	13.0	26.0	2179.0	10,137	1500
6PM-12M		42.0	12.0	27.0	2195.0	10,117	

70 mg/l. It was noticed, also that after the thirteenth day, effluent characteristics as monitored in terms of clarifier effluent COD, S_t, filtrate COD, S_e, and supernatant solids concentration, X_e, were subject to less fluctuation (compare Figures 15 and 16). Excess sludge production ranged from 1400 to 1600 mg/day, and appeared to be somewhat cyclic. On day 20, batch studies to determine μ_{max}, K_s, and Y_t were performed. These values were 0.5 hr^{-1}, 131 mg/l, and 0.55, respectively. Average protein and carbohydrate contents for the cells were 52 and 19 percent, respectively. It was also found that very little substrate was left in the recycle filtrate, S_R (12 mg/l). The volatile suspended solids was in the range of 70 to 75 percent.

2. Cyclic Hydraulic Shock Loads With Varying α

It was interesting to study in this experiment the effect of cyclic fluctuation in hydraulic loading along with a change in the recycle flow ratio, α, during a 24-hour period. The mode of hydraulic loading and cycling to which the system was subjected is given in Table X. Three separate hydraulic retention times were employed; the changes were from 8 to 4 to 16 hrs. In the laboratory pilot plant these correspond to flow rates, F, of 4, 8, and 2 ml/min and they were maintained in the system for periods of 12, 6, and 6 hrs, respectively. On the other hand, the recycle flow ratio, α, was varied by keeping the recycle flow rate, F_R, at one ml/min. This resulted in variation of α from 0.25 to 0.125 to 0.50 (Figure 17).

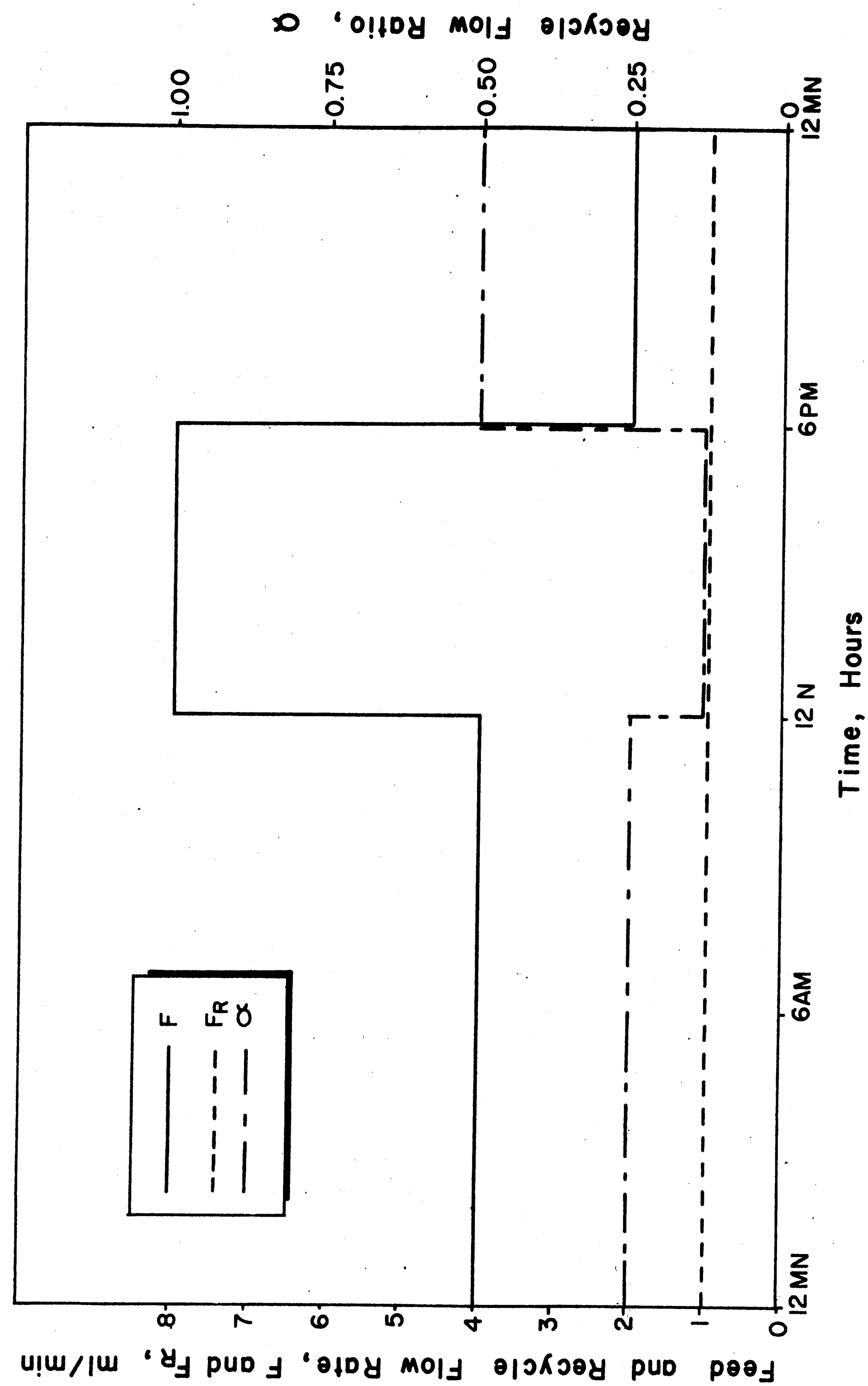
The system was operated for eight days under steady state conditions before applying the shock (Figure 18). The feed concentration, S_i, was 500 mg/l, recycle solids concentration was kept very close to

TABLE X

RELATION BETWEEN MEAN HYDRAULIC RETENTION TIME, $\bar{t}$, DILUTION RATE, D, REACTOR DILUTION RATE, D_1, RECYCLE FLOW RATIO, α, AND REACTOR VOLUME, V (14-day run)

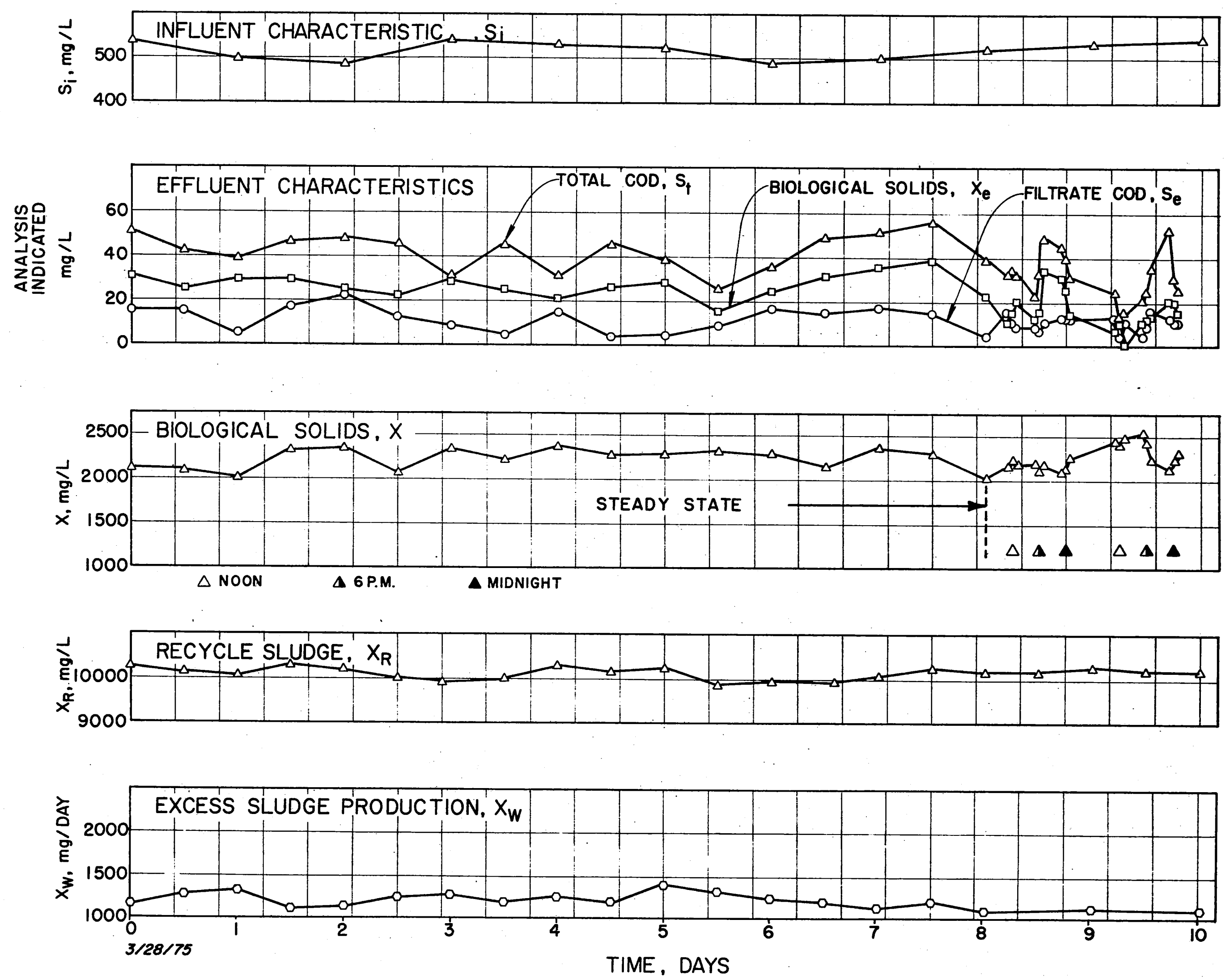
	$\bar{t}$	D	D_1	α	V
Time	hours	hr^{-1}	hr^{-1}	$\frac{F_R}{F}$	liters
12M-12N	8	0.125	0.1563	0.25	1.92
12N-6PM	4	0.250	0.2813	0.125	1.92
6PM-12M	16	0.0625	0.0938	0.50	1.92

Figure 17. Mode of Operation During Cyclic Hydraulic Shock Load With Varying α



Feed and Recycle Flow Rate, F and F_R, ml/min
0
1
2
3
4
5
6
7
8
Recycle Flow Ratio, α
0
0.25
0.50
0.75
1.00
Time, Hours
12MN
6AM
12N
6PM
12MN
F
F_R
α

Figure 18. Operational Characteristics for an Activated Sludge Process With Constant X_R of 10,000 mg/l at an S_i of 500 mg/l Subjected to Cyclic Hydraulic Shock Loading at Dilution Rates of 0.125, 0.25, and 0.0625 hr^{-1} Every 24-hour Period With Varying α (from 3-28-75 to 4-7-75)

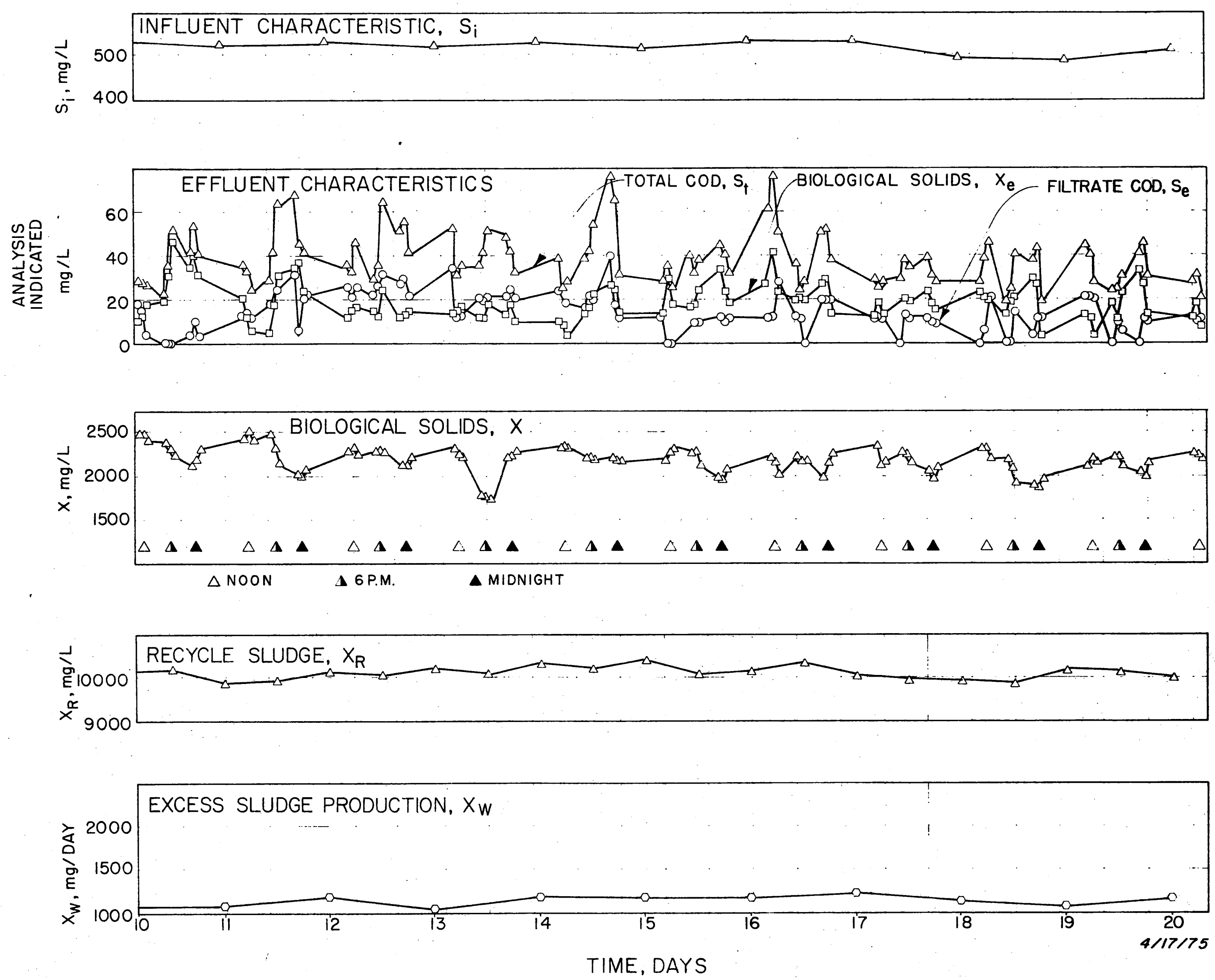


INFLUENT CHARACTERISTIC , Si
Si, mg/L
400
500
EFFLUENT CHARACTERISTICS
TOTAL COD, St
BIOLOGICAL SOLIDS, Xe
FILTRATE COD, Se
ANALYSIS INDICATED mg/L
0
20
40
60
BIOLOGICAL SOLIDS, X
X, mg/L
1000
1500
2000
2500
STEADY STATE
△ NOON
6 P.M.
▲ MIDNIGHT
RECYCLE SLUDGE, XR
XR, mg/L
9000
10000
EXCESS SLUDGE PRODUCTION, XW
XW, mg/DAY
1000
1500
2000
0
1
2
3
4
5
6
7
8
9
10
3/28/75
TIME, DAYS

10,000 mg/l, which is close to the values observed in the field. In Table VI, line 28, the average performance characteristics of the pilot plant are shown. The loading ranged from 482 to 535 mg/l COD, with an average of 508 mg/l, and recycle solids concentration, X_R, ranged from 9880 to 10,280 mg/l, with an average of 10,075 mg/l. The effluent filtrate COD varied from 5 to 22, with an average of 12 mg/l, and the filtrate substrate in the recycle biomass, S_R, varied between zero and 20, with an average of 7 mg/l. The average biological solids concentration, $\bar{X}$, in aerator #1 was 2210 mg/l, ranging from 2021 to 2374 mg/l, and the volatile suspended solids ranged from 70 to 76 percent. The excess sludge production, X_W, was 1222 mg/day on average, with a range of 1000 to 1361 mg/day. In Table VII, experiment 28, the biological constants, μ_{max}, K_s, and Yt, determined from the batch growth pattern, are shown. The μ_{max} value was 0.44 hr^{-1}, the K_s value was 110 mg/l, and the batch growth yield was 0.45.

After determining the steady state performance, the system was subjected to cyclic hydraulic shock loading for almost twelve days. Figures 18 and 19 show the behavior of the biological solids in aerator #1, X, the effluent characteristics as indicated by total COD, S_t, filtrate COD, S_e, and the biological solids in the effluent, X_e. The biological solids showed a cyclic trend with a cycling increase and decrease in amplitude of approximately 500 mg/l. It was noticed that the biological solids concentration decreased slightly in the period from 6 PM to 12 midnight, when $\bar{t}$ was changed from 4 to 16 hrs and α from 0.125 to 0.50. The fluctuation in biological solids concentration in aerator #1 was not accompanied by severe losses of cells and substrate in the effluent; however, as seen in Figures 18 and 19, the

Figure 19. Operational Characteristics for an Activated Sludge Process With Constant X_R of 10,000 mg/l at an S_i of 500 mg/l Subjected to Cyclic Hydraulic Shock Loading at Dilution Rates of 0.125, 0.25, and 0.0625 hr^{-1} With Varying α Every 24-hour Period (from 4-7-75 to 4-17-75)



INFLUENT CHARACTERISTIC, S_i
S_i, mg/L
500
400
EFFLUENT CHARACTERISTICS
TOTAL COD, S_t
BIOLOGICAL SOLIDS, X_e
FILTRATE COD, S_e
ANALYSIS INDICATED mg/L
60
40
20
0
BIOLOGICAL SOLIDS, X
X, mg/L
2500
2000
1500
△ NOON
◭ 6 P.M.
▲ MIDNIGHT
RECYCLE SLUDGE, X_R
X_R, mg/L
10000
9000
EXCESS SLUDGE PRODUCTION, X_W
X_W, mg/DAY
2000
1500
1000
10
11
12
13
14
15
16
17
18
19
20
TIME, DAYS
4/17/75

effluent characteristics during the cyclic shock load, as monitored by the total substrate COD, S_t, reached a maximum value of 76 mg/l, which resulted in a minimum total removal efficiency of 85 percent. The maximum filtrate COD, S_e, was 40 mg/l, giving a 92 percent biochemical removal efficiency. During this experiment, total organic carbon determinations for effluent filtrate (TOC) were added to those usually run. However, they were run each two days rather than daily. During the cyclic shock, TOC ranged between 2.1 and 4.45 mg/l, with an average of 3.5 mg/l. In Table XI, the average biomass in aerator #1, the effluent characteristics, recycle sludge and excess sludge production are tabulated for each loading period in the 24-hour day for the entire experiment. The average values for the effluent characteristics in the periods 12M-12N and 6PM-12M remained approximately the same, while the period 12N-6PM gave slightly higher values. The average biomass in the period 12M-12N was higher by 200 and 300 mg/l than in the periods 12N-6PM and 6PM-12M, respectively. However, regardless of the changes in the biomass in aerator #1, on the average basis the effluent characteristics did not change drastically. Excess sludge production, X_W, during the entire cycling experiment stayed fairly steady, with an average of 1139 mg/day. On day 19, batch studies to determine μ_{max}, K_s, and Y_t were performed. These values were 0.5 hr^{-1}, 285 mg/l, and 0.54, respectively (not recorded in Table VII).

3. Cyclic Quantitative Shock Loads With Constant α

Quantitative shock loads of a cyclic nature were also investigated. The normal 500 mg/l standard feed solution was pumped for twelve hours, and a triple increase in substrate concentration was introduced into the

TABLE XI

AVERAGE CYCLIC HYDRAULIC SHOCK LOAD DATA AT S_i = 500 mg/l GLUCOSE, X_R = 10,000 mg/l AND WITH DIFFERENT VALUES OF RECYCLE FLOW RATIO, α (14-day run)

Time	S_i mg/l	S_t mg/l	S_e mg/l	X_e mg/l	X mg/l	X_R mg/l	X_W mg/day
12M-12N	525	32.0	13.0	15.0	2426.0	10,136	
12N-6PM	525	45.0	20.0	26.0	2249.0	10,104	1139.0
6PM-12M	525	33.0	13.0	16.0	2147.0	10,177	

reactor for the remaining 12-hour period. The feed dilution rate, D, was kept constant ($D = 0.125\ hr^{-1}$) during the 24-hour period as well as the recycle flow ratio ($\alpha = 0.25$). The mode of quantitative cycling to which the system was subjected is entered in Table XII. The mean hydraulic retention time was eight hours during the entire run. The feed flow rate applied to the pilot plant was 4 ml/min, while the recycle flow rate was one ml/min (Figure 20).

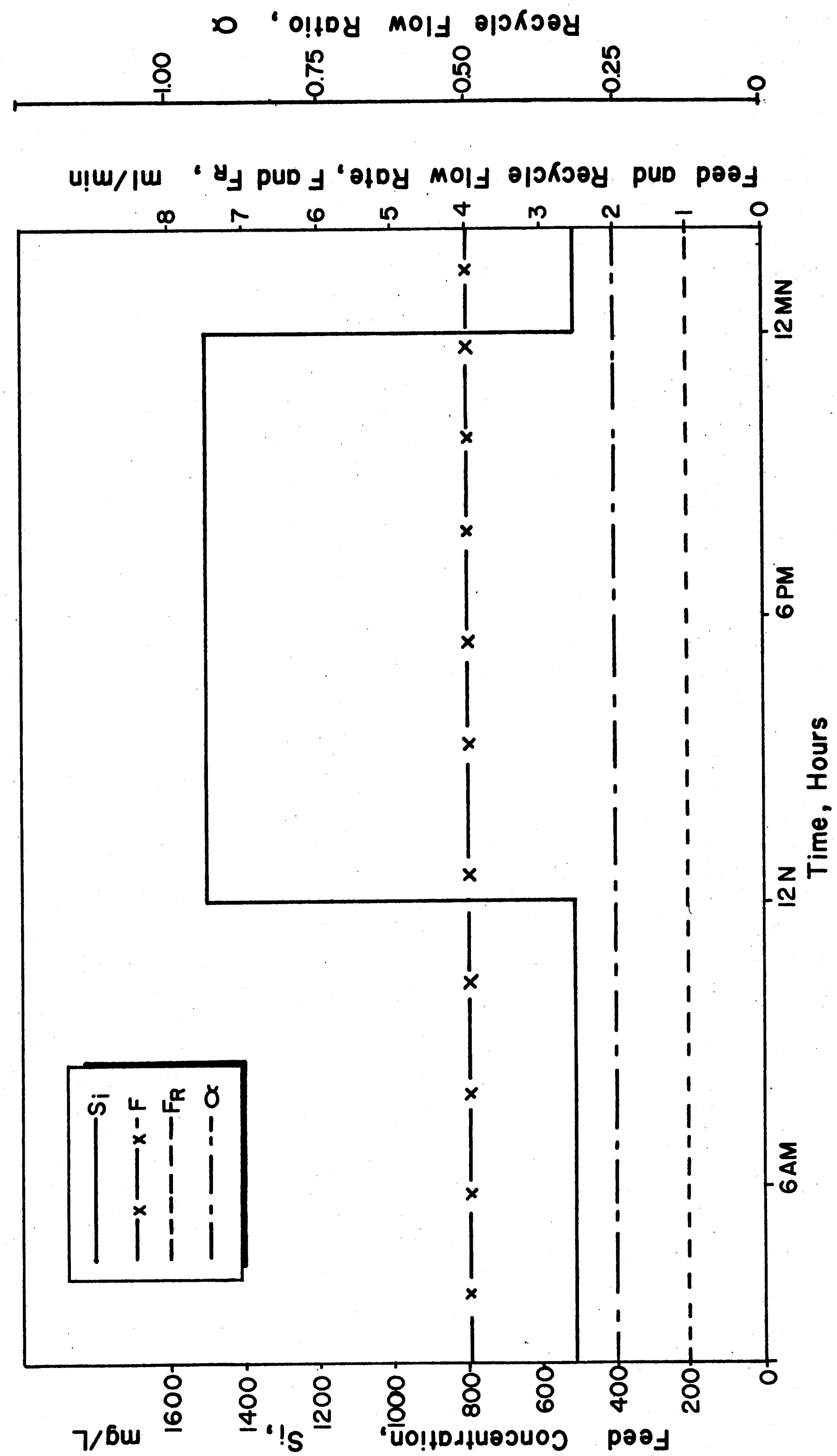
Before administering the new quantitative shock load, a steady state was maintained for twelve days (in the interest of brevity, not shown in Figure 21). The recycle solids concentration, X_R, at which the behavior of the system was tested during this experiment, was 10,000 mg/l. In Table VI (line 29), the average performance characteristics of the pilot plant for an S_i loading ranging from 492 to 541 mg/l COD and recycle biological solids concentration ranging from 9814 to 10,140 mg/l, with an average of 10,008 mg/l, are recorded. Ammonia in the feed was in the range from 48 to 60 mg/l, with an average of 52 mg/l. The total effluent COD, S_t, was in the range from 21 to 38 mg/l, with an average of 29 mg/l, and the biological solids in the effluent was in the range from 10 to 25 mg/l, with an average of 17 mg/l. The effluent filtrate COD varied from 4 to 14, with an average of 10 mg/l, while the 5-day BOD samples indicated lower values ranging from zero to 12 mg/l. Ammonia in the effluent was in the range from 30 to 38 mg/l, and TOC ranged from 1.4 to 8.6 mg/l. The percent volatile suspended solids was in the range from 68 to 78, with an average of 74 percent. Nitrate was determined for the filtrate effluent, and very low concentrations were observed, varying between zero and 3 mg/l. Protein and carbohydrate contents of the sludge averaged 40 and 23 percent,

TABLE XII

RELATION BETWEEN FEED SUBSTRATE CONCENTRATION, S_i, HYDRAULIC RETENTION TIME, $\bar{t}$, DILUTION RATE, D, REACTOR DILUTION RATE, D_1, AND RECYCLE FLOW RATIO, α (17-day run)

	S_i	$\bar{t}$	D	D_1	α
Time	mg/l	hours	hr^{-1}	hr^{-1}	$\frac{F_R}{F}$
12M-12N	500	8	0.125	0.15625	0.25
12N-12M	1500	8	0.125	0.15625	0.25

Figure 20. Mode of Operation During Cyclic Quantitative Shock Load


Recycle Flow Ratio, α
0
0.25
0.50
0.75
1.00
Feed and Recycle Flow Rate, F and F_R, ml/min
0
1
2
3
4
5
6
7
8
Feed Concentration, Si, mg/L
0
200
400
600
800
1000
1200
1400
1600
Time, Hours
6AM
12N
6PM
12MN
Si
x-F
F_R
α

respectively. The average biological solids concentration in this steady state was 2204 mg/l, with a range from 2048 to 2304 mg/l. The excess sludge production, X_W, was 1316 mg/day on average, and was relatively steady throughout the run. The cyclic quantitative shock load was imposed for seventeen days. Table XII and Figure 20 show the operational parameters and cyclic schedule during any given 24-hour period. The system biomass fluctuated in a cyclic manner every day. In Figures 21 and 22 it is seen that the biological solids concentration increased in response to the three-fold increase in substrate concentration, and decreased upon decreasing the feed substrate concentration to 500 mg/l. It should be noted that although the inflowing feed concentration was changed abruptly from 500 to 1500 mg/l glucose, the 12-hour cyclic period was not long enough to have permitted complete dilute-in of this S_i. For a feed COD of 1590 mg/l (due to 1500 mg/l glucose), the S in the reactor, were it not removed by the cells, could attain a value of 1590 $\left(\frac{1}{1+\alpha}\right)$ = 1272 mg/l. In twelve hours, 1200 mg/l concentration according to the theoretical dilute-in curve could attain a value of 1200 mg/l and would follow the course of the dotted line shown in the top graph of Figures 21 and 22. The dotted lines are shown simply to given an idea of the rate at which the loading came on and off the system. The difference between the maximum and the minimum biological solids concentrations during the day was 300 mg/l. This difference in biomass concentration was observed for almost twelve days, after which a 200 mg/l difference was recorded. The total effluent COD, S_t, showed a maximum value of 70 mg/l, while the filtrate effluent substrate COD, S_e, did not rise higher than 26 mg/l. It was interesting to note that there was a greater steadiness in effluent characteristics after the fifth day,

Figure 21. Operational Characteristics for an Activated Sludge Process With Constant X_R of 10,000 mg/l at an S_i of 500 mg/l Subjected to Cyclic Quantitative Shock Loading of 500 and 1500 mg/l Every 24-hour Period (from 5-2-75 to 5-10-75)

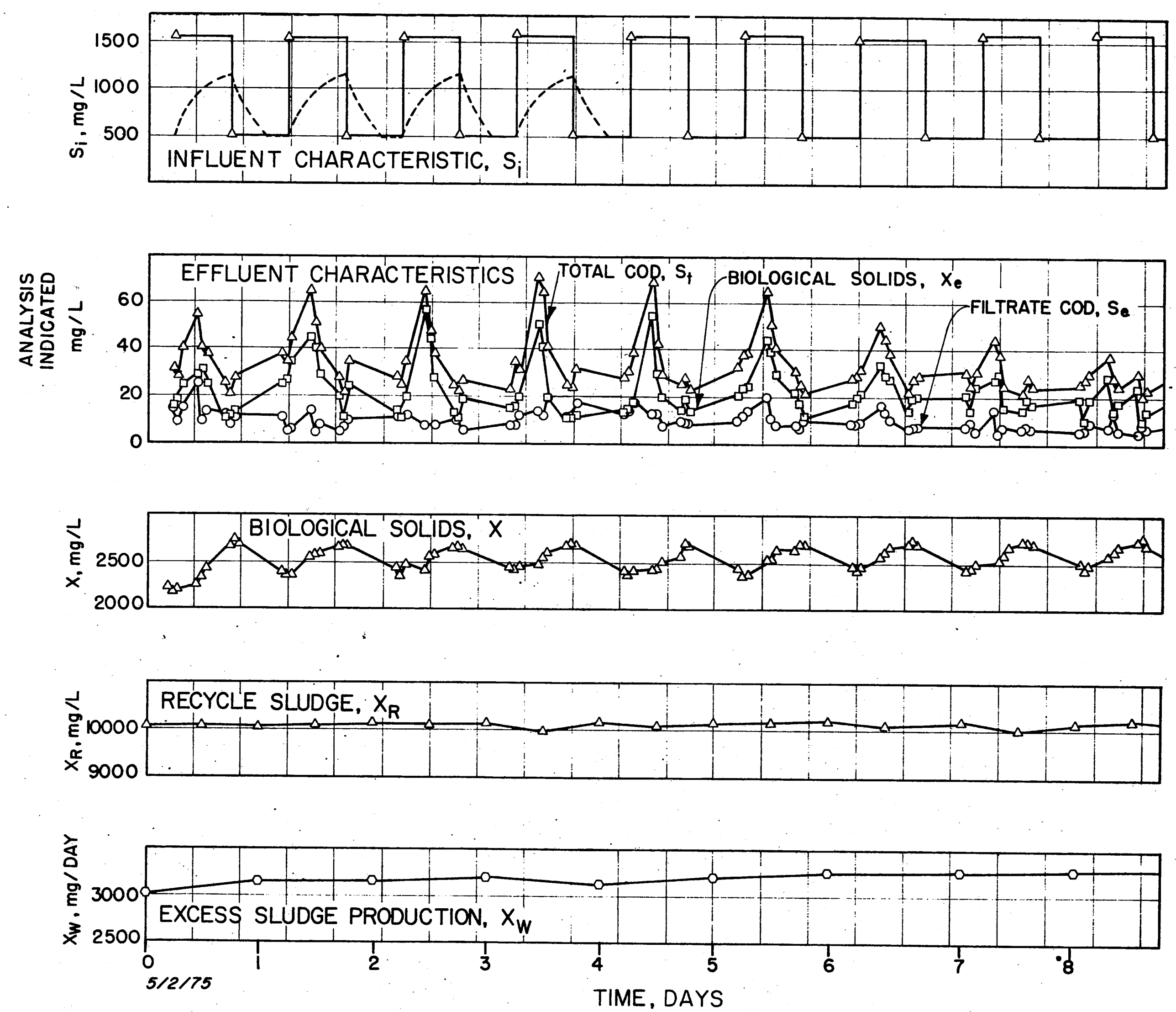
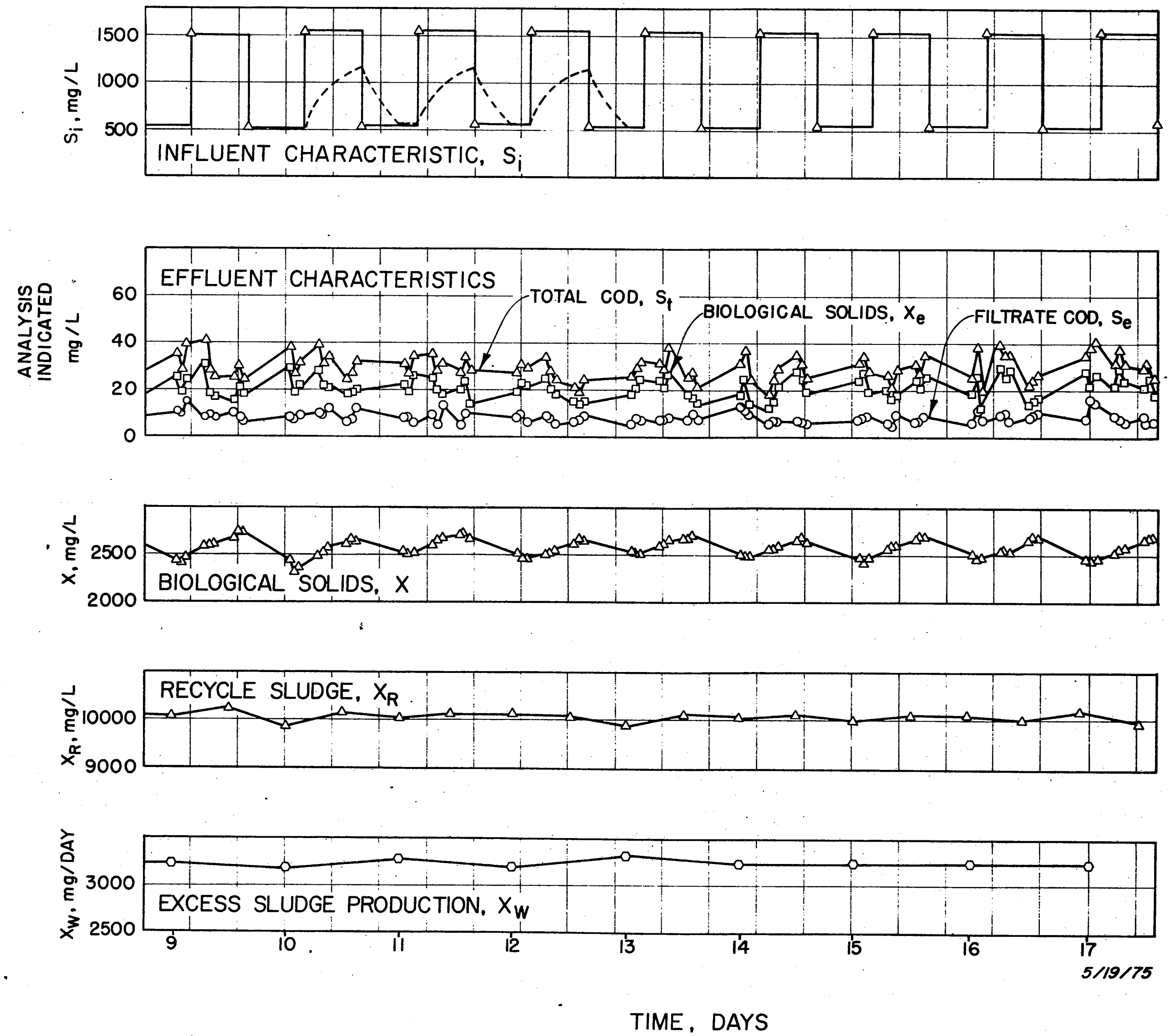

INFLUENT CHARACTERISTIC, S_i
S_i, mg/L
1500
1000
500
EFFLUENT CHARACTERISTICS
TOTAL COD, S_t
BIOLOGICAL SOLIDS, X_e
FILTRATE COD, S_e
ANALYSIS INDICATED mg/L
60
40
20
0
BIOLOGICAL SOLIDS, X
X, mg/L
2500
2000
RECYCLE SLUDGE, X_R
X_R, mg/L
10000
9000
EXCESS SLUDGE PRODUCTION, X_W
X_W, mg/DAY
3000
2500
0
1
2
3
4
5
6
7
8
5/2/75
TIME, DAYS

Figure 22. Operational Characteristics for an Activated Sludge Process With Constant X_R of 10,000 mg/l at an S_i of 500 mg/l Subjected to Cyclic Quantitative Shock Loading at an S_i of 500 and 1500 mg/l Every 24-hour Period (from 5-10-75 to 5-19-75)


INFLUENT CHARACTERISTIC, S_i
S_i, mg/L
1500
1000
500
EFFLUENT CHARACTERISTICS
ANALYSIS INDICATED mg/L
TOTAL COD, S_t
BIOLOGICAL SOLIDS, X_e
FILTRATE COD, S_e
60
40
20
0
BIOLOGICAL SOLIDS, X
X, mg/L
2500
2000
RECYCLE SLUDGE, X_R
X_R, mg/L
10000
9000
EXCESS SLUDGE PRODUCTION, X_W
X_W, mg/DAY
3000
2500
9
10
11
12
13
14
15
16
17
5/19/75
TIME, DAYS

and the trend continued until the end of the experimental run. After the fifth day of operation, the total effluent COD, S_t, did not rise to a value more than 40 mg/l. A few samples were checked for the filtrate COD, S_{R_1}, in aerator #1. They were approximately the same values obtained in the effluent filtrate COD, S_e. The recycle sludge concentration was very close to the desired 10,000 mg/l. The excess sludge produced per day was in the range of 3100 to 3300 mg/day. In Table XIII, the average biomass in aerator #1, the effluent characteristics, recycle sludge and excess sludge production are tabulated for each applied period in the 24-hour day for the entire experiment. The average values for effluent characteristics were almost the same regardless of the fluctuation in loading. The biomass concentration in the period from 12M-12N was higher by approximately 300 mg/l than the average in the period 12N-12M.

Checks for protein and carbohydrate content of the cells indicate fluctuation of values (not plotted in Figures 21 and 22). Excess sludge produced, X_W, during the cyclic experiment was two and one-half times the average in the previous steady state (compare values in Table XIII and line 29 in Table VI). It ranged from 3019 to 3306 mg/day, with an average of 3260 mg/day.

4. Cyclic Quantitative-Hydraulic Shock Loading With Constant α

It was decided to study in this experiment the response of the system to simultaneous cyclic fluctuation in substrate and hydraulic loading during each 24-hour period. The mode of quantitative and

TABLE XIII

AVERAGE CYCLIC QUANTITATIVE SHOCK LOAD DATA AT S_i OF 500 TO 1500 mg/l GLUCOSE, X_R = 10,000 mg/l AND WITH CONSTANT VALUE OF RECYCLE FLOW RATIO, α = 0.25 (17-day run)

	S_i	S_t	S_e	X_e	X	X_R	X_W
Time	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/day
12M-12N	504	30.0	9.0	19.0	2421	10,082	3260
12N-12M	1569	29.0	9.0	24.0	2165	10,180	

hydraulic cycling to which the system was subjected is entered in Table XIV. Two hydraulic retention times were employed, $\bar{t}$ = 8 and 4 hrs. In the laboratory pilot plant these corresponded to flow rates, F, of 4 and 8 ml/min, and they were held on the system for equal durations of twelve hours. At the same time the feed concentration, S_i, was increased from 500 mg/l to 1500 mg/l at twelve noon and was kept on the system for a duration of twelve hours, after which it decreased at twelve midnight to 500 mg/l and was kept on the system for the remaining twelve hours (also see Figure 23). The recycle flow rate was changed during the hydraulic shock period in order to keep the ratio between the recycle flow rate and the inflow rate, α, constant at 0.25. On the basis of daily mass loading, the system was subjected to a six-fold increase during the period of twelve hours. In other words, the system was exposed to two different mass loading rates, 3000 and 18,000 mg/day (glucose) during each 12-hour period. Before subjecting the system to the hydraulic-quantitative cyclic shock load, the system was tested for steadiness with recycle solids concentration, X_R, of 10,000 mg/l. In Table VI (line 30) the average performance characteristics of the pilot plant are given. The feed concentration, S_i, ranged from 512 to 541 mg/l of COD, with an average of 526 mg/COD. The steadiness of the system in this pre-shock state is shown by the effluent characteristics, as well as by the biological solids concentration X (see Figure 24). The effluent COD, S_e, varied from 4 to 20 mg/l, with an average of 9 mg/l, while the 5-day BOD in the supernatant ranged from 5 to 10 mg/l, with an average of 8 mg/l. The biological solids concentration, X, ranged from 2154 to 2344 mg/l, with an average of 2247 mg/l. The range in which recycle sludge, X_R, varied was from 9889 to 10,204 mg/l, and the filtrate, S_R, in reactor #2

TABLE XIV

RELATION BETWEEN FEED SUBSTRATE CONCENTRATION, S_i, HYDRAULIC RETENTION TIME, $\bar{t}$, DILUTION RATE, D, REACTOR DILUTION RATE, D_1, AND RECYCLE FLOW RATIO, α (18-day run)

	S_i	$\bar{t}$	D	D_1	α
Time	mg/l	hours	hr^{-1}	hr^{-1}	$\frac{F_R}{F}$
12M-12N	500	8	0.125	0.15625	0.25
12N-12M	1500	4	0.250	0.3125	0.25

Figure 23. Mode of Operation During Cyclic Hydraulic-Quantitative Shock Load

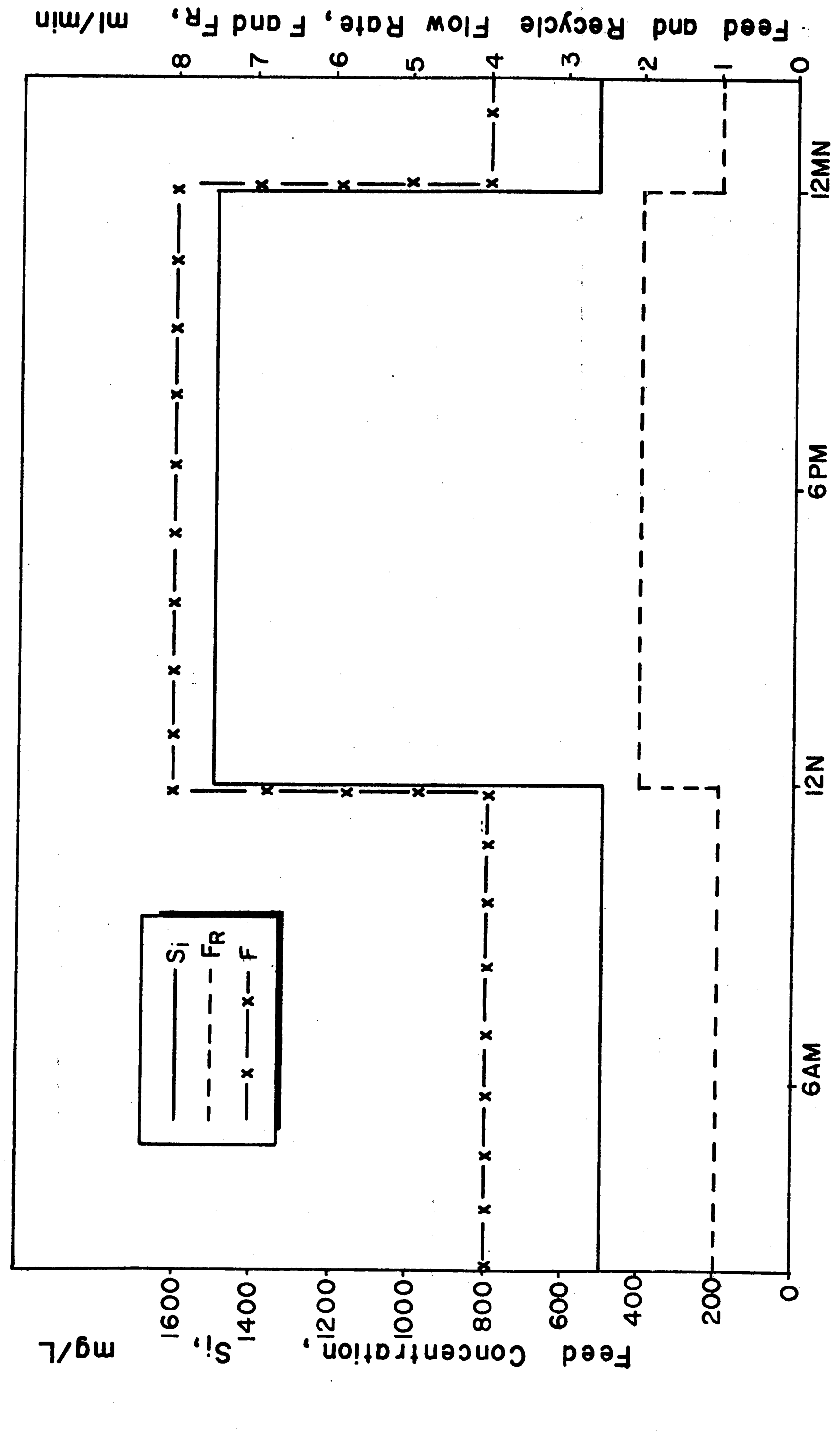
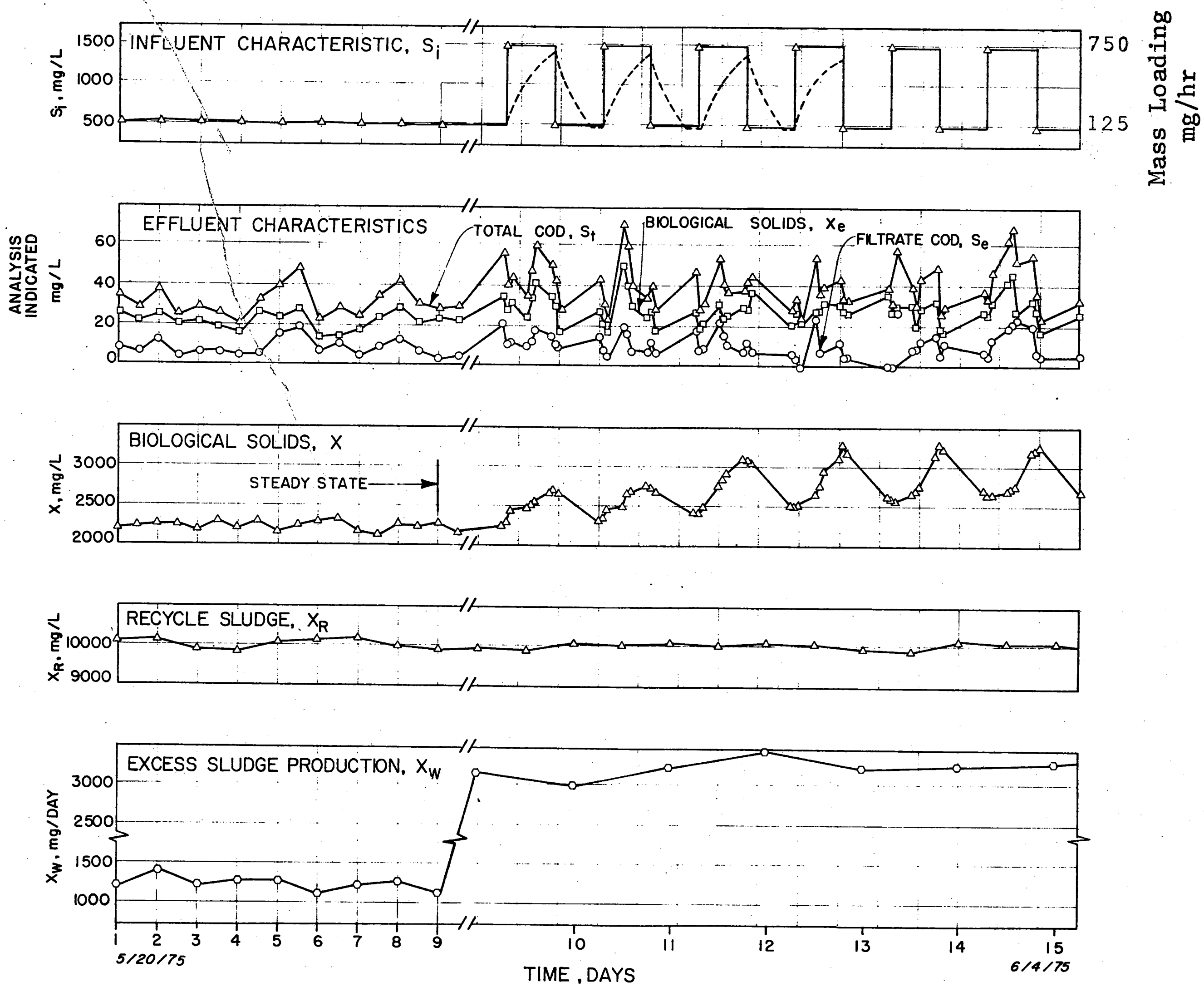

Feed and Recycle Flow Rate, F and F_R, ml/min
0
1
2
3
4
5
6
7
8
Feed Concentration, S_i, mg/L
0
200
400
600
800
1000
1200
1400
1600
6AM
12N
6PM
12MN
S_i
F_R
F

Figure 24. Operational Characteristics for an Activated Sludge Process With Constant X_R of 10,000 mg/l at an S_i of 500 mg/l Subjected to Cyclic Hydraulic and Quantitative Shock Loading by Changes in D and S_i From 0.125 to 0.25 hr^{-1} and From 500 to 1500 mg/l, Respectively, Every 24-hour Period (from 5-28-75 to 6-4-75)

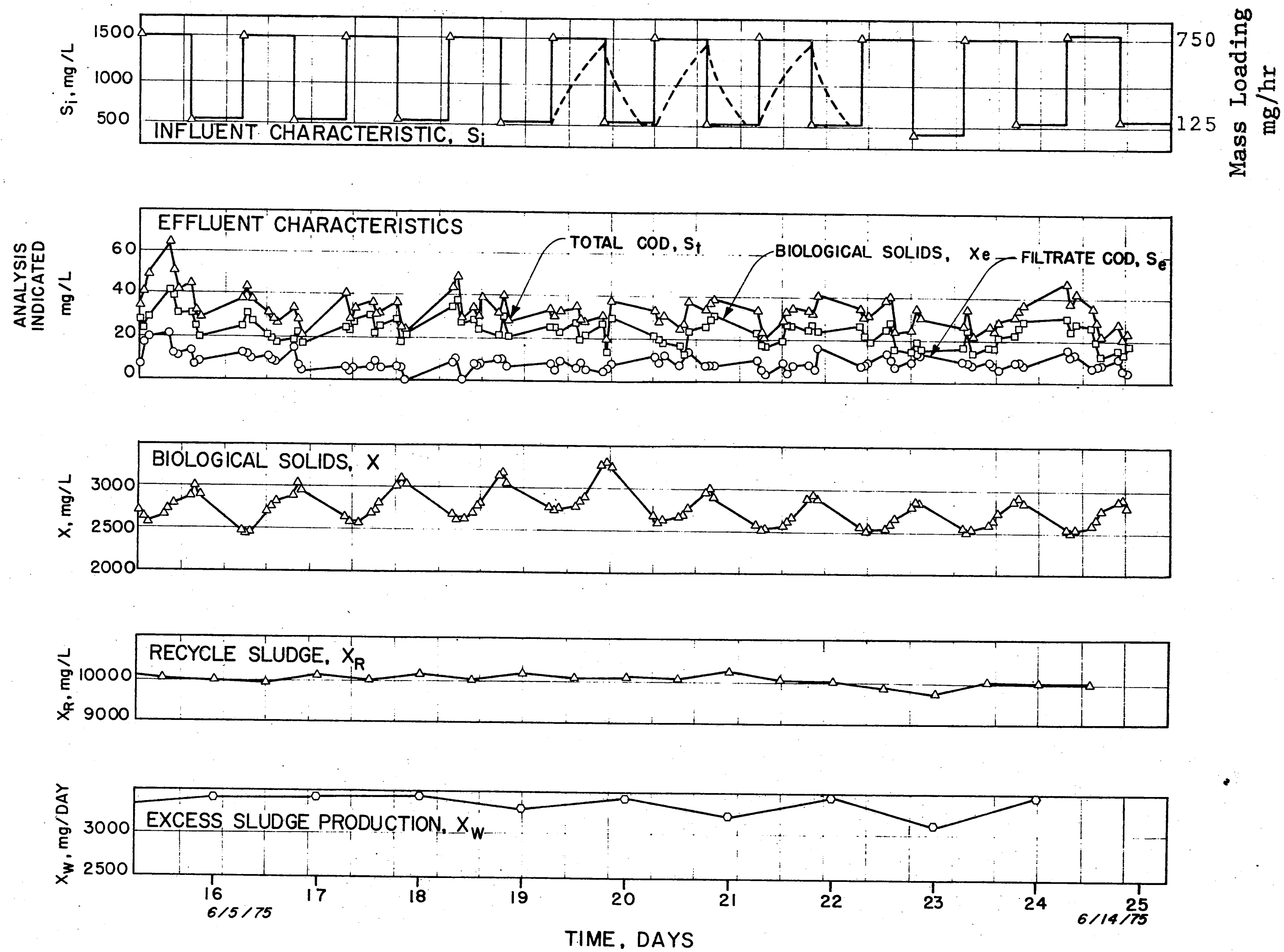


INFLUENT CHARACTERISTIC, S_i
S_i, mg/L
1500
1000
500
750
125
Mass Loading mg/hr
EFFLUENT CHARACTERISTICS
ANALYSIS INDICATED mg/L
TOTAL COD, S_t
BIOLOGICAL SOLIDS, X_e
FILTRATE COD, S_e
60
40
20
0
BIOLOGICAL SOLIDS, X
X, mg/L
3000
2500
2000
STEADY STATE
RECYCLE SLUDGE, X_R
X_R, mg/L
10000
9000
EXCESS SLUDGE PRODUCTION, X_W
X_W, mg/DAY
3000
2500
1500
1000
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
5/20/75
6/4/75
TIME, DAYS

ranged from zero to 14 mg/l. Excess sludge production, X_W, was 1288 mg/day on the average, and was relatively steady throughout the run. Protein and carbohydrate contents of the cells were 51 and 20 on average. The volatile suspended solids ranged from 69 to 78 percent.

The hydraulic-quantitative cyclic shock load was administered for 15 days (Figures 24 and 25). The top graph of Figures 24 and 25 shows the influent substrate concentration, S_i. The dotted lines show the course of mass loading in mg glucose/hr. This curve is plotted to provide a picture of the changes in loading conditions. The system biological solids concentration fluctuated in a cyclic manner each day. The biological solids increased in response to the increase in substrate and hydraulic flow rate, and decreased when the flow rate and substrate concentrations were decreased. During the first four days there was a cyclic but generally rising trend in solids concentration. The net result at the end of the fourth day of shock was an increase in concentration of biological solids in aerator #1 to a value of 3200 mg/l. During the first six days of shock, effluent COD, S_t, did not rise above 70 mg/l. The highest filtrate effluent COD, S_e, was 26 mg/l. The biological solids concentration continued to fluctuate for another seven days, with an amplitude of 500 mg/l. On the twelfth day of the cyclic shock, the biomass in aerator #1 began to fluctuate in a narrower range of 300 mg/l until the end of the experiment. In general, the biomass behaved like a sine curve from the 12th to 17th days with high and low peaks of 2960 and 2550 mg/l, respectively. During the last nine days of the run, the total effluent COD, S_t, was excellent and, in general, did not rise above 40 mg/l. The biological solids, X_e, was 32 mg/l on average. Daily excess sludge production, X_W, was on average

Figure 25. Operational Characteristics for an Activated Sludge Process With Constant X_R of 10,000 mg/l at an S_i of 500 mg/l Subjected to Cyclic Hydraulic and Quantitative Shock Loading by Changes in D and S_i From 0.125 to 0.25 hr^{-1} and From 500 to 1500 mg/l, Respectively, Every 24-hour Period (from 6-5-75 to 6-14-75)



INFLUENT CHARACTERISTIC, S_i
S_i, mg/L
1500
1000
500
750
125
Mass Loading mg/hr
EFFLUENT CHARACTERISTICS
ANALYSIS INDICATED mg/L
60
40
20
0
TOTAL COD, S_t
BIOLOGICAL SOLIDS, X_e
FILTRATE COD, S_e
BIOLOGICAL SOLIDS, X
X, mg/L
3000
2500
2000
RECYCLE SLUDGE, X_R
X_R, mg/L
10000
9000
EXCESS SLUDGE PRODUCTION, X_W
X_W, mg/DAY
3000
2500
16
17
18
19
20
21
22
23
24
25
6/5/75
6/14/75
TIME, DAYS

3300 mg/day, and was steady during the entire experiment.

In Table XV, the average biomass in aerator #1, the effluent characteristics, recycle sludge and excess sludge production are tabulated for each applied period in the 24-hour day for the entire experiment. The average biomass concentration in the period from 12M-12N was 200 mg/l more than in the period 12N-12M. The effluent characteristics as monitored by S_t, S_e, and X_e remained almost the same, regardless of the changes in hydraulic flow and the feed concentration.

D. Steady State Results

A summary of all steady state continuous flow data collected between shock load experiments has been given in Table VI. The values given for various parameters in this table are averages obtained from individual determinations in steady state operation plotted in Figures 4 through 24. The total number of steady states examined was thirty-eight, and the period for each run is indicated by the date of beginning and ending in two separate columns. In each period, samples were taken at least daily, and often more frequently; the runs are arranged chronologically. Although most of the runs were made at the same dilution rate, the variations of X_R and S_i provided a rather wide range of values of μ_n (and its reciprocal, Θ_c), and it can be seen that at any μ_n employed, the system operated at better than 92 percent efficiency throughout this investigation based on filtrate COD and was, for the most part, above 90 percent removal based on supernatant COD. It is also seen that very little carbohydrate was left in the filtrate effluent. Anthrone test results showed a maximum of 28 mg/l in the filtrate effluent, which represents about 99 percent removal of the original

TABLE XV

AVERAGE CYCLIC HYDRAULIC-QUANTITATIVE SHOCK LOAD DATA AT S_i OF 500 to 1500 mg/l GLUCOSE, X_R = 10,000 mg/l, AND WITH CONSTANT VALUE OF RECYCLE FLOW RATIO, α = 0.25 (17-day run)

Time	S_i mg/l	S_t mg/l	S_e mg/l	X_e mg/l	X mg/l	X_R mg/l	X_W mg/l
12M-12N	522	35	10.0	26	2888	10,146	3317
12N-12M	1530	38	11.0	27	2704	10,083	

carbohydrate (Table VI, line 32). The quality of the clarifier supernatant is expressed in terms of total COD, BOD, and biological solids concentration. The purification efficiency based on S_i was as high as 98 percent, and as low as 83 percent. The low removal efficiency was due to the effect of poor settling of the biomass as a result of previous severe hydraulic shock loading (lines 22 and 37). BOD values were, in general, very low; the highest recorded values were for steady states following rather severe shock loads (see lines 32, 34, and 38). The average values of X were dependent on the concentration of recycle sludge, X_R; e.g., steady states at lines 18, 9, 21, 1, and 15 were obtained with recycle sludge concentrations of 15,000, 12,000, 10,000, 8000, and 6000 mg/l, respectively, and the corresponding biological solids concentrations in aerator #1 were 3115, 2513, 2200, 1766, and 1421 mg/l. The feed concentration, S_i, also affected the biological solids concentration, X, in aerator #1. For example, comparison of biological solids concentrations for runs #3, 4, and 7, which were made with approximately 8000 mg/l X_R and S_i loadings of 500, 1500, and 3000 mg/l, reveals values of X of 1776, 2237, and 3095 mg/l, respectively. Dilution rate, D, exerted only a slight effect on the biological solids concentration, X. For example, comparison of lines 12, 14, and 13, which represent operation with approximately 8000 mg/l X_R and S_i loading of 500 mg/l with values of D ranging from 0.125 hr^{-1} (lines 12 and 14) to 0.25 hr^{-1} (line 13), reveals values of 1775, 1760, and 1794, respectively. During all steady state runs, the filtrate COD of the recycle sludge, S_R, was negligible compared to feed COD. The protein content of the sludge ranged from 40 to 53 percent, while carbohydrate content varied between 16 and 26 percent. The excess sludge production,

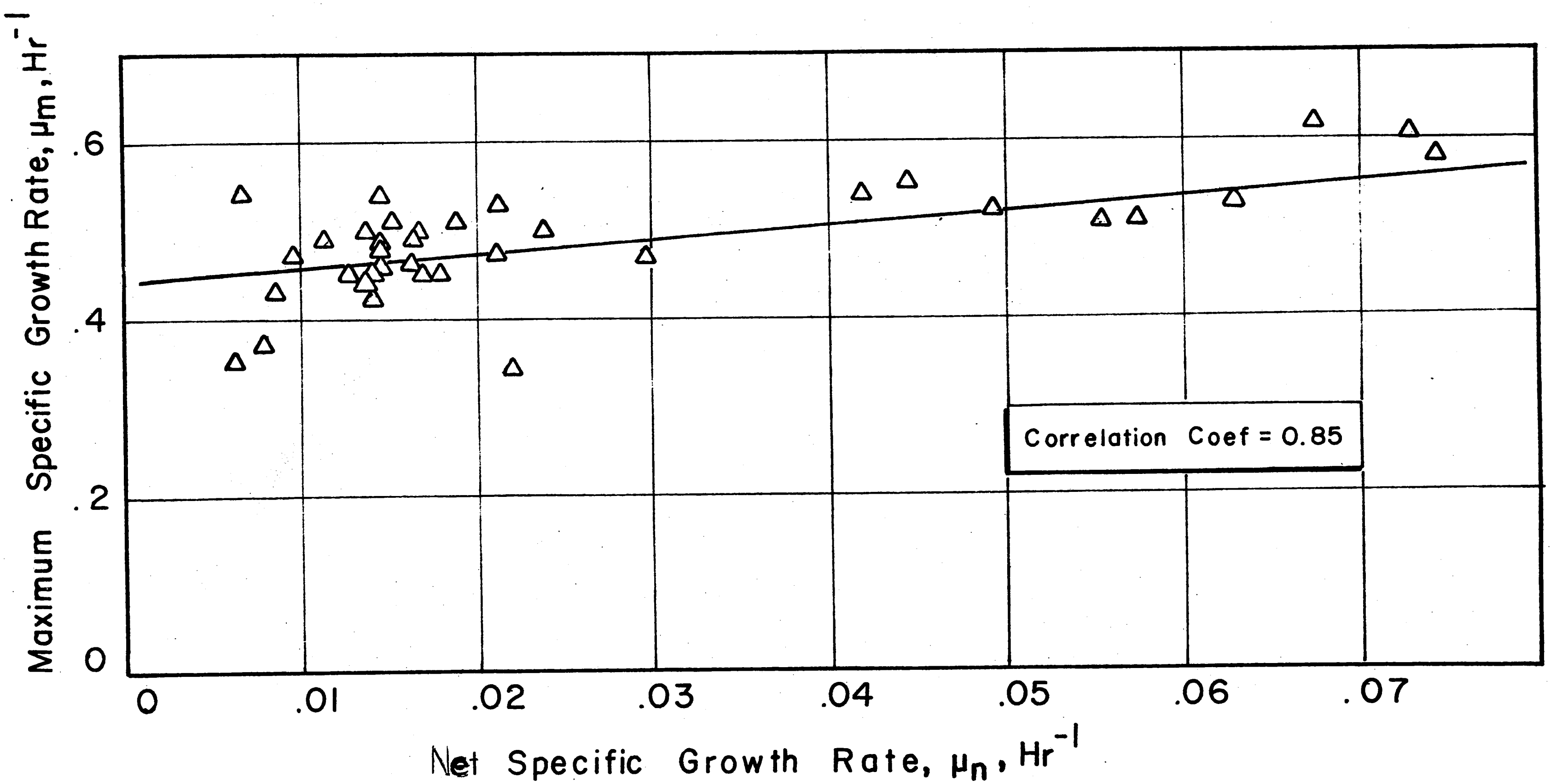
X_W, mg/day was affected by three parameters. First, when the feed concentration, S_i, was constant (500 mg/l) and the recycle sludge concentrations were varied at 15,000, 12,000, 10,000, 8000, and 6000 mg/l, respectively (lines 18, 9, 21, 3, and 15), the amounts of excess sludge production, X_W (mg/day) were 1120, 1140, 1280, 1416, and 1430 mg/day. Thus, X_W decreased with increasing X_R. Second, when the recycle sludge concentration, X_R, was held constant at 8000 mg/l and the feed concentration, S_i, was varied at 500, 1500, and 3000 mg/l (lines 3, 4, and 7), excess sludge production, X_W, was 1416, 4850, and 10,272 mg/day. Third, when S_i and X_R were both constant at 500 and 8000 mg/l, respectively, and dilution rate, D, was varied between 0.125 and 0.25 hr^{-1} (lines 3 and 13), X_W was 1416 and 2502 mg/day, respectively. Thus, X_W is decreased by increasing X_R, and increased by increasing S_i and D.

The results of batch growth studies conducted using cells obtained during different steady state operations were given in Table VII. This table gives the biological constants, μ_{max}, K_s, and Y_{t_B}, at each steady state growth rate, μ_n. Bracketed results, e.g., experiments 3, 4, and 5, indicate results using cells taken from initial, new, and return to initial steady state during step change experiments. It is seen thus, in general, the pre- and post-shock steady state net growth rates were the same; that is to say, the operational conditions did essentially determine the net growth rate. This, in turn, indicates the relative constancy of the biological constants and/or the overriding effect of the selectable operational parameters. Analyses of these related data indicate there were no drastic differences in the biological constants in the initial and post-shock steady states. It can also be seen that experimental runs carried out under the same operational conditions but at widely different times gave rather close values of μ_n.

Examination of the relationship (if any) between μ_n and the biological constants obtained in batch culture is best facilitated by making plots of μ_n vs. μ_{max}, K_s, and Y_{t_B}. Such plots are shown in Figures 26, 27, and 28. It is seen in Figure 26 that there was a slight increase in μ_{max} as μ_n increased; however, no trend was observed for K_s (Figure 28). It is seen in Figure 27 that the true cell yield, Y_{t_B}, decreased with decreasing net growth rate, μ_n.

It was of interest to study the effect of temperature on the biological constants, μ_{max}, K_s, and Y_t. Batch growth studies were conducted on cells taken from aerator #1 during the period 4-20-75 to 5-1-75 (see Table VI, line 29). Experiments were controlled at 30^o, 25^o, and 20^{o}C. Figures 29, 30, and 31 are the plots of the batch growth pattern and relationship between μ and S_o determined from the controlled temperature growth experiments. The μ_{max} values were 0.5, 0.46, and 0.42 hr^{-1} at temperatures of 30^o, 25^o, and 20^o, respectively. The batch yield values were .52, 0.49, and 0.46, respectively. The saturation constant values, K_s, were 278, 270, and 300 mg/l. The values of K_s were higher than those usually observed, though they were not abnormally high.

Figure 26. Relation Between Maximum Specific Growth Rate, μ_{max} and Net Specific Growth Rate, μ_n



Maximum Specific Growth Rate, μm, Hr-1
.6
.4
.2
0
0
.01
.02
.03
.04
.05
.06
.07
Net Specific Growth Rate, μn, Hr-1
Correlation Coef = 0.85

Figure 27. Relation Between Saturation Constant, K_s, and Net Specific Growth Rate, μ_n

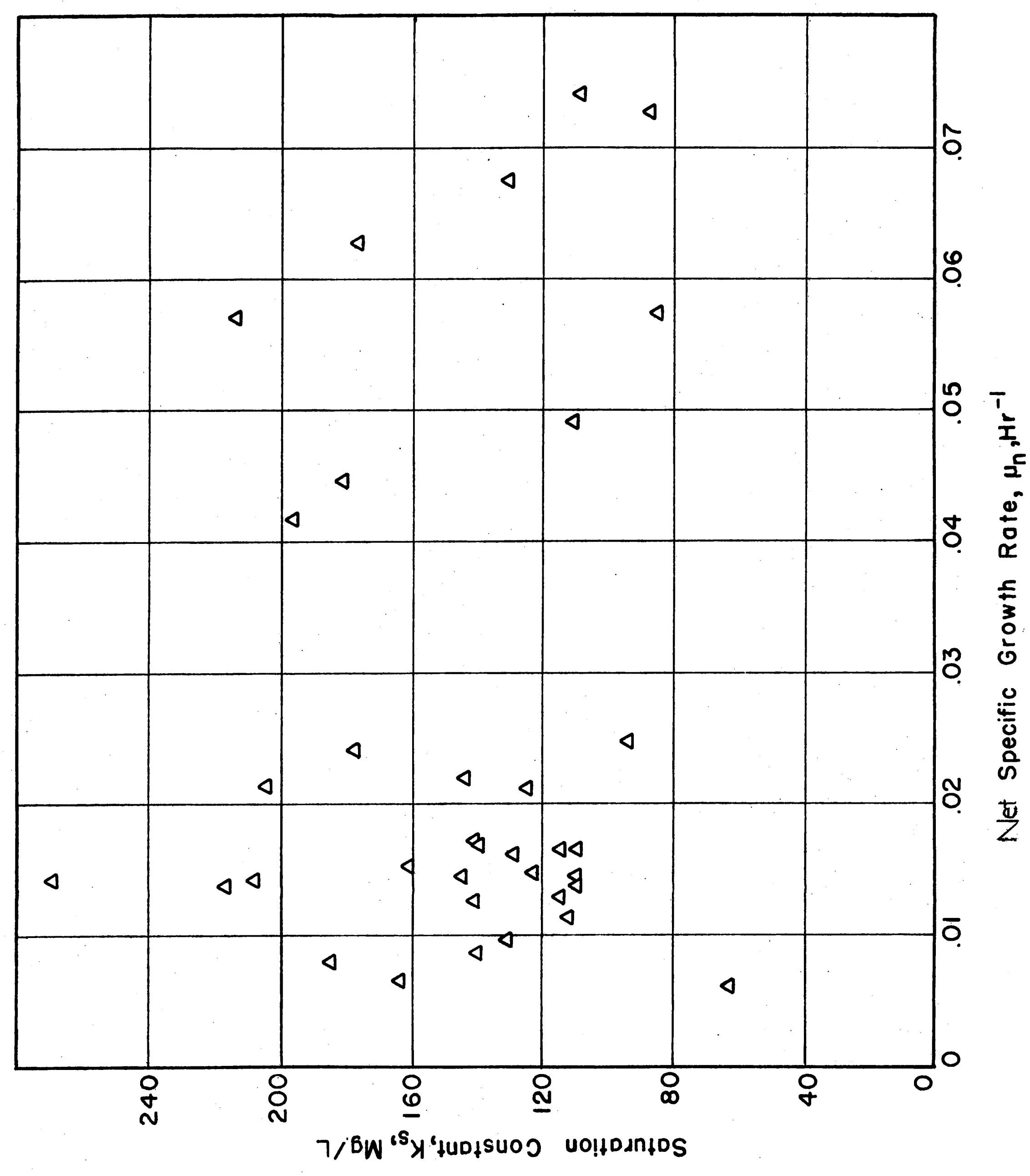

Saturation Constant, K_s, Mg/L
0
40
80
120
160
200
240
0
.01
.02
.03
.04
.05
.06
.07
Net Specific Growth Rate, μ_n, Hr^{-1}

Figure 28. Relation Between Cell Yield, Y_{t_B}, and Net Specific Growth Rate, μ_n

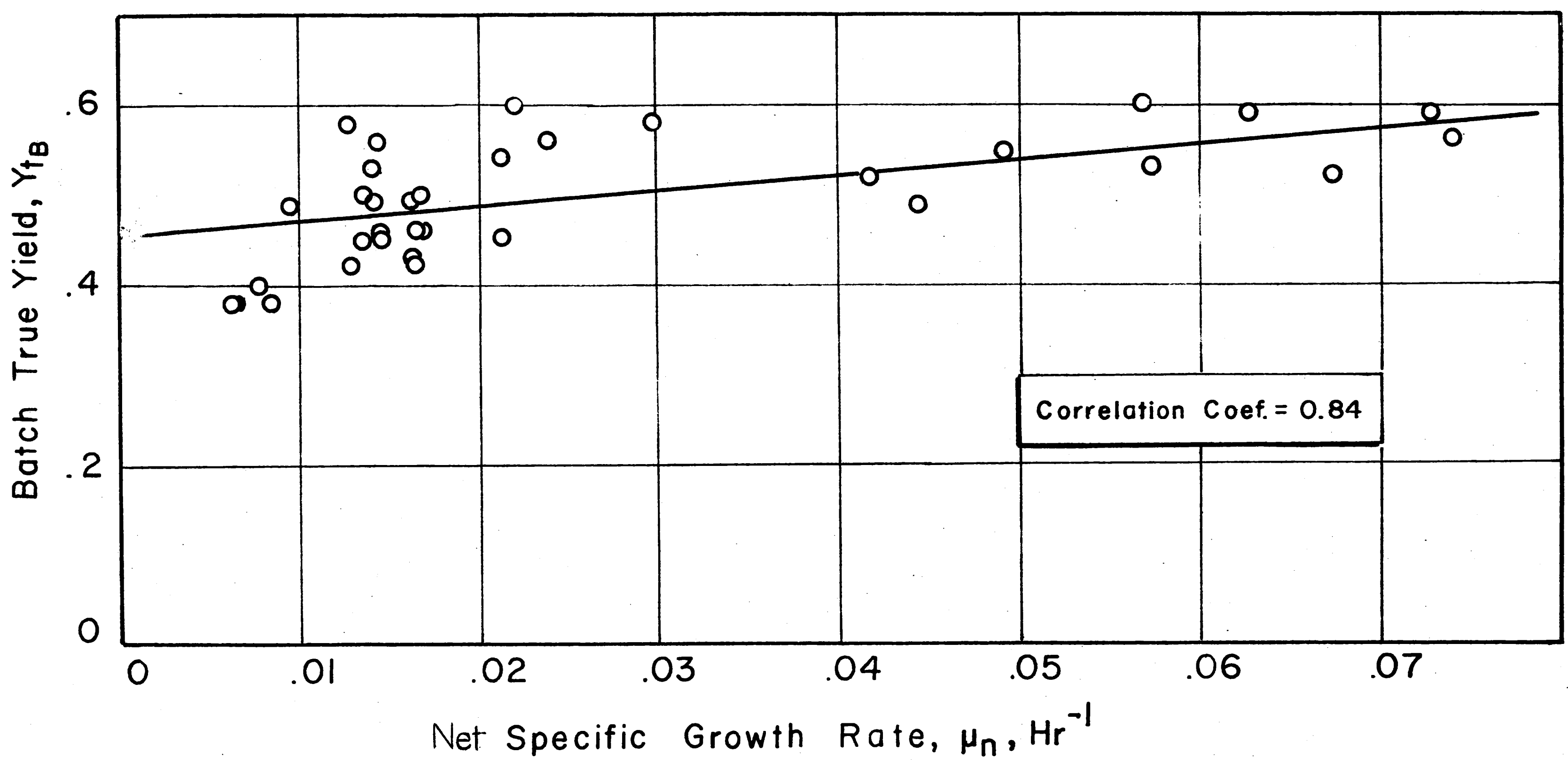
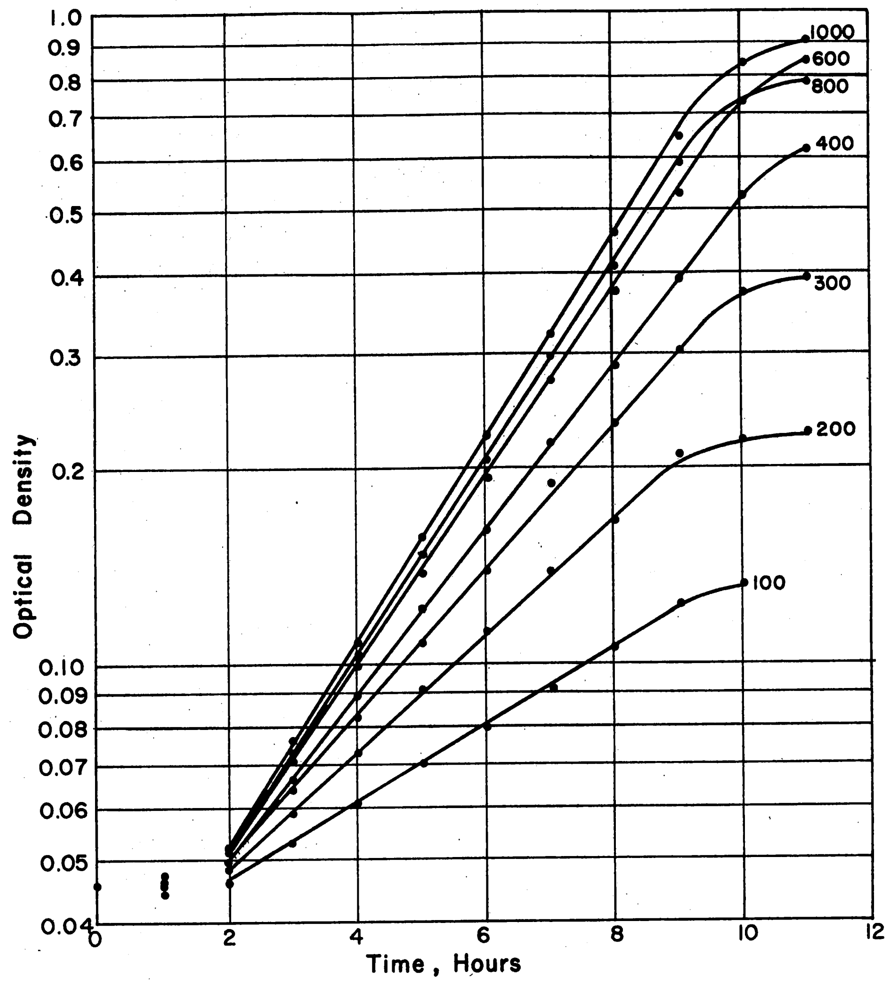

Batch True Yield, Y_{tB}
.6
.4
.2
0
.01
.02
.03
.04
.05
.06
.07
Net Specific Growth Rate, μ_n, Hr^{-1}
Correlation Coef. = 0.84

Figure 29. Batch Growth Curves at Various Initial Substrate Concentrations at 30^{o}C and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 500 mg/l and X_R of 10,000 mg/l

The μ_{max} and K_s Values Obtained From Plot of $1/\mu_o$ vs. $1/S_o$ are 0.5 hr^{-1} and 278 mg/l, Respectively


Optical Density
Time , Hours
1000
600
800
400
300
200
100
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
2
4
6
8
10
12

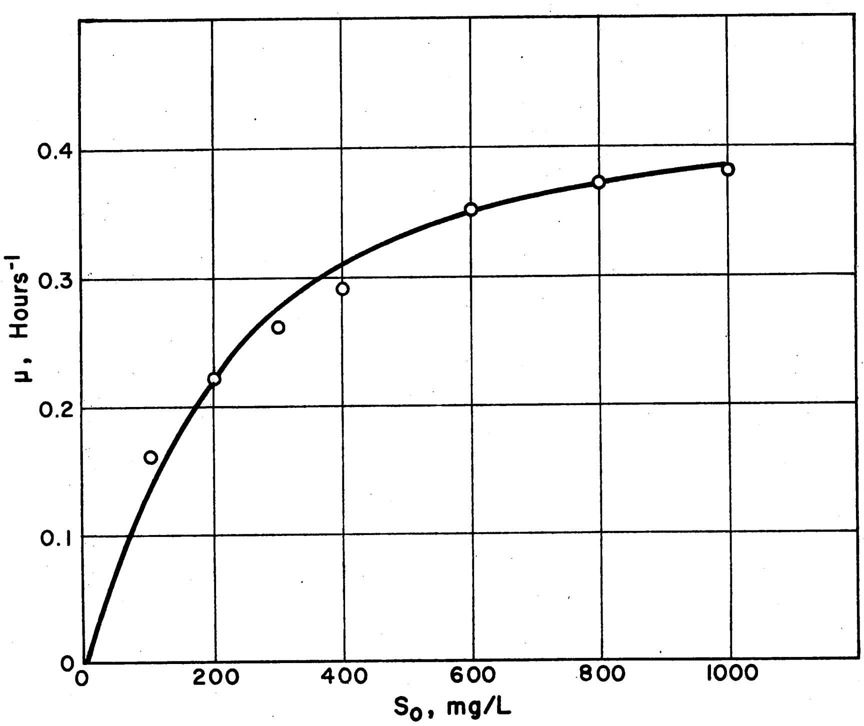

μ , Hours⁻¹
S₀, mg/L
0.4
0.3
0.2
0.1
0
0
200
400
600
800
1000

Figure 30. Batch Growth Curves at Various Initial Substrate Concentrations at 25°C and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 500 mg/l and X_R of 10,000 mg/l

The μ_{max} and K_s Values Obtained From Plot of $1/\mu_o$ vs. $1/S_o$ are 0.46 hr^{-1} and 270 mg/l, Respectively

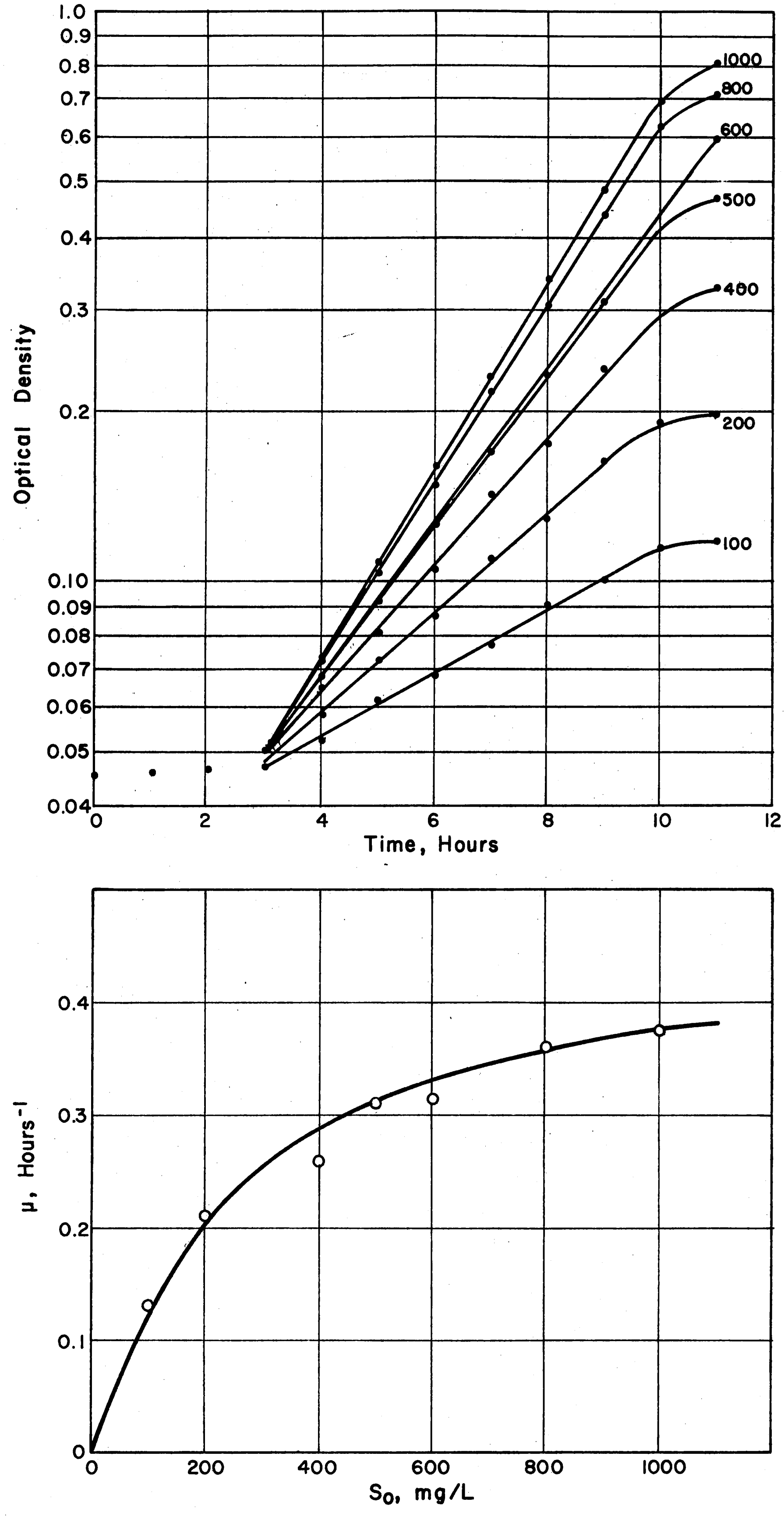
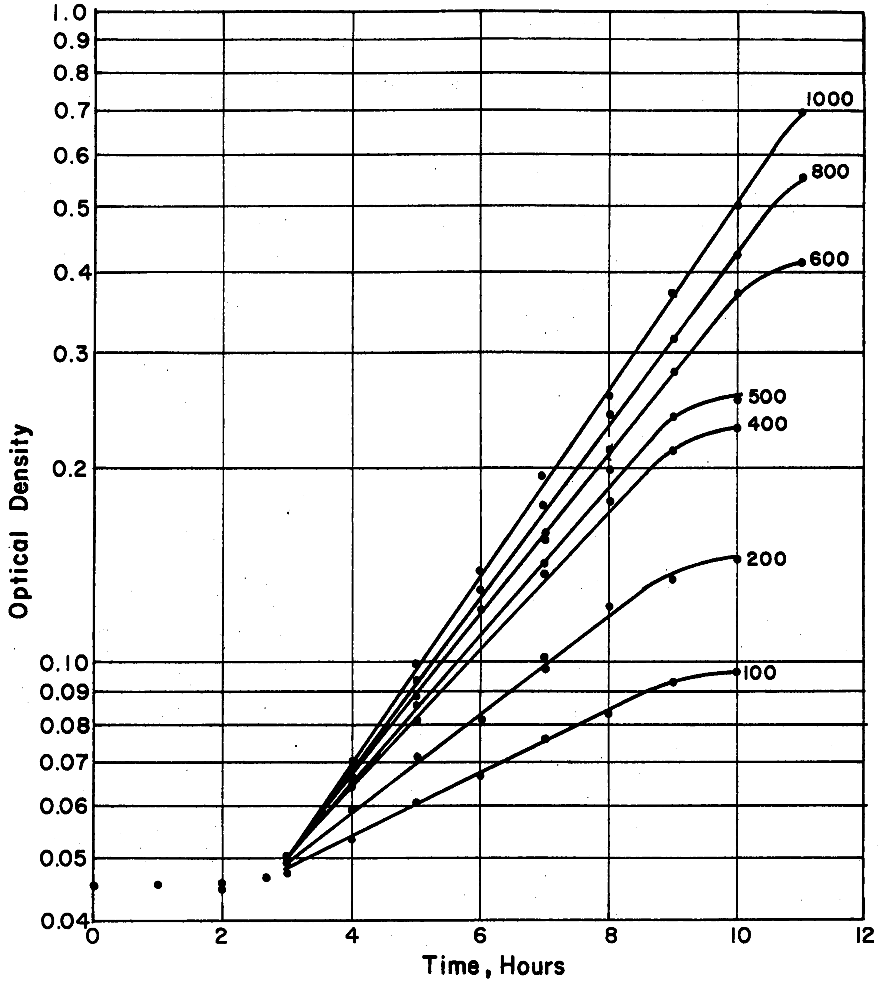
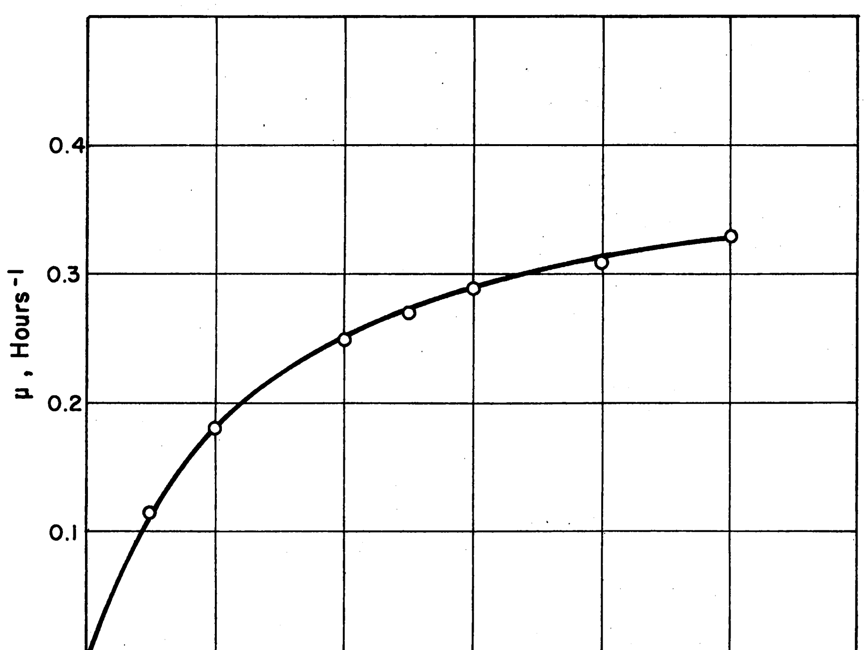

Optical Density
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0
2
4
6
8
10
12
Time, Hours
1000
800
600
500
400
200
100
μ, Hours-1
0.4
0.3
0.2
0.1
0
200
400
600
800
1000
So, mg/L

Figure 31. Batch Growth Curves at Various Initial Substrate Concentrations at 20°C and Relationship Between μ and S_o for Cells Harvested From the Activated Sludge Pilot Plant Operating at an S_i of 500 mg/l and X_R of 10,000 mg/l

The μ_{max} and K_s Values Obtained From Plot of $1/\mu_o$ Vs. $1/S_o$ are 0.42 hr^{-1} and 300 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
Optical Density
0
2
4
6
8
10
12
Time, Hours
1000
800
600
500
400
200
100


0.4
0.3
0.2
0.1
0
μ, Hours-l
0
200
400
600
800
1000
So, mg/L

CHAPTER VI

DISCUSSION

The aim of this investigation was to study the behavior of the activated sludge process model with constant X_R under shock loading conditions as well as to gain more information on the performance of the model under various modes of steady operation. Three types of shocks were applied to test the system response.

The first type was hydraulic shock loads under conditions of constant influent organic concentration. Upon increasing the dilution rate, the amount of organic matter entering the system in a given time increased as the dilution rate increased, and decreased for loads involving a decrease in dilution rate. This type of shock was applied in order to determine the magnitude of changes which could be administered without causing a long-lived or serious deleterious response with respect to substrate leakage or solids loss.

The second type of shock applied was the quantitative shock load. This involved a step change in S_i. It was of interest to compare this type of step change with the hydraulic shock and to compare both responses for this recycle system with results for once-through systems obtained previously in these laboratories.

The third type of shock was administered as a change in flow rate or feed concentration, or a combination of both, during each 24-hour period.

The fourth aspect of the results discussed in this chapter is the steady state behavior of the model at various steady operational modes before and after step changes in loading conditions, as well as average response during cyclic loading.

A. Hydraulic Shock Loads

Results of the hydraulic shock loading studies were shown in Figures 4 through 9. Figures 4 and 5 show the results of similar shock loadings consisting of a four-fold increase in hydraulic flow rates. This 300-percent increase in dilution rate was seen to disturb effluent quality approximately to the same extent in both experiments, although they were accomplished ten months apart. Thus, the response appears to be, in general, a reproducible one regardless of the changing ecological character of the biomass which one expects for heterogeneous populations. The system did appear to attain the new steady state more rapidly in the run shown in Figure 4 than in that shown in Figure 5, but the effluent COD was approximately the same in each case. It is interesting to compare the filtrate COD in aerator #1 with that in the clarifier effluent. It is obvious that the clarifier served in some small capacity as a reactor for removal of soluble substrate. The amount of soluble substrate leaked from aerator #1 during the transient phase (area under the filtrate COD curve) was 8550 mg COD, and the amount of soluble substrate in the clarifier effluent was 4000 mg COD. Thus, more than 50 percent of the soluble substrate coming from aerator #1 was biologically removed in the clarifier.

The fact that the biological solids concentration was increased only slightly in the final steady state after the step increase in dilution rate shows that X_R exerts the major control over X. The small increase in X was due to the increase in μ_n caused by the increase in D (see equation 11). If X had remained the same before and after the four-fold step increase in flow rate, then μ_n would have increased four-fold. However, μ_n is also dependent upon the biomass concentration, X. The value of X is expected to be higher at the new steady state because the increase in μ_n due to increased D lessens the effect of the auto-digestive constant, k_d. Thus, the increases in μ_n for experiments shown in Figures 4 and 5 were in the range of five- to six-fold rather than four-fold (see Table VI, lines 22 and 37 for μ_n values). These results are consistent with the maintenance concept, i.e., as specific growth rate increases, the observed yield, Y_o, increases.

Analysis and, indeed, determination of the rate at which the specific growth rate, μ, or net specific growth rate, μ_n, makes the transition from former to new steady state is rather complicated and more data than those obtained during this investigation would be necessary. One of the complicating aspects would appear to be that specific growth rate must have gone down before it went up. This seems apparent from analysis of the changes in biomass concentration and composition in the transient state. In both Figures 4 and 5, it is seen that X attained a low transient value approximately equal to that contributed solely by X_R ($10{,}000 \times \frac{\alpha}{1+\alpha} = 2000$ mg/l). Also, drastic changes in protein and carbohydrate took place. Protein content decreased from average values of 47 and 51 percent (Figures 4 and 5) to low values of 39 and 36 percent during the transient phases. Carbohydrate content increased from pre-shock average values of 22 and 17 percent to maximum values of 25 and 35 percent.

It would appear from the decrease in protein content as well as the low biomass concentration that the shock seriously curtailed growth. However, it is obvious that the biomass removed the substrate and that it was channelled largely into carbohydrate.

The experiments shown in Figures 6 through 9 were accomplished to assess the effect of X_R on response to hydraulic shock. The first experiment was that shown in Figure 8 with X_R of 12,000 mg/l. The step change was an increase in D from 0.125 to 0.25 hr^{-1}. There was a slight disruption in effluent quality, a decrease in protein, and an increase in carbohydrate content. It was estimated that a decrease in X_R would increase the transient disturbance, thus the experiment shown in Figure 7 was run at X_R = 8000 mg/l. Approximately the same concentrations of S_t, S_e, and X_e were obtained; however, the transient phase lasted for a longer period of time. An experiment was then carried out at X_R = 6000 mg/l (Figure 6), and again the maximum transient leakage in the effluent was approximately the same as for the previous two experiments. However, when the system was adjudged to have attained a steady state at the new flow rate, the effluent quality had not returned to that of the pre-shock condition, whereas for the previous shock, such was the case. Thus, halving the X_R concentration did not have a great effect on the magnitude of the transient leakage, but did exert some effect on the length of the transient phase and the behavior of the system at the new steady state. It was thought that an increase in X_R above the 12,000 level would exert a steadying influence on the magnitude of transient disturbance, and as seen in Figure 9, it did.

It is interesting to note that the same general trends in protein and carbohydrate content during the shocks from D = 0.125 hr^{-1} to 0.5

hr^{-1} were evidenced for the shocks from D = 0.125 to 0.25 hr^{-1}. Furthermore, comparison of these results with those of George and Gaudy (83) for once-through systems indicates similar trends in cell composition. Both results indicate that the cells do not immediately respond to a change in μ imposed by the hydraulic shock. The fact that the biomass concentration decreased in both types of systems is evidence that the immediate response to the hydraulically imposed increase in μ was actually a decrease in μ. However, it is evident that the oxidative assimilation capacity of the cells increased in response to the change in feed flux and the carbon source which was removed was channelled largely into carbohydrate. For the experiments in which D was doubled (i.e., D = 0.125 $\rightarrow$ 0.25 hr^{-1}), both the cell recycle and once-through systems experienced only rather slight leakage of soluble substrate. Cell recycle did result in a lower concentration in the effluent, i.e., 130 mg/l COD for the once-through vs. approximately 40 mg/l COD for the recycle systems. The similarity in biochemical response as well as substrate leakage is interesting in view of the fact that there was such a large difference in specific growth rate in the once-through and cell recycle systems. In the once-through systems, the μ was hydraulically changed from 0.125 to 0.25 hr^{-1}, whereas in the cell recycle systems of the current research, μ changed from 0.0128 to .0322 hr^{-1}. Although both types of systems gave biochemical responses of similar magnitude to doubling of dilution rate, the power of X_R to steady the system is really evidenced by comparing results at the more severe changes in D. Figures 4 and 5 indicate that a quadrupling of D was rather readily handled by the system. However, for the once-through system, a somewhat less severe change (from 0.125 to 0.44 hr^{-1}) resulted in permanent leakage of a high concentration of soluble COD. It should be pointed out that there was a large difference in μ for these systems. In the once-through reactors, μ was changed from $\mu = D = 0.125$ to 0.44 hr^{-1}. The higher μ was rather close to μ_{max} ($\mu_{max} \sim .5\ hr^{-1}$). However, in the cell recycle system, a similar change in D caused a change in μ from the range 0.0131-0.0096 hr^{-1} to 0.0629-0.0575 hr^{-1}. Thus, the recycle system was growing at a rate approximately ten times slower before and after the shock.

B. Quantitative Shock Loads

Quantitative shock load studies were presented in Figures 10 through 13. Figures 10 and 13 showed the response to similar shock loadings consisting of a three-fold increase in substrate concentration. Response to this 200-percent increase in substrate concentraton was essentially the same in both experiments, although they were run thirteen months apart. Thus, the response to this level of shock would appear to be generally expected regardless of difference in species. The system did appear to attain the new steady state at the same time in both figures, but the effluent COD shown in Figure 10 was slightly less than that in Figure 13. It is interesting to compare the filtrate COD in aerator #1 with that in the clarifier effluent (Figure 13). There was no significant difference between filtrate COD in aerator #1 and the clarifier filtrate.

The amount of soluble substrate leaked from aerator #1 during the transient phase (area under the filtrate COD curve) was 1080 mg COD, and the amount of soluble substrate in the clarifier effluent was 900 mg COD. Thus, during the transient phase, sixteen percent of the soluble substrate coming from aerator #1 was biologically removed in the clarifier. The fact that the biological solids concentration was increased in the final steady state after the step increase in substrate concentration shows that S_i exerts a considerable effect on X. An average increase in biomass concentration of 500 $\pm$ 50 mg/l in the final steady state was recorded in both Figures 10 and 13. This increase in biomass was in response to an increase of feed concentration by 1000 mg/l.

During the transition stage, the growth response to the step shock load is controlled primarily by the rate of increase of substrate concentration in aerator #1 (in accordance with the Monod relationship). If the rate of increase of substrate concentration cannot be balanced by an increased rate of solids accumulation, either by recirculation or production, substrate will continue to be lost in the effluent until the biological solids concentration does eventually attain a level at which the substrate removal rate comes into balance with the rate of feeding the substrate. It can be seen that in equation (5)

$$X = \frac{Y_t\left[S_i - (1+\alpha)\bar{S}\right] + \alpha X_R}{1+\alpha+ K_d/D}$$

the biomass concentration in aerator #1 is proportional to the feed concentration, and will have a large effect on the value of X in the new steady state. However, an increase in dilution rate (i.e., hydraulic shock) has a lesser effect on $\bar{X}$. A comparison of biomass concentration in aerator #1 (Table VI, lines 3, 4, 33, and 34, and Figures 10 and 13) reveals that an increase of 25 to 30 percent biomass concentration occurred in response to the three-fold increase in S_i. In the transient state, biomass concentration increased by approximately 66 percent. However, this increase did not proceed at a rate sufficiently rapid to prevent the small leakage of substrate.

In Figure 13, where protein and carbohydrate analyses were made, there was seen to be a drastic change in biomass composition. Protein decreased from an average of 47 to 34 percent. Carbohydrate content increased from pre-shock average value of 17 to a maximum value of 30 percent during the transient. The decrease in protein indicates that synthesis of new cells slowed down while the increase in carbohydrate indicates that the substrate removed by the biomass was channelled largely into non-nitrogenous oxidative assimilation products.

The responses to a six-fold increase in feed concentration were shown in Figures 11 and 12 and, as for the three-fold increase, the results were similar even though the experiments were conducted thirteen months apart. However, there were differences in effluent characteristics with respect to S_e and X_e. In Figure 11, X_e increased faster than S_e, while an opposite effect was evidence in Figure 12. It is interesting to compare the filtrate COD in aerator #1 with that in the clarifier effluent. It is obvious that some biological action took place in the clarifier (Figure 12). The amount of soluble substrate from aerator #1 during the transient phase (area under the filtrate COD curve) was 4440 mg COD, and the amount of soluble substrate in the clarifier effluent was 3550 mg COD. Thus, 20 percent of the filtrate COD coming from aerator #1 was biologically removed in the clarifier. In contrast to the response to the 200 percent increase in feed concentration (Figure 13), the use of an X_R of 8000 mg/l did not provide a high degree of protection against the 500 percent shock load. It is interesting to note that the same general trends in protein and carbohydrate content during shocks for S_i = 500 mg/l to S_i = 1500 mg/l were evidenced for the shocks at S_i = 500 mg/l to S_i = 3000 mg/l. Furthermore, comparison of these results with those of Krishnan and Gaudy (80) for once-through and cell recycle systems indicates some similarity, but there appear also to be significant differences. They reported, for both once-through and recycle systems, that there was a fairly rapid increase in both protein and carbohydrate after shock was applied. The concurrent increase in both protein and carbohydrate content indicated that the response was one of balanced growth; that is to say, there was no disproportionate synthesis of nonproteinaceous material, e.g., carbohydrate, during the early portion of a successful response. This was not the case in the present study, since there is evidence (the rapid increase in carbohydrate) that oxidative assimilation accounted for most of the increased biomass in response to the change in feed concentration. It is known that oxidative assimilation of substrate into non-nitrogenous synthesis products can occur readily and that it is most clearly manifested at high biological solids concentrations (87). In the current study, the ratio of S_i to X was much lower than in the study previously cited. Thus, it would be expected that oxidative addimilation would play a more evident role in shock load response in the current study.

In the current studies, the response to quantitative shock was less severe with respect to substrate leakage than in the study made by Krishnan and Gaudy. It is believed that the reason is related to the higher concentration of X caused by the higher X_R. The higher X_R led to lower values of specific growth rate, μ. Whether the better response was due to higher biomass concentration or due to some beneficial effect of slower specific growth rate cannot be decided based upon the experimental results. Regardless of the specific reason, it must be concluded that there is a practical relation between ability to take shock and the value of X_R employed in the system. The studies were not exactly comparable because different S_i values were employed. However, comparing results for an increase in S_i of 200 percent, the COD in the filtrate attained a transient value of 150 mg/l in the study of Krishnan and Gaudy, but reached only 40-80 mg/l in the current study. The values of specific growth rate prior to the shock were 0.046 and 0.0165 hr^{-1}, respectively, and the recycle solids concentration was approximately one-fifth of that in the current study. The most severe shock in the study of Krishnan and Gaudy was a five-fold increase (1000 to 5000 mg/l S_i), and the maximum leakage of COD was nearly 700 mg/l. In the current study, a six-fold shock led to a maximum COD leakage of 300 mg/l in one experiment, and only 100 mg/l in the other. Comparable growth rates in the study of Krishnan and Gaudy and the current study were 0.04 and 0.016 hr^{-1}, respectively.

C. Cyclic Shock Loads

The primary aim of the four studies on cyclic shocks was not so much to develop information to describe the transient phase response, but to evaluate the degree of steadiness imparted by operation at constant X_R under cyclic hydraulic, quantitative, and combined loading conditions. Forced changes in inputs for F, α, and S_i were applied as well as combined changes in F and α and F and S_i. To compare the effect of cyclic variations in loading on the various effluent and biomass characteristics, the data for steady state operation were compared with the average values of the parameters during the cyclic loading periods; that is to say, the means and the central tendency around the means were compared for both types of operation. In addition to making statistical comparisons of pre- and post-cyclic shock operations for the four individual runs, statistical analyses for all steady state data obtained with the same base line operational conditions were made and compared with the data for cyclic operation.

The results of the statistical analyses are shown in Table XVI. In all cases, the pre-shock steady state operational conditions were as follows: S_i = 500 mg/l glucose, X_R = 10,000 mg/l, α = 0.25, and D = 0.125 hr^{-1}. The first four sets of data (identified by figure numbers) show the pre-shock values for the individual runs, whereas the fifth set of data shows the results for the four runs and an additional five steady states (see Table VI, lines 21, 23, 24, 36, and 38). It is noted that by including all steady state values, the number of samples from both the steady and cyclic operations are approximately equal.

It is apparent from comparison of the results under steady and cyclic loading that the effluent quality (S_t, S_e, X_e) was essentially the same with respect to mean, coefficient of variation, and range. Thus, it seems reasonable to conclude that the capacity of the mode of operation with constant X_R to accommodate cyclic perturbance was not exceeded in this study. The system could safely accommodate a two-fold cyclic hydraulic shock with constant α. Also, the system could accommodate this magnitude of cyclic shock with changes in recycle flow rate, i.e., with variable α. Also, it withstood successfully a three-fold cyclic change in S_i and quite significantly, a six-fold increase in mass loading rate under conditions of concurrent quantitative and hydraulic cyclic shock.

TABLE XVI

VARIATION AND RANGE OF VALUES FOR MEAN EFFLUENT CHARACTERISTICS, BIOMASS CONCENTRATION IN AERATOR #1, RECYCLE SOLIDS CONCENTRATION, AND EXCESS SLUDGE PRODUCTION

Figure #	Analysis Indicated mg/l	Steady State Before Shock						Cyclic Shock Load						Remarks
		N	Mean	Variance	Standard Deviation	C.V.%	Range	N	Mean	Variance	Standard Deviation	C.V.%	Range	
15 & 16	S_t	24	33.38	32.32	5.68	17.03	22-45	162	40	64.87	8.05	20.13	28-62	Cyclic hydraulic shock load with constant α
	S_e	24	10.33	11.14	3.34	32.3	5-19	162	12.53	29.26	5.41	43.2	0-28	
	X_e	24	20.71	26.54	5.15	24.88	9-28	162	25.39	37.81	6.15	24.22	16-40	
	X	24	2210.25	7732.69	87.94	3.97	2041-2418	162	2183.48	5648.6	75.16	3.4	2006-2386	
	X_R	12	10070.75	7314.10	85.52	0.8	9891-10214	36	10155.69	13427.02	115.88	1.14	9984-10381	
	X_W	12	1291.42	10810.2	103.97	8.1	1166-1488	18	1512.63	8720.65	93.38	6.17	1376-1693	
18 & 19	S_t	16	42	61.63	7.85	18.69	25-55	96	35.85	101.54	10.08	28.11	19-65	Cyclic hydraulic shock load with varying α
	S_e	16	11.88	29.61	5.44	45.8	4-22	96	14.67	40.60	6.37	50.29	1-30	
	X_e	16	26.5	28.88	5.37	20.28	15-38	96	18.79	60.17	7.76	41.28	6-34	
	X	16	2210.3	10905.7	104.4	4.6	2021-2374	96	2284.05	93834 82	3063	114	2002-2459	
	X_R	16	10075.13	24273.45	155.79	1.5	9812-10281	96	10038.95	22358.19	149.53	1.49	9805-10566	
	X_W	8	1222.25	4955.56	70.39	5.76	1100-1361	14	1138.57	3012.96	54.9	4.8	1050-1229	
21 & 22	S_t	24	28.92	23.83	4.88	16.88	19-38	162	30.25	93.6	9.67	29.99	18-71	Quantitative cyclic shock load with constant α
	S_e	24	9.75	11.27	3.36	34.43	4-18	162	9.17	12.26	3.50	38.18	0-26	
	X_e	24	17.42	19.16	4.38	25.13	10-25	162	21.95	67.53	8.22	37.44	11-57	
	X	24	2204	3375	58.09	2.6	2048-2304	162	2561.23	52103.4	228.26	8.7	2194-2741	
	X_R	12	10008.79	8942.75	94.57	0.9	10140-9814	162	10080	7140.8	84.5	0.8	9831-1023	
	X_W	12	1315.6	3546.31	59.55	4.55	1229-1496	36	3260.67	3743.78	61.19	1.9	3019-3306	
24 & 25	S_t	18	31.57	43.14	6.57	21	21-49	144	36.52	38.25	6.18	16.93	28-55	Cyclic quantitative-hydraulic shock load with constant α
	S_e	18	9.0	18.22	4.27	47	4-20	144	10.86	18.86	4.34	40.67	4-19	
	X_e	18	22.17	17.92	4.23	19.09	14-29	144	26.10	20.02	4.47	17.14	20-36	
	X	18	2246.72	2627.5	51.26	2.28	2154-2344	144	2793.6	24618.4	156.90	5.6	2509-3098	
	X_R	9	10052.3	13461.55	116.02	1.15	9911-10204	144	10114.52	8878.3	94.22	0.9	9810-10212	
	X_W	9	1288.0	6225.78	78.90	6.13	1188-1455	32	3317.38	16211.23	127.30	3.8	3028-3461	
4 & 5	S_t	158	37.6	158.78	12.6	33.5	19-79							
	S_e	158	13.01	39.6	6.3	48.0	0-34							
	X_e	158	23.38	98.69	9.9	42.34	0-60							
	X	158	2241.09	5037.16	70.97	3.17	2021-2418							
	X_R	149	10001.33	558198	747.13	7.4	9730-10318							
	X_W	113	1251.16	5470.75	73.96	5.9	1100-1496							

D. Steady State Evaluation

Examination of the performance characteristics at various organic loadings, S_i, hydraulic loadings, D, and recycle solids concentrations, X_R, of the activated sludge pilot plant employing constant X_R, indicates that the system delivered excellent effluent with respect to COD (both filtrate and total) and biological solids concentration, X_e. Also, the few determinations of 5-day BOD indicated high purification efficiency (see Table VI). The biochemical removal efficiency based on effluent filtrate COD in all of the runs made, on average, was 95 percent or better, and based on total or supernatant COD, the biochemical removal efficiency was 90 percent or better, except for three steady state runs where the solids in the effluent were slightly higher. The supernatant COD in the latter three cases was in the range of 83 to 87 percent purification (lines 37, 16, and 22), while the supernatant BOD for lines 16 and 37 was only 14 mg/l. Thus, the effluent was, on the average, very good and efficiency of substrate removal was high. Especially interesting was the capability of the system to attain a high degree of effluent quality in the new steady state after a significant increase in S_i.

Another important parameter in evaluating the steadiness of a model is the biological solids concentration, X, in the aeration tank. From the standpoint of testing the steadiness of the model, X is a more sensitive parameter than is S. A close examination of the plots of steady state aerator biological solids concentration, X, reveals that it did not fluctuate over a wide range during any loading, but remained steady within a very narrow range. Table XVII shows

TABLE XVII

STATISTICAL ANALYSES FOR ALL STEADY STATE RUNS

Line #	Anal. Ind. mg/l.	Mean	N	S	C.V. %	Range	Line #	Mean	N	S	C.V. %	Range	Line #	Mean	N	S	C.V. %	Range	Line #	Mean	N	S	C.V. %	Range
	S_t	35	11	8	22	25-50		36	18	12	32	15-55		33	22	9	28	20-56		34	18	12	35	15-56
	S_e	22	11	8	35	10-38		28	18	11	39	12-50		24	22	6	27	12-36		19	18	7	38	3-32
	X_e	20	11	8	40	12-32		15	18	6	38	6-30		27	22	7	27	17-42		22	18	12	53	0-38
1	X	1766	11	43	2	1690-1820	2	1788	18	42	2	1700-1850	3	1776	22	57	3	1678-1860	4	2237	18	53	2	2170-2338
	X_R	8012	11	453	6	7600-8900		8088	18	348	4	7500-8800		7935	22	314	4	7443-8510		7998	18	242	3	7600-8470
	X_W	1290	11	67	5	1070-1390		1302	18	398	2	1190-1392		1416	22	28	2	1365-1458		4850	18	22	0.4	4610-4920
	S_t	32	13	8	24	19-45		38	16	7	19	48-28		46	14	9	19	32-60		33	18	6	19	25-45
	S_e	15	13	5	30	8-25		14	16	6	43	6-24		30	14	9	29	10-44		14	18	5	32	6-25
	X_e	18	13	6	35	12-31		28	16	6	23	18-33		28	14	8	28	13-38		19	18	6	29	12-30
5	X	1774	13	30	2	1740-1832	6	1782	16	43	2	1720-1884	7	3095	14	107	3	2980-3304	8	1777	18	120	7	1730-1920
	X_R	7996	13	137	2	7850-8350		8064	16	389	5	7340-8840		8047	14	149	2	7820-8370		7946	18	174	2	7704-8350
	X_W	1302	6	58	4	1254-1330		1330	8	32	2	1227-1398		10272	7	451	4	9876-10479		1398	9	83	6	1150-1499
	S_t	48	22	14	159	10-60		30	14	9	30	18-50		37	24	10	27	10-51		36	24	7	19	25-50
	S_e	12	22	5	43	0-15		6	14	7	113	0-20		9	24	7	79	0-25		22	24	6	27	10-28
	X_e	37	22	11	30	10-40		21	14	10	46	8-45		24	24	10	43	0-40		23	24	6	24	14-28
9	X	2513	22	76	3	2318-2601	10	2554	14	35	1	2401-2610	11	2553	24	78	3	2405-2704	12	1775	24	60	3	1709-1921
	X_R	12033	22	326	3	11650-12940		11899	7	170	1	11605-12108		12060	14	300	2	11704-12312		8075	24	386	5	7584-9210
	X_W	1140	22	65	6	1035-1270		2697	7	83	3	2612-2718		1137	24	74	6	1009-1280		1422	24	38	3	1314-1486
	S_t	31	15	10	30	25-60		38	18	7	19	24-55		57	20	11	19	44-84		72	12	5	7	62-81
	S_e	15	15	4	24	12-26		13	18	4	33	6-23		18	20	9	49	8-39		33	12	4	11	30-42
	X_R	16	15	9	53	10-42		23	18	6	25	14-38		39	20	5	13	27-50		38	12	4	10	32-46
13	X	1794	15	37	2	1729-1880	14	1760	18	42	2	1768-1910	15	1421	20	43	3	1348-1488	16	1450	12	29	2	1391-1541
	X_R	8113	15	244	3	7604-8504		7983	18	129	2	7699-8224		6014	20	213	4	5716-6315		5969	12	189	3	5709-6304
	X_W	2502	15	137	6	2481-2688		1420	18	67	5	1334-1554		1430	20	45	3	1332-1480		3558	12	116	3	3448-3848
	S_t	57	14	7	13	42-71		39	18	12	31	25-55		46	14	11	25	25-67		32	16	7	21	21-48
	S_e	22	14	8	34	10-35		16	18	5	33	8-29		20	14	9	47	0-38		13	16	5	42	6-28
	X_e	35	14	5	13	23-40		23	18	7	30	12-37		24	14	7	30	12-38		19	16	4	22	14-28
17	X	1399	14	22	2	1361-1425	18	3115	18	68	2	3004-3214	19	3324	14	48	1	3179-3336	20	3170	16	56	2	3144-3377
	X_R	6037	14	235	4	5614-6381		14963	18	177	1	14719-15212		14983	14	112	1	14829-15168		15026	16	120	1	14831-15261
	X_W	1495	14	34	2	1404-1522		1120	18	62	6	1071-1289		3167	7	48	2	3014-3454		1087	9	50	5	1010-1196
	S_t	45	22	10	23	28-68		69	14	7	10	58-85		37	14	11	30	21-58		33	24	6	17	22-45
	S_e	15	22	6	40	0-24		25	14	5	19	18-34		13	14	7	51	0-25		10	24	3	32	5-19
	X_e	28	22	9	31	14-48		43	14	5	13	34-52		23	14	8	36	14-41		21	24	5	25	9-28
21	X	2200	22	45	2	2141-2311	22	2249	14	24	1	2214-2310	23	2220	14	24	1	2214-2301	24	2210	24	88	4	2041-2418
	X_R	10075	22	135	1	9847-10318		10116	14	83	1	9981-10212		10069	14	132	1	9814-10231		10071	12	86	1	9891-10214
	X_W	1280	22	40	3	1110-1378		6724	7	80	1	6614-6821		1237	12	65	5	1121-1281		1291	12	104	8	1166-1488

TABLE XVII (Continued)

Line #	Anal. Ind. mg/l.	Mean	N	S	C.V. %	Range	Line #	Mean	N	S	C.V. %	Range	Line #	Mean	N	S	C.V. %	Range	Line #	Mean	N	S	C.V. %	Range
	S_t	33	20	9	29	21-56		40	18	11	26	22-65		47	16	11	23	24-67		42	16	8	19	25-55
	S_e	17	20	7	40	3-34		13	18	4	29	5-22		15	16	5	31	5-25		12	16	5	46	4-22
25	X_e	14	20	6	43	0-25	26	26	18	7	26	14-35	27	31	16	8	24	19-45	28	27	16	5	20	15-38
	X	2205	20	62	3	2154-2341		2187	18	84	4	2012-2313		2818	16	49	2	2763-2940		2210	16	104	5	2021-2374
	X_R	10121	20	59	1	10051-10210		8015	18	108	1	7841-8212		8005	16	96	1	7864-8141		10075	16	156	2	9812-10281
	X_W	1205	10	315	26	1168-1272		4368	18	58	1	4244-4464		9129	16	48	1	8912-9382		1222	8	70	6	1100-1361
	S_t	29	24	5	17	19-38		32	18	7	21	21-49		50	12	6	12	41-59		87	8	14	16	69-120
	S_e	10	24	3	34	4-18		9	18	4	47	4-20		11	12	2	17	8-14		45	8	18	41	25-85
29	X_e	17	24	4	25	10-25	30	22	18	4	19	14-29	31	33	12	4	12	26-38	32	39	8	8	20	25-48
	X	2204	24	58	3	2048-2304		2247	18	51	2	2154-2344		1820	12	22	1	1814-1904		3018	8	100	3	2856-3148
	X_R	10009	12	95	1	9814-10140		10052	9	116	1	9911-10204		8107	12	99	1	7889-8241		8047	8	122	2	7884-8204
	X_W	1316	12	60	5	1229-1496		1288	9	79	6	1188-1455		1419	12	79	6	1321-1561		10630	8	728	7	9980-11220
	S_t	57	10	8	14	48-74		64	10	11	17	52-81		44	6	8	17	34-54		61	6	15	24	33-78
	S_e	42	10	9	21	28-55		31	10	9	29	20-51		24	6	7	28	10-30		20	6	4	20	15-26
33	X_e	10	10	4	38	5-18	34	36	10	16	44	5-46	35	25	6	5	20	15-34	36	43	6	17	40	12-60
	X	1799	10	37	2	1838-1960		2359	10	51	2	2310-2482		1804	6	42	2	1724-1860		2132	6	55	3	2050-2310
	X_R	8055	10	152	2	7841-8231		8090	7	178	2	7820-8380		8142	6	151	2	7830-8312		10000	6	213	2	9810-10270
	X_W	1428	10	188	13	1288-1960		4683	8	133	3	4310-4716		1342	6	47	4	1291-1431		1209	6	16	1	1185-1231
	S_t	70	9	9	13	64-95		59	8	11	18	45-79		57	34	9	16	42-84	1,2	39	206	7	18	15-74
	S_e	16	9	12	73	0-34		20	8	9	39	10-33	15	~~20~~	~~34~~	~~9~~	~~45~~	~~8-39~~	3,5	21	206	6	29	6-55
37	X_R	63	9	7	12	51-74	38	39	8	3	9	35-44	17	37	34	5	14	23-50	6,8 12,14	22	206	8	36	5-42
	X	2240	9	98	4	2181-2480		2210	8	45	2	2212-2340		1410	34	36	3	1348-1488	31,33	1784	206	53	3	1678-1960
	X_R	10172	9	224	2	9850-10470		10028	8	151	2	9812-10212		6026	34	222	4	5614-6381	35	8037	206	262	3	7340-9210
	X_W	6221	7	94	2	6098-6391		1260	8	44	4	1191-1321		1463	34	41	3	1332-1522		1370	182	140	10	1070-1960
	S_t	38	158	13	34	19-79		43	46	12	28	10-60		36	34	10	28	21-55		46	46	11	24	15-81
21,23	S_e	13	158	6	48	0-34	9	11	46	6	55	0-25	18	15	34	5	33	6-29	4,26	21	46	7	33	3-51
24,25	X_R	23	158	10	42	0-60	11	31	46	11	35	0-40	20	21	34	6	29	12-37	34	28	46	12	43	0-46
28,29	X	2241	158	71	3	2021-2418		2533	46	77	3	2318-2704		3143	34	63	2	3004-3377		2261	46	67	3	2012-2482
30,36	X_R	10001	149	747	7	9730-10318		12047	36	316	3	11650-12940		14995	34	153	1	14719-15261		8034	43	186	2	7600-8470
38	X_W	1251	113	74	6	1100-1496		1139	46	70	6	1035-1280		1104	27	58	5	1010-1289		3634	44	69	2	4244-4920
	S_t	60	38	11	18	24-120		70	23	8	11	58-95												
	S_e	30	38	10	33	5-85		21	23	9	43	0-34												
7,27	X_e	33	38	8	24	13-48	37	53	23	6	11	34-74												
32	X	2977	38	103	4	2763-3304	22	2245	23	64	3	2181-2480												
	X_R	8033	38	123	2	7820-8370		10144	23	154	2	9850-10470												
	X_W	10010	31	429	4	8912-11220		6473	14	87	1	6098-6821												

statistical analyses for the 38 steady state runs. It can be seen that all of the coefficients of variation were rather low for X as well as for the other parameters. In addition, runs made under similar operational and loading conditions were summed for statistical analyses.

It is apparent from the results that concentration of solids in the reactor is dependent mainly on the concentration of recycle sludge X_R. The second factor that controlled the value of X but to a lesser extent, was S_i. The third factor which exerted some (but only a slight) control on X was the dilution rate, D. It should be noted that recycle flow ratio, α, was constant at 0.25. This parameter can also exert an effect on X. Analyses of the steady state plots of X at any loading before or after shock show beyond doubt that X_R is the main variable which controls and helps to maintain the system in a new steady state with minimum fluctuations.

In addition to analyzing the steadiness of the model in terms of $\bar{S}$ and $\bar{X}$, it is also appropriate to analyze the parameters that lead to this steadiness, that is, the recycle solids concentration, X_R. The nominal X_R concentrations used were 6000, 8000, 10,000, 12,000, and 15,000 mg/l, and it is seen that X_R was held very close to these concentrations. It can be seen also that it was possible to control the recycle sludge concentration at a value approximately equal to the desired concentration for rather long operational periods. In most cases, the range observed was $\pm$ 500 mg/l at higher X_R, and $\pm$ 200 mg/l at lower X_R values.

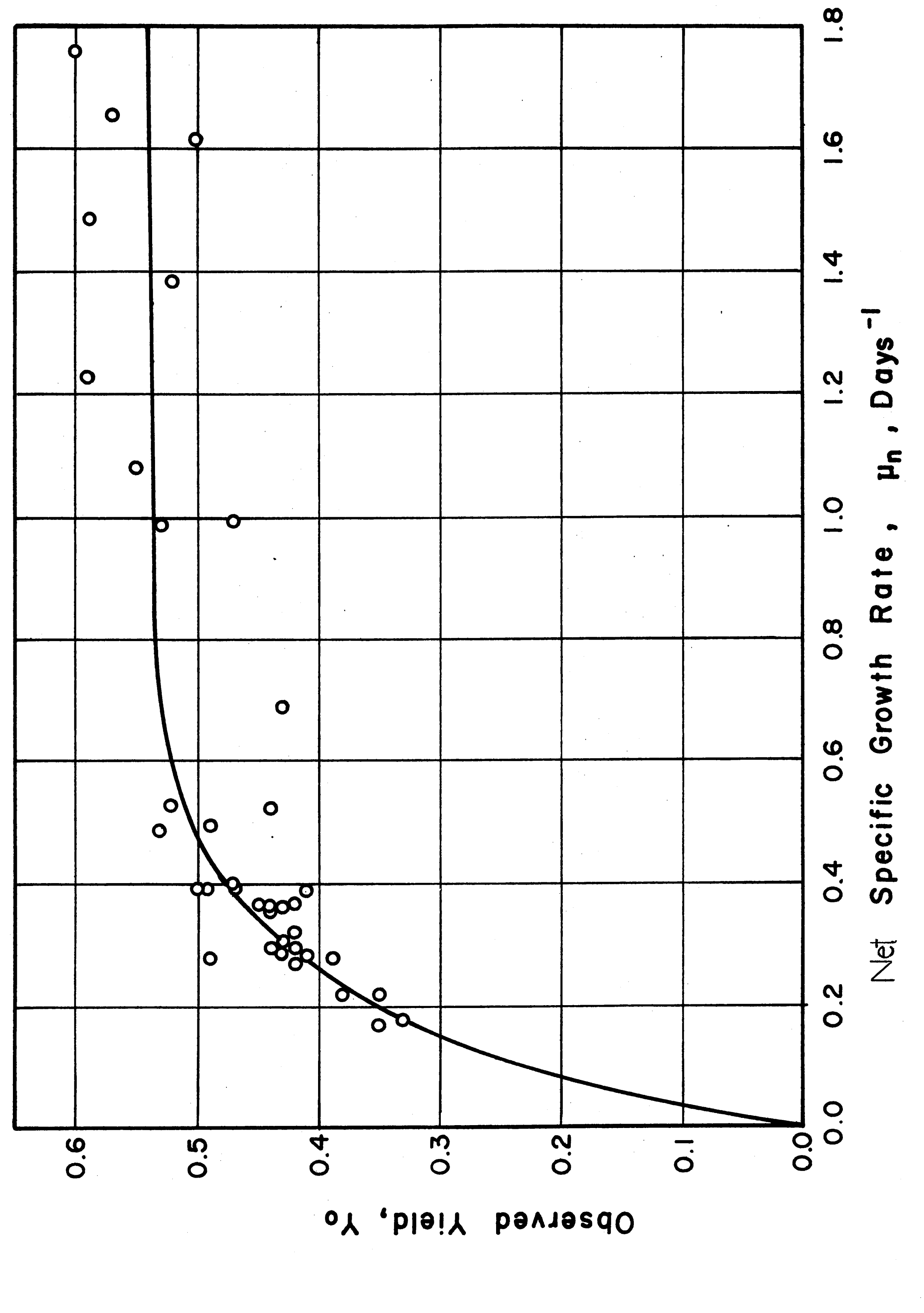
Since X_R is held constant, i.e., is relatively independent of responses in the system, aerator #2 served during hydraulic and quantitative shock load experiments as a ready store or supply of biological solids to aerator #1, thus aiding the system in approaching the new steady state. The steadying effect of using aerator #2 as a biochemical dosing tank for aerator #1 was also evident during the cyclic shock experiments.

The filtrate COD in aerator #2 was extremely low, and this agreed with assumptions made in the derivation of steady state equations for $\bar{X}$ and $\bar{S}$ that the substrate concentration in the recycle sludge, X_R, is negligible (1). This assumption was valid during all steady states before and after shock loading (see Table VI). In addition, values for S_R during transients in response to all shock loadings indicated S_R values approximately the same as the average values shown in Table VI for the pre- and post-shock steady states.

Excess sludge production, X_W, is one of the most important parameters in designing waste treatment facilities, and it is seen in Table XVII that sludge production remained very steady during each run. Furthermore, there was also considerable steadiness in daily sludge production during the cyclic shock load studies. The amount of excess sludge production is related to the net specific growth rate, μ_n, in accordance with equation (9). It is important, therefore, to examine the parameters which affect the net specific growth rate. In accordance with equation (11), these are D, α, X_R, and X. The first three are selectable operational parameters, and X is a consequence of these parameters and the biomass constants, as well as S_i. In the current study, α was maintained at 0.25, and the biological constants remained fairly constant. Thus, one can select random data from the 38 steady state runs (see Table VI) to determine if the experimental results bear out the model equations. For example, comparing lines 18, 9, 25, 5, and 17, the effects of recycle sludge concentration on μ_n can be seen. All of these runs were made at the same loading conditions (S_i, concentration, X_R: 15,000, 12,000, 10,000, 8000, and 6000 mg/l. The corresponding growth rates were 0.0063, 0.0066, 0.0129, 0.0153, and 0.0214 hr^{-1} (0.15, 0.159, 0.310, 0.369, and 0.514 day^{-1}). Thus, a decrease in X_R from 15,000 to 6000 mg/l caused more than a three-fold increase in μ_n. The factor exerting the second most significant effect on μ_n was S_i. In lines 5, 34, and 7 (Table VI), the recycle cell concentrations were approximately 8000 mg/l, and S_i values were 500, 1500, and 3000 mg/l glucose, respectively. The corresponding μ_n values were 0.0153, 0.0492, and 0.0742 hr^{-1} (0.367, 1.18, and 1.78 day^{-1}). Thus, an increase in S_i from 500 to 3000 caused a five-fold increase in μ_n. The third most significant factor which affected the value of μ_n was the dilution rate, D. Comparison of any of the three steady state values during each complete hydraulic shock experiment gave the effect of D. For example, lines 16 and 17 (Table VI) represent two steady states at D of 0.25 and 0.125 (Figure 6). The μ_n was 0.0554 and 0.0214 hr^{-1} (1.33 and 0.514 day^{-1}) at X_R of 6000 mg/l. Thus a doubling in dulution rate, D, caused a two- to three-fold increase in μ_n. Thus, it can be seen that an increase in X_R decreases X_W, and an increase in D or S_i increases X_W. These trends are borne out by both the model equation and the results.

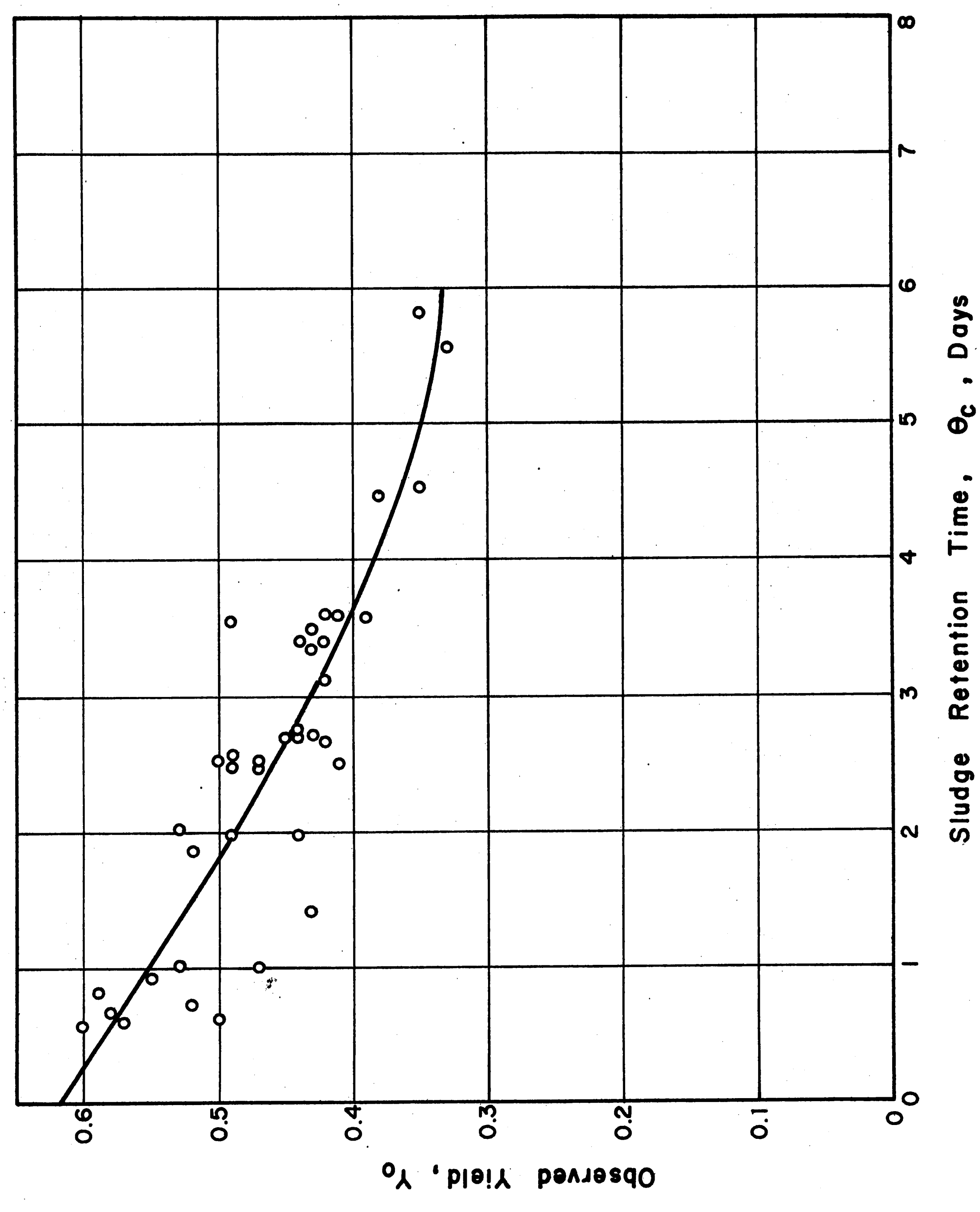
The relation between specific growth rate, μ_n, and the observed cell yield, Y_o, for steady state runs can be seen in Figures 32 and 33. It is seen that cell yield decreases with decreasing μ_n or increasing Θ_c. Observed cell yield is related directly to cell age, Θ_c, i.e.,

Figure 32. Relation Between Observed Cell Yield and Net Specific Growth Rate in Continuous Systems



Observed Yield, Y_o
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Net Specific Growth Rate, μ_n, Days^{-1}

Figure 33. Relation Between Observed Cell Yield and Cell Age in Continuous Systems



Observed Yield, Y_o
Sludge Retention Time, θ_c, Days
0.6
0.5
0.4
0.3
0.2
0.1
0
1
2
3
4
5
6
7
8

the higher the cell age, the lower the observed yield, and vice versa. This attributed to the maintenance energy requirements, i.e., the utilization of exogenous substrate to maintain the cells. It was found that Y_o is related to μ_n. A decrease in growth rate was accompanied by a decrease in observed yield (Table XVIII).

According to the maintenance energy theory, the fraction of exogenous substrate required for maintenance is minimal at high growth rates. Therefore, cell yield should be maximum at or near μ_{max}. This yield value is defined as "true yield." Thus, batch experiments where cells are grown at high substrate concentrations and close to μ_{max} should give "true yield," (Y_{t_B}).

A comparison of Y_o at low and high μ_n shows that it is in accordance with the theory of maintenance requirements (Figures 32 and 33). When cells were taken out of continuous flow pilot plants growing at a low μ_n and tested under batch conditions, at substrate concentrations yielding high μ values, they did not have a higher yield than in the continuous system. By comparing the last two columns in Table XVIII, it is apparent that Y_o was almost the same as Y_{t_B}. Actually, Y_{t_B} and μ_{max} varied with μ_n, as did Y_o (Figures 26 and 27). During thirty-four of the steady state runs, batch growth studies were made for measurement of μ_{max}, K_s, and Y_{t_B}. The differences between μ_n in continuous flow and μ_{max} in batch ranged between a seven- and 80-fold increase. However, there was little or no change between Y_o and Y_{t_B}. These observations are not consistent with the theory of maintenance energy. Gaudy and Srinivasaraghavan (2) observed the same phenomena. However, the results in continuous operation indicate that during steady state, there is a dependency of observed cell yield on the net

TABLE XVIII

RELATIONSHIP BETWEEN SPECIFIC GROWTH RATE AND CELL YIELD UNDER DIFFERENT CONDITIONS OF CONTINUOUS AND BATCH GROWTH

Line #	S_i Glucose mg/l	Specific Growth Rate, 1/hr		Cell Yield mg/mg	
		μ_n	μ_B	Y_o	Y_{tB}
18	500	0.0063	0.35	0.33	0.38
9	500	0.0066	0.54	0.35	0.38
11	500	0.0086	0.43	0.36	0.38
20	500	0.0079	0.37	0.39	0.40
25	500	0.0129	0.45	0.46	0.42
28	500	0.0138	0.44	0.49	0.45
3	500	0.0166	0.50	0.49	0.46
31	500	0.0171	0.45	0.49	0.50
17	500	0.0214	0.53	0.51	0.54
34	1500	0.0492	0.52	0.60	0.55
7	3000	0.0742	0.58	0.61	0.56

specific growth rate or cell age. Thus, the analytical equations developed for determination of Y_t and k_d can be used for design purposes. Linearization of observed yield was accomplished by employing two different methods. Two equations employed to determine the value of the "true yield," Y_t, and maintenance energy coefficient, k_d, are as follows:

$$\frac{1}{Y_o} = \frac{1}{\mu_n} \cdot \frac{k_d}{Y_t} + \frac{1}{Y_t} \quad (12)$$

$$\mu_n = Y_t U - k_d \quad (13)$$

Equation 12 was used by Marr, et al. (93), and equation (13) was used by Schulze, et al. (94). Y_o and Y_t are observed and true values; U is the specific substrate utilization rate, day^{-1}. The data used to obtain these maintenance plots are shown in Table XIX. This table shows values of μ_n determined by different formulas:

$$\mu_n = D\left(1+\alpha-\alpha \frac{X_R}{\bar{X}}\right) \quad 1/day \quad (11)$$

$$\mu_n = \frac{\bar{X}_W}{V\bar{X}} \quad (9)$$

$$= \frac{1}{\Theta_c}$$

where X_R, $\bar{X}$, and $\bar{X}_W$ are the average values for each parameter during steady state. Also, the observed yield was calculated by three equations:

TABLE XIX

DATA EMPLOYED FOR MAINTENANCE PLOTS

Line #	S_i Glucose mg/l	(1) μ_n	(2) μ_n	(3) Θ_c	(4) U	(5) Y_o	(6) Y_o	(7) Y_o	(8) Y_o	(9) $\frac{1}{Y_o}$
1	500	0.347	0.365	2.74	0.84	-	0.42	0.43	0.42	2.33
2	500	0.357	0.36	2.75	0.84	-	0.43	0.44	0.43	2.27
3	500	0.399	0.399	2.51	0.81	0.49	0.49	0.49	0.44	2.04
4	1500	1.069	1.084	0.92	1.98	0.54	0.54	0.55	0.54	1.82
5	500	0.369	0.367	2.73	0.84	.44	0.45	0.44	0.43	2.27
6	500	0.356	0.370	2.68	0.89	.43	0.40	0.42	0.43	2.38
7	3000	1.780	1.660	0.60	2.94	0.57	0.61	0.57	0.57	1.75
8	500	0.396	0.393	2.54	0.84	0.47	0.47	0.47	0.44	2.13
9	500	0.159	0.220	4.55	0.58	0.28	0.35	0.35	0.31	2.86
10	500	0.510	0.530	1.89	1.21	0.43	0.42	0.44	0.47	2.27
11	500	0.207	0.220	4.49	0.58	0.36	0.36	0.38	0.35	2.63
12	500	0.340	0.390	2.5	0.87	0.40	0.39	0.41	0.42	2.44
13	500	0.717	0.697	1.43	1.61	0.46	0.45	0.43	0.51	2.33
14	500	0.350	0.400	2.48	0.85	0.42	0.41	0.47	0.43	2.13
15	500	0.575	0.500	1.99	1.03	0.55	0.56	0.49	0.49	2.04
16	500	1.330	1.230	0.82	1.94	0.62	0.64	0.59	0.55	1.69
17	500	0.514	0.530	1.87	1.03	0.50	0.51	0.52	0.48	1.92
18	500	0.150	0.179	5.56	0.46	0.33	0.33	0.33	0.33	3.03
19	500	0.529	0.490	2.04	0.93	0.57	0.57	0.53	0.53	1.89
20	500	0.190	0.170	5.83	0.49	0.38	0.39	0.35	0.34	2.86
21	500	0.315	0.291	3.44	0.66	0.47	0.48	0.44	0.41	2.27
22	500	1.510	1.490	0.66	2.59	0.59	0.59	0.58	0.56	1.72
23	500	0.350	0.280	3.57	0.67	0.52	0.53	0.49	0.43	2.04
24	500	0.332	0.300	3.40	0.70	0.47	0.48	0.42	0.42	2.38
25	500	0.310	0.270	3.66	0.68	0.45	0.46	0.42	0.41	2.38
26	1500	1.000	1.000	1.00	2.11	0.49	0.47	0.47	0.53	2.13
27	3000	1.620	1.620	0.62	3.27	0.53	0.50	0.50	0.56	2.0
28	500	0.330	0.280	3.6	0.67	0.48	0.49	0.41	0.42	2.44
29	500	0.344	0.290	3.35	0.70	0.48	0.49	0.43	0.42	2.33
30	500	0.390	0.320	3.13	0.69	-	0.49	0.42	0.46	2.38
31	500	0.410	0.390	2.57	0.85	0.48	0.48	0.49	0.45	2.04
32	3000	1.750	1.760	0.57	2.96	0.58	0.59	0.60	0.57	1.67
33	500	0.390	0.396	2.53	0.79	0.49	0.50	0.50	0.44	2.0
34	1500	1.18	0.990	1.01	1.90	0.59	0.63	0.53	0.55	1.89
35	500	0.37	0.370	2.70	0.84	0.44	0.45	0.45	0.43	2.22
36	500	0.23	0.280	3.57	0.78	0.32	0.32	0.39	0.37	2.56
37	500	1.38	1.390	.72	2.66	0.52	0.52	0.52	0.56	1.92
38	500	0.35	0.300	3.5	0.69	0.52	0.52	0.43	0.43	2.33

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

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

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

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

(5) $Y_o = \frac{\mu_n \bar{X}}{D\left[S_i-(1+\alpha)\bar{S}\right]}$ mg/mg

(6) $Y_o = \frac{\mu_n \bar{X} \text{ pred.}}{D\left[S_i-(1+\alpha)\bar{S}\right]}$ mg/mg

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

(8) $Y_o = \frac{Y_t \cdot \mu_n}{\mu_t}$ mg/mg

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

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

$$Y_o = \frac{\mu_n \bar{X}}{D\left(S_i - (1+\alpha)\ \bar{S}\right)} \quad (14)$$

$$Y_o = \frac{\bar{X}_W}{F\left(S_i - S_e\right)} \quad (15)$$

$$Y_o = \frac{Y_t \cdot \mu_n}{\mu_t} \quad (16)$$

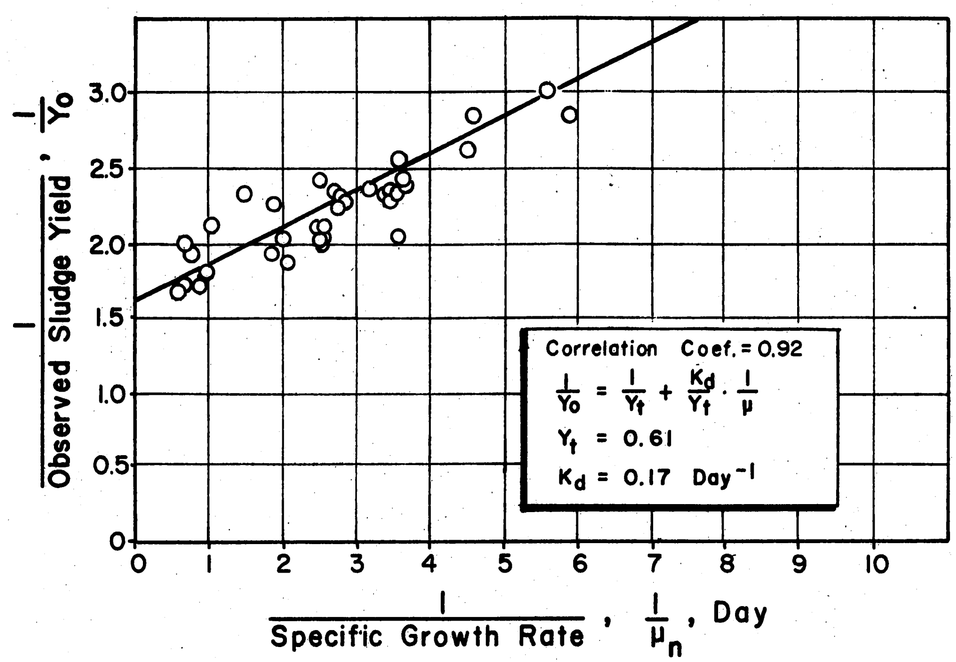
In general, there was essentially no difference for the μ_n and Y_o values calculated by the various equations.

Figure 34 shows maintenance plots as per equations (12) and (13). It is seen from this figure that the data fit the equations very well. The "true yield" value from these plots are found to be 0.62, and k_d to be 0.16 day^{-1}. The maintenance coefficient, k_d, is somewhat higher than most of those reported in the pollution control literature, but much higher values than this have been reported (95)(96).

It was of interest to determine the closeness with which the model equations (see Table XX) could predict the experimentally observed values of S, X, and X_W. In making these predictions, both average and individual values for biological constants, μ_{max}, K_s, and Y_{t_B} were used. The value of k_d was the same for all runs, i.e., 0.16 day^{-1}. Values were also calculated for the model equations, neglecting k_d.

From Table XX, it is seen that each set of equations predicts lower $\bar{S}$ than the observed $\bar{S}$ in the effluent. The use of COD as a measure of microbial substrate in the effluent leads to a conservative estimate. The predicted values are closer to the values of glucose measured in the effluent; nevertheless, it is evident that there is little

Figure 34. Plots of Maintenance Energy Equations to Determine "True Yield," Y_t, and Maintenance Coefficient, K_d


1 / Observed Sludge Yield , 1 / Yo
0
0.5
1.0
1.5
2.0
2.5
3.0
0 1 2 3 4 5 6 7 8 9 10
1 / Specific Growth Rate , 1 / μn , Day
Correlation Coef. = 0.92
1/Yo = 1/Yt + Kd/Yt · 1/μ
Yt = 0.61
Kd = 0.17 Day-1

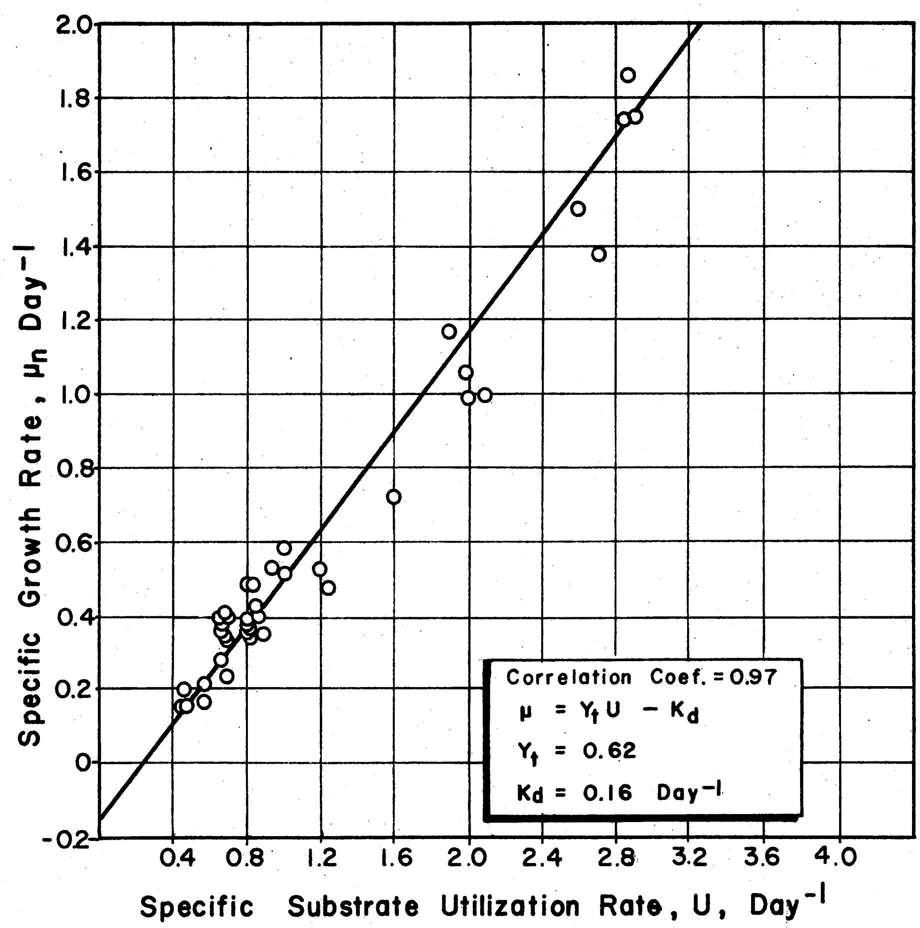

Specific Growth Rate , μn Day-1
-0.2
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0.4 0.8 1.2 1.6 2.0 2.4 2.8 3.2 3.6 4.0
Specific Substrate Utilization Rate, U, Day-1
Correlation Coef. = 0.97
μ = Yt U − Kd
Yt = 0.62
Kd = 0.16 Day-1

TABLE XX

EFFECT OF MAINTENANCE COEFFICIENT, k_d, USING INDIVIDUAL AND AVERAGE VALUES OF BIOLOGICAL CONSTANTS, μ_{max}, K_s, AND Y_{t_B}, on PREDICTION VALUES OF $\bar{S}$, $\bar{X}$, AND $\bar{X}_W$

		Effluent, Substrate, $\bar{S}$, mg/l					Biological Solids, $\bar{X}$, mg/l					Excess Sludge, X_W, mg/day				
			Predicted					Predicted					Predicted			
Line #	S_i Glucose mg/l	Obs.	Y_t=0.62 K_s(ind.) μ_{max}(ind.) K_d=0.16	Y_{t_B}(ind.) K_s(ind.) μ_{max}(ind.) K_d=0.16 (5)	Y_{t_B}(av.)=0.5 K_s(av.)=145 μ_{max}(av.)=0.5 K_d=0.16 (6)	Y_t=0.62 K_s(ind.) μ_{max}(ind.) K_d=0	Obs.	Y_t=0.62 K_s(ind.) μ_{max}(ind.) K_d=0.16	Y_{t_B}(ind.) K_s(ind.) μ_{max}(ind.) K_d=0.16 (10)	Y_{t_B}(av.)=0.5 K_s(av.)=145 μ_{max}(av.)=0.5 K_d=0.16 (11)	Y_t=0.62 K_s(ind.) μ_{max}(ind.) K_d=0	Obs.	Y_t=0.62 K_s(ind.) μ_{max}(ind.) K_d=0.16	Y_{t_B}(ind.) K_s(ind.) μ_{max}(ind.) K_d=0.16 (15)	Y_{t_B}(av.)=0.5 K_s(av.)=145 μ_{max}(av.)=0.5 K_d=0.16 (16)	Y_t=0.62 K_s(ind.) μ_{max}(ind.) K_d=0
1	500	22	-	-	5.4	-	1766	-	-	1725	-	1290	-	-	1259	-
2	500	28	-	-	5.4	-	1788	-	-	1741	-	1302	-	-	1253	-
3	500	24	5.4	4.10	5.4	5	1776	1766	1689	1723	1842	1416	1409	1348	1375	1912
4	1500	19	18.2	14.4	14.0	18	2237	2239	2091	2104	2335	4850	4854	4533	4561	5516
5	500	15	9.4	6.5	8.0	9	1774	1762	1699	1720	1838	1302	1293	1247	1262	1791
6	500	14	6.3	4.6	5.2	6	1782	1765	1733	1754	1840	1330	1306	1282	1298	1704
7	3000	20	16.2	14.6	23.4	16	3095	2939	2849	2708	3064	10272	9757	9459	8991	10910
8	500	14	5.3	3.6	5.4	5.1	1777	1765	1685	1719	1841	1398	1387	1324	1351	1889
9	500	12	3.0	2.0	4.0	2.1	2513	2539	2450	2499	2647	1140	1117	1078	1100	1803
10	500	6	1.0	1.0	7.0	2.6	2554	2579	2484	2529	2634	2697	2733	2633	2681	3820
11	500	9	12.4	8.0	3.8	12.0	2553	2548	2451	2508	2657	1137	1121	1078	1104	1835
12	500	22	10.2	8.7	5.1	9.8	1775	1792	1721	1753	1869	1422	1398	1342	1367	1905
13	500	15	6.7	6.3	12.0	6.5	1794	1821	1740	1758	1860	2502	2538	2426	2451	3558
14	500	13	5.3	4.8	5.3	5.1	1760	1766	1707	1725	1842	1420	1413	1366	1380	1842
15	500	18	7.0	6.3	6.1	6.8	1421	1383	1378	1345	1442	1430	1383	1378	1345	1794
16	500	33	24.9	24.1	15.0	24.6	1450	1406	1421	1357	1433	3558	3459	3496	3338	3588
17	500	22	24.4	21.3	6.3	25.2	1399	1382	1356	1348	1442	1495	1465	1437	1429	1761
18	500	16	6.5	4.0	3.0	6.4	3115	3096	3009	3059	3228	1120	1108	1077	1095	1768
19	500	20	11.0	10.6	6.1	10.8	3224	3173	3165	3133	3241	3167	3110	3102	3070	3671
20	500	10	6.7	4.3	2.9	6.4	3170	3127	3042	3085	3261	1087	1063	1034	1049	1922
21	500	15	5.6	5.2	4.0	5.4	2200	2163	2149	2125	2261	1280	1259	1251	1237	1847
22	500	25	23.5	22.4	20.0	23.5	2249	2237	2227	2194	2261	6724	6666	6637	6538	7143
23	500	13	4.7	4.2	3.9	4.5	2220	2164	2139	2124	2257	1237	1212	1198	1189	1823
24	500	10	14.8	11.9	3.6	14.3	2210	2176	2130	2133	2269	1291	1306	1278	1280	1910
25	500	17	5.3	3.7	3.4	5.1	2205	2178	2102	2140	2271	1205	1176	1135	1156	1851
26	1500	13	32.4	27.1	12.0	31.3	2187	2245	2151	2128	2342	4368	4490	4302	4256	5540
27	3000	15	47.0	43.2	23.4	45.8	2818	2996	2877	2708	3124	9129	9707	9321	8774	11420
28	500	12	4.8	3.5	3.9	4.6	2210	2167	2103	2126	2260	1222	1214	1178	1191	1835
29	1500	10	4.5	3.6	3.6	4.3	2204	2163	2113	2120	2256	1316	1255	1226	1230	1908
30	500	9	-	-	3.7	-	2247	-	-	2126	-	1288	-	-	1361	-
31	500	11	7.2	5.8	5.2	6.8	1820	1804	1752	1755	1839	1419	1407	1367	1369	1632
32	500	45	12.6	12.0	23.5	12.2	3018	2946	2887	2693	3072	10630	10370	10162	9479	10970
33	500	42	6.4	5.1	5.3	6.1	1799	1765	1721	1742	1840	1428	1398	1363	1380	1718
34	1500	31	12.0	10.6	13.4	11.5	2359	2233	2178	2189	2328	4683	4421	4312	4334	5325
35	500	24	4.7	4.7	5.5	4.5	1804	1770	1737	1781	1845	1342	1310	1285	1318	1625
36	500	20	5.0	4.0	3.2	4.9	2132	2151	2110	2122	2242	1209	1205	1182	1188	1815
37	500	16	11.6	9.9	18.0	11.4	2240	2215	2220	2046	2239	6221	6158	6172	5688	6138
38	500	20	5.4	4.0	3.4	5.2	2210	2218	2101	2123	2241	1260	1331	1261	1274	1610

difference in the predicted values of $\bar{S}$ whether the original or modified equations are used. Comparison of predicted and observed values of $\bar{X}$ leads to the conclusion that if one does not really require a very close prediction of X, there is little difference in using either the original equation neglecting k_d, or the latter ones employing it. However, the modified equations predict $\bar{X}$ closer to the observed value. This is more true at lower growth rates, when the effect of k_d will be more manifest than at higher growth rates. Regarding prediction of excess sludge, X_W, it is seen that at high growth rates, the new model provides rather good prediction, but the original model without k_d does not predict X_W closely. At low μ_n, the model including k_d provides a very good estimate of X_W, whereas the one without k_d predicts about 70 percent more excess sludge than was observed experimentally.

Comparison of predicted values of $\bar{X}$, $\bar{S}$, and $\bar{X}_w$, using either the average or the individual values of the biological constants, Y_{t_B}, K_s, and μ_{max} (i.e., compare columns 5, 6, 10, 11, 15, 16) reveals that there is little numerical difference. This may be useful for design purposes wherein average values for biological constants, K_s, μ_{max}, and Y_{t_B} for a particular waste could be substituted in the model equations to predict the values of $\bar{S}$, $\bar{X}$, and $\bar{X}_W$. However, such a shortened design approach cannot be recommended on the basis of one set of experimental results. It would be interesting to see if one could show this same trend for a waste of a different nature (see suggestions for future work).

CHAPTER VII

CONCLUSIONS

The results of this investigation support the following conclusions:

1. Steady state systems operating at a dilution rate of 0.125 hr^{-1} (8-hour detention time) with recycle sludge concentrations of 6000, 8000, 10,000, 12,000 and 15,000 mg/l and α = 0.25, can accommodate a 100 percent increase in flow rate without harmful effect on effluent quality.

2. For a 100 percent increase in hydraulic loading, a decrease of the recycle sludge concentration from 12,000 mg/l to 8000 mg/l yielded the same transient effluent characteristics, S_t, S_e, and X_e. However, the transient phase lasted for a longer period of time in the case of X_R = 8000 mg/l than was the case for X_R = 12,000 mg/l.

3. For a 100 percent increase in hydraulic loading, a decrease in the recycle solids concentration from 12,000 mg/l to 6000 mg/l yielded the same values for S_t in the transient stage, i.e., an increase in X_R did not improve the transient response.

4. For a 100 percent increase in hydraulic loading, an increase in X_R concentration from 12,000 to 15,000 mg/l led to an improvement, i.e., less substrate leakage in the transient.

5. Quadrupling of D (0.125-0.5 hr^{-1}) for a system with X_R = 10,000 mg/l, led to a short-lived transient disturbance and rapid

recovery.

6. For quantitative shock, a successful response was obtained for a 200 percent increase in feed concentration (500 mg/l to 1500 mg/l) at X_R = 8000 mg/l.

7. The use of 8000 mg/l for X_R did not provide a high degree of protection during the transient phase for a 500 percent increase of feed concentration (500 $\rightarrow$ 3000 mg/l).

8. In the current studies, there was evidence that oxidative assimilation of carbonaceous into non-nitrogenous material played a significant mechanistic role.

9. In all cases wherein shock experiments were rerun under similar conditions but employing cells from different inocula of sewage, the response to the shock exhibited a high degree of reproducibility.

10. In regard to cyclic rather than step shocks, the system could safely accommodate a two-fold hydraulic shock with constant α. Also, the system could accommodate this magnitude of shock without change in recycle flow rate, i.e., with variable α. Also, it successfully withstood a three-fold cyclic change in S_i and, quite significantly, a six-fold increase in mass loading rate under conditions of concurrent quantitative and hydraulic cyclic shock.

11. Statistical analyses of the experimental results for "steady states" prior to and after shocks provide evidence that this mode of operation, i.e., constant X_R, does much to ensure that the steady state in $\bar{S}$ and $\bar{X}$ assumed in the derivation of the model, is actually observable.

12. Steady state runs conducted under similar operational conditions indicated a high degree of reproducibility with respect to X,

S, and X_W. The biological constants, k_d, μ_{max}, and Y_{t_B}, were essentially the same under similar operational conditions, but there was some variation in K_s.

13. Values of the maximum specific growth rate and yield obtained during the batch growth experiments show a general trend with the observed specific growth rate, μ_n, in the continuous system. There was a tendency for Y_{t_B} and μ_{max} to increase with an increase in μ_n.

14. There was essentially no difference in observed and predicted values of $\bar{S}$, $\bar{X}$, and $\bar{X}_W$ using either individual or average values for Y_{t_B}, μ_{max}, and K_s when the model employing k_d was applied. On the other hand, using the original equations without k_d, there was little difference in predicted and observed $\bar{S}$ and $\bar{X}$, while there was a significant difference in prediction of $\bar{X}_W$.

CHAPTER VIII

SUGGESTIONS FOR FUTURE STUDY

Based on the findings of this study, the following suggestions are presented for future investigation involving the new activated sludge process with constant recycle sludge concentration.

1. The response to various combinations of hydraulic and quantitative shock loads may be extended to study a wider set of conditions.

2. A study of the response to various combinations of quantitative and qualitative shock loads should prove valuable.

3. The effect of changing recycle sludge concentration during the transient, in order to overcome substrate leakage, should be studied.

4. The response of the system to temperature shock loads should be studied.

5. The complete aerobic treatment flow sheet suggested by Gaudy and Gaudy (87) for carbon removal and sludge disposal should be investigated using the present results to guide design of the experimental program.

6. Steady state operation at lower growth rate, μ_n (i.e., higher Θ_c) may lead to demonstration of the zero sludge production indicated by the model equations (97).

7. A larger scale pilot plant may now be tried to study the operational ease and performance of the model.

8. A complete engineering design detail with a cost analysis is required for the future use of the model in the field. These may proceed in a preliminary manner immediately and can be refined after larger scale pilot plant studies.

9. The model equations should be tested for ability to predict under different operational conditions the values of $\bar{S}$, $\bar{X}$, and $\bar{X}_W$ for a waste using average values for biological constants, K_s, μ_{max}, and Y_{t_B}.

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