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SWEDISH EXPERIENCES OF INSTRUMENTATION AND CONTROL OF WASTEWATER TREATMENT PLANTS

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Abstract

In the last decade the great expansion period in Sweden of wastewater treatment plant design has been more or less completed. Biological and chemical treatment is now available for a majority of the Swedish population. At present the operational problems tend to gain interest. This has created a growing interest in plant dynamics, instrumentation and control, as well as in the relation between plant operation and design.

Projects on dynamical studies and on-line control have been supported in the last few years. Several studies have been focused on the activated sludge processes. The relation between chemical dosage and biological treatment as well as aspects of both carbonaceous and nitrogeneous control are being studied.

The use of computers for plant supervision and on-line control has been exploited. Several computer systems for data logging are installed in Sweden, but hitherto only one system is designed for direct digital control. The potential of computers for on-line calculations will be discussed. Examples from plants in Stockholm (Käppala) and in Gävle are used as illustrations.

Presented at Institut National de Recherche Chimique Appliquee, Paris, Dec 1, 1978.

Introduction

Sewage treatment plant construction has undergone a tremendous development in Sweden during the last twenty years. The great construction period was initiated when the authorities started to require a substantial upgrading of all wastewater treatment, thus implying both "mechanical" and biological treatment necessary. The required effluent standards were formulated so as to force the treatment to maximum possible, according to known technology, i.e. 95 % reduction in BOD. This was documented in the Swedish Water Protection Act of 1969 (see Isgård et al. 1974). During the sixties chemical precipitation was required extensively by the authorities in order to diminish the eutrofication caused by phosphorus. Later both biological and chemical treatment has been required when granting permits for new constructions of wastewater treatment plants. In the beginning of 1977 some 66 % of the Swedish urban population was connected to biological and chemical wastewater treatment works (see Grönqvist et al. 1978). To get this achievement the Swedish state and municipalities have invested some 300-400 M Sw Kr per year during the last ten years (see Hawermann 1978).

Now, with most of the plants constructed, the interest is gradually directed from design towards operation. A maximum use has to be made of existing plant constructions. Operational costs have to be minimized while the effluent quality is maintained. The cost for wastewater treatment has increased considerably (see Fig. 1), and there is a clear incentive to reduce the costs. It is getting recognized that instrumentation and control has the potential for increasing effluent quality, enhancing treatment reliability and reducing the operational costs. This has been well documented in recent conferences like the 1977 IAWPR international workshop on instrumentation and control for water and wastewater treatment and transport systems in London - Stockholm. An interesting survey of the US situation on instrumentation and control has been published by EPA recently, see Molvar et al. (1976).

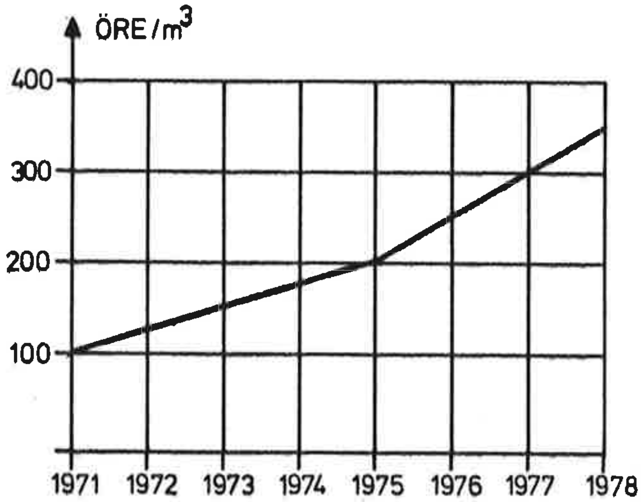

Figure 1. Illustration of the wastewater treatment cost development in Sweden.

Disturbances and control

A wastewater treatment plant is constantly affected by disturbances. This is the reason, why instrumentation and on-line control are crucial tools for a successful operation. Unlike many chemical plants the disturbances are significant in amplitude, so that a steady-state approach would not be relevant at all in most plants. The disturbances can be categorized into three groups:

- hydraulic
- concentration and composition
- microbial

Hydraulic changes are often significant in amplitude. The amplitudes are related to the size of the sewer network. Some disturbances, like rainstorms and melting snow, may upset the whole process. The frequency of the disturbances as well as their duration are of course important, and the proper control action is depending on these factors.

There are also significant hydraulic disturbances within a plant. Disturbances from the primary pumps may upset the operation, if the pumps are not operated properly. Recirculation in the activated sludge, pumping of reject water from sludge treatment, backwashing of deep-bed filters are other important internal disturbances.

Concentration or composition disturbances often occur in phase with the hydraulic disturbances. To detect concentration variations or sudden toxic loads etc. is quite expensive. Very seldom there is a regular on-line concentration measurement of the influent wastewater concentration, e.g. by COD. There is also a trade-off between the costs for measurements and the costs caused by undetected concentration disturbances. As for hydraulic loads, concentration variations appear with quite different frequencies. Some of them come as shock loads, others are diurnal or slower variations. There are also significant internal loads, coming from digesters and centrifuges.

From a control point of view it is interesting to distinguish between concentration disturbances and microbial disturbances. In the first case the character or composition of the species of organisms will not be influenced, only their growth rate and concentration. In the other case, however, the composition of organisms will be affected. For example, if the influent water contains toxic substances some species may be significantly reduced, thus affecting both substrate elimination and sludge floc formation. Likewise a wrong F/M ratio may favour the growth of filamentous organisms, resulting in bulking sludge.

In a wastewater treatment plant there are several possible control actuators. Here we will distinguish between two different types of controllers. The first kind is classified as automation, the other type as process control. Examples of the first kind are motor, pump, and valve controllers, local level and pressure controllers etc. All of these controls are of course important for the operation of the process itself, but they do not require any specific process knowledge. Their purpose is instead to make the work easier for the operators. Here we will consider the other kind of controllers, requiring specific process knowledge and measurements.

The most flexible but also the most difficult unit process to control is probably the activated sludge process. At least four control variables can be distinguished:

- air flow
- return sludge flow
- waste sludge flow
- step feed pattern

In some plants even the spatial distribution of the air flow can be controlled, at least manually.

In chemical treatment for phosphorus removal the dosage of chemicals as well as pH adjustment solutions can be controlled. For sludge conditioning the dosage of polymers or polyelectrolytes can be controlled. In anaerobic digesters the temperature is often controlled.

In order to overcome the problem of large disturbances and significant influent variations there are two principal ways to go. The traditional way has been to design large tanks with sufficiently high hold-up time. This is an expensive way to solve dynamical problems. Another way is to compensate for the disturbances by instrumentation and control. This will demand more process knowledge and operational costs. Therefore there is a trade-off between design and operational costs, that has to be considered.

More details about dynamics and control can be found e.g. in a couple of recent survey papers (see Olsson 1977, 1978).

Studies on wastewater plant dynamics and control

The author has been deeply involved in a project on dynamics and control of wastewater treatment plants, that was initiated in Sweden in 1973. The project has been a cooperative effort between the Datema AB, the Käppala sewage treatment works, and the Department of Automatic Control at the Lund Institute of Technology, see Olsson et al. (1973).

Some of the research goals has been to

- control the dissolved oxygen (DO) concentration to an adequate level,
- try the return sludge flow to control the F/M ratio,
- avoid upsets of the settler, such as rising and bulking sludges,
- avoid by-passing.

Particular interest was devoted to the DO dynamics, as the DO concentration is related to several crucial parameters of the reactor. The DO dynamics was examined in a series of dynamical experiments on the Käppala wastewater treatment plant in Stockholm. Then a DO control system was implemented. The control was performed first with the existing plant data acquisition computer Siemens 303, and later changed to a minicomputer DEC LSI 11 in order to achieve more flexibility. In early 1977 a computer PDP 11/04 was installed at a plant in Gävle, serving about 100 000 people. The computer is controlling the activated sludge process, bypass flow, centrifuges, and will later control the chemical treatment for phosphorus removal.

Results from the project have been reported e.g. in Olsson/Hansson (1976 a,b), Gillblad/Olsson (1977, 1978), and Olsson (1977). Some control and instrumentation experiences will be described later in this paper.

Dissolved oxygen control

The air flow to an activated sludge process is an essential control variable. It has a significant impact on the plant economy, and it will play an important role in the quality of the plant performance. The required concentration of dissolved oxygen for the microorganisms depends on the specific type of organisms. The synthesis rate depends on the DO concentration up till a certain concentration (1.5 - 2 mg/l). At higher concentrations the DO level will not influence the growth rate. Therefore it is natural to try to minimize the air flow rate, but still keep the growth rate at a maximum.

The control of DO as a physical variable does not demand any in-depth knowledge of the plant dynamics. The problem is to have the right control actuators and a proper control authority so that large disturbances can be damped by control. The sensors are generally considered reliable enough to grant a good performance. In a diffuser system the air pressure has to be kept within quite narrow margins. Therefore the DO control system has to include a control of the air pressure. Otherwise oscillations of the air pressure may easily occur.

It is not trivial to determine the proper set-point value of the DO concentration. It requires a detailed knowledge of the dynamics of the biological part of the reactor. First the limiting concentration of the organisms has to be known. It is different for Heterotrophs compared to Nitrifyers or filamentous bacteria. Therefore the DO level is of significance to determine which types of bacteria should be supported in the system.

The DO concentration is also strongly related to the degree of mixing. As a minimum amount of mixing is needed the DO concentration may stay unnecessary high in low load situations. In aerators that are not complete mix the DO concentration is not constant. Instead it varies along the tank in such a way as to reflect the oxygen demand of the organisms. Such a profile is shown in Fig. 2. Therefore the profile of DO can be used in order to measure the load to the plant of biodegradable organics.

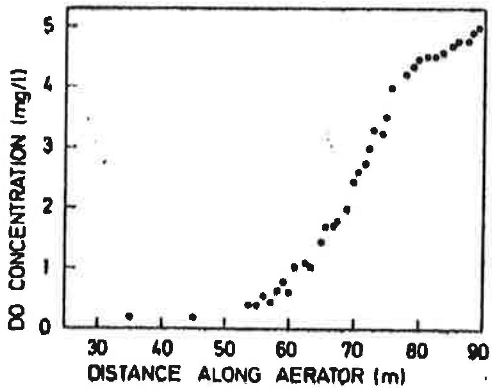

Figure 2. Typical DO concentration in a long aerator.

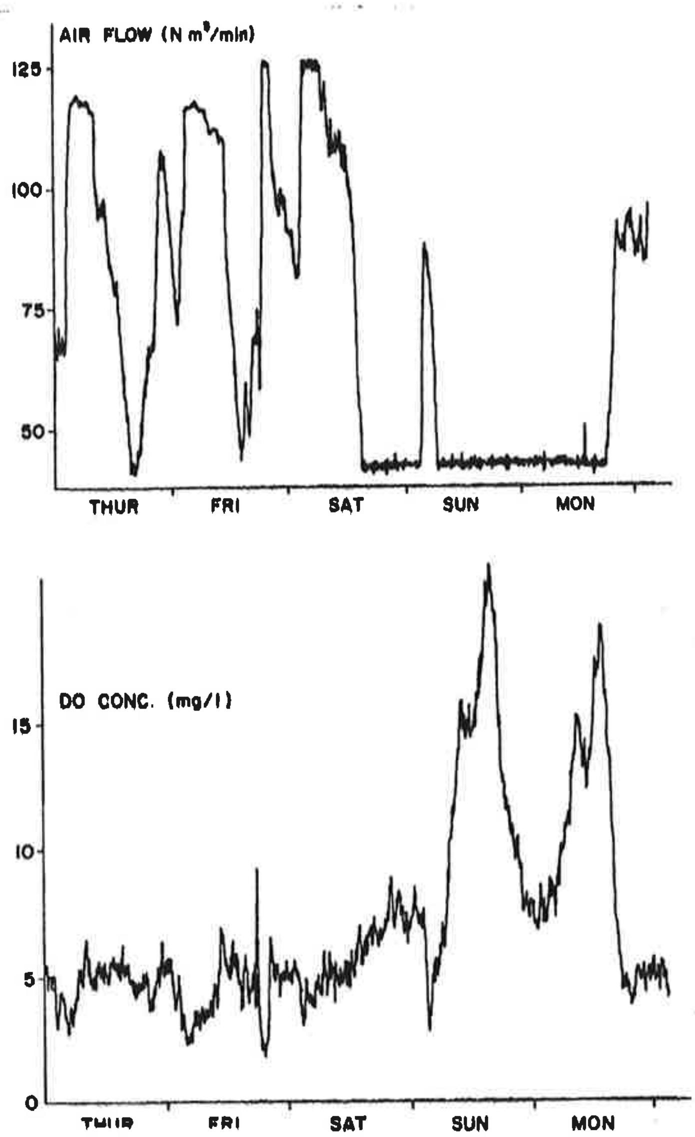

Figure 3. Control of the DO concentration. The air flow is limited between 45 and 130 m^3/min.

Another measure of the organic load to the plant is the air flow needed to control the DO at a constant value in one point. Usually the needed air flow variations are verv large to keep the DO at a desirable value. See Fig. 3.

DO control experiences have been described in e.g. Olsson/Hansson (1976 b), Gillblad/Olsson (1977), Petersack/Smith (1975), Flanagan (1977). The idea of using the DO profile as information about the load is published in Olsson/Andrews (1977, 1978).

Return sludge control

With return sludge control the internal distribution of sludge can be affected in the reactor-settler system. It is conventionally used as a control variable for the control of organic loading. A change in the return sludge flow however, will cause changes in several outputs. The hydraulic change of the return sludge flow will immediately affect the hydraulic load to the aerator and consequently to the settler. Therefore the effluent content of suspended solids (containing BOD) may increase. The possible reduction in soluble BOD, due to more organisms in the aerator, may be counteracted by the increase in suspended BOD.

With an increasing return sludge flow rate the sludge concentration will decrease. Therefore, there is an upper capacity of dry substance transport through the return line. In Gävle (see Gillblad/Olsson, 1977) the computer is used to calculate the maximum return sludge flow. Both the flow rate and the concentration are measured. The flow rate can only be increased, if the corresponding dry substance flow rate will increase.

The hold-up time of sludge in the settler is affected by the return sludge flow rate. In a nitrifying plant denitrification may occur in the settler, given enough hold-up time. This will cause rising sludge, due to nitrogen gas formation. Therefore, at some plants with nitrification, the return sludge flow rate is kept very high, and no sludge is stored in the settler.

In some plants the recycle flow rate is ratio controlled, proportional to the influent flow rate. This control strategy is not recommendable. It does not take the hydraulic effects into consideration. Moreover, influent wastewater concentration variations are not taken into account. Finally, changes in the return sludge concentration due to the flow rate changes are essential.

Waste sludge control

The waste sludge control has a very slow impact on the plant behaviour because of the small waste flow rate. The control action is noted over days to weeks instead of hours. The waste sludge flow rate will determine the mass of solids remaining in the system, i.e. the sludge age (or sludge retention time). Therefore, in order to determine which type of organisms to support in the system, the waste sludge control is important. It will influence the specific growth rate of different species of organisms, particularly nitrification.

Chemical treatment for phosphorus removal

The majority of Swedish treatment plants are designed for post-treatment of the effluent from the biological treatment processes. Generally the effluent from the secondary clarifier is mixed with chemicals in a flocculation tank before separation in a final sedimentation basin.

In Sweden the most common chemical is alum, marketed by the Boliden company as AVR (6.9 - 7.4 % Al and 2.8 - 3.5 % Fe). It has been proven by operational records in several plants that the total P content is reduced by 95 % to about 0.5 mg/l. There is also a remarkable secondary effect of the chemical treatment in the sense that suspended BOD from the secondary clarifier is trapped by the chemical flocs. This will cause a reduced BOD content as well as a reduced BOD variation of the effluent. Some records have shown (see Swedish Environmental Protection Board, 1974) a 78 % BOD reduction with just biological treatment and a 95 % BOD reduction with the chemical treatment added (i.e. 31 ± 26 mg/l and 7.2 ± 4.2 mg/l of BOD, respectively). Moreover the effluent quality variation with only biological treatment is significant. This clearly shows the need for better on-line control of the activated sludge process. The variations do not depend on overloading. Instead the plants were loaded at an average only 59 % of their design flow.

At a plant without post-precipitation design the chemicals can be added to the biological treatment process at different points, Fig. 4. The addition points 3 - 6 corresponds to the so called simultaneous precipitation, while 1 - 2 is called chemical pre--treatment. A majority of Swedish plants are supplied with post--precipitation. This, however, requires quite high investment costs, as both flocculation and sedimentation tanks have to be constructed. In several plants - but not in all - there has been successful applications of simultaneous precipitation, which has meant a significant saving in both design and in operational costs.

For simultaneous precipitation ferrous sulphate ($FeSO_4$ 7 H_2O) - a waste product from the production of titanium dioxide or from pickling of steel - has been used. At the Käppala wastewater treatment plant outside Stockholm simultaneous precipitation has been tested for a long time (Dahlqvist et al., 1975), and all the injection points 1 - 6 has been tried. No difference in chemical precipitation efficiency could be found. A significant reduction in operational costs compared to alum sulphate was shown.

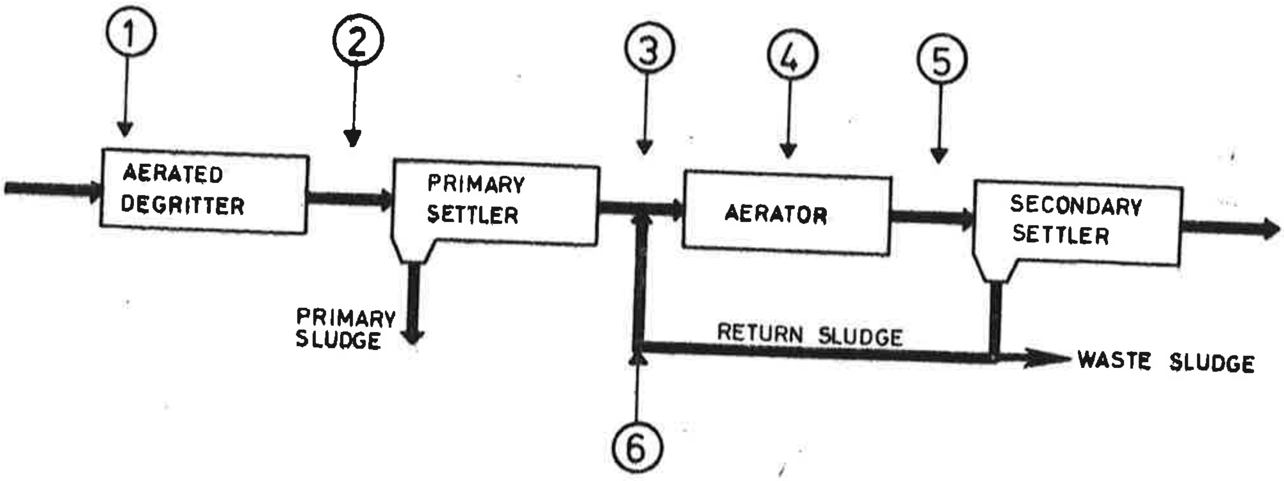

Figure 4. Six possible locations of chemical dosage at a regular plant.

Chemical dosage control

From a control point of view the pH is a crucial parameter, especially for metal salt precipitation. Alkalinity is also important not only for lime precipitation. It also determines the buffer capacity of the wastewater. It is of course desirable to know the phosphorus or phosphate content, but this is very difficult except in terms of total phosphorus content.

The control schemes applied can be divided into two basic groups. In one the control is flow proportional with manual updating of the dosage rate. It is applied both for phosphorus removal and sludge conditioning. In the other group the control is flow-proportional with on-line sensor based feedback updating, such as pH controllers. Also some additional check of the effluent ought to be made, such as turbidity and phosphorus content.

At a sewage plant in Stockholm experiments were performed to regulate the dosage of aluminum sulphate from continuous analyses of the phosphorus concentration after the chemical precipitation step. The effective operational use of the instrument used was very low and therefore the studies were discontinued. At present an investigation is being performed in Sweden to evaluate if the fluorescence of the wastewater might be used to control the chemical dosage (Wikselløet al., 1977).

Influence of nitrification on chemical precipitation

There are no specific requirements in Sweden of nitrogen removal. Nevertheless, nitrification has been observed and purposefully tried in some Swedish plants, causing interesting side-effects on the dosage of chemicals for phosphorus removal. It is now well known, that nitrification can cause the dosage of chemicals to be significantly reduced. The pH conditions have to be well-defined in order to get a good performance of a phosphorus removal system. Often, the desired pH value is obtained by addition of extra chemicals. The chemical dosage required for pH adjustments depends mainly on the alkalinity of the water.

Nitrification can cause a considerable loss of alkalinity. The following overall reaction is proposed to describe the conversion of ammonium to nitrite thus removing alkalinity,

$$22\ NH_4^+ + 37\ O_2 + 4CO_2 + HCO_3^- \rightarrow C_5H_7O_2N + 21\ NO_3^- + 20\ H_2O + 42\ H^+.$$

The buffer capacity of the sewage is reduced, and consequently less chemicals are needed to obtain the optimal flocculation pH value.

The combination of nitrification followed by post-precipitation with aluminum sulphate may lead to a substantially lower dosage of the precipitant. This has been demonstrated in some plants, notably in Himmersfjärden, south of Stockholm and in Örebro. By use of the dosage 75 mg/l Boliden AVR an effluent total P content of 0.2 - 0.5 mg/l could be obtained (see Larsson, 1975). In Örebro the dosage of AVR could be reduced from 120 to 85 mg/l.

It is an interesting optimization problem to match the costs for increasing aeration (due to the higher sludge age and higher DO level needed) and the decreased cost for chemicals. Recent studies (see Grönqvist et al., 1978) indicate that the total cost for an increase of the sludge age from 5 to 20 days in biological treatment of wastewaters with the activated sludge process is rather small (about 5 - 10 %). The increase in costs for a larger aeration basin and additional supply of air in nitrification is to a high degree compensated by reduced costs for sludge handling.

Control for centrifuges

In order to condition the sludge before the centrifuges polymers or polyelectrolytes are added to the sludge. The cost of the polymers is very high, so the dosage should be controlled in order to minimize the suspended solids content of the reject water. In some plants the feed of sludge to the centrifuges is controlled according to the suspended solids measurements of the reject water. It is more suitable to control the dosage of polyelectrolytes. The dosage of polymers is first linearly adjusted to a feed-forward signal of the dry mass flow of influent sludge to the centrifuge. The dosage is then adjusted according to a feedback signal from a turbidity measurement of the reject water. Promising results have been obtained at two Stockholm plants (see Wiksell et al., 1977) and in Gävle. In the Stockholm plants the control was performed with analog techniques. In Gävle the existing PDP 11/04 computer for DDC of the activated sludge process was used.

Computer control

There are a few computer installations at sewage works in Sweden. All of them but one, however, are used for only data acquisition. In Gävle there is a computer for both data recording, and direct digital control (Gillblad/Olsson, 1977). Some of the basic ideas and experiences about the usefulness of the computer in a wastewater treatment plant are mentioned here.

The computer can make the maximum use of available instrumentation. This is important, as there will always be insufficient amount of instruments in wastewater treatment. The complexity of the measurements and the costs of the instruments will always be a limiting factor. Simple but very useful calculations of indirect variables can be performed such as a dry mass flow computed from flow rate and concentration, flow rates from pump speeds, mass balances for tanks and reactors etc. The return sludge is one example. In Gävle the return sludge flow rate is controlled according to the calculated mass flow rate in the return sludge pipe.

There are several dynamical variables that need to be calculated on-line from given measurements. The specific oxygen uptake rate (SCOUR) can be calculated from DO measurements. In Gävle an automatic sample of liquid is taken. With DO readings registered in the computer and some calculations the SCOUR can be computed every five or ten minutes.

Calibration is made much simpler with automatic recording and subsequent automatic adjustment of scales. Most often the computer can automatically recognize when a calibration or instrument cleaning takes place.

Maintenance scheduling is quite important in a big wastewater treatment plant. The normal operating times of pumps, valves, motors etc. are recorded. The operator will get information each day from the computer which actuators and instruments are up for maintenance.

To use the computer for trouble shooting is well recognized. Just the fact that crucial variables are recorded makes the search so much easier. It is natural to record alarm limits for each individual instrument available in a plant. Likewize trends and trend limits can be observed. Most often, however, human observations or laboratory analyses must be added to the automatic instruments before final diagnosis can be made of certain operational conditions.

The computer is an excellent tool to combine all instruments readings in order to detect dangerous combinations of process variable values. Given certain instrument combinations it can alarm the operator for certain states like

- large hydraulic load
- poor settling
- sludge buffer full or empty

etc. Sometimes it asks the operator for further information in order to give a more precise diagnosis. It may require a sludge volume index, a microscopic test for filamentous bacteria etc. In this way the operator's experience and superior way of recognizing patterns, colours, odors and so on can be combined with the ability of the computer to combine information. Such a system of analyzing "operational states" has been in operation successfully in Gävle since 1977.

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