Prog. Wat. Tech. Vol. 8, No. 1, pp 41-68, Pergamon Press 1976. Printed in Great Britain

CONTROL SYSTEMS FOR THE REDUCTION OF EFFLUENT VARIABILITY FROM THE ACTIVATED SLUDGE PROCESS

John F. Andrews and Michael K. Stenstrom
Environmental Systems Engineering, Clemson University, Clemson, South Carolina 29631
Current address-Department of Civil Engineering, University of Houston, Houston, Texas 770004
and
Heinrich O. Buhr
Department of Chemical Engineering, University of Cape Town, South Africa

INTRODUCTION

A reduction in the variability of the effluent from wastewater treatment processes can be obtained in several ways and included among these are increasing the physical size of the process, the use of equalization basins and the installation of modern control systems. In past years, the most common technique for reducing variability has been to increase the size of the process and, in some instances, to install equalization basins. However, both of these techniques involve substantial capital investments (1) and the third technique, application of modern control systems, should be explored in more depth since it offers the potential for reducing effluent variability at considerably lower capital cost.

It is not surprising that control systems should be considered for reducing effluent variability since the need for control, whether it be manual or automatic, is brough about by dynamic behavior and a reduction in variability involves changing dynamic behaviour. However, there are many other potential benefits from the incorporation of modern control systems into process design and included among these are the maintenance of process efficiency nearer the optimum, decreasing physical size, improving reliability and stability, decreased operational costs and faster start-up. A more detailed discussion of these potential benefits has been presented by Andrews (2). The economic feasibility of installing such systems in wastewater treatment plants has been addressed by Smith (3) and Andrews (4).

Since this paper is primarily concerned with process control systems, which are not normally covered in environmental engineering educational programs, a brief description of the basics of process control is in order. These basic principles will then be illustrated by simplified examples using computer simulation of an autocatalytic reaction in a continuous flow, stirred tank reactor (CFSTR). A brief description of a dynamic model of the activated sludge process will then be presented and computer simulation will again be used to illustrate a proposed control signal, specific oxygen utilization rate (SCOUR), and a proposed control action, this being change in the feed points for the step feed activated sludge process.

PROCESS CONTROL SYSTEMS

Control systems are primarily involved with the handling of information. This may be done manually or by automatic control systems. As environmental engineers, we are familiar with the theory and technology involved in the collection, transportation, processing and distribution of materials and energy. However, we are not as accustomed to thinking of information in the same terms.

Information Flow Diagrams

Flow diagrams are used in the handling of information just as they are used in the handling of materials and energy and examples of information flow diagrams are given in Fig. 1 where the temperature of a process is to be controlled either manually or automatically. The temperature is changed from its desired or reference value by some input disturbance such as a change in environmental temperature. This change is measured by a sensor such as a thermometer. In a manual control system (Fig. 1a), the measured

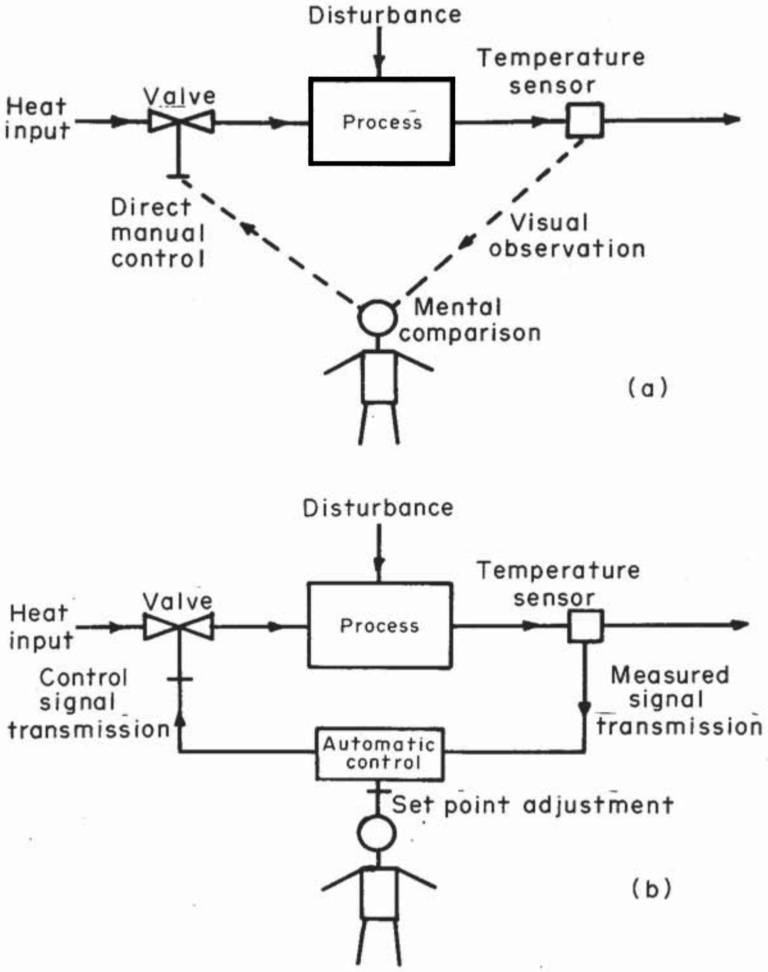


FIG. 1. Feedback control loops as information flow diagrams.

temperature is transmitted to the man in the control loop by visual observation. The man processes this information by mentally comparing the observed temperature with the desired temperature, and adjusts the heat input to the process in an attempt to bring the temperature back to its desired value. Several iterations of this procedure may be needed before the desired temperature has been attained. The man has "closed the loop" by "feedback" of information from the process output to the process input.

In the automatic system (Fig. 1b), the man is replaced in the feedback loop by a controller. The temperature sensor transmits a signal to the controller. Generally an additional device, a transducer, is needed between the sensor and controller for amplification or changing the form of the signal so that it can be transmitted to or understood by the controller. The controller compares the signal with a stored reference signal, or set point, to determine whether an error exists. If an error does exist, the controller computes, by means of a control equation (algorithm), the amount of control action needed. It then transmits a signal to the final control element, a valve in this instance, to adjust the heat input to the process. A transducer may also be needed between the controller and the final control element. The automatic system also has iterative characteristics since the computed adjustment of the control valve may not give the desired temperature. It should be noted that the man continues to participate in the feedback loop on an intermittent basis since he must select the set point value on the basis of his judgement and experience.

Basic Questions

Regardless of whether control is to be manual, automatic, or a mixture of the two, some of the same basic questions must be answered in the development of a process control system. Included among these are:

1. What measurements should be made for initiation of the control action? Measurements might be made on the process influent or effluent, the process environment, or could be internal to the process. Associated items of importance are the required accuracy and frequency, time required for making the measurements, and the availability, accuracy and reliability of sensors. The dynamic behavior of the process and its associated control system must be considered in establishing the type and frequency of measurements.

2. What control action should be taken? This is of particular importance for wastewater treatment processes since many plants have been designed without adequate consideration of dynamic behavior or operational characteristics. The prevailing philosophy in wastewater treatment plant design has been to provide a minimum number of control actions and attempt to take care of variability in the process influent and environmental conditions by provision of additional capacity. In most processes, possible control actions are

therefore very limited.

3. How should the information be transmitted from the sensor to the controller and from the controller to the final control element? This is an elementary question, but in many wastewater treatment plants, information which has been collected is not used for initiation of control but is simply filed for the record. The control loop is therefore broken.

4. How should the information be processed in order to determine the type and amount of control action needed? A variety of control algorithms involving such mathematical operations as conversion of units, comparison with desired values, averaging, multiplication,integration, etc., are available.

A sizeable body of literature relative to questions three and four is available in the field of control engineering. Some of the more pertinent material related to control algorithms will be briefly discussed herein; for more details, the reader should consult the books of Perlmutter (5), Shilling (6), Hougen (7), Tucker and Wills (8), and Lloyd and Anderson (9).

Control Algorithms

The simplest form of a control algorithm is two-position or on-off control, which means that the final control element is either in the completely "on" or completely "off" position. The amount by which the measured value of the controlled variable differs from the desired value is termed the "error", and in on-off control the final control element is either completely opened or completely closed depending upon whether the error signal is positive or negative. A common variation of this algorithm is differential gap control in which the final control element is activated only when the error signal is outside some specified range. This prevents too frequent operation or "chatter" of the final control element. A typical variation of two-position control in wastewater treatment plants is coupling of on-off with a time cycle controller, for pumping of sludge from a primary sedimentation basin. For example, the timer may turn the sludge pump on once each hour and the pump will run until it receives a signal from a sludge density meter indicating that the sludge density has fallen below some desired or set point level.

A commonly used control algorithm is that provided by the three-mode controller equation. This is also known as PID control and the control equation is given below:

$$C_A = K_B + K_P\, e + K_I \int_0^t e\, dt + K_D \frac{de}{dt} \qquad (1)$$

where:

C_A = amount of control action;

K_B = bias;

K_P = proportional control coefficient or "gain"

K_I = integral control coefficient;

K_D = derivative control coefficient;

e = error signal.

This equation allows calculation of the amount of control action as a function of four terms. The first term is called the bias and provides for manual adjustment of the amount of control action. For example, K_B may be adjusted to give 50% of the full value of C_A when the error signal is zero. Addition of the second term provides proportional (P) control in which the amount of control action is proportional to the error signal. From the nature of the second term it may be seen that, in order for this action to be effective, the error (e) must have some non-zero value, the magnitude of which will depend on K_P, the proportional gain. This "offset" of the controlled variable from the set point is a characteristic of proportional control systems. Offset may be corrected by manual resetting of the controller bias coefficient. Addition of the third term gives integral (I) control action which is proportional to the integral of the error signal and therefore continues to change C_A for as long as the error persists. In this way, the integral term provides an automatic reset action. The integral term may also be looked upon as factoring into control the "history" of the process since it reflects the length of time that the error has persisted. The fourth term is proportional to the derivative (D) of the error signal and thus attempts to predict the "future" of the process by considering the rate of change of the error. In using the PID controller equation, one or more of the terms may be deleted and the derivative term is frequently omitted since it may result in "chatter" for noisy signals.

Two-position and variations of PID controllers are widely used and have proven their value in a variety of control applications. However, there are many situations in which process performance could be further improved by the use of more advanced control algorithms. One of these is feedforward control in which information for control is obtained by measuring the inputs to the process instead of the outputs as in feedback control. The amount and type of control action needed is then predicted using either process history or a dynamic mathematical model. Feedforward control is classified as open loop control since there is no feedback from the variable of interest and is theoretically capable of perfect control since no error need exist, as for feedback control, before the control action is initiated. However, the future can rarely be completely predicted based on history, and dynamic models are seldom perfect. There may also be limitations on the amount and type of control action that can be exerted. For these reasons, feedforward control is usually combined or "trimmed" with some feedback control.

A crude form of feedforward control commonly used for the activated sludge process is ratio control in which the recycled sludge flow rate is maintained as a preset fraction of the wastewater flow rate to the aeration basin. This type of control is usually initiated in an attempt to maintain a more constant concentration of mixed liquor suspended solids (MLSS) in the aeration basin and is open loop control since there is no feedback from the controlled variable, the MLSS.

Control systems involving many control loops, or using advanced control algorithms, require considerable computing power and it is only logical that digital computers are being increasingly used for process control. However, computer control is not the subject of this paper and for a detailed description of the application of computers in several wastewater treatment systems, the reader is referred to the book edited by Andrews *et al.* (10).

SIMPLIFIED EXAMPLES OF PROCESS CONTROL

The application of control systems for reducing effluent variability is best illustrated by specific examples and for this purpose an autocatalytic reaction in a single stage CFSTR has been selected as illustrated in Fig. 2. The reaction is given in eqn 2 and the rate expression is shown in eqn 3.

$$A \xrightarrow{B} y\,B \qquad (2)$$

$$\frac{dA}{dt} = -\,k\,A\,B \qquad (3)$$

where:

A = concentration of A, mass/volume;

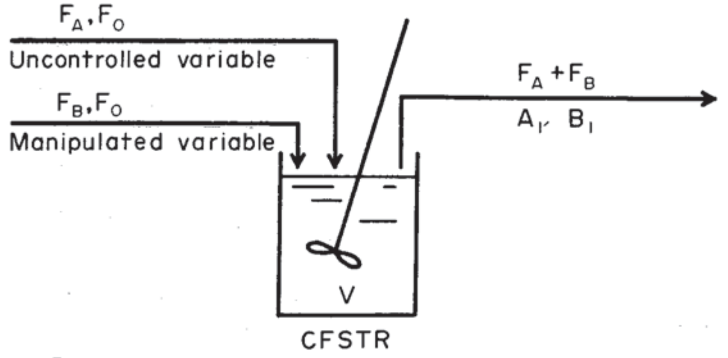
B = concentration of B, mass/volume;

y = yield coefficient;

k = rate coefficient, time^{-1};

t = time;

$0,1$ = subscripts denoting influent and effluent, respectively.



$$A \xrightarrow{B} yB \qquad F_A = 1.0\ \text{l/hr} + 0.5\sin\left(\frac{2\pi}{24}t\right)$$

$$\frac{dA}{dt} = -kAB \qquad A_0 = 100\ \text{mg/l} + 50\sin\left(\frac{2\pi}{24}t\right)$$

$$y = 0.5\ \text{mg B/mg A} \qquad V = 4\ \text{l}$$

$$k = 0.001\ \text{hr}^{-1} \qquad B_0 = 8{,}000\ \text{mg/l}$$

FIG. 2. Autolytic reaction in single stage CFSTR.

Both the reaction and rate expression are analogous to those occurring in the activated sludge process with A corresponding to the BOD concentration and B corresponding to the concentration of activated sludge. The numerical values used for the coefficients and input variables have been selected within the range of those commonly used for the activated sludge process. However, different symbols (A,B) have been chosen, instead of those customarily employed (S,X), to emphasize that these are simplified expressions and should not be used for representation of the process except under restricted conditions. Two of the major factors not considered in the expressions are the reduction in concentration of B which would occur through organism decay and the influence of a solids - liquid separator on the concentrations of A_1 and B_0. A_1 and B_0 would be influence by the clarification and thickening functions, respectively, of the solids - liquid separator. Both of these are considered in the dynamic model which will be presented in a later section of this paper.

The flow rate (F_A) of the stream containing A and the concentration of A in this stream, are both assumed to vary in a sinusoidal manner and to be in phase with maximum and minimum amplitudes being ± 50% from the averages. The flow rate (F_B) of the stream containing B is the control or manipulated variable and the concentration of B in this stream is assumed constant. The base case with which the effectiveness of the different control systems is to be compared is that for which F_B is constant at a value equal to 0.333 of the average value of F_A. Under these conditions, the concentration of A in the effluent from the reactor (A_1) varies with time as shown in Fig. 3 and has an average value of 12.5 mg/liter. For a numerical rather than a graphical comparison of variability, an index of variability is needed and for the purposes of this paper, a variability index is defined as shown in eqn 4 below.

$$VI = \left[\frac{1}{T} \int_0^T (A - A_{avg})^2 \, dt\right]^{1/2} \qquad (4)$$

where:

$T = 24$ hr.

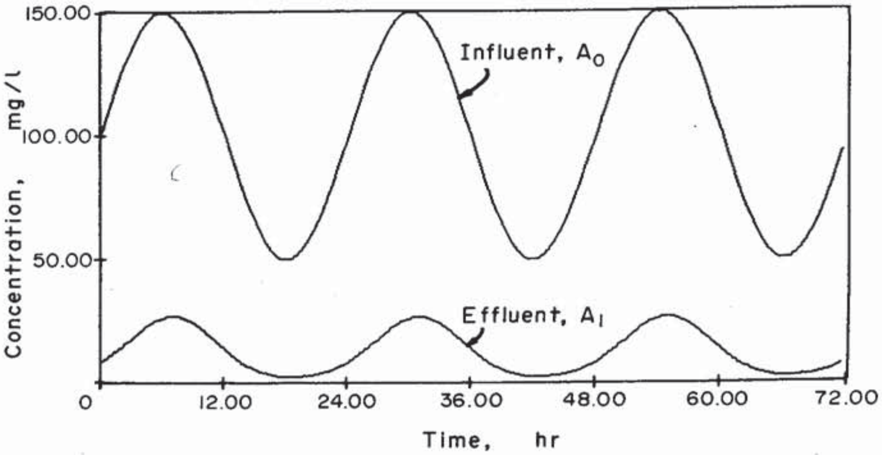


FIG. 3. Effluent variability for the base case.

TABLE 1. Average Value and Variability Index of A

Case	System	A_{avg} mg/liter	VI mg/liter
1	Base case, V = 4 l	12.5	8.73
2	Double reactor volume, V = 8 l	6.6	4.38
3	Equalization basin:		
a.	Equalization of concentration only	12.5	7.56
b.	Equalization of flow & concentration	11.9	2.90
4	Proportional feedback control:		
a.	Low gain ($K_p = -0.04$)	12.5	5.42
b.	Intermediate gain ($K_p = -0.20$)	12.5	2.85
c.	High gain (on-off) ($K_p \rightarrow -\infty$)	12.5	1.89
5	Feedforward control:		
a.	Ratio control, flow-proportional	12.5	7.30
b.	Ratio control, mass-proportional	12.5	6.24
c.	Theoretical, with limits on F_B	12.5	1.61
6	Two reactors in series:		
a.	Feed to reactor 1, no control	6.6	5.77
b.	Control of fraction to reactor 1	12.5	3.59

The variability indices and average values of A in the effluent for the simulations presented herein, are given in Table 1. The simulations were performed using CSMP-III on an IBM 370/165 digital computer.

Reactor Volume and Equalization Basin

Two techniques, other than the use of a control system, which may be employed for reducing effluent variability are an increase in the reactor volume and the installation of an equalization basin upstream from the reactor. An example of the use of these two techniques is presented in Fig. 4. In one instance the reactor volume was doubled (4-8 l.) and in the other, a completely mixed equalization basin with a variable liquid volume was placed upstream from the reactor. The volume of liquid in the basin varied from 0 to 4 liters and was selected to maintain a constant flow rate into the reactor under the conditions specified for this example.

Both of these techniques reduced the variability, with the equalization tank being more effective (VI = 2.90 mg/l, Table 1) than the doubling of reactor volume (VI = 4.38 mg/l). However, doubling of the reactor volume also offers the advantage of reducing the average concentration of A in the effluent (6.6 mg/l vs 12.5 mg/l). For the purposes of this paper, it has been assumed that no reaction occurs in the equalization basin whereas in wastewater treatment practice there would be some removal of BOD in the equalization basin as indicated by Smith et al. (1).

Two types of basins may be used for equalization, these being a constant

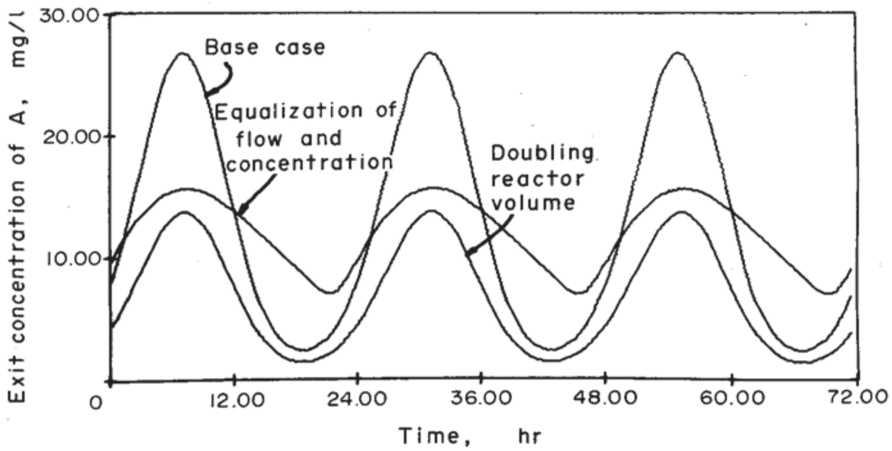


FIG. 4. Effluent variability for increased reactor volume and equalization basin.

volume tank for equalization of concentration only, or a tank with a variable liquid volume for equalization of both concentration and flow. The use of a constant volume tank has been studied by Novotny and Englande (11) and that of a variable volume tank by Smith et al. (1). A comparison of the two is presented in Fig. 5, from which it can be seen that the equalization of both flow and concentration is much more effective in reducing variability (VI = 2.90 mg/l vs 7.56 mg/l) than is the equalization of concentration alone. It should be noted that this improvement would most likely be accomplished by the use of a control system to maintain a regulated flow from the variable volume basin and could therefore be attributed to the use of a control system.

Feedback Control

The most common type of control system would be feedback control (Fig. 1) using the concentration of A in the reactor effluent (A_1) as the measured variable, F_B as the controlled variable (Fig. 2) and a PID control algorithm (eqn 1). For the simulations to be presented herein, only the simplest form of eqn 1, proportional control, will be used as shown in eqn 5. C_A, the

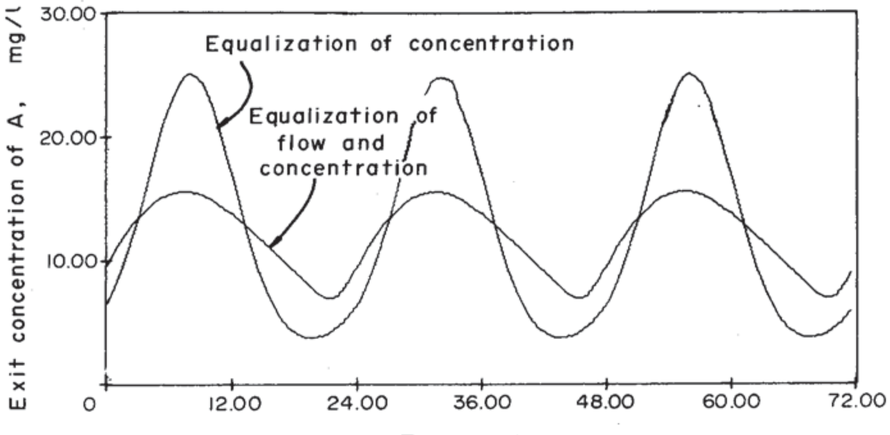


FIG. 5. Effect of equalization on effluent variability.

amount of control action,

$$F_B = K_B + K_p \, (\text{set point} - A_1) \qquad (5)$$

is equal to F_B; K_B, the bias coefficient, is appropriately selected to eliminate offset of the mean value of A_1 from the desired value; and e, the error signal, is equal to the desired or set point value of A_1 minus the actual value at any time. The set point used for the simulations presented herein is 12.5 mg/l, which is the average value of A_1 for the base case with no control. This particular value of A_1 was chosen to permit a comparison of effluent variability under conditions of equal average performance. Minimum and maximum limits of 0 to 1.0 1/hr have been placed on F_B, to correspond to typical limitations on recycle sludge pumping rate that exist in practice.

A comparison of the effect of proportional feedback control on the variation of A_1 with the effects of doubling the reactor size and the use of an equalization basin is presented in Fig. 6. The decrease in variability realized by the control system (VI = 2.85 mg/l) is approximately the same as that attained by the equalization of concentration and flow (VI = 2.90 mg/l), thus indicating that the control system constitutes an effective means for reducing effluent variability.

From a practical point of view, the application of conventional feedback control would depend on the availability of a sensor for measuring A_1. Insofar as this example approximates the activated sludge process, A_1 corresponds to the BOD of the process effluent, and no suitable measuring instrument is currently available. This problem is further considered in a later section of this paper, where the specific oxygen utilization rate (SCOUR) is proposed as a control variable. At the same time it should be borne in mind that the measurement of A_1 need not necessarily be continuous, and could be performed off-line, such as in a laboratory. Further dynamic analysis using sampled-data theory would be required to determine the frequency and accuracy with which A_1 should be measured to provide effective control.

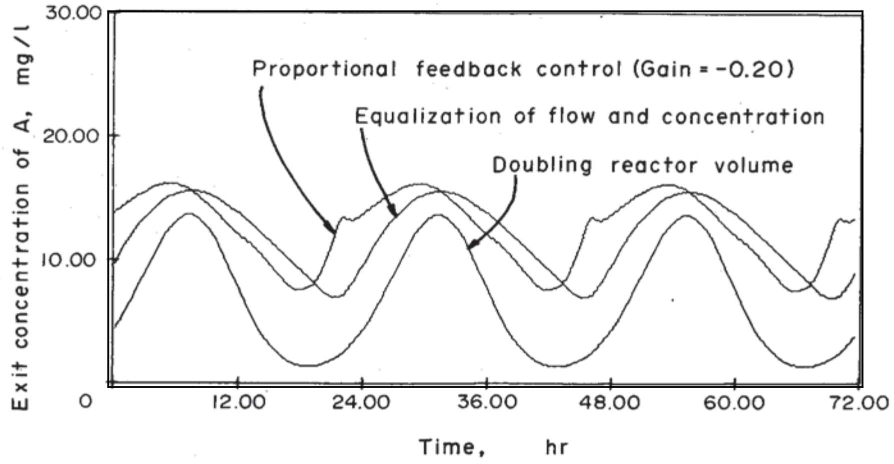


FIG. 6. Comparison of feedback control with equalization and doubling reactor size.

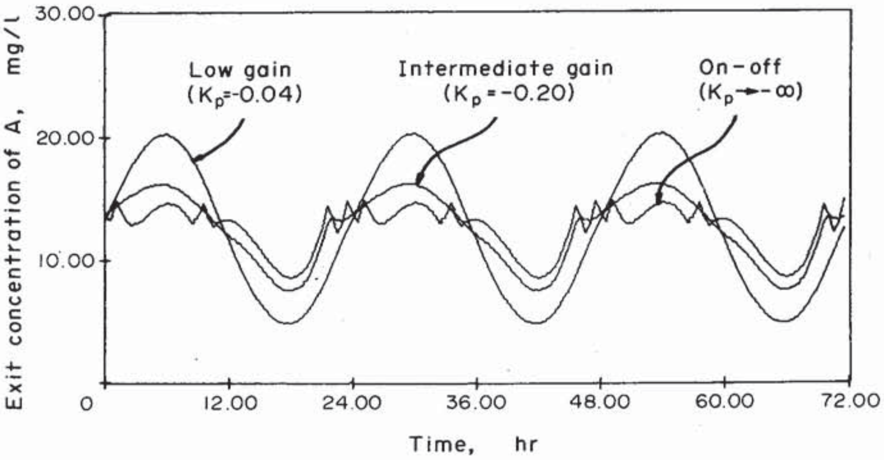


FIG. 7. Proportional feedback control with varying gain.

The effect of the numerical value of the gain coefficient on the variability of A_1 is presented in Fig. 7. Low, medium and very high gains give values of 5.42, 2.85 and 1.89 mg/l respectively for the variability index. Because of the limits (0 to 1.0 l/hr) which have been placed on F_B, high-gain ($K_p \rightarrow -\infty$) proportional control is essentially equivalent to on-off control, and in fact the simulation shown as $K_p \rightarrow -\infty$ in Fig. 7 was performed for differential gap on-off control. The effect of the limits on F_B is illustrated in Fig. 8 where the flow rate of the controlled variable (F_B) is plotted against time.

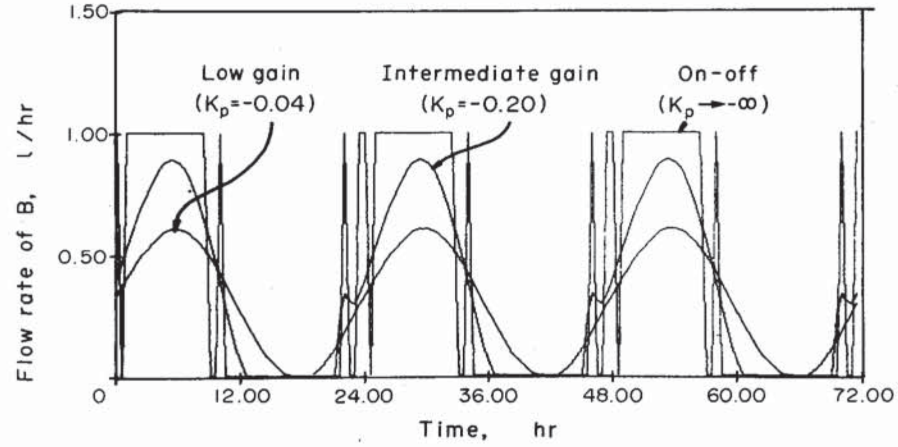


FIG. 8. Control variable (F_B) for proportional feedback control.

For the low gain, there is an almost continuous variation of F_B; for the medium gain the lower limit of zero is reached over a substantial portion of the day and for on-off control F_B varies in a discrete fashion between the limits of 0 and 1.0. It should be noted that this discrete type of operation would probably not be desirable for the activated sludge process since the possibility exists that the sludge storage capacity of the solids - liquid separator could be exceeded if the recycle sludge pump is turned off for substantial periods of time and the sludge could also go anaerobic during these periods. Another practical limitation is that the concentration of recycled sludge would not be constant whereas B_O is constant for the example presented herein. The above statements clearly indicate the need to couple a dynamic model of the solids - liquid separator with the dynamic model for the biological reactor for proper representation of the dynamic behavior of the activated sludge process.

Feedforward Control

As previously mentioned, one of the disadvantages of feedback control is that an error must exist before any control action is exerted. This can be a serious disadvantage for processes with a slow response to changes since considerable time may elapse before the change in the effluent is detected and control action is exerted. In extreme cases, such as the input of "slugs" or pulses of toxic or rapidly biodegradable materials, the use of only feedback control could lead to process failure. This situation can be remedied by the use of feedforward control in which the inputs to the process are measured and more immediate control action taken based on either process history or predictions from a dynamic mathematical model.

Ratio control is a form of feedforward control and is widely practiced in the activated sludge process. The application of ratio control to the simplified reactor shown in Fig. 1 is illustrated in Fig. 9 where flow ratio control is used to maintain F_B equal to 0.30 F_A. As illustrated in Table 1, some improvement of the variability index with respect to the base case of no control is attained (7.30 vs 8.73 mg/l). Further improvement could be attained by using a higher ratio: however, this would also result in a lower average value for A_1 so that it would not be possible to compare this with the base case.

If a sensor were available for measuring the concentration of A in the influent, ratio control could be improved by maintaining F_B in proportion to the mass flow rate of A into the reactor or in effect using ratio control based on $F_A A_O$. A simulation based on mass ratio control is also presented in Fig. 9.

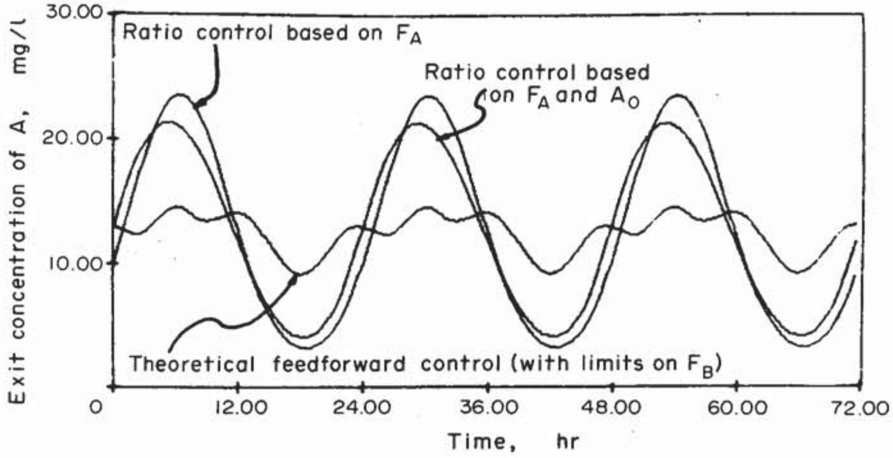


FIG. 9. Feedforward control.

If a dynamic mathematical model of the process is available along with measurements of the inputs, the amount of control needed may be calculated from the dynamic model whenever a change in the inputs occurs. The simulated result of such a control system is presented in Fig. 9 and shows the lowest variability index (1.61 mg/l) of all the cases considered. Theoretically, feedforward control is capable of perfect control if the model and measurements are correct. However, perfect control is not obtained in this instance because of the limits on F_B. This is illustrated in Fig. 10 which shows that both the upper and lower limits on F_B are reached over the course of a 24 hr cycle. Another limitation on feedforward control is that dynamic models and measurements are usually far from perfect thus limiting the effectiveness of feedforward control. There are techniques available in the control engineering literature which can be used to improve models while the process is in operation: however, these have yet to be applied to the wastewater treatment field.

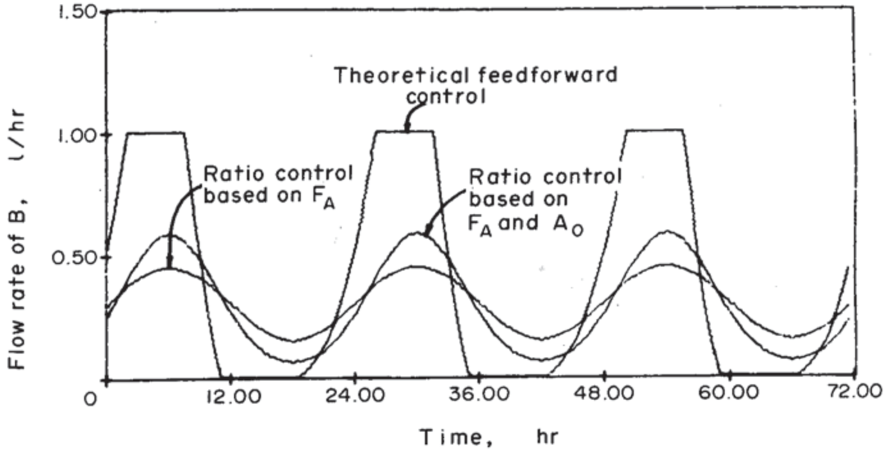


FIG. 10. Control variable for feedforward control.

Reactors in Series with Variable Feed Point

In both the feedback and feedforward control systems with F_B as the control variable, better control could be obtained if there were no limits on F_B. This is clearly evident in both Figs. 8 and 10 which show that F_B is at the limit values over a substantial portion of the 24 hr cycle. An analogue can be drawn with the activated sludge process in which similar limits exist on both the pumping rate of return sludge and the mass of sludge which can be stored in the solids - liquid separator.

The use of reactors in series with variable feed points, which is analogous to the step feed activated sludge process, offers a control action which can be used to overcome the limitations mentioned above. By shifting the feed point toward the outlet end of the reactor system, one or more of the reactors at the head of the plant becomes available for storage of B thus providing an additional means of adding or removing B as needed. Such a system is illustrated in Fig. 11 where the single CFSTR used for previous simulations has been divided into two CFSTR's in series with the capability

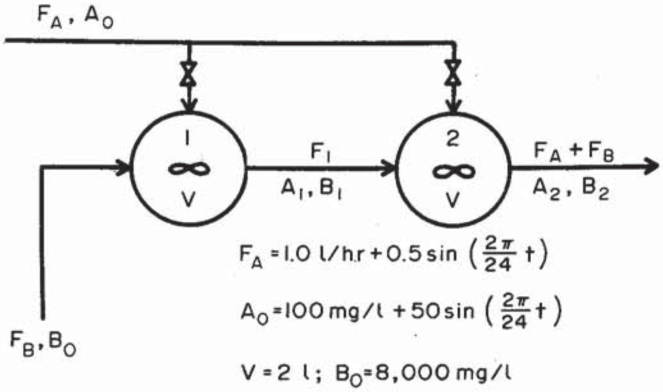


FIG. 11. Reactors in series with variable feedpoint.

of adding F_A to either or both reactors. The use of this control action in a feedback control system is simulated in Fig. 12. The measured signal is the concentration of A in the effluent from reactor 2 and proportional control is used to vary the fraction of F_A which is fed to reactor 1. This has the effect of increasing the flow rate of B to reactor 2, as needed, by washing it from reactor 1 into reactor 2. The variability index for this control system is 3.59 mg/l which should be compared with a VI of 5.77 for the case (Fig. 12) where all of F_A goes to the first reactor. In both cases, F_B is maintained constant at 0.33 l/hr. It should be noted that division of the reactor into stages results in a lower average concentration of A in the effluent (6.6 vs 12.5 mg/l) when compared with a single CFSTR with twice the volume.

Further improvement in variability could be attained by division of the reactor into more stages thus providing more flexibility. In this connection, it should be noted that the step feed activated sludge process provides for addition of wastewater at four points instead of only two points as used for the example presented herein. The Salt Creek plant at Chicago will also provide for addition of return sludge at four points thus giving additional flexibility.

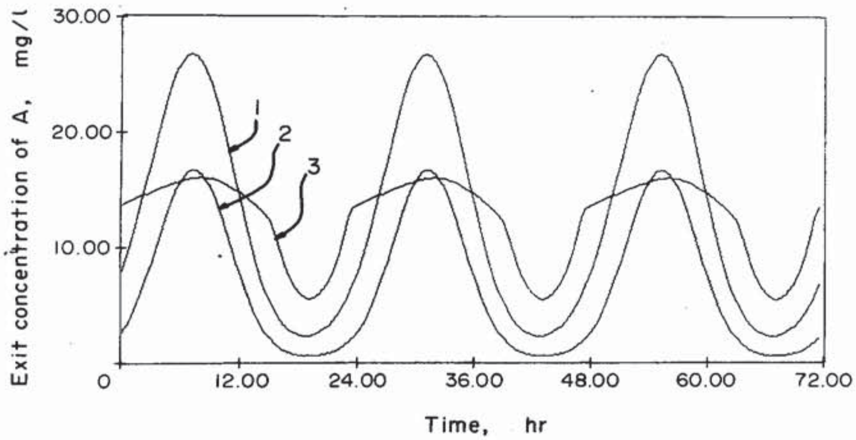


FIG. 12. Variable feedpoint as a control action. 1. Base case-single reactor, V = 4 l. 2. Two reactors in series with no control. 3. Control of fraction of F_A going to reactor 1.

CONTROL STRATEGIES FOR THE ACTIVATED SLUDGE PROCESS

At several points in the previous discussion it has been shown that analogues can be drawn between the reaction system illustrated and the activated sludge process. However, it could be misleading and perhaps even dangerous to design a control system for the activated sludge process based on simulations of a simple autocatalytic reaction in a CFSTR. In developing control strategies for the activated sludge process, several additional factors must be considered and prominent among these are:

1. Development of a dynamic model for the process. Since variation in feedpoint of the wastewater (step feed) is proposed as a control action, the model must be capable of predicting the rapid BOD uptake phenomena observed in the contact stabilization version of the process. Also, it is imperative that the model reflect the strong interactions between the biological reactor and the solids - liquid separator.

2. Quantitative consideration of the interactions between the activated sludge process and the other processes in the treatment plant. For example, the inputs to the activated sludge process are modified by the primary sedimentation basin and the outputs from the process influence other processes such as the anaerobic digester and the chlorine contact basin. Quantitative consideration of these interactions would lead to the establishment of an objective function for the process which will be needed for exploration of optimal control strategies.

3. Definition of the measurements and control actions to be used for most effective control. Some of the current measurements, such as BOD_5, are not useable because of the long time lags involved or because on-line sensors are not available. Only a limited number of control actions are available and changes in process design, such as the incorporation of step feed capability, will be needed if control is to be improved.

Dynamic Model

Andrews *et al*. (12 - 18) have been engaged for the past six years in the development of a dynamic model for the activated sludge process which includes some of the factors mentioned above. The latest version of the model is that by Busby and Andrews (19) and additional work is in progress by Stenstrom (20). The key features of the model to be used in the simulations presented herein are listed below.

1. Incorporation of a dynamic model of the primary settler into the overall model. This model is similar to that used by Bryant (13) and serves the purpose of modifying the

characteristics of the raw wastewater before it enters the biological reactor.

2. Inclusion of a dynamic model of the final settler. The model is based on solids flux theory and has outputs of sludge blanket height, underflow solids concentration and effluent suspended solids concentration. The effluent suspended solids concentration is based on a relationship developed by Pflanz (21). Although there are deficiencies in this relationship, it is nonetheless better than the usual assumptions of a constant or zero concentration of suspended solids in the overflow from the solids - liquid separator since these solids comprise a significant, and frequently the major component of the BOD in the process effluent.

3. Structure of the biological mass in the reactor into three portions, these being (a) stored mass, (b) active mass, and (c) inert mass. The relative fractions of these three masses, which comprise the total sludge mass, are variables thus providing a rational basis for changes in "activity" or "condition" of the sludge.

4. Consideration of the overall removal of pollutants to be a sequential process as indicated in eqn 6. The first

$$\begin{array}{c}\text{Soluble}\\ \text{and}\\ \text{Suspended BOD}\end{array} \longrightarrow \begin{array}{c}\text{Stored}\\ \text{Mass}\end{array} \longrightarrow \begin{array}{c}\text{Active}\\ \text{Mass}\end{array} \longrightarrow \begin{array}{c}\text{Inert}\\ \text{Mass}\end{array} \qquad (6)$$

step in the sequence, transfer of pollutants from the fluid to the floc phase, is considered to be primarily a physical phenomenon since the major fraction of the organics in domestic wastewater are suspended. The rate at which pollutants are transferred from the fluid to the floc phase is considered to be a function of the concentration of pollutants in the fluid phase and concentration of stored mass in the sludge up to some limiting value as expressed by a saturation or "Monod" type function. The fact that the sludge mass has a finite capacity for storing material removed from the fluid phase is responsible for the model exhibiting a variable time lag which is important in predicting dynamic behavior. Microorganisms do not respond instantaneously to changes in substrate concentrations as would be indicated by the simple autocatalytic expression previously presented. Structuring of the biological mass and the sequential removal of pollutants also permits the model to exhibit a "rapid uptake" phenomenon, as observed in the contact stabilization process, and as would occur in the step feed process when variation in feed point is used as a control action.

The variable time lag and rapid uptake characteristics of the model are demonstrated in Fig. 13 which shows the simulation of a batch reactor. Curve A, where the sludge is initially saturated with stored material, illustrates a condition for which no rapid uptake occurs and hence there is a maximum time lag in substrate removal. Curves B and C are for lower initial concentrations of stored mass and illustrate both the rapid uptake of substrate and the consequent variation in time lag with variation in stored mass initially present in the sludge.

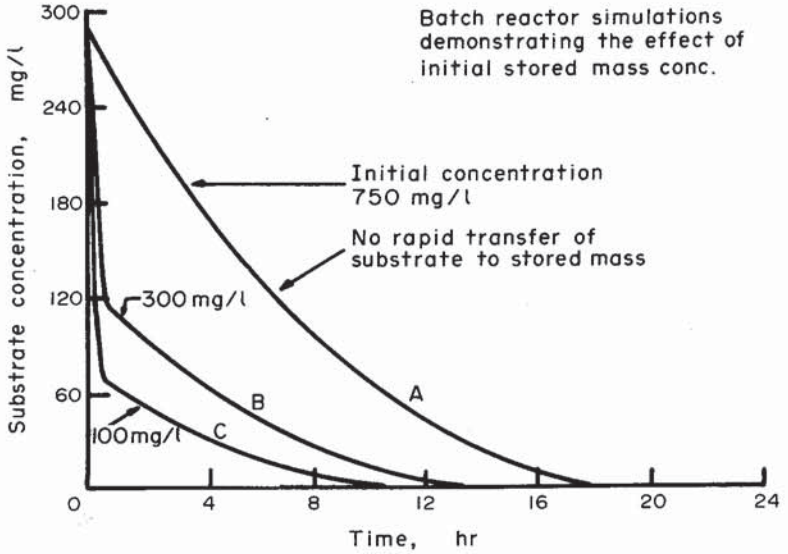


FIG. 13. Batch reactor simulations demonstrating the effect of the initial stored mass concentration.

5. The use of reactors in series with provision for control of the addition of wastewater to each stage so that variation of feed point may be used as a control action. The model developed is for a four pass aeration basin (Fig. 14) with each pass being approximated as a single CFSTR.

Incorporation of the abovementioned features provides a wide spectrum model which can be used to simulate the behavior of several versions of the activated sludge process. Included among these are conventional, extended aeration, high rate, step feed and contact stabilization. Busby and Andrews (19) should be consulted for a comparison of model predictions vs reported performance for these versions of the process.

The dynamic model of the process which has been presented is by no means complete and will require further development. There is a need for an improved relationship for prediction of solids concentration in the overflow from the solids - liquid separator and the establishment of a quantitative relationship between the settling characteristics of the sludge and the process parameters. The effects of substrate composition (suspended or dissolved) on removal rates needs investigation. Also, the model has only

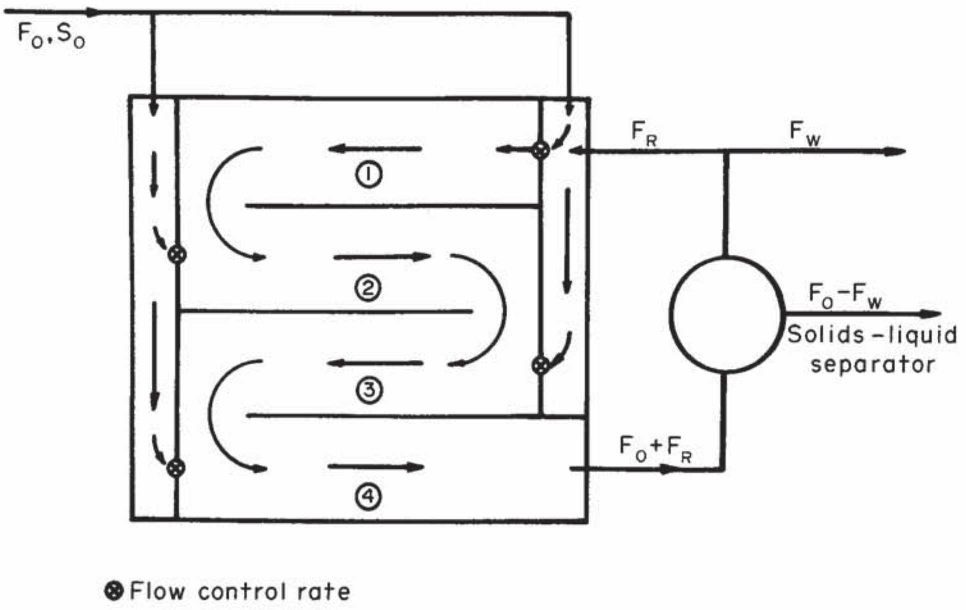


FIG. 14. Step feed activated sludge process.

been validated by a combination of simple laboratory experiments, literature searches, and discussions with knowledgeable operations engineers. This is, at best, only semiquantitative validation (responses are in the right direction and have the right order of magnitude) and both pilot and full-scale field experimentation will be needed for quantitative validation.

It is not the purpose of this paper to present and discuss all of the dynamic studies and control strategies which have been performed using the above mentioned model. However, two examples will be presented, these being the dynamic behavior of a proposed control signal, specific oxygen utilization rate (SCOUR), and the effect of using variation in feed point as a control action.

Specific Oxygen Utilization Rate

For the simple autocatalytic reaction system previously presented, it was assumed that the concentrations of the reactants could be easily measured. However, this is not the case for the activated sludge process where substantial difficulties are encountered in measuring both the concentration of pollutants and microorganisms. Moreover, even if the concentrations can be measured the problem is still not solved since, for example, the pollutants may be nonbiodegradable and the microorganisms may have a low biological activity with respect to metabolism of the pollutants. Where then, are we to obtain our signals for the initiation of a control action?

The most common index used for measuring the concentration of pollutants is the 5-day BOD test. However, this time lag is unacceptable for the initiation of automatic control and there has therefore been a great deal of work devoted to the development of more rapid analyses such as COD, TOD and TOC. However, all of these suffer from the fact that they do not give any indication of the biodegrability of the pollutant.

The most common index used for measuring the concentration of microorganisms is the MLVSS. However, this gives no indication of the activity of the sludge with respect to the metabolism of pollutants except in the steady state and over the range of loadings normally encountered in the conventional process as indicated by Weddle and Jenkins (22). Moreover, the test for MLVSS is not well adapted to on-line analysis. There has been considerable work devoted to other measures of sludge activity such as ATP and DNA concentrations and dehydrogenase activity. However, none of these analyses seem to be adapted to on-line analysis and moreover there is considerable disagreement in the literature as to their value as a measure of sludge activity. There is one variable on which there does seem to be near universal agreement as an indicator of biological activity in aerobic systems, this being the specific oxygen utilization rate (SCOUR), which is expressed as the mass of oxygen utilized per unit mass of sludge per unit of time. When the rate at which oxygen is utilized for organism decay is also known, this same indicator can be used to calculate the initial amount of pollutants present (23) or indicate when the reaction has gone to completion (24). Moreover, the determination of volumetric oxygen utilization rates by respirometry has a long history (25) and there are now several automated instruments available with several of these being proposed for on-line use.

Dynamic Response of SCOUR

The dynamic response of SCOUR to sinusoidal variations in influent flow rate and substrate concentration is presented in Fig. 15. S_0 and F_0 are assumed to be in phase with a 24 hr period and maximum and minimum amplitudes being ± 50% from the averages of 200 mg/l and 1.6×10^6 l/hr, respectively. The reactor system consists of four CSFSTR's in series (Fig. 14) with all of the wastewater going to the first reactor and the recycle flow being constant at 30% of the average wastewater flow rate. The sludge is assumed to have the settling characteristics of "normal" activated sludge (15) and the settler is sized so that the average overflow rate is 660 gal/ft^2-day. Under these conditions, the hydraulic residence time in the reactors is 4.3 hr and the

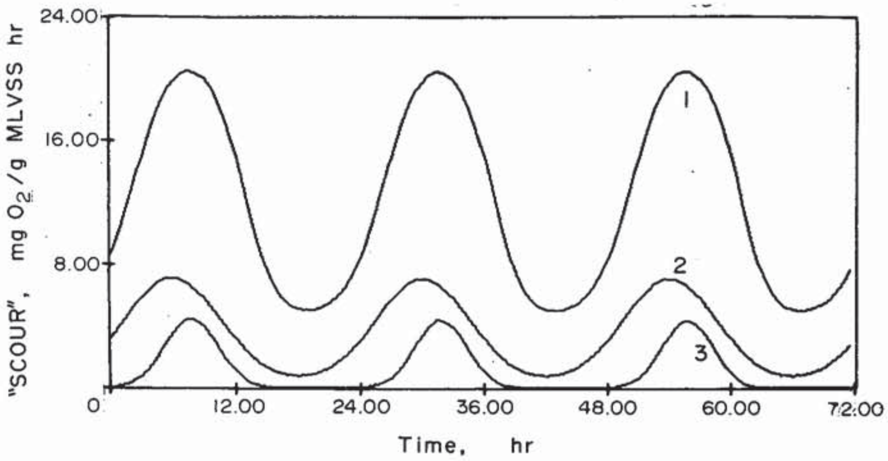


FIG. 15. Dynamic response of SCOUR to sinusoidal variation in S_o and F. 1. SCOUR (mg O_2/g MLVSS hr). 2. mass flow of S_o (kg x 10^2/hr). 3. Effluent substrate (mg/l).

sludge age is approximately 3 days.

Also shown in Fig. 15 are the mass flow rate of substrate to the reactor ($S_O \times F_O$) and the dissolved substrate concentration in the effluent from the fourth reactor (S_4). It will be noted that SCOUR rapidly responds to an increase in the mass flow rate of substrate thus indicating that it would be a good signal for process control. It is also closely related to the effluent substrate concentration and leads this somewhat which is desirable for a more rapid response. This is as would be expected since SCOUR is intimately related to the growth rate of the sludge, as shown in eqn 7, and thus is a direct measure of the activity of the sludge.

$$\text{SCOUR} = a_1 \mu + a_2 k_d \tag{7}$$

where:

a_1 = stoichiometric coefficient, kg O_2 consumed/kg sludge growth.

μ = specific sludge growth rate, kg sludge growth/kg sludge in reactor.

a_2 = kg O_2 consumed/kg sludge destroyed by organism decay.

k_d = organism decay coefficient, kg sludge destroyed/kg sludge in reactor.

Response to Substrate and Toxic Pulses

SCOUR should also provide an excellent means for detecting the "slug" or pulse input of toxic or rapidly biodegradable materials into the aeration basin. The response of SCOUR to a 3 hr pulse of a conservative toxic material (TX) with a concentration of 150 mg/l is shown in Fig. 16. The destruction of active mass by the toxic material is assumed to be first order with respect to the toxic material concentration, with a rate coefficient (K_{TX}) of 0.01 hr^{-1}. SCOUR shows a rapid response to the toxic material and Fig. 17 shows that it also responds rapidly to substrate pulses. These responses indicate that SCOUR would be a good signal for the initiation of control action.

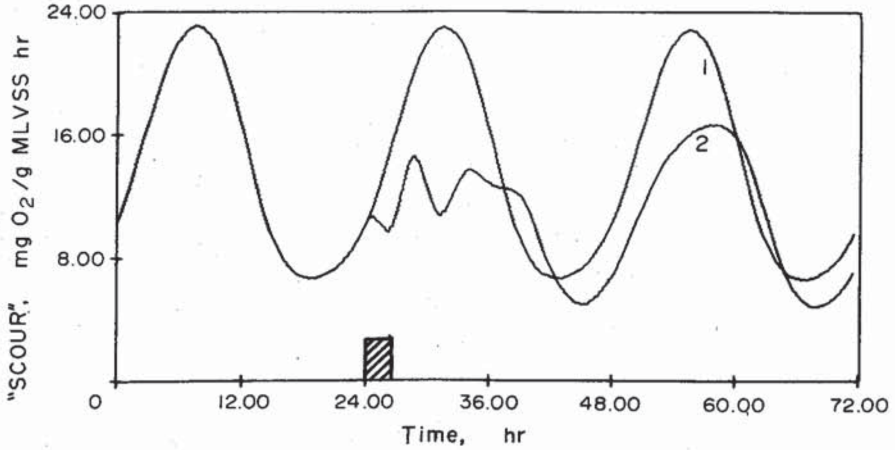


FIG. 16. Response of SCOUR to a toxic pulse. 1. Base case for comparison. 2. Response to toxic pulse.

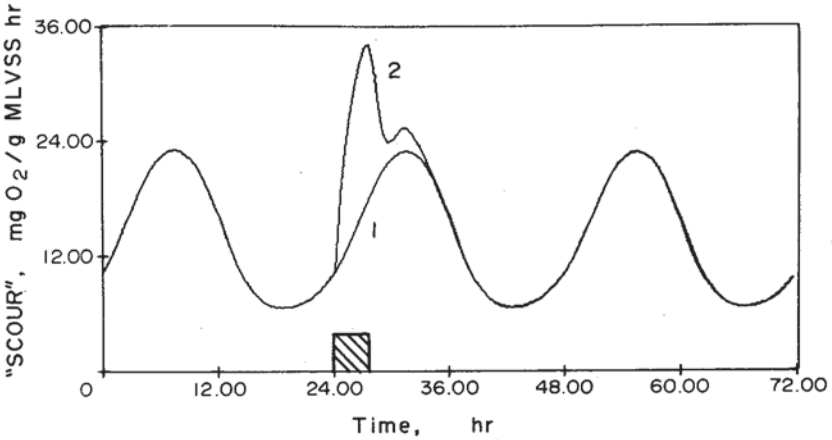


FIG. 17. Response of SCOUR to a substrate pulse. 1. Base case for comparison. 2. Response to substrate pulse.

Busby (15) has explored possible control strategies using SCOUR as a signal. His simulations indicate that a good control action when SCOUR indicates the presence of a toxic material is to shift the flow of all the wastewater to the fourth reactor (Fig. 14) with a simultaneous increase of the recycle flow to rapidly remove sludge from the solids - liquid separator. This action passes the toxic material through the process as rapidly as possible and minimizes exposure of the sludge to the toxic material. Clearly, precautions should be taken to ensure that the decrease in SCOUR is due to a toxic material and not simply a decrease in the substrate concentration in the reactor influent.

Busby (15) has also simulated a control strategy using SCOUR as a signal to detect a substrate pulse as might be cause by an industrial discharge of concentrated biodegradable organics. The control action in this instance was to switch from a mode of operation where the influent flow is equally divided between reactors 2 and 3 (Fig. 14) to a mode of operation where all of the flow was added to reactor 1. Although this action did not reduce the total mass of substrate discharged from the reactor, it did reduce the peak concentration, thus reducing the variability.

Feedback Control

The use of SCOUR as the control signal in a feedback control loop with the return sludge recycle rate (F_R) as the controlled variable is portrayed in Fig. 18. Only proportional control was used with the control algorithm being given in eqn 8. The proportional control coefficient used was equal

$$F_R = 5.3 \times 10^5 \text{ l/hr} + K_p \text{ (set point - SCOUR)} \quad (8)$$

to -0.1 x the average flow rate to the reactor and the set point was 13.0 mg O_2/gm MLVSS-hr. F_R was also constrained between the limits of 10 and 100% of the average flow rate to the reactor. For comparison, the base case with no control (recycle flow rate constant) and ratio control of the recycle flow rate (F_r/F_O = 0.30) are also shown. As indicated SCOUR provides the

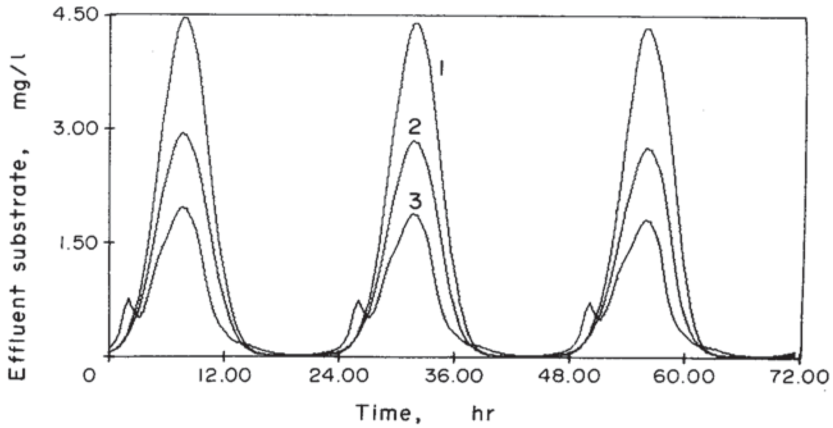


FIG. 18. Feedback and ratio control with sludge recycle rate as control variable. 1. No control. 2. Ratio control. 3. Feedback control.

better control as measured by dissolved substrate. Although not shown, the recycle flow rate reaches both the high and low limits over the 24 hr period thus indicating the need to add or remove more sludge to or from the reactors during the day. It is also important to note that the interaction of the reactor with the thickening function of the solids - liquid separator is reflected in this simulation. As the recycle rate is decreased, a more concentrated sludge is obtained from the separator underflow and as the recycle rate increases, a more dilute sludge is obtained. Thus the separator tends to average out the mass flow rate of the recycled sludge.

The substrate concentrations shown in Fig. 18 should not be construed as the process effluent since they represent only the dissolved substrate in the fourth reactor and do not include the contribution due to the suspended solids in the overflow from the solids - liquid separator. This purposeful omission of the contribution of these suspended solids to the effluent BOD is not intended to de-emphasize their importance. However, at the present time the authors know of no way to quantitatively express the relationship between SCOUR and the concentration of these solids.

Application of SCOUR to the Oxygen Activated Sludge Process

The use of SCOUR as a control signal would appear to be especially appropriate for the oxygen activated sludge process since the reactors are covered and can be used as on-line respirometers. If computing power is available, as would be the case for a plant with a process control computer, SCOUR could be continuously calculated on-line using only four measurements, these being:

1. Influent oxygen flow rate.
2. Influent wastewater flow rate.
3. Recycle sludge flow rate.
4. Solids concentration of recycled sludge.

The oxygen utilization rate would be relatively easy to calculate from a materials balance on-line since the influent oxygen flow rate is metered and the majority of this is used in the biological oxidation with only small quantities (<10%) escaping in the effluent gas or liquid streams. Little error would be involved in assuming the oxygen utilization rate (mass/time) to be equal to the influent oxygen flow rate minus an empirical coefficient times the influent wastewater flow rate.

The other term needed to calculate SCOUR is the mass of solids in the reactor. For a single CFSTR, this would be equal to the concentration of solids in the effluent times the volume of the reactor. However, most high purity oxygen processes are multi-stage systems and for these the mass of solids in the reactor could be calculated by numerical integration of the differential equations resulting from material balances on solids for each of the stages as given in eqns 9 and 10. Sludge growth and decay terms, although important for predicting the mass of sludge which should be wasted, are insignificant for calculating the mass of sludge in the reactor since they are small in comparison with the mass of sludge added by the recycle sludge flow stream. The concentration of solids in the influent wastewater, X_O, may also be neglected for the purposes of this calculation.

<u>1st stage</u>

$$V \frac{dX_1}{dt} = F X_O + F_R X_R - (F + F_R) X_1, \qquad (9)$$

<u>nth stage</u>

$$V \frac{dX_n}{dt} = (F + F_R)(X_{n-1} - X_n), \qquad (10)$$

where:

V = reactor volume,
X = solids concentration in reactor,
F = influent wastewater flow rate,
F_R = recycle sludge flow rate,
X_R = recycle sludge solids concentration.

The measurements needed for calculating SCOUR are three flow rates and one concentration measurement. Accurate and reliable flow sensors have been available for many years and there are several instruments now on the market for measurement of solids concentration although there are still some questions concerning the accuracy and reliability of these instruments. However, considering the importance of this measurement, it would appear that both accuracy and reliability could be improved, by more frequent maintenance and calibration, to the point where the measurement was satisfactory.

SCOUR, as calculated above, is averaged over n stages. More information could be obtained from SCOUR if gas flow rate meters and gas composition analyzers were installed between each stage. SCOUR could then be calculated for each stage. The time lag for taking control action would be decreased by using SCOUR for the first stage and SCOUR from the last stage would be a better indicator of whether or not the reaction has gone to completion. The availability of SCOUR for each stage would also permit the on-line calculation of reaction rates. In a crude sense, this might be compared to taking readings on a respirometer at different time intervals and using these readings to calculate rate coefficients or incubating BOD bottles for different periods of time and calculating rate coefficients from the results. Rates determined using the reactor itself would be more accurate than those determined using either a respirometer or BOD bottles since the environmental conditions in these are not the same as those in the reactor. However, there are problems involved in making these calculations and included among these are the difficulties of making measurements between stages and taking into account the rapid removal of pollutants which may occur in the first stage without concurrent uptake of oxygen. Still another problem, even when SCOUR is averaged over all stages, is establishing the appropriate set point for use of SCOUR as a signal. A numerical value of SCOUR at which a satisfactory removal of pollutants is obtained may not be the same as that at which the sludge will have satisfactory clarification and thickening characteristics. Pilot and full scale experiments will be needed to answer these questions.

Step Feed Activated Sludge

In the conventional activated sludge process, the operator has a relatively limited choice of control actions, these being: (1) air flow rate, (2) sludge wasting rate, and (3) sludge recycle flow rate. The step feed activated sludge process (Fig. 14) permits a fourth control action, this being the ability to vary the points at which wastewater is added along the length of the reactor, and may be one of the most effective types of control for poorly settling or bulking sludge. Figure 19 shows the transient effect of shifting, at a time of 7.5 hr, the feed point from stage 1 to stage 2 (Fig. 14). This results in a rapid decrease in the solids flux to the solids - liquid separator and, since the recycle rate remains unchanged, a subsequent decrease in the mass of sludge stored in the separator. This control action would therefore be quite effective in preventing a gross carryover of sludge in the process effluent as might be the case in the

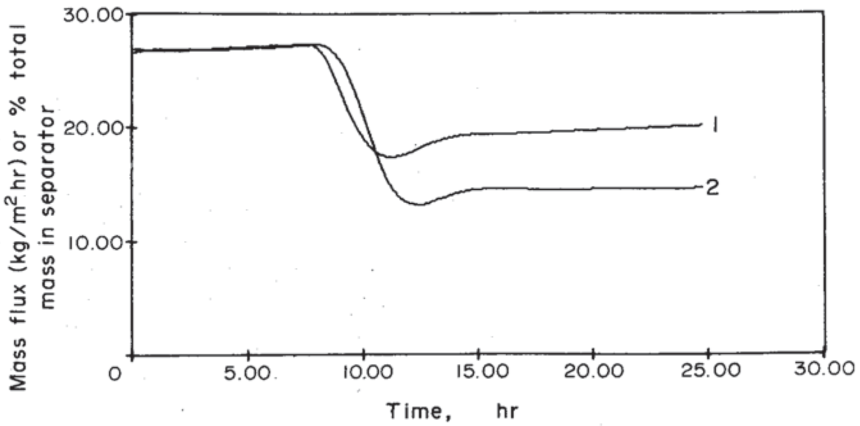


FIG. 19. Dynamic response of solids to a change in contacting pattern. 1. Mass flux to solids-liquid separator (kg MLVSS/m^2 hr). 2. Percentage of system (reactor + separator) mass in solids-liquid separator.

occurrence of sludge bulking. An increase in sludge recycle rate would not be nearly as effective since although it would increase the sludge withdrawal rate from the separator, it would also simultaneously increase the solids flux to the separator.

The response mentioned above is relatively rapid (hours). However, there is also a long term effect (days) which will be obtained in that if the bulking is due to organic overloading, as is frequencly the case, a larger mass of sludge would ultimately be carried in the reactor thus decreasing the overloading and improving the flocculation and settling characteristics of the sludge. This would require days to take effect since only a limited mass of sludge is available for rapid transfer from the separator to the reactor; the additional sludge needed to reach steady state for the new operational mode must be obtained through growth and this is slow because of the low substrate concentration in domestic wastewaters. In this respect it should be mentioned that an increase in sludge wasting rate to control sludge bulking could have the proper short term effect (sludge blanket immediately lowered) but the wrong long term effect. Increased sludge wasting would decrease the mass of sludge in the reactors thus further increasing the organic overloading and, if continued, could ultimately lead to process failure.

These predictions are qualitatively verified through the field studies by Torpey (26) in his work on the step feed activated sludge process at the Bowery Bay plant in New York City. As is frequently the case, practice preceded prediction by theory and many activated sludge plants are now designed to permit operation in the step feed mode. However, the advantage of the process is thought of as being more one of design (smaller reactors can be used and still contain the same mass of sludge) and the operational advantage is still not well recognized.

The use of step feed as mentioned above is more in the nature of an emergency control action to prevent the overflow of solids in the event of the occurrence of bulking sludge. However, variation of feed point can also be used on a more rapid basis (hourly) to decrease the variability of the effluent from the activated sludge process as proposed by Andrews and Lee (18) and simulated by Busby and Andrews (19). Both Figs. 8 and 10 indicate that there may be limitations on the amount of control that can be exerted by changing the sludge recycle rate because of inadequate recycle pump capacity or the ability of the separator to either thicken or store sludge. Step feed could overcome these limitations by utilizing one or more stages to either add or remove sludge from reaction with the wastewater. When coupled with a measurement of SCOUR in each stage, this additional flexibility could permit the production of sludge with optimum characteristics for rapid removal of pollutants, clarification and thickening. Research on this topic is in progress by Stenstrom (20).

SUMMARY

A brief description of some of the basic principles of process control systems has been presented. Included among these have been the representation of control systems as information flow diagrams, the basic questions which must be answered in the development of a control system and a description of several commonly used control algorithms.

The application of these principles to the development of control systems for reducing effluent variability has been illustrated by computer simulations of an autocatalytic reaction in a CFSTR. Reductions in effluent variability by feedback and feedforward control of this reactor have been compared with those attainable by increasing the reactor volume and installation of two types of equalization basins. The simulations indicated that the control systems would be of equal or greater effectiveness. Greater reductions in variability could have been attained with the control systems if the control variable had not purposefully been constrained by limits. However additional simulations indicated that the effects of these limits could be reduced by the use of an additional control variable, this being the variation of feed point in a multi-stage reactor.

A brief description of a dynamic model of the activated sludge process has been presented. Three of the key features of this model include the incorporation of a dynamic model of the solids - liquid separator, structuring of the sludge into stored, active and inert mass, and consideration of the overall removal of pollutants as a sequential process. Inclusion of these features allows the strong interactions between the biological reactor and separator to come into play and provides a rational expression for a variable time lag and the rapid uptake of BOD in the biological reactor.

The specific oxygen utilization rate (SCOUR) is proposed as a control signal since it is a direct measure of the activity of the sludge and shows a rapid response to both substrate loading changes and the input of toxic materials. SCOUR should be especially appropriate for the high purity oxygen process since these reactors are covered and can be used as on-line respirometers. It is shown how SCOUR could be easily calculated on-line using a process control computer and only four on-line sensors with three of these being flow meters.

Simulations of the step feed activated sludge process are presented to show that the ability to vary the feed point offers a valuable control action by enabling the rapid transfer of sludge to and from the reactor and solids - liquid separator. This can be used as an emergency control action to prevent the overflow of solids in the event of bulking sludge or can be used on a more routine basis to control the variability of the process effluent.

ACKNOWLEDGEMENTS

In addition to the work of others, as indicated by the references, the authors wish to acknowledge the encouragement of Mr. Carmen Guarino, Commissioner, Water Department, City of Philadelphia, and Mr. Elmer Ballotti, (Partner), Greeley and Hansen Engineers, in connection with the potential application of SCOUR to the oxygen activated sludge process.

REFERENCES

1. Smith, R., Eilers, R. G. and Hall, E. D. (1973) *Design and Simulation of of Equalization Basins*, EPA Report No. 670/2-73-046, Environmental Research Center, Cincinnati, Ohio.
2. Andrews, J. F. (1974) Dynamic models and control strategies for wastewater treatment processes. *Wat. Res.* *8*, 261.
3. Smith, R. (1971) Wastewater treatment plant control. Paper presented at the Joint Automatic Control Conference, Washington University, St. Louis, Missouri.
4. Andrews, J. F. (1971) Control of wastewater treatment plants - The engineer as an operator. *Water and Sewage Works* *118*, 26.
5. Perlmutter, D. D. (1965) *Introduction to Chemical Process Control*. Wiley, New York.
6. Shilling, G. D. (1963) *Process Dynamics and Control*. Holt, Rinehart & Winston, New York.
7. Hougen, J. O. (1972) *Measurements and Control Applications for Practising Engineers*. Cahners Books, Boston.
8. Tucker, G. K. and Wills, D. M. (1962) *A Simplified Technique of Control System Engineering*. Honeywell, Fort Washington, Pennsylvania.
9. Lloyd, S. G. and Anderson, G. D. (1971) *Industrial Process Control*. Fisher Controls Co., Marshalltown, Iowa.
10. Andrews, J. F., Briggs, R. and Jenkins, S. H., eds. (1974) *Instrumentation, Control and Automation for Wastewater Treatment Systems*. Pergamon Press, Oxford.
11. Novotny, V. and Englande, A. J. (1974) Equalization design techniques for conservative substances in wastewater treatment systems. *Wat. Res.* *8*, 325.
12. Blackwell, L. G. (1971) *A Theoretical and Experimental Evaluation of the Transient Response of the Activated Sludge Process*. Ph.D. Dissertation, Clemson University, Clemson, South Carolina.
13. Bryant, J. O., Jr. (1972) *Continuous Time Simulation of the Conventional Activated Sludge Wastewater Renovation System*. Ph.D. Dissertation, Clemson University, Clemson, South Carolina.
14. Weers, W. A. (1972) *The Effect of Contacting Patterns on the Transient Response of Activated Sludge Systems*. Ph.D. Dissertation, Clemson University, Clemson, South Carolina.
15. Busby, J. B. (1973) *Dynamic Modeling and Control Strategies for the Activated Sludge Process*. Ph.D. Dissertation, Clemson University, Clemson, South Carolina.
16. Tracy, K. D. (1973) *Mathematical Modeling of Unsteady-State Thickening of Compressible Slurries*. Ph.D. Dissertation, Clemson University, Clemson, South Carolina.
17. Poduska, R. A. (1973) *A Dynamic Model of Nitrification for the Activated Sludge Process*. Ph.D. Dissertation, Clemson University, Clemson, South Carolina.
18. Andrews, J. F. and Lee, C. R. (1972) Dynamics and control of a multistage biological process. *Proceedings 4th International Fermentation* Symposium (Gyozo, T., ed). Society of Fermentation Technology,

Yamada-Kami, Suita-Shi, Osaka, Japan.

19. Busby, J. B. and Andrews, J. F. (In Press) A dynamic model and control strategies for the activated sludge process. Journal Water Pollution Control Federation.

20. Stenstrom, M. K. (In Preparation) Computer Based Control Strategies for Wastewater Treatment Plants. Ph.D. Dissertation, Clemson University, Clemson, South Carolina.

21. Pflanz, P. (1969) Performance of (activated sludge) secondary sedimentation basins. Advances in Water Pollution Research (Jenkins, S. H., ed.). Pergamon Press, Oxford.

22. Weddle, C. L. and Jenkins, D. (1971) The viability and activity of activated sludge. Wat. Res. 5, 621.

23. Schulze, K. L. and Kooistra, R. D. (1969) Oxygen demand and supply in an activated sludge process. J. Water Pollution Control Federation 41, 1763.

24. Ahlberg, N. R. and Boyko, B. I. (1972) Evaluation and design of aerobic digesters. J. Water Pollution Control Federation 44, 1782.

25. Montgomery, H. A. C. (1967) The determination of biochemical oxygen demand by respirometric methods. Wat. Res. 1, 163.

26. Torpey, W. N. (1948) Practical results of step aeration. Sewage Works Journal 20, 781.