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THE AXEL JOHNSON
INSTITUTE
FOR INDUSTRIAL RESEARCH

ERRATA "Control problems in wastewater treatment plants",

Olsson et al.

Page	Line	
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41	16+	qualizing → equalizing
47	figure to the right	$s\beta x$ → $s, \beta x$
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57	11+	$xz \to x_a z$
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	ref 27	Waste → Wastes
	ref 78	Hygianisk → Hygienisk

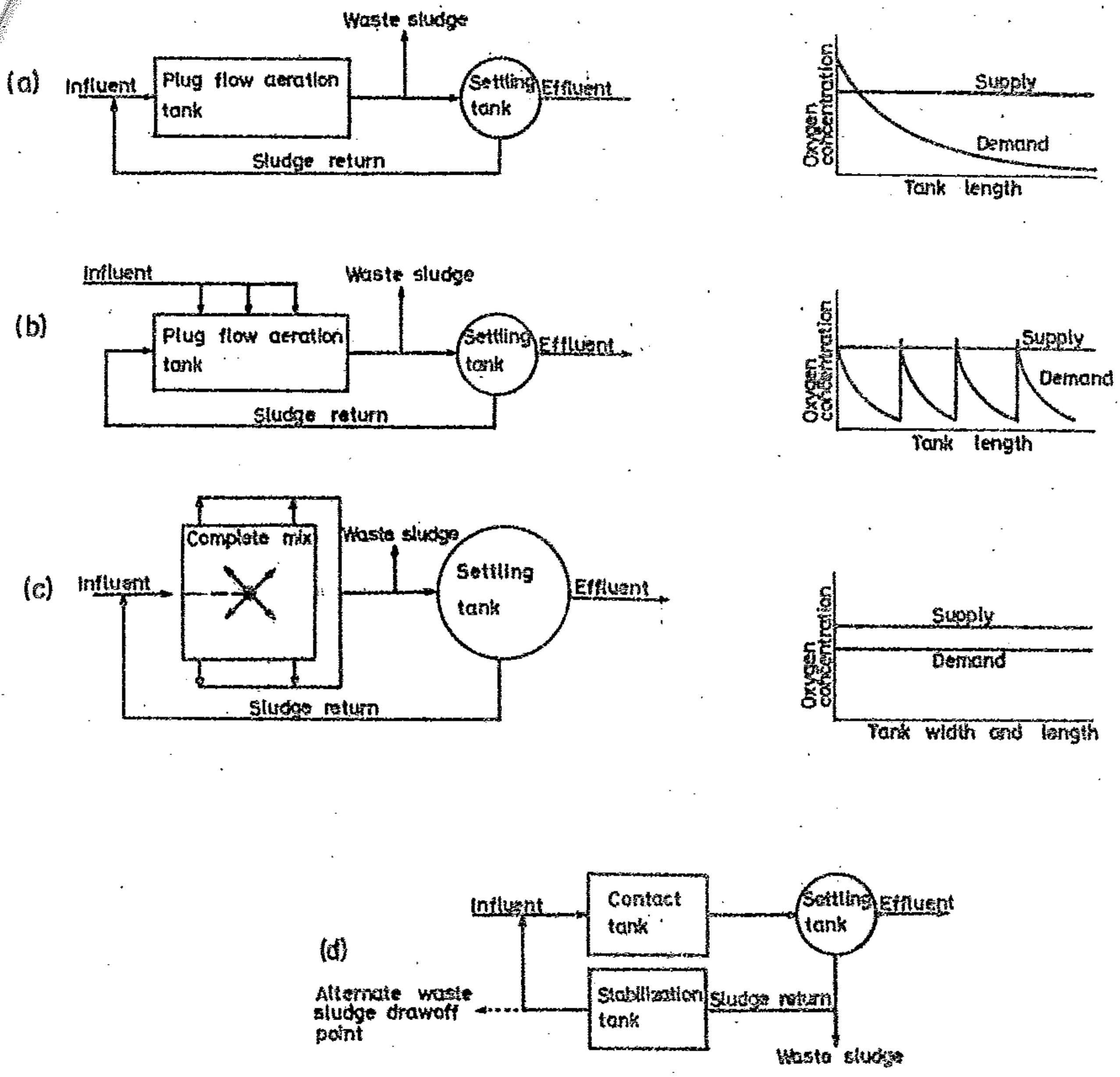

FIG. 3.4. Flowsheet and plot of oxygen demand and oxygen supply versus tank length

(a) Conventional
(b) Step-aeration
(c) Complete mix
(d) Contact stabilization

CONTROL PROBLEMS IN WASTEWATER TREATMENT PLANTS

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ABSTRACT

This report is a partial result of a feasibility study on control problems in wastewater treatment plants.

An attempt is made to define suitable parameters for on-line control and to characterize good performance of control systems. Typical disturbances, such as flow rate changes, organic load changes etc. are described and control strategies are suggested to overcome such disturbances. It is also noted, that today there are no control strategies available for several external disturbances e.g. dumps of oil, industrial chemicals and heavy metals.

A lot of mathematical models of the dynamics of different unit processes have been described in the literature. The most important ones are surveyed especially for the activated sludge process. Some control strategies based on these mathematical models are reported.

A good on-line instrumentation is of primary interest for an accurate control. A summary is made of available on-line instrumentation for wastewater plants. The instrumentation equipment situation for Swedish plants is reported as well.

It is also emphasized the importance of an adequate instrument service if any automatic control should be successful at all.

CONTENTS

CONTROL PROBLEMS IN WASTEWATER TREATMENT PLANTS

1. Purpose of the work

A feasibility study on control problems in wastewater treatment plants was initiated during the spring 1973. The study has been supported by the Swedish Board for Technical Development (STU) and it has been performed as a joint study with the Axel Johnson Institute for Industrial Research, the Swedish Environment Protection Board, the Käppala wastewater treatment plant, the Division of Hydraulics at the Lund Institute of Technology (LTH) and finally the Division of Automatic Control at LTH.

The purpose of the study has been limited mainly to the control of wastewater treatment plants and to some important parts of the sludge treatment. The goal can be summerized in the following items, to find out

- typical dynamical disturbances in a wastewater treatment plant
- potentially essential control loops
- existing mathematical models for different unit processes of wastewater treatment plants
- problems in on-line instrumentation

- characterization of which parameters are important in on-line control of wastewater treatment plants
- state of the art of the control of Swedish and some important foreign plants
- what can possibly be done in control with on-line instruments and actuators available in the market today
- how can automatic control improve the economy or quality of a plant

In order to clearly define what is meant by automatic control it is stated here some ingrediences in an automatic control system. It should include

- capabilities for on-line registration of physical and chemical variables. The measurement information should be transferred directly to a device for information handling, such as a regulator or a computer
- a device for calculation of a control strategy or simple control law based on the measurement values, i.e. a controller or a computer
- presentation of the control signal for the operator (operator′s guidance) or a control signal transfer directly to a control device, such as a motor, pump, valve etc. (closed loop)
- control devices that are designed so that continuous adjustments can be made according to the external disturbances. Such control inputs could be pump speed, blower capacity, chemical dosage etc. In an operator′s guidance control system the devices are changed manually according to the control signal information given to the operator.

The study has been undertaken by literature studies, and study travels to plants and institutions in Sweden, USA and Canada. The travel to USA and Canada has been reported separately by Olsson - Ulmgren (1973).

2. Wastewater composition

The main goal of a wastewater treatment plant is to produce an acceptable output product independently of the influent to the plant. Contrary to popular belief, sewage is only slightly contaminated water.

In fact, usual domestic wastewater is 99.95 % water. For most uses, however, the water must contain much lower levels of contamination. This shows, that even if waste treatment technology need only extract small quantities of contaminants from wastewater, these contaminants must be reduced to very low levels.

Another major characteristic of wastewater which must be considered is the great diversity of contaminants. In fact, the variety of contaminants is so great and the concentrations so low, that only a few substances exist at a measurable level. This makes much of the instrumentation to a major problem.

Even if the long term average characteristics of the wastewater coming to a certain plant can be worked out, it is almost impossible to get the momentary characterization of the "raw material" coming in for processing.

Despite this fact the treatment must be performed such that the final product is satisfactory.

It would be interesting to know the bioligical activity going on, but it can not be measured. Other external vaiables have to be measured instead, such as oxygen demand, respiration, suspended solids, dissolved oxygen etc.

Wastewater can be characterized by a number of quality vaiables. Typical values of the most important parameters are given in table 2.1

	Influent raw wastewater	Effluent in an acceptable plant
Biochemical oxygen demand (BOD) mg/l	100 - 250	5 - 15
Chemical oxygen demand (COD) mg/l	200 - 700	15 - 75
Total phosphorus mg/l	6 - 10	0.2 - 0.6
Nitrogen mg/l	20 - 30	2 - 5
Suspended solids mg/l	100 - 400	10 - 25

Table 2.1 Typical values of some important water quality parameters.

It should be observed that neither BOD nor COD gives a complete determination of the organics content.
There is a large variety of contaminants except those mentioned in table 2.1. The most important types are

- heavy metals
- trace organics, such as phenol and other industrial chemicals
- pesticides
- virus

The heavy metals content include a large number of metals. The most important ones are listed in table 2.2

Element	"Normal" sludge	"Contaminated" sludge
Zink	1 - 3 g	> 10 g
Copper	0.5 - 1.5 g	> 3 g
Manganese	0.2 - 0.5 g	> 2 g
Lead	0.1 - 0.3 g	> 1 g
Chromium	50 - 200 mg	> 1 g
Nickel	25 - 100 mg	> 500 mg
Cobolt	8 - 20 mg	> 50 mg
Cadmium	5 - 15 mg	> 25 mg
Mercury	4 - 8 mg	> 25 mg

Table 2.2 Levels of heavy metals in sludge from approximately 100 plants. Levels are per kg of dry matter.

The heavy metal content in the wastewater has been analyzed for some Swedish wastewater plants, and the local variations are of course very large, see Lind et. al (1971).

The possibilities to remove some of these hazardous components are varying, and generally very little hard information has been developed about treatment of these pollutants. A discussion about removal of hazardous components has been made by Cohen (1971).
He gives some further references on the subject.

It has turned out, that the processes developed to meet the usual water quality requirements are remarkably capable of removing a wide range of hazardous components.

The effluent quality should generally satisfy some minimum requirements. It should be stressed, that this quality requirement has to be given in terms of absolute values of contaminants in the water, i.e. kg per day etc. for every contaminant. To present the removal only in percent is irrelevant in most cases.

In order to know the quality, the effluent stream has to be monitored more or less continuously.

In this report the possibilities for improvement of the plant operation by automatic control are considered. As there is no price defined for quality improvements of effluent water, it is of course difficult to make a complete economic evaluation. This problem is discussed in chapter 12.

3. Some basic features of wastewater treatment plants

A wastewater treatment plant consists of a large number of complicated unit processes. Some of them, e.g. the activated sludge process, are not at all completely known in detail, and especially the dynamic behaviour is highly complex. One reason is, that the raw wastewater consists of so many contaminants, and in most cases their concentrations are to some extent unknown at the input of the plant.

In this chapter there is given a brief description of the most important unit processes of a wastewater treatment plant. The description has no intention to be complete, but to give a general background to the later discussions. All unit processes (especially those of "advanced" treatment) are not discussed, such as filtration and activated carbon treatment. Nitrogen removal and sludge treatment are breifly mentioned for completeness, but are not further discussed in the report. For details it is referred to some standard textbooks, e.g. Culp (1971), Eckenfelder (1966) or Metcalf & Eddy (1972).

3.1 Biological treatment

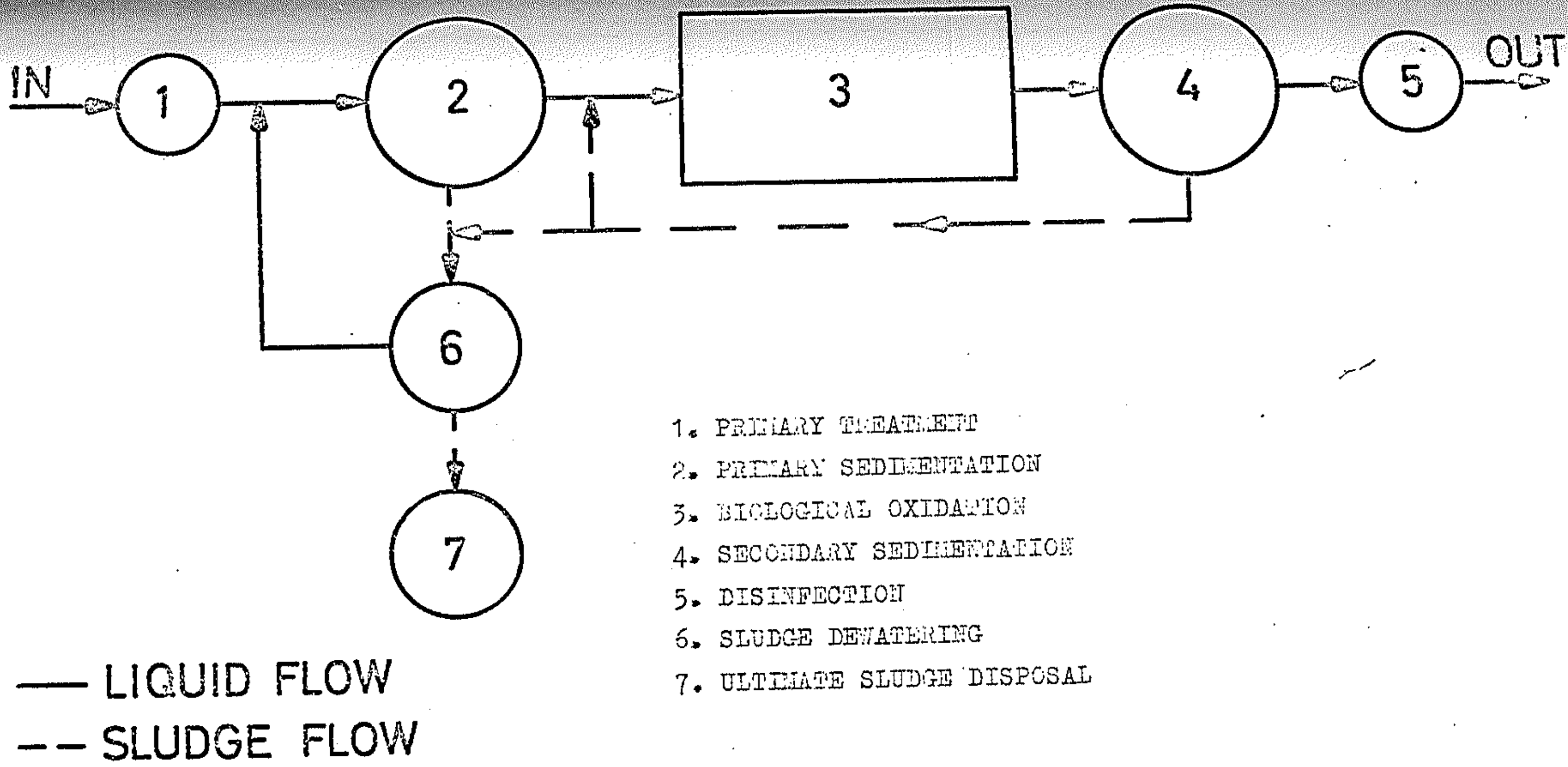
One of the mostcommon biological methods of wastewater treatment is that illustrated in fig. 3.1. It is sometimes referred to as biological treatment, sometimes conventional treatment, sometimes secondary treatment.

This process has been specifically developed to remove suspended solids, biodegradable organics and microorganisms from the wastewater. The wastewater is first passed through screens and a grit removal unit. This is made to protect pumps and pipes from large articles which are often found in wastewater. Primary sedimentation is provided to remove settleable solids.

The next step is a biological oxidation of soluble organic material by microorganisms. They consume the organics thus producing cell mass, carbon dioxide and water.

The two most important highloaded systems for biological oxidation are the activated sludge process, fig. 3.2 and the trickling filter fig. 3.3

The microorganisms which are active in the biological oxidation are separated from the flow in the secondary sedimentation tank. Some of the settled material, which is mainly organic material, is recycled to the aeration tank, in order to maintain an adequate population of the microorganisms. The excess sludge is sent to the sludge treatment part of the plant.



1. PRIMARY TREATMENT
2. PRIMARY SEDIMENTATION
3. BIOLOGICAL OXIDATION
4. SECONDARY SEDIMENTATION
5. DISINFECTION
6. SLUDGE DEWATERING
7. ULTIMATE SLUDGE DISPOSAL

FIG. 3.1 BIOLOGICAL TREATMENT SYSTEM.

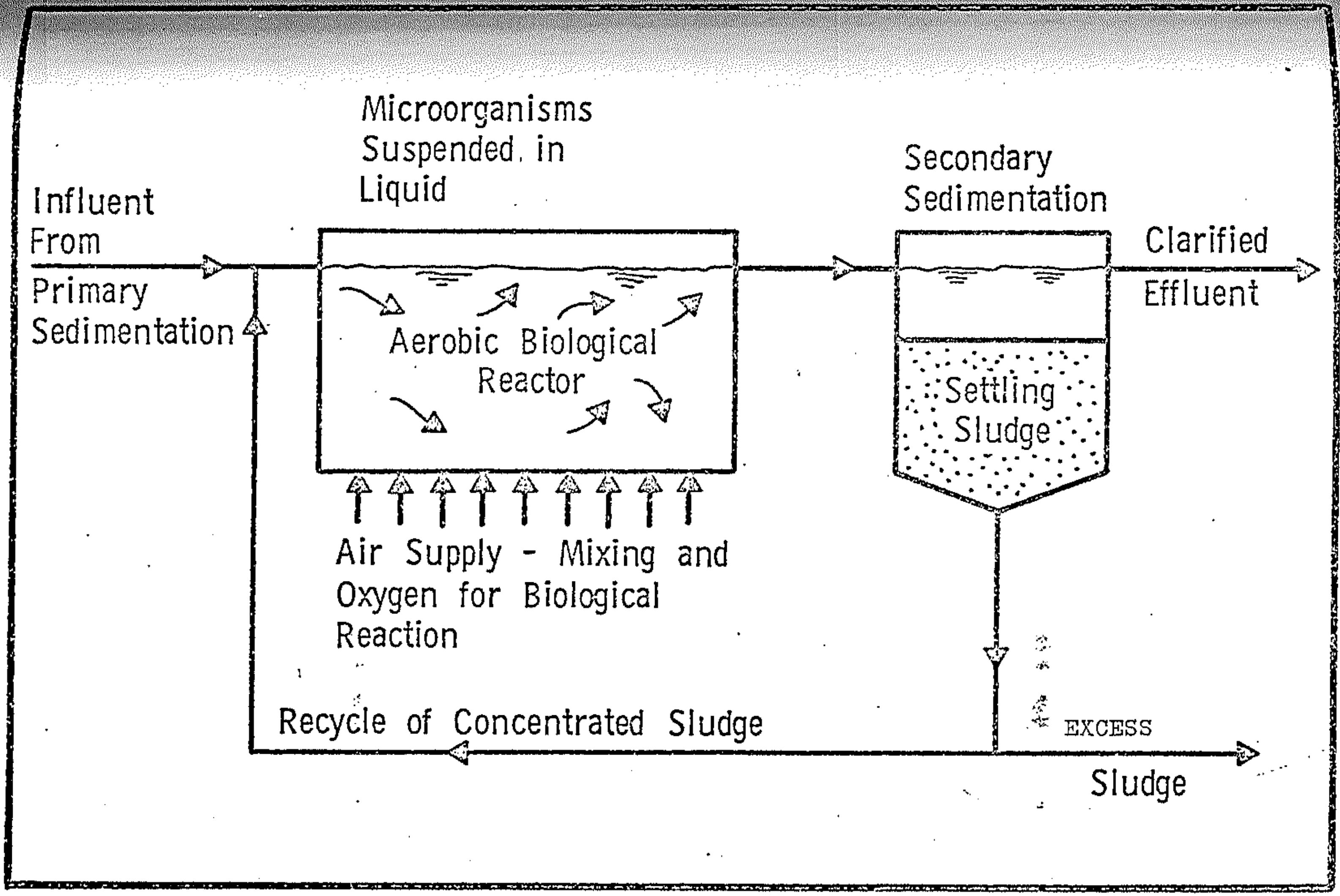


FIG. 3.2 THE ACTIVATED SLUDGE PROCESS

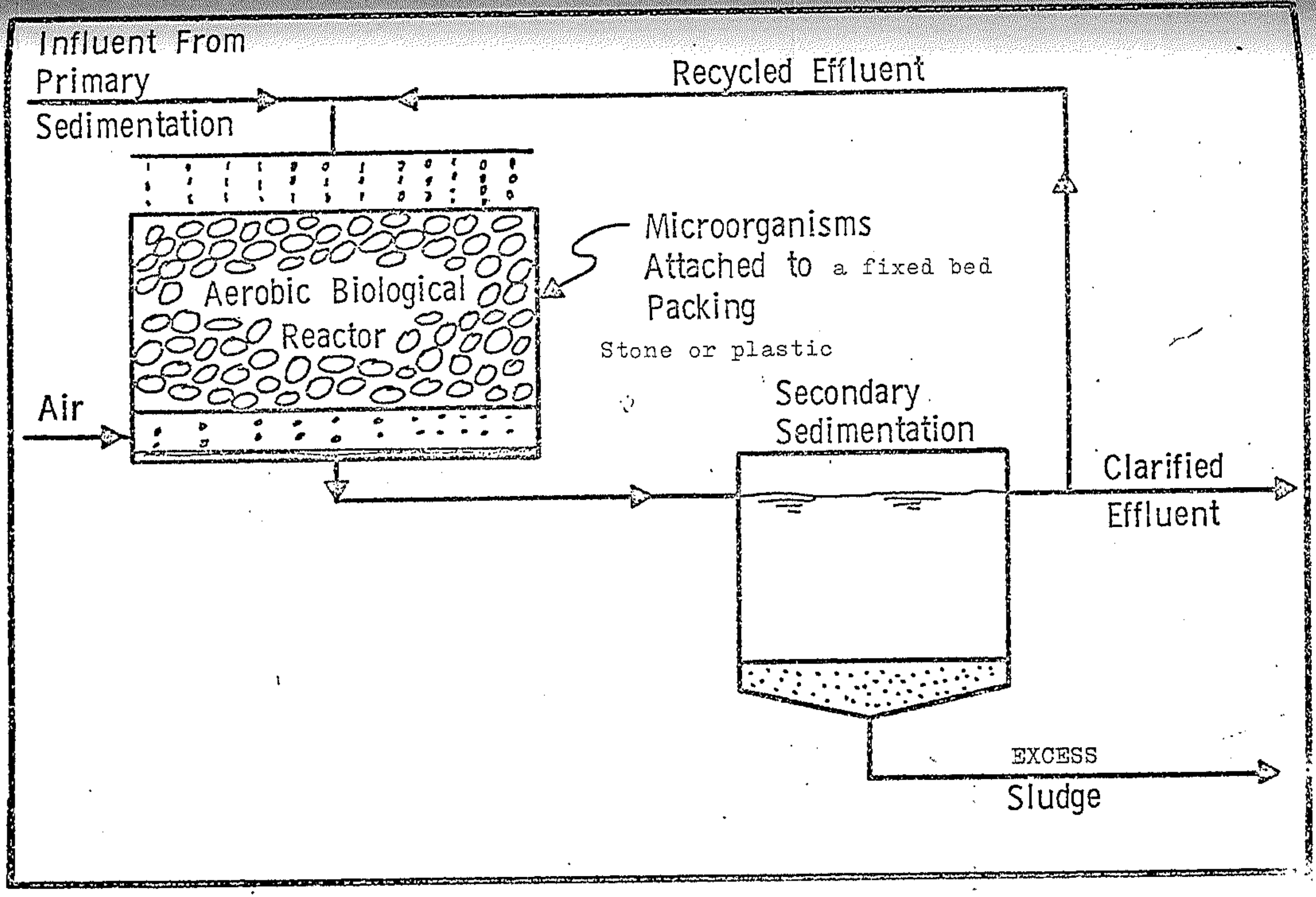


FIG. 3.3 THE TRICKLING FILTER PROCESS

3.2 The activated sludge process

For the nearest future the activated sludge process is considered to be the most important biological process of wastewater treatment. Therefore much attention has been paid to this unit process, both through theoretical and by practical studies. Further a good control of the activated sludge process is essential for the entire plant operation.

The two most important parameters for the design of an activated sludge process are the food-to-microorganism ratio (BOD/SS) (SS = suspended solids) and the mean cell residence time (sludge age T_s). Typical values given for BOD/SS in the literature vary from 0.2 to 0.5. Actual operating experiences point out that a mean cell residence time about 6 to 15 days results in a good effluent with the "best" settling characteristics.

The sewage water detention time is greater than the hydraulic detention time due to the recirculation. It approximates the average period of contact between the sludge and the sewage. Typically the hydraulic detention times for the aeration tank are in the range of 1 to 8 hours. The organic loading can also be expressed in kg of BOD per day per m^3 tank volume. These figures are not directly related to the mixed liquor concentration, the food-to-microorganism ratio or the cell retention time.

Some typical design guidelines for Swedish plants are found in table 3.1, Ulmgren (1973 B).

Type of plant	Sludge loads kg BOD_7/kg SS	kg BOD/m^3,d	Hydraulic Detention time h
	Including primary sedimentation		
Peak loads	1.0-1.5	3.0-4.5	0.8-1.2
Normal loads	0.4-0.8	1.2-1.8	1.5-2
Low loads	0.2-0.3	0.6-0.9	1.5-4
	Without primary sedimentation		
Peak loads	0.8-1.3	2.5-4.0	1 -15
Normal loads	0.3-0.5	1.0-1.5	2 -3
Low loads	0.1-0.2	0.3-0.6	3.5-8
Extended aeration	0.15-0.1	0.05-0.30	8 -24

BOD_7 = biochemical oxygen demand measured after 7 days
SS = suspended solids in the aeration tank
m^3 = tank volume in m^3

Table 3.1 Recommended design data for activated sludge processes in Sweden

There are different variants of the activated sludge process in real installations. Here five variants of the activated sludge process will be described, the conventional activated sludge process, the tapered system, the step aerator, the complete mix reactor and contact stabilization.

A more detailed description can be found e.g. in Metcalf & Eddy (1972) and Stewart (1971).

The conventional activated sludge process is illustrated by fig. 3.4 a. The return activated sludge is entered at the head end of the tank. The influent sewage and the recirculated sludge are mixed and aerated during 1 - 5 hours by diffused air (bottom) or mechanical aeration, which is constant as the mixed liquor moves along the tank. The return sludge flow is about 25 to 150 percent of the influent flow rate. As the oxygen demand decreases along the tank (see fig. 3.4 a) the aeration is not ideal from an economic point of view.

In order to improve the balance between oxygen demand and supply, tapered aeration has been used mostly instead of conventional aerators. This means, that the aeration is greater in the head end of the tank and smaller at the other end.

In the step-aeration process the organic loading is distributed along the length of the tank, and the peak oxygen demand is thus lowered, see fig. 3.4 b. Return activated sludge enters the first step of the aeration tank along with the influent. The piping is so arranged that an increment of sewage is introduced into the aeration tank at each step. If desired, the first step can be used for reaeration of the return activated sludge. The step aeration method results in relatively high mixed liquor solids concentration at the head end of the tank and successively lower concentrations downstream. Therefore a step aeration plant can carry a higher organic load in the system than a conventional plant.

The complete-mix process is an attempt to get a process with a uniform oxygen demand throughout the tank. The volume can be made smaller than the other aerators and the retention time is generally smaller.

The influent and the return sludge are introduced at several points from a central channel, fig. 3.4 c. The mixed liquor is aerated during its

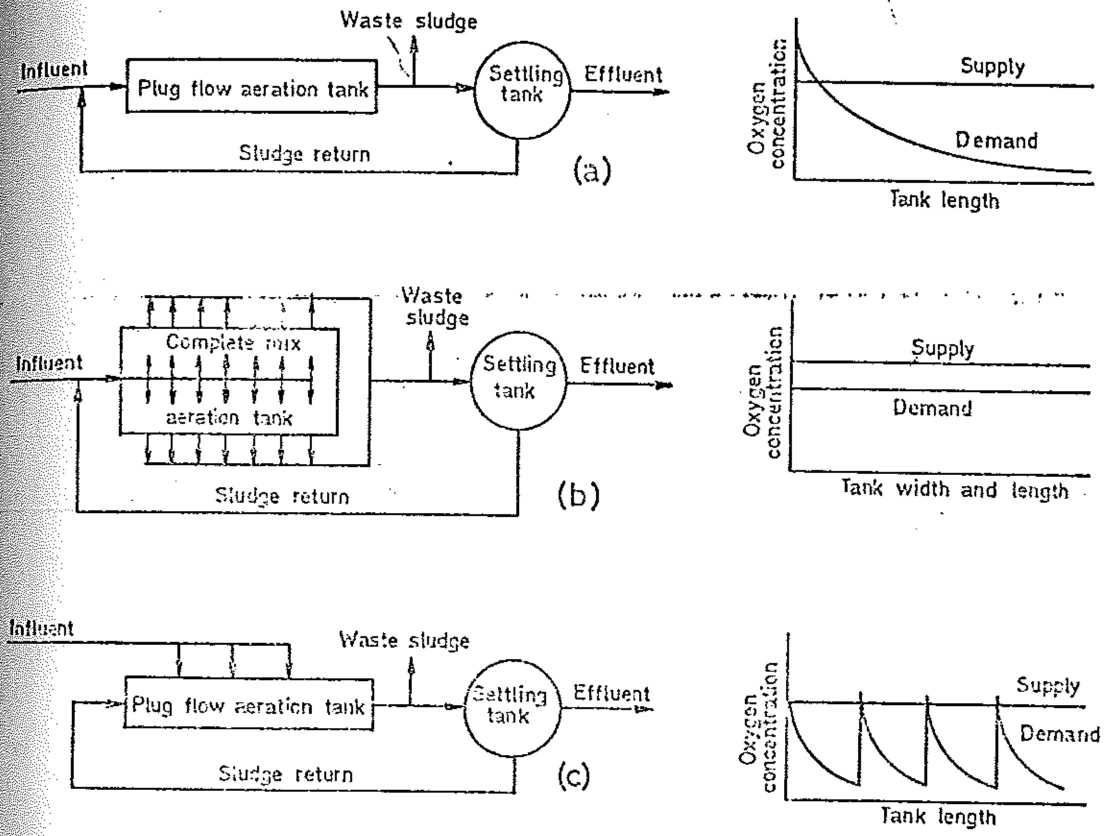


FIG. 3,4, FLOWSHEET AND PLOT OF OXYGEN DEMAND AND OXYGEN SUPPLY VERSUS TANK LENGTH

(A) CONVENTIONAL

(B) COMPLETE MIX

(C) STEP AERATION

way to the effluent channels.

The flowsheet of the contact stabilization process is shown in fig. 3.4 d. It has been postulated that BOD removal occurs in two stages in the activated sludge process. During the first phase (20 to 40 minutes) most of the collodial and dissolved organics are absorbed in the activated sludge. In the second phase oxidation takes place and the absorbed organics are metabolically assimilated. In the activated sludge processes mentioned earlier both these processes take place in one tank. In the contact stabilization process these two phases are separated in different tanks.

The aeration time in the contact tank is 30 to 90 minutes, and the suspended BOD will be rapidly absorbed by the well-activated organisms. The return sludge is aerated some 3 - 6 hours in the reaeration tank. During this time the absorbed organics are oxidized and thus stabilized.

The aeration volumes required are about 50 percent of those of a conventional plant. It is thus often possible to double the plant capacity of an existing conventinal plant by redesigning it to use contact stabilization.

3.3 Typical disturbances of the activated sludge process

The disturbances which are interesting and difficult to handle have to do with changes of the feed, either the flow rate or the concentration of contaminants. The most essential disturbance is the flow rate change. During the day the flow changes significantly depending on domestic sewage and industrial wastes. In large plants the sewers have many different lenghts from the different sources and the diurnal variations are attenuated. Normally the variations are 30 - 50 % (see fig. 4.1). In other cases the diurnal variations can be as much as 5 - 10 times between the high and low flow during the day.

In all unit processes the operation of course is most reliable and efficient if the flow is as constant as possible.

At a sudden flow change several undesired phenomena can occur. The detention time decreases in the sedimentation and thus the effluent contains more sludge. This will also decrease the microorganism content. The flow in the separation tank may change from laminar to turbulent flow. Lamella sedimentation units for example are sensitive to sudden flow increases, as the volumes are small.

The oxygen demand also changes because of changing amounts of organics, industrial chemicals, heavy metals, oil and toxics. Some of these disturbances can be detected by oxygen demand monitoring of the influent.

Some operational problems can be related to the sludge properties. One measure of the sludge properties is the sludge volume index (SVI). The index can be used as an indication of the settling characteristics of the sludge. A rising SVI indicates trouble ahead and operational precautions should be taken to bring the problem under control. Two such problems are called sludge <u>bulking</u> and <u>rising</u> sludge.

When the settling rate gets poor the sludge is said to be bulking. The causes of sludge bulking that are most commonly cited in the literature are related to changes in

(1) physical and chemical characteristics:
flow, pH, temperature, nitrogen content, oxygen demand, phosphorus content
(2) treatment plant design
(3) plant operation:
  - too low dissolved oxygen level
  - organic waste overloading
  - food-to-microorganism ratio change

Low dissolved oxygen content seems to be one of the most common causes to bulking sludge.
The sludge wasting rate should also be checked so that the food-to-microorganism ratio is within the range of accepted values. Also the average return sludge flow rate should be checked so as to maintain an acceptable food-to-microorganism ratio.

In order to attenuate peak flows in the plant, returning liquid from the sludge treatment as well as backwash water from filtration should be buffered adequately.

Rising sludge is a different phenomenon than bulking sludge. Generally the sludge may have good settling characteristics but occationally sludge rises or floats to the surface after a settling period. This is sometimes caused by denitrification, in which nitrites and nitrates in the wastewater are converted to nitrogen gas. As nitrogen gas is formed in the sludge layer, much of it is trapped in the sludge mass. If enough gas is formed the sludge may rise to the surface. Rising sludge can be differentiated from bulking sludge by noting the presence of small gas bubbles attached to the floating solids.

The problem can at least partially be solved with operational means. The return activated sludge flow as well as the sludge wasting rate can be increased.

3.4 Phosphorus removal from wastewater

3.4.1 Introduction

The key role of phosphorus in the process of eutrophication (aging of lakes etc.) has been known for many years. Today phosphorus is considered one major contaminant in wastewater, because of the large increase of phosphorus discharges in lakes and rivers during the last decades.

Phosphorus is present in municipal wastewater in many forms. The raw wastewater contains organically-bound phosphorus, and the inorganic phosphorus will be mainly a mixture of orthophosphate, pyrophosphate and triphosphate. The two latter ones (condensed phosphates) can hydrate to ortophosphate under a variety of conditions. Very high or low pH and enzyme actions are the dominant mechanisms. In biologically treated wastewater nearly all the complex forms have been degraded to the ortophosphate by enzyme reaction.

The scientific and technical details of the various processes are outlined in many articles. Some important ones are the Process Design Manual for Phosphorus Removal (1971) and two other symposia on phosphorus removal [37], [54].

A comprehensive survey of the chemical processes is given by Jenkins et.al. (1971). No effort is made to repeat the details of phosphorus removal. Instead a listing of the main features of the most common practical processes is given.

3.4.2 Phosphorus removal in conventional biological treatment

Phosphorus removal in conventional treatment is relatively poor (15-40%). Primary treatment (sedimentation) can remove only about 10 % of the total phosphorus which is initially insoluble. The removal of phosphorus in the biological process due to the synthesis into the biomass is limited, see Process design. Recent studies have indicated that considerably more phosphorus can be removed through the mechanism of "luxury uptake", see Levin (1965), Mulbarger (1970)Yall(1970)and Cecil(1971)A successful luxury uptake removal of phosphorus has been reported from several plants. Some studies indicate, that luxury uptake may in fact be a chemical precipitation rather than a biological phenomenon, see

Menar et. al. (1970).
The problem with luxury uptake is, that there is no good method to predict it. Until the mechanism is understood it is not possible to evaluate its general application. Therefore it can not be considered in the context of automatic control.

3.5 Phosphorus removal by chemical precipitation

Phosphorus forms essentially onsoluble precipitates with a number.
The different compounds of phosphorus in the wastewater may exist in solution and as particulates. Phosphorus removal consists of its conversion into solid phase followed by the removal of this phase from the main stream.
In most circumstances the only possible way to get a high phosphorus removal is by chemical precipitation. Phosphorus forms essentially insoluble precipitates with a number of substances. High level of phosphorus removal thus can be obtained when the right chemicals are added in proper doses. Several chemicals can be used, but because of economic reasons, the use of salts of aluminum and iron or lime are dominating. In Sweden the dominating chemicals are Al-sulphate, ferric (III) chloride, ferrous (II) chloride and lime in the two forms slaked lime ($Ca(OH)_2$) or quicklime (CaO).

3.5.1 Metal salt precipitation

The major reactions taking place when metallic ions are added to the wastewater are the formations of insoluble phosphates. Metal hydroxides are also formed as flocculants for the phosphates. Moreover a large number of complex compositions are formed.
The distribution of different phosphates depends strongly on pH and a large number of different phosphates species can occur in raw wastewater. This makes the precipitation mechanisms extremely complicated and a large number of different reactions take place.
Fig.3.5 illustrates distributions of different phosphates in typical raw domestic wastewater as function of pH.

The dominating reaction between the phosphate and the metal salt can be represented by

$$3\,M^{n+} + nPO_4^{3-} \longrightarrow M_3(PO_4)_n$$

Because there are other reactions taking place the necessary dosage tends to increase over the stochiometric relation shown in the above reaction.

The metal salt can also form an insoluble hydroxide

$$M^{n+} + n \cdot HCO_3^- \longrightarrow M\,(OH)_n + n \cdot CO_2$$

This hydroxide is in fact necessary for removal of precipitants because it forms a good flocculant. Therefore the reaction is not a waste of metallic ions.

The pH of the water is the most important parameter that determines the dosage. The precipitation as function of pH is illustrated by fig. 3.6. It shows that the solubility of aluminium phosphate is smallest at about pH 6 while iron phosphate is best precipitated at pH 4-5.

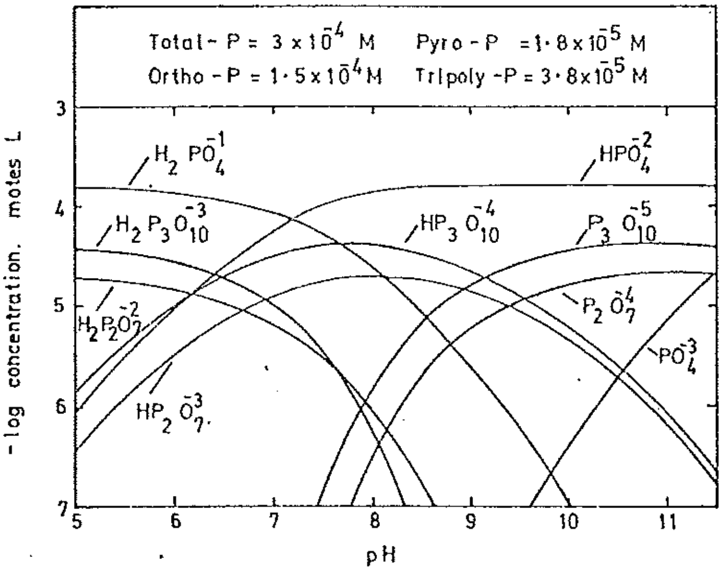


Fig. 3.5

pH concentration diagram for phosphate species typical of raw wastewater.

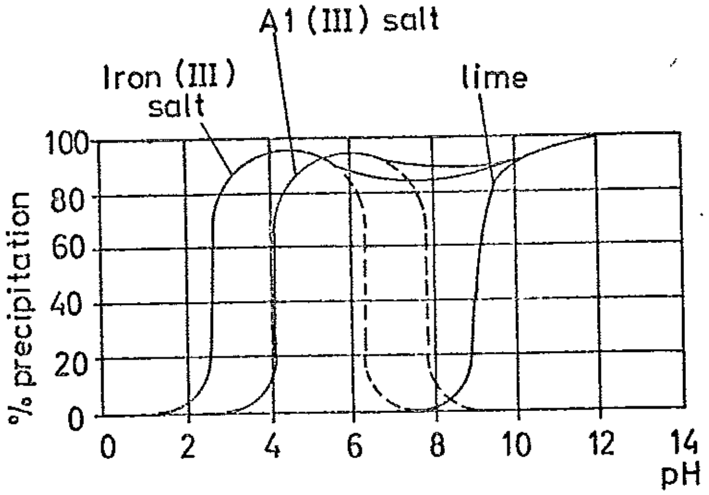


Fig. 3.6

Precipitation of orthophosphate with different chemicals as function of pH. The dotted lines show the precipitation in deionized water.

The pH decreases with increasing metal salt dosage (Al and Fe). The presence of organic solids also increases the doses of chemicals. Part of the metal salt is used for the coagulation of these materials.

The molar ratio Al/p or Fe/P is normally around 2. In table 3.2 average of results from many american installations are given, see [55]

% P removal	Dose metal salt mol ratio M^{3+}/P
75	1.4
85	1.7
95	2.3

Table 3.2 Average metal salt required for specified phosphorus removal.

This table, however, can not be used as a guide for the design of an individual process, as the individual variations are very large. In some cases a molar ratio of 4 has been necessary.

Because of the extremely complex precipitation reactions it is very difficult to predict the amount of chemical required with great accuracy. Emphirical measurements at the individual plant are necessary in order to determine the right molar ratio.

3.5.2 Lime precipitation

Most calcium phosphate precipitation schemes involves raising the pH of the waste stream to at least 9.5 (and often above pH 11), because at this pH range experience has shown that low dissolved phosphate residuals are obtained together with a settleable precipitate. At this high pH some of the condensed phosphates may be hydrolyzed to the ortho form and some organic phosphorus componds are coagulated.

A major reaction taking place is the formation of calcium hydroxyapatite,

$$3\ PO_4^{3-} + 5Ca^{2+} + OH^- \longrightarrow Ca_5(OH)(PO_4)_3$$

Here the phosphate is represented by the PO_4^{3-} ion.

The lime also reacts with the bicarbonate alcalinity of the wastewater to form calcium carbonate,

$$Ca^{2+} + HCO_3^- + OH^- \longrightarrow CaCO_3 + H_2O$$

This reaction illustrates, that part of the lime does not remove any phosphorus, a situation similar to the metal salts. In fact the bicarbonate concentration in wastewater is much higher than the phosphorus concentration and therefore most of the lime is used just to meet this alcalinity demand. The product of the reaction is however good as a flocculant, and thus this lime is not completely lost.
The pH is even more important with lime than with metal salt precipitation. This is clearly illustrated with fig. 3.6. The precipitation is extremely sensitive to pH at about pH 9.
Calcultation of the lime required for removal of phosphorus from wastewater must take into account the fact that lime reacts also with several of the other constituents of municipal wastewater. These are free carbon dioxide, half bound carbon dioxide, magnesium and the ammonium ion.
The lime dose required to achieve a given pH and phosphorus removal is primarilya function of the wastewater alcalinity and it is relatively independent of the phosphorus concentration in the influent. This is not true for the metal salts.

Wastewater with a high content of sodium bicarbonate is not a good canditate for lime treatment. The high pH of 11 or more is produced by sodium hydroxide instead of calcium hydroxide when the wastewater does not contain sodium bicarbonate.

The pH requirements are different for pre-precipitation and post-precipitation (see next section). In the former case the pH mustnot be too high for the subsequent biological treatment. Therefore pH should not exceed 9.5 in pre-precipitation. If it is higher the effluent has to be recarbonated before the biological step. For post-precipitation, however, the pH should be higher than 11 in order to get small residual phosphorus levels. A reduction of pH might be required before disposal, but today no such pH reduction is used in Sweden.

Lime sludges are easier to dewater than iron or alum sludges. Lime sludge can also be recalcined to reusable lime in an incinerator. Incineration is a complex process, and detailed experiences can be found in the literature cited.

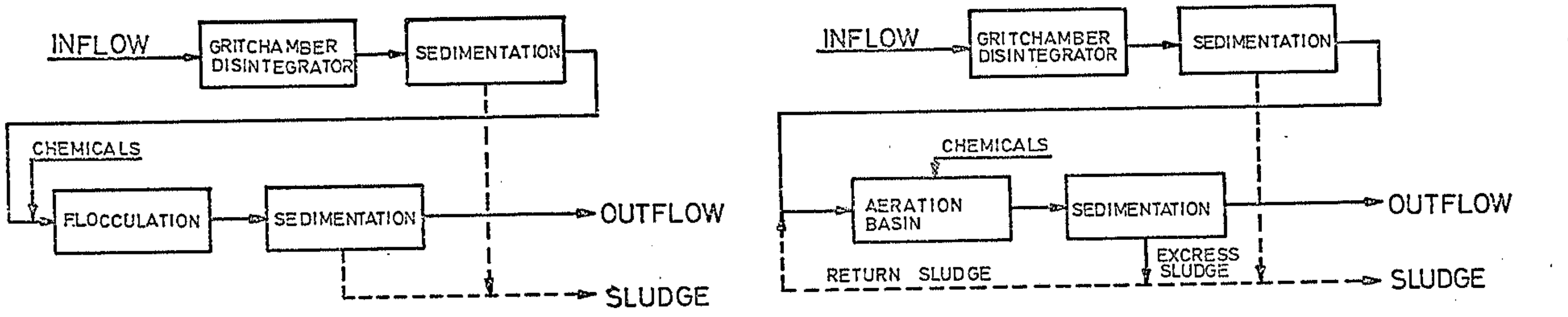
3.5.3 Where to add the chemicals?

The sedimentation taking place after the precipitation is similar to what happens in other sedimentation tanks. For removal of the chemical flocs one can use flotation and lamella sedimentation as well. This has been done with good experience in Sweden.

The chemicals can be added in different parts of a wastewater treatment plant, as illustrated by fig. 3.7.

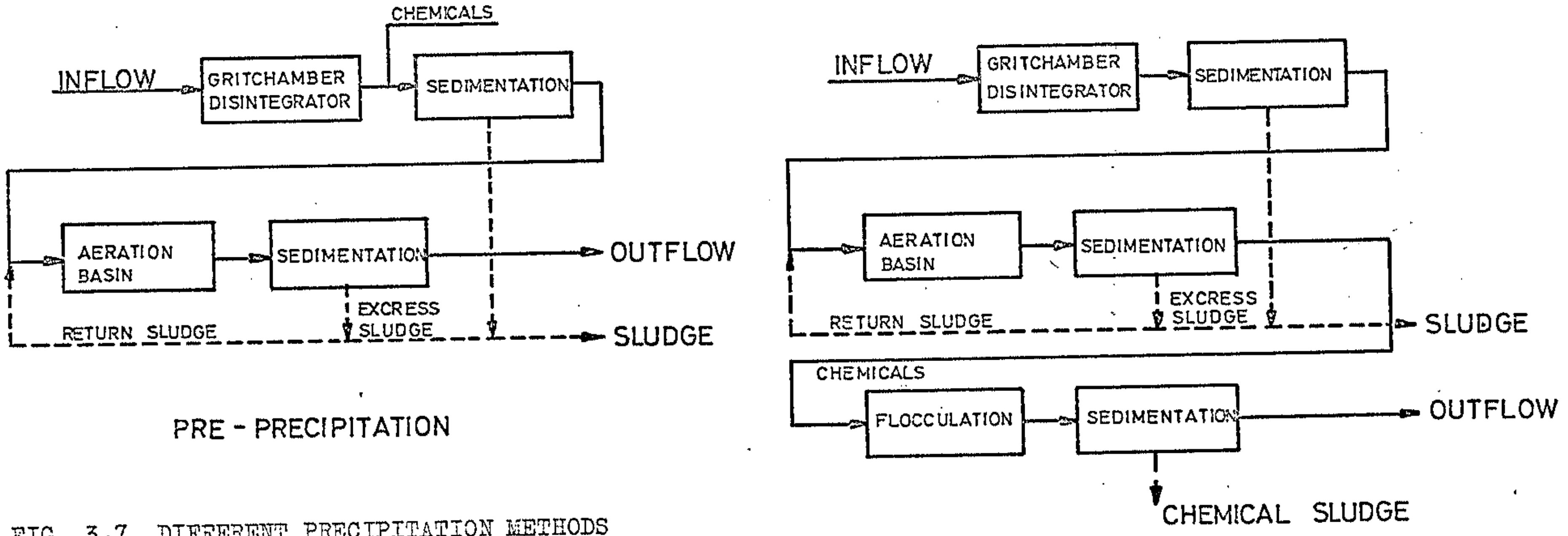
- before a flocculation and sedimentation unit, where no biological unit process is available (direct precipitation)
- in the biological section with removal in the secondary sedimentation tank (simultaneous precipitation)
- just before the primary tank with removal taking place in the primary (pre-precipitation)
- in a separate stage after the biological treatment (post-precipitation)

In Sweden simultaneous precipitation is used to a less extent than the others. It has, however, been met with increasing interest especially together with external aeration and ironsalts as precipitants. Post-precipitation is the most common process in Swedish plants (80 - 85 % of the chemical plants). For further details, see Ulmgren (1973 B) and (1971), Kugelman (1972), Hannah (1971) and Hilmer (1971).



SECONDARY PRECIPITATION (DIRECT)

SIMULTANOUS PRECIPITATION



PRE - PRECIPITATION

POST- PRECITATION

FIG. 3.7 DIFFERENT PRECIPITATION METHODS

3.5.4 Typical disturbances of the chemical treatment

Several sources for dynamical disturbances of the precipitation process have been mentioned previously in this section. The sedimentation and flocculation properties are not only depending on the phosphorus content but on quite a lot of different factors. The most important disturbances can be summarized as

- flow changes giving different settling characteristics in the primary treatment and in the clarifier
- pH changes
- bicarbonate alcalinity changes
- phosphate content changes
- organics solids load changes

Especially flow and pH changes have to be detected carefully. They can also appear suddenly as chock loads. The other disturbances mainly occur as diurnal variations.

3.6 Nitrogen removal

Nitrogen can exist in wastewater in four different forms: organic-N, ammonia-N, nitrite-N and nitrate-N. It is found primarily in the first two forms.

In Swedish plants phosphorus removal has been emphasized at the cost of nitrogen removal, but despite this fact nitrogen contamination is an important factor in wastewater. Here the main problems and the most important methods for nitrogen removal will be mentioned. A large number of reports are treating nitrogen removal, especially at the Environmental Protection Agency, USA much attention has been paid to this problem. European work is also presently going on, Ulmgren (1973 C).

The major water quality objective of nitrogen control is to prevent excessive depletion of dissolved oxygen of the recipient by the biological oxidation of ammonia-N to nitrate-N. This conversion is illustrated by following reactions:

$$NH_4^+ + 1.5\ O_2 \xrightarrow{\text{Nitrosomonas sp.}} NO_2^- + H_2O + 2H^+$$

$$NO_2^- + 0.5\ O_2 \xrightarrow{\text{Nitrobacter sp.}} NO_3^-$$

Nitrogen control is also important because ammonia-N have a chlorine demand which reduces disinfection efficiency.

A conventional activated sludge process can be altered to provide for significant degree of nitrification. Such changes include increase of aeration rate, contact time and sludge age as well as maintaining the pH at 8.0 - 8.4, see Wild (1971).

Normally a 20 - 25 % reduction of nitrogen can be achieved in an activated sludge process. Under good circumstances the nitrogen removal can be much higher. In the Käppala plant outside Stockholm it is about 50%. The reactions are quite temperature sensitive and below 18°C there is a significant decrease in the reaction speed.
As nitrogen in any form can serve as an algal nutrient, nitrification of sewage is not enough to get good nitrogen control.
Under anaerobic conditions the nitrate ion can react with an organic such as menthanol to form nitrogen gas,

$$5\ CH_3OH + 6\ NO_3^- \longrightarrow 5\ CO_2 + 3\ N_2 + 7H_2O + 6\ OH^-$$

Heterotrophs serve as a catalyst in this biological denitrification. The dosage of methanol is a typical loop which is suitable for automatic control. In practice the dosage of methanol is close to 3 mg methanol to 1 mg nitrate-N. Some experiences of biological denitrification have been achieved at the Blue Plains Wastewater plant, Washington DC, see Olsson-Ulmgren (1973).

There are also physical-chemical means to remove nitrogen. Breakpoint chlorination has been tried in pilot plants, e.g. in Blue Plains, as reported in Bishop et.al. (1972) and Olsson-Ulmgren (1973). The preferred reaction is

$$3\ Cl_2 + 2\ NH_4^+ \longrightarrow N_2 + 8H^+ + 6\ Cl^-$$

There are, however, several side reactions competing with this reaction giving undesirable nitrogen trichloride (which is odorous) and nitrate. Breakpoint chlorination also gives an interesting control problem, because the desired reaction is dominating when the pH is held between 6 and 7. As the pH tends to decrease because of the reaction it has to be adjusted continuously.

Nitrogen removal by air-stripping has been tried at some places, as reported in Olsson-Ulmgren (1973). Nitrogen is present in either ammonium or ammonia form, depending on pH. When pH in increasing the ammonium ion is converted to the NH_3 form which is a slightly soluble gas. The solubility is a function of temperature. By rising pH above 11 ammonia-N can be removed by stripping it out with air. The potential for the integration of air stripping with lime precipitation is obvious, see Culp (1971). The problems at low temperatures are, however, prohibitive, and the method is considered doubtful at many places, see Olsson-Ulmgren (1973).

3.7 Sludge treatment

When considering the cost and effectiveness of waste treatment technology sludge disposal is often overlooked. This is unfortunate as up to half the cost of the conventional treatment can be charged to sludge handling and disposal.

Therefore the water treatment and sludge handling should be considered together in order to get realistic cost to performance figures of the plant.

Sludge is a thick suspension of organic solids which is drawn from the clarifiers.

The sludge handling involves severals steps, such as thickening or stabilization, dewatering and ultimate disposal.

The sludge handling has also to be considered in water treatment because of some feedback effects. The sludge water which is brought back from the stabilization and dewatering processes can give significant disturbances, such as

- flow disturbances, often as chock loads
- pH changes
- high suspended solids disturbances

As the sludge water has a very high suspended solids content the disturbances in the prmary treatment can be significant even if the flow rate is not high. Sometimes lime is added to the sludge for stabilization. The return water (reject water) can give some undesired disturbances in the biological treatment or metal salt precipitation.

In the sludge treatment processes there are some control problems which can be considered separate from the water treatment problems. As one example of control problems anaerobic digesters can be considered. There the organics are reacting with microorganisms acting as catalysts to form new anaerobic microorganisms, carbon dioxide, methane and water.
The operation of digesters is by no means simple and many failing digesters have been reported.

Some control problems connected to anaerobic digesters have been discussed by Wells (1971).

Temperature control of incinerator furnaces can be considered as a separate problem too. This control generally does not cause any special problems.

3.8 Filtration

Some major problems in in-depth filtration will be considered in this section. In Sweden there is now an increasing interest in this type of processes. Surface filtration by means of microscreens or diatomaceous earth filtration or sand filters will not be discussed here.
The objective of filtration is to produce an effluent that meets the established treatment criteria at minimum cost. Then trade-offs have to be discussed between the degree of pretreatment, desired length of filter run and filter cleaning requirements. A quite complete discussion of these topics is found in Culp (1971) and Tchobanoglous (1970 A, B).

It has been found that the nature of the particulate matter in the influent to be filtered and the size of the filter materials are perhaps the most important process variables. Influent characteristics such as suspended solids concentration, particle size and distribution and floc strength are crucial. Turbidity is often used as a practical means of monitoring the filtration process, and is often correlated to the suspended solids concentration.

Floc strength is probably the most important influent characteristic. For example, the residual floc from the chemical precipitation of biological processed wastewater may be considerably weaker than the residual biological floc before precipitaion. Further the strength of the biological floc will vary with the mean cell residence time, i.e. increase with longer mean cell residence times.

The filtration process influences the operation of the other parts of the plant in the sense, that backwash water has to be recycled into the process. The backwash flow, if returned directly to a clarifier, is usually large enough in relation to the design flow through the clarifier to cause a hydraulic overload of the clarifier. Typically the length of the filter run may be 10 - 12 hours, while the backwashing time is normally 5 - 8 minutes. To avoid the chock load of the returning water the backwash wastes should be stored in a buffer tank and be returned in a controlled flow rate.
The volume of the backwash water is typically 2 - 5 percent of the whole design plant flow, and therefore the units must be designed in a proper way to meet this new demand.

4. Some essential control problems in a wastewater treatment plant

In this chapter the wastewater treatment will be considered out of a control point of view. In 4.1 some introductory remarks are made and after that, in 4.2 the most essential control loops are listed. The most common external disturbances are described as well. It is essential to distinguish between small and large disturbances, which is illustrated in 4.3.

4.1 Introductory remarks

Automatic control in wastewater treatment plants occurs very seldom today. Very little on-line instrumentation and control equipment has been introduced and only some local controllers are common today. Those controllers might be essential for the operation of the plant but they represent by no means automatic control of entire unit processes.

Some examples of frequently used local controllers can be mentioned. Level control for the influent pumps is quite common. Temperature control of anaerobic digesters and of incineration furnaces is also well established.

The interest for more advanced control naturally increases when the quality regulations get more strict and the processing costs are rising.
A good automatic control of a plant is intimately related to a number of demands. The following questions must be considered before a new control system is designed:

- does it exist suitable instruments and control devices?
- are there reliable process models for control purposes?
- what are the estimated process improvements?
- what is the economic justification?

The first two questions will be discussed more in detail in following chapters. The third and fourth ones are certainly very difficult to answer. Nevertheless, they are the fundamental questions. Some aspects will be given in chapters 8 and 9.

It should be noted, that for several external disturbances there are no control strategies available today. Such disturbances include dumps of oil, grease, industrial chemicals or heavy metals. Storm floods often cause overflows, thus giving an insufficient degree of contaminant removal. In some cases on-line instruments are not mandatory for control purposes. In the biological processes some time constants are of the order of several days, and therefore laboratory tests are adequate.

4.2 Essential control loops

In table 4.1 the most important control loops of a wastewater treatment plant are listed along with possible measurement and control variables. In the table there is no indication of the size of the disturbances, and certainly the control action will be different depending on the amplitudes, which is further discussed in 4.3 and in following chapters.

It should also be observed, that all the loops are not decoupled from each other. For example, in the activated sludge process the control of the return sludge flow rate could not be separated from the dissolved oxygen control. There are also many disturbances to which the control system has to respond by acting on the same control variable.

Many disturbances occur early in the plant. If they could be detected properly it should theoretically be possible to control them by feed-forward control strategies. Now there are model inaccuracies and process disturbances which make feed-forward control insufficient. It has to be combined with feedback control. As an examlpe pH control of chemical precipitation could be considered. An approximate dosage of chemicals could be calculated out of influent pH. In order to get more accurate control, however, the effluent pH has to be fed back to the dosage controller in order to make adjustments.

The table also shows the need for a careful and thourough evaluation of available and reliable gauges. These problems are further discussed in chapter 10.

process	performance criteria	function of control	process control variable	desired measurement variable	external disturbances	available on-line instruments
plant influent gates	Influent to the plant as constant as possible	Maintain steady state flow through plant by the gates	Influent gates	Depth Flow	Influent flow rate	depth flow

Table 4.1 page 1

Essential control loops of a wastewater treatment plant.

process	performance criteria	function of control	process control variable	desired measurement variable	external disturbances	available on-line instruments
mechanical screens	Reduced screen cleaning costs	optimizing screen cleaning activity	frequency of cleaning of screens	diff. pressure across bar screen	varying load of large articles	diff. pressure level meters
	Minimal coarse solids to plant			(by measuring liquid level)	in raw sewage	
raw wastewater pumping	Desired flow for the plant	Maintain a flow rate close to desirable flow through plant despite influent flow changes by controlling the pumps	pump speed (can the speed be varied?)	wet well level flow	influent flow	depth flow
	Maximum efficiency and life of the pumps			pump speed pump power pump bearing temperature		power current voltage temperature
Primary sedimentation	1) Maximum removal of solids Optimal concentration of sludge for dewatering	1) pumping the sludge from sedimentation tank, when sludge level exceeds set point value	1) sludge pumping cycle	sludge concentration and sludge level	varying settleable solids load	Nuclear radiation density meter Sludge level meters
	2) Maximum removal of solids	2) adding of chemicals	2) chemical dosage	2) Influent and effluent SS and volatile matter. pH and DO important for further treatment. Hydraulic load Phosphorus. COD (or TOC), pH and DO important for further treatment	varying hydraulic and settleable solids load, varying P load Return sludge water loads	COD TOC pH DO Flow SS P-analyzer

Table 4.1 page 2.

process	performance criteria	function of control	process control variable	desired measurement variable	external disturbances	available on-line instruments
activated sludge process	Maximized BOD removal Minimized need for air for power saving. Keeping enough amount of micro-organisms	1) influent flow rate	1) hold influent flow rate constant by means of equalization tank	1) flow	1) influent load	flow
		2) Keep the DO level at an optimal value	2) Air blower speed	2) DO	2-5) Changing flow,MLSS, food-to-microorganism ratio (both in influent and in aeration), changing oxygen demand because of organics, oil, grease, heavy metals, industrial chemicals. Changing sedimentation properties.	DO probes
		3) Oxidation Reduction Potential (ORP) to indicate the state of oxygen utilization	3) Air blowers	3) ORP		ORP (not reliable)
		4) RAS flow to supply required biomass	4) RAS flow rate	DO MLSS RAS flow Influent flow. Oxygen uptake		RAS flow DO MLSS Influent flow Respirometer
		5) Sludge blanket control to increase storage capacity of active biomass	5) Sludge wasting flowrate or RAS flow rate	5) Sludge blanket level		Sludge blanket

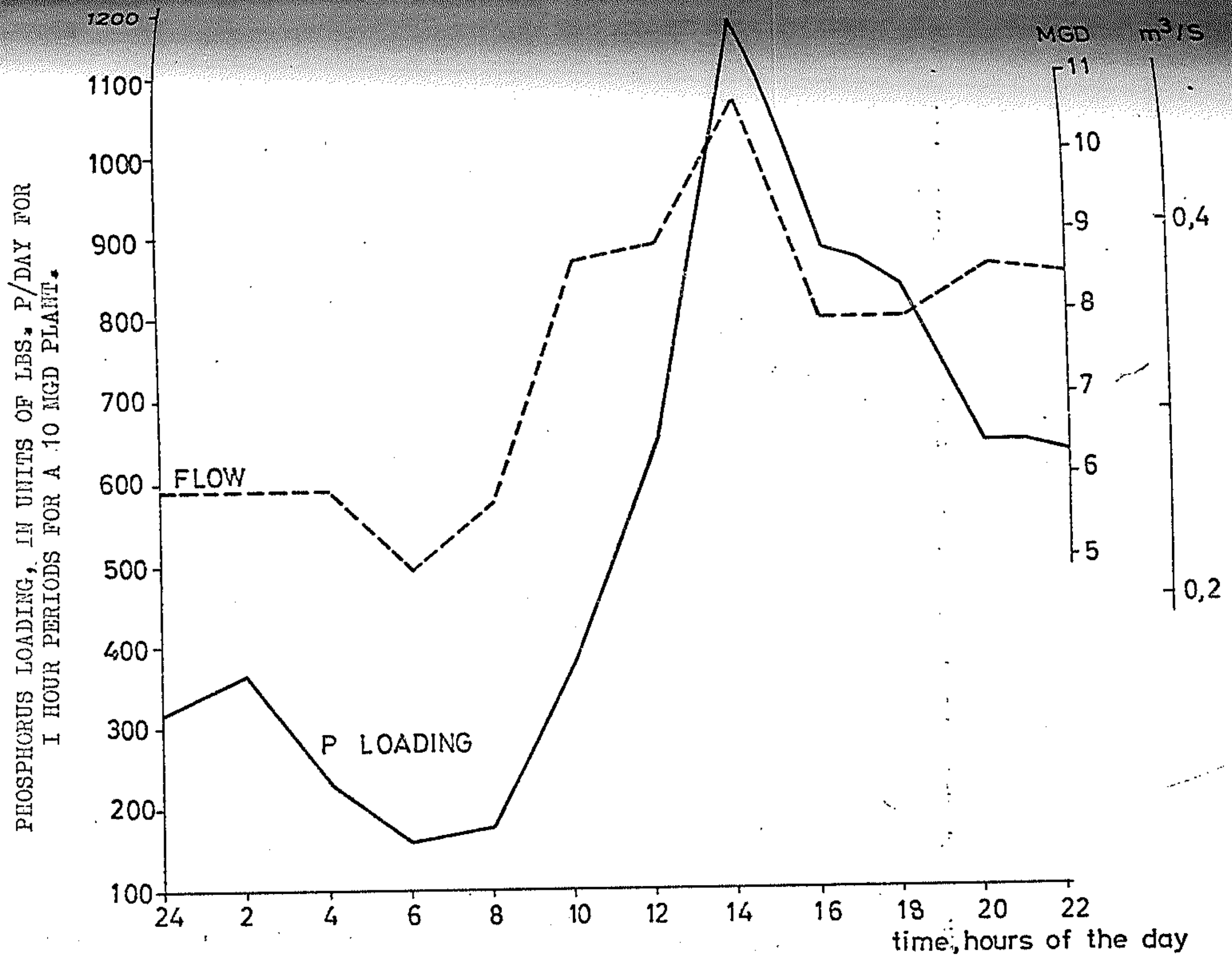
Table 4.1 page 3.

process	perfomance criteria	function of control	process control variable	desired measurement variable	external disturbances	available on-line instruments
Chemical precipitation (Al or Fe) or lime	Minimize P and SS content in effluent to minimal cost At the same time minimize the sludge volume due to added chemicals Good flocculation	Dosing chemicals in order to remove P and SS	Chemical feed	pH Flow total-P SS	Hydraulic load variations, P content pH disturbances (incl. sludge return water) Alcalinity Organic solids	pH flowmeters autoanalyzers
Trickling filter	Steady, continuous flow High percent BOD and SS removals	Maintain well distributed flow, proper loading rates, effluent recycling, air circulation	Recycle pumping rate	Recycle volume Oxygen uptake SS	varying primary effluent flow	flow SS meters temp Respirometers

Table 4.1 page 4

In order to illustrate the time scale of the disturbances two typical diurnal flows are shown in fig. 4.1 and 4.2.
The first plant is an American one, designed for 0.44 m^3/s (or 75000 p.e.) see Roesler (1972 A). The figure shows that the phosphorus disturbances are roughly varying with the same speed as the flow but may be delayed.
Fig. 4.2 shows the flow variations together with the BOD_5(BOD_5= BOD_7/ 1.15) load for the Henriksdal Wastewater treatment plant in Stockholm, Sweden. (650 000 p.e.)
The oxygen demand, measured in TOC (Total Organic Carbon) or COD (Chemical oxygen demand), is also related to the flow variations.

As mentioned in 3.7 the sludge return water can cause chock loads occurring roughly ones an hour.



PHOSPHORUS LOADING AND FLOW
FOR A 10 MGD PLANT (~0,45 m^3/S)

FIGURE 4.1

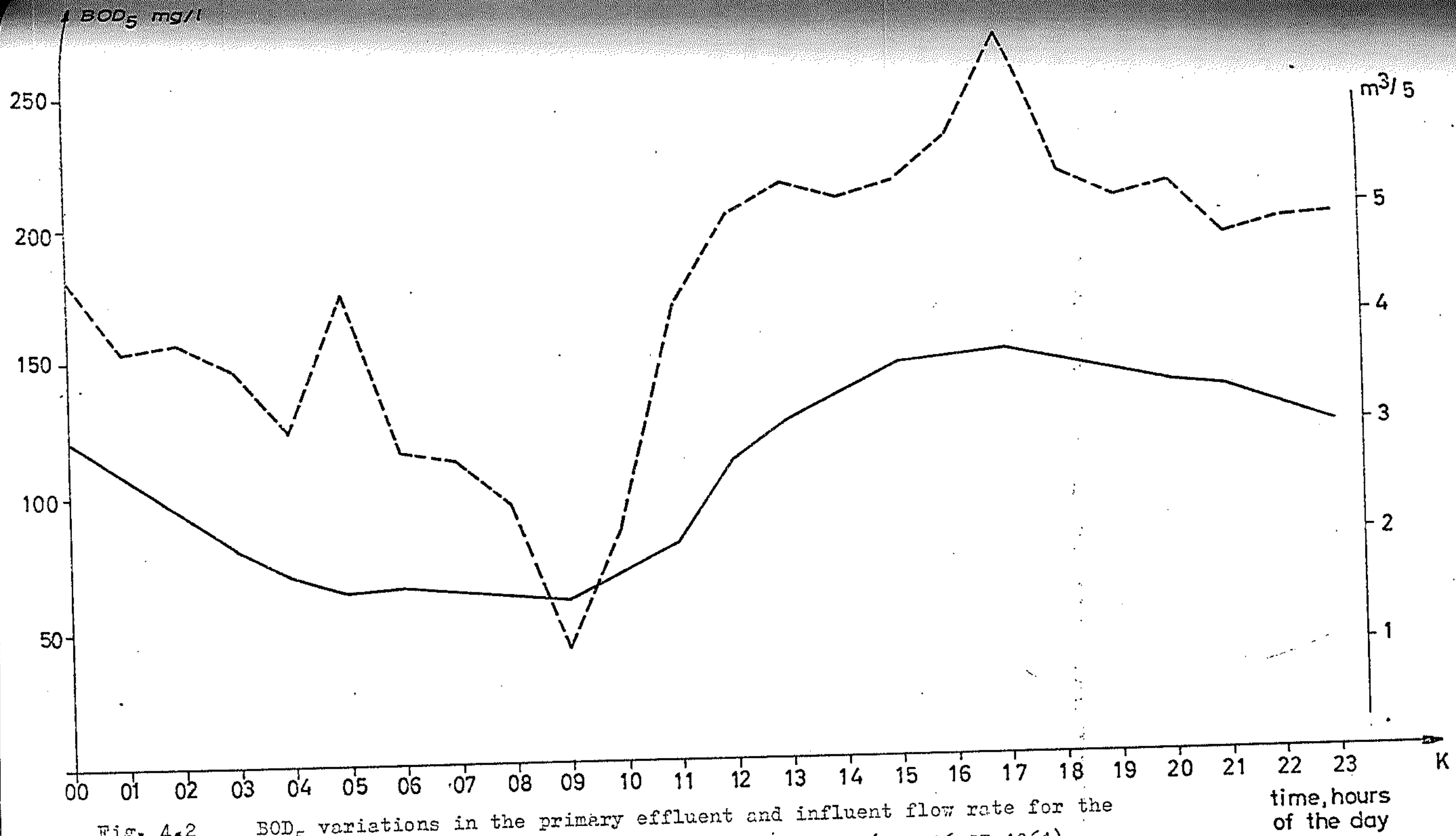


Fig. 4.2 BOD_5 variations in the primary effluent and influent flow rate for the Henriksdal Wastewater Treatment plant, Stockholm. (Jan 26-27,1961)

4.3 Small and large disturbances

The amplitude if the disturbances occuring are important in deciding what control strategy to use. In this section it will be discussed two different types of strategies, depending on if there are small or large disturbances on the plant.

As enphasized in 4.1 there are disturbances which are not possible to control, either because of their amplitude or on their very nature, such as toxic chock loads heavy metals etc.

In a real plant small disturbances occur all the time and small corrective actions could be taken to eliminate the consequences of them. Typically the dynamic parameters of the plant, such as the time constants are not changed significantly under these conditions.

Linear controllers can handle this type of disturbances in general, and most often a PID controller is sufficient. In some cases a linear multivariable controller might be rewarding to use, e.g. in the activated sludge process, but yet no experience is available from any plant.

The performance criterion is often to minimize the variations around a certain reference value for a parameter, see table 4.1. Loops of that nature include the control of

- pH in chemical precipitation
- dissolved oxygen level in aerator
- mixed liquor suspended solids value

A large disturbance causes significant changes in the dynamics of the process, such as time constants if nonlinear effects are dominating.

As an example the time constants of the sedimentation tanks and the activated sludge process change whenever the influent flow changes. During such large disturbances there is an obvious risk for decreased control performance due to decreased detention times, deteriorating sludge properties which increasing sludge volume index, changes of the spatial distribution of the oxygen demand in the aerators or changes of the content of microbes.

To handle large disturbances PID or similar regulators might be insufficient. Either the correction has to be more elaborate or the process has to be operated differently.

As an example consider what can be done at a large flow disturbance, which is in fact a grade change of the process. If there is a hold basin before the plant the influent gates could be used to level out the disturbances. Chemicals could be added to the primary sedimentation tanks in order to improve the effluent going to the biological process. Special holding tanks of microbes might be used to get enough amount of activated sludge. On the other hand, if the influent flow rate is very low compared to the design flow, the process operation might be changed to meet another demand. There is e.g. a chance to increase the detention time in the primary sedimentation tanks.

5 Control of the influent flow rate

One of the requirements for optimum wastewater treatment is a steady influent flow. Since raw wastewater flow is characteristically not steady, some influent control to allow constant flow would aid the treatment and automation. A basin for raw wastewater storage prior to plant entry could prove to be useful for qualizing flow, especially during storms.In very large plants, however, this strategy is not considered realistic, see Olsson-Ulmgren, (1973), chapter 7.

Another approach can be used if the plant is superimposed on the existing sewerage system. Then it should be potential possibilities to pump a steady flow to the plant, while the sewer is the buffer system.
At a municipal wastewater treatment plant the flow is generally characteristically diurnal depending on the habits of people. A plant serving a large sewerage system has generally quite a small variation in the day, because of the different lengths of the partial flows to the plant. The difference between peak flow and minimum flow might be 30 - 50 %. On the other hand in plants with a geographically concentrated sewerage system the difference might be a factor of ten between max and min flows.
The variations between different days depend mainly on the weather. At storm floods and rains the flow can increase several times.

Control of the influent gate will therefore be discussed here. As an example experiences from the Käppala wastewater treatment plant in Stockholm will be discussed.

At Käppala one of the gates, the so called segment gate, has been equipped with control equipment and a hydraulic motor in order to control the influent to the plant.

During the tests of smoothing the influent variations some problems appeared. The raw water basin functioned as a sedimentation tank. If the raw water was held more than one day the amount of suspended material was so large, that the screens were overloaded when the gate was opened. This test indicates, that the gate must be opened at least once a day. This means that only smoothing of diurnal variations should be possible. At the design stage of a plant, however, it should be possible to design the screens so that they do not get overloaded at such gate openings. Then the basin could be used for storing raw water for several days.

Thus there are several factors which must be taken into account when the influent flow rate should be controlled, and they can be summarized as follows,

- the average flow varies from day to day
- the gate must be opened at least once a day
- the gate should be opened during normal working hours, so that the screens can be monitored

In general conventional equipment can be used for the control, even if manual supervision is necessary.

6 Control of sedimentation tanks

The clarification process going on in a sedimentation tank, either a primary or a secondary clarifier, is purely fluid mechanical. Clarification is a basic element in all wastewater treatment, and suspended solids are removed by sedimentation.

6.1 Sedimentation

There are different natures of the sedimentation going on. In discrete settling, the particle remains its individuality and does not change its shape, size or density during the settling process. Flocculant settling occurs when the particles agglomerate during the settling period. Zone settling, finally, involves a flocculant suspension which forms a lattice structure and settles as a mass.

The theory of the different sedimentation processes which can occur can be found in some standard text book, i.e. Eckenfelder (1966), Culp et.al. (1972) or Metcalf & Eddy (1972).

Most works on operation of sedimentation tanks have been based on steady state analysis, i.e. Smith (1968 A, 1968 C, 1970 B), Hansen et.al. (1969). Design is then generally based on some assumptions of a certain inflow rate and constant particle size and mass concentration.

The flow rate, however, is deviating considerably from the normal flow at most times and it is varying significantly. Therefore the operation of the sedimentation tank should be considered carefully, especially to tackle the diurnal variations of the influent flow rate.

6.2 Dynamical models

Schainker et.al. (1970) have developed a mathematical dynamic model of suspended solids in clarifiers. The derivation of the model is based on the physical laws in fluid mechanics. This structural model has then been adjusted to real data from a real plant.
The purpose of the model is first to give the engineers added insight into the time-varying process. It has also been used to evaluate different coagulant control policies for primary clarifiers.
The particles are divided into a number of size classes. For every size class the settling velocity of the particles is governed by Stoke's law. The differental equations describing the settling are in general nonlinear. The observed output of the system is the concentration of suspended solids in the effluent.

Another approach is presented by Bryant et.al. (197). They use the relation between the overflow rate and the suspended solids removal efficiency as a basis for the model. The clarifier is structured as an ideal liquid-solids separator followed by a series of complete mixing department tanks. These tanks are used to simulate the hydraulic delays. The model is derived by mass balance equations around each element.

6.3 Disturbances and control strategies

The essential disturbance to a sedimentation tank is the influent flow rate. Therefore a control strategy should mainly recognize this fact in order to give an acceptable effluent quality.

Schainker et.al. (1970) have studied the effect of chemical coagulant control. Because of the increased size of the particles the settling velocity was significantly increased and the effluent quality consequently improved.

Often a peak load occurs which is greater than the design flow, and the activated sludge process can easily be overloaded during a storm flood. The wastewater then can only be treated by the primary sedimentation process and it is interesting to try some improvement of the sedimentation during these peak hours.

Flotation and lamella sedimentation processes offer special problems. Some operational experiences of lamella sedimentation tanks are reported in Ulmgren et.al. (1972). The lamella sedimentation tank is more sensitive for load variations than an ordinary tank. If the amount of sludge grows too much, then the distance between the lamellas might be insufficient and thus the efficiency is decreased.

7. Mathematical models of the activated sludge process

7.1 Introduction

The activated sludge (AS) process dynamics is quite complicated and it includes many unknown and unmeasurable phenomena. Still it is of course important to develop mathematical models in order to increase the understanding of the dynamics.

Although the unit processes of a wastewater treatment are simple in concept, in reality they are highly complex biological systems with poorly understood behaviour. From a biological point of view, most of these processes may be classified as continuous-flow enrichment cultures of microorganisms with the species of microorganisms predominating being determined by the characteristics of the input wastes and the environmental conditions created through process design and operation.

An excellent survey of the kinetics of biological processes is found in Andrews (1970), where different growth and decay theories are compared. A literature survey of biológical kinetic models is also made by Carlsson (1973).

As many phenomena in the AS process are spatially dependent, the dynamics should be described by partial differential nonlinear equations. By invoking a number of simplifications more reasonable mathematical models can be developed, consisting of ordinary differential equations and lumped parameter descriptions. The models, however, have to be nonlinear. Only a very limited number of models have been verified during transient operating conditions, and mostly only in laboratory scale.

The most popular process model is based on the complete mix AS process (CMAS). Quite a large number of authors have described different approaches to this type of process. An important contribution was made by Westberg (1967) and the model was using mass balance equations for living as well as dead bacteria, and the balance between substrate and living bacteria. Curds (1971) has considered sewage bacteria instead of dead bacteria and has considered the presence of ciliated protoza as well. The Westberg model has been used by Brett et. al. (1973) to synthesize a feed-forward control of an AS process. Another approach, but still based on mass balance equations has been made by Ott et.al. (1971).

The Environmental Protection Agency (EPA) in USA has sponsored the development of mathematical models for wastewater treatment unit processes, among others an AS process, described in Smith (1970 A) and Smith et.al. (1969 B).

In order to describe the spatial dependence better Curds (1971) assumes that the aeration tank is split up into a number of complete mix tanks. He considers only living organisms.

7.2 Mathematical model of the Complete-mix activated sludge (CMAS) process

The process dynamics is assumed to be described by ordinary differential equations. Here the most important state variables will be considered, namely living organisms, dead organisms, sewage bacteria and substrate. All derivations are based on mass balance equations for the aeration tank.

The sludge density in the clarifier is assumed to have a concentration C times the activated sludge concentration in the aerator. The volume of the aerator and clarifier are assumed constant.

7.2.1 Mass balance for living organisms

Consider the material flows around the aeration tank of fig. 7.1. The mass balance equations are generally formulated as

Ackumulation = input + recycle - outflow - endogeneous decay + growth

The sludge inflow is

$$\text{inflow} = Q \cdot x_o \qquad (1)$$

where Q = influent flow rate, x_o = influent sludge concentration. Most often X is considered to be zero. x_o is certainly much smaller than the activated sludge concentration x in the aeration tank.

The return activated sludge is assumed to be

$$\text{recycle} = r\ Q\ C\ x \qquad (C > 1) \qquad (2)$$

where r = ratio of return sludge flow rate to influent flow rate, C = compaction ratio so that $C \cdot x$ is the sludge concentration in the final clarifier.

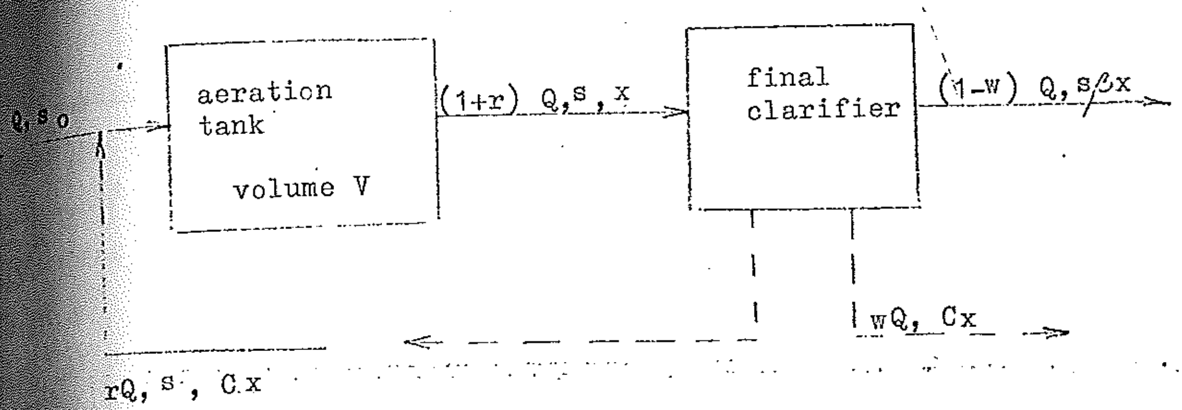


fig. 7.1 Schematic flow sheet of a complete mix AS process. The symbols are defined in the text.

Westberg (1967) adds the input and recycle terms in a different way

$$\text{input} + \text{recycle} = Q\,(1 + r)\; x_{in} \qquad (3)$$

where x_{in} = concentration of living bacteria in the total flow supplied to the aeration tank. He then neglects the influent sludge concentration and the final results resembles that of (1) and (2).

The outflow is simply assumed to be

$$\text{outflow} = (1 + r)\; Q\; x \qquad (4)$$

The bacterial growth and decay terms are the most controversial ones. Bacterial growth will take place in the reactor and at the same time, the substrate will be consumed. The rate of growth depends on the number of bacterial present and on the supply of substrate. The growth of bacteria is not proportional to the number of living bacteria as pointed out e.g. by Westberg (1967). Death and redissolving of cells can not be disregarded, especially in case of recirculating and high sludge ages.

Westberg assumes the net growth would be

$$\text{net growth} = V(\mu x - \eta \frac{x}{s}) \qquad (5)$$

where V = tank volume, μ = growth rate coefficient, η = death rate coefficient (assumed greater than zero) ans s = substrate concentration.

Some authors, e.g. Ott (1971), assume the death rate proportinal to the living organisms, i.e.

$$\text{net growth} = V\,(\mu \cdot x - \mu_d\, x) \qquad (6)$$

thus disregarding the influence of the substrate. Curds (1971) completely neglects the death of bacterias.

The specific growth rate coefficient is often expressed as

$$\mu = \mu_m^1 \frac{s}{K_x + s} \qquad (7)$$

in which μ_m^1 is the maximum growth rate and K_x the substrate concentration at which μ is equal to $0.5\mu_m^1$. This equation is commonly known as the Monod equation, Monod (1949).

Another expression derived by Teissier (1936) has the form

$$\mu = \mu_m'' \left(1 - \exp(-cs)\right) \tag{8}$$

where c is a constant for the system. Especially at high substrate concentrations the latter expression is considered more accurate.

Sometimes a simpler expression for μ is used,

$$\mu = \mu_0 \cdot s \tag{9}$$

where μ_0 is an empirically determined constant for a certain plant.

A modification of the Monod theory was presented by Haldane (1930). He assumes the growth rate to be

$$\mu = \frac{\mu m}{1 + \frac{K_s}{s} + \frac{s}{K_i}} \tag{10}$$

This growth theory has been used by D'Ans et.al. in their models, see section 8.3.

Combining equations (1) - (5) the active sludge mass balance equation is achieved to

$$V \frac{dx}{dt} = \underbrace{Q \cdot x_0}_{\text{input}} + \underbrace{r \cdot Q \cdot C \cdot x}_{\text{recycle}} - \underbrace{(1 + r)\, Q \cdot x}_{\text{output}} + \\ + V \left(\underbrace{\mu x}_{\text{growth}} - \underbrace{\eta \cdot \frac{x}{s}}_{\text{decay}} \right) \tag{11}$$

Disregarding the influent sludge concentration x_0 and the substrate variations (s = constant), eq. (11) can be simplified to

$$\frac{dx}{dt} = r \cdot F \cdot C \cdot x - (1 + r)\, F \cdot x + \mu x - \mu_d\, x \tag{12}$$

where $F = Q/V$

writing $\mu - \mu d = a$ the equation gets

$$\frac{dx}{dt} = ax + F\,(rC - 1 - r)\,x \tag{13}$$

This equation has interesting structure from a control point of view. It reminds of a bilinear equation as the control variable r is multiplied with the state variable . The main disturbance of the system is the influent flow rate Q. Thus also this term F is multiplied with x.

The consequence of this structure is, that the system time constant is changed both for changing influent as well as changing return sludge flow rates. Whenever some of these flow rates is increased the constant of the living organisms of the AS process is decreased.

7.2.2 Mass balance for dead bacteria

The net growth of the dead bacteria is desribed according to Westberg (1967) by

$$\text{net growth per } m^3 \text{ and h} : \eta \frac{x}{s} - \vartheta xz \qquad (14)$$

where s = substrate concentration
x = activated sludge concentration
z = concentration of dead bacterias

The first term represents the adding of new dead bacterias. (Cf eq.(5))
The second term represents the redissolution of the dead bacterias. This is supposed to be proportional to living as well as dead bacterias (z). This dissolution is caused by enzymes , and the concentration of them is supposed to be proportional to the activated sludge concentration.
The total balance equation can be derived similarly to the living organisms and the result is

$$\frac{dz}{dt} = x \left(\frac{\mu}{s} - \vartheta \cdot z \right) - z \cdot f(t) \qquad (15)$$

where the function f(t) is:

$$f(t) = \frac{wQ}{V} \frac{(1 + r)}{(r + w)} \qquad (16)$$

7.2.3 Mass balance for substrate

The mass balance can also here be expressed as

Accumulation = inflow + recycle - output - utilization

The mass flow terms are defined from fig. 7.1 where s denotes the substrate concentration in the aeration tank and s_o the influent substrate concentration, measured as BOD (mg/l).
The input, output and recycle terms are derived analogously to the previous discussion. Here the utilization terms will be commented on especially. The utilization of substrate as the living organisms grows is assumed to be

$$\frac{\mu x}{Y} \tag{17}$$

where Y = the yield constant = weight of sludge mass formed / weight of substrate consumed.
The μ coefficient is the same one as in 7.2.1.
Another utilization term is discussed by Curds (1971), by sewage bacteria. These organisms are defined as those bacteria which are born in sewage in considerable quantities.
On entry into the aerator they do not flocculate and are considered to remain in suspension in the sedimentation tank. These organisms are like the sludge bacteria able to utilize the soluble constituents of sewage but since they remain dispersed are themselves available as a food source for ciliated protozoa that may be present.
Defining the yield constant for the sewage bacteria to Y_b and growth rate coefficient μ_b the utilization is

$$\frac{\mu_b x_b}{Y_b} \tag{18}$$

where x_b is the concentration of sewage bacteria.
Westberg (1967) does not discuss any sewage bacteria but adds another term coming from the dead bacteria. The negative term $\gamma \cdot x z$ from eq. (14) corresponds to a positive term in the substrate mass balance. The substrate mass balance equation thus reads

$$V \frac{ds}{dt} = \underset{\text{input}}{Q \cdot s_o} + \underset{\text{recycle}}{Q \cdot r \cdot s} - \underset{\text{output}}{(1 + r) Q \cdot s} + \underbrace{\vartheta \cdot x \cdot z}_{\text{from dead bacteria}} - \underbrace{\frac{\mu \cdot x}{Y} - \frac{\mu_b \cdot x_b}{Y_b}}_{\text{utilization}} \tag{19}$$

The equations (11), (15) and (19) thus define the dynamics of the CMAS process.

The equations should be combined with a solid balance equation around the final clarifier. We assume no solids built up in the clarifier and the input (on the LHS) equals the output (on the RHS)

$$(1 + r)\, Qx = (1 - w)\, Q \beta x + w\, Q\, C\, x + r\, Q\, C\, x \tag{20}$$

where β = fraction of clarifier solids escaping the effluent, w = waste sludge flow rate as a fraction of the sludge entering the clarifier. If β is assumed negligible compared to the sludge waste rate, then w can be solved from eg. (20) to

$$W = \frac{(1 + r - rC)}{C} \tag{21}$$

Thus the excess sludge can be expressed by the parameters r and C.

Typical numerical values of the coefficients of the CMAS dynamics equations can be found in Westberg (1967), Smith (1969 B, 1970 A) and Ott (1971). These authors refer to other sources as well for parameter values.

Curds (1971) also includes other state variables in the CMAS dynamics, not only a single flocculated bacterial species. He considers a ciliate and bacteria growing together in the aeration tank, and three types of ciliated protozoa are included in his AS model.

7.3 Mathematical model of a spatially dependent AS process

In a step aerated AS process (SAAS) or a plug flow AS process the spatial distribution of the sludge and substrate concentrations must be taken into account. This is made by introducing finite differences in the spatial variable along the tank. This is easiest accomplished by assuming that the aerator consists of a number of completely-mixed tanks arranged in series.

The derivation of the mass balance equations is a trivial extension of the CMAS models, see fig. 7.2 describing three tanks in series. The number of equations is of course increased as every tank of the system is described as a CMAS system.

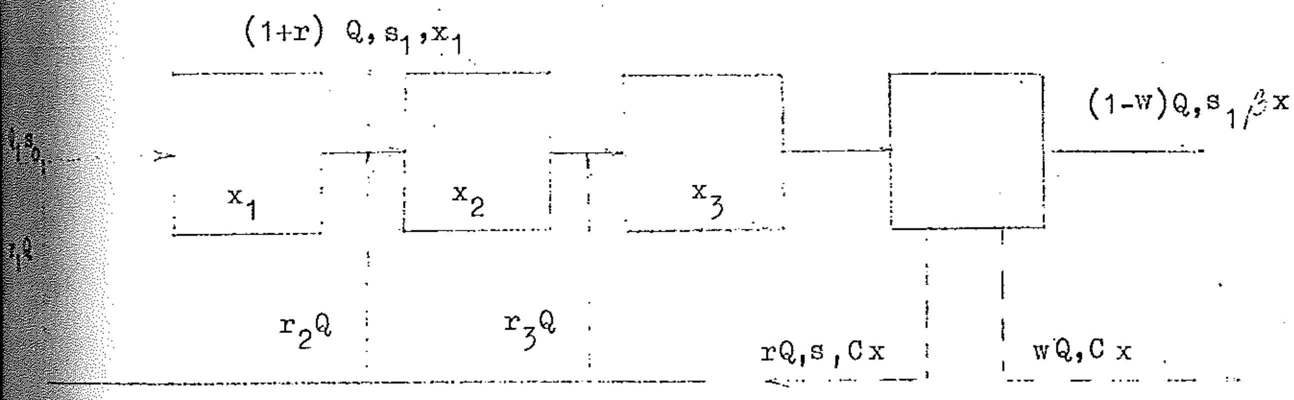


Fig. 7.2 Schematic flow-sheet of a step aerated AS process, approximated with three complete-mix AS tanks.

Some details can be found in Smith et.al. (1969 B), Curds (1971) and Milbury et.al. (1965).

7.4 Dissolved oxygen models

The dissolved oxygen balance has not been included in the models, presented in 7.2 and 7.3, but it could be incorporated easily as shown by Smith and Eilers (1970 A). In the previous models it was assumed that the dissolved oxygen (DO) concentration was large enough, so that it can be considered an excess nutrient. In fact, if the DO concentration is maintained at 2.0 mg/l or greater the removal of BOD of the process can not be influenced by DO changes. The DO becomes an important variable however, if one attempts to optimize the operation and the economy of the AS process.

A material balance equation of the dissolved oxygen can be formulated as follows (the variable names refer to fig. 7.1).

$$\frac{dD}{dt} = \underbrace{-\frac{\Omega}{V}\cdot D}_{\text{net outflow}} + K_L \cdot \underbrace{\theta\,(D_s - D)\cdot u_{air}}_{\text{from blowers}} \underbrace{-\frac{dO}{dt}}_{\text{respiration}} \qquad (22)$$

where D = dissolved oxygen concentration (mg/l)

D_s = saturation level of DO in water, ~ 8 mg/l

u_{air} = air flowrate from the blowers

$k_L \cdot \theta$ = overall liquid phase gas transfer coefficient

$\frac{dO}{dt}$ = oxygen uptake rate.

The oxygen uptake can be modeled according to an expression of McCinney (1962),

$$\frac{dO}{dt} = \alpha \sum_i S_i + \beta \sum_i X_i \qquad (23)$$

where S_i represents the concentration of the i^{th} substrate and X_i represents the concentration of the i^{th} microorganism.

Experiences in Palo Alto, California reported by Wells (1973) indicate that the term Q/V can be neglected compared to the other terms in (22). It should also be observed that the DO dynamics is a bilinear system, like the mass balance eq. (11).

The DO model of the type (21) has been compared to actual performance in an AS process in Palo Alto, see Wells (1973). It was found large discrepances between the theoretical model and practical experiments. A simplified linear model of second order with time delay was identified, based on simulated data from the model from Smith (1970 A). The structure then was

$$\frac{d}{dt}\begin{pmatrix} x_1 \\ x_2 \end{pmatrix} = \begin{bmatrix} -a_1 & a_1 \\ 0 & -a_2 \end{bmatrix}\begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} 0 \\ b_2 \end{pmatrix} u_{air}(t - T_d),$$

with both time constants about 6 hours and the time delay T_d about 5 minutes. Experimental experiences, however, indicated that the time constants are in the order of about 15 minutes.

The differential equations in fact are time variable, thus creating different time constants at different times.

Present identification works at the Division of Automatic control at Lund Institute of Technology seem to verify this result.

Data are supplied from the Palo Alto Plant.

8. Control of the activated sludge process

8.1 Introduction

There are several theories how to control an activated sludge process. The most common strategy is based on the assumption, that the food to microorganism ratio should be constant. Another one assumes a strategy so that the life time of the microbes is constant at a desired value. No successful full scale control implementations based on theoretical models like those in chapter 7 have been reported, as far as the authors are aware. Generally those models have been shown to be too simple to really describe what happens in a real plant.

There are so many different types of microbes, both active and dead, and it is not possible to measure the microorganism concentration on-line. Moreover ideal mixing is not possible in the aeration tank. There are so many other contaminants in the water, that the accuracy of the bacterial growth models gets too low.

The essential variable describing the activated sludge process is the concentration of living and dead bacterias. Since there are no instruments to measure these variables, some indirect variables have to be measured instead. BOD, TOC, COD, etc. are measures of the biological activity, but the problem is to get rapid measurements to be used on-line. As remarked in chapter 10 there are respirometers being developed today, which at least can give quite a good measurement of the oxygen uptake as function of time. To the authors' knowledge there is no closed loop application, based on any COD, BOD or TOC meter. Other interesting substrate variables are the mass of organisms (MLSS etc.) and the amount of oxygen supplied by the blowers (dissolved oxygen DO).

Because of the measurement problems in biological environment many plants are using indirect methods of control. Such a control is based on measurements of DO, sludge level, MLSS, respirometers etc. Return activated sludge flow rate, excess activated sludge flow, blower power, sludge pumping etc. then can be used as control variables.

8.2 Feedforward-feedback control of the activated sludge process

The control of the dynamics described by the balance equations between bacteria and substrate has been studied by Westberg (1969) and Brett et.al. (1973). A further attempt in the same direction is presented in Davis-

Kermode-Brett (1973). The authors have not considered any external variables such as dissolved oxygen or pH in the models.

The purpose of the feedforward control is to keep the substrate at a constant level, independent of disturbances in influent substrate and flow rate.

The CMAS process, defined by eq.(7.11), (7.15) and (7.19) is to be controlled by a control structure showed in fig. 8.1.

The disturbance appears as a product $Q \cdot s_o$ in eq. (7.19), and the flow rate also directly disturbs the bacteria concentrations in eq. (7.11) and (7.15).

Westberg has made two major assumptions in the model. The term · x z in eq. (7.15) and (7.19) is replaced by · x z where x_a is the average concentration /x_a z over a cycle (= a day). The other assumption is that the disturbances are known and they are specifically assumed to be sinusoidal.

The return sludge flow rate can be calculated algebraicly so that disturbances in s_o and Q are completely outleveled by the feedforward controller.

As in all feedforward control systems, the major difficulty is that the system model has to be accurate, otherwise the feedforward will create problems. Small errors now are corrected by the feedback control law. Moreover, the time derivatives of the disturbances Q and the product $Q \cdot s_o$ have to be calculated.

It should also be stressed, that the size of the disturbance can be very large, as discussed earlier. An accurate control of such a disturbance is certainly not a simple task.

Brett (1973) has considered the same problem as Westberg but his assumptions are somewhat different. The model has been linearized around an operating level and the feedforward control then has been evaluated to extinguish the disturbances in the substrate level. Also here the control law includes derivatives of the disturbances.

The validity of the model is further decreased because of the linearization.

8.3 Optimal control by the influent flow rate

A simple model of an activated sludge process has been used by D'Ans et.al. (1971A, 1971B, 1972) mainly for the purpose of the application of optimization theory. The dynamics is represented only by the state variables living bacteria and substrate. The control variable $u = Q/V$ (see fig. 7.1)

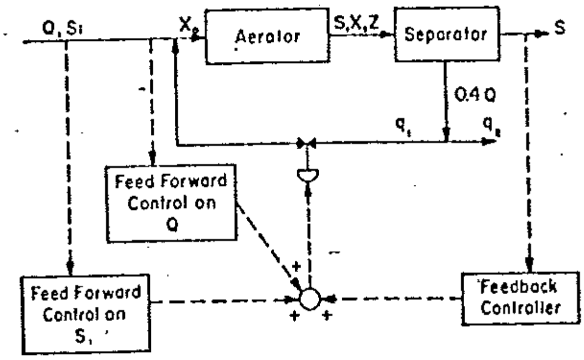


Fig. 8.1 Feedforward - feedback control of an activated sludge process according to Brett.

is considered limited,

$$0 \quad u \quad M \tag{1}$$

The reactor is a CMAS process where the growth rate is described by eq. (7.10).

The differential equations describing the system then are of the form

$$\frac{dx}{dt} = \frac{s}{K_2 s^2 + s + K_1} \cdot x - u \cdot x \tag{2}$$

$$\frac{ds}{dt} = \frac{-sx}{K_2 s^2 + s + K_1} + u(1 - s) \tag{3}$$

where x, s, u and t are normalized suitably

If μ is inserted according to (7.10)

$$\frac{dx}{dt} = \mu \cdot x - u \cdot x \tag{4}$$

$$\frac{ds}{dt} = -\mu x + u(1 - s) \tag{5}$$

Now, if (4) and (5) are compared to (7.11) and (7.19) respectively ($u \Rightarrow F$) then it can be seen that significant simplifications have been made in (4) and (5). As the equations are not verified to measurements, the model cannot be very reliable.

This system has only one stable stationary point. The amount of bacteria produced shall be maximized, i.e. the performance index is

$$H = u \cdot x$$

This gives control programs u* for different areas of the state space.

8.4 Some essential activated sludge process feedback loops

8.4.1 Dissolved oxygen control

The most common loop considered is the control of dissolved oxygen (DO). The blower speed or mechanical aerator power is used to control the DO level in the aerator. This type of control has been realized at some plants, see Olsson-Ulmgren (1973), Wells (1972), Stepner (1972). The reason this control can be used in the proposed way is, that the micro-organism food uptake rate is not affected by the dissolved oxygen content, if this content is above a certain level ($\sim$ 1 mg O_2/l).

The output variable is measured by one or more DO sensors in the aeration basin. Such a control system is intended to reduce the variations in the amount of oxygen delivered. This control scheme can save electrical power. In section 8.5 it is shown the cost savings in one installation.

There are some models evaluated of the DO dynamics, as shown in chapter 7.4.

The position of DO probe is very important. Consider e.g. if the probe is placed near the influent to the aeration tank. The influent consumes oxygen very rapidly. This control system ensures that only at the point where the probe is placed the oxygen level will be satisfactory. The mixed liquor could possibly be anaerobic at the end of the tank with such a control system. Thus the DO profile is important.

8.4.2 Return_activated_sludge control

Another important loop is the control of the return activated sludge (RAS). This control is intended to supply the required biomass to the aeration tank based on oxygen requirements, thus maintaining a constant food-to-microorganism ratio.

It is early demonstrated by the equations (7.11), (7.15) and (7.19) that the RAS control variable (r) is essential.

The RAS flowrate is manipulated in response to a change in the total air requirements operating under DO control.

Then, if the DO control is good enough, a change of the DO concentration can be taken as an indication that the food-to-microorganism ratio has changed. This procedure then is analogous to using the entire process as a respirometer. From the mass balance equations it can then be calculated the required solids concentration to maintain a constant food-to-microorganism ratio.

A direct measurement can also be made by measuring the microorganism respiration rate. On-line respirometers will be available soon commercially, and today there exists some prototypes in the market (see ch. 10). The RAS flow rate is then changed in order to get the desired food-to-microorganism ratio.

8.4.3 Mixed liquor suspended solids control

The activated sludge process is getting more effective when the mixed liquor suspended solids concentration (MLSS) increases in the aerator. If the MLSS is held too high, however, the final settler will be overloaded and the sludge will escape in the final effluent. Now the MLSS can be controlled in different ways. Wells (1973) suggests that the MLSS is controlled around a certain setpoint by the RAS flow rate. In this particular control system the food-to-microorganism ratio is not held constant. The setpoint could be established by the operator, or it can be adjusted by other measurements, as discussed in 8.4.4.

Smith (1971) has suggested another control variable, the excess sludge flow rate. This loop is however very slow, and it is therefore quite difficult to control the MLSS level within given limits. On-line meters to measure MLSS in the aeration tank are available and are claimed to behave satisfactorily.

8.4.4 Total organic carbon (TOC) or chemical oxygen demand (COD) control

There are several signals which can be used as indications, of changes of the food-to-microorganism ratio. Except those mentioned in 8.4.2 the primary effluent can be monitored by a TOC or COD measurement and a feed-forward signal can be used for control of the activated sludge process. The signal can e.g. adjust a setpoint of a MLSS controller. The control has to be corrected for small variations by feeding back TOC or COD signals from the secondary effluent. The control signal is also here the return activated sludge flow rate (RAS).

8.4.5 Sludge blanket control

Sludge blanket control is sometimes used as an alarm system for too high level blanket. The objective is to prevent overflow of solids from the secondary clarifiers. Corrective action is required whenever the sludge blanket alarm is activated. The return sludge pump is then turned on.

8.4.6 Controllers

From the discussion in 8.4 it has been demonstrated that the activated sludge process is a truly multivariable system. The input variables i.e. the blowers and the return activated sludge flow rate, are coupled to several outputs, and therefore a good control strategy should take these couplings into account.

To the authors' knowledge no multivariable control is implemented today in any activated sludge process, but some discussions on this problem have taken place, see Olsson-Ulmgren (1973).

Many of the control loops could possibly be cascaded together as single-input-single-output control loops. An ordinary PID controller might be insufficient in some cases, especially for large disturbances. The reason is, that the dynamics is nonlinear, as shown in chapter 7. For large disturbances or at grade changes the PID controller either has to have a very low sensitivity or has to be tuned automatically. In the former case the controller will give a poor control.

It should be emphasized, that the measurement problem is crucial. First, an accurate control requires accurate measurements, i.e. good instruments. The instrumentation problem is further discussed in chapter 10. Then there are some variables which cannot be measured automatically. One example is the sludge volume index as an indication of bulking sludge or rising sludge (see 3.3).

As the activated sludge process is spatially dependent there is also an important question where to place the measurement instruments. If the DO profile is time varying in the aerator, then one DO probe is certainly insufficient.

8.5 Examples of dissolved oxygen control performance

The performance of DO control has been compared to manual control for the Renton Sewage Treatment Plant in Seattle, Washington, USA described by Roesler (1973). The plant is a conventional activated sludge plant with plug flow in the aerators. Twelve DO-probes were installed in the aerator. Only one of the probes was used for control purposes while the other 11 ones were used for monitoring the DO profile.

The plant was run manually during a three month test period in 1970 and automatically during corresponding three months in 1971. The estimated economic improvements were 10 % in power cost savings or approximately \$ 7000 per year in the plant, designed for 1,1 m^3/s (= 190.000 pe). The DO control had an effect only on the biological activity as measured by the BOD. The BOD removal increased from about 82 % to 95,5 % because of DO control. Considering loading differences, differences in mixed liquor, suspended solids and hydraulic flow the improvement was even far more substantial in biological degradation. Also Ryder (1969) has reported experiences from this plant.

Respirometer control has been tested at the Jones Island Treatment Plant, Milwaukee, Wisconsin, as reported by Genthe (1972). With this control it was possible to keep the food-to-microorganism ratio closer the desired value, thus saving blower costs. A saving of 15 % out of $ 560 000 annual blower costs is claimed to be realized due to the respirometer monitoring.

9. Control of phosphorus reduction

It is clear that chemical precipitation costs are significant in the operation of wastewater treatment plants, and therefore the adding of chemicals must be optimized.

9.1 Control of chemical precipitation

In order to determine the feed of chemicals not only the flow of the influent must be measured but also the concentration of phosphorus, and the pH value. Not even this information is satisfactory as the solids removal is a function of the flocculation of other compounds than phosphorus, as remarked in 3.5.

A good control system must of course take these influences into consideration. In many cases a certain mole ratio between phosphorus and chemicals added can be stated out of experience, for the individual plant and a control system must of course take this into account. With lime as the coagulant a good control is obtained by pH measurement.

It is important that feedforward control is combined with feedback control. Thus the actual pH value in the flocculation should be measured in order to make corrections of the dosage. Moreover online monitoring of the effluent can indicate the chemical precipitation effectiveness. Such monitoring may include turbidity, pH, dissolved oxygen and oxygen demand e.g. COD.

Automatic control of lime precipitaion has been tested in pilot plant scale in Blue Plains, Washington DC, see Convery et.al. (1972), Bishop et.al. (1972) and Olsson-Ulmgren (1973). The amount of lime fed to the process is controlled by conductivity, pH or alkalinity. The pH control system philosophy in the lime precipitation is also applicable to other pH control systems, such as recarbonation, prechlorination or breakpoint chlorination. Since these unit processes are unusual in Sweden, they are not discussed in this report. Some experiences are reported in Olsson-Ulmgren (1973).

There exist instruments for continuous monitoring of the phosphorus content in the water. e.g. the Tellusond, Johnson and Technicon Phosphorus meters.

9.2 Example of performance of chemical precipitation control

The economics associated with four alternative strategies for removing phosphates by precipitation by alum has been calculated by Convery (1972), Roesler (1972A). The phosphate loading has been given for a 0.5 m^3/s plant (= 85 000 pe). The four different strategies are

a) addition of a fixed amount of alum to precipitate out the maximum amount of daily phosphate loading

b) two daily dosage levels of alum according to diurnal variations of load

c) alum addition as a function of flow

d) alum addition as function of mass loading of phosphate

To remove one mole of phosphorus 1.5 mole of aluminum was used. The study showed clearly that the savings were successively larger when going from strategy a to d. At a cost of $ 46.90/ton, 17.15% dry Al_2O_3 the saving were about $ 75.000 a year for strategy d) compared to a). Then the control equipment costs were not taken into account.

10. On-line measurement for control

In chapters 4, 8 and 9 a number of variables have been mentioned, which are important for the control schemes. In the text consideration has already been taken to the status of existing online instruments. There are two principal types of instruments for aquiring process information.

1. In-stream probe or sensor which generates an analog signal of the variable measured.
2. Automated analytical procedure (or automated wet chemistry) which samples a quantity from the flow and subjects the sample to an automatic laboratory procedure, requiring reagents. Although the procedure may be rapid, a certain amount of time must elapse before the measured value is recorded.

The maintenance problems seem to be the real hard ones to solve.

The environment is of course very destructive for a sensor, and therefore regular cleaning, calibration and other maintenance should be the natural routine. The problem is, that there is too little personnel for this type of business and most often the personnel is not adequately trained for on-line instruments.

In the following paragraphs the status of the instrumentation will be briefly reported for the most important water characteristics variables.

10.1 Flow measurements

Measurement of flow is the most important monitoring in a wastewater treatment plant. The flow changes cause the major disturbances, and flow measurements are necessary for the control of several unit processes, e.g. primary pumps, sludge wasting, supernatant return, chemical dosage. It is beyond the scope of this work to look in detail at the flow measurement methods. It can be found elsewhere e.g. Ulmgren (1973), Metcalf & Eddy (1972) chap 3, Nordström (1972), Wiksell (1973B) and in standard books on instrumentation.

Today all new plants are equipped at least with some flow meter. In Sweden the most common principle is based on level measurement either in an overflow or in a Parshall flume, where the level can be measured with ultra sound.

These flowmeters seem to be reliable and the accuracy is about 1 - 3%. The calibration may, however, be complicated as there is no linear relationship between flow rate and level. Magnetic flowmeters are getting more common even if they are sometimes expensive. The accuracy is claimed to be between 1 and 2%. For small water velocities the accuracy may be as bad as 5%. Some experiences are reported in Olsson et. al. (1973).

10.2 pH-measurements

pH is important for the chemical dosage as well as for characterization of influent and effluent. As remarked in chapter 3.5 the precipitation is very sensitive to the pH value. It is also an indication to changing conditions for the activated sludge process, see chapter 3.3. The pH can be conveniently measured with a pH meter.

10.3 Temperature

Temperature is important for certain unit processes, especially sludge treatment (digestion) and is automatically measured.

It is also essential for the activity of the microorganisms in an activated sludge process. The temperature variations, however, are generally so small, that they can be neglected as influencing the operation and control.

10.4 Dissolved oxygen

As mentioned in chap. 8.4 the DO concentration is critical in the control of the activated sludge process. DO check of final effluent is also interesting.

Today there are several DO-probes available, but the experiences of the reliability seem to be very varying. Some users claim, that the correlation between the instrument signal and the oxygen concentration is very poor, others that the probes give adequate information, see Werner (1970, 1972), Olsson-Ulmgren (1973) ch. 3.6 and 9.9, and Roesler (1972), Wiksell (1973B).

It is true that many DO probes require significant amounts of maintenance due to membrane clogging and rupture. The DO probe is also an essential part of a respirometer to measure the oxygen uptake.

It should be mentioned that both stationary and portable DO probes are in use. Naturally the latter ones are more reliable in general as they are more maintained.

10.5 Biochemical oxygen demand

BOD indicates the oxygen requirements of the organic and chemical matter. BOD removal is a prime function of the activated sludge process.

The BOD is an effective parameter for measuring biodegradable organics. Since it takes 5 or 7 days for the standard determination and 20 days for an estimation of complete bio-oxidation it is certainly inappropriate for automatic control.

The determination of BOD is also in general very inaccurate. It is not unusual to get 20% error in the determination. Despite the mentioned drawbacks some experts consider BOD still interesting, see Helfgott et. al. (1972). The problem is to use the information correctly. BOD has some nice properties. It can tell what the bacteria can do by way of assimilation and oxidation. If toxics enter the system the BOD may serve as a bioassay test. Both BOD_5, BOD_7 and BOD_{20} are points on a first order decay curve. In order to determine this curve one needs several points to get a better accuracy; then one gets a Warburg respirometer response curve. Such data can only be collected in days and weeks and not in some minutes to some hour necessary for automatic control of the activated sludge process.

On-line BOD respirometers are presently developed, Genthe et. al. (1972), and some prototype is today in the market (Badger Meter), see Olsson-Ulmgren (1973). The respirometer automatically withdraws a sample (some liters) from the wastewater stream and measures the oxygen utilized by the biomass in the sample as it consume waste material. The test period may be from 15 minutes to some hours. An acceptable accuracy between the relation of this short term oxygen demand and a long term BOD has been reported, see Genthe (1972).

The principle of oxygen uptake measurements basicly employs the principle of the Warburg respirometer. The sample has to be taken in a sealed container and the oxygen concentration (dissolved oxygen) has to measured at time zero and time t. With the Badger Meter instrument the oxygen depletion is measured by means of a sensitive pressure transducer, see Arthur (1968). Another principle has been developed by Abson et. al. (1967). The consumed oxygen is gradually replaced coulometrically and the amount of replaced oxygen is measured (the Simcar respirometer). Montgomery et. al. (1971) have also described this instrument. Still another principle is presented by Ingols (1968). A repetitive short BOD test is performed by using a dissolved oxygen electrode.

10.6 Oxygen reduction potential

ORP (oxygen reduction potential) is the potential required to transfer electrons from the oxidant to the reductant and it presents a qualitative measure of the state of oxidation in the treatment processes.

Continuous ORP monitoring as a measure of biological activity has been proposed e.g. by Dirasian (1968).

In biological degradation of organics many oxidation-reduction reactions take place, where different compounds act as final hydrogen acceptors. In aerobic systems (e.g. the AS process) molecular oxygen is the ultimate acceptor of hydrogen. Effenberger (1967) has related ORP to dehydrogenase activity and the correlation was found to be good. The correlation coefficient is, however, a function of the specific activated sludge process.

The reliability of ORP sensors seems still to be low, see e.g. Helfgott (1972).

10.7 Total carbon and total organic carbon

TC and TOC represent an approach to use non-biological techniques for demand measurements. It is assumed that TC and TOC are in constant proportion to the oxygen demand. The TOC does not include the oxygen demand equivalent of nitrogen and some organically bound reduced metals that can be present. A TOC determination thus specifically represents oxidation of only carbonaceous materials. While inorganic carbon may cause interference, it is removed by acid treatment of the sample or by a separate determination and subtraction of the inorganic carbon from the total sample reading (TC).

Typical ranges of operating values of TOC are 60 - 350 mg/l for raw wastewater and 3 - 18 mg/l after 95 % removal.

TOC measurements are very common in the USA. There is an increasing interest also in Sweden for this type of instruments.

10.8 Chemical oxygen demand

Chemical oxygen demand (COD) also represents a demand measure and is used to represent BOD. An effluent sample is reacted with a strong oxidizing chemical at elevated temperatures. The intent is to measure all oxidizable substances in the sample and thus obtain a value somewhat higher than (but correlated with) ultimate BOD. The COD analysis is considered to be repeatable with good satisfaction. However, it takes some time to get the answer, of the order half an hour or more.

It is often possible to establish a satisfactory linear relationship between BOD and COD (or between BOD and TC). Any correlation is, however, generally characteristic of the plant and its own data, see e.g. Rowe et.al. (1968). Davis (1971) and Ford (1968) have compared COD with TOC. The COD-to-TOC ratio varies as a function of aeration time for biological treatment of domestic wastes.

Today there are several COD meters in the market e.g. Johnson, Tellusond and Technicon. The COD meters have been used e.g. for final effluents. Sometimes the accuracy has been unsatisfactory. One problem is; that the COD test in most cases generates mercury contaminants. The TOC test is better in this special context. If the residual chlorine concentration is too large, then the test is also disturbed by wrong reactions.

10.9 Total oxygen demand

Still another method of analysis uses combustion of all the oxygen-demanding matter. Total oxygen demand (TOD) analysis reacts the sample with oxygen gas at about 900°C and the oxygen consumption is measured. The results are available in a few minutes. Replicate samples give closely similar answers - within 2 to 5 percent, according to Bochinski (1973). There are interferents, notably nitrate. Nitrate interference varies from a relatively small effect to a highly significant one, depending on the design of the specific TOD instrument. Bochinski (1973) supports the view that the TOD test is quite realistic and correlated to the COD but more convenient to determine.

Today there are two principal types of TOD instruments available in the market. In one instrument type a continuous flow is entering the instrument, in the other discrete filtered samples are drawn from the stream.

10.10 Automatic analyzers

There are some other analyzers except the ones mentioned for different oxygen demand analysis. There is one analyzer (Technicon) for phosphorus (phosphate) analysis. At Tellusond and the Axel Johnson Institute in Sweden analyzers have been developed recently.

Phosphorus appears in several forms, such as total phosphate, orthophosphate, pyrophosphate, condensed phosphates and organic phosphates. One way to measure the phosphorus content is by the amount of total hydrolyzable phosphate. This principle is used in many instruments, like the Johnson, Tellusond and Technicon Autoanalyzers. The specific range is about 0.1 - 20 mg/l, measured as total phosphorus.

Nitrogen also appears in various forms. Usually ammonia, nitrate and total Kjeldahl are measured. Two ammonia probes have been developed - one by Orion Research and another by Electronic Instruments, Ltd. The methods are described by Harwood (1970 a, b).

10.11 Suspended solids

There are several methods for suspended solids measurements. Here only the methods based on light-absorbance and light-scattering will be discussed. The light can be either visible or infra-red. Ultrasonic waves and gamma radiation have also been used. The problems have been penetrated in detail in Zenz (1969), Wiksell et. al. (1973 A, B) and Downing (1965). The experiences indicate that visible light gives poor result, both absorbance and reflectance. The influence of colours in the water are negligible for infra red light, and also the influence of collodial particles diminishes. The normal accuracy is about 10%. One instrument based on light transmission has been developed at the Royal Institute of Technology as reported by Wiksell. Another instrument based on infra red light was tested as early as 1968 by EPA in USA. Still another sensor is available from Keene for the range 500 -

5000 mg/l.

The maintenance problem should be emphasized also for SS meters. Accumulated material on the sensing probe should be removed regularly.

11. Instrumentation and control in Swedish plants

Until some years ago the wastewater treatment plants were poorly equipped with on-line instrumentation. Automatic control equipment was missing completely.

During the great building program during the 1960 decade the interest for instrumentation and control increased considerably. The plants at Käppala (Stockholm) and Rya (Göteborg) are two examples of more elaborate instrumentation and computer installations. The computers are used for data aquisition and storage.

There are flow meters in all large plants and this was considered natural until the end of 1960's. Of economic reasons flow meters were not installed in the plants during this period, but nowadays the new plants are equipped with these instruments again.

The flow rate can be measured either in open systems (Parshall flumes, overflows) or in closed systems (magnetic flowmeters, differential pressures).

In open systems the flow is registered by some level sensor.

Most sensors are either based on ultra sound techniques or different types of level meters. The old types of capacitance meters are unusual today in the municipal wastewater plants, mainly because of maintenance reasons.

Magnetic flowmeters are not yet very common, but in the new large plants they are getting common.

Dissolved oxygen is measured mostly in laboratory tests. There are some few plants equipped with continuous DO meters.

Some respirometer prototype is available in Sweden.

A new type of sludge level indicator has been developed among others by Tellusond. It can be used for sludge removal in the sedimentation tanks.

COD-analyzers and suspended solids sensors are installed at some Swedish plants, e.g. Käppala, Växjö, Frövifors and Sundsvall.

For the quality control of the final effluent pH, SS, COD and phosphorus could be measured. In Sweden it is, however, not considered realistic to install all these sensors for quality control, except for the plants bigger than 6000-10000 m^3/day (12000 - 20000 p e). In most cases only the turbidity will probalby be monitored on-line.

Automatic control is applied in very few plants. In most cases only some alarm indication is installed, and the correction has to be manually performed.

In some plants primarily the chemical dosage is controlled based on the influent flow. Sometimes the pH is measured in the flocculation unit.

In some cases the sludge pumping in the sedimentation tanks is controlled by an open loop program at fixed time intervals. This is the case in Västerås, where one tank at a time is pumped during a certain time interval.

At sludge dewatering in centrifuges, the polymers may be dosed automatically according to the sludge feed.

There is no sophisticated automatic control installed today. There are, however, some potential possibilities for automatic control at Käppala, where a computer and several on-line instruments are available. Data logging is also possible in Gothenburg.

12 Some principal problems in a performance test

In order to compare automatic control with manual control some evaluation has to be done of the performance of the plant. There are several principal problems connected to this question and there is no obvious answer.

The test period has to be long enough to include the longest time constants of the process, and the biological process constants are of the order some weeks. Therefore such a test period should last a least for a month. It is not correct to compare the behaviour during two months after each other as the flow and contaminant patterns are not constant. On the other hand, if the same month is compared two years after each other many things might have changed too, including new operational experiences.

There are some obvious measures of improvements and saving, such as the costs for power and chemicals. The problem is to compare the costs during unchanged conditions around the plant.

The influent flow rate and content of contaminants should be comparable for two test periods. This is not easy to do, but of course oxygen demand, phosphorus analysis, pH etc. can be monitored during an intensive test period, e.g. each hour.

The quality of the effluent might also be different for two different control test periods. The primary problem then is, that no price is given for quality changes in the receiving water. Therefore only qualitative measures can indicate, if an improvement has occurred.

The maintenance problem should again be emphasized. Many of the instruments discussed require regular maintenance. In order to improve the operation the service personnel has to aquire a certain level of maturity to handle advanced instrumentation, as the wastewater treatment plant gets more sofisticated.

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References

Abbreviations:

AIChE	American Institute of Chemical Engineers
ASCE	American Society of Civil Engineers
EPA	Environmental Protection Agency
FWQA	Federal Water Quality Administration
IEEE	Institute of Electrical and Electronic Engineers
JACC	Joint Automatic Control Conference
WPCF	Water Pollution Control Federation
WQO	Water Quality Office
W&SW	Water & Sewage Works

1 Abson, J. W. C. D. Furness and C. Howe: (1967) J. Inst, of Wat. Pollut. Control, No 6, p 1, 1967.

2 Andrews J. (1970) Kinetics of Biological Processes used for Wastewater Treatment, presented at a Workshop on Research Problems in Air and Water Pollution, Univ of Colorado, Boulder, Colorado August 1970.

3 Arthur, R. M. and W. N. Hursta (1968): Short Term BOD Using the Automatic Respirometer. Proc. of the 23rd Industrial Waste Conf., May 7-9, 1968, Purdue Univeristy, Lafayette, Indiana, USA.

4 Bishop, D. F., W.W. Schuk, R. B. Samworth, R. Bernstein, and E. D. Fein (1972), Computer Control of Physical-Chemical Wastewater Treatment, in Pollution: Engineering and Scientific solutions, 522 - 547, Plenum Pulb. Corp. New York.

5 Bochinski, J. (1973) Measuring Oxygen Demand? Take your pick - TC, BOD, COD, TOC and TOD. Pollution Engineering, 45-46, Jan 1973.

6 Boughton, W. H., Richard J. Gottfried, Norval A. Sinclair, and Irving Yall, (1971) "Metabolic Factors Affecting Enhanced Phosphorus Uptake by Activated Sludge", <u>Applied Microbiol</u>., <u>22</u>, pp 571-577.

7 Brett, R. W. J., R. I. Kermode and B. C. Burrus (1973), Feed Forward Control of an Activated Sludge Process, Water Research, 7, 525-535, 1973.

8 Bryant, J. O. and L. C. Wilcox ( ) Real-time Simulation of the Conventional Activated Sludge Process.

9 Carlsson, B.: (1972) "Models for bacteria cultures" (in Sweden), Linköping University, Linköping.

10 Cecil, L. K. (1971) Evaluation of Processes Available for Removal of Phosphorus from Wastewater, EPA Project 17010 DRF, October 1971.

11 Cohen J. M. (1971):"Control of Environmental Hazards in Water" Symposia on Environmental Hazards, ACS Third Central Ragional Meetting, Cincinnati, Ohio, June 1971.

12 Convery, J. J. Roesler J. F. and R. H. Wise (1972) Automation and Control of Physical-Chemical Treatment for Municipal Wastewater, Applications of New CONCEPTS of Physical-Chemical Wastewater treatment, Sept 18-22, 1972, Pergamon Press, USA.

13 Culp, R. L. and G. L. Culp (1971): "Advanced Wastewater Treatment, Van Nostrand Reinhold Co., New York.

14 Curds, C. R. (1971), Computer Simulations of Microbial population Dynamics in the Activated Sludge Process, Water Research, 5, 1049--1066, 1971.

15 D'Ans, G., Kokotovic, P. and D. Gottlieb: (1971). "A nonlinear Regulator Problem for a Model of Biological Waste Treatment", IEEE Trans on Automatic Control, AC-16, 341-347.

16 D'Ans, G., et.al. (1971): "Time Optimal Control for a Model of Bacterial Growth, J. of Optimization Theory and Applications, 7, 1, 61-69.

17 D'Ans, G., et.al.: (1972) "Optimal Control of Bacterial Growth" Automatica, 8, 729-736.

18 Davis, E. M. (1971), Water and Wastes Engineering, p 33, Feb 1971.

19 Davis, J. J., R. I. Kermode and R. W. J. Brett (1973),"Generic Feed Forward Control of Activated Sludge", Department of Chemical Engineering, Unvi. of Kentucky, Lexington, Kentucky.

20 Dirasian, H. A. (1968), Water and Sewage Works, 115, 10, 453.

21 Dowing A. L., G. E. Eden and R. Briggs, (1965), Some Recently Developed Instruments: Can they assist sewage works operations? J. Inst. Sew. Purif., 64, 74-92.

22 Eckenfelder, W. W. Jr. (1966) Industrial Water Pollution Control, Mc Graw Hill, 1966.

23 Effenberger, M. (1967), Proc. 3rd Int. Conf. Water Pollut. Res., Munich, 1966, 2, 94-97.

24 Eilers R. G. and R. Smith (1971), "Wastewater Treatment Plant Cost Estimating Program" WQO Publicqtion April 1971.

25 Evans, D. R. and J. C. Wilson: "Actual Capital and Operating Costs for Advanced Waste Treatment".

26 Ford, D. L., (1968) Public Works, p 89, April.

27 Genthe, W. K., R. M. Arthur and R. Srinivasaraghavan (1972): Go online: it is vital for automation, Water & Waste Engineering, 9, 7, 42-44.

28 Haldane, J. D. S. (1930), Enzymes, pp. 84-85, Longmans, London.

29 Hannah, Sidney A. (1971) "Chemical Precipitation", <u>Advanced Waste Treatment and Water Reuse Symposium, FWQA, Dallas, Texas, January 12 - 14</u>.

30 Hansen S. P., G. L. Culp and J. R. Stukenberg (1969) "Practical Application of Idealized Sedimentation Theory in Wastewater Treatment", J. WPCF, 1421-1444, Aug 1968.

31 Harwood, J. E. and D. J. Hayser (1970), Water Research, 4, 695.

32 Harwood, J. E. and D. J. Hayser (1970), Water Research, 4, 539.

33 Helfgott, T., T. Wilson and L. K. Cecil (1971) "What wastewater parameters shall we measure in the automation of wastewater treatment plants", AICHE Symp series, 68, 124, 1972.

34 Hilmer, A. (1971) Flotation contra sedimentering för avskiljning av kem-flock (in Swedish) Nordforsk 1971.

35 Ingols, R. S. (1968) Short term BOD, Water & Sewage Works, April 1968.

36 Jenkins, D., J. F. Ferguson and A. B. Menar (1971): Chemical Processes for Phosphate Removal, Water Research, 5, 369-389.

37 Kemisk fällning av kommunalt och industriellt avloppsvatten (in Swedish). Course STF, April 1973.

38 Klei, H. E. (1971) "Automatic Control of an Activated Sludge Reactor", FWQA Grant 17070 EVF, Feb 1971.

39 Kugelman, I. J. (1972) Status of Advanced Waste Treatment EPA, Cincinnati, 1972.

40 Lacroix P. and D. Bloodgood (1972 A) Computer Simulation of Activated Sludge Plant Operation, Journal WPCF, 44, 1778-1788, Sept 1972.

41 Lacroix P. and D. Bloodgood (1972 B) Computer Assisted Activated Sludge Plant Operation, Journal WPCF, 44, 2205-2217, Dec 1972.

42 Levin, G. V., Shapiro, J. (1965) "Metabolic Uptake of Phosphorus by Wastewater Organisms" Journal WPCF, 37, 800.

43 Lind, J. E. and A. Österman (1971) Tungmetaller i kommunalt avloppsvatten (in Swedish), Swedish Environmental Protection Board, March 1971.

44 McCinney R. E. (1962): "Mathematics of Complete Mixing Activated Sludge", J. of the Sanitary Engineering Division, Proc. of the ASCE, 88, SA3, 87-113, 1962.

45 Menar, A. B., Jenkins, D. (1970) "Fate of Phosphorus in Waste Treatment Processes; Enhanced Removal of Phosphate by Activated Sludge". Environmental Science and Technology, 4, 1115.

46 Metcalf & Eddy, Inc., (1972) Wastewater Engineering, McGraw Hill, 1972.

47 Milsury, W. F., Pipes W. O. and R. B. Grieves (1965) Compartmentalization of aeration tanks. J. of the Sanitary Eng. Div., June 1965, 45-61.

48 Monod, J. (1949)"The Growth of Bacterial Cultures", A. Rev. Microbiol., 3, 371, 1949.

49 Montgomery et.al. (1971) Effluent and Water Treatment Jour., 11, 1, 23, Jan 1971.

50 Mulbarger, M. C., D. G. Shifflett, M. C. Murphy, and D. D. Huffman, (1971) "Phosphorus Removal by Luxury Uptake", J. WWPCF, 43 pp. 1617--1628.

51 Nordström B. (1972) Flödesmätning vid avloppsverk (in Swedish) National Environment Protection Board, Internal report July 6, 1972.

52 Olsson, G. and L. Ulmgren (1973) Reglering av Avloppsreningsverk. Studieresa till USA och Canada (in Swedish), National Environment Protection Board and Division of Automatic Control, Lund University, Sweden.

53 Ott, C. R., R. H. Bogan (1971) Theoretical Analysis of Activated Sludge Dynamics, J of the Sanitary Engineering Division, Proc. of the ASCE, SA1, 1-17, Feb 1971.

54 Phosphorus Removal Design Seminar, Toronto, Canada, May 1973, Ministry of Environment, Onatario, Canada, Environment, Canada.

55 Process Design Manual for Phosphorus Removal (1971), EPA Techology Transfer, Washington, DC (Oct 1971).

56 Roesler, J. F. (1972 A) Factors to Consider in the Selection of a Control Strategy, EPA, Cincinnati, May 1972.

57 Roesler, J. F. (1972 B) "What Variables Should be Measured to Monitor and Control a Waste Treatment Plant", presented at AIChE Meeting, St. Louis, Missouri, May 1972.

58 Roesler, J. F. (1973) Performance Evaluation of Automatic DO Control at Renton Sewage Treatment Plant, Seattle, Washington, EPA, Cincinnati, April 1973.

59 Rowe D. R. and L. W. Canter (1968): "Public Works, p 100, Oct 1968.

60 Ryder, R. A. (1969) "Dissolved Oxygen Control in Activated Sludge" 24th Industrial Waste Conference, Purdue Univ., Lafayette, Indiana, 1969.

61 Schainker R. B. and C. H. Wells (1970): "Dynamic Modeling and Control of Suspended Solids in Clarifiers", Systems Control Inc., Technical Note, 1970.

62 Sherrard J. H. and E. D. Schroeder (1971)"Variation of Cell Yield and Growth Rate in the Completely Mixed Activated Sludge Process", Presented at the 27th Industrial Waste Conference, Purdue University, Lafayette, Indiana, 1971.

63 Smith R., (1968 A) "Preliminary Design and Simulation of Conventional Wastewater Renovation Systems Using the Digital Computer, FWPCA Publication (=EPA) No WP-20-9, March 1968.

64 Smith R., (1968 B) "Cost of Conventional and Advanced Treatment of Wastewater, FWPCA Publication (=EPA) July 1968.

65 Smith R., R. G. Eilers and E. D. Hall (1968C): "Executive Digital Computer Program for Preliminary Design of Wastewater Treatment Systems, FWPCA (=EPA) Publication No WP-20-14, Aug 1968.

66 Smith, R., and W. F. McMichael (1969 A): "Cost and Performance Estimates for Tertiary Wastewater Treating Processes" FWPCA (=EPA) Publication June 1969.

67 Smith R., and R. G. Eilers (1969 B): "A Generalized Computer Model for Steady-State Performance of the Activated Sludge Process". FWPCA (=EPA) Publication, Oct 1969.

68 Smith R., and R. G. Eilers (1970 A): "Simulation of the Time-Dependent Performance of the Activated Sludge Process Using the Digital Computer", EPA Cincinnati, Feb 1970.

69 Smith R., (1970 B): "Mathematical Models for Wastewater Treatment" A. I. Ch. E. Workshop - Industrial Process Design for Water Pollution Control, San Francisco, California, March 31 - April 1, 1970.

70 Smith R., (1971) "Wastewater Treatment Plant Control" JACC, St. Louis, Missouri, 1971.

71 Stepner D. (1972): "Design of DO controller for Palo Alto Wastewater Treatment Plant" Technical note, Systems Control Inc., Palo Alto, Calif., Sept 1972.

72 Stewart, M. J. (1971) Activated Sludge System Variations - Specific Applications, W & SW Reference Number, R-7, 1971.

73 Tchobanoglous, G. (1970 A) Filtration Techiques in Tertiary Treatment, J WPCF, 42, No 4, 1970.

74 Tchobanoglous, G. and R. Eliassen (1970 B) Filtration of Treated Sewage Effluent, J. of the Sanitary Division, ASCE, vol 96, No SA2, 1970.

75 Teissier, G. (1936), Les Lois Quantitatives de la Croissance, Anna. Physiol. Physicochim. Biol., 12, 527-586, 1936.

76 Ulmgren L. et.al. (1971) Experiences from Chemical Treatment Processes for Municipal Sewage Water in Sweden. National Environment Protection Board, Report SNV-PM 268, September 1971. (Sweden)

77 Ulmgren L. and C. Andersson (1972) Erfarenheter från Lamellsedimentering vid Avloppsrening, (in Swedish), Vatten, No 5, 455-468, 1972.

78 Ulmgren L. : (1973 A) Utrustning för flödesmätning och provtagning vid avloppsreningsverk (in Swedish) Hygianisk revy, no 3, 2-11, 1973.

79 Ulmgren L. (1973 B) Swedish Experiences in Sewage Treatment, Symposium on Waste Water Treatment in Cold Climates, Saskatoon, Canada, Aug. 22 - 24, 1973.

80 Ulmgren L. (1973 C) Private communication.

81 Wells, C. (1971) "One the practical application of "A Nonlinear Regulator Problem for a Model of Biological Waste Treatment", IEEE Trans Automatic Control, AC-16, 385-388, (1971).

82 Wells C., and D. Stepner (1972): "Automatic Control of Dissolved Oxygen in the Palo Alto Regional Wastewater Treatment Plant", presented at the 65th Annual Meeting of the A. I. Ch. E, Nov 1972.

83 Wells C. (1973): Dissolved Oxygen Control at Palo Alto", JACC, Columbus Ohio.

84 Werner, J. (1970) Syremätning i luftningsbassänger
I Olika mätprinciper (in Swedish) Vatten, No 2, 113-119
II Behov av syremätning (in Swedish)Vatten, No 4, 360-364

85 Werner, J. (1972) Kontinuerlig syremätning - kontroll i reningsverk (in Swedish), Vatten, No 1, 49-53, 1972.

86 Westberg, N. (1967): "A Study of the Activated Sludge Process as a Bacterial Growth Process" Water Research, 1, 795-804, 1967.

87 Westberg, N. (1969): "An Introductory Study of Regulation in the Activated Sludge Process" Water Research, 3, 613-621, 1969.

88 Wiksell H., J. Hultgren and B. Hultman (1973 A): "Några synpunkter på fotomerisk slamhaltsmätning vid kommunala avloppsverk" (in Swedish) Division of Water and Sewage Works, Royal Inst. of Techn., Stockholm, Sweden.

89 Wiksell H. (1973 B) Utredning, miljöteknik inom VA-området (in Swedish) Preliminary report, Swedish Board for Technical Development, July 1973.

90 Wild, H. E., Jr., Sawyer, C. N., McMahon, T. C (1971) "Factors Affecting Nitrification Kinetics," Journal WPCF 43, 1845.

91 Yall, I., W. H. Boughton, R. C. Knudsen, and N. A. Sinclair (1970) "Biological Uptake of Phosphorus by Activated Sludge". Applied Microbiol., 20, pp 145-150

92 Zenz, D. R., T. J. McAloon and C. L. Weddle (1969) "Sensors for the Analysis and Control of Biological Processes". presented to the Division of Water, Air and waste Chemistry, American Chemical Society Minneapolis, Minnesota, April, 1969.