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Real-Time Control of Activated Sludge Process

By Michael K. Stenstrom,[1] A. M. ASCE and John F. Andrews,[2] M. ASCE

Introduction

Most activated sludge plants operate in a dynamically changing environment. It is not uncommon to observe large variations in wastewater flow rate, concentration, and composition in municipal wastewaters. Most activated sludge plants subjected to changing influent wastewater quality operate without "closed-loop" real-time process control systems. Fluctuations in process inputs cause changes in process operation and efficiency that are often unnoticed or ignored for long periods of time. Control of disturbances that decrease process performance is a promisiing technique of increasing wastewater treatment efficiency at low cost.

The techniques for activated sludge process control stem primarily from the two prevailing design techniques—food-to-mass, ratio (F/M) and mean cell retention time (33). Using one of the popular steady-state mathematical models for the activated sludge process (24), it can be shown that maintaining constant mean cell retention time (MCRT) or F/M, within certain assumptions, maintains constant growth rate.

The relationship between MCRT (or sludge age) and organism growth rate can be derived from a steady-state microorganism material balance around the activated sludge process with the following result:

$$\frac{1}{\theta_C} = \mu - K_D \qquad (1)$$

in which θ_C = mean cell retention time; μ = specific organism growth rate; and K_D = the specific organism decay rate. A similar analysis, using the steady-state substrate material balance, yields:

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[1] Asst. Prof., Engrg. Systems Dept., Univ. of California, Los Angeles, Calif.
[2] Prof., Dept. of Civ. Engrg., Univ. of Houston, Houston, Tex.

$$\frac{S_o - S}{\theta_H X} = \frac{\mu}{Y} \qquad (2)$$

in which S_o and S = influent and effluent substrate concentrations; θ_H = hydraulic retention time; X = the mixed liquor volatile suspended solids concentration; and Y = the yeild of microbial sludge produced per unit mass of substrate removed. The left-hand side of Eq. 2 is an approximation of F/M, if the effluent substrate is negligible.

The success of both process design techniques is due to the relationship between the design parameter, MCRT or F/M, and organism growth rate, μ. The importance of maintaining constant growth rate has been demonstrated by a number of investigators. Garrett (15) developed a hydraulic technique for controlling MCRT in 1958 and demonstrated its usefulness on a full-scale treatment plant. Weddle and Jenkins (38) have demonstrated that indicators of process efficiency, such as substrate removal and sludge activity are related to growth rate. Bisogni and Lawrence (3) have shown sludge settling characteristics are functionally related to MCRT and growth rate.

Unfortunately, the relationship between growth rate and F/M or MCRT, which is derived from steady-state models, has limited value for nonsteady-state applications, where process control is used. The derivations for Eqs. 1 and 2 are both made from steady-state material balances, where the accumulation terms, or terms containing time derivatives, are zero. The existence of nonzero accumulation terms can introduce considerable error between the measured parameter, F/M or MCRT, and growth rate, μ. Obviously, the value of steady-state models is limited for control purposes.

The use of the effluent pollutant concentration is also of limited value for control purposes. Biochemical oxygen demand, which routinely requires 5 days for measurement, cannot be measured rapidly enough to be used for real-time control. Other indicators of process effluent quality, such as total organic carbon (TOC), total oxygen demand (TOD), and chemical oxygen demand (COD) have also been proposed as controlled variables. However, all three parameters are somewhat less than ideal. Instruments for measurement of the TOC, TOD, or COD are expensive and require sophisticated maintenance and operation. However, the most serious limitation of all three parameters for real-time control is that they do not always measure the biological condition of the activated sludge process, i.e., TOC, TOD, or COD are not necessarily related to growth rate. For example, the effluent TOC, TOD, or COD of an activated sludge process could increase for one of three reasons: (1) A slug of influent high strength biodegradable wastes that overloads the process; (2) the influence of some toxic or inhibitory material that reduces biological activity; or (3) the presence of a nonbiodegradable material that passes through the process without affecting it. In all three cases, the net effect upon the final effluent is a deleterious decrease in effluent quality, but in each case, the process control action to be initiated is different. Some other indicator of process performance and sludge activity is needed in lieu of, or in addition to, effluent TOC, TOD, or COD.

Several indicators of sludge activity have been proposed. Patterson, et al. (29) and others (21) have proposed the use of adenosine triphosphate (ATP) while Hartman and Lanbenberger (20) have proposed particulate organic nitrogen,

and Gaudy (16) has considered protein. Ford, et al. (14), among others, have proposed dehydrogenase enzyme activity as an indicator of sludge activity. Weddle and Jenkins (38) have investigated several of the proposed variables and concluded that ATP, dehydrogenase enzyme activity, and specific oxygen uptake rate (SCOUR) can all be meaningful indicators of the viable organism concentration, and are all related to process performance.

Specific oxygen uptake rate (SCOUR) has long been recognized as an indicator of sludge activity. Wuhrman (40) concluded that oxygen uptake rates observed at different activated sludge plants could in part be attributed to their loading rates and the past history of the sludge under aeration. Eckenfelder (13) as early as 1961, showed that SCOUR could be used as an indicator of sludge stability. Bisogni and Lawrence (3) have shown experimentally that growth rate, as measured by MCRT, is functionally related to specific oxygen uptake rate. Andrews, et al. (1) have demonstrated using mathematical modeling and simulation methods of reducing effluent variability through process control of SCOUR.

The relationship between SCOUR and growth rate can be shown theoretically using the previously cited mathematical model (24). However, it is not necessary to write a material balance around the process, nor is it necessary to assume steady-state conditions. SCOUR can be directly related to the growth rate as follows:

$$\text{SCOUR} = \frac{\text{OUR}}{XV} = \frac{(1 - Y)\mu}{Y} + K_{OEX} K_D \qquad (3)$$

in which SCOUR = specific oxygen uptake rate; OUR = oxygen uptake rate; V = aeration tank volume; and K_{OEX} = conversion factor, in units of mass of oxygen demand per unit mass of VSS.

It will be shown later that the oxygen uptake rate (OUR) is either directly measurable or easily calculated. Knowledge of OUR along with measurement of the mixed liquor volatile suspended solids, defines the value of SCOUR. Therefore, SCOUR can be measured directly in real time. Furthermore, the relationship between SCOUR and growth rate is valid for both dynamic and steady-state conditions.

It is the object of this paper to demonstrate the value of SCOUR for real-time control of the activated sludge process. The relationship of SCOUR to process performance, and its use for process control is demonstrated using mathematical modeling and computer simulation techniques. It is shown that SCOUR is a valid indicator of growth rate in a dynamically changing environment, such as that encountered in domestic wastewater treatment facilities. Furthermore, it is also shown that MCRT does not indicate growth rate in a dynamic environment, due to limitations that result directly from steady-state assumptions in the derivation of MCRT.

The value of SCOUR is shown through computer simulations of the step feed modification (36) of the activated sludge process. The results of SCOUR control by manipulation of recycle sludge rate, and contacting pattern (changing the point of influent wastewater addition to a dispersed flow aeration tank) are simulated. The effects of slugs of toxic or biodegradable materials and their influence upon SCOUR are also shown through simulation.

Dynamic Mathematical Model Development

The development of control strategies for the activated sludge process can be a challenging and expensive task. Two approaches are available for development of the strategies. The most straightforward approach is to implement the control strategies directly in an activated sludge plant or pilot plant. However, this approach would be very expensive and time consuming, since there are hundreds of alternate strategies that could be tested before a suitable strategy is developed. The alternate and less expensive approach is to develop mathematical models that can be used to simulate the control strategies. After a suitable control strategy is developed using the mathematical model, it can be implemented and verified. The results can then be used to improve the quality of the model, which can than be used to refine the control strategies. This type of iterative approach is the least expensive and time consuming, and has been adopted

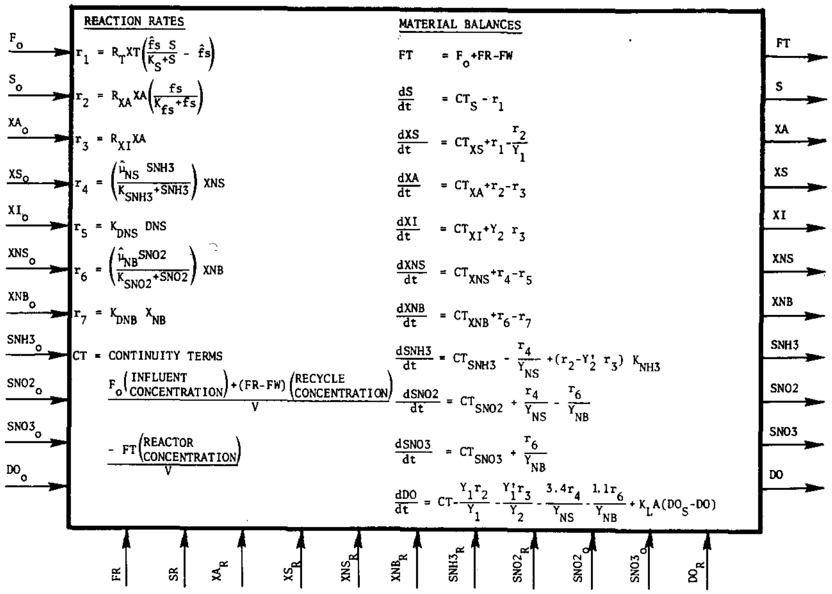

FIG. 1.—Material Balances, Inputs, and Outputs for Structured Biological Reactor Model

in this investigation. However, the results reported herein should be considered as tentative since they require further development in field investigations.

The dynamic model developed to investigate process control strategies has been examined previously (34); therefore, only a brief description of the model will be given here. The model included the aeration basin, secondary clarifier, and time-series models of influent wastewater quality. The aeration basin, or biological reactor, was modeled by assuming that the microbial mass consisted of stored, active, and biologically inert fractions. Tench (35), McKinney (27), Powell (32), Blackwell (4), Jacquart, et al. (22), and Busby and Andrews (7) have also developed structured models for biomass. Using a structural model

of this type, it is possible to simulate modifications of the activated sludge process such as step feed and contact stabilization.

Nitrification was included in the model using the kinetic expressions developed by Poduska and Andrews (31). Material balances were included for ammonia, nitrite, nitrate, *Nitrosomonas,* and *Nitrobacter.* The ammonia required for heterotrophic growth was also included in the ammonia balance. A balance on dissolved oxygen was included in the model in order that oxygen uptake rate and dissolved oxygen concentration could be calculated or controlled.

Fig. 1 is a summary of the biological reactor model. The kinetic and stiochiometric coefficients were estimated from literature data (19,23,25,26,28,41). The entire aeration basin model was programmed in such a manner that any number of tanks-in-series could be simulated. In this manner, it was possible to simulate the commonly designed "four-pass" aeration basin.

The secondary clarifier, or solids-liquid separator model, was based partially upon the work of Bryant (6), who developed a one-dimensional dynamic model. Bryant's model describes the commonly observed (10,12) behavior of sedimentation. Similar models have been developed by Tracy and Keinath (37) and Busby

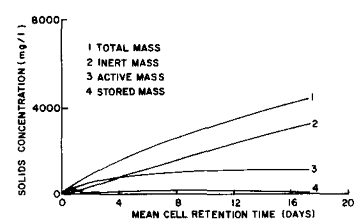

FIG. 2.—Activated Sludge Plant Steady-State Response: Mixed Liquor Solids Concentration

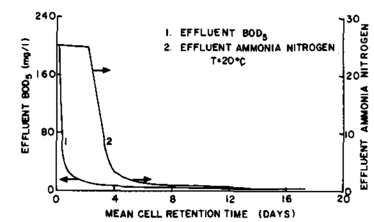

FIG. 3.—Activated Sludge Plant Steady-State Response: Effluent Concentrations

and Andrews (7). The previously described models and the writers' model are basically an adaptation of the one-dimensional convective transport equation, subject to a flux constraint. The model will predict the time-dependent behavior of the separator, including sludge blanket height, and failure due to solids overloading. Effluent suspended solids were modeled using an empirical relationship based upon the data of Pflanz (30). The entire model was implemented using CSMP III (11) and FORTRAN.

Activated Sludge Plant Simulation

Steady-State Analysis.—The steady-state response of the model is shown in Figs. 2 and 3. For this analysis, a constant flow rate of 10,000,000 gal/day (38,000 m^3/day) was simulated. The plant aeration tank hydraulic retention time was 4.3 hr and a solids-liquid separator with an area of 12,500 sq ft (1,160 m^2) was simulated. This size solids-liquid separator allowed the plant to operate at MCRT up to, but not exceeding, 10 days. For MCRT longer than 10 days, it was necessary to simulate separators with surface areas greater than 12,500 sq ft (1,160 m^2), due to solids overloading of the separator.

It can be observed that the simulated process performance, as shown in Figs.

2 and 3, is indicative of field performance of activated sludge plants. An interesting phenomena that the simulations show is the lack of accumulation of active mass at higher MCRT. The increase in MLSS concentration at higher MCRT is due primarily to accumulation of biologically inert mass, which is partially a function of influent inert mass. The simulations show that reducing influent inert solids concentration reduces the steady-state MLSS concentration required to maintain a given MCRT.

Dynamic Analysis.—The dynamic analysis of the plant is shown in Figs. 4 and 5. Fig. 4 shows the influent BOD_5 and the effluent BOD_5 for two MCRT's, 4 days and 10 days. The effluent BOD concentration, assuming the sludge clarification characteristics do not change, is nearly the same for both MCRT's.

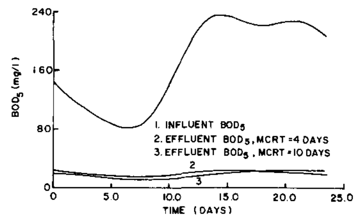

FIG. 4.—Activated Sludge Plant Dynamic Response: Effluent BOD_5 Concentration

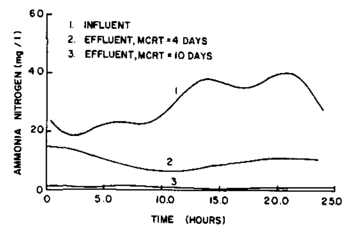

FIG. 5.—Activated Sludge Plant Dynamic Response: Effluent Ammonia Nitrogen Concentration

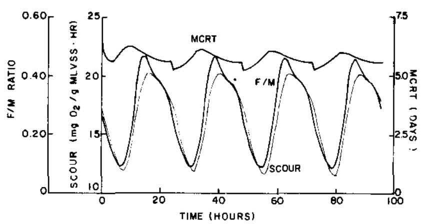

FIG. 6.—Relationship Among F/M, MCRT, and SCOUR for Nonsteady-State-Activated Sludge Plant

Fig. 5 shows the influent and effluent ammonia concentrations for the same MCRT as shown in Fig. 4. It is interesting to note the nitrification efficiency under dynamic conditions as compared to steady-state conditions. The effluent ammonia concentration for steady conditions, as shown in Fig. 3, is approx 3 mg/l at 4 days MCRT. Under dynamic conditions for the same average MCRT, the effluent ammonia concentration ranges for approx 7 mg/l–15 mg/l. This decrease in efficiency was noted earlier by Poduska and Andrews (31) who attributed it to nonsteady-state operation.

It was stated previously that MCRT and F/M were not valid indicators of growth rate for nonsteady-state conditions. The deficiencies of F/M and MCRT as indicators of growth rate in a dynamic environment are shown in Fig. 6. The only control used in this simulation was MCRT control using a constant sludge wasting rate over a 24-hr period. At the end of each 24-hr period a new sludge wasting rate was calculated and used for the next 24-hr period. It is observed that MCRT is controlled at 6 days, within 10%–20% variation; however, the instantaneous F/M ratio, which is also shown in Fig. 6, changed from 0.1/day to nearly 0.5/day, during each 24-hr period. The value of SCOUR, which is a dynamic indicator of growth rate, changes from about 12 mg O_2/g MLVSS hr to over 20 mg O_2/g MLVSS hr. It is apparent that controlling MCRT by the aforementioned techniques does not control instantaneous F/M or growth rate. This is a logical conclusion from the derivation and meaning of MCRT and F/M. The results of this simulation demonstrate that controlling F/M or MCRT can be useful for regulating sludge inventory, but not for organism growth rate.

It was noted earlier that SCOUR could be used to detect the presence of toxic materials and slugs of readily biodegradable materials. Toxic or inhibitory materials should cause marked decreases in the value of SCOUR, and slugs of biodegradable organic materials should rapidly increase the value of SCOUR. Fig. 7 shows two simulations of the response of SCOUR to slugs of toxic and biodegradable material. For the toxic simulation, a conservative toxic material

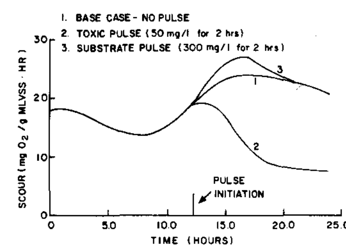

FIG. 7.—Response of SCOUR to Slugs of Toxic and Biodegradable Materials

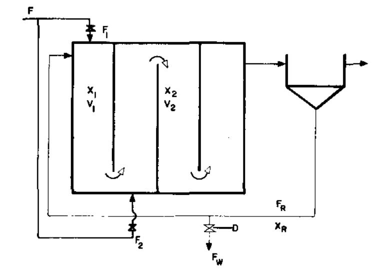

FIG. 8.—Variables Used with Contacting Pattern Control

was assumed, with a first-order toxicity coefficient of 0.01/hr. It is apparent that the response of SCOUR can be used to indicate the presence of process disturbances such as the two mentioned previously.

Activated Sludge Process Control Strategies

It was stated previously that it is not possible to control the activated sludge process using BOD as a controlled parameter due to the inability to measure BOD in real time. Other parameters such as TOC, COD, and TOD have advantages and disadvantages and can be used in conjunction with other parameters such as MCRT, F/M, or SCOUR. In order to develop the best possible real-time control strategy, a two-loop multivariant control approach was taken. SCOUR was selected as the controlled variable for the "fast" loop, because of its unique ability to respond to process inputs and changes in a dynamically changing environment. A slower control loop was also used with MCRT serving as the controlled variable. This proved to be an excellent combination. The mean cell retention time was controlled in the slow loop by manipulating sludge wasting rate. This control action also regulated sludge inventory. SCOUR was controlled in the fast loop by manipulating sludge recycle rate and contacting pattern, defined as the method of feeding influent wastewater to the step feed modification of the activated sludge process as shown in Fig. 8. The effects of manipulating the contacting pattern will be examined in more detail later.

Objective Function.—In order to evaluate the merits of the various control strategies an objective function was used. The variance of SCOUR was selected and calculated as follows:

$$V = \frac{\displaystyle\int_0^T P^2\,dt - \frac{\left(\displaystyle\int_0^T P\,dt\right)^2}{T}}{T} \quad \text{(4)}$$

in which V = variance of the controlled parameter from the mean; P = controlled parameter; T = period of observation; and t = time. It can be shown that this objective is similar to the commonly used integrated squared error (ISE), except that the value of the error is divided by the period of observation, T. It is convenient to use the time divisor in the objective function in order to "normalize" with respect to time. By using this technique, it is possible to compare the value of the objective function for different periods of observation. Also, it is convenient to calculate the dimensionless variance in order to compare control strategies with different set point values of SCOUR, as follows:

$$V_D = \frac{V}{\bar{P}^2} \quad \text{(5)}$$

in which V_D = dimensionless variance; and $\bar{P}$ = mean value of P.

The following control strategies are compared using the variance and dimensionless variance of SCOUR. This technique is a realistic approach since the value of SCOUR must be measured and it is a direct indicator of process performance (38), and is also indicative of effluent biodegradable substrate concentration (34).

The ability to store sludge in order to facilitate control of the effects of diurnal fluctuations in flow and wastewater strength has long been recognized (39). One technique for storing sludge is to manipulate the sludge recycle rate in order to use the storage capacity of the solids-liquid separator. Although this technique was investigated for SCOUR control and showed improvement in process performance, two more promising techniques were developed and are reported.

SCOUR Control by Manipulating Recycle Rate.—The first control strategy is to control SCOUR in the step feed modification of the activated sludge process as shown in Fig. 8. For this control strategy, the entire influent flow was directed to the second segment of the biological reactor. The first segment served as a sludge storage and reaeration section, receiving only recycle sludge. The value of SCOUR for control was averaged over the last three segments of the reactor. The value of SCOUR in the first section remained relatively constant between 7 mg O_2/g MLVSS hr and 9 mg O_2/g MLVSS hr.

Although several popular methods of manipulating recycle rate exist, such as proportioning the recycle rate to the influent flow rate (often called ratio-recycle), a better technique can be developed using feed-forward techniques from the definition of SCOUR. The desired value of the MLVSS concentration can be calculated as follows:

$$X_{DES} = \frac{\text{OUR}}{V_2\,\text{SCOUR}_{SP}} \quad \text{(6)}$$

in which X_{DES} = the desired value of X or MLVSS; V_2 = volume of the last three segments of the reactor, and SCOUR_{SP} is the set point of SCOUR. Using Eq. 6, an explicit expression can be developed for recycle flow rate, using a material balance around the last three sections in the biological reactor, as follows:

$$FR = \frac{V_2 \dfrac{dX_{DES}}{dt} + FX_{DES}}{X_1 - X_{DES}} \quad \text{(7)}$$

in which X_1 = MLVSS concentration in the reaeration segment of the reactor. The measurements required to implement the control law of Eq. 7 are OUR, F, and X_1. The value of flow rate F is easily measured, and would normally be measured at the influent to the activated sludge plant. Therefore, the control law provides for feedforward control, for flow rate disturbances. For this reason, it is referred to as feedforward-feedback (FF), hereafter.

All of the information needed to implement the control law can be measured in real time. The value of OUR can be measured or calculated. For pure oxygen activated sludge plants, the value of OUR can be determined directly from oxygen flow rate. For conventional activated sludge processes, OUR can be measured experimentally using respirometers, or can be estimated from oxygen transfer rate, air flow rate, and blower speed. The details of this technique have been considered by Stenstrom (34) and Andrews, et al. (1).

The only other measurement needed is the MLVSS concentration that can be determined by an automated suspended solids analyzer or by periodic manual measurement. Several types of suspended solids and analyzers have been used with success (5,18). Also, it is not necessary to measure the solids concentration in the first section, if the recycle solids concentration is known. The solids concentration in the first segment can be calculated using a dynamic material balance (34). It is also necessary to estimate the relationship between MLSS and MLVSS. This can be done less frequently than the solids analysis, since the relationship between MLSS and MLVSS does not change as rapidly as the controlled variable SCOUR changes (34).

The value of the derivative term, dX_{DES}/dt, can also be calculated, if a process control computer is used. Normally, calculation of the derivative in control techniques magnifies the influence of "noise" in the measured variables. To determine the importance of the derivative term in the overall controller's performance, a sensitivity study using weighting factors was performed, and is presented later.

The simulated response of this control strategy is shown in Fig. 9, along with the value of the manipulated variable sludge recycle rate. It is observed that the variability of SCOUR is decreased significantly, corresponding to a 70% decrease in the objective function.

TABLE 1.—Summary of Controller Performance with Sludge Storage

Method (1)	$SCOUR_A$, in milligrams per gram-hour (2)	$SCOUR_V$, in (milligrams per gram-hour)^2 (3)	$SCOUR_{VD}$ (4)	FR_A, in million gallons per day (5)
Base case (no control)	17.0	12.9	0.0446	3.00
Ratio-recycle	17.0	9.8	0.0339	2.83
Proportional feedback	16.9	4.7	0.0164	3.21
Feedforward-feedback (*WF* = 1.0)	17.9	3.6	0.0116	2.75
Feedforward-feedback (*WF* = 0.66)	17.9	3.4	0.0106	2.48
Feedforward-feedback (*WF* = 0.44)	17.9	4.65	0.0145	2.29
Feedforward-feedback (*WF* = 0.33)	17.9	5.8	0.0181	2.21
Feedforward-feedback (*WF* = 0.0)	18.2	11.0	0.0332	2.00
Variable contacting (*WF* = 1.0)	16.4	8.5	0.0316	3.00
Feedforward-feedback (1-hr prediction)	16.2	2.3	0.0088	6.03
Feedforward-feedback (2-hr prediction)	16.3	1.8	0.0068	5.91
Feedforward-feedback (3-hr prediction)	16.5	1.6	0.0059	5.72
Variable contacting (1-hr prediction)	14.7	2.1	0.0097	3.00
Variable contacting (2-hr prediction)	14.8	2.1	0.0096	3.00
Variable contacting (3-hr prediction)	14.9	2.3	0.010	3.00

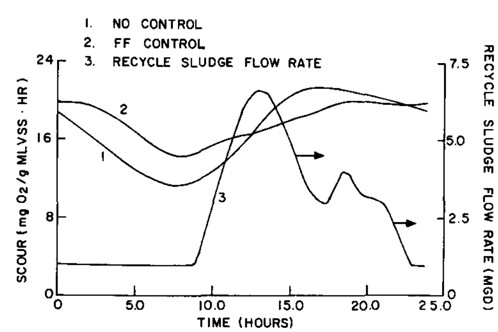

FIG. 9.—Response of the Activated Sludge Process with SCOUR Control: Manipulating Sludge Recycle Rate

Table 1 is a summary of the performance of the various control laws developed for the step feed modification of the activated sludge process shown in Fig. 9, along with the results of other control strategies to be considered later. A base case value is given along with a tabulation of the objective function (both the variance and the dimensionless variance), average values of SCOUR, and total volume of sludge recycled. Comparative values of the objective function for ratio recycle, and simple proportioned feedback control are also given.

In order to determine the importance of the derivative term in Eq. 7, a weighting factor, WF, has been used. The weighting factor is multiplied times the derivative term dX_{DES}/dt. Therefore, a value of 1.0 for WF corresponds to full weighting, and a value of 0.0 corresponds to no influence of the derivative term. The results, shown in Table 1, indicate that the optimal value of the derivative weighting factor is about 0.66. Using this control law, the variability of SCOUR is decreased by 76% over the uncontrolled case, with a savings in total recycle sludge pumping of 17%. Simple proportioned feedback control reduced the variability of SCOUR by 63% at a cost of 7% increased recycle sludge pumping. Ratio-recycle control produced a 23% reduction in the variability of SCOUR.

No optimization of the controller was attempted since it was felt that experimental confirmation is required before optimization can be justified. However, it is obvious that several alternatives are possible and that many factors, including pumping cost and control equipment cost, will influence optimal controller design. The size of solids-liquid separator also influences controlled design and has been examined (34).

SCOUR Control by Manipulating Contacting Pattern.—The previously examined control strategies require the use of variable recycle rates. To vary sludge recycle rate, it is necessary to control flow by control valves, multiple pumps, or by variable speed pumps. Either technique is expensive and more maintenance intensive than operating with constant recycle.

A more serious objection to the use of variable recycle rate has been raised by Cashion, et al. (9), who state that the influence of changing flows in the solids-liquid separator, due to changing recycle rate may create more problems, in terms of effluent suspended solids, than the benefits obtainable by better control.

An alternate control strategy proposed here, which does not have the weakness that Cashion, et al. (9), suggest, uses contacting pattern as a manipulated variable, with a constant recycle rate. Contacting pattern can be changed by manipulating the valves that control the distribution of influent flow to the first and second sections of the biological reactor. By changing contacting pattern, it is possible to change process operation from conventional to step feed or vice versa. This method of control provides for sludge storage, but does not require variable recycle rates.

Fig. 8 shows the process and related variables. Using techniques similar to those used to derive Eqs. 6 and 7, the following control law can be developed:

$$F_1 = \frac{(\mathrm{WF})V_2 \dfrac{dX_{des}}{dt} + (\mathrm{FR} + F)X_{DES-FR}}{X_1} \qquad (8)$$

and $$F_2 = F - F_1 \qquad (9)$$

in which F_1 = portion of the influent flow directed to the storage segment of the biological reactor; and F_2 = the remainder of influent flow, directed to the second segment of the biological reactor.

Fig. 10 shows the response of SCOUR when using the variable contacting control technique of Eq. 1. The variance of SCOUR using this technique was reduced by 30%. The marginal improvement results from the inability to rapidly transfer sludge from the rearation section (first section) to the other three sections. Nevertheless, this control strategy provides for significant improvement, without changing recycle rate.

Control with Flow Rate Prediction.—It is well known that many domestic wastewater treatment facilities experience periodic variations in influent flow rate and pollutant concentration. It is possible to predict influent parameters and to use the predicted values in control techniques. The technique of prediction has been demonstrated by Bertheoux, et al. (2) who used time series models for predicting influent BOD concentration, and Goel and LaGrega (17) who used similar techniques to predict wastewater flow rates.

To illustrate the value of prediction and determine the significance of prediction

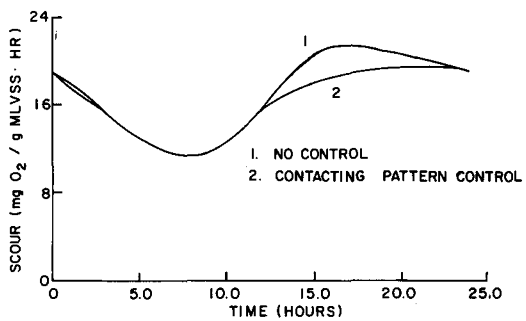

FIG. 10.—Response of the Activated Sludge Process with SCOUR Control: Manipulating Contacting Pattern

for SCOUR control, flow rate prediction was simulated. In order to simulate flow rate prediction, a time substitution was made in the time series models used for the input functions. To simulate the error that must occur in prediction, a random noise component was superimposed upon the simulated flow rate to aeration tank. The variability of the random component was selected so that the variance between prediction and measured flow would be equal to the difference between the time series model and the data used to develop the time series model. The flow rates fed into the control laws (Eqs. 7 and 8) were the "ideal" predicted flows. Fig. 11 shows the predicted flow that was used as the controller input and flow with stochastic components, which was used as the model input.

Both variable contacting and feedforward-feedback control strategies were simulated using flow rate prediction of 1 hr, 2 hr, and 3 hr. The results are also summarized in Table 1. The variability of SCOUR was reduced by 86% for the best feedforward-feedback strategy, which is a 16 percentage point improvement over the equivalent strategy without prediction. The variability

of SCOUR using the variable contacting control strategy with prediction was reduced by 78%, which is 48 percentage points better than the performance without prediction. Fig. 12 shows the uncontrolled and controlled variables using the feedforward-feedback control strategy.

Note that the mean value of SCOUR decreased when using the control strategies with prediction. The reason for the decrease is a change in average distribution of sludge mass between the first and remaining sections of the biological reactor.

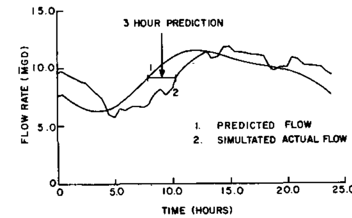

FIG. 11.—Simulated Flow Rates

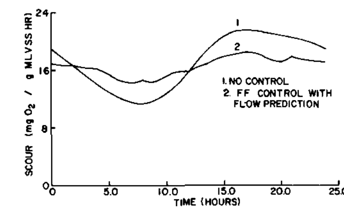

FIG. 12.—Response of the Activated Sludge Process with SCOUR Control, Manipulating Recycle Rate, with Influent Flow Rate Prediction

No attempt was made to quantify or correct this change, and is a subject of future research.

Summary and Conclusions

The potential for improvement in process efficiency and operation has been shown, through modeling and simulation, using SCOUR as a controlled variable. It has been shown that SCOUR is a dynamic indicator of growth rate and can be used for real-time process control. The use of F/M and MCRT for real-time control is limited, due to their derivation from steady-state material balances.

It has been shown that SCOUR and MCRT can be used, in a multivariant, feedforward-feedback control strategy, to reduce the variability of mean organism growth rate by 70%, and to regulate sludge inventory. Using techniques for predicting influent flow rate, it is possible to reduce the variability of growth rate by 86%. Contacting pattern control, with constant recycle rate, can reduce growth rate variability by 76% with flow prediction, and 30% without flow prediction.

The control strategies simulated can be used to control disturbances due to periodic variations in influent parameters or to control disturbances caused by slugs of toxic or biodegradable materials. It has been shown through simulation that SCOUR rapidly indicates the presence of shock loads and that F/M or MCRT do not.

The control strategies developed here require real-time measurement of several process variables. Implementation of the strategies will require the use of data acquisition and control facilities that can best be provided by process control computers.

There are also further research needs that can best be accomplished by a combination of mathematical modeling and simulation, in conjunction with experimental investigations. Two areas in particular can be further developed. It should be possible to develop better strategies using prediction; the strategies presented here with flow rate prediction used the predicted variable in place of a measured variable. They did not explicitly consider the time of prediction, or time lags. It should be possible to incorporate deterministic aspects of the process to determine an optimal prediction time. Also, the oxygen uptake due to the heterotrophic organisms and nitrifying organisms was not separated. It should be possible to extract more information from SCOUR, using instruments to determine oxygen uptake rate for each group of organisms, and to incorporate this knowledge into the control strategies.

Acknowledgments

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14521 REAL-TIME CONTROL OF ACTIVATED SLUDGE

KEY WORDS: **Activated sludge process; Computers;** Control; Environmental engineering; **Mathematical models;** Oxygen demand; Sanitary engineering; **Simulation;** Wastewater treatment

ABSTRACT: A technique for real-time control of the activated sludge process using specific oxygen uptake rate (SCOUR) has been developed. Mathematical modeling and computer simulation techniques were used to develop multivariant control strategies using SCOUR and mean cell retention time as the controlled variables, and manipulating sludge recycle rate, sludge wasting rate, and wastewater feed point location. It is shown that SCOUR is a valid indicator of process efficiency and sludge activity for nonsteady state operation, and that multivariant control techniques using SCOUR are superior to techniques that use only food-to-mass ratio, or mean cell retention time. It is also shown that SCOUR can be used to detect shock loads of toxic and biodegradable materials. The value of forecasting flow rates for improving control is illustrated through the use of time-series models.

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