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ASCL - An Activated Sludge Process Control Language

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Abstract

The report addresses dynamic modeling and automatic control to wastewater treatment. A background review of the field is included. Several dynamic models of increasing complexity are presented. They are mechanistic models based on the fundamental biological, chemical, and physical phenomena which occur in the process. Different control strategies including S/M and sludge aid control, are presented for the process. The model and control strategies have been programmed in a program package called ASCL (Activated Sludge Control Language). The programmed package provides the user with interactive possibilities to change the dynamics or the parameters of the process.

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ASCL

AN ACTIVATED SLUDGE PROCESS CONTROL LANGUAGE

Prepared
for

THE WEYERHAEUSER COMPANY

Prepared
by

John F. Andrews
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Robert D. Hill

September 23, 1981

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1. EXECUTIVE SUMMARY

Most research projects on wastewater treatment are oriented toward plant design. This project is concerned with plant operations and has the goal of minimizing operating costs while yet meeting permit limits. However, plant design is also considered in that the effects of major plant modifications on process operation are evaluated. The objective of the project was to develop dynamic models and control strategies for the activated sludge process with specific application to Weyerhaeuser treatment systems. The models and control strategies are structured so as to take advantage of the latest advances in computer control.

Since the application of dynamic modeling and automatic control to wastewater treatment is relatively new, a background review of this field has been included. Dynamic models have the advantage over steady-state models of being able to predict the effects on the process of disturbances in the process influent such as may be caused by black liquor spills, sudden increases in BOD, etc. They are also necessary for the evaluation of different control strategies.

Several dynamic models of increasing complexity are presented. They are mechanistic models based on the fundamental biological, chemical, and physical phenomena which occur in the process. They have been made flexible so that the reactions, stoichiometry, rate expressions, and types of reactors can be configured so as to represent a number of versions of the process. As dynamic data are collected for model validation, stochastic components can be included in the models to improve the "fit" between the data and the models.

A variety of control strategies, including F/M and sludge age control, are presented for the process. Some of these will require more specific knowledge about individual process characteristics prior to implementation. Others, such as DO, pH, N, and P control are relatively standard and should be implemented at full scale as soon as possible since they have the potential for improving performance and reducing operating costs at Weyerhaeuser treatment plants.

The model and control strategies have been programmed to provide a simulation package for implementation on the Weyerhaeuser Technology Center VAX-11 computer. This program, known as ASCL (Activated Sludge Control Language), is interactive so that a user with little or no computer training will be able to utilize the program to study the effects on the process of changes in the influent, controller settings, and major facility modifications. ASCL is also structured to permit easy updating of the models and control strategies as dynamic data are accumulated from pilot or full-scale plant operation. A user's guide for ASCL is provided in a companion document to this report.

Reliable sensors are of key importance for the implementation of control. A separate report on sensor availability has therefore been prepared by Dr. Ronald Briggs.

As a conclusion to the report, recommendations as to the steps required for adaptation of the dynamic models and control strategies to computer control of full-scale plants are presented. A major recommendation is that the models and control strategies be validated and improved through pilot plant experimentation. ASCL is a valuable tool for preparing the experimental plan for the pilot studies. Another recommendation is development of a dynamic model for the aerated lagoon since this process is widely used by Weyerhaeuser.

2. INTRODUCTION

Large sums of money have been devoted to the construction of wastewater treatment plants in the past few years. Unfortunately, this attention to construction has not been matched by an equivalent consideration of how to operate these plants with the result that many of the plants constructed, at least for the municipal sector, are not removing the amount of pollutants for which they were designed. This is well documented by papers in the professional literature (1, 2, 3) and a series of reports to Congress by the Comptroller General (4, 5, 6). Equivalent documentation is not available for the industrial sector but, considering the state-of-the-art in treatment plant operations, it would be surprising if performance was any better than for the municipal sector.

Another serious problem is that of high operating and maintenance costs for wastewater treatment. Most existing plants, and many still under construction, were designed based on the availability of inexpensive energy. A 1977 Engineering News Record survey (7) of 18 municipal plants showed that cumulative operation and maintenance costs at six of these exceeded their design and construction costs in less than four years. As the price of energy continues to increase, this situation can only become worse.

There are many reasons for the poor performance of wastewater treatment plants. These range through the spectrum of operation, design, maintenance and administration. A more detailed discussion of the general factors limiting performance has been presented by Hegg, et al (3). The problem which will be addressed in this research is that of improving performance and reducing operating costs through obtaining a better understanding of the dynamics of the plant and the application of modern control theory.

Attention will be focused primarily on the activated sludge process since this forms the heart of most wastewater treatment plants and usually requires the highest expenditure of energy. It also has the reputation of being difficult to operate and not infrequently exhibits gross process failure as evidenced by the discharge of large quantities of suspended solids. However, when properly designed and handled by skilled operating engineers, the process can easily meet or exceed normal effluent requirements. The potential for high quality performance is therefore present; what is needed is a better understanding of the dynamics of the process and how it should be controlled. The potential also exists for obtaining improved performance with simultaneous reduction in energy requirements as evidenced by the work of Genthe, et al (8), among others, on automatic control of dissolved oxygen.

2.1 Objectives

The long term objective of this research is to enable Weyerhaeuser wastewater treatment plants to satisfy their permit requirements at minimum operating cost through the application of computer control based on dynamic models of the plants. The work reported upon herein represents a first step in this direction and had the specific objectives listed below:

(1) Development of dynamic models of the activated sludge process with specific application to the pulp and paper industry. The models should be capable of describing the performance of the more common reactor configurations and should include rate limitations by nitrogen and phosphorus.

(2) Develop control strategies for the process. These should be structured to take advantage of the capabilities of computer control. The ultimate objective of the control strategies is to minimize operating costs while satisfying permit requirements. They should make maximum use of available sensors which have been proven reliable in field applications.

(3) Prepare an interactive simulation package for the process based on the above dynamic model and control strategies. The package should be readily usable on Weyerhaeuser computers by personnel with minimal computer expertise. Complete documentation and a user's guide for the simulation package should be provided.

(4) Make preliminary recommendations on adaptation of the dynamic model and control strategies to real time computer control in Weyerhaeuser treatment plants. This would include advice for model validation at pilot scale as well as suggestions for full scale implementation of some of the more promising control strategies.

2.2 Conduct of Research

This research required knowledge from several disciplines and was therefore conducted as a team effort. Professor John Andrews, Department of Civil Engineering, University of Houston, is an Environmental Engineer experienced in the dynamics and control of biological processes for wastewater treatment. He served as the project director. Dr. Gustaf Olsson, Department of Automatic Control, Lund University, Sweden, has been engaged in research on the dynamics and control of the activated sludge process for several years. He is especially knowledgable in the areas of dynamic modeling, computer simulation, state/parameter estimation, and computer control. Dr. Ronald Briggs was in charge of the instrumentation Division, Water Research Centre, England, at the time that the project commenced. He has extensive experience in the development and application of sensors for wastewater treatment. Dr. Briggs is now with John Taylor and Sons, a consulting engineering firm in London. The fourth member of the team was Mr. Robert Hill, a Ph.D. student at the University of Houston, whose research is in the area of computer control of the activated sludge process.

The dynamic models and control strategies presented herein are based primarily on the literature, computer simulations, and discussions with Weyerhaeuser research engineers and treatment plant operating personnel. They should be validated at pilot scale prior to implementation at full scale. An exception would be some of the control strategies, such as dissolved oxygen or pH control, which have been well tested in other installations and could be implemented using standard feedback control laws.

2.3 Report Organization

Since the application of dynamic modeling and automatic control to wastewater treatment is relatively new, a brief background review of this field will be presented first. This will be followed by the development of dynamic models and control strategies for the activated sludge process with specific application to the pulp and paper industry. The models and associated control strategies have been programmed to provide an interactive simulation package. This package is described in full in a companion document, the ASCL User's Guide.

As a conclusion to the report, recommendations as to the steps required for adaptation of the dynamic models and control strategies to real time computer control are presented. Since reliable sensors are a key to this implementation, a separate report on instrumentation requirements has been prepared by Dr. Ronald Briggs.

3. BACKGROUND

The need for consideration of dynamic behavior in both the design and operation of processes used for wastewater treatment is frequenty greater than that for industrial processes because of the large temporal variations which occur in wastewater composition, concentration, and flow rate. Gross process failures are all too frequent and even when these are avoided, it is not unusual to find significant variations in process efficiency, not only from one plant to another but also from day-to-day and hour-to-hour in the same plant. A better understanding of this dynamic behavior and the incorporation of modern control systems to correct unsatisfactory behavior, has the potential for effecting substantial improvements in performance. Other potential benefits include increased productivity, greater reliability, lower operational costs, more stable operation, and faster start-up. Another attractive concept is that of operating the treatment plant at variable efficiency in order to match the assimulative capacity of the receiving body of water which usually varies with time. This would require a good knowledge of the dynamic behavior of both the treatment plant and receiving waters.

3.1 Process Dynamics

Changes are always taking place in the inputs, outputs, or environment of a process as well as in the characteristics of the process itself. It is important to identify the nature of these changes or disturbances and the rates at which they occur. Mathematical modeling and computer simulation are key tools for accomplishing this.

3.1.1 Mathematical Modeling

Mathematical modeling is a technique frequently used (and sometimes abused!) in today's scientific and engineering investigations. However, modeling itself is not new since scaled-down physical models have long been used in such diverse areas as astronomy (planetariums), hydraulic engineering (river models), architecture (building models) and chemical engineering (pilot plants). Even the hypotheses which are formulated in applying the scientific method can be thought of as verbal models.

A mathematical model of a process usually consists of one or more equations relating the more important factors which influence the process. Many mathematical tools, such as algebra, ordinary and partial differential equations, probability theory, etc., are available for relating these characteristics. Occam's razor applies here as well as to verbal hypotheses in that the simplest possible expressions should be used. From an engineering point of view, mathematical elegance is secondary; a model which is too complex may be subject to either misuse or disuse.

In developing models it must also be realized that they are evolutionary in nature and subject to change as more knowledge is gained about the process. A model which is quite adequate as a first approximation may be replaced at a later date by a more exact model with better estimates of the parameters, fewer empirical relationships, and inclusion of more variables.

Mathematical models may be classified in many different ways and one of the most important for wastewater treatment processes is the distinction between dynamic and steady state models. Most models currently in use are based on the assumption of steady state. Such models have proven their value on a qualitative basis by indicating needed changes in process design and also have the advantage of experimental and computational simplicity. However, in most instances they are not adequate to describe process operation since the inputs to the processes are far from constant and there is considerable variation in effluent quality with respect to time. Wastewater treatment processes should be modeled as dynamic systems and especially so if these models are to be used to explore control strategies.

Another important classification of mathematical models is as mechanistic or empirical. Mechanistic models are based on scientific knowledge about the fundamental biological, chemical, and physical phenomena which govern the process. Some of the more important phenomena for biological processes are stoichiometry, equilibrium relationships, reaction and transport kinetics, gas laws, and conservation equations (mass and energy balances). Models based on fundamental principles give more insight into process behavior and may be more reliably extrapolated to different process designs or control strategies. In addition, the use of fundamental principles enables one to draw on existing knowledge in the other branches of science or engineering.

Still another classification of models is as deterministic or stochastic. Deterministic models are those in which the inputs, outputs, and system parameters can be assigned a definite fixed number, or series of fixed numbers, for any given set of conditions. In contrast, the principle of uncertainty is introduced in stochastic models and statistical techniques must be used to express the model in a mathematical form.

The dynamic mathematical models to be developed in this research will, whenever possible, be based on fundamental principles and are deterministic in nature. However, it should be realized that the final models for field implementation will have to incorporate some empirical relationships whenever theoretical knowledge is lacking. Moreover, at that time it will also be necessary to superimpose some stochastic features on the deterministic components to take into account the random nature of some of the phenomena.

3.1.2 Computer Simulation

After a dynamic mathematical model has been developed for a process, the equations which comprise the model must be solved in order to predict the behavior of the process with respect to time. This procedure is known as simulation and can be defined as the use of a model to explore the effects of changing conditions on the real system.

Realistic dynamic models usually contain several non-linear differential equations for which analytical solutions are not available. Thus, prior to the advent of the computer, a computational or simulation bottleneck existed and efforts at dynamic modeling were frequently of no practical value since the equations could not be solved. However, computers have now largely eliminated this bottleneck and the current problem is not so much one of being able to obtain a solution as it is to insure that the model adequately describes the dynamic behavior of the process.

The early use of computers was largely restricted to specialists since a considerable amount of time was required to learn to use a computer. However, this problem was overcome in the 1960s by the development of general purpose simulation languages which were heavily user-oriented thus permitting the engineer to concentrate on model development and simulation results rather than on the details of the computations. A more recent development is that of interactive simulation languages for special purposes such as ASCL (Activated Sludge Control Language) which has been developed in this research. Although such languages can be used for model development, they are primarily oriented toward obtaining simulation results. The command or question-answer format used in these languages permits their use by those with little or no formal training in computer programming.

Computer simulation has many of the same advantages--and disadvantages--as physical simulation. A great deal of knowledge can be gained about a process through the development of a mathematical model and the subsequent computer simulations using the model. Considerable monetary savings can be realized by using simulation, since experimentation on the computer is usually less expensive than construction of a full scale plant or physical model with subsequent experimentation. Time can be compressed on the computer with simulations being conducted in minutes. This is especially important for processes such as biological processes where rates are slow and physical experimentation may require weeks and even months.

There are, of course, disadvantages to computer simulation. The results of the simulations are not better than the mathematical model and data on which they are based. Simulation using physical models does not have this disadvantage; however, it does present the problem of scale-up. This disadvantage of computer simulation can be overcome by working back and forth between mathematical modeling, computer simulation, experimentation with physical models, and field observations since these complement one another. Knowledge gained in simulation is useful for modifying the mathematical model, guiding physical experimentation, and establishing the type and frequency of field observations needed. This iterative technique also points out another important aspect of modeling and simulation, this being the need for model validation. The ease and speed with which computer simulations can frequently be made may lead to a neglect of this essential portion of model development and, in the extreme, can result in one becoming so enamoured with the techniques that the purpose for using them is almost forgotten. This can lead to the generation of large quantities of worthless results if the model is not a reasonable representation of the real process.

3.2 Control Strategies

When the dynamic behavior of a plant has been defined, the process engineer then becomes interested in modifying this behavior so that it will conform to some desired behavior. This can usually be accomplished through either process design or the incorporation of control systems. In the past, the major efforts in wastewater treatment have been devoted to process design with relatively little attention being paid to process operation. Most control systems reported on in the literature have been selected on an empirical basis because of a lack of fundamental knowledge regarding dynamic behavior or control strategies.

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

The handling of materials, energy, and information all involve collection, transportation, processing, storing, and distribution. Flow diagrams are customarily used to portray this and examples of information flow diagrams are given in Fig. 3.1 where the temperature of a process is to be controlled either manually or automatically. The need for a control system is brought about by a change in the temperature of the process from a 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. 3.1a), the measured 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 is attained. The man has "closed the loop" by "feedback" of information from the process output to the process input.

In the automatic system (Fig. 3.1b), the man is replaced in the feedback loop by a controller. The temperature sensor transmits a signal to the controller. An additional device, a transducer, may be 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, known as a set point, to determine if an error exists. If an error does exist, the controller computes, by means of equations known as "control laws," the amount of control action needed. It then transmits a signal to a final control element, the valve in this instance, to adjust the manipulatable variable for the process. The manipulatable variable in this case is the heat input to the process. A transducer may also be needed between the controller and the final control element. The automatic system is also iterative 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.

Regardless of whether control is to be manual, automatic, or a mixture of the two, Fig. 3.1 illustrates that some of the same basic quesitons must be answered in development of a conotrol strategy. Included among these are:

(1) What measurements should be made for initiation of the control strategy?

(2) How should this information be transmitted from the sensor to the controller and from the controller to the final control element?

(3) What control law should be used to determine the type and amount of control to be exerted?

(4) What variable should be manipulated?

Dynamic modeling and computer simulation can be of considerable value in obtaining answers to these questions. However, of equal or greater importance is an intimate knowledge of the process since the answers are highly dependent

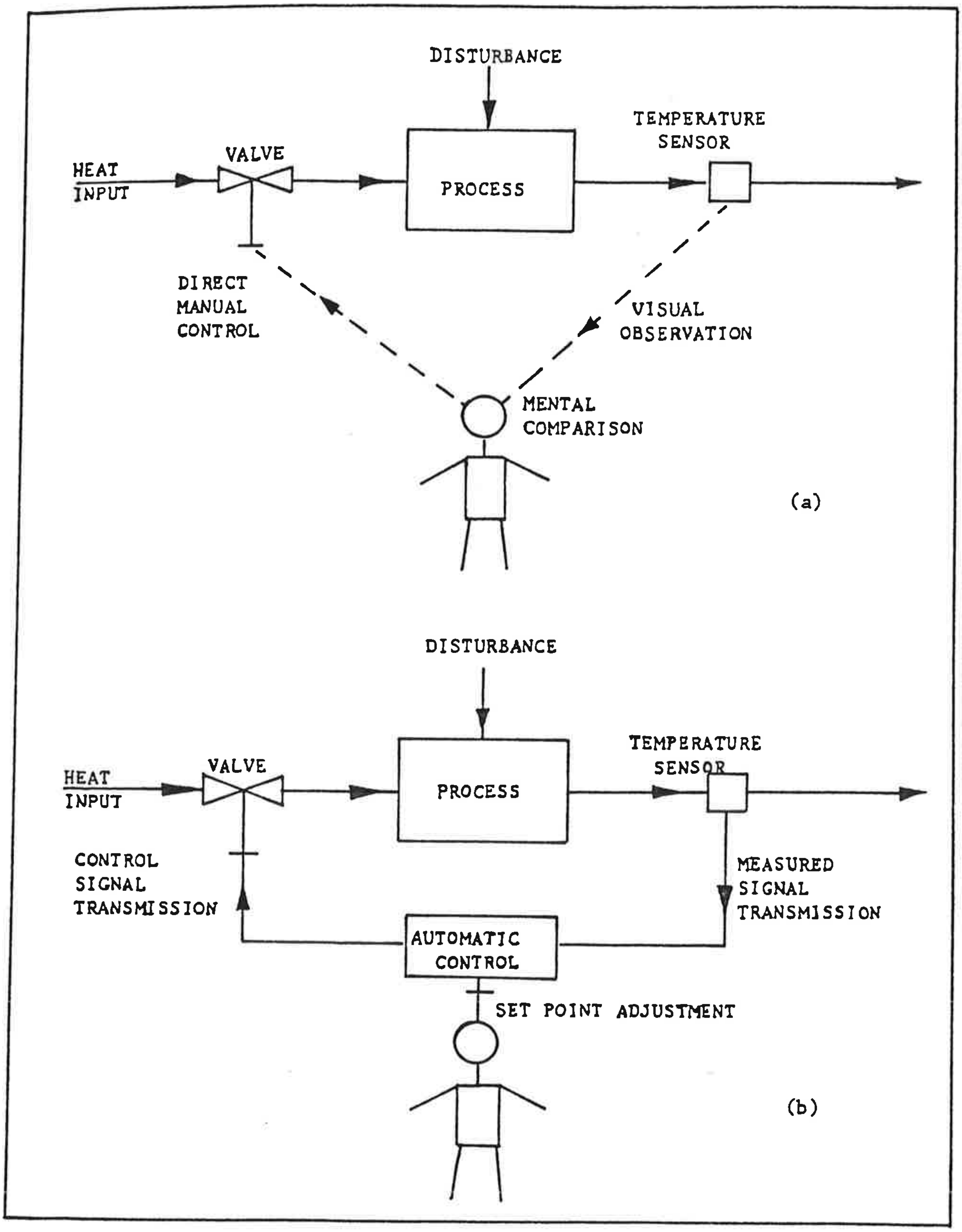

FIGURE 3.1 INFORMATION FLOW DIAGRAMS

upon the wastewater to be processed, plant characteristics, quantity and quality of operating personnel, and environment in which the plant will be operated.

3.2.1 Measurements

The appropriate measurement, combination of measurements, or variables calculated from measurements must be selected for initiation of the control strategy. Measurements may be made on the process influent or effluent, the process environment, or can be internal to the process. Associated items of importance are the required accuracy and frequency, time required for making the measurements, and the availability of instruments. The dynamic behavior of the process and its associated control system must be considered in establishing information needs.

The availability, accuracy, and reliability of sensors is of special importance in deciding whether measurements should be made automatically on-line or manually off-line. Over the design life of a plant, it is certain that new sensors will become available and provision should be made at the appropriate points for the addition of these senors. In the interim, provision should be made for easy access to sample points and for the pumping of samples to selected remote stations or the central laboratory for manual or automatic wet chemical analysis.

Some of the problems associated with sensor reliability can be overcome by using redundant sensors when the price of the primary sensor is relatively low and the value of the information obtained by the sensor is high. An example would be the use of three dissolved oxygen probes instead of one. Sensor malfunction subroutines can be used in the computer to indicate which of the multiple sensors is giving a bad reading and therefore needs recalibration or replacement. When sensors are expensive, the opposite approach should be considered in which one sensor is used for measuring, on a time shared basis, the characteristics of several sample streams. This is usually quite feasbile for permanent gas analysis since such streams are easily pumped and hydraulically multiplexed.

An objection frequently raised to the incorporation of control systems in wastewater treatment plants is that reliable on-line sensors are not available for many important measurements. However, this problem is not as serious as might be expected since many changes in treatment processes occur relatively slowly and there is frequently adequate time for a man to perform analyses on-site or in the plant laboratory. Also, the provision of computing power frequently permits the calculation of important variables which cannot be mesured directly. Examples are the calculation of the specific oxygen utilization rate from mass balances using mesurements of flow rates and suspended solids concentrations and evaluation of the status of the biological reactions in the activated sludge process from the dissolved oxygen profile.

The obtaining of reliable sensors is crucial to the success of both the pilot and full-scale implementation of this research. A separate state-of-the-art report on sensors and their availability has therefore been prepared by Dr. Ronald Briggs and should be considered as a key portion of this report.

where:

C_A = amount of control to be exerted

K_B = steady state control coefficient

K_P = proportional control coefficient (P)

K_I = integral control coefficient (I)

K_D = derivative control coefficient (D)

e = error signal

steady state value of the measured signal. Under these conditions, the measured value is equal to the set point and there is no error signal. The second term provides control proportional to the error and thus reflects the current status of the process. The third term is proportional to the integral of the error and therefore takes into account the history of the process whereas the fourth term is proportional to the derivative of the error and represents an attempt to predict the future. It should be noted that Eq. 3.1 is the classical textbook PID controller and many variations of the basic equation exist. Several of these, including the variation used in ASCL, are presented in Section 5 of this report.

On-off and PID controllers are widely used and have proven their value in a variety of control applications. However, there are many instances in which performance could be further improved by the use of more advanced control laws. Among these are ratio control, cascade control, feedforward control, dead time compensation, and self-tuning regulators.

Ratio control is frequently used in the activated sludge process. In this type of control, the recycled sludge flow rate is maintained as a set fraction (ratio) of the wastewater flow rate to the aeration basin. It is usually initiated in an attempt to maintain a more constant concentration of mixed liquor suspended solids (MLSS) in the aeration basin. It would be classified as open loop control since there is no feedback from the key variable of interest, the MLSS.

Feedforward control is similar to ratio control in that it is open loop control. Information for feedforward control is obtained by measuring the inputs to the process instead of the outputs as in feedback control. The amount and type of control to be exerted is then predicted using a dynamic model. Feedforward control is theoretically capable of perfect control since no error need exist, as for feedback control, before the control is initiated. This can be of special importance for processes with large time constants as commonly encountered in wastewater treatment. However, since dynamic models are seldom perfect and there are constraints on the amount of control which can be exerted, some feedback control for "trimming" is necessary as will be illustrated in Section 5.

Control systems involving many control loops, or using advanced control laws, require considerable computing power and it is only logical that digital computers have been increasingly installed for process control in wastewater treatment plants. This trend has been accelerated in recent years by the rapid advances in computer technology and the substantial decreases in cost of computers. Examples of where this computing power is valuable include calculation of the specific oxygen utilization rate from mass balances and the rapid solution of dynamic models for the initiation of feedforward control. Another major advantage of computer control is that the control strategy can be easily changed by reprogramming (software changes) the computer whereas conventional controllers may require replacement or rewiring (hardware changes). Still another advantage is that the large memory permits storage of sizeable amounts of historical data. The rapid reduction, manipulation, and display of this data can be of substantial assistance to treatment plant operators.

Smith (9) in 1972 listed those characteristics of processes that are most likely to justify the installation of a control computer. These are:

(1) Plants with Large Throughputs. With very high throughputs, only a small percentage improvement is spread over a high volume thus generating a large return. For example, an increase in the BOD removal in a wastewater treatment plant from 85 to 90 percent results in a one-third reduction in the mass discharge rate of BOD and thus has a substantial influence on meeting permit requirements when they are expressed as mass discharge rates.

(2) Very Complex Plants. In such plants, it is very difficult for the operating personnel to assimilate all of the various factors necessary to operte at the optimum operating objectives. The computer is very good at assimilating, reducing, and displaying these factors for operator assistance.

(3) Plants Subject to Frequent Disturbances. Although first level control systems can compensate for many of these, the operating objectives (e.g., shift from meeting permit limits to avoiding gross process failure) must be modified for others, a task for which the frequent attention of the computer will be superior to the operator's attention.

There is no question but that wastewater treatment plants, with their high throughputs, complex biological processes, and frequent feed stream disturbances, possess all of the above characteristics.

There have been many advances in computer technology since 1972. Good illustrations of these advances, as well as available products, may be found in journals such as Instrumentation Technology and Control Engineering. Especially notable have been substantial reductions in both size and cost of computers and improvements in reliability. As a result of these advances, computer control should now be considered even for small systems such as package treatment plants. There are several manufacturers of these small computer control packages which are known as local digital controllers. They are tending to replace conventional analog controllers because of their many advantages such as:

(1) Fewer problems with electronic shift.

(2) Improved techniques for communication with central computers.

(3) More flexible control strategies, such as the use of dead time compensators, are possible.

(4) Provision of a low cost method of taking a first step toward more advanced computer control.

Standard software is available for these local digital controllers. Also, software development is less cumbersome today because of the availability of compilers for high level languages. Nonetheless, program development is still usually the most expensive portion of a computer control system since it involves a detailed study of the specific process to be controlled.

3.2.4 Manipulatable Variables

The prevailing philosophy in the design of wastewater treatment plants has been to provide a minimum number of variables for manipulation and attempt to take care of fluctuations in plant inputs and environmental conditions by provision of additional capacity. In addition to being expensive, this philosophy has frequently not been successful as evidenced by the poor performance of many existing plants. Also, research on the dynamic behavior and control strategies for wastewater treatment plants has only recently begun to receive attention. For these, as well as other reasons, the number of variables which can be manipulated is very limited in conventional plant designs and additional research is needed to establish the type and amount of control which should be provided. In the interim, it is suggested that more flexibility be incorporated into piping, valving, pumping rates, points for chemical addition, etc., during the design phase so that appropriate control can be taken as new control strategies are developed. One of the most frustrating experiences for an operating engineer is when he discovers the need for a change in operational strategy but is unable to make this change because of inflexibility in plant design.

An example of additional flexibility which has proven valuable in plant operations is the provision of piping for the activated sludge process so that influent wastewater can be distributed along the length of a plug flow reactor or fed independently to any one of several reactors in series. This is known as the step feed version of the process and has been shown to be successful for preventing the gross discharge of solids due to either hydraulic shocks or poor settling of the sludge. Still other examples are the provision of polymer feed for decreasing the concentration of solids in the effluent and diversion basins for preventing the discharge of toxic or inhibitory materials to the process.

3.3 Dynamics and Control of the Activated Sludge Process

The activated sludge process is the heart of the fluid processing train and consists of three units, the biological reactor, the solids-liquid separator, and the air supply as illustrated in Fig. 3.2. The three major inputs to the biological reactor are the wastewater from the primary settler, concentrated activated sludge from the solids-liquid separator, and air or high purity oxygen. The microorganisms in the activated sludge react with the organic pollutants in the wastewater and oxygen to produce more activated sludge, carbon dioxide, and water. The effluent from the biological reactor flows to the solids-liquid separator where the activated sludge is separated from the fluid phase. The solids-liquid separator serves three functions, these being the

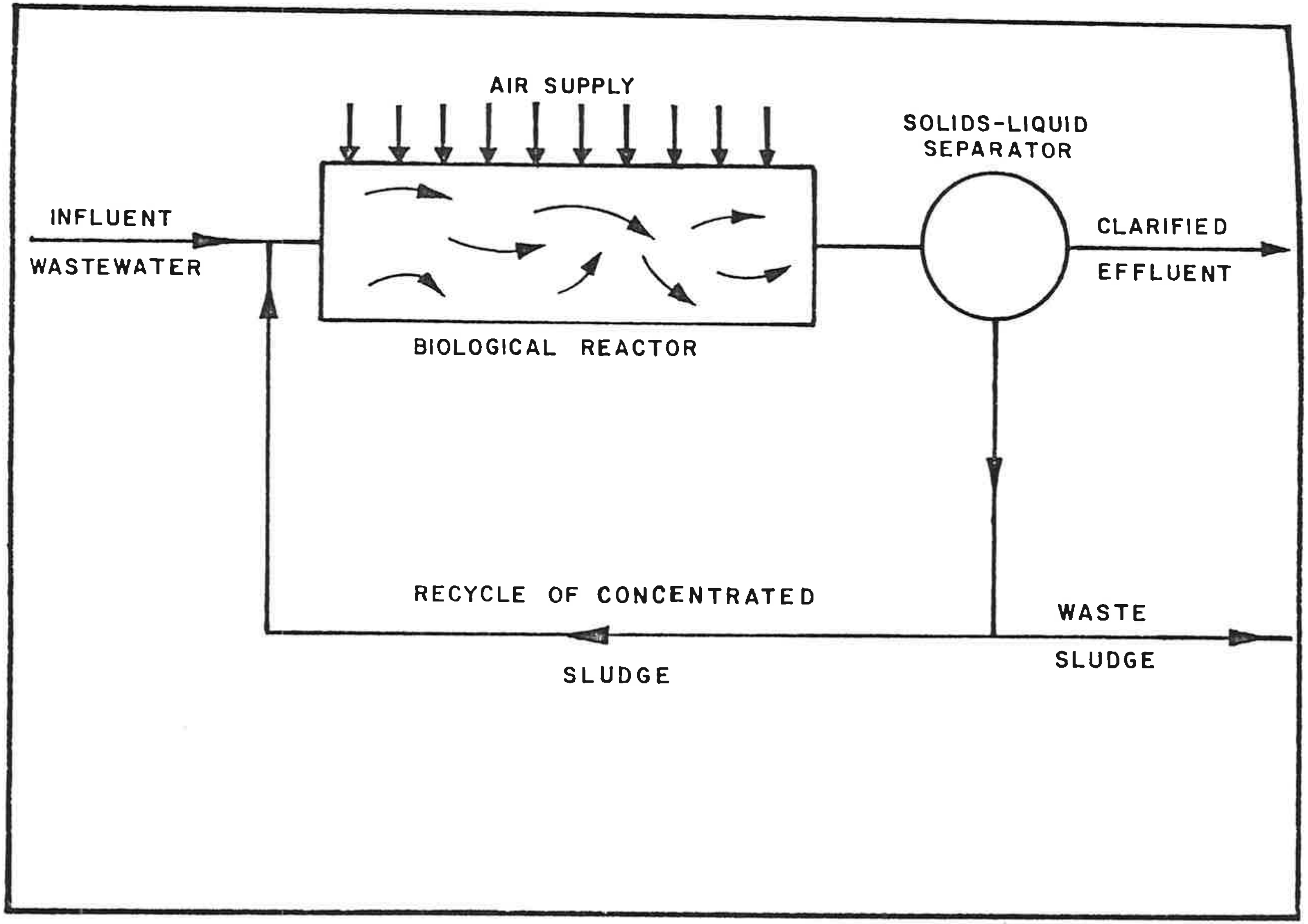

FIGURE 3.2 THE ACTIVATED SLUDGE PROCESS

production of a clarified overflow, storage of sludge, and concentration of the sludge for recycle to the biological reactor.

The recycle of concentrated sludge is an essential feature of the process since it serves to both increase the concentration of microorganisms in the reactor, thus increasing reaction rates, and maintain these organisms in a physiological condition such that they will readily flocculate and settle. However, recycle has also resulted in difficulties in understanding and modeling the process since it creates a feedback loop thereby causing a strong interaction between the biological reactor and the separator. The two units must therefore be modeled as a system, a fact which has not been widely appreciated in past years. Consideration must also be given to interactions with the air supply since this not only influences reaction rates but can also have a marked influence on settling characteristics. Moreover, it is in control of the air supply system that the greatest potential exists for reducing operating costs.

3.3.1 Dynamic Models

Andrews and co-workers have been engaged for the past fourteen years in the development of a dynamic model for the process. The most recent work includes that of Busby and Andrews (10), Stenstrom and Andrews (11), Olsson and Andrews (12), and Clifft and Andrews (13). The key features incorporated in the model are:

(1) Consideration of the effects of both suspended and soluble BOD.

(2) Structure of the sludge mass into four portions, these being (a) stored mass, (b) stored particulate substrate, (c) active mass, and (d) inert mass.

(3) Consideration of the overall removal of pollutants and growth of microorganisms as series-parallel in nature (Fig. 3.3).

(4) Inclusion of the reactions for conversion of ammonia to nitrate.

(5) Limitation of reaction rates by dissolved oxygen concentration.

(6) Modeling of the hydraulic regime of the reactor as either plug flow (with dispersion) or CFSTRs in series with provision for the feeding of wastewater to any stage.

(7) Incorporation of a dynamic model of the solids-liquid separator.

A major objection which could be raised to the use of this model has been the limited amount of experimental validation. However, the recent experimental work of Ekama and Marais (14) and Tsuno, et al (15), who used models incorporating many of the above features, has demonstrated the validity of the basic structure of the biological reactor portion of the model.

Improvements are still needed in the model. One of the most pressing needs is a reliable expression for predicting the concentration of suspended solids in the overflow from the soilds-liquid separator. Another important improvement needed is the development of a quantitative relationship between the settling characteristics of the sludge and the operation of the biological reactor.

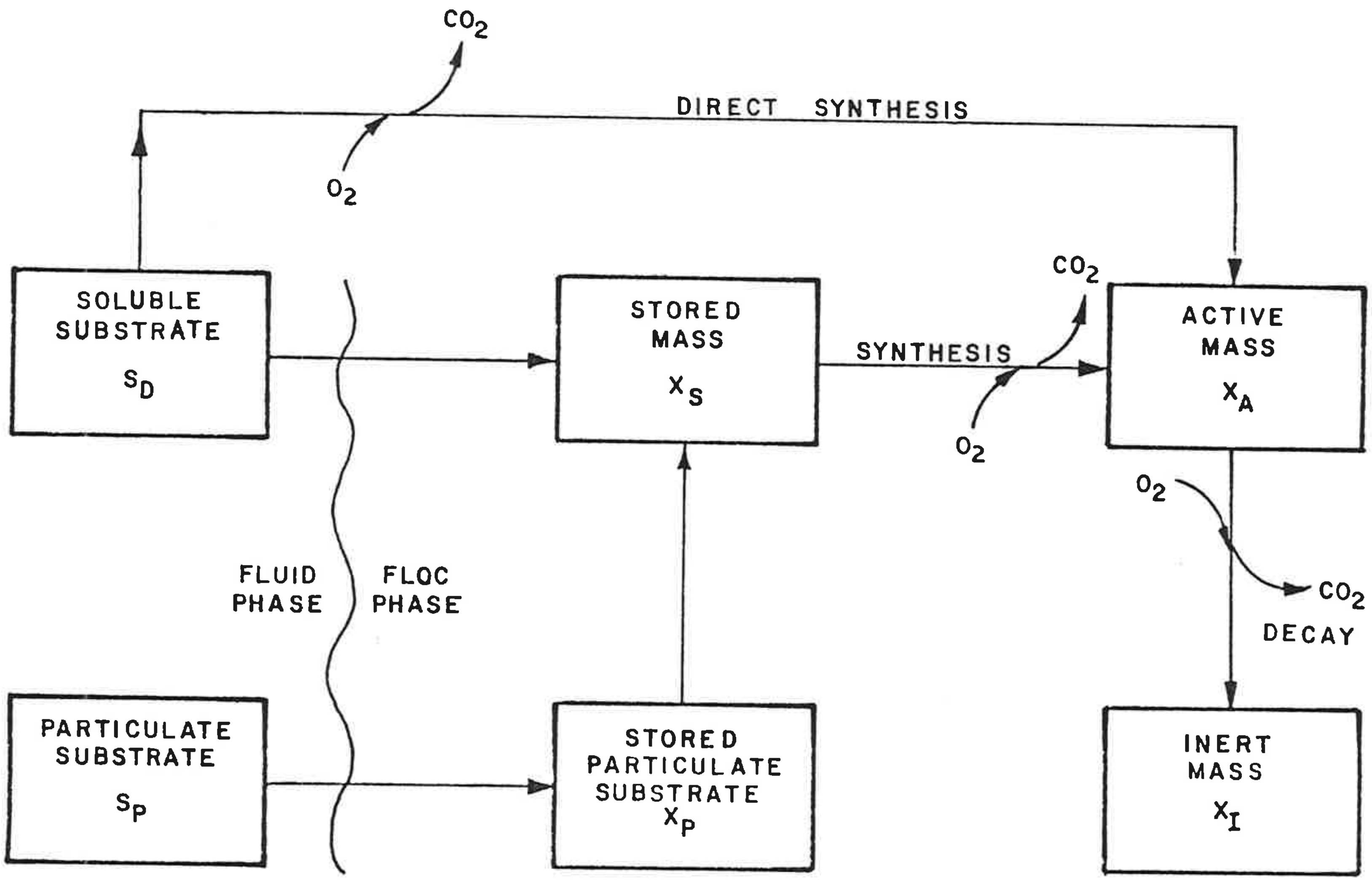

FIGURE 3.3 DYNAMIC MODEL FOR THE ACTIVATED SLUDGE PROCESS

A dynamic model for the activated sludge process which is specifically oriented toward the treatment of wastewater from the pulp and paper industry is not available. However, two dynamic models of the process for the treatment of wastewater from the chemical process industry have been developed. The first of these, developed by Poduska (16) for the Tennessee Eastman plant, is a mechanistic model which is similar to that developed by Andrews and co-workers. Using this model and computer simulation, Poduska has explored the effects of different control strategies on plant performance. The second model, developed by Hansen, et al (17) for a Union Carbide plant, is an empirical model developed by multiple linear regression using the daily data collected during normal plant operations. This model was used to relate the effluent characteristics to system variables and to define long-term operating strategies and process modifications for improving performance.

The model to be presented in Section 4 of this report is based primarily on that developed by Andrews and co-workers. However, several modificatons were necessary in order to adapt it to predicting the performance of activated sludge processes treating wastewater from the pulp and paper industry. Nitrogen and phosphorus are not available in sufficient quantities in these wastes to sustain microbial growth and instead have to be added. This means that limitation of reaction rates by nitrogen and phosphorus concentrations must be included in the model. These concentrations can also have a marked influence on the settling characterisics of the sludge (18) although this is difficult to quantify at present.

The model has also been made more flexible by providing for the separate addition of recycled sludge to any of the CFSTRs in series. A first attempt has also been made to quantify the influence of substrate, dissolved oxygen, nitrogen, and phosphorus concentrations on the settling characteristics of the sludge by further structuring of the sludge into filamentous and zoogleal microbial mass.

3.3.2 Control Strategies

When compared with industrial processes, the application of modern control theory to wastewater treatment is more recent and more difficult. Among the reasons for this are:

(1) Wastewater treatment plants are subjected to very large disturbances in the feed stream. Thus, they are seldom at steady state.

(2) The concentration of pollutants in the wastewater are relatively low and flow rates are large.

(3) The biological processes used are strongly non-linear. Moreover, they may undergo drastic changes in character such as when filamentous organisms become predominant or microorganisms are inhibited or killed by substances in the water.

(4) Only a few reliable sensors are available for on-line measurements. This is largely due to the harsh environment in which the sensors must be operated.

(5) The response times which must be considered range over several orders of magnitude. Some, like pumps and blowers, respond in seconds.

Oxygen transfer takes place in minutes. Transfer of sludge between the reactor and separator may require hours whereas sludge wasting rates may only need to be changed daily. Superimposed on these are the effects of seasonal changes in temperature.

(6) There are strong interactions between the processes in the plant as well as internally in some of the processes. Multivariable control is therefore required.

(7) Wastewater treatment lacks the incentive of a profit-making enterprise.

It can be seen from the above why progress in the application of modern control theory to wastewater treatment has been slow. Fortunately, this situation is now changing due to the increased attention to the poor performance of plants and the high operating and maintenance costs for such plants. Andrews (19) in 1974 prepared a review article on the dynamics and control of wastewater treatment processes. This was followed in 1976 by Olsson's (20) state-of-the-art paper on sewage treatment plant control. Although these publications are primarily oriented toward municipal wastewater treatment, the principles involved are also appicable to industrial wastewater treatment.

The International Association on Water Pollution Research (IAWPR) has sponsored three workshops (London and Paris, 1973; London and Stockholm, 1977; and Munich and Rome, 1981) on this topic. These workshops have been well attended by both practitioners and researchers from all of the developed countries. Increasing attention to this topic is evidenced by the fact that the proceedings of the first workshop (22) contained 70 papers, the second (23) 95 papers, and the third (24) 113 papers. A U.S. workshop (25), sponsored by the Environmental Protection Agency, was conducted in 1975 to establish research needs for the automation of wastewater tretment systems. This workshop was also well attended by practitioners.

A graphical summary of the more common variables which may be measured or manipulated in the activated sludge process is shown in Fig. 3.4. It is obvious from this figure that the process is multivariable and that a large number of control strategies are possible. Only a few of the more common strategies, classified as to the variables which can be manipulated, will be briefly discussed in this section. More detail, as well as other possible strategies, will be presented in Section 5 of this report.

(1) Air Flow Rate Control. Control of the dissolved oxygen concentration in the biological reactor by manipulation of the air flow rate is being increasingly used since this results in substantial energy savings. This strategy has been reasonably successful with a design manual (26) being published in 1977.

(2) Return Sludge Flow Rate Control. In this strategy, the ratio of the recycled sludge flow rate to the influent wastewater flow rate is maintained at a preset value using a conventional ratio controller. The objective is to influence the relative distribution of the sludge between the reactor and separator and, within limits, this control is effective in doing so.

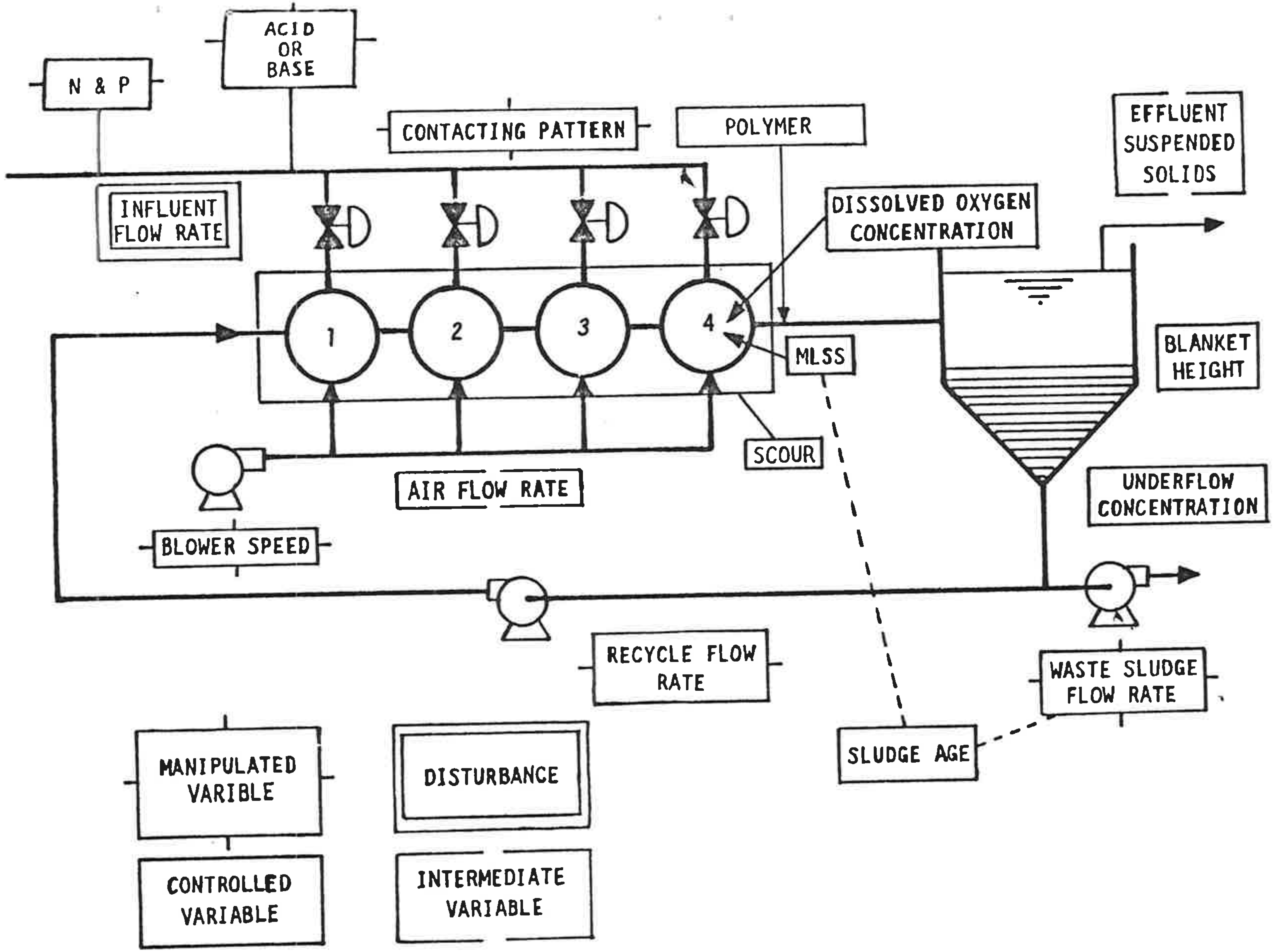

FIGURE 3.4 MEASURED AND MANIPULATED VARIBLES FOR ACTIVATED SLUDGE PROCESS

(3) Waste Sludge Flow Rate. This variable is manipulated to control the sludge age which is usually defined as the mass of sludge in the reactor divided by the mass of sludge wasted per unit of time. Sludge age has been shown to affect the effluent BOD concentration, settling characteristics of the sludge, and mass rate of sludge production. This type of control has come into common use in recent years although the term "mean cell retention time (MCRT)" is frequently used in lieu of the term sludge age.

(4) Step Feed Control. In the step feed version of the activated sludge process an additional manipulatable variable is available, this being the ability to regulate the point(s) at which the wastewater is added along the length of a plug flow reactor or to which reactor it is added for reactors in series. This permits a rapid transfer (hours) of sludge from the separator to the reactor and has been shown, both by field application (27) and computer simulation (10, 11) to be effective in preventing process failure by spillover of sludge from the separator.

The work of Brouzes (28) is an early example of the application of the computer to control of the activated sludge process. He regulated and measured the air flow rate required to maintain a constant DO concentration in the reactor. Assuming a constant oxygen transfer coefficient, he then calculated the oxygen uptake rate and related this, using stoichiometric coefficients, to the sludge production rate. He then calculated and controlled the rate of sludge wasting to maintain a constant specific growth rate (reciprocal of sludge age) of the sludge. Sørensen (29) used a somewhat similar approach in that he also regulated and measured the air flow rate required to maintain a constant DO. However, he used the air flow rate to adjust the point at which wastewater was added to the reactor. The sludge wastage rate was controlled by a signal from a sludge blanket level detector. Busby and Andrews (11) have proposed a multivariable strategy based on using the specific oxygen utiliation rate (SCOUR) as a set point. SCOUR is calculated from measurements of the gas and liquid flow rates and the concentration of solids in the return sludge. The variables manipulated to maintain a constant value of SCOUR are both recycle sludge flow rate and wastewater feed point. Waste sludge flow rate is manipulated in a slower loop to maintain a constant sludge age.

Other variables are frequenty available for manipulation in the control of industrial wastewater treatment plants. For example, wastewaters from the pulp and paper industry usually have inadequate nitrogen and phosphorous to support biological growth and these have to be added to the wastewater. The amount to be added is usually based on stoichiometric calculations such as mass of N or P to be added per unit mass of sludge produced or per unit mass of BOD removed. Quite naturally, there is a tendency to keep the addition of N and P as low as possible since this is a controllable operating cost. The application of automatic control can therefore be frequently justified on an economic basis.

One must be careful, however, in considering only stoichiometry for control of the rate of addition of N and P. Eberhardt, et al (18), working with the activated sludge process for the treatment of wastewater from the sulfite pulping process, have shown that the addition of inadequate amounts of N and P can cause severe sludge settling problems. This is most likely related to the N and P concentrations in the reactor which means that the addition rate should be controlled based on measurement of these concentrations and not on the

4. DYNAMIC MODELS FOR THE ACTIVATED SLUDGE PROCESS

The fundamental principles of biological, chemical, and physical phenomena can be used in a systematic manner for the development of dynamic mathematical models for biological processes such as the activated sludge process. The first step is to identify the major reactions involved. For the activated sludge process, the biological reactions of interest are aerobic and may be subdivided into synthesis, respiration, and organism decay. Once these reactions have been identified, the stoichiometry must be determined. Knowledge of the stoichiometry is necessary to calculate the quantity of pollutants destroyed, the oxygen, nitrogen (N), and phosphorus (P) utilized, and microorganism production. The basic kinetic relationships must then be determined to define the rates of these reactions. Limitations due to substrate, oxygen, or N and P should be accounted for in the kinetic expressions. These principles are combined with equilibrium relationships, gas laws, diffusion theory, and mass balances to form the basis for the dynamic models.

In the course of this project, a sequence of dynamc models of varying complexity were developed. These models are specifically for the activated sludge process as applied in the paper and pulp industry. They may be used to predict the performance of the process in response to dynamic disturbances, control strategies, and manual operator manipulations. The model should not be used to predict the performance of aerated lagoons or pure oxygen systems since they do not include provisions for photosynthesis, solids deposition, or gas phase interactions, all of which have been shown to be of importance in these processes.

4.1 Biological Reactions

In the activated sludge process, a mixed culture of microorganisms is brought into contact with the wastewater under aerobic conditions. Through various sorption processes (13), soluble and particulate organic material, as well as N and P, are removed from the wastewater. These nutrients and organic materials are assimilated by the microorganisms producing carbon dioxide, water, and additional cell mass. A typical net reaction is shown as Eq. 4.1.

$$\text{Organics} + O_2 \xrightarrow[\text{as catalyst}]{\text{Aerobic Microorganisms}} \text{Aerobic Microorganisms} + CO_2 + H_2O \qquad [4.1]$$

Balanced equations can be developed if an elemental analysis is performed on both the organic substrate and microorganisms produced. An example for an aerobic reaction is given in which the organic substrate is assumed to have the composition of glucose and the organisms an empirical composition of $C_5H_7NO_2$. The respiration equation (Eq. 4.1) is assumed to be the same whether the reaction is used to supply energy for synthesis (Eq. 4.3) or for maintenance.

Respiration

$$C_6H_{12}O_6 + 6\ O_2 \longrightarrow 6\ CO_2 + 6H_2O \qquad [4.2]$$

Synthesis

$$5/6\ (C_6H_{12}O_6) + NH_4^+ \longrightarrow C_5H_7NO_2 + 3H_2O + H^+ \qquad [4.3]$$

stoichiometry (mass of N or P added per unit mass of BOD removed). A first attempt to quantify the relationship between sludge settling characteristics and N and P concentrations has been made in the model presented in Section 4 by structuring the sludge into filamentous and zoogleal microbial mass with the growth of each type of mass being a function of the N and P concentrations.

Sezgin, et al (30), among others, have shown that DO concentration also has a significant influence on settling characteristics. This concentration also has a very significant influence on operating costs since the DO concentration should be kept as low as possible (highest driving force in the two-film mass transfer equation) to minimize operating cost. Therefore, in the control of DO, N, and P, the control objective should be to minimize operating cost subject to lower concentration limits as constraints to avoid setting problems.

Even when the sludge settles rapidly, the concentration of suspended solids in the process effluent may still be too high to meet permit limits. Poduska (16), working with a Tennessee Eastman plant which treats wastewater from the organic chemical industry, has solved this problem by the continuous addition of a polymer. The required dosage is determined each eight-hour shift by a batch test conducted by the plant operator. Since polymers are expensive, the dosage should be kept to a minimum and the possibility exists that this could be automated by the installation of an effluent turbidimeter to provide a signal for regulating the polymer dosage. Poduska also found that during cold weather operation, it was necessary to add two types of polymers; one to control effluent suspended solids (clarification) and another to control settling rate (thickening).

Other variables which can sometimes be manipulated in industrial wastewater treatment are pH and temperature. Microorganisms can be developed which grow at almost any reasonable pH and temperature. What they cannot stand is sudden changes in these variables and acceptable rates of change should therefore be considered in establishing control strategies. In controlling pH, it should be kept in mind that microorganisms do have the capacity, within limits, for self-regulation of their environment. For example, they can metabolize most organic acids thus increasing the pH. This should be kept in mind when controlling pH. For example, if a pH of 7 is desired in the reactor, the influent wastewater pH need not be this low because of the self-regulating capabilities of the microorganisms. Similarly, the use of surface aerators for oxygen supply can also affect substantial cooling and should be taken into account when controlling influent wastewater temperature.

Another possibility existing in industrial wastewater treatment is the use of diversion or equalization basins to prevent spills of toxic/inhibitory materials from reaching high concentrations in the biological reactor. Many of these materials, such as phenols, thiocyanates, etc., can be metabolized by the microorganisms at low concentrations but are inhibitory or toxic at higher concentrations. They can be diluted by the provision of an in-line equalizaton basin; however, the possibility of using much smaller volume basins exists if the spill of toxic material can be detected and diverted to an off-line basin from which it can be gradually fed back into the reactor at a rate which will not cause problems.

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$$5/6\ (C_6H_{12}O_6) + NH_4^+ \longrightarrow C_5H_7NO_2 + 3H_2O + H^+ \qquad [4.3]$$

An equation for organism decay (Eq. 4.4) is also necessary since the organism residence time in the activated sludge process is usually sufficiently long for this to be of significance.

Organism Decay

$$C_5H_7NO_2 + 5\ O_2 + H^+ \longrightarrow 5\ CO_2 + NH_4^+ + 2\ H_2O \qquad [4.4]$$

In applying these equations it must be remembered that they have been simplified and do not consider that portions of the organic substrate and microbial mass are not biodegradable and that some of the waste products formed can serve as an additional source of substrate. These deficiencies have been accounted for in the models by further structuring of the microbial mass and the influent substrate.

4.2 Stoichiometry

The respiration and synthesis equations are usually combined into a single net equation using an experimentally determined yield coefficient to relate the mass of microorganisms produced to the mass of substrate consumed. Mathematically, the yield may be expressed as shown in Eq. 4.5.

Yield

$$\frac{dX}{dt} = -Y\frac{dS}{dt} \qquad [4.5]$$

where:

X = concentration of microorganisms

S = concentration of substrate

Y = yield coefficient

t = time

Similar relationships can be established for the utilization of other substances, such as oxygen and nitrogen and phosphorus, or the formation of products such as carbon dioxide. Expressing yields and concentrations in terms of oxygen equivalents is especially useful since it eliminates many conversion factors. For an assumed yield of 0.5 moles X/mole S, the respiration (Eq. 4.2) and synthesis (Eq. 4.3) equations may be combined as follows:

Net Reaction

$$C_6H_{12}O_6 + 0.5\ NH_4^+ + 3.5\ O_2 \rightarrow 0.5\ C_5H_7NO_2 + 3.5\ CO_2 + 5\ H_2O + 0.5\,H^+ \qquad [4.6]$$

The yield coefficient is a function of the species of microorganism, type of substate, and environmental conditions but, as a first approximation, is usually assumed to be constant for a given biological process treating a specific wastewater.

4.3 Kinetics

Basic kinetic relationships must be determined to define the rates of these reactions. The rates of organism growth, substrate removal, oxygen utilization, etc. are usually described as functions of the various concentrations. The rate of exchange between phases (i.e., oxygen transfer) is usually described by transport theory.

4.3.1 Reaction Kinetics

Monod (31) proposed an equation extending the quantitative description of the classic growth curve to both the constant and declining growth rate regions by allowing the growth rate to be a function of both organism concentration and some limiting nutrient concentration. This growth rate is first order with respect to organism concentration and variable order (zero to first) with respect to substrate concentration. The carbon source is usually considered to be the rate limiting nutrient in the activated sludge process. However, it is well known that the growth of microorganisms can be controlled by many other substances such as oxygen, nitrogen, phosphorus, sulfur, iron, etc. Control by N and P is of special significance for the treatment of paper and pulp wastes deficient in these elements. Variations of the Monod expression (Eq. 4.7) allowing multiple limiting nutrients are used in reactor model types 1, 2, and 3 to presented later in this section.

$$\frac{dX}{dt} = \hat{\mu}\left(\frac{S_1}{K_{s1} + S_1}\right)\left(\frac{S_2}{K_{s2} + S_2}\right)\ldots\left(\frac{S_n}{K_{sn} + S_n}\right)X - d_z X \qquad [4.7]$$

where:

$\hat{\mu}$ = maximum specific growth rate

S_i = concentration of ith limiting nutrient

K_{si} = saturation coefficient of ith limiting nutrient

d_z = specific organism decay rate

The specific organism decay rate (Eq. 4.7) is usually at least an order of magnitude less than the specific growth rate but must be considered in calculating both the net amount of microorganisms produced and oxygen utilization rates. The decay rate is not a true constant since it decreases with organism age. However, the concept of a constant decay rate has been found satisfactory when applied over a limited range of organism ages.

While the Monod expression has been found useful in describing the kinetics for conventional activated sludge, it is inadequate for describing the contact stabilization version of the process. Models for contact stabilization must be able to predict the rapid sorption of both soluble and particulate substrate, the hydrolysis of particulate substrate, and the consequent synthesis of microbial mass. This requires a more structured model of microbial mass including active mass, stored soluble mass, stored particulate mass, and inert mass. These kinetics are more fully described with reactor model type 4 later in this section.

The kinetic relationships which have been presented pertain only to the production of microorganisms. Similar expressions are also needed for the consumption of substrate, oxygen, and nutrients. These rates are usually assumed to be proportional to the rates of organisms production and decay as illustrated by the yield coefficient relating organism production and substrate consumption (Eq. 4.5).

4.3.2 Transport Kinetics

Oxygen transfer is a transport phenomenon which is usually described by the two-film theory. Under ordinary conditions in the activated sludge process, the transfer rate is controlled by resistance through the liquid film and may be described as the product of a rate coefficient and a driving force:

$$\frac{dC}{dt} = K_L a \, (C_s - C) \qquad [4.8]$$

where:

C = dissolved oxygen concentration

C_s = saturation value for dissolved oxygen

$K_L a$ = mass transfer rate coefficient

The value of C_s, the saturation value for dissolved oxygen, is a function of oxygen partial pressure, temperature, salinity, and concentration of surfactants. The value of $K_L a$, the transfer rate coefficient, is a complex function of aerator type, water depth, basin shape, air flow rate, etc. However, for a given aeration system operated over a limited range, $K_L a$ can often be related to air flow rate as follows:

$$K_L a = a_1 \, F_{air} + a_2 \qquad [4.9]$$

where:

a_1, a_2 = coefficients

F_{air} = air flow rate

Values for both $K_L a$ and C_s may be obtained experimentally by analyzing data from non-steady state reaeration tests run at a full-scale facility or by online estimation as will be described in Section 5. Values obtained in clean water, however, may vary significantly from those in wastewater, and thus are a function of degree of treatment of the wastewater.

4.4 Reactor Classification

One method commonly used for reactor classification is the amount of mixing provided. The two extremes in this case are plug flow and complete mixing.

In a plug flow reactor, no attempt is made to induce longitudinal mixing. It is assumed that each fluid element moves through the reactor as a "plug." All fluid elements stay in the reactor for a length of time equal to the theoretical detention time. In a plug flow reactor, the concentrations of oxygen, substrate, organisms, etc. vary both with time and longitudinal position.

In a complete mixing reactor, the influent streams are immediately dispersed throughout the reactor volume. The concentrations of oxygen, substrate, organisms, etc. are uniform throughout the reactor (being the same as the effluent concentrations) and vary only with time.

The condition of complete mixing is not difficult to attain in practice and is a satisfactory assumption for many activated sludge plants. Plug flow, however, is much more difficult to attain since there is almost always some longitudinal mixing introduced due to inlet and outlet disturbances, aeration, and other induced currents. Many activated sludge plants, therefore, have a mixing condition intermediate between plug flow and complete mixing. It is necessary to take this into account in developing a model for the process. Several techniques are available, but one of the simplest is to equate the process to an equivalent number of complete mixing reactors in series. This provides a mixing pattern intermediate between plug flow and complete mixing. As the number of stages into which the reactor is divided is increased, the hydraulic characteristics approach that of a plug flow reactor.

The hydraulic reactor model used in the interactive simulation package developed for this project is shown as Fig. 4.1. The user is given the option of using from one to ten complete mixing reactors in series. This allows for a range of hydraulic characteristics varing from completely mixed to near plug flow. Additionally, the model includes the ability to divide the influent and recycle streams between any of the reactors. This allows the model to be used for the conventional activated sludge process as well as the contact stabilization and step feed variations.

4.5 Material Balances

A material (or mass) balance is an application of the principle of continuity. The balance may be applied to any component in a reactor such as organisms, substrate, etc., and has a general form as follows:

$$\begin{array}{c}\text{Rate of}\\ \text{Accumulation}\\ \text{of Material}\\ \text{in Reactor}\end{array} = \begin{array}{c}\text{Rate of}\\ \text{Material}\\ \text{Flow Into}\\ \text{Reactor}\end{array} - \begin{array}{c}\text{Rate of}\\ \text{Material}\\ \text{Flow Out}\\ \text{of Reactor}\end{array} \pm \begin{array}{c}\text{Rate of Appear-}\\ \text{ance or Disappear-}\\ \text{ance of Material}\\ \text{Due to Reaction}\end{array} \qquad [4.10]$$

When the concentration of material within the reactor is uniform as in a complete mixing reactor, the material balance may be made over the whole reactor. When the concentration is not uniform as for a plug flow reactor, the balance must be made over a differential element of reactor volume and then

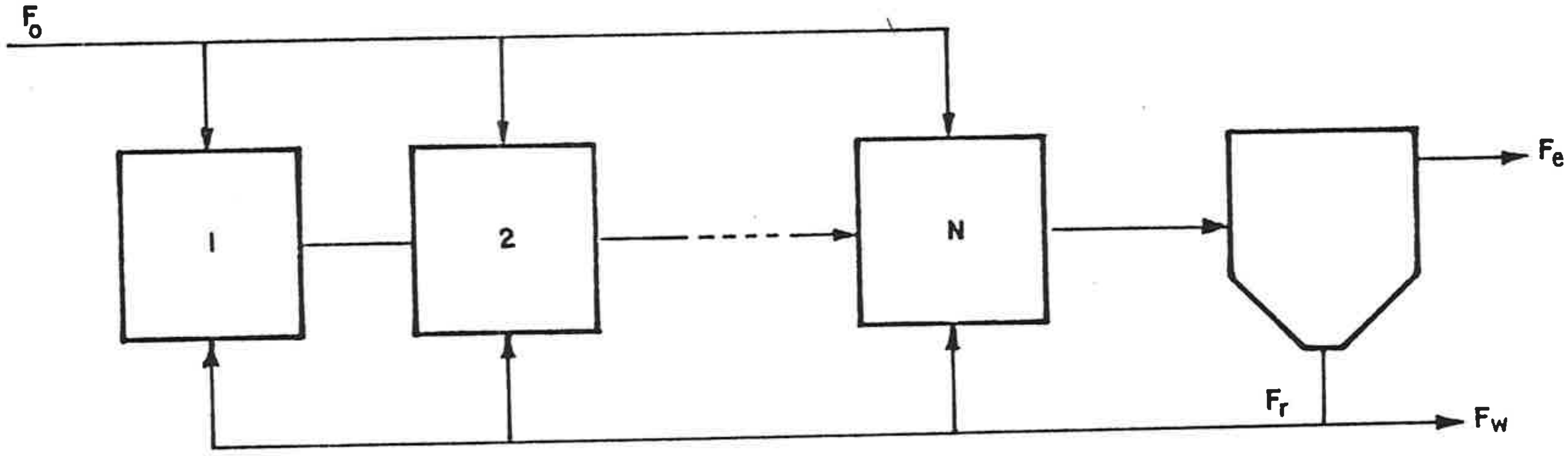

FIGURE 4.1 HYDRAULIC REACTOR MODEL

integrated. Detailed material balances for each reactor model type and the secondary settler models are given in the following sections.

4.6 Reactor Models

Four reactor models were developed for use in the interactive simulation package. The four models vary in complexity and phenomena to which they are applicable. The possible uses and limitations of each model are discussed in the following subsections.

4.6.1 Reactor Model 1

Reactor model 1 includes a simple reaction with the reactants being dissolved substrate (S_d) and dissolved oxygen (C) and products of zoogleal (floc-forming) organisms (X_z), inert mass (X_I), water, and carbon dioxide.

Material Balance on Zoogleal Organisms. The growth rate for zoogleal organisms (Eq. 4.11) is assumed to be a Monod type function with reaction rate limitations by both dissolved oxygen and substrate. The decay rate for zoogleal organisms (Eq. 4.12) is also assumed to be a Monod type function with a limitation by dissolved oxygen.

$$\mu_z = \hat{\mu}_z \left(\frac{S_d}{K_{zs} + S_d}\right) \left(\frac{C}{K_{zc} + C}\right) \qquad [4.11]$$

where:

μ_z = specific growth rate for zoogleal organisms

$\hat{\mu}_z$ = maximum specific growth rate for zoogleal organisms

Kzs = saturation coefficient of zoogleal organisms for dissolved substrate

Kzc = saturation coeficient of zoogleal organisms for dissolved oxygen

$$d_z = d_{mz} \left(\frac{C}{K_{zc} + C}\right) \qquad [4.12]$$

where:

d_z = specific decay rate for zoogleal organisms

d_{mz} = maximum specific decay rate for zoogleal organisms

Eqs. 4.11 and 4.12 may be combined with a material balance as follows:

$$\frac{d(X_z)}{dt} = \text{(Flow Terms)} + X_z(\mu_z - d_z) \qquad [4.13]$$

Material Balance on Dissolved Substrate. The rate of removal of dissolved substrate is assumed to be proportional to the growth rate for zoogleal organisms. The proportionality constant is the experimentally determined yield coefficient, Y_z. The mass balance for dissolved substrate is:

$$\frac{d(S_d)}{dt} = (\text{Flow Terms}) - \frac{X_z \mu_z}{Y_z} \quad [4.14]$$

where:

Y_z = mass X_z produced/unit mass S_d removed

Material Balance on Inert Mass. Inert (non-biodegradable) mass is assumed to be both present in the influent stream as well as being produced by the decay of zoogleal organisms. This production of inert mass is assumed to be proportional to the rate of decay of organisms. The proportionality constant, Y_I, is the fraction of the microbial mass which is non-biodegradable. A mass balance on inert mass is:

$$\frac{d(X_I)}{dt} = (\text{Flow Terms}) + Y_I X_z d_z \quad [4.15]$$

where:

Y_I = mass X_I formed/unit mass X_z destroyed

Material Balance on Dissolved Oxygen. Dissolved oxygen is transferred to the reactor by the aeration system. The rate of this transfer is governed by a mass transfer equation of the formed of Eq. 4.8 which is repeated below.

$$[r_c]_{OT} = K_L a \, (C_s - C) \quad [4.8]$$

where:

$[r_c]_{OT}$ = DO reaction term due to oxygen transfer

Oxygen is used both in the removal of substrate and decay of microorganisms. The oxygen usage due to substrate oxidation is assumed to be proportional to the rate of substrate removal. The proportionality constant, Y_{OS}, may be determined experimentally or from a net equation such as Eq. 4.6.

$$[r_c]_{SR} = - Y_{OS} \frac{X_z \mu_z}{Y_z} \quad [4.16]$$

where:

$[r_c]_{SR}$ = DO reaction term due to substrate removal

Y_{os} = mass O_2 used/unit mass S_d removed

The oxygen usage due to decay is assumed to be proportional to the decay of the biodegradable portion of the microbial mass. Again, the proportionality constant, Y_{ox}, may be determined experimentally from an organisms decay equation such as Eq. 4.4.

$$[r_c]_{OD} = - Y_{ox} (1 - Y_I) X_z d_z \qquad [4.17]$$

where:

$[r_c]_{OD}$ = DO reaction term due to organism decay

Y_{ox} = mass O_2 used/unit mass X_z destroyed

The mass balance for dissolved oxygen combines Eqs. 4.8, 4.16, and 4.17 as follows:

$$\frac{d(C)}{dt} = (\text{Flow Terms}) + K_La (C_s - C) - Y_{os} \frac{X_z \mu_z}{Y_z} - Y_{ox} (1 - Y_I) X_z d_z \qquad [4.18]$$

Uses. Although simplified, this model is capable of predicting several common phenomena observed in the activated sludge process. Due to the substrate limitation on the growth rate, the model is capable of predicting varying oxygen demands due to changes in influent flow and substrate concentration. Also, due to the oxygen limitation on the growth rate, the model is capable of predicting the effects of inadequate oxygenation on substrate removal.

Model Limitations. Model 1 is inadequate for predicting rate limitations due to nitrogen and phosphorus, the occurrence of filamentous organisms, or the rapid uptake phenomenon exhibited by contact stabilization activated sludge.

4.6.2 Reactor Model 2

Reactor Model 2 is similar to 1 with the exception that the growth rate for zoogleal organisms also includes limitation by nitrogen and phosphorus.

Material Balance on Zoogleal Organisms. The growth rate for zoogleal organisms (Eq. 4.19) is assumed to be a Monod type function with reaction rate limitations by substrate, oxygen, N, and P.

$$\mu_z = \hat{\mu}_z \left(\frac{S_d}{K_{zs} + S_d}\right) \left(\frac{C}{K_{zc} + C}\right) \left(\frac{NH_3\text{-}N}{K_{zn} + NH_3\text{-}N}\right) \left(\frac{PO_4\text{-}P}{K_{zp} + PO_4\text{-}P}\right) \qquad [4.19]$$

where:

K_{zn} = saturation coefficient of zoogleal organisms for nitrogen

K_{zp} = saturation coefficient of zoogleal organisms for phosphorus

The decay rate (Eq. 4.12) and mass balance on zoogleal organisms (Eq. 4.13) take the same form as in reactor model 1.

Material Balance on Nitrogen. Nitrogen is consumed in the synthesis of microorganisms (Eq. 4.3) and released into solution by organism decay (Eq. 4.4). The rates of consumption and release are proportional to the growth and decay rates, respectively, for the microorganisms. This proportionality constant, Y_{nx}, may be determined experimentally or from an organism decay equation such as Eq. 4.4. The mass balance for nitrogen is:

$$\frac{d(NH_3\text{-}N)}{dt} = (\text{Flow Terms}) - Y_{nx}\, X_z\, \mu_z + Y_{nx}\,(1 - Y_I)\, X_z\, d_z \qquad [4.20]$$

where:

Y_{nx} = mass NH_3-N used/unit mass X produced

Material Balance on Phosphorus. Phosphorus is also consumed in the synthesis of microorganisms. The amount of phosphorus consumed is typically about twenty percent that of nitrogen. The mass balance for phosphorus is:

$$\frac{d(PO_4\text{-}P)}{dt} = (\text{Flow Terms}) - Y_{px}\, X_z\, \mu_z + Y_{px}\,(1 - Y_I)\, X_z\, d_z \qquad [4.21]$$

where:

Y_{px} = mass PO_4-P used/unit mass X produced

Other Material Balances. Material balances on dissolved substrate (Eq. 4.14), inert mass (Eq. 4.15), and dissolved oxygen (Eq. 4.18) take the same form as in model 1.

Uses. Like model 1, this model is capable of predicting interactions between zoogleal organisms, dissolved substrate, and dissolved oxygen. Additionally, the model is capable of predicting growth rate limitations due to N and P.

Limitations. Reactor model 2 is not capable of predicting the occurrence of filamentous organisms or the rapid uptake phenomenon of contact stabilization activated sludge.

4.6.3 Reactor Model 3

Reactor model 3 builds upon model 2 with the addition of filamentous organisms (X_f). These organisms have a marked influence on the sludge settling characteristics and are included for future work on the prediction of setting velocities.

Material Balance on Filamentous Organisms. The growth rate for filamentous organisms (Eq. 4.22) is identical in form to that used for zoogleal oranisms in model 2 (Eq. 4.19). It is a Monod type equation with growth rate limitations by substrate, oxygen, nitrogen, and phosphorus. The decay rate for filamentous organisms (Eq. 4.23) is also assumed to be a Monod type function with a limitation by dissolved oxygen.

$$\mu_f = \hat{\mu}_f \left(\frac{S_d}{K_{fs} + S_d}\right) \left(\frac{C}{K_{fc} + C}\right) \left(\frac{NH_3\text{-}N}{K_{fn} + NH_3\text{-}N}\right) \left(\frac{PO_4\text{-}P}{K_{fp} + PO_4\text{-}P}\right) \qquad [4.22]$$

where:

μ_f = specific growth rate for filamentous organisms

$\hat{\mu}_f$ = maximum specific growth rate for filamentous organisms

K_{fs} = saturation coefficient of filamentous organisms for dissolved substrate

K_{fc} = saturation coefficient of filamentous organisms for dissolved oxygen

K_{fn} = saturation coefficient of filamentous organisms for nitrogen

K_{fp} = saturation coefficient of filamentous organisms for phosphorus

$$d_f = d_{mf} \left(\frac{C}{K_{fc} + C}\right) \qquad [4.23]$$

where:

d_f = specific decay rate for filamentous organisms

d_{mf} = maximum specific decay rate for filamentous organisms

Eqs. 4.22 and 4.23 are used with a material balance on filamentous organisms as follows:

$$\frac{d(X_f)}{dt} = (\text{Flow Terms}) + X_f\,(\mu_f - d_f) \qquad [4.24]$$

Other Material Balances. The material balance for zoogleal organisms (Eq. 4.13) is identical to that used in models 1 and 2. The material balances for both zoogleal and filamentous organisms. This may be used to demonstrate under what conditions the growth of filamentous organisms would be favored.

Limitations. Model 3 is not capable of predicting the rapid uptake phenomenon of contact stabilization activated sludge.

4.6.4 Reactor Model 4

Reactor model 4 is subsantially different from models 1, 2, and 3 in that both the substrate and microbial mass are structured. This is necessary to predict the rapid initial uptake phenomenon of contact stabilizaton activated sludge. The model includes dissolved substrate (S_d), particulate substrate (S_p), active mass (X_a), inert mass (X_I), stored mass (X_s), and stored particulate mass (X_p). A general representation of the model has been presented in Fig. 3.3. Another difference in model type 4 is that all substrate and mass concentrations are expressed in oxygen equivalents rather than on a mass basis. This simplifies the material balance equations by eliminating conversion factors. A more detailed derivation of the model is given by Clifft (32).

Removal of Particulate Substrate. Particulate substrate is assumed to be transferred rapidly to the floc phase by physical mechanisms at a rate much faster than the removal of dissolved substrate. In this model, the removal of particulate substrate from the liquid is assumed to occur immediately upon contact with the floc. Thus a rate expression for this transport process is not needed. When the particulate substrate becomes part of the floc, it is considered to be stored particulate mass.

Material Balance on Dissolved Substrate. Dissolved substrate is consumed in the formation of stored mass and by direct utilization by the active mass. The formation of stored mass is assumed to be a transport phenomena which can be described as a transport rate coefficient times a driving force. The direct utilization is assumed to be first-order with respect to both active mass and dissolved substrate. A mass balance on dissolved substrate is:

$$\frac{d(S_d)}{dt} = (\text{Flow Terms}) - K_T X_a S_d (\hat{fs} - fs) - R_{SD} X_a S_d \qquad [4.30]$$

where:

K_T = transport rate coefficient

$\hat{fs}$ = maximum fraction of stored mass

fs = fraction of stored mass, $X_s/(X_s + X_a)$

R_{SD} = direct growth rate coefficient

Material Balance on Stored Particulate Mass. The stored particulate mass is hydrolyzed and converted to soluble materials. For this model, it is assumed that these soluble products are then converted to stored mass. A Monod-type equation is used to describe this hydrolysis. A mass balance on stored particulate mass is:

$$\frac{d(X_p)}{dt} = \text{(Flow Terms)} - R_H \left(\frac{fp}{K_{sp} + fp}\right) X_a \qquad [4.31]$$

where:

R_H = hydrolysis rate coefficient

K_{sp} = saturation coefficient

fp = fraction of stored particulate mass, $X_p/(X_p + X_a)$

Material Balance on Active Mass. The rate of production of active mass from stored mass is assumed to be first-order with respect to the fraction of stored mass. The rate of production of active mass by direct metabolism is proportional to the third term in Eq. 4.30. Since a portion of the substrate oxygen equivalents are utilized during respiration, only a fraction (Y1) of the dissolved substrate is converted to active mass. Additionally, the rate of decay of active mass is first-order with respect to active mass. The material balance on acive mass is:

$$\frac{d(X_a)}{dt} = \text{(Flow Terms)} + R_{XA}\, X_a\, fs + Y_1\, R_{SD}\, X_a\, S_d - K_d\, X_a \qquad [4.32]$$

where:

R_{XA} = storage growth rate coefficient

Y_1 = mass X_a produced/unit mass X_s or S_d utilized

K_d = decay rate coefficient

Material Balance on Stored Mass. Stored mass is assumed to be derived from dissolved substrate and the hydrolysis of stored particulate mass and consumed by the formation of active mass. The formation of stored mass is described by terms in Eqs. 4.30 and 4.31. Additionally, the consumption of stored mass to active mass is described by the second term in Equation 4.32. A complete material balance on stored mass is:

$$\frac{d(X_s)}{dt} = \text{(Flow Terms)} + K_T\, X_a\, S_d\, (\hat{fs} - fs) + R_H\, X_a \left(\frac{fp}{K_{sp} + fp}\right) - \frac{R_{XA}\, X_a\, fs}{Y_1} \qquad [4.33]$$

Material Balance on Inert Mass. The rate of formation of inert mass is proportional to the decay of active mass. A material balance on inert mass is:

$$\frac{d(X_I)}{dt} = (\text{Flow Terms}) + Y_2 K_d X_a \qquad [4.34]$$

Material Balance on Dissolved Oxygen. Oxygen is consumed in the synthesis and decay of active mass. Since the biological reactions are described in terms of oxygen equivalents, the formation of the material balance on dissolved oxygen (Eq. 4.35) is particularly simple.

$$\frac{d(C)}{dt} = (\text{Flow Terms}) + K_L a\ (C_s - C) - (1 - Y_2)\ K_d\ X_a$$

$$- (1 - Y_1)\ X_a\ (R_{XA}\ fs/Y_1 + R_{SD}\ S_d) \qquad [4.35]$$

Uses. This model is capable of predicting the rapid uptake of substrate that is observed in the contact stabilizaton version of the activated sludge process. It is also capable of predicting a lag period between substrate removal and oxygen consumption.

Limitations. Model 4 is not capable of predicting limitations due to oxygen, nitrogen, or phosphorus. Additionally, it is not capable of predicting the occurrence of filamentous organisms.

4.7 Solids-Liquid Separator Models

The solids-liquid separator or settler serves several important functions including clarification, thickening, and solids storage. The clarification function is obviously very important since the effluent quality is directly related to the separation of biological solids from the effluent stream. The thickening capacity of the settler must be sufficient to concentrate the incoming biomass and maintain a sufficient solids concentration in the aeration basins. The volume of the settler must also be sufficient to store solids and prevent them from spilling over the effluent weirs during times of high loading. Additionally, the settler dampens soluble components in the effluent stream.

4.7.1 Settler Model 1

Settler model 1 is a relatively simple representation of solids-liquid separation which corresponds to the case of oversized settlers with excess capacity.

Dissolved Components. The settler is assumed to act like a complete mixing reactor with respect to all dissolved components (S_d, NH_3-N, PO_4-P) except dissolved oxygen. All biological reactions are assumed to stop, and mass is conserved over the settler. The effluent and recycle concentrations are assumed to be equal. A mass balance on each dissolved component has the following form:

$$\frac{d(S_r)}{dt} = \frac{d(S_e)}{dt} = \frac{F_0(1 + r)}{V} (S_{in} - S_e) \qquad [4.36]$$

where:

S_r = recycle concentration

S_e = effluent concentration

F_0 = influent flow rate

V = volume of settler

S_{in} = concentration entering settler

r = recycle ratio

Dissolved Oxygen. The dissolved oxygen concentrations in the recycle and effluent streams are assumed to have constant values, usually zero.

Effluent Solids Concentrations. The effluent solids concentration for each type of microbial mass is assumed to have a constant value, usually non-zero.

Recycle Solids Concentrations. Solids are assumed to be instantly thickened to the recycle concentration in the settler with no time delay. Accumulation of solids in the settler is assumed to be zero. It is assumed that no reactions take place and that mass is conserved over the settler. A mass balance on each solid component has the following form:

$$X_r = \frac{F_0 (1 + r) X_{in} - (F_0 - F_w) X_e}{F_r + F_w} \qquad [4.37]$$

where:

x_r = recycle solids concentration

X_{in} = solids concentration entering settler

X_e = effluent solids concentration

F_r = recycle flow rate, F_0 r

F_w = wastage flow rate

Uses. Settler model 1 is often adequate to describe the interactions between the reactors and the settler for cases where settler overloading is not a serious problem. It has the computational advantage of having only a few differential equations which results in fast run times on the computer.

Limitations. Due to the simple nature of the equations, this model is not capable of predicting storage of solids in the settler or changes in the effluent solids concentrations.

4.7.2 Settler Model 2

Settler model 2 is a more complete representation of the solids-liquid separator which may be used for both oversized and undersized settlers.

Dissolved Components. All dissolved components except dissolved oxygen are assumed to be damped as in settler model 1. Dissolved oxygen concentrations are assumed constant (usually zero), as in settler model 1.

Effluent Suspended Solids. Effluent solids are assumed to be predicted by the Pflanz (33) relationship. The effluent concentration of each suspended component is assumed to be proportional to the product of the flow and MLSS concentration.

$$X_e = K_p \frac{F_0 (1 + r)}{A} X_{in} \qquad [4.38]$$

where:

K_p = Pflanz's proportionality coefficient

A = surface area of settler

Recycle Suspended Solids. The solids thickening model used in this model is a variation of that developed by Stenstrom (34). This model uses the following assumptions.

(1) The solids concentration in any horizontal plane in the settler is uniform.

(2) Mass is conserved over the settler.

(3) The settler may be modeled as a plug flow reactor (dispersion is zero).

(4) The bottom of the settler represents a physical boundary to sedimentation. Therefore, the settling flux at the bottom of the settler is zero.

(5) The settling velocity is a function only of solids concentration except when the next assumption (flux constraint) is violated.

(6) The settling flux into a differential volume can never exceed the flux which the volume is capable of passing nor can it exceed the flux which the next higher differential volume is capable of transmitting.

The continuity equation (Eq. 4.39) describing the transport of solids through the settler is derived from a mass balance of solids on a differential element in the settler.

$$\frac{\&X}{\&t} = - U\frac{\&X}{\&Z} - \frac{\&(Vs\ X)}{\&Z} \qquad [4.39]$$

where:

U = bulk downward velocity

Z = vertical dimension

Vs = settling velocity

For implementation, it is convenient to rewrite Eq. 4.39 in terms of finite element dimensions. In this implementation, the settler was assumed to have ten elements.

$$\frac{\&X_i}{\&t} = \frac{U\ (X_{i-1} - X_i) + (Vs_{i-1}\ X_{i-1} - Vs_i\ X_i)}{\&Z} \qquad [4.40]$$

where:

X_i = solids concentration in the "ith" element

Vs_i = settling velocity in the "ith" element

The quantity $Vs_i{*}X_i$ represents the flux settling into the "ith" element. The flux constraint requires that this quantity be equal to or less than the flux that can be accepted or passed by the "ith" element. This constraint can be compactly implemented as:

$$\frac{\&X_i}{\&t} = \frac{U\ (X_{i-1} - X_i)}{\&Z} + \frac{MIN(Gs_i, Gs_{i-1}) - MIN(Gs_i, Gs_{i+1})}{\&Z} \qquad [4.41]$$

where:

Gs_i = settling flux in the "ith" element, $Vs_i{*}X_i$

MIN = minimum function

5. CONTROL STRATEGIES FOR THE ACTIVATED SLUDGE PROCESS

Three major types of control strategies will be analyzed and presented, these being the control of DO concentration, sludge inventory, and sludge distribution. These strategies all demand specific knowledge about the process characteristics, both from a physical-chemical and biological point of view. Other control strategies, such as pH, N and P addition, etc., are not discussed in detail herein since they are more direct applications of chemical process control and are well described in the traditional control engineering literature.

Some general difficulties encountered in control of the activated sludge process were discussed in Section 2. In Section 5.1, the disturbances to the process which make control necessary are described. The variables which can be manipulated are discussed in 5.2 while Section 5.3 describes in detail several different control laws for the process. Due to the complexity of the process, simple feedback control loops are not always adequate. Instead, be it manual or automatic, a hierarchical concept of control has to be implemented. This is illustrated in 5.4 where control by operational states is described. Since not all important variables are directly measurable, estimation is a crucial portion of most advanced control techniques. This is briefly presented in 5.5.

5.1 Disturbances

The large variations which can occur in wastewater composition, concentration, and flow rate create significant disturbances to the treatment plant. This fact often makes the application of conventional control laws difficult, since the large amplitudes of the disturbances cause the process to exhibit significant non-linear behavior. Moreover, the basic structure of the control strategy needed to overcome the effects of the disturbances may be changed by the nature of the disturbance; e.g., the variable which should be manipulated may depend on the nature of the disturbance. This is further illustrated in Section 5.4. Also, disturbances may not be caused only by the influent wastewater. For example, there can be hydraulic disturbances due to pumps or interactions between the different processes in the plant.

5.1.1 Hydraulic Disturbances

Generally, hydraulic disturbances due to changes in the influent wastewater flow rate are not severe for treatment plants used in the pulp and paper industry. This is fortunate since the performance of the solids-liquids separator is sensitive to such disturbances.

Significant operational problems can be caused by hydraulic disturbances initiated within the plant. If pumps are used to lift the wastewater to the primary sedimentation basins, it is important to avoid large, abrupt changes in flow rate to prevent disturbance of the settler. No known control can damp such a disturbance. Also, disturbances affecting the performance of the secondary sedimentation basin can be caused by the return sludge pumps.

5.1.2 Concentration Disturbances

Concentration disturbances, such as changes in the influent BOD or COD appear

(3) Sludge Distribution Control.

DO, pH, N, and P control are examples of concentration controls. Once a setpoint has been established, the structure of the control law is relatively straightforward. Sludge inventory control is for the purpose of maintaining a given mass of sludge in the system and uses a specified sludge age (or MCRT) as the setpoint. The manipulated variable is the sludge wastage rate. Sludge distribution control is concerned with the relative distribution of sludge between the reactor and separator. For reactors in series, the relative distribution of sludge between the subreactors is also of concern. There are strong interactions between the reactor(s) and separator which have to be considered for sludge inventory and sludge distribution control. The corresponding control laws are therefore more complex than those for concentration control.

5.3.1 DO Control

The DO concentration is an important variable in that it has a strong influence on both the cost of operation and the biological activity in the reactor. From a physical point of view, the control of DO concentration can be accomplished relatively easily with only superficial knowledge of the process dynamics. The relatively poorly understood influence of DO concentration on biological activity, however, makes this control law much more of a challenge.

Control of the DO concentration by the air flow rate is considered an established technique with a design manual (26) being published in 1977. These techniques are, however, mostly oriented toward the control of complete mixing reactors (CFSTRs). For many plants, the degree of mixing lies somewhere between complete mixing and plug flow and a DO concentration profile is therefore exhibited along the length of the reactor. The question thus arises as to where the DO concentration should be measured for exerting control. Olsson and Andrews (12, 37, 38) have shown, that instead of measuring the DO concentration at only a single point, it is preferred to make sufficient measurements (at least three) along the length of the reactor so that the DO profile can be described. The profile contains significant information about process status (completion of reactions, reaction rates, etc.) which is useful for the implementation of more advanced control strategies. This will be further discussed in Section 5.5.

It is not a trivial matter--even in a CFSTR--to determine the "optimal" DO setpoint for the reactor. For example, the limiting concentration for growth is different for different species of microorganisms. It is lower for filamentous organisms than for floc-forming organisms and may thus influence sludge bulking. The limiting DO concentration also depends upon the sludge age. As sludge age increases, lower DO concentrations can be accepted.

There is also a complex relationship beween mixing and DO concentration. The intensity of mixing does influence the DO concentration; however, it also influences floc formation and the size of floc produced. Mixing therefore influences not only oxygen transfer but also settling characteristics of the sludge. Still another factor contributing to the complexity of the problem is that the concentration of suspended solids in the process effluent is usually quite low when bulking sludge is present. This indiates the need for optimization between sludge clarification and sludge thickening properties.

The DO concentration is affected by a large number of variables such as the hydraulic flow rate, mass transfer coefficients, oxygen utilization by the sludge (growth or decay), sludge distribution patterns, toxic materials, etc.

The time scale of interest for DO control is measured in minutes up to a few hours. In this time scale, shifts in microbial population or overall growth rates can usually be neglected. However, longer term effects can also be significant. Different DO concentrations or different sludge ages can favor the growth of different types of microorganisms (filamentous or zoogleal) which can lead to different settling characteristics or different types of reactions. The long term effects must therefore also be considered in testing different DO control strategies.

Several different types of reliable DO probes are available as documented in the report prepared by Dr. Briggs. Thus, feedback control of DO concentration is realistic even for smaller plants provided a reasonable amount of maintenance of the sensor is provided. However, it must be possible to vary the air supply within reasonable limits if any appreciable energy savings are to be obtained.

Most of the commercially-available DO control systems are based on analog PI regulators. These will usually give satisfactory results, however, several conditions have to be satisfied. The problems of finding suitable locations and set points have already been mentioned. The amplitude of the noise and the quality of the measurement has to be such that complicated filtering of the measurement data is not critical for good control.

In general, analog PI control systems cannot easily handle time delays. These can result in either very slow responses or oscillatory behavior, both of which give poor control. In most plants, dead time compensation is therefore essential for good control. A digital controller is ideal for handling dead time since it can store historical data for both the measurements and control signals which are needed to compensate for time delays. Consequently, digital PID controllers with dead time conpensaton are very good for DO control.

The air supply system frequently does not permit large variations in the air flow rate. Consequently, both the absolute value and the time derivative of the control signal are limited. Such limitations can easily cause wind up of the controller resulting in large overshoots of the DO concentration. An anti-reset windup feature should therefore be incorporated in the controller.

A digital PID controller with anti-reset windup has been incorporated in the interactive simulation package. If found necessary, the response time of the control system might be further improved by the use of a feedforward signal from such devices as TOC analyzers or on-line respirometers.

5.3.2 Sludge Inventory Control

The steady state value of the total sludge inventory can be controlled only by the waste sludge flow rate. Since this flow rate is very small, control is therefore slow. It may be a matter of weeks before a new value of the sludge inventory can be established. As previously mentioned, the waste sludge flow rate affects the sludge age (MCRT) which is usually defined as the mass of sludge in the reactor divided by the mass of sludge wasted (both from the waste sludge line and in the overflow from the separator).

The response time of the sludge inventory to a change in waste sludge flow rate can be calculated. The analysis shows that the time constant of the system is approximately equal to the sludge age. As emphasized in Section 5.2, it takes a time equal to about three sludge ages to come from one steady state value to another steady state value of the sludge age.

Contrary to common belief, the waste sludge control system is a dynamic system. Calculation of the sludge age from a single set of measurements does not represent a true steady state. Instead, a suitable sampling rate for the measurements has to be established in order to determine the current sludge inventory and to calculate the desired sludge wasting rate. A rule of thumb may be a sampling rate of about 1/5 of the time constant, e.g. a one-day sampling time for a sludge age of five days.

In order to control the sludge inventory, the following steps should be taken:

(1) Calculate the current sludge inventory.

(2) Convert the desired sludge age to a desired value of the sludge inventory.

(3) Calculate the waste sludge flow rate that will achieve the desired value of the sludge inventory as quickly as possible. This is the feedforward portion of the control law.

(4) Use the value of the current sludge age as feedback to the waste sludge flow rate. This represents feedback tuning of the control.

Several measurements are necessary in order to calculate the current sludge inventory. For a complete mixing reactor, the mass of sludge in the reactor can be calculated from a measurement of the mixed liquor suspended solids (MLSS) and a knowledge of the reactor volume. The sludge content of the separator is normally not included in the calculations although errors may result from not doing this if there is appreciable variation in the mass of sludge in the separator from one sampling interval to another.

The mass of sludge wasted from the waste sludge flow line is relatively easy to calculate if the underflow concentration is known or the sludge is wasted directly from the reactor. The mass of sludge wasted in the effluent from the separator requires measurement of the effluent suspended solids and flow rate. These measurement should reflect averages over the sampling interval which is usually one day. With the above measurements completed, the sludge age can easily be calculated. Assume that the current sludge age is θ_x and that the desired sludge age is θ_{xd}. The signal for the feedforward waste sludge control is given in Eq. 5.1 where the "bar" denotes average values over the sampling interval.

$$(F_W)_{FF} = \frac{(\bar{X}_T/\theta_{xd}) - \overline{(F)\,(x_e)}}{\bar{x}_r - \bar{x}_e} \qquad [5.1]$$

where:

F_W = waste sludge flow rate

X_T = sludge mass in the reactor

F = influent flow rate

x_e = effluent suspended solids concentration

x_r = return sludge concentration

If this feedforward structure is applied, it will result in a sludge age equal to the desired value. Note, however, that this is steady state relationship and does not give the time required to reach the desired sludge age. As previously discussed, this can be quite long.

The control law given in Eq. 5.1 is the traditional equation used for sludge age control. However, since the sudge age is dynamic and not steady state, the measurements should be made typically once each day, the sludge age calculated, and the waste sludge flow rate adjusted. Moreover, since the current sludge age as well as the desired sludge age are both known, advantage should be taken of this information for feedback tuning of the waste sludge flow rate, typically with a PID controller.

The sludge inventory control strategy recommended herein is illustrated in Fig. 5.1. The equation included in the box labeled "feedforward" is Eq. 5.1. If there were no constraints on the waste sludge flow rate, then the feedforward portion of the control would, at least momentarily, attain the desired sludge age. However, there are always constraints (maximum and/or minimum flow rates or the ability to process the waste sludge) and because of these, the feedforward equation makes the best of the situation and attains the desired sludge age as rapidly as possible. The feedback loop uses the calculated value of the current sludge age to fine tune the waste sludge flow rate.

To the authors' knowledge, the feedback loop shown in Fig. 5.1 has not been implemented at full scale despite its relative simplicity.

5.3.3 Sludge Distribution Control by Return Sludge Flow Rate

The distribution of sludge between the reactor and the separator can be influenced on an hour-to-hour basis by control of the return sludge flow rate. Several different techniques are used for control of the return sludge flow rate. In some plants, this flow rate is maintained at a constant value while in others the ratio of the return sludge flow rate to the influent wastewater flow rate is maintained at a preset value using a conventional ratio controller. Sometimes the objective of return sludge flow rate control is to keep the MLSS concentration constant while in other cases it is used simply to keep the sludge blanket level in the separator within prescribed limits.

There is considerable controversy on the use of return sludge flow control. The major reasons for this sometimes very confusing issue have to do with two items:

(1) The constraints on the amount of control which can be exerted.

(2) The feedback between the separator and the reactor.

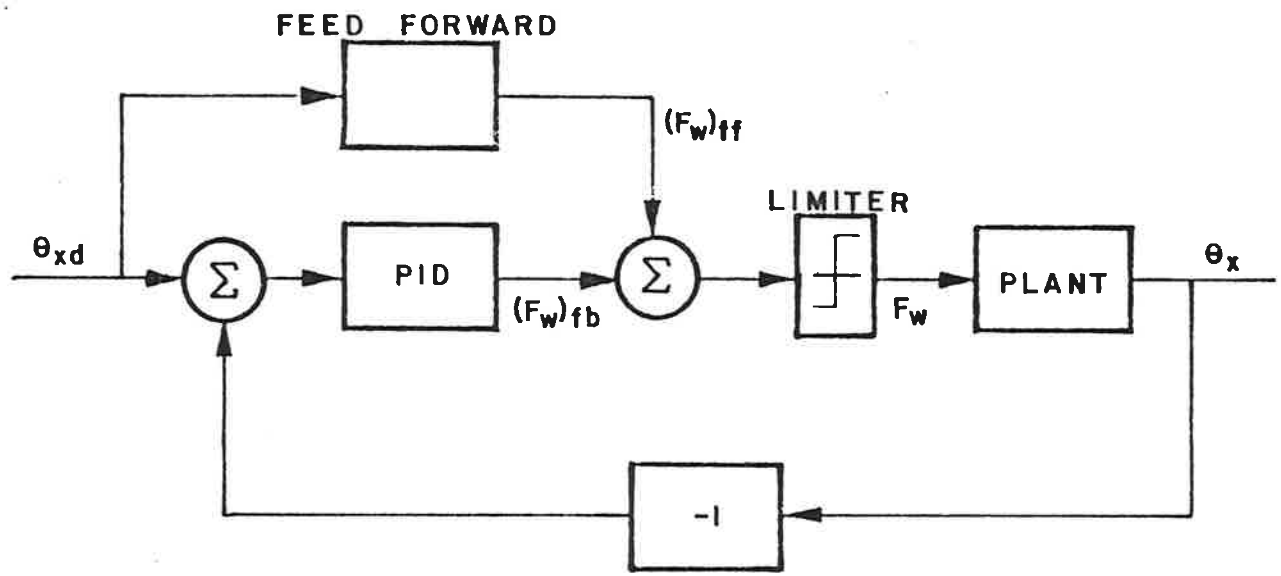

FIGURE 5.1 STRUCTURE OF THE FEEDFORWARD-FEEDBACK WASTE SLUDGE FLOW CONTROL SYSTEM

Constraints

The constraints on the control authority of the return sludge flow rate are basically due to the operation of the separator. A high rate of recycle can infuence both the clarification and thickening functions of the separator. Within limits, an increase in the recycle flow rate can increase the MLSS in the reactor which in turn will result in a reduction in dissolved BOD. However, if the efficiency of the separator in removing suspended solids decreases at the same time, then the decrease in dissolved effluent BOD may be more than offset by an increase in suspended effluent BOD.

The concentration of sludge in the underflow from the separator is also influenced by the recycle flow rate. This can be easily checked using simple logic in a computer control system. If the mass flow rate of solids in the underflow decreases for an increasing recycle flow rate, then excess water is being withdrawn with the solids which results in dilution. In other words:

$$\frac{(F_r x_r)}{F_r} > 1 \qquad [5.2]$$

where:

F_r = return sludge flow rate

x_r = return sludge concentration

The capacity of the separator to store solids also has to be considered which means that the sludge blanket level has to be kept within certain limits. Here there is a wide variation in practice. In some plants the sludge blanket level may remain near its maximum height, which can be a dangerous situation in the event of sudden decreases in sludge settling rates (sludge bulking) or sudden increases in flow rate to the separator. On the other hand, some feel that a certain minimum height of blanket is advantageous in reducing suspended solids in the overflow through the "filtering action" of the blanket. In other plants, the quantity of sludge stored in the separator is kept to a minimum in order to avoid problems due to sludge bulking or sudden increases in flow rate. These limitations on the sludge storage capacity of the separator create another set of constraints for the return sludge flow rate.

Another reason for placing a lower limit on the recycle flow rate (and thus a maximum on the mass of sludge stored in the separator) is to avoid oxygen depletion by biological reactions in the separator. Another obvious limitation on flow rate is pump capacity.

The different constraints on the return sludge flow rate may conflict in which case there will be no maneuverability left for control. Even when the constraints permit some control, the amount which can be exerted may be quite small. These are major reasons why recycle flow rate control is often misunderstood and misused.

Set Point

The objective of recycle control (within the limits of constraints) must be carefully selected. It may be to maintain either a desired F/M ratio or a desired oxygen uptake rate. In either case these may be translated into a desired MLSS concentration. Given the desired F/M ratio, $(F/M)_d$, the corresponding set point for the MLSS concentration is:

$$x_d = \frac{\overline{Fs_0}}{V(F/M)_d} \qquad [5.3]$$

where:

F = influent flow rate

s_0 = influent BOD concentration

V = reactor volume

x_d = desired MLSS concentration

The dynamics of this equation are important since the return sludge flow rate can affect the MLSS concentration on an hour-to-hour time scale. The sampling rate for the measurements should therefore also be on the order of one hour and should represent hourly averages. This is the reason for the "bar" sign over Fs_0.

When the objective is to maintain a desired oxygen uptake rate (OUR), x_d is calculated as shown in Eq. 5.4.

$$x_d = \frac{\overline{OUR}}{V\ (SCOUR)_d} \qquad [5.4]$$

where:

$\overline{OUR}$ = average value of OUR over the sampling interval

$(SCOUR)_d$ = desired value of the specific oxygen utilization rate (OUR/MLSS concentration)

The procedure for estimating the value of OUR is discussed in Section 5.5.

Control Law Structure

Just as for the sludge inventory control strategy, the control system for the return sludge flow rate strategy also consists of two portions, these being a feedforward signal, $(F_r)_{FF}$, and a feedback signal, $(F_r)_{FB}$. The sum of these two signals, Fig. 5.2, has to satisfy the combinations of all of the constraints.

A mass balance on sludge can be established for the actual as well as for the desired sludge concentration. From these balances one can derive an equation that will give the return sludge flow rate that will cause the actual MLSS to attain the desired value. For a single complete mixing reactor, this flow rate is given by:

$$(F_r)_{FF} = \frac{(\theta_H)\,\frac{dx_d}{dt} + x_d - (\theta_H)\,\frac{x_d}{M}}{x_r - x_d} \qquad [5.5]$$

where:

θ_H = hydraulic detention time

x_d = desired sludge concentration in the reactor

x_r = return sludge concentraton

M = value related to the sludge age (the reciprocal of the sludge growth rate minus the sludge decay rate)

Note that the actual measurement of MLSS is not included in the equation so that the control is feedforward in nature. Again, the time scale must be considered. This means that the derivative, dx_d/dt, is approximated by the difference over one sampling interval, e.g., one hour.

Control strategies found in the literature can be derived as special cases of Eq. 5.5. If the first and last terms in the numerator are considered to be negligible, the resulting equation (5.6) is the same as that suggested by

$$(F_r)_{FF} = \frac{1}{(x_r/x_d) - 1} \qquad [5.6]$$

Petersack and Smith (35) and Tanuma (39). One problem with the use of Eq. 5.6 for control, however, is that it does not give results consistent with the calculated value of the waste sludge flow rate. Consequently, the sludge inventory control strategy and the sludge distribution control strategy do not match in the steady state.

The first term in the numerator of Eq. 5.5 represents only a small percentage of the recycle flow and corresponds to the sludge that is wasted through the separator overflow and by the waste sludge pump. Ching (40) uses sludge age instead of M in this last term. This can create confusion since a variable (sludge age) calculated from a steady state equation is inserted in a control system that acts on an hour-to-hour basis. A preferred form of Eq. 5.5 would be:

$$(F_r)_{FF} = \frac{(\theta_H)\frac{dx_d}{dt} + x_d - (\theta_H)SCOUR_d}{x_r - x_d} \qquad [5.7]$$

In order to implement feedback trim, the current value of the MLSS concentration in the reactor must be measured. The feedforward structure represented by Eq. 5.5 or 5.7 is then complemented by a PID controller in the feeback loop as given in Fig. 5.2.

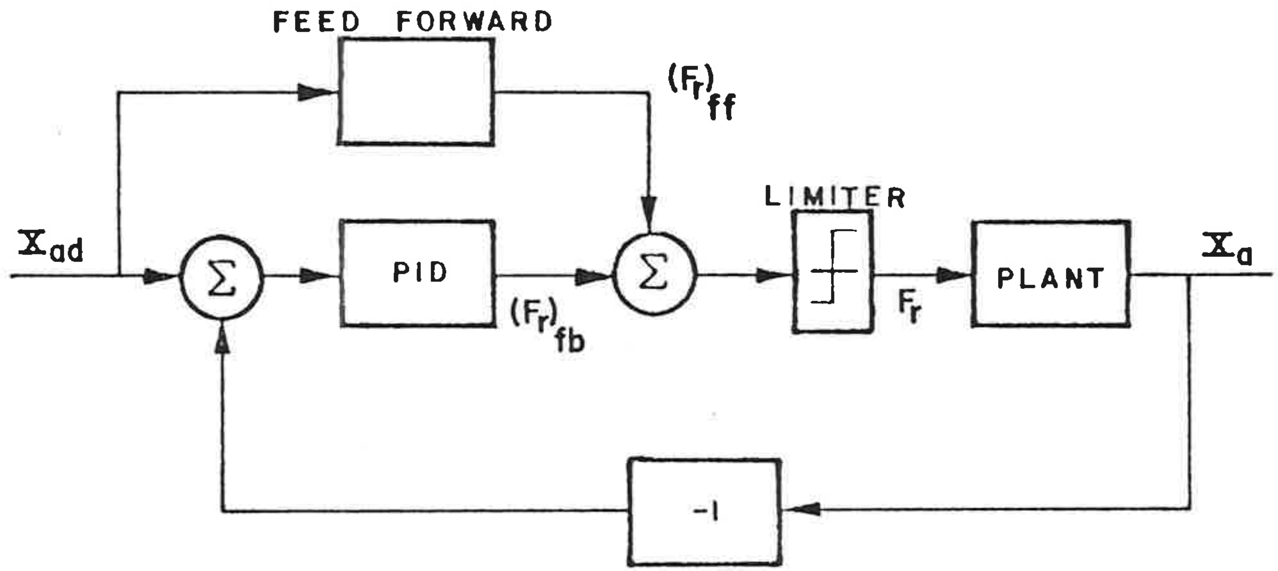

FIGURE 5.2 STRUCTURE OF THE FEEDFORWARD-FEEDBACK RETURN SLUDGE CONTROL SYSTEM

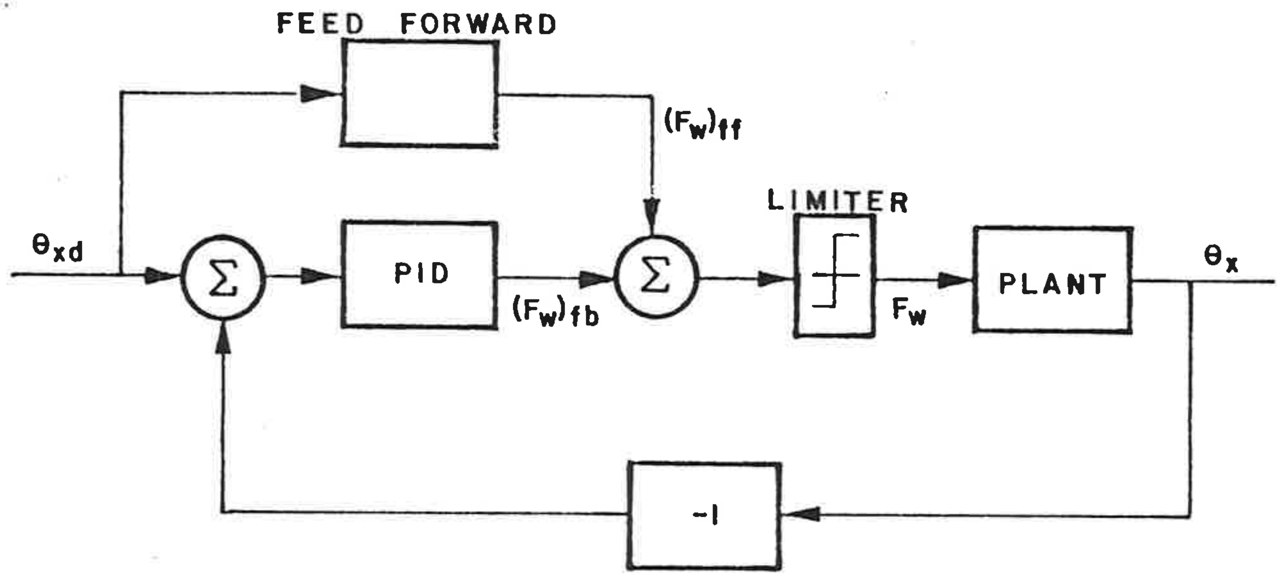

FIGURE 5.1 STRUCTURE OF THE FEEDFORWARD-FEEDBACK WASTE SLUDGE FLOW CONTROL SYSTEM

Constraints

The constraints on the control authority of the return sludge flow rate are basically due to the operation of the separator. A high rate of recycle can infuence both the clarification and thickening functions of the separator. Within limits, an increase in the recycle flow rate can increase the MLSS in the reactor which in turn will result in a reduction in dissolved BOD. However, if the efficiency of the separator in removing suspended solids decreases at the same time, then the decrease in dissolved effluent BOD may be more than offset by an increase in suspended effluent BOD.

The concentration of sludge in the underflow from the separator is also influenced by the recycle flow rate. This can be easily checked using simple logic in a computer control system. If the mass flow rate of solids in the underflow decreases for an increasing recycle flow rate, then excess water is being withdrawn with the solids which results in dilution. In other words:

$$\frac{(F_r x_r)}{F_r} > 1 \qquad [5.2]$$

where:

F_r = return sludge flow rate

x_r = return sludge concentration

The capacity of the separator to store solids also has to be considered which means that the sludge blanket level has to be kept within certain limits. Here there is a wide variation in practice. In some plants the sludge blanket level may remain near its maximum height, which can be a dangerous situation in the event of sudden decreases in sludge settling rates (sludge bulking) or sudden increases in flow rate to the separator. On the other hand, some feel that a certain minimum height of blanket is advantageous in reducing suspended solids in the overflow through the "filtering action" of the blanket. In other plants, the quantity of sludge stored in the separator is kept to a minimum in order to avoid problems due to sludge bulking or sudden increases in flow rate. These limitations on the sludge storage capacity of the separator create another set of constraints for the return sludge flow rate.

Another reason for placing a lower limit on the recycle flow rate (and thus a maximum on the mass of sludge stored in the separator) is to avoid oxygen depletion by biological reactions in the separator. Another obvious limitation on flow rate is pump capacity.

The different constraints on the return sludge flow rate may conflict in which case there will be no maneuverability left for control. Even when the constraints permit some control, the amount which can be exerted may be quite small. These are major reasons why recycle flow rate control is often misunderstood and misused.

Set Point

The objective of recycle control (within the limits of constraints) must be carefully selected. It may be to maintain either a desired F/M ratio or a desired oxygen uptake rate. In either case these may be translated into a desired MLSS concentration. Given the desired F/M ratio, $(F/M)_d$, the corresponding set point for the MLSS concentration is:

$$x_d = \frac{\overline{Fs_0}}{V(F/M)_d} \qquad [5.3]$$

where:

F = influent flow rate

s_0 = influent BOD concentration

V = reactor volume

x_d = desired MLSS concentration

The dynamics of this equation are important since the return sludge flow rate can affect the MLSS concentration on an hour-to-hour time scale. The sampling rate for the measurements should therefore also be on the order of one hour and should represent hourly averages. This is the reason for the "bar" sign over Fs_0.

When the objective is to maintain a desired oxygen uptake rate (OUR), x_d is calculated as shown in Eq. 5.4.

$$x_d = \frac{\overline{OUR}}{V\ (SCOUR)_d} \qquad [5.4]$$

where:

$\overline{OUR}$ = average value of OUR over the sampling interval

$(SCOUR)_d$ = desired value of the specific oxygen utilization rate (OUR/MLSS concentration)

The procedure for estimating the value of OUR is discussed in Section 5.5.

Control Law Structure

Just as for the sludge inventory control strategy, the control system for the return sludge flow rate strategy also consists of two portions, these being a feedforward signal, $(F_r)_{FF}$, and a feedback signal, $(F_r)_{FB}$. The sum of these two signals, Fig. 5.2, has to satisfy the combinations of all of the constraints.

A mass balance on sludge can be established for the actual as well as for the desired sludge concentration. From these balances one can derive an equation that will give the return sludge flow rate that will cause the actual MLSS to attain the desired value. For a single complete mixing reactor, this flow rate is given by:

$$(F_r)_{FF} = \frac{(\theta_H)\frac{dx_d}{dt} + x_d - (\theta_H)\frac{x_d}{M}}{x_r - x_d} \qquad [5.5]$$

where:

θ_H = hydraulic detention time

x_d = desired sludge concentration in the reactor

x_r = return sludge concentraton

M = value related to the sludge age (the reciprocal of the sludge growth rate minus the sludge decay rate)

Note that the actual measurement of MLSS is not included in the equation so that the control is feedforward in nature. Again, the time scale must be considered. This means that the derivative, dx_d/dt, is approximated by the difference over one sampling interval, e.g., one hour.

Control strategies found in the literature can be derived as special cases of Eq. 5.5. If the first and last terms in the numerator are considered to be negligible, the resulting equation (5.6) is the same as that suggested by

$$(F_r)_{FF} = \frac{1}{(x_r/x_d) - 1} \qquad [5.6]$$

Petersack and Smith (35) and Tanuma (39). One problem with the use of Eq. 5.6 for control, however, is that it does not give results consistent with the calculated value of the waste sludge flow rate. Consequently, the sludge inventory control strategy and the sludge distribution control strategy do not match in the steady state.

The first term in the numerator of Eq. 5.5 represents only a small percentage of the recycle flow and corresponds to the sludge that is wasted through the separator overflow and by the waste sludge pump. Ching (40) uses sludge age instead of M in this last term. This can create confusion since a variable (sludge age) calculated from a steady state equation is inserted in a control system that acts on an hour-to-hour basis. A preferred form of Eq. 5.5 would be:

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In order to implement feedback trim, the current value of the MLSS concentration in the reactor must be measured. The feedforward structure represented by Eq. 5.5 or 5.7 is then complemented by a PID controller in the feeback loop as given in Fig. 5.2.

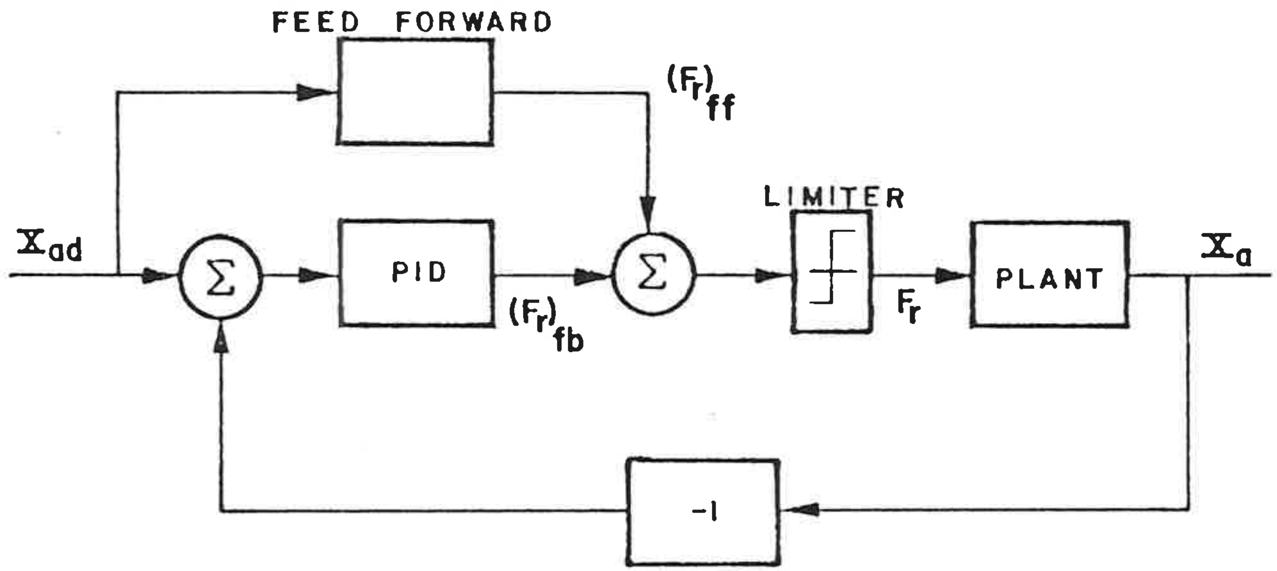

FIGURE 5.2 STRUCTURE OF THE FEEDFORWARD-FEEDBACK RETURN SLUDGE CONTROL SYSTEM

5.3.4 Sludge Distribution Control by Step Feed

The use of step feed is at present not possible for any of the Weyerhaeuser treatment plants. However, since this type of control has significant potential, it will be briefly described so that it may be considered in new designs or plant modifications.

The use of step feed to prevent process failure by spillover of sludge from the separator has already been described in Section 3. The use of step feed to regulate biological activity, as measured by SCOUR, will be described in this section. The system to be considered, consisting of two reactors in series, is presented in Fig. 5.3.

Assume that the second reactor is to be operated around a desired value of SCOUR such that:

$$SCOUR_2 = SCOUR_{2d} \qquad [5.8]$$

Such a criterion was used by Yust et al (41) in their pilot studies.

To illustrate the use of this type of control, assume that $SCOUR_2$ (the observed value) is too low. A possible reason for this could be that almost all of the substrate has been consumed in the first reactor. If this is the case, then a portion of the feed stream can be shifted to the second reactor. This will result in an increase in $SCOUR_2$; however, it will also result in a change in the distribution of sludge between the two reactors with the concentration in No. 1 increasing while that in No. 2 decreases. The effluent BOD may also increase depending upon the magnitude and duration of the flow shift.

A low value of SCOUR may also occur because of the presence of toxic materials. In this instance also, the appropriate action is to shift the flow into the second reactor.

If SCOUR is too high, as might be caused by a sudden increase in the concentration of biodegradable substances, the flow should be shifted to the first reactor.

To sum up, the specification of a set point for $SCOUR_2$ can be of substantial value in plant operations. This desired value for $SCOUR_{2d}$ corresponds to a desired value of the sludge concentration in the second reactor (x_{2d}) as stated below:

$$x_{2d} = \frac{(OUR_2)}{V_2(SCOUR_{2d})} \qquad [5.9]$$

where:

OUR_2 = oxygen uptake rate in the second reactor

$SCOUR_{2d}$ = desired value of SCOUR in the second reactor

V_2 = volume of the second reactor

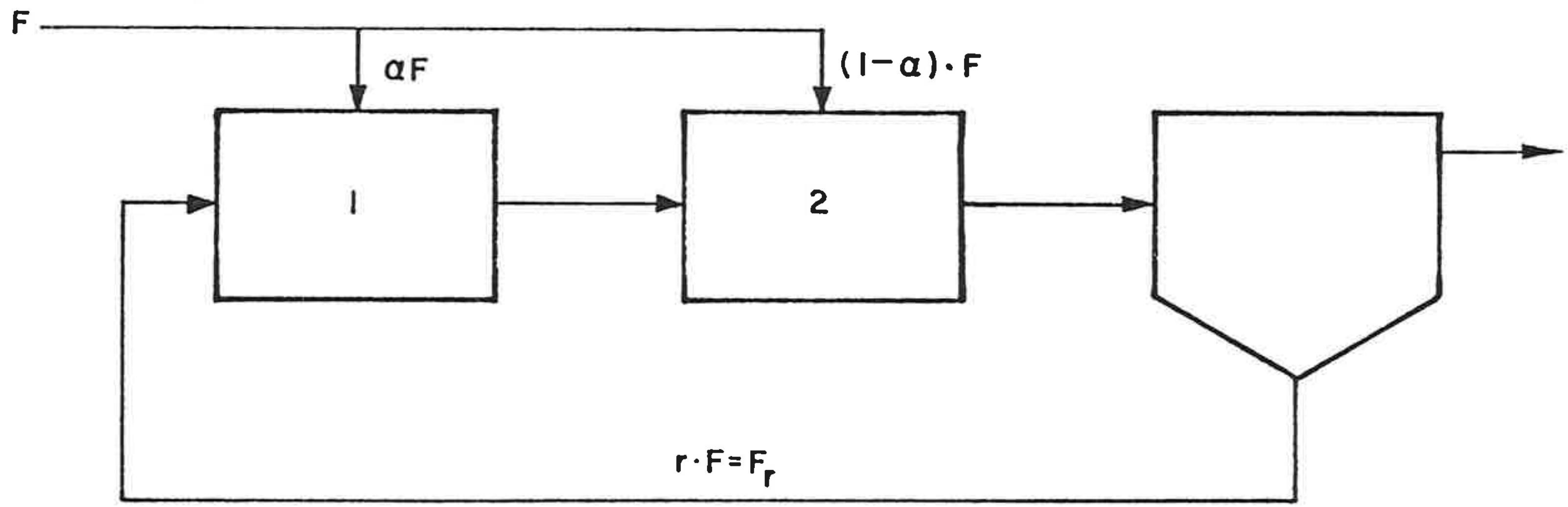

FIGURE 5.3 STRUCTURE OF A STEP FEED REACTOR SYSTEM

The desired sludge concentration, x_{2d}, can best be obtained by a combination of feedforward and feedback control. The information flow diagram for the controller would be similar to that shown for the return sludge rate control in Fig. 5.2.

As illustrated in Fig. 5.3, α represents the fraction of the total flow to the plant which is fed to reactor one with $(1 - \alpha)$ being the fraction of the flow which goes to reactor two. A good choice for α can be shown to be:

$$FF = \frac{1}{x_1} \left\{ \frac{V_2}{F} \frac{dx_2}{dt} + x_{2d} (1 + r) - r x_1 - \frac{\theta_{H2}}{M} x_{2d} \right\} \qquad [5.10]$$

where:

x_1 = sludge concentration in reactor one

x_{2d} = desired concentration of sludge in reactor two

F = influent flow rate

r = ratio of return flow rate to influent flow rate

θ_{H2} = hydraulic detention time for the second reactor

M = a value related to the sludge age (see Eq. 5.5)

If the model was absolutely perfect and there were no constraints on α_{FF}, the feedforward equation (5.10) would lead to exactly the desired sludge concentration in reactor two. However, the natural limits on α_{FF} (between 0 and 1) have to be considered. Moreover, there may be errors in calculation of the derivative. For example, the relevant sampling rate (in the order of one hour) will require that the derivative be approximated by the finite difference over one sampling interal. The concentrations also have to be defined as averages over one sampling interval.

The structure of the second control law for the two-reactor, step feed system is shown in Fig. 5.4. As usual, it is necessary to trim the feedforward control with feedback because of inadequacies in both the model and the measurements. The feedback controller can be a standard PID controller.

5.4 Control by Operational States

There is a scarcity of reliable sensors for use in wastewater treatment plants and it is expected that this situation will prevail for some time. Even with the development of new sensors, it will still not be possible to measure automatically more than a few of the many substances found in wastewater. Moreover, a skilled operator frequently factors into his decisions such poorly defined "measurements" as odor, color, and sound. A good control system would therefore be constructed so as to maximize the use of both automatically obtained measurements and human judgement based on manual observations. Any additional information available from laboratory measurements should also be considered. This is the background to "operational state" control.

The exertion of control in a complex system such as an activated sludge process

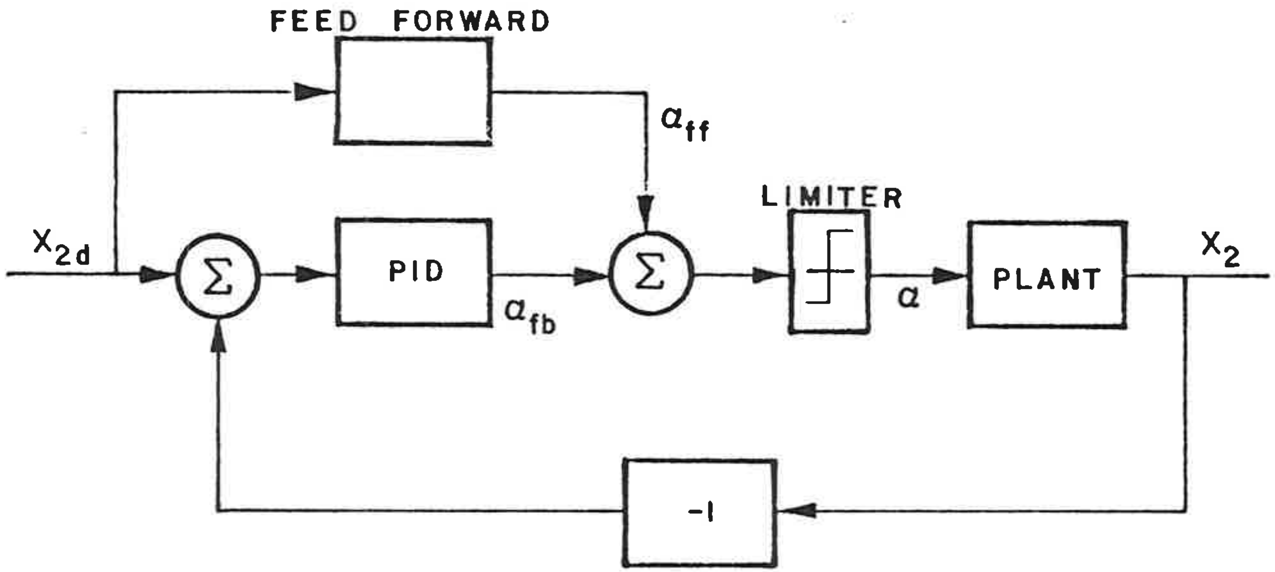

FIGURE 5.4 STRUCTURE OF THE FEEDFORWARD-FEEDBACK STEP FEED CONTROL SYSTEM

estimate changes in process loading and the degree of completion and rate of the reactions. For example, the slope of the profile near the reactor outlet provides an indication of the degree of completion of the reactions. If this slope is sufficiently small, then the reactions can be considered essentially complete. Also, at some point in the reactor, a "break" in the profile will occur. The maximum slope occurs at this break and can be used to estimate the maximum growth rate of the sludge.

(2) What should be the duration of each experiment? This is highly dependent upon the speed of response of the variables being studied and can therefore range over several orders of magnitude for the activated sludge process. The duration must be sufficiently long to adequately define the phenomena being studied; however, too long a duration results in less time to study other phenomena.

(3) What measurements should be made, how frequently should they be made, and how accurate should they be? These are among the most important questions to be answered for biological processes since few reliable on-line sensors are available and many analyses are manual. There are severe constraints, due to the availability of time and personnel, on the number of analyses which can be performed. Yet, a large amount of data is needed to adequately define dynamic systems. This is one of the major reasons why dynamic models have not been as fully validated as steady state models.

Also of considerable importance in experimental design is provision for rapid data reduction and display. An on-line computer is ideally suited for this. Experimentation should be an iterative process in which future experimentation is guided by knowledge gained from past experiments. Rapid data reduction and display is essential for this purpose.

The pilot plant will also provide valuable knowledge and experience to Weyerhaeuser personnel in adaptng full-scale treatment plants to real time computer control. It should not be the purpose of this experimentation to duplicate the hardware and software normally supplied by vendors of process control computers (this should be purchased) but instead to gain knowledge as to how to properly interface the computer with the activated sludge process and with the plant operating staff. It is in this aspect of computing that the process control computer most differs from the usual research computer. Items to be studied include:

(1) Use of a real time clock for proper timing of strategy execution.

(2) Programming for priority interrupts from the real time clock, the process, the operator, or the computer itself.

(3) The application of digital filters to noisy signals.

(4) The application of state/parameter estimation techniques.

(5) The use of human judgement in process control through the application of the operational state concept.

(6) Study of the most appropriate techniques for displaying data to the plant operator.

6.2 Modeling of Other Processes

Work should also commence on the development of dynamic models and control strategies for other wastewater treatment processes used by Weyerhaeuser. It is recommended that the next process modeled be the aerated lagoon. Not only is this process widely used by Weyerhaeuser; it also offers significant potential for reducing operating costs through a reduction in energy utilization. The aerated lagoon was widey adopted by industry in the 1950s and 1960s because of its low capital cost. At that time, energy costs were also low so little attention was paid to the fact that the aerated lagoon is an energy intensive process. However, this is of substantial concern today.

The same basic principles applied to the development of models for the activated sludge process also apply to the aerated lagoon. However, some additional factors of importance which must be included in the dynamic model of an aerated lagoon are:

(1) Insufficient mixing may be applied to permit the reactor to be characterized as either complete mixing or a number of complete mixing reactions in series.

(2) The mixing may not be sufficient to avoid the sedimentation of solids in the reactor or to provide oxygen at a high enough rate for the aerobic decomposition of these solids. Benthal decomposition may therefore become significant, requiring the addition of other biological reactions to the model.

(3) Surface aerators, instead of diffused aeration devices, are normally used for supplying oxygen in aerated lagoons. These aerators are also excellent heat transfer devices and this, along with the longer hydraulic detention times used in aerated lagoons, results in the temperature in the lagoon being significantly below that of the influent wastewater as well as being markedly dependent upon the season of the year. Reaction rate coefficients must therefore be expressed as functions of temperature. This requires the addition of a heat balance to the model in order to predict lagoon temperatures.

(4) DO control systems are different for surface aerators in that the manipulatable variable is not air flow rate but instead either the number of aerators in service or the depth of submergence of the aerator blades.

It would also be worthwhile to commence the development of models and control strategies for other processes, such as primary settlers, thickeners, sludge dewatering equipment, etc., used along with the activated sludge process in Weyerhaeuser treatment plants. There are strong interactions between some of these processes which necessitate the consideration of all of the processes as a wastewater treatment system. Also, the cost of sludge processing and disposal usually represents a significant portion of the total plant operating expenses.

6.3 Treatment Plant Interactions with Other Systems

In the long term, the dynamics of the treatment plant should be coupled with the dynamics of the production facility as well as with the dynmics of the receiving body of water. Sensors located in the production facility can provide early warning of spills of toxic/inhibitory substances which can impair the operation of biological processes. Such sensors can also provide valuable information for the design and/or operation of diversion or equalization basins which serve as interfaces between the treatment plant and the production facility. Gove and McKeown (47) have discussed the use of dynamic models and computer control for the control of process losses and spills in the Kraft industry.

As previously mentioned, another attractive concept is that of operating the treatment plant at variable efficiency in order to match the assimilative capacity of the receiving body of water which usually varies with time. This may not be feasible at present since the time varying capacity of receiving waters for waste assimilation is not well recognized by regulatory agencies. However, this may become feasible in the future and should be kept in mind. In this case, it would be important to have a good dynamic model of the receiving body of water and appropriate sensor packages located both upstream and downstream of the treatment plant discharge to provide signals for controlling the efficiency of the plant.

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