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DEVELOPMENT OF PERFORMANCE INDICATORS FOR THE OPERATION AND MAINTENANCE OF WASTEWATER TREATMENT PLANTS AND WASTEWATER REUSE

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TABLE OF CONTENTS

EXECUTIVE SUMMARY 1

1. CONTEXT AND OBJECTIVES 4

2. CHARACTERISATION AND SAMPLING OF WASTEWATER 6

2.1 Representative parameters of wastewater pollution 6
2.2 Wastewater sampling 8
2.2.1 Grab samples 9
2.2.2 Composite samples 9
2.2.3 Representative samples 9
2.2.4 Control of sampling equipment and preservation 9

3. PRIMARY SETTLING 11

3.1 General considerations 11
3.2 Indicators of process operation 11
3.2.1 Process control monitoring 11
3.2.2 Sludge thickness 12
3.2.3 Hydraulic loading 12
3.2.4 Skimming of floatable solids 12
3.2.5 Odour control 13
3.3 Operational problems and solutions 13

4. ACTIVATED SLUDGE SYSTEMS 15

4.1 General considerations 15
4.2 Indicators of process operation 16
4.2.1 Process control monitoring 17
4.2.2 Dissolved oxygen control 18
4.2.3 RAS control 18
4.2.4 WAS control 19
4.2.5 Control of biological activity 20
4.2.6 Operational monitoring of activated sludge in water reuse systems 20
4.3 Operational problems and solutions 21

5. MEMBRANE BIOREACTORS 24

5.1 General considerations 24
5.2 Indicators of process operation 26
5.2.1 Process control monitoring 26
5.2.2 Dissolved oxygen control 27
5.2.3 Other parameters to control biological activity 27
5.2.4 Control of membrane filtration performance 29
5.3 Operational problems and solutions 31

6. HIGH RATE CLARIFICATION 34

6.1 General considerations 34
6.2 Indicators of process operation 34
6.2.1 Water quality monitoring 35
6.2.2 Optimisation of chemical dosage by jar tests 35
6.2.3 Control of chemical sludge recycling 36
6.3 Other operational control parameters 36

6.3.1 Control of sedimentation 36
6.3.2 Control of mixing 36
6.3.3 Main control points for regular cheeking 36
6.4 Operational problems and solutions 36

7. TERTIARY DEPTH FILTRATION 38

7.1 General considerations 38
7.2 Indicators of process operation 38
7.3 Operational problems and solutions 39

8. ULTRAVIOLET IRRADIATION 40

8.1 General considerations 40
8.2 UV performance control strategies 41
8.2.1 Monitoring of UV disinfection performance 41
8.2.2 Control strategies of UV disinfection 42
8.2.3 Power supply 42
8.2.4 On-line cleaning systems 43
8.3 Main indicators of process operation 43
8.3.1 UV intensity 43
8.3.2 Hydraulic characteristics of the UV reactor 44
8.3.3 Wastewater effluent quality 45
8.3.4 Lamp aging 46
8.4 Main operational and maintenance tasks of UV systems 46
8.5 Operational problems and solutions 47

9. CHLORINATION 49

9.1 General considerations 49
9.2 Indicators of process operation 49
9.2.1 Chlorine residual 49
9.2.2 Indicator bacteria concentration in disinfected effluent 50
9.2.3 Influence of wastewater quality on chlorine dose 50
9.2.4 Contact time 50
9.3 Safety of handling and operation of chlorine products 51
9.4 Operational problems and solutions 52

10. CONCLUSIONS AND SUMMARY TABLE OF OPERATIONAL INDICATORS, CONTROL PARAMETERS AND TROUBLESHOOTING 53

REFERENCES 56

GLOSSARY 57

EXECUTIVE SUMMARY

During the last ten years, wastewater treatment in Southern Europe and MEDA countries has improved significantly. The main reference for treatment objectives is the Urban Waste Water Treatment Directive (UWWTD 91/271/EEC) that makes secondary treatment mandatory for urban wastewater. The implementation of UWWTD in the Mediterranean region should be considered as not only a necessary measure for environmental and health protection, but also as an excellent opportunity for accelerated implementation of water reuse.

For the past few years, the number of wastewater treatment plants with tertiary treatment and reuse has increased in a number of Mediterranean countries. Several new regulations on water reuse have already been adopted or are currently under discussion, aiming at more stringent standards for wastewater disinfection requesting very low concentration of indicator bacteria.

In the context of a continuously increasing development of wastewater treatment and reuse, the **main objective** of this document is to **provide comprehensive compliance indicators for the operation and maintenance of wastewater treatment plants and reuse** facilities. The target audience is broad, including supervisors and/or operators of treatment plants, as well as competent representatives of the end-users and decision-makers.

This guidance document is elaborated on the basis of a long-term experience in wastewater treatment design and operation. It emphasises basic operational and maintenance principles and **defines the major control indicators** that can help operators to **maintain wastewater treatment compliance over time**.

The types of treatment processes that are discussed below are the most representative for the existing wastewater treatment plants in Europe and MEDA countries: (1) activated sludge process, as the most commonly used biological secondary treatment, and the rapidly growing innovative technology of membrane bioreactors (MBR); (2) some common physical-chemical processes such as primary sedimentation, tertiary depth filtration and high rate clarification, and (3) the most common disinfection processes of UV irradiation and chlorination.

It is important to stress that successful operation of a given wastewater treatment process requires good training of operators and knowledge of basic process principles, good operational practices and strong follow-up of recommended preventive maintenance.

To help operators to take the right decision, this document presents not only the main operational indicators and control parameters, but also the **most common operational problems and recommended solutions**. The most important information for each treatment process is summarised in the table here below. In all cases, any decision following a process failure or any troubleshooting should be taken only after verification of the correct power supply of all electrical devices.

It is crucial to underline that each wastewater treatment plant is unique and the operation of a particular process should always be based on its specific performance and response to the control technique applied. This may require the process to be run outside the typical range of the operating parameters presented in this document.

Main Operational Performance Indicators and Operational Control Parameters of the Most Common Wastewater Treatment Processes

Water Quality Control Parameters	Main Operational Indicators	Main Operational Control Parameters	Main Operational Problems
1. Characterisation and Sampling of Wastewater			
Depending on process: Flow rate, T°C, pH, TSS, BOD_5, COD, turbidity, coliforms or other microbial indicators, N and P forms, chlorine residual	**Representative samples**, adequate equipment; good sample preservation **Consistent monitoring**	**Flow-proportioned composite samples**: the most representative and required by regulations; **Grab samples**: discrete samples for unstable parameters (T°C, pH, bacteria);	Problems of calibration of sensors Inadequate choice of sampling location (poor mixing, sediments) Use of time composite sample on the place of flow-proportioned composite samples
2. Primary Settling			
Suspended and settlable solids, total and volatile solids, COD, BOD5, pH, oil and grease concentration Sludge monitoring	**Sludge Thickness**: <1% (5-10 g/L) **Detention time**: 1 to 2 hours **Hydraulic loading**	Continuous desludging Equal flow distribution among multiple tanks Consistent removal of skimming of floatable solids Odour control	Fermentation of settled sludge (floating sludge, black sludge or wastewater, gas bubbling, odours) Hydraulic overloading with low concentration of sludge
3. Activated Sludge			
F:M ratio (BOD, COD) Sludge retention time SRT Mixed liquor concentration: MLSS and MLVSS, TKN loading, BOD/TKN ratio and nitrification rate Removal efficiency of BOD, TKN	**Dissolved oxygen**: >2 mg/L **Return activated sludge rate**: 50 to 100% **Waste activated sludge rate**: to achieve constant SRT or MLSS	**Microscopic exam** of activated sludge **Sludge volume index** SVI **Control of sludge blanket** depth of clarifiers Mixed liquor **respiration rate** or nitrification rate	Problems of aeration system including low DO, poor mixing and foaming. Problems of clarifiers that include solids loss, bulking sludge, rising sludge, etc. Filamentous foaming and bulking
4. **Membrane Bioreactors (MBR)**			
Idem as §3 plus Rags, grease & oils, surfactants, monomers (inducing membrane fouling)	**Dissolved oxygen**: >2-3 mg/L **Membrane permeability** no less than 50% of the initial value **Membrane integrity** by means of on-line turbidity monitoring	**Settling test** with examination of supernatant **Microscopic examination** of activated sludge Control of **membrane integrity** periodical air bubbling or on-line turbidity measurement) Control of **membrane filterability** (optional)	Faulty pretreatment (rags, grease) Poor insufficient aeration (anaerobic fermentation, turbid black supernatant) Loss of membrane permeability (membrane fouling) Loss of suspended sludge (leakage or membrane damage)
5. High Rate Clarification			
Suspended solids Turbidity Phosphorus contents Indicator microorganisms Heavy metals Temperature, pH	**Coagulant dosage** **Polymer dosage** Chemical sludge **recirculation rate** Effluent **turbidity**	Optimisation of **chemical dosage** by jar tests Control of chemical **sludge recycling** and **sludge blanket level** Control of **sedimentation** Control of **mixing**	Faulty dosage of coagulant or polymer Sludge fermentation and/or high sludge blanket level Too low or too high recirculation rate Faulty mechanical equipment
6. Tertiary Depth Filtration			
Flow rate, T°C TSS, turbidity Indicator microorganisms	Filter **headloss**: critical parameter with a predetermined setpoint to start backwashing	**Hydraulic loading** **Turbidity** on-line control: to prevent solids backtrough **Chemical dosage** to improve filter performance	Filter bed clogging Poor backwashing High effluent turbidity (overloading, poor backwashing)

7. Ultraviolet Irradiation			
Flow rate UV intensity UV transmittance Turbidity (optional) Indicator microorganisms	**UV intensity**: by monitoring UV Intensity, UV intensity plus transmittance or calculated UV dose **Flow rate**	**Power supply** **Lamp aging** (control of operating hours) **On-line cleaning** systems	Excessive lamp fouling Low UV intensity and related poor disinfection efficiency Ballast card failure Too frequent lamp replacement
8. Chlorination			
Total chlorine residual Residual indicator microorganisms	**Chlorine residual** Residual **indicator microorganisms**	**Chlorine dose** **Contact time** **Handling** of chlorine products	Failures of chlorine equipment Poor disinfection efficiency due to poor wastewater quality

1. CONTEXT AND OBJECTIVES

Every community produces liquid wastes, solids wastes and gas emissions. The liquid wastes, named wastewater, is the combination of used drinking water and carried wastes originating in the sanitary conveniences of dwellings, commercial or industrial facilities and institutions, in addition to any groundwater, surface water and storm water that may be present[1]. Untreated wastewater generally contains high levels of organic material, numerous pathogenic microorganisms, as well as nutrients and toxic compounds. Thus it entails environmental and health hazards, and, consequently, must immediately be conveyed away from its generation sources and treated appropriately before final disposal. The ultimate goal of wastewater management is the protection of the environment in a manner commensurate with public health and socio-economic concerns.

During the last ten years, wastewater treatment in Southern Europe and MEDA countries has improved significantly. According to the EEA[2], from 601 coastal cities with a population of more than 10,000 inhabitants (total population of 58.7 million), only 69% operate wastewater treatment plants (WWTP) and 21% do not possess any treatment (data record in 2004). The remaining 10% include plant under construction (6%) and plants out of operation (4%). It is important to stress that 55% of the Mediterranean WWTPs use secondary treatment, while 18% of the plants have only primary treatment. Tertiary treatment is of concern in only 15% of the plants. In addition, the distribution of treatment plants is not identical in the different Mediterranean areas, the northern coast having a greater part of urban population served by WWTP.

The need for new wastewater plants is exacerbated due to the rapid growth of many coastal cities and towns, especially on the southern Mediterranean coast, as well as to the tourism, which leads to double population during summer period. Moreover, wastewater treatment is becoming a critical issue worldwide due to diminishing water resources, increasing wastewater disposal costs, and stricter discharge regulations that have lowered permissible contaminant levels in waste streams promoting thus water reuse.

In Europe, wastewater treatment requirements are defined by the Urban Waste Water Treatment Directive (UWWTD; 91/271/EEC), which main goal is to protect the environment from the adverse effects of urban wastewater discharge. The UWWTD prescribes the level of treatment required before discharge and aimed to be fully implemented in the EU-15 countries by 2005 and in the ten new Member States by 2008-2015. The directive requires Member States to provide all agglomerations with wastewater collecting and treatment systems by December 2005, including small communities of less than 2000 p.e., which are discharging in fresh water and estuaries.

Moreover, secondary treatment (*i.e*. biological treatment) must be provided for all agglomerations of more than 2000 p.e. which discharge into fresh waters, as well as for small works depending on dilution factor in fresh water. More advanced treatment – tertiary treatment – is required for effluent discharge into sensitive areas to limit eutrophication and preserve the biodiversity, as well as for water reuse purposes.

The implementation of UWWTD in the Mediterranean region should be considered as not only a necessary measure for environmental and health protection, but also as an excellent opportunity for an accelerated implementation of water reuse. During the past few years, the number of wastewater treatment plants with tertiary treatment and reuse has increased in a number of Mediterranean countries, including Cyprus, Greece, France, Jordan, Italy, Morocco, Spain, Tunisia.

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[1]Metcalf & Eddy (2003) Wastewater Engineering: Treatment and Reuse, 4rd Edition, Mc-Graw-Hill, New York, USA

[2]EEA Report No 5/2005 “Priority issues in the Mediterranean environment”

The new WHO Water Reuse Guidelines (2006) establish health-based targets for water reuse in agriculture. In practice, health risk can be reduced either by treating wastewater at a high level or by combining several interventions methods (multi-barrier approach), including not only the disinfection performance of wastewater treatment, but also natural die-off of microorganisms and crop washing.

In this context of constantly increasing development of wastewater treatment and reuse for small and large communities, the **main objective** of this document is to provide **comprehensive compliance indicators for the operation and maintenance of wastewater treatment plants and reuse** facilities. This document aims to be a reference for supervisors and/or operators of treatment plants, as well as to competent representatives of the end-users and decision-makers.

This document also includes performance indicators to satisfy the suitability of the recycled water (treated wastewater) for the required use by considering a number of parameters related to environmental, personnel, physical and operational indicators. The proposed indicators comply in general with the quality standards that are in force in most European and Mediterranean countries considering also the 2006 WHO guidelines for safe water reuse.

The **types of treatment processes** that are discussed below are the most representative for the existing wastewater treatment plants in Europe and MEDA countries. Specific attention has been given to the **activated sludge process**, as the most commonly used biological secondary treatment, and on the rapidly growing innovative technology of **membrane bioreactors** (MBR). Some common physical-chemical processes such as **primary sedimentation, tertiary depth filtration and high rate clarification**, are also covered. **UV irradiation and chlorination** are considered as widely used disinfection processes and therefore also discussed.

This document is elaborated on the basis of a **long-term experience in wastewater treatment design and operation**, taking into account the **feed-back from operation** of small, medium and large treatment works in Europe and all the Mediterranean region, together with the recent advance in fundamental research in this field.

It is important to stress that successful operation of a given wastewater treatment process requires good training of operators and knowledge of basic process principles, good operational practices and stringent follow-up of recommended preventive maintenance. In addition, each operator must be able to recognise system changes and trends, and makes the proper decision to successfully counteract potential harmful events.

It is crucial to underline that **each wastewater treatment plant is unique** and the operation of a particular process should always be based on its specific performance and response to the control technique applied. This may require the process to be run outside the typical range of the operating parameters presented in this document.

2. CHARACTERISATION AND SAMPLING OF WASTEWATER

Effective operation and control of wastewater treatment plants requires that operators have a good knowledge of the composition of the influent, effluent and internal process streams. To obtain such a good knowledge, the operator has to analyse representative samples throughout the plant.

2.1 Representative parameters of wastewater pollution

The principal contaminants of urban wastewater are given in Table 1. The most common contaminants are: total suspended solids (TSS), with typical concentration range of about 100-300 mg/L, and organic matter expressed by 1) the chemical oxygen demand (COD) of about 200-1000 mg/L, or 2) biological oxygen demand (BOD) within the range of 100-500 mg/L. Accordingly, the treatment of municipal wastewater is typically designed to meet water quality objectives based on: 1) suspended solids (<5 to 35 mgSS/L); 2) organic content (<10 to 45 mgBOD/L or <50 to 125 mgCOD/L); 3) nutrient levels (<10 to 20 mgN/L and <0.1 to 2 mgP/L) and, 4) in some cases, such as water reuse or bathing zones protection, biological indicators (total or fecal coliforms or *E.coli* within the range *of* <10 to 10^4 cfu/100 mL, helminth eggs <0.1 to 5/L, enteroviruses) and chlorine residual (>0.5 to 5 mgCl/L).

Table 1

Main characteristics of wastewater

Parameter	Description	Unit	Standard Methods
Physical characteristics			
Flow rate	Wastewater flows vary consistently during days, weeks, seasons. Inlet flow measurement is very important to calculate hydraulic and mass loads.	m^3/h or m^3/d	-
T°C	The temperature of wastewater indicates the amount of thermal energy and highly influences biological treatment efficiency and membrane filtration flux.	°C	
Colour	Normal fresh domestic wastewater is grey-brown. A darker colour indicates wastewater septicity (anaerobic fermentation in sewers) which will requires more oxygen for aeration of activated sludge. Other colours may indicate industrial wastewater discharge.		
Odour	Odour is a highly subjective parameter but represents a good indicator of the status of wastewater treatment. The normal odour of fresh domestic wastewater is earthy or musty. The presence of an odour of rotten eggs or decayed cabbage indicates anaerobic fermentation and influent septicity (hydrogen sulphide or reduced sulphides).	Odour units, OU/m^3	-
Turbidity	Turbidity, measured by a special device, is increasingly used as an indicator of the removal of suspended solids in water reuse systems. On-line turbidity meters are highly recommended at the outlet of the tertiary treatment to control any process failure and implement quick corrective measures.	NTU	Turbidimeters
Conductivity	Conductivity, measured by specific sensors, indicates the quantity of dissolved matters (water salinity). The occurrence of high peaks of conductivity indicates industrial discharges or seawater intrusion and can negatively impact the activated sludge (deflocculation).	µS/cm	Specific sensors

Parameter	Description	Unit	Standard Methods
Chemical characteristics			
pH	The pH is a measure of the concentration of hydrogen ions, with a neutral reading of 7. pH below 7 indicates acidic conditions, while a pH above 7 shows basic conditions. pH is extremely important for the good efficiency of biological treatment and should be in the range of 6,5 – 8.	-	Specific sensors
Total suspended solids	Total suspended solids refer to the nonfilterable fraction of particles remaining after a glass fiber filtration and drying at 103°C. The volatile suspended solids represent the remaining fraction after heating to 550°C.	mg/L	EN 872:1996 NF T 90-105 / EN12879:2000 NF X 33-004
BOD_5	The biological oxygen demand test measures the amount of oxygen required during 5 days for biological oxidation of carbon pollution at 20°C. This parameter is very important for determining plant loading and the amount of biodegradable carbon pollution. If sample is allowed to react further, nitrification can occur.	mgO_2/L	ISO 5815 EN 1899 NF T 90-103
COD	The chemical oxygen demand indicates the quantity of oxygen required for the oxidation of the major part of organic compounds and some inorganic compounds, using a strong oxidant. The COD values are normally higher than BOD. Because the rapidity of the COD test, it is used for preliminary estimation of BOD.	mgO_2/l	ISO 6060:1989 NF T 90-101
Nitrogen	Nitrogen occurs in 4 basic forms in wastewater: organic nitrogen, ammonia, nitrite and nitrate. These forms indicate the level of organic stabilisation. For example, fresh wastewater has higher concentration of organic nitrogen and ammonia, measured as Kjeldahl nitrogen (TKN). Nitrite and nitrate are measured directly and indicate nitrification of activated sludge.	mg/L	ISO 5663:1984 EN 25663 NF EN ISO 10304-1
Phosphorus	Phosphorus, as nitrogen, occurs in different forms in wastewater (orthophosphate, polyphosphate and organic phosphate) and is an essential element for biological growth. An excess amount in effluents favours algae blooms and eutrophication.	mg/L	NF EN ISO 15681-1
Chlorine	Free chlorine is normally not found in wastewater because of its extreme reactivity. Chlorine is commonly used for disinfection and residual chlorine is used as a control parameter of disinfection efficiency and measure to control bacteria regrowth in distribution systems.	mg/L	
Biological characteristics			
Coliforms	Total and fecal coliforms are indicator organisms and not pathogens. They are much more numerous in wastewater than pathogens and are easily counted. Depending on the methods used, they are reported in units of colonies (UFC) per 100 mL for the membrane filter technique, or most probable number (MPN) for the multiple tube method.	UFC/100 mL or MPN/100 mL	
Escherichia coli	*E.coli* is increasingly used as indicator of microbial pollution because is more representative of intestinal flora, as well as its rapid and easy detection using membrane filter techniques.	UFC/100 mL	
Helminth eggs	Helminth eggs are recommended as control indicator in reuse systems for the removal of protozoa and cysts, in particular in developing countries. In several recent reuse regulations, turbidity is used as more reliable on-line indicator.	eggs/L	

The Urban Waste Water Treatment Directive (UWWTD 91/271/EEC) makes secondary treatment mandatory for urban wastewater and biodegradable industrial sewage. Minimum water quality requirements have been set at 25 mgBOD/L, 35 mgSS/L and 125 mgCOD/L (Table 2). As mentioned previously, by the end of 2005, all municipalities should have complied with these requirements, including small communities of less than 2000 p.e., which are discharging in fresh water and estuaries.

Table 2

Requirements of the UWWTD 91/271/EEC for discharge of wastewater: the values for concentrations or for percentage removal shall apply)

Parameter	Target concentration limit	Minimum reduction of pollution
BOD_5	25 mgO_2/L	70-90%
COD	125	75%
Suspended solids	35 mg/L	90%
Total nitrogen	(1)15 mgN/L	70-80%
	(2)10 mgN/L	70-80%
Total phosphorus	(1)2 mgP/L	80%
	(2)1 mgP/L	80%

(1)mean annual concentration for plant size from 10,000 to 100,000 p.e. (daily average not exceeding 20 mgN/L)
(2)mean annual concentration for plant size >100,000 p.e. (daily average not exceeding 20 mgN/L)

More advanced treatment (biological nutrient removal and/or tertiary treatment) with removal of nutrients (nitrogen N and phosphorus P) is required for discharges into sensitive areas. The level of disinfection and the microbial indicators depend on the type of water reuse and specific regulations.

2.2 Wastewater sampling

An effective sampling program is very important for an efficient control of wastewater treatment efficiency and reliability. It provides information on loading and performance of each unit process. This allows the operator to **anticipate and adjust operating parameters** according to plant loads and treatment performance. **Visual inspection** and **on-line monitoring** also provides an **early warning** on process performance.

As a rule, the sampling and analysis program is a legal requirement included in wastewater treatment plant's permits. In addition, safety and health considerations are the subject of specific regulations.

Sampling frequency depends on licence requirements and can by daily, weekly or monthly as a function of the monitored parameters.

Sampling location also depends on licence requirement and most commonly includes plant inlet and outlet. Storage reservoirs and some points of use can be also included for monitoring of recycled water quality.

In all cases, it is strongly recommended to follow sampling methods and techniques of the *Standard methods for the examination of water and wastewater*.

2.2.1 Grab samples

Grab samples are discrete samples collected manually during a short laps of time. As a rule, grab samples are used to measure unstable parameters as pH, temperature, chlorine, dissolved oxygen and microbial parameters.

2.2.2 Composite samples

A **composite sample** is a single sample prepared by combining **a number of grab samples during a period of time**, as a rule 24 hours. Composite samples can be prepared either manually or using automatic sampling equipment, refrigerated, if possible. Composite samples provide information on average characteristics of influents and effluents and are, as a rule, required by regulations (plant's permits).

The **most representative composite samples** are **flow-proportioned**. Such composite samples can be prepared either by varying the volume of grab samples, or the sampling frequency, in order to obtain a reasonably equivalent composite sample to the flow-weighted average composition of wastewater or process stream. It is important to notice that flow-proportioned composite sampling requires accurate measurement of the flow rate. This kind of sampling is often required for the plant influent and effluent.

Time composite samples consist of fixed-volume samples at specific time intervals and are used mostly to characterise treatment processes with low variations of flow rates (activated sludge; for example).

2.2.3 Representative samples

The main aim of sampling is to ensure that the sample is **representative of the flow stream**. Because samples represent only a small portion of the analysed flow, **both the site selection and sampling technique are crucial**. Failure to obtain representative samples can induce invalid data and erroneous process control decisions.

The following **recommendations** can help operators to ensure representative sampling:

- Collect samples at points where the flow is well mixed,
- Avoid areas with floating debris and deposits,
- Collect samples upstream of any recycle stream discharge,
- Always use the same sampling points,
- When using pumping for sampling, keep the sample line as short as possible,
- Clearly mark sample containers for each sample location and sampling time,
- After collection, store samples at dark and in a refrigerator at 4°C and analyse as soon as possible.

2.2.4 Control of sampling equipment and preservation

Many **automatic sampling devices** are marketed (Figure 1). Before any of these devices are purchased, their proposed use and installation require careful consideration. When collecting samplers, PVC pipes must be used to avoid sample contamination. **Often, automatic sampling devices are ignored by operators until strong failure is detected.** Appropriate maintenance and surveillance program is needed to ensure reliable operation of automatic sampling devices. **Routine monitoring of sampler operation** allows timely detection of malfunctions and prompt correction. Regular cleaning of samplers and piping is necessary to prevent biological fouling and sample's contamination. Sampler's temperature should be monitored regularly for refrigerated samplers.

According to the compounds to be monitored, appropriate preservation techniques are available for each analytical method. As a rule, analytical laboratories provide sample bottles and chemicals for sample preservation.

When possible, **immediate analysis is the best solution for representative monitoring**.

Figure 1. View of a mobile and a fixed automatic wastewater samplers

3. PRIMARY SETTLING

3.1 General considerations

Primary sedimentation is commonly used in wastewater treatment before biological treatment. The main goal is the **removal of suspended solids through gravity settling** of particle with density greater than water. Circular or rectangular sedimentation tanks with vertical or horizontal flow have been developed[1].

Sludge collection consists in moving settled sludge to a point in the settling tank where it is drawn off. As a rule, mechanical sludge collection systems are used, such as travelling bridge or rotating sludge scrapers. Settled sludge are removed more commonly by pumping, but sometimes gravity flow can be used.

The TSS and BOD removal efficiency of primary sedimentation depends on wastewater quality and settling tank design. As a rule[3], suspended solids removal efficiency of primary settling is about 50%. About 40% of the BOD and COD are also removed. It should be noticed the significant removal of some heavy metals up to 35-50% (Cd, Cr, Pb, Zn) with few exception such as mercury (Hg, 11%). Primary settling performances decrease with the increasing of hydraulic loading.

Figure 2. View of a primary sedimentation tank

3.2 Indicators of process operation

The **main indicators** of process operations of primary sedimentation are[4]:

- Sludge Thickness
- Detention time
- Hydraulic loading

In addition to the control of these parameters, efficient operation of primary settling requires equal flow distribution among multiple tanks, consistent removal of skimming of floatable solids and odour control (prevention of sludge fermentation).

3.2.1 Process control monitoring

The water quality testing for primary treatment vary among plants and depends on permit agreement. **Typical tests** for the evaluation of the performance of primary settling include the analysis in primary influent and effluent of suspended and settlable solids, total and volatile solids, COD, BOD_5, pH, oil and grease concentration (periodically). Sludge monitoring consists in the measurement of total and volatile solids and pH.

[3]Lazarova, V. and Bahri, A. (2005) Water Reuse for Irrigation: Agriculture, Landscapes and Turf Grass. CRC Press, Boca Raton, Florida, USA.
[4]WPCF (1990) Operation of Municipal Wastewater Treatment Plants: Manual of Practice MOP 11, Water Pollution Control Federation, USA

3.2.2 Sludge thickness

Sludge thickness or solid concentration is the **most important parameter** to ensure good operation of primary settling. To prevent sludge fermentation and mass overloading of aeration tanks, the good practice requires to **extract primary sludge at a concentration <1%** (between 5 and 10 g/L) if sludge is pumped to thickeners. In this case, sludge collection must run continuously. **Continuous desludging is necessary** for the good operation of circular or square primary tanks because sludge movement to the hoppers requires more time than that for rectangular tanks. Because the many advantages, continuous sludge collector operation is preferred for most wastewater treatment plants.

If the sludge is pumped directly to the digesters or sludge dewatering device, a thicker sludge is necessary. With reasonable control of sludge removal and intermittent sludge collection, the operator may obtain a sludge thickness up to 5%.

A single pump should withdraw sludge from a single hopper at a time, because differing headlosses among the sludge suction lines may cause unequal sludge withdrawals from the individual tanks. **Pumping for a short duration at frequent intervals is recommended as a good practice.**

The operator should monitor sludge concentrations from sample ports in the sludge discharge lines to confirm the choice of pumping duration and frequency. Sludge level in the primary tanks can be controlled by sample aspiration at various depths, core sampling or specific electronic devices.

3.2.3 Hydraulic loading

The **control of hydraulic conditions** is **very important for the treatment efficiency** and reliability of operation of primary sedimentation. The recommended operating parameters for proper settling are as follows[1]:

- Detention time: 1 to 2 hours
- Hydraulic loading rate: average daily loading 40±10 $m^3/m^2/d$ and peak hourly loading 100±20 $m^3/m^2/d$ (4.2±0.8 $m^3/m^2/h$)

Operators have very limited possibilities to control the inlet flow, and consequently the main hydraulic control variable is the number of tanks in service. When the plant flow is considerably less than the design flow, some of the primary tanks may be taken out of service.

Moreover, the idle tanks should be emptied and filled out with plant effluent and all the mechanical devices should be run on daily for a short time.

Equal flow distribution among multiple tanks may be an important objective for operators in order to minimise variations in sludge blankets and aid overall performance. Level weirs and properly adjusted influent gates can help to equalise inlet flows to each settling tank and may require several adjustments during the day.

3.2.4 Skimming of floatable solids

Grease, oils, plastics and other **floatables must be consistently removed**. Circular tanks are, as a rule, skimmed continuously. In the case of rectangular tanks with manual skimming, the recommended removal frequency is at least once per day.

3.2.5 Odour control

Improperly operated primary sedimentation may generate significant odour emissions. The **recommended operational practices to control odour nuisance** are as follows:

- Remove sludge before it can bubble or float,
- Remove scum routinely with increased frequency during warm weather,
- Wash weirs and other points where floatable and slime collect,
- If sewage is septic, add chemicals to reduce sulphides (for example $FeCl_3$),
- When draining a tank, immediately flush it completely.

3.3 Operational problems and solutions

The **most frequent problem** of primary sedimentation is **related to septic wastewater or fermentation of settled sludge**. Fermentation results in the solubilisation of the settled sludge, COD increasing and thereby increasing of the load on the aeration basins. In addition, fermentation provokes gas generation with the concomitant sludge flotation and odour emissions. Besides the presence of readily biodegradable soluble COD can favour the development of filamentous bacteria.

Another common problem of primary settlers is hydraulic overloading, occurring frequently after heavy storms (Figure 3). The main consequence is an increase of sludge blanker level and a loss of sludge

Figure 3. View of poor solid removal of a primary settler due to hydraulic overloading with storm water

It is important to underline that the nature of operational problems is frequently temperature dependent: during cold weather sludge is more dense and difficult to extract, while high temperatures favour sludge fermentation and odour emissions.

The most common operational problems and recommended correctives actions are summarised in Table 3.

Table 3

Rapid identification of some common operational problems of primary sedimentation and guidelines for troubleshooting

Indicator	Probable cause	Explanation	*Immediate action	Solutions
Floating sludge	Sludge fermentation	Damaged scrapers Lack of sludge withdrawal Plugged pipes for sludge collection	Inspect scrapers Inspect sludge pump output	Remove sludge more frequently or increase sludge removal rate Repair or replace the damaged equipment Add chemical to decrease septicity Flush the sludge extraction pipes
Black wastewater or sludge		Too long residence time Improper sludge removal Damaged sludge collectors Recycling of strong digester supernatant	Inspect sludge collectors and pumps Check sludge density Check the return flow from sludge digestion Check the septicity of raw wastewater	
Scum overflow	Inadequate removal frequency or damaged scum equipment	Damaged scum wiper blades Improper alignment of skimmer Inadequate depth of scum baffle	Check scum removal rate Check wiper blades, alignment and baffles	Increase scum removal frequency Clean or replace wiper blades Adjust alignment Increase baffle depth
Poor suspended solid removal	Hydraulic overloading	Too high up-flow velocity Short circuiting Too high recycle flow	Check flow rate and see for short circuiting Monitor pumping duration and sludge levels Monitor wastewater quality Check flow distribution	Shave peak flow or add chemicals Adjust sludge withdrawal frequency and flow Eliminate potential storm overflow
Low solids content of sludge		High influent flow rate Short circuiting Sludge over pumping		Provide uniform flow distribution if multiple tanks Reduce frequency and duration of sludge extraction
Sludge hard to remove from hopper	Compacted sludge Low velocity of sludge extraction	Excessive grit, clay and other easily compacted particles Clogged extraction pipe or pump	Check the operation of grit removal Check sludge removal velocity	Improve grit removal Increase sludge removal velocity Flush pipelines and pumps

Source: Adapted from [4] and feed-back from operators

*Any decision following a process failure or any troubleshooting should be taken only after verification of the correct power supply of all electrical devices

4. ACTIVATED SLUDGE SYSTEMS

4.1 General considerations

Activated sludge is the most common biological treatment process operated continuously, and is widely used for secondary wastewater treatment. By definition[1], the basic activated sludge treatment process consists of the following three basic components (Figure 4):

1. Single or multiple aeration tanks in which the microorganisms responsible for wastewater treatment are kept in suspension and aerated,
2. Clarifiers or liquid-solids separation tanks to separate the activated sludge flocs from treated wastewater gravity settling,
3. Recycle system for returning the settled sludge from clarifiers to aeration tanks.

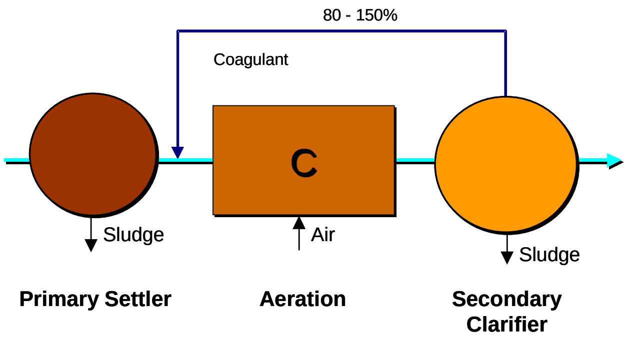

Figure 4. Principle treatment scheme for secondary treatment (activated sludge)

The treatment performance of activated sludge is based on the metabolic reactions of microorganisms, which reduce the organic content of wastewater. An important feature of the activated sludge process is the formation of settleable bacterial flocs that can be removed by gravity settling in the clarifiers (secondary sedimentation tanks). After the clarifiers, part of the settled sludge is returned to the head of the aeration system to re-seed the new sewage entering the aeration tanks. A part of settled sludge, named excess sludge, is removed from the process and further treated prior to disposal.

In addition to the three main components of the basic activated sludge process, the following mechanical devices are very important for process operation:

- Aeration device to provide adequate aeration (compressed air via fine bubble aeration or mechanical aeration)
- Mixing devices for anaerobic or anoxic zones
- Means of collecting settled sludge in the clarifiers and recycling the major part to the aeration tank (return activated sludge)
- Means of removing excess sludge from the system (waste activated sludge)

Figure 5. View of aeration tanks and clarifiers

The majority of the activated sludge processes are designed to remove carbonaceous BOD, but increasing number of plants includes also nitrification and/or phosphorus removal. The main design parameters are food to microorganism ratio (F:M), hydraulic retention time and sludge retention time (Table 4).

Table 4

Typical design parameters for activated sludge processes

Parameter	**Extended aeration**	**Low loading rate**	**Medium loading rate**	**High loading rate**
Mass load (F/M), $kgBOD_5/kg$ VSS.d	<0.1	0.1-0.2	0.2-0.4	>0.4
BOD_5 removal rate, %	98	95	90	80
Volumetric loading rate, $kgBOD_5/m^3.d$	<0.35	0.35-0.5	0.5-1	>1
Concentration of mixed liquor, MLSS g/L	3-4	3-4	2-3	<2
VSS/SS ration, %	65	70	75	80
Sludge age, d	15-30	8-20	5-15	3-5
Sludge production, kgSS/kg BOD removed	1	1.15	1.25	1.4
Sludge index, mL/gSS	150	200	250	300
Sludge characteristics	well stabilised	stabilised	susceptible to fermentation	high fermentation

4.2 Indicators of process operation

Successful operation of activated sludge can be achieved only if each operator is able to recognise system changes and trends and makes the proper decision to successfully counteract potential harmful events. These decisions should reflect judgment gained from a good understanding of the biological and chemical principles at work and from past experience of the system, rather than being based on rigid application of general rules.

Because successful operation of activated sludge depends on living organisms, strongly influenced by specific environment, setting up efficient rigid rules of operation is impossible. Each wastewater treatment plant is unique and the operation of a particular activated sludge process should always be based on its specific performance and response to control technique applied. This may require the process to be run outside the typical range of the operating parameters presented in this document.

The **main indicators** of process operations of activated sludge are[1,4]:

- **Dissolved oxygen**
- **Return activated sludge rate**
- **Waste activated sludge rate**

In addition to the control of these critical operational indicators, efficient operation of activated sludge requires also the frequent inspection of the following **operational control parameters**:

- **Microscopic examination** of activated sludge
- Control of **mixed liquor respiration rate** or nitrification rate
- Measurements of **sludge volume index** SVI
- Control of **sludge blanket depth** of clarifiers

4.2.1 Process control monitoring

Activated sludge process control consists of reviewing present and historical operating data and lab tests results to select the proper operational parameters that provide the best performance at lower cost.

The main **water quality related operational parameters** that should be monitored are as follows:

- F:M ratio (BOD to MLVSS)
- Sludge retention time (SRT)
- Mixed liquor concentration (MLSS and MLVSS)
- Sludge quality
- Additional parameters for nitrification: TKN loading, BOD/TKN ratio and nitrification rate

The results of the measurement of these parameters allow the control of aeration rates, return activated sludge (RAS) rates and waste activated sludge (WAS) rates.

The way the activated sludge process is operated will not only affect the effluent compliance, but also the operation costs, which are strongly influenced by the energy consumption and the excess sludge production.

When properly operated, the activated sludge process is reliable and can achieve high removal efficiencies for carbon and nitrogen handling as well shock loads (Table 5).

Table 5

Typical average removal rates of properly operated activated sludge

Parameter	Removal rate, %
Suspended solids	80
BOD_5	90
COD	70
TOC	80
Ammonia nitrogen	70
Phosphorus	45
Cr, Cu, Fe, Pb, Ag	70-80
Zn, Cd	50

4.2.2 Dissolved oxygen control

The **main indicator** for the proper operation of aeration tanks is **dissolved oxygen** (DO).

The average DO concentration should be maintained at about 2 mg/L in all areas of the aeration tanks for adequate microorganism activity[1]. Higher DO concentration >2 mg/L may improve nitrification.

The **major consequence of low DO** below 1 mg/L is **filamentous organism growth** and **poor sludge settling**. However, it is important to notice that in advanced activated sludge processes designed for total nitrogen removal, DO can and must be near zero in the anoxic and anoxic zones.

The amount of oxygen that must be transferred by the aeration system is theoretically equal to the amount of oxygen required by the mixed liquor to oxidise the organic pollution and ammonia (in the case of nitrification), as well as for endogenous respiration. As a rule, if oxygen demand of the biomass is satisfied, then the mixing requirements are also met.

4.2.3 RAS control

The **return activated sludge rate** (**RAS)** is another **key control parameter** that determines the concentration of mixed liquor, its settling properties and sludge residence time in clarifiers. The rate at which the activated sludge is returned from secondary clarifiers to the aeration tanks affects the solid balance between these units. The primary objective of returning sludge control should be to maintain sludge blanket levels and RAS concentrations within a desired range.

For activated sludge with good settling properties, the RAS is typically in the range of 50 to 75% of the average design flow rate[1]. For poorly settlable sludge, the recirculation rate can be increased to 150%.

Several **techniques**[4] can be applied **for the return flow control**:

- Direct sludge blanket control using special sludge blanket detectors
- Settleability tests
- Mass balance of secondary clarifiers or aeration tanks

Direct sludge blanket control aims to maintain an optimum sludge blanket level in clarifiers. Generally, **sludge blanket** level should be maintained between **0.3 and 0.9 m**. Despite the variations of wastewater flow and characteristics, the variations of sludge blanket levels should be maintained low, no more than ±10% per day, with a maximum allowed increase of +25%.

Settleability tests do not require sophisticated test devices and are based on the measurement of sludge volume in a settleometer after 30 minutes settling period (SSV in mL/L). The ratio of return sludge flow R (m^3/d) to plant influent flow Q (m^3/d) is calculated according to the following equation:

$$R/Q = SSV/(1000-SSV)$$

The use of **mass balance approaches** is **more complex** and based on several assumptions, such for example, the sludge blanket level in clarifiers is constant. For these reasons, these methods are not easy to be used by operators.

4.2.4 WAS control

The **waste activated sludge** (**WAS)** control is another **key control parameter** that regulates sludge inventory and affects the process more than any other process control adjustment. The WAS removal affects the following parameters:

- Effluent quality
- The growth rate of microorganisms and population dynamics
- Mixed liquor settleability
- Oxygen consumption
- Nitrification rates
- Foaming, etc.

WAS is removed from the treatment process to keep the ratio of biomass to food supplied in the wastewater in balance. After extraction, WAS is thickened and is further treated by digestion and/or dewatering prior to disposal.

Typically, excess activated sludge is removed from the RAS flow, which is characterised by a higher sludge concentration that the mixed liquor in the aeration tanks.

The optimisation of activated sludge treatment depends on properly controlling the mass of active microorganisms in the system, which depends on WAS. The **most common methods of controlling of excess sludge removal** are as follows:

- Constant SRT
- Constant MLSS
- Constant F:M ratio
- Sludge quality

All these methods give different WAS values at any specific times and for this reason, the same method should be used all time.

The most important requirement is to have **accurate flow measuring devices** associated with WAS pumping system. Sludge should be wasted as slowly as possible to avoid shacking the process.

The **SRT method** is widely used and reliable. The SRT is the average number of days that microorganisms are kept in the activated sludge process before being wasted, either intentionally or unintentionally.

SRT = Total weight of solids in aeration tanks and clarifiers / Total weight of solid leaving the process

The weight of leaving solids includes both suspended solids in WAS and suspended solids in effluent.

The easiest way to adjust SRT is to adjust the wasting rate daily, taking into account that variations do not exceed ±10% per day. The target SRT should be selected each month by monitoring the process (sludge settleability, respiration rate, microscopic examinations).

Constant MLSS technique is used by many operators because it is simple to understand and involves a minimum amount of laboratory control. This method usually produces a good quality effluent as long as the incoming wastewater characteristics are fairly constant (flow rates or BOD).

For example, if a concentration of 2 g/L of MLSS produces a good effluent solids are wasted as necessary to maintain this concentration. The target MLSS concentration can be defined by experiments with various F:M ratio during a few weeks. Once an F:M ratio, which produces good secondary effluent and good settling sludge is found, the average MLSS is recorded and becomes the target MLSS. Because this method ignores the F:M ratio, it may not provide adequate process control at plants where loadings variations are high (daily, weekly or monthly).

Constant F:M ratio has not this disadvantage, but requires a significant amount of laboratory work.

4.2.5 Control of biological activity

Process performance is dramatically affected by the nature and activity of the microorganisms in activated sludge flocs. The crucial parameters that affect biological activity are oxygen and food. Other factors such as toxic compounds, temperature, pH, nutriments, can also affect biological activity.

The most commonly used tool to control biological activity is indicator organisms identified by means of **microscopic examination** (inexpensive microscopes at lower magnification of 100x to 400x). For operational purposes, the relative types of microorganisms present in the activated sludge sample, the predominance of each of the various types and the mobility of microorganisms are the primary concerns. Relative predominance of some microorganisms gives an indication of F:M ratio and SRT (see Standard Methods for detailed information). For decision making, microscopic observations should be coordinated with results from other process control tests. It is not necessary to be a skilled microbiologist to identify or count individual species and recognise the major groups such as protozoa, rotifers and filamentous bacteria (Figure 6).

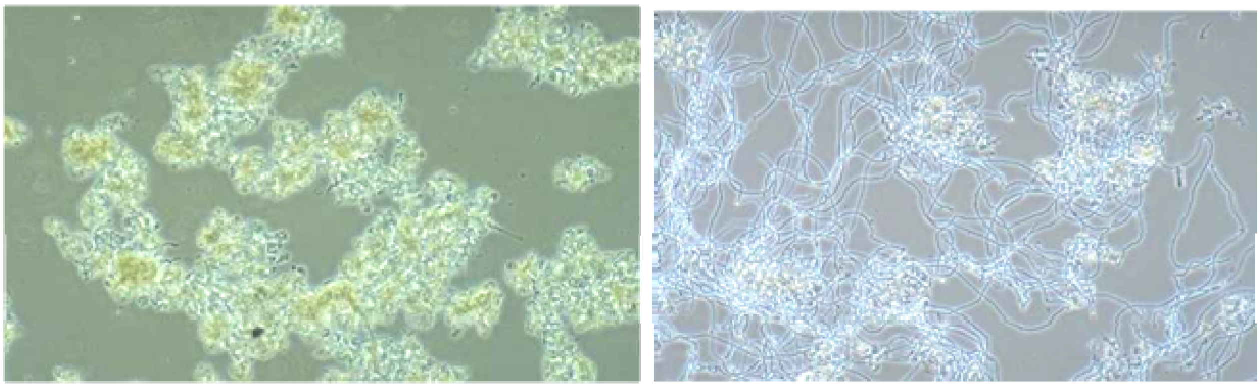

Figure 6. Microscopic view of good settling flocs and bulking sludge

4.2.6 Operational monitoring of activated sludge in water reuse systems

When secondary effluent undergoes tertiary treatment such as disinfection or membrane filtration to produce recycled water for various reuse purposes, **more stringent operational monitoring should be implemented** to ensure the good disinfection efficiency.

In addition to the good operational practices described previously, the following operational monitoring of activated sludge is recommended for water reuse systems:

- On-line measurement of turbidity, dissolved oxygen and effluent flow to better control the performance of clarifiers and activated sludge
- Regular observation of clarifier performance such as sludge settling supplemented with SVI quantification
- Regular quantification of activated sludge properties such as MLSS concentration
- Determination of critical limits on key operational parameters such as DO, sludge blanket depth, sludge age, ammonia concentration, turbidity of clarified effluent

4.3 Operational problems and solutions

The identification of the probable cause of operational problems of activated sludge is very complex and operator needs a thorough knowledge of the plant's activated sludge process and how it fits into overall plant operation. In many cases, plant design may limit the ability to respond to operational problems, such as deficiencies in sludge wasting capability, aeration capability or process flexibility or controllability.

The most important **troubleshooting tests** are similar to operational indicator methods:

- Settleability tests of mixed liquor
- Microscopic observation
- Determination of sludge blanket level
- Mixed liquor respiration rate or nitrification rate

The main operational problems of activated sludge can be summarised in three categories:

1. Problems of aeration system including low DO, poor mixing and foaming,
2. Problems of clarifiers that include solids loss, bulking sludge, rising sludge, etc.,
3. Filamentous foaming and bulking (Figure 7).

These problems can be corrected by using sound operational control practices and indicators, described previously, and by maintaining proper equipment operation. Preventive maintenance program plays an important role for improvement of process efficiency and reliability.

The most common operational problems and recommended correctives actions are summarised in Table 6. Some remedies produce quick results, while others react only after many days. In most cases, aeration adjustment, flow balancing and return sludge adjustment will produce quick results. Generally, the impact of adjustment of sludge wasting takes longer and is less reversible, that is more prone to overcorrecting.

In the case of bulking, chlorination of mixed liquor or return sludge produces quick results at moderate or greater application rates, but poses significant risks if done improperly. For this reason, chlorination should be considered as a remedy of last resort.

Reducing or controlling sludge recycle flows produces quick positive results, but may require changes in the operation of sludge treatment processes.

It is recommended to **take only one corrective action at a time** to avoid confusing effects of multiple changes. After attempting a remedy, be sure to allow enough time for the process to respond before trying something else (commonly 2 to 3 SRTs).

Figure 7. View of foaming in activated sludge systems

Major changes may result in overcorrecting which can create additional problems just as severe as the initial problem they were intended to cure.

If operating problems cannot be solved in-house, help should be obtained from other, such as operators of other plants, consultants and other experts.

It is important to stress that **preventive maintenance is very important**, in particular for aeration system. Blowers and turbines need periodical inspection, lubrification and repair. Daily inspection of blowers is highly recommended for excessive vibration, overheating and unusual noises. Air distribution pipes generally require very little maintenance, but regular inspection for leakage is needed, as well as accurate air flow measurement. Concerning aeration devices, fine bubble aeration is much more susceptible to fouling than coarse bubble units. Therefore, preventive maintenance of fine-pore diffusers is critical (in-situ acid cleaning). The effectiveness of the preventive maintenance program must be based on controlling increases in operating pressure and losses in oxygen transfer efficiency (OTE).

Preventive maintenance is also very important for clarifiers and includes regular inspection of weir by checking for equal flow, clean and adjust scum removal equipment regularly, inspect underwater portion regularly, once at year (dewater the tank and check, clean and repair all mechanical equipment, concrete surfaces and suction lines).

Table 6
Rapid identification of some common operational problems of activated sludge and guidelines for troubleshooting

Indicator	Probable cause	Explanation	*Immediate action	Solutions
Foaming problems				
White, stiff or sudsy foam	Normal phenomenon during start-up	Young sludge in an overloaded aeration tank	Check BOD loading of aeration tank and solids loss in clarifiers	Increase MLSS concentration by minimisation of wasting rate Maintain DO levels between 2 and 3 mg/L Seed the process with healthy activated sludge
	Unfavourable conditions	Highly toxic waste, abnormal pH, insufficient DO, colder temperature	Check respiration rate Check mixed liquor with microscope Check T°C and solid washout	In case of toxicity, new inoculation may be necessary with healthy activated sludge Perform settling test for foaming
Shiny, dark brown foam	Under loaded activated sludge	Low F:M ratio Insufficient sludge wasting	Check for increasing MLVSS, increasing SRT, decreasing F:M, decreasing DO, increasing T°C or decreasing wasting rate Check influent and return rate to each aeration tank	Increase wasting rate by not more than 10%/day until process approaches normal control parameters Equalise influent and return rates to each aeration tank
Thick, scummy, dark brown foam	Critically under loaded activated sludge	Too low F:M		
Greasy, dark tan foam that is strong and carries over to clarifiers	Filamentous growth (Nocardia)	High grease/oil	Check mixed liquor with microscope	Lower SRT to 2-9 days and physically remove foam Do not recycle foam through the plant Control influent and recycled grease and fats
Dark brown, almost black sudsy foam and black mixed liquor	Anaerobic conditions	Anaerobic fermentation occurring in the aeration tank	Check DO for proper aeration and mixing Check aeration equipment Check MLSS	Increase aeration and maintain 2-3 mgO_2/L Repair leaks and clean diffusers If too high, adjust MLSS to proper F:M If proper F:M, reduce MLSS
Bulking sludge				
Clouds of billowing homogenous sludge rising in clarifiers	Toxics causing floc dispersion High F:M bulking	Industrial waste peak discharge	Check mixed liquor respiration rate Check mixed liquor with microscope Check for changing MLVSS, SRT, F:M or DO	Decrease wasting and return rate Use settling add, if possible
	Filamentous builking (Thiotrix, types 021N, *S. natans, H. hydrossis*)	Wastewater nutrient deficiencies, N or P Low DO High F:M bulking Septic wastewater	Check nutrient level Check mixed liquor with microscope for identification of filamentous bacteria Check DO at various locations	Chlorinate RAS starting with low rates Monitor settleability and turbidity Observe filaments to stop chlorination Increase aeration and ensure homogenous aeration
Poor nitrification				
Loss of nitrification	Decrease of pH	Insufficient addition of lime Acidic waste	Check pH and alkalinity in effluent Check raw effluent pH and alkalinity	If alkalinity is less than 20 mg/L, start adding lime
High effluent ammonia above permit value	Poor aeration Overloading Loss of nitrifiers	Low DO High nitrogen loads Cold T°C Low alkalinity	Check DO Check influent TKN and flow Check nitrification rate and MLVSS	Increase aeration and maintain minimum 2 mgO_2/L Decrease N loading or increase MLVSS Add nitrification tanks Increase alkalinity Decrease wasting
Slow settleability	Toxic influent Filamentous growth	Industrial waste Low DO	Check mixed liquor with microscope Check DO and pH	Eliminate toxic flow Depending on filamentous organisms apply adequate corrective measures

Source: Adapted from [4] and the feed-back from operators
*Any decision following a process failure or any troubleshooting should be taken only after verification of the correct power supply of all electrical devices

5. MEMBRANE BIOREACTORS

5.1 General considerations

One of the newer and most promising technologies is the **membrane bioreactor** (MBR). MBR process is a **modification of the confventional activated sludge where the clarifier is replaced by a membrane unit** for the separation of the mixed liquor from treated effluents[5]. Consequently, membranes function replaces sedimentation, sand filtration and disinfection for the removal of suspended solids and microorganisms.

Most of MBR systems are of proprietary design with different configurations. The most common configuration for treatment of urban wastewater is submerged membranes located in aeration tanks or in separated membranes tanks. The permeate collection is vacuum-driven and coarse-bubble aeration is introduced below the membranes to limit membrane fouling. Pressure-driven membranes with external recirculation (side-stream membranes) are also available, but are more commonly used for treatment of industrial wastewater.

The common feature of all MBR is the low-pressure membrane system, *e.g*. microfiltration (MF) or ultrafiltration (UF) for liquid/solids separation. Various types of membranes are used for MF and UF, most commonly hollow fibers UF (Zenon system of GE Water, MemJet of US Filter, Mitsubishi, Koch/Puron) or plane membranes (Kubota, Toray).

The main advantages of MBR are their small footprint and higher effluent quality. The reliability of operation and the production of a disinfected effluent are the major advantages for water reuse. MBR can also incorporate nutrient removal.

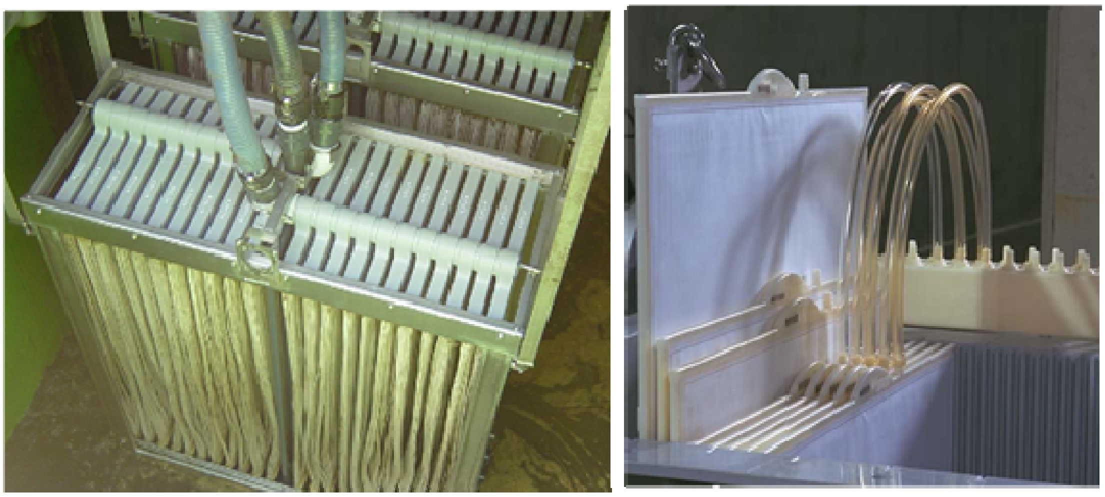

Figure 8. View of submerged membranes Zenon (hollow fibers) and Kubota (plane membranes)

A number of recent publications demonstrate the higher reliability of operation of MBR and their ability to consistently achieve high effluent quality in terms of removal of TSS, BOD, COD and microorganisms. Nevertheless, it is important to stress that the **complexity of MBR operation is higher compared to conventional activated sludge** (CAS) because the strong interaction between the biological process and membrane filtration. These two processes work in conjunction with one another rather as connected by independent operations.

[5] Judd S. (2006) The MBR Book: Principles and Applications of Membrane Bioreactors in Water and Wastewater Treatment, Elsevier, Oxford, UK.

The fundamental differences in the biology of an MBR compared to CAS are not yet very well documented[5]. As a rule, the flocs of MBR were shown to be significantly smaller and more active with a greater diversity of species.

The MBR design is very important in achieving consistent and reliable operation. In particular, the **pre-treatment plays a very important role** for the protection of membrane by fouling by rags, grease and oil. The **most important design and operational considerations** to be taken into account for MBR design in order to achieve reliable operation are described here below[6]:

1. Pre-treatment
    - Buffer tanks (equalisation of inlet flows)
    - Robust pre-treatment including coarse screens, grease & oil removal, fine screening (automatic 6-10 mm), fine sieves (holes of <1-3 mm, no by-pass allowed)

2. Aeration tanks
    - Sludge age >12 d, typically 20-40 d
    - Mass loading (F:M ratio) <0,15 kgBOD/kgMVS.d, typically 0,05-0,15 kgBOD/kgMVS.d
    - Sludge concentration of 6 to 8 g/L (maximum 12 g/L) to avoid oxygen mass transfer limitations
    - Sludge production: similar to CAS, may be slightly smaller
    - Control of dissolved oxygen (DO) strongly recommended with a minimum allowed value of 2 mg/L

3. Membrane filtration
    - Membrane situated in a well adapted zone with at least 2 units (cassettes)
    - Sludge recirculation 200 to 400% to avoid any higher concentration of mixed liquor in membrane tanks
    - Cleaning procedures: strongly follow the manufacturer's recommendations (air back-pulses, relaxation, retro-cleaning, weekly maintenance cleaning, mechanical and chemical cleaning 1 to 4 times per year
    - Membrane flux: operate the membrane in relatively low flux, the average value, to limit membrane fouling (average flux for Zenon membranes 25 $L/m^2/h$ (from 15 to 40 25 $L/m^2/h$ at 20°C)

4. Produced water quality
    - Higher water quality than CAS, similar to tertiary treatment
    - Effluent free from suspended solids (turbidity <0,1 NTU), total elimination of BOD, improved elimination of COD and disinfection (retention of viruses, bacteria and protozoa)
    - Nutrient removal (N and P) similar to CAS

[6]WEF (2006) Membrane Systems for Wastewater Treatment, ed. by Water Environment Foundation, WEFPress/McGraw-Hill, New York, USA

Table 7

Typical characteristics of raw urban wastewater and MBR effluents

Parameter	Raw sewage concentration, mg/L	Treated MBR effluent, mg/L	
		Concentration	Discharge consent
COD	776 (348-1555)	25 (13-38)	50
BOD_5	320 (110-460)	<3	10
TSS	320 (153-1330)	<2	3
NTK	77 (31-133)	5 (3-13)	12 (2h)
Phosphorus	12 (7-17)	1.1 (0.6-2)	2 (2h)

Average (minimum – maximum value) of composite 24 samples proportional to hydraulic flow Source: [7]

5.2 Indicators of process operation

Successful operation of MBR requires good training of operator and good knowledge of both biological process and membrane filtration. Because the MBR systems are, as a rule, fully automated, high qualification staff is needed.

The **main indicators** of process operations of membrane bioreactors are:

- **Dissolved oxygen**
- **Membrane permeability and/or transmembrane pressure (TMP)**
- **Membrane integrity (on-line turbidity measurement)**

In addition to the control of these critical operational indicators, efficient operation of MBR systems requires also the regular checking of the following **operational control parameters**:

- **Settleability test** with examination of the supernatant (low turbidity, lack of small flocs or free particles)
- **Microscopic exam** of mixed liquor
- Control of **mixed liquor respiration rate** or nitrification rate
- Control of **membrane integrity** (air bubbling)
- Control of **membrane filterability** (optional)
- Control of **pre-treatment efficiency** for the presence of rags, plastics or grease

5.2.1 Process control monitoring

Process control monitoring is similar to those of activated sludge. In the case of MBR more attention should be made on the monitoring of influent water quality, because some constituents can favour membrane fouling, especially some industrial influents. The following **wastewater constituents** have negative effects on membrane filtration:

- Rags, hair, plastics (clogging and fouling)
- Oil and grease (fouling)
- Surfactants (foaming)
- High variations of salinity (deflocculation of flocs and fouling)
- Temperature variations (affects water viscosity and flux)
- Dissolved monomers (polymerisation and fouling)
- Colloidal organic matters (fouling)

[7] Lazarova V., Bonroy J.L. and Richard J.L. (2008) Reliability of operation and failure management of membrane wastewater treatment. Wat. Practice. Tech. 3(2), 8p.

The main operating parameters of biological treatment that should be monitored are similar to those in CAS:

- F:M ratio (mass loading)
- Sludge retention time (SRT)
- Mixed liquor concentration: MLSS and MLVSS
- Dissolved oxygen (DO)
- Microscopic examination
- Sludge quality and more importantly the quality of supernatant
- Additional parameters for nitrification: TKN loading, BOD/TKN ratio and nitrification rate

The results of the measurement of these parameters allow to control aeration rates and waste activated sludge (WAS) rates.

The main operating parameters of membrane filtration that should be monitored are as follows:

- Membrane flux, L/m²/h at 20°C
- Transmembrane pressure (TMP), bar
- Membrane permeability (specific flux), L/m²/h.bar

5.2.2 Dissolved oxygen control

The operation of MBR as those of activated sludge in terms of **good aeration is a critical factor** with strong impact on membrane performance. In fact, any deterioration of activated sludge flocs with release of colloids and soluble microbial products due to fermentation, peaks of salinity or toxic shock loading, leads to loss of membrane permeability and membrane fouling.

Compared to conventional activated sludge, poor characteristics of the mixed liquor does not significantly affect permeate quality in terms of compliance with discharge consents. This is the main reason why MBR systems are considered as more efficient and reliable. Nevertheless, it is important to stress that lifetime and permeability of membranes can be reduced, impeding thus the overall technical-economic performance.

As demonstrated for CAS, the **main indicator** for the proper operation of aeration tanks is **dissolved oxygen** (DO).

The average DO concentration in MBR aeration tanks should be normally 2 to 3 mg/L for adequate microorganism activity.

Automatic control of DO in aeration tanks is recommended to ensure good treatment performance and reduce energy costs.

It is important to underline that oxygen transfer coefficient decreases with the increasing of the concentration of mixed liquor, with a very strong decrease where MLSS are over 8-10 g/L.

5.2.3 Other parameters to control biological activity

5.2.3.1 WAS control

The **WAS** control is the **key control parameter** of MBR that regulates sludge age and concentration and affects the biological process.

Typically, excess activated sludge is wasted by removing a portion of RAS flow characterised by a higher sludge concentration than the mixed liquor in the aeration tanks, or directly from the aeration tanks.

As for activated sludge systems, the optimisation of biological treatment depends on properly controlling the mass of active microorganisms in the system, which depends on WAS. The **most common methods** of **controlling of excess sludge removal** in MBR are as follows:

- Constant MLSS
- Constant SRT, or
- Constant F:M ratio

Constant MLSS and SRT are widely used in MBR systems and are described in the previous section (§0, page 19). For more reliable operation of MBR, it is recommended on-line MLSS measurement.

5.2.3.2 RAS control

For MBR systems with separated membrane filtration tanks, RAS is adjusted at 200 to 400% in order to control the increase of sludge concentration during filtration. No RAS can be required when membranes are located in the aeration tanks and the aeration process is only one step.

5.2.3.3 Control of biological activity

Control of biological activity of MBR is strongly recommended to avoid biological process failure and membrane fouling. As a rule, MBR sludge is characterised by poor settleability. Nevertheless, settling tests are highly recommended, in particular to control the **quality of interstitial water** (the supernatant). If, after settling, supernatant is turbid, with small floating flocs, this means that the status of aerated sludge is not good and urgent corrective measures must be taken to avoid membrane fouling.

The **microscopic examination** is a powerful tool to follow the status if activated sludge flocs and indicator organisms. As a rule, MBR flocs are more compact and small, <100 µm (Figure 9).

The most common causes of deflocculation and poor quality of interstitial water is low DO, toxic overloading or peak salinity concentrations.

Figure 9. View of MBR flocs with good settleability

5.2.4 Control of membrane filtration performance

As a rule, membrane filtration is fully automated and the **critical control operational values** are integrated in the SCADA system: membrane flux, TMP lower value requiring recovery chemical cleaning, target values or time intervals to start on-line cleaning, preventive maintenance, air scouring, permeate flow rate for membrane cleaning, chemical flow rates, etc.

5.2.4.1 Preventive measures against membrane fouling

Preventive measures against membrane fouling recommended by membrane manufacturer are the **crucial factor avoiding excessive loss of membrane permeability**. Both physical and chemical cleaning are used, depending of membrane configuration and manufacturer's recommendations.

The **main operational unit processes implemented as preventive measures** to avoid membrane fouling are as follows (on the example of for the widely used Zenon membranes):

- **Air-scouring**, mostly coarse bubble aeration, applied continuous or intermittently at the bottom of membrane modules, is commonly used to limit particle deposition on the membrane surface
- **On-line cleaning** by air scouring plus backpulses with permeate during filtration or relaxation of membrane fibbers
- **Relaxation sequence**, is another physical method to mitigate membrane fouling (elimination of the reversible foulant layer)
- **In-situ preventive maintenance cleaning** (1-2 times per week) with short contact time using low dose chemicals
- **Recovery cleaning** (at least 1-2 times per year) with long contact time and high concentrations of chemicals

Depending on MBR configuration, the **air scouring flow rate**, expressed as a ratio by membrane area, varies between **0.28 and 1.24 $m^3/m^2/h$**. As a rule, the transferred oxygen during air scouring is not included in the calculation of biological demand as it represent less than 5-10% of the total air supply in MBR systems.

Maintenance cleaning is entirely automated and scheduled to occur during off-peak hours by night when the membrane units can be in standby mode. This cleaning procedure is similar to backpulse with the major difference of higher duration over one-hour period. The typically used chemical to prevent membrane biofouling is sodium hypochlorite at a concentration of 200 mg/L, which periodically is replaced by citric acid to remove potential inorganic fouling.

As a rule, **recovery cleaning** (chemical cleaning) is performed when membrane permeability falls below 50% of the initial value (200 $L/m^2.h.bar$ for Zenon membranes), or by safety measure once a year. To initiate recovery cleaning, the given membrane unit is isolated and the mixed liquor is evacuated. The cleaned membrane box is filled with industrial water and sodium hypochlorite (1000 to 2000 mg/L) is added by backpulsing. If after a contact time of 6 to 12 h (or 24 h if biofouling is important), the membranes recover their permeability, they can be put in operation.

Depending on wastewater quality and potential membrane scaling, an additional chemical cleaning with citric acid can be performed. During recovery cleanings additional tests are also performed including visual observation of fouling, checking of tensile strength, as well as membrane integrity test via bubble-point observation after membrane pressurisation.

5.2.4.2 Control of membrane permeability (specific flux)

Membrane permeability or the **specific membrane flux**, expressed at L/m²/h.bar at 20°C is the **main operational parameter used for the control of membrane filtration performance** (calculated by dividing the membrane flux by TMP).

Figure 10 illustrates the evolution of membrane permeability of four MBR membrane units for one-year period[7]. Applying the recommended maintenance and cleaning procedures, a good recovery of membrane permeability was observed, 170 to 220 L/h.m² bar at 20°C compared to the initial permeability of 250 L/h.m² bar at 20°C. Few peaks of permeability have been observed in two of membrane units occurring in early morning due to very low hydraulic loading rates. The average membrane flux par unit was 20 L/h.m² at 20°C with variations between 10 and 35 L/h.m² at 20°C depending on hydraulic loads. The average temperature of wastewater was 22°C with strong variations from 8.5°C in winter to 28°C in summer.

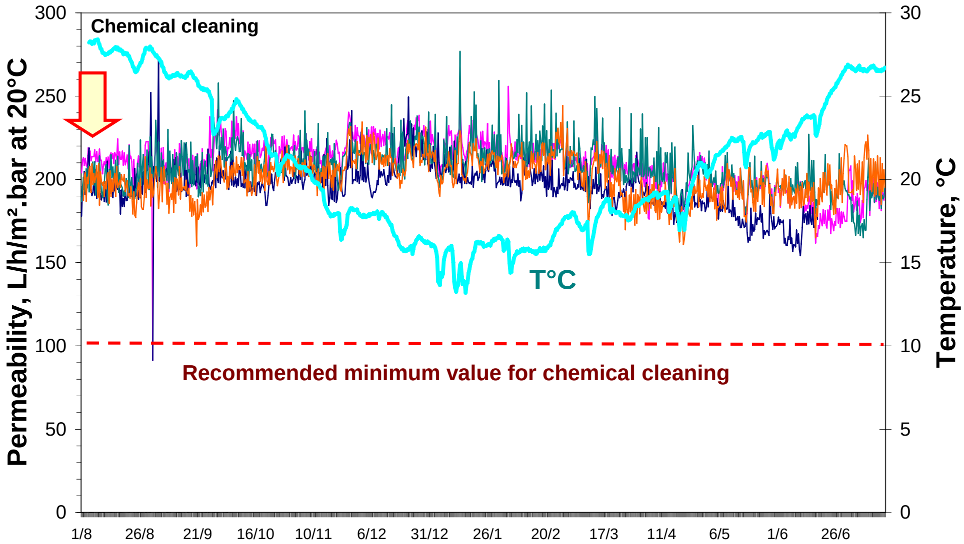

Figure 10. Evolution of normalised membrane permeability of a four submerged membrane units during one-year period

It is important to underline that the design flux rate is typically for the peak day or hour flow, which can be attenuated by peak flow management (buffer tanks, inlet pumping control, etc.). Whatever the submerged MBR configuration or membrane geometry, the **membrane flux** varies in the same range from **10 to 35 L/m^2/h** at 20°C, mostly between 20 and 27 L/m^2/h.

The recommended strategy to limit membrane fouling is to filter the mixed liquor at low fluxes, far below the maximum design flux.

5.2.4.3 Control of membrane filterability

Several laboratory tests are proposed to evaluate and follow the variations of the filterability of the mixed liquor. Because these tests are time-consuming to use by plant operators, they are not recommended for routine control of MBR operation.

The easiest and strongly recommended test is the daily investigation of the mixed liquor by settling test with verification of the quality of interstitial water. Once the water above the settled sludge becomes turbid with small floating flocs and dispersed individual bacterial cells or aggregates, immediate corrective measures must be applied to adjust aeration and verify any toxic or septic overloading.

5.2.4.4 Control of membrane integrity

Integrity testing is very important, in particular when treated wastewater is reused. The main aim is to determine the existence of any breaches, leaks or defects that allow unfiltered water to by-pass membrane barriers. **Integrity test must be conduced at least after each recovery cleaning on each membrane unit.**

The most easy to use **direct integrity test** is **air-bubbling**. After chemical cleaning, the membrane filtration tank is filled with clear water (permeate) and pressurised air is supplied in the permeate line. The air bubbling indicates the location of any breaches or leaks.

A very reliable and strongly recommended **indirect integrity test** for water reuse systems is the **on-line turbidity measurement**. Although this indirect method is not as sensitive as the direct integrity air-bubbling test, its main advantage is the continuous control of effluent quality. If permeate turbidity exceeds 0.2 NTU, this indicates the existence of leakage or breaches.

5.3 Operational problems and solutions

The MBR wastewater treatment works must be equipped with **redundant power supply**, **pumps and blowers**. Because membrane operation is fully automated, PLC system (Programmable Logic Controller system) plays a crucial role and all electric equipments need **excellent grounding** and **control of electromagnetic harmonics**.

By using the Failure Mode Effects and Criticality Analysis, a risk matrix has been proposed for the most important functional elements of MBR (Table 8). The occurrence (frequency) of failures is classified from very unlikely to frequent with ranks from 1 to 10. Similarly, the severity of the impact of a given failure is ranked from a minor impact to critical effect, especially on membrane performance. A higher risk is associated with the equipment situated at the upper right side of the table (in red), while a lower risk (cells in green) is linked with the elements at the left-bottom side. Moderate risks are in the middle (yellow cells).

As shown in Table 8, the major risk for system failure is related to the pre-treatment in terms of grease & oil removal and pre-screening, which is commonly a crucial factor for membrane clogging and damage by sticky oily sludge, rags and plastic materials[7]. Several other recent publications confirmed that **pre-treatment is the crucial element** for the reliability of operation and fouling protection of MBR. Clogging of micro-screens is detected as the major failure mode for all the investigated full-scale MBR systems. The major consequence of faulty pre-treatment is the accumulation of hairs, rags and grease on membrane fibers inducing accelerated fouling and risk for membrane damage and/or decrease of membrane lifetime.

Even if foaming is frequent phenomenon, its impact on membrane performance is relatively minor. Nevertheless, it is highly recommended to implement a foaming removal device in aeration tanks of MBR systems in order to remove foams. Foam removal is particularly important in presence of filamentous bacteria and grease as they can accelerate membrane fouling.

Table 8

Example of risk matrix for the reliability of operation of a municipal MBR plant (analysis of the failures during 3-year operation)

Occurrence/ Severity	Very unlikely	Remote	Occasional	Probable	Frequent
Very high (health risk)	–	–	–	–	–
Critical	Damage of membrane modules	Membrane fouling	Membrane clogging	Fin screen clogging (3 mm)	–
Major	Failure of SCADA & HMI	Failure of chemical dosage (polymer, $FeCl_3$)	Fault of recirculation of mixed liquor	Fault of membrane air-scouring	Micro-sieve clogging (0,75 mm)
Moderate	Failure of PLC	Fault of inlet pumps	Failure of membrane auxiliary equipment	Fault of blowers & diffusers of aeration basins	Fault of PLC-link (modems, etc.)
Minor	Failures due to low temperature	Failure of buffer tank equipment	Failure of odor or sludge treatment	Foaming	-

Source: [7]

As underlined in the previous sections, **preventive maintenance is very important** for the reliable operation of MBR systems.

The most common operational problems and recommended correctives actions are summarised in Table 9. For foaming problems, see Table 6.

Figure 11. View of MBR plants

Table 9

Rapid identification of some common operational problems of MBR systems and guidelines for troubleshooting

Indicator	Probable cause	Explanation	*Immediate action	Solutions
Problems of biological treatment				
Dark brown, almost black sudsy foam and black mixed liquor	Anaerobic conditions Septic influent	Anaerobic fermentation occurring in the aeration tank	Check DO for proper aeration and mixing Check aeration equipment Check homogenous aeration and mixing Check MLSS	Increase aeration and maintain >2 mgO_2/L If too high, decrease MLSS Improve mixing and aeration Remove foams
High Turbidity of interstitial water above the settled sludge	Poor aeration Toxic overloading Salinity peaks	Deflocculation Anaerobic fermentation	Check influent characteristics Check aeration and mixing	Stop the discharge of toxic influents Increase aeration and maintain minimum 2 mgO_2/L Decrease wasting
Poor nitrification	Poor aeration Overloading Low pH	Low DO High nitrogen loads Cold T°C Low alkalinity	Check DO Check influent TKN and flow Check nitrification rate and MLVSS	Increase aeration and maintain minimum 2 mgO_2/L Increase MLVSS Increase alkalinity
Problems of membrane operation				
High turbidity of permeate	Presence of unfiltered mixed liquor	Leakage or membrane damage	Stop membrane filtration Check membrane units Perform direct membrane integrity test (air-bubbling) Check for any by-pass of membrane filtration	Repair the faulty equipment (O-rings, broken fibers, etc.) Avoid any by-pass of membrane filtration Flush permeate pipes Clean permeate reservoir
Strong and sharp decrease of permeability	Membrane fouling	Increase of membrane resistance due to excessive fouling	Remove the membrane unit, inspect and clean mechanically Perform recovery chemical cleaning of membrane units If the recovery of permeability is not complete after bleach soaking, perform acid cleaning	Identify the cause of excessive fouling: • Check pre-treatment and efficiency of rags, grease and oil removal • Inspect inlet wastewater quality for unusual chemical compounds (silicone, monomers, grease) • Check the biological activity and the status of the biomass

Source: Adapted from the feed-back from operators

*Any decision following a process failure or any troubleshooting should be taken only after verification of the correct power supply of all electrical devices

6. HIGH RATE CLARIFICATION

6.1 General considerations

The first tertiary treatment process that should be considered is the chemical precipitation using advanced processes for **coagulation/flocculation and lamella settling**. Known also as ***high rate clarification,*** coagulation/flocculation or ballasted flocculation, this advanced treatment allows improving settling properties of suspended solids by the generation of microfloc particles and their separation by lamella clarification[1].

During the last decades, several proprietary technologies have been implemented in numerous wastewater treatment schemes, both as primary, storm water treatment and tertiary treatment. The major advantage of this process is its ability to efficiently remove suspended solids (80-95%, including colloidal particles), carbon removal (50-80% of BOD), disinfection (80-90% of coliforms and helminth eggs), as well as phosphorus, and thus with short hydraulic residence times. The residual turbidity is <1 NTU (<5 mgSS/L). The high-rate clarification allows achieving target consents of <2 mgP/L.

The implementation of high rate clarification for wastewater tertiary treatment is recommended for enhanced phosphorus removal in secondary effluents or before water reuse, in particular when high content of suspended solids in inlet effluent can occur (>30 mgSS/L).

The high rate clarification typically involves **three separate operations (Figure 12)**:

- **Injection and mixing of coagulants** that neutralise the predominantly negative charges on suspended matters
- **Injection and mixing of polymers** that help the agglomeration of the flocs (Interparticle bridging)
- **Lamella settling** to separate the flocculated material from the effluent

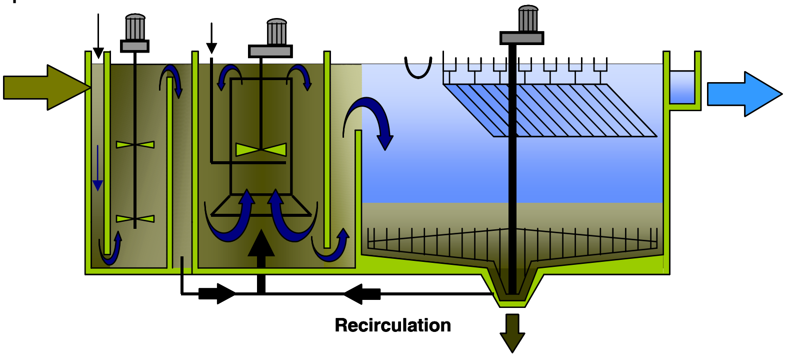

Figure 12. Principle scheme of the high rate clarification (process Densadeg, Degremont)

6.2 Indicators of process operation

The **main indicators** of process operations of high rate clarification are:

- **Coagulant dosage**
- **Polymer dosage**
- **Chemical sludge recirculation rate**
- **Effluent turbidity**

In addition to the control of these critical operational indicators, efficient operation of high rate clarification requires also the control of the following **operational control parameters**:

- Optimisation of chemical dosage by **jar tests**
- Control of chemical sludge recycling and **sludge blanket level**
- Control of **sedimentation**
- Control **of mixing**

6.2.1 Water quality monitoring

The efficiency of high-rate clarification can be defined by the monitoring of the following water quality parameters:

- Suspended solids
- Turbidity
- Phosphorus contents
- Indicator microorganisms (coliforms or helminth eggs)
- Heavy metals
- Temperature, pH

The sampling frequency depends on permit requirements.

6.2.2 Optimisation of chemical dosage by jar tests

The main operational control parameter is **chemical dosage**. Insufficient coagulant dosage will produce an effluent of excessive turbidity. The same result will be achieved using excessive chemical dosage.

The most widely used technique for determination of the adequate dosage of coagulants and flocculants is the **jar test**. This test involves collecting a sample of wastewater, transporting it to laboratory and dividing it into several samples in breakers. Increasing coagulant dosages are added. After an appropriate period of mixing, stirring is stopped and the flocs are allowed to settle. The clarity of the supernatant is used to determine the optimum coagulant dose. By using this optimal coagulant dose added to all recipients, the optimal polymer dose is determined by a similar jar test.

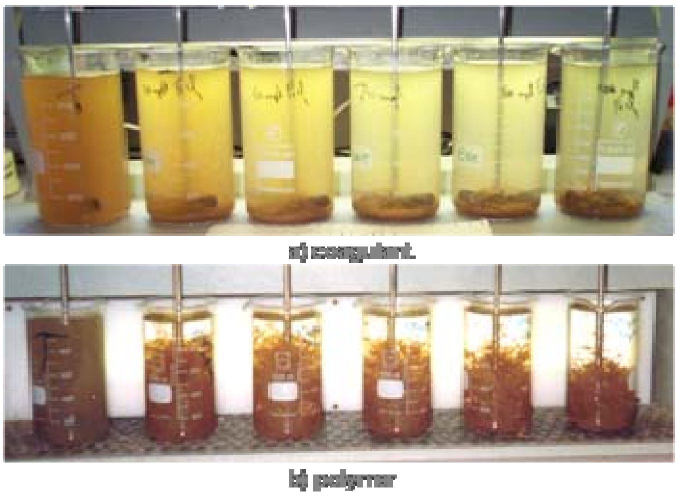

Figure 13. Optimisation of chemical dosage by Jar-tests

The required frequency for jar tests will vary widely from one plant to another and depends on the variations of wastewater quality and temperature.

Because jar tests have limitations, it is recommended to operators to visually control the quality of clarification and effluent turbidity.

Modern plant designs include automation of coagulant dosage by means of on-line control of coagulant feed in proportion to plant inlet flow and on-line control of effluent turbidity.

6.2.3 Control of chemical sludge recycling

The return of chemical sludge enhances the floc formation and can be either recycled to the mixing or flocculation tank. The control of sludge recirculation is very important to maintain constant solids concentration in the flocculation zone without exceeding the mass flux settling capability that can negatively affect settling efficiency.

Similarly to chemical dosage, sludge recirculation must be proportional to the inlet flow.

6.3 Other operational control parameters

6.3.1 Control of sedimentation

The sedimentation process is a key to overall plant performance. Surface overflow rate and sludge withdrawal rate are important variables to be considered in the operation of high rate clarification.

Surface overflow rate depends on inlet flow and recycle rate and consequently, it can be **controlled by the timing of recycled flow**.

The amount of sludge withdrawal must be sufficient to avoid overloading of collection arms, to prevent floc carryover from the basin and to avoid septic conditions.

Modern plant designs are equipped with sensors enabling the control of sludge blanket level and a better adjustment of sludge withdrawn.

6.3.2 Control of mixing

Proper mixing allows efficient use of coagulant. As the rapid mixing process in the coagulation tank has little operational flexibility, good maintenance is necessary to keep a proper operation of mechanical mixing devices.

Many flocculator designs provide for varying the speed of the slow mixer. Determination of the optimum speed depends on plant-scale tests. Also varying the amount of recycled sludge may enhance the flocculation process.

6.3.3 Main control points for regular cheeking

The proper operation of high rate clarifier requires the **regular cheeking of the equipment**, including:

(a) Assembly, speed and rotation direction of impellers; (b) Injection point of coagulant; (c) Injection point of recycled sludge; (d) Draw-off in the stilling zone;
(e) Correct operation of dosing pumps; (f) Extraction frequency during a 24h period

6.4 Operational problems and solutions

The **main operational problems** of high rate clarification can be classified in four categories:

(a) Problems related to hydraulics; (b) Problems related to chemical dosage;
(c) Problems related to mechanical devices; (d) Problems related to electricity and instrumentation

The most common operational problems of high-rate clarification and some solutions are given in Table 10.

Table 10

Rapid identification of some common operational problems of high rate clarification and guidelines for troubleshooting

Indicator	Possible cause	Explanation	*Immediate action	Solutions (Troubleshooting)
Excessive loss of suspended solids in the effluent	Faulty polymer dosage	Poorly flocculated sludge	Check preparation tank, polymer pump flow rate, and injection ring	Temporally increase polymer injection
	Sludge blanket is too high	Sludge is flushed because the blanket is too close to the lamella	Increase up to maximum the sludge extraction	Intensive sludge extraction allows lowering the sludge blanket; also, increase polymer dosage
	Excessive sludge concentration in the flocculation tank	Too much sludge is returned and the maximum admissible flux for settling is exceeded	Decrease sludge recirculation and increase, for a short time, polymer dosage	Increase sludge extraction, if too much sludge has accumulated in the settling zone Decrease recirculation rate to limit sludge return Increase polymer dosage
Effluent turbidity too high	Inadequate dosage (or lack) of coagulant	Insufficient coagulation	Check the level of the storage tank, mixing and the adequate dosage	Increase, for short time, the coagulant dose and/or repair and restart the operation of the flash mixer
	Poor particle recovery in the flocculation zone	Too low sludge concentration in the flocculation zone	Check the polymer dosage	Slowly increase the recirculation rate and polymer dosage
	Poor mixing	Blocked impeller by rags	Check for the presence of rags on the impellers	Clean the impellers and check the good operation of the inlet screening device
Floating mud balls	The lamellas are dirty	Hydraulic flushing easily withdraws deposits from the lamella	Remove the large mud balls	Increase the cleaning frequency of the lamellas
	Sludge fermentation at the bottom of the settler (thickening zone)	In case of an excessive residence time of sludge, gas bubbles produced by fermentation induce the flotation of large black mud blocks	Check the speed of the picket fence and the residence time of sludge	Increase the rotation speed of the picket fence and the sludge extraction frequency
Poor sludge flocculation	Addition of inadequate polymer or involuntary mixing of anionic and cationic polymers	As a rule, the association of different types of polymers leads to compaction of the resulting mixture	Immediately stop operation (influent supply)	Empty and clean carefully all the polymer network Start ASAP the addition of an adequate polymer
	Insufficient in-line dilution of the polymer	Too concentrated polymer has poor mixing properties	Check the flow rate of polymer injection in carrier water system	Restore in-line dilution and clean polymer injection ring
	Excessive sludge concentration in the flocculation zone	High sludge concentration makes heterogeneous polymer distribution	Decrease sludge recirculation and increase, for a short time, polymer dose	Decrease sludge concentration by reducing recirculation rate. Check the level of sludge blanket and sludge concentration in the recirculation line. Increase, if necessary, sludge extraction frequency.
	Variation in salinity (seawater intrusion)	Water density increases at high salt concentrations	Slowly increase polymer dosage	Identify the cause or source of salt intrusion and adjust chemical doses
Too high sludge blanket	Extraction pump failure and/or inadequate extraction sequence	If sludge withdrawal is insufficient, sludge level will increase	Manually re-start the extraction pump and check the evolution of the sludge blanket	Check the correct sludge extraction and good operation of the extraction pump, as well as the level of the excess sludge storage tank
Picket fence switched Off by the torque controller	Sludge blanket is too high or an object blocks the fence	If sludge withdrawal is insufficient and sludge is too heavy, the increased sludge resistance can set off torque controller	Stop operation, check the sludge level and the presence of any visible mechanical failures	Reduce sludge level by continuous extraction of excess sludge and after, re-start the picket fence

Source: Adapted from the feed-back from operators
*Any decision following a process failure or any troubleshooting should be taken only after verification of the correct power supply of all electrical devices

7. TERTIARY DEPTH FILTRATION

7.1 General considerations

Filtration, a key step in producing high-quality effluent, combines physical and chemical processes to remove solids from liquid phase. This technology has been used both as a final stage preceding disinfection before water reuse or as one of a series of tertiary treatment processes. As a rule, filtration is used when the effluent limit is equal or **less than 10 mgSS/L.** The principle of filtration consists in **passing wastewater through a bed of granular media**. For the removal of solids retained in the media and avoid clogging, backwash flushes are used.

The direct application of water treatment technologies in water reuse systems was unsuccessful because of the distinctive character of wastewater solids. For this reason, specific filtration equipment has been developed for tertiary wastewater treatment and reuse using **mono-, dual and multimedia filter beds**[8]. Some common combinations include anthracite and sand, activated carbon and sand, resin bed and sand, etc. The choice of **filter vessels**, either **gravity or pressure**, is generally determined by the role of filtration in water reuse scheme in terms of interactions with the other processes, as well as space availability and plant capacity.

Early problems with **effective bed cleaning** and economical volumes of backwash water seem to be solved by using an **air backwash with a water rinse**. Continuously cleaned filters, named also moving bed filters (up or downflow moving beds or pulsed beds) have been developed specifically for wastewater treatment[1,8].

It is important to stress that conventional sand filters, also named **three-dimensional conventional filters,** are characterised by ***retaining solids throughout the whole bed height***. **Two-dimensional filtration processes**, such as **microscreens and cloth filtration** can also be used. In this case, the captured solids collect on the filter surface (similar to the sieving process). Both types of filters can be used for solids removal (physical) and for combined solids and P-removal (physical-chemical). Solids removal combined with biological activity can only be realised in three- dimensional sand filters.

The performance of tertiary filtration is affected by many factors. For this reason, accurate design can be achieved by means of pilot plant studies. It is important to stress that **upstream secondary treatment highly influences filtration efficiency**. Extended aeration allows achieving the highest SS removal of <5 mgSS/L after tertiary filtration, while after high-rate trickling filters, the target concentration limits in the filtered effluents should be in the range of 10-20 mgSS/L. Better performances could be achieved using chemical addition and dual media filters. The presence of algae impedes filtration. Pre-treatment with coagulants is considered as a good practice for such cases.

7.2 Indicators of process operation

The principal operational consideration for tertiary depth filtration is the volume of water produced in given period of time[4]. The volume of filtered water is related to the development of headloss and filter performance, typically measured in terms of turbidity. The most critical filter elements are medium characteristics, backwashing system and filter control system and instrumentation.

The efficient control of tertiary filtration is ensured by the following **operational indicators**:

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[8]Asano T., Burton F.J., Leverenz H.L., Tsuchihashi R. and Tchobanoglous G. (2007) Water Reuse: Issues, Technology, and Applications, McGraw-Hill Professional Publishing, New York.

- **Headloss control**: headloss through each filter is recorded and, as a rule, when it reaches a predetermined setpoint, backwash start-up. Sharp increase of headloss indicates filter clogging
- **Turbidity monitoring**: turbidity of each filter is recorded continuously and when it exceeds the maximum predefined allowable value, the filter should be taken off of service automatically and backwashed

Successful plant operation demands effective cleaning of the filter media during **backwashing**. If the bed is not cleaned adequately, a long-term accumulation of biological organisms could result in plugging. Adequate backwash can be achieved by air-water backwash and at least 25% bed expansion.

The more detailed recommendation for efficient filter washing are given by manufacturers, as many of the wastewater filtration technologies are proprietary. The typical volume of the required **backwash flow** is **5%** of the filter throughput, and may reach 8% for small units.

Figure 14. View of backwashing of a high rate gravity sand filter

In many cases, **chemical dosage** can help to improve filter performance. Commonly, polymers and/or alum are used with special care for determination of the adequate dosage. The optimum dosage causes the maximum desired headloss to be reached just as turbidity breakthrough is impeding.

7.3 Operational problems and solutions

The most common operational problems of tertiary filtration and some solutions are given in Table 11.

Table 11
Some common operational problems of tertiary filtration and possible solutions

Indicator	Probable cause	Solutions
High effluent turbidity	High hydraulic and organic loading Improper upstream coagulation Algal growth	Backwash filter Run jar tests and adjust coagulant dosage High turbidity is not associated to a corresponding increase of head loss: chlorine addition is the solution in this specific case
Short filter runs due to head loss	Surface clogging Inadequate filter cleaning	Surface wash operation, increase surface wash cycle length Reduce solids loads by improving upstream treatment Replace sand media with dual media; Increase backwash duration and rate
Mud ball formation	Inadequate backwash and surface wash	Increase backwash duration and rate and length of surface wash cycle
Loss of media during backwashing	Backwash rate too high Wash water troughs not level Surface wash cycle too long Uneven distribution of backwash water	Reduce backwash rate Adjust wash water troughs Reduce length of surface wash so that it goes off at least 1 minute before backwash is complete Clean filter under drains
Excessive amount of backwash water (>5%)	Too high solids content Surface wash system failed Inadequate surface wash Excessive length of backwash	Improve upstream treatment (coagulation and settling) Repair surface wash system Increase duration of surface wash Reduce backwash cycle length

Source: Adapted from [3] and the feed-back from operators
*Any decision following a process failure should be taken only after verification of the correct power supply of all electrical devices

8. ULTRAVIOLET IRRADIATION

8.1 General considerations

Ultraviolet irradiation represents a disinfection technology where **microorganisms are inactivated by UV radiation** with a given intensity and wavelength[9]. UV light at a wavelength of 265 nm causes the most cellular damage. This wavelength coincides closely with the absorption maximum of nucleic acids. In the majority of UV disinfection applications, low-pressure mercury lamps have been used because 92% of their emitted light is monochromatic at a wavelength of 253.7 nm[8,9,10]. Thus, these lamps are nearly ideal UV light generators. However, low-pressure lamps also produce less intensity, and thus require more lamps and larger installations than medium-pressure systems with polychromatic radiation (190 to 2000 nm).

The implementation of UV irradiation for wastewater disinfection and reuse is rapidly growing and during the last 10 years is becoming the preferred alternative to chlorination[3,8]. Since the demonstration of the efficiency of UV light for the inactivation of *Cryptosporidium* and *Giardia* in the early 2000s, its application for drinking water treatment is also rapidly increasing.

UV systems are designed to reduce bacteria count to a certain allowable level depending of the dosage of UV light, measured in mJ/cm^2. UV dose is defined as the product of UV irradiance or intensity (mW/cm^2) multiplied by the irradiation time (s). The units of UV dose are expressed as mWs/cm^2, which is equivalent to mJ/cm^2.

Commercial UV reactors consist of open or closed channel vessels (Figure 15) containing UV lamps housed within lamp sleeves, lamp UV intensity sensors and electronic control system (ballasts, etc.)[10]. Some UV systems include automatic cleaning mechanisms. Fixed-weirs, flap gates or motorised weirs are used to control the water level in the channel.

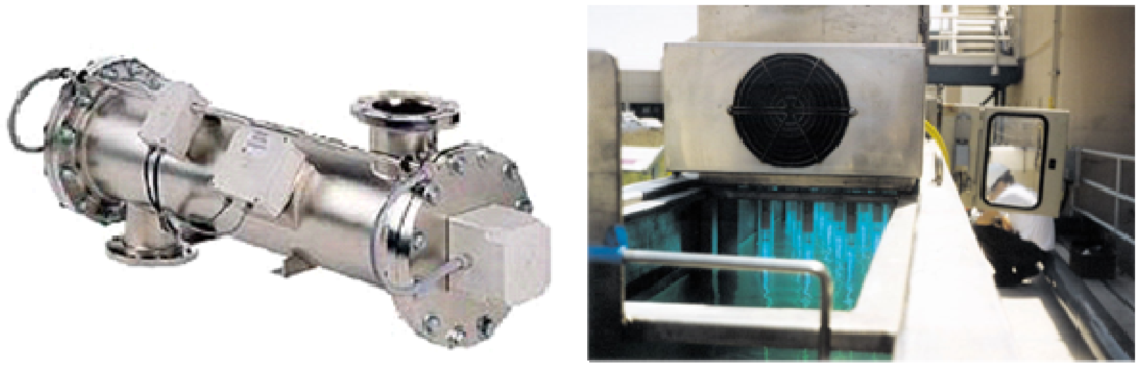

Figure 15. Example of closed and open UV reactors

Ballasts supply the UV lamps with the appropriate power to operate the UV lamps. Ballasts use inductance (coil or transformer), capacitance and a starting circuit. Power supply and ballasts are available in different configurations depending on lamp type and manufacturers. UV reactors can use electronic ballasts, magnetic ballasts or transformers.

UV intensity sensors are the only indicators that disinfection is being achieved in a UV reactor[3,10]. Hence, sensor reliability is critical for demonstrating regulatory compliance and must be regularly calibrated (usually monthly). UV sensors are specific to each manufacturer and are subject to validation.

[9] Masschelein W.J. (2002)) Ultraviolet Light in Water and Wastewater Sanitation, Lewis Publishers
[10] WEF (1996) Wastewater Disinfection Manual of Practice FD-10 of Water Environmental Federation, USA

The effectiveness of a UV disinfection system depends on the following main factors:

1. Wastewater characteristics, especially transmittance, iron, colloidal and particulate constituents
2. Intensity of UV radiation and emission spectrum
3. Exposure time of microorganisms (flow rate)
4. Reactor configuration (hydraulics, engineering devices)

Great care must be taken to ensure that upstream treatment facilities are properly designed and operated. Undersizing of clarifiers, process upset (e.g. rising sludge) and lack of maintenance (filamentous growth) lead to increase of suspended solids and attached bacteria that will deteriorate UV disinfection performance.

Numerous studies demonstrated that pathogen inactivation decreases significantly as the total suspended solids concentration of the effluent increases[3]. The effect of filtration before disinfection is drastic: the UV dose required for a given-log inactivation could be more than halved.

8.2 UV performance control strategies

Reliable operation of UV disinfection units requires[4]:
(1) Proper training
(2) Timely maintenance
(3) Calibration of system components

8.2.1 Monitoring of UV disinfection performance

The ability to monitor operating parameter continuously is important for the operation of UV disinfection system to ensure that adequate disinfection is provided[10,11]. The continuous monitoring of parameters used to adjust the operational UV dose, UV disinfection components and proper calibration on on-line monitoring equipment are critical to maintaining the effectiveness of UV disinfection.

The following **operational parameters** must be **monitored continuously**:

- Flow rate
- UV intensity
- UV transmittance
- Turbidity (optional)
- Operational UV dose (calculated)

In addition to on-line monitoring of water quality, **microorganisms sampling** must be collected downstream of the UV disinfection for coliform bacteria (*E.coli*, total or fecal coliforms) and/or other microorganisms as required by permit requirement. The sampling frequency shall be consistent with permit requirement.

In addition, monitoring of the following **UV system components** shall be provided:

- Status of each UV reactor (On/Off)
- Status of each UV lamp (On/Off)
- UV intensity measured by at least one probe per reactor
- Lamp age in hours

[11]Ultraviolet Disinfection: Guideliines for Drinking Water and Water Reuse (2000) ed. by National Water Research Institute, American Water Works Association Research Foundation, USA

- Cumulative number of reactor On/Off cycles
- Cumulative UV disinfection system power consumption
- Reactor power set point (for systems with variable power input to lamps)
- Liquid level (for open channel UV systems)

To protect public health, **priority alarms** are also required:

- Lamp failure (single or multiple)
- Low UV intensity when the intensity probe reading drops below a predetermined set point
- Low UV transmittance when the UV transmittance drops below a predetermined set point
- High turbidity when the influent turbidity exceeds a predetermined set point
- Low operational UV dose
- Low or high water level (for open channel reactors)

8.2.2 Control strategies of UV disinfection

The **most common control strategies** in wastewater UV disinfection systems are:

1) No regulation, all the UV lamps are off during all the time of operation. This is a specific case occurring only in very rare conditions and will not be discussed for the reason that it is not recommended for wastewater disinfection
2) UV control depending on flow rate commonly used before the implementation of UV intensity sensors and recommended as alternative method during temporary failure of UV intensity monitoring
3) **UV control depending on UV dose** (UV intensity, flow rate and transmittance), the most common approach strongly recommended for all new wastewater disinfection systems and the rehabilitation of existing UV facilities

With the increasing complexity of UV control strategies from flow-related to UV-dose related approaches, the delivered UV dose is more accurately controlled, ensuring thus significant decrease of energy consumption.

Reliable power supply and backup power are **essential** to ensure continuous disinfection.

8.2.3 Power supply

The sensitivity of UV reactor to power fluctuations make the **electrical power supply** a **critical point** of UV design and operation. UV lamps can potentially lose their arc if a voltage fluctuation, power quality anomaly or power interruption occurs. As a rule, low pressure lamps generally can return to full operating status within 15 s after power is restored. However, low pressure high intensity and medium pressure lamps require significant restart times if power is interrupted (2 to 5 min).

The proper supply voltage and total load requirements must be coordinated with the UV supplier, considering the available power supply. It is important to stress, that power needs for each of UV reactors components may differ, some requiring a 3-phase service and other single phase 220-volt service. Due to the varying nature of UV reactor loads, current and voltage harmonic distortion can be induced. Such disturbances can results in electrical system problems including over heating of some power supply components and effects on other critical systems such as variable frequency drives, program logic controllers, various electronic equipment and computers.

A separate transformer for the UV reactor is highly recommended. If this solution is impractical, harmonic filters could be added to the UV reactor power supply to control distortion.

Another important safety feature for UV reactor is ground fault interrupt, which should be provided by UV reactor supplier. For its accurate operation, the transformer in the UV reactor ballasts must not be isolated from the ground. If the ballasts isolate the output from the ground, ground faults will not be properly detected and safety could be compromised.

Uninterruptible power supply is necessary to avoid frequent, undesired lamps failures.

8.2.4 On-line cleaning systems

Quartz sleeves' fouling is ineluctable and involves mainly carbonates and iron. Nowadays, most suppliers provide automatic cleaning systems with their UV installation. **Automatic cleaning systems** should be implemented in all new installations. This allows increasing the reliability of UV disinfection, with reduced investment cost (lower installed power) and operational cost (energy and labour).

Available cleaning systems use mechanical wiping, possibly associated with an injection of acid. Wipers are Teflon rings. A brush is also provided to wipe the intensity sensor. The acid containers move along with this system. Acid solutions usually need replacement every few months.

Typically, the wiping system is powered either by a timer, or in few cases by an intensity measurement.

8.3 Main indicators of process operation

The recent more stringent regulations require improving UV control strategy. The performance of an operating UV disinfection system must be correctly monitored to demonstrate that adequate disinfection is being achieved. As the target microorganisms cannot be measured continuously in the UV-treated effluent and the dose distribution cannot be measured directly in real time, various strategies have been developed to **monitor dose delivery**[4,11].

The **main operational indicators** that determine UV reactor efficiency are:

- **UV intensity**
- **Hydraulic characteristics** of the reactor (flow and contact time)
- **Wastewater characteristics**
- **Aging** and fouling of UV lamps

In the case of water reuse, the UV disinfection systems must be capable of producing disinfected effluent during any component failure prior to distribution. **A minimum of two operating reactors per train** ensures that some disinfection occurs until a standby reactor is brought on line.

8.3.1 UV intensity

The widely used operational parameter to monitor UV disinfection performance is UV intensity. Currently[11], there are **three fundamental approaches to monitor UV intensity**:

1. UV Intensity Setpoint, where dose delivery is monitored by sensor measurement of UV intensity
2. UV Intensity and UVT Setpoints, where dose delivery is monitored by sensor measurement of UV intensity and transmittance
3. Calculated UV dose using sensor measurement of UV intensity

The strategy for dose monitoring depends on the manufacturer and may be proprietary. According to the method used and specificities of the given equipment, UV sensors can be located near the lamp sleeve to measure only lamp output, or at any distance from the lamp to take also into account the water transmittance.

8.3.1.1 UV intensity set point approach

The **UV Intensity Set Point** Approach consists in measurements of UV intensity sensor, which is located in a position that allows it to properly respond to both changes in UV intensity output of the lamps and also wastewater transmittance. The UV sensor output and the flow rate are used to monitor dose delivery. The set point value for UV intensity over a range of flow rates is determined during validation tests.

The simplest operational strategy uses one single UV intensity set point for all flows. Therefore, the intensity set point, validated for a given range of flow rates can be used also for any transmittance with defined limits of variation. Although this is simple and straightforward operating strategy, single set point operation is not energy efficient as using a variable set point approach. The variable UV intensity set point approach has a different UV intensity set point at different flow rates. This operation promotes more energy efficient operation compared to single set point approach for the reason that the UV intensity set point can be decreased at lower flow rates.

8.3.1.2 UV intensity and UV transmittance set point approach

The **UV Intensity and UV Transmittance Set Point** Approach is similar to the previous one, except that the UV sensor is placed to the lamp such that it only responds to changes in UV lamp output. UV transmittance is monitored separately. For a specific flow rate, the UV intensity and transmittance measurements are used to monitor dose delivery. The set points for UV intensity and transmittance over a range of flow rates are determined during validation.

8.3.1.3 Calculated UV dose

The **calculated dose** control strategy uses UV intensity, transmittance and flow measurements to estimate a UV dose. In this approach, the UV intensity sensor is placed close to the lamp, which is similar to the UV intensity and transmittance set point approach. Flow rate transmittance and UV intensity are all monitored and the outputs are used to calculate UV dose via a validated computational algorithm developed by the UV reactor manufacturer.

8.3.2 Hydraulic characteristics of the UV reactor

The efficiency of UV disinfection depends on the exposure time and lamp spacing. Accordingly, proper flow rate distribution and measurement are essential for compliance monitoring of UV facilities.

Confirmation of compliance will be dependent on understanding the flow through each UV reactor, regardless of the dose monitoring or control strategy used. Moreover, UV reactors are validated within **specific flow ranges** and have associated operating characteristics that demonstrate dose delivery as a function of flow. Therefore, the flow rate through the UV reactor must be known to ensure that proper dose delivery is achieved.

For this reason, **individual flow measurement device is recommended for each UV reactor.**

8.3.3 Wastewater effluent quality

The most significant water quality factors that significantly impact UV disinfection effectiveness are UV transmittance, suspended solids and constituents that foul lamp sleeves. Consequently, higher doses are required with increasing concentrations of suspended solids, UV absorbance, some inorganic matter, which absorb UV light such as ferric ions In addition, physical-chemical characteristics of wastewater also determine lamp fouling.

Suspended solid concentration is the variable that can most inhibit UV disinfection. The higher TSS, the less effective the UV disinfection. For best UV reactor operation, the effluent should contain less than 10-15 mgTSS/L (less 5-10 NTU of turbidity).

UV transmittance significantly influences UV disinfection efficiency with strong inhibition effect for values below 50%. For this reason, it is recommended[3] to implement tertiary filtration (Table 12).

Table 12

Typical range of UV transmittance and turbidity of several effluents

Parameter	Primary effluents	Secondary effluents	Tertiary effluents	MF/RO effluents
UV transmittance (%)	5-25*	45-65	55-85	75-95
Turbidity (NTU)	-	>6-10	2-4	<0.2

**Up to 50 in the case of chemical precipitation (enhanced primary treatment)*

For open channel UV reactors installed directly after clarifiers, foam, rags and other floating material must be considered also as critical elements. They often accumulate in the channel, causing severe disturbances such as blockage of the wiping system, erroneous water level signal and clogging of inlet flow distribution screens (Figure 16).

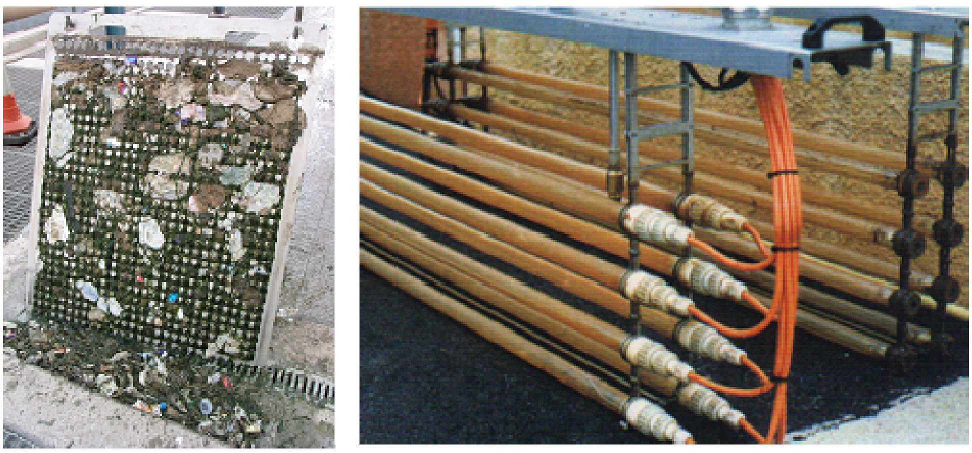

Figure 16. View of clogging of the inlet plate of UV reactors by plastics, rags and algae and iron fouling of UV lamps

Iron compounds have also several adverse effects on UV disinfection, decreased UV transmittance and increased fouling (Figure 16) **Figure 16**. Processes that use high concentrations of ferrous or ferric compounds for solids or phosphorous removal may produce effluents that have a lower UV transmittance. The UV industry has adopted a level of 0.3-0.5 mg/L of maximum allowable level of iron.

8.3.4 Lamp aging

As the lamps age, the electrical yield and the emitted light power decrease, up to a point when the lamps have to be replaced. Thus, lamps are considered as a consumable[10].

In practice, **lamp ageing cannot be checked** or measured by the operator. As a consequence, the lamps need to be changed when they reach the lifetime given by the supplier. For a given bank or module, the lamp age is shown on the LCD screen. A major downside of this strategy is that lamp ageing is significantly increased at each start-up. The supplier does not take this into account – the procedure for lifetime evaluation involves lamps continuously on.

The **recommended lamp aging management** is therefore:

- To allow on/off cycles when the influent demand allows it, in order to minimise the energy consumption
- Ban short on/off cycles (< 60 min) with the use of adequate timers, in order to limit premature lamp ageing

Because of the individual lamp age is not recorded, lamps usually have to be replaced by whole banks.

8.4 Main operational and maintenance tasks of UV systems

UV disinfection units typically use automatic control systems and **do not need significant operational attention**[4]. However, UV disinfection systems **require good maintenance**. Poor maintenance is frequently the cause of non-compliance of disinfected effluents. As important part of maintenance tasks, UV reactor components need to be regularly replaced. For this reason the inventory of spare parts is necessary.

Before any maintenance is performed, the main electrical supply to UV unit should be disconnected, lockout and the operator should wait at least 5 min or as recommended by manufacturer for the lamp to cool down and energy to dissipate.

The **principal components** of UV systems **that need periodic maintenance** are as follows:

- UV lamps inspection (at least monthly) and replacement according to the utility schedule
- UV intensity sensors calibration (at least monthly), rotation and replacement
- Lamp sleeves replacement when damaged and, as a rule, every 3 to 5 years
- Transmittance monitor calibration (manufacturer specific)
- Flow meter calibration (at least weekly)
- Electrical concerns, including ballast cooling, measures against harmonic distortions, regular checking of accurate grounding, etc. (manufacturer specific frequency)

The **general operational tasks that are recommended**[12] are summarised in Table 13. Site-specific operational tasks should be determined by the manufacturer and plant operator and included in the site-specific O&M manual.

Table 13

Recommended operational tasks for UV disinfection systems

Frequency	Recommended Tasks
Daily	• Perform overall visual inspection of the all UV reactors. • Ensure system control is on automatic mode (if applicable). • Check control panel display for status of system components and alarm status and history. • Ensure all on-line analyzers, flowmeters, and data recording equipment are operating normally. • Review 24-hour monitoring data to ensure that the reactor has been operating within validated limits during that period.
Weekly	• Initiate manual operation of wipers (if provided) to ensure proper operation.
Monthly	• Check lamp run time values. Consider changing lamps if operating hours exceed design life or UV intensity is low.
Semi-annually	• Check ballast cooling fans for unusual noise. • Check operation of automatic and manual valves.

Source: [12]

8.5 Operational problems and solutions

The most common operational problems of UV reactors and recommended corrective actions are given in Table 14.

It is important to stress that UV light may severely damage eyes and unprotected skin. For this reason, **Safety measures** must be taken for proper protection.

[12] EPA Victoria (2003) “Guidelines for Environmental Management: Use of reclaimed water”, EPA Victoria, Publication 464.2, ISBN 0 7306 7622 6.

Table 14

Routine operational problems of UV disinfection and recommended corrective actions

Indicator	What to check	Potential problem	Explanation	*Corrective actions
Ballast cards failure	Surface T°C Proper grounding	Overheating due to poor ventilation Frequent failures	The lack of adequate ventilation and air conditioning during summer, and the associated high temperatures (>30°C), lead to damage of the electronic compounds of the ballast cards The life cycle of the ballast cards is at least 3-4 years, and even 10 years according to some suppliers. Besides heating, the ballasts are very sensitive to electromagnetic disturbance due to poor grounding or poor connexions	Add panel ventilation or cooling system. Adequate grounding according to supplier recommendations Change ballast cards if necessary
High frequency of lamp replacement	Lamps status Heat build-up GFI indicator O-rings	Burned out Little or no flow Broken quartz sleeve or seal system failure Water leaks Malfunction of level control system	Poor compression of o-rings (poor gasket clamping) and associated water intrusion into the quartz sleeves leads to premature lamp burn out High frequency of shut down of UV lamps and short operating cycles lead to vaporisation of tungsten and other oxides from the lamp electrodes Another aging mechanism is associated with excessive temperatures leading to de-vitrification (crystallisation) and chemical structural damage of quartz sleeves Any blocking of the weir control device due to insufficient lubrication, for example, leads to unacceptable water levels and associated high temperatures and lamp burning	Replace as necessary Increase water supply Check sleeves for breaks and leaks; dry contacts; replace components Clean level sensors; repair/replace as necessary Check the water level control system and repair if necessary. Take appropriate measures for flow rate control to avoid excessive variations of flow rates
Low intensity signal	UV intensity sensor, its signal and sensor fouling or wearing	Wrong signal in the PLC system associated with parasite interferences, build-up on quartz jackets or on intensity sensor	Because of the measurement of low intensity (in particular during low flow operation) and the lack of amplification, the electrical signal is often disturbed High temperatures and other factors could accelerate the sensor wearing Because of the measurement is carried out on only two lamps (situated as a rule at the top of the module), any chemical and/or organic deposits and build-up on the quartz jackets lead to decrease of the measured intensity (especially after shut down of UV operation)	Clean routinely UV intensity sensors as necessary Clean routinely quartz sleeves Check and repair if necessary the electronic system: long or overloaded 4-20 mA loop, troubles in the analog-to-digital converter, fault of the protection against electromagnetic disturbance, poor quality of grounding, etc.
Poor lamp cleaning	Wiper Compressor	Water leaks	The cleaning systems can be affected by several malfunctions including low pressure in the cleaning loop (compressor fault or too much water in the backwash tank), clogging by rags or poor adjustment of the wiper scraping rings	Tighten the gland nut to compress o-ring or replace. Clean lamps as necessary Check the downstream treatment and take measures to improve water quality
Excessive lamp fouling due to iron salts	Check and adjust the Fe dosage downstream	Yellow to brown deposits on lamp sleeves	Excessive iron content (> 0.5 mgFe/L) leads to precipitation of brown deposits on the quartz sleeves and decrease of UV intensity, followed by fast development of additional organic fouling	Check the residual $FeCl_3$ concentration, decrease and control the $FeCl_3$ dose and/or replace the Fe salts with alum
Failure in water level control and poor disinfection	Weir control device Flow rate	Inadequate level control	Excessive flow rates, after heavy rain for example, or blocking of weir device can lead to unacceptable increase of water level in the UV channel	Check the water level control system and repair if necessary

Source: Adapted from [11,12] and feed-back from operators
*Any decision following a process failure or any troubleshooting should be taken only after verification of the correct power supply of all electrical devices

9. CHLORINATION

9. General considerations

As the most universally practised wastewater disinfection method since many years, chlorination plays a major role in preventing waterborne infectious diseases throughout the world[8]. The disinfection efficiency and the possibility of maintaining residual chlorine are the main advantages of chlorine disinfection. Chlorination systems are reliable and flexible and the equipment is not complex.

The main disadvantage of chlorine for wastewater disinfection is the generation of toxic by-products (DBP)[3,4]. For this reason, UV disinfection is becoming the preferred option for existing plant upgrading and new water reuse systems, especially in Europe.

Several chlorine derivatives can be applied such as gaseous chlorine, hypochlorite, chlorine dioxide, calcium hypochlorite or chloramine compounds[1,13] . During the last years, numerous wastewater treatment facilities have replaced gaseous chlorine by hypochlorite in order to improve operator safety and decrease operation and maintenance costs.

In fact, from the various chemicals present in wastewater treatment plants, chlorine is perhaps the most dangerous. Chlorine is a highly toxic gas, which, if inhaled, can injure or kill quickly. A major chlorine leak in the plant, if not handled properly, can injure or kill plant personnel and may require evacuation of the facility neighbours.

9.2 Indicators of process operation

The **process control variables** associated with chlorination systems are:

- **Wastewater quality** and chlorine dose
- **Contact time**
- **Chlorine residual**
- **Indicator bacteria** concentration in disinfected effluent
- **Handling** of chlorine products

The effectiveness of chlorination can be enhanced by improving mixing characteristics of chlorine contactors and process control strategy.

Two main **operational indicators** are used for testing the chlorination performance:

- **Total chlorine residual** (mg/L)
- **Residual concentration of indicator bacteria** (CFU/100 mL or MPN/100 mL)

9.2.1 Chlorine residual

Depending on the type of reuse, chlorine residual can be required[8]. The two types of chlorine residuals that can be monitored are free and total chlorine.

A free residual, the hypochlorite ion [OCl^-] attained after breakpoint chlorination, may be present in secondary and tertiary effluents with low ammonia concentration[1,13]. Much more chlorine is required to achieve a free residual than for attaining a residual. After the breakpoint is reached, when all of the chlorine demand has been satisfied, each mg/L of added chlorine dosage adds a mg/L of chlorine residual.

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[13]WEF (1979) Wastewater Treatment Skill Training Package: Chlorination, ed. by Water Environment Federation, USA

Chlorine demand represents the difference between the concentration of free chlorine applied (hypochlorous acid HOCl and hypochlorite ion OCl^-) and the concentration of chlorine residual remaining at the end of the contact period. Consequently, chlorine demand represents the chlorine quantity that is chemically reduced or converted to less active forms of chlorine by substances in the water, such as ammonia compounds, organic matters, iron and sulphur compounds. In the case of partial nitrification, the chlorine demand exerted by nitrite may consume significant quantities of chlorine, detected by increase in chlorine demand.

A total residual, also referred as combined residual, is present in any chlorinated effluent. This residual, therefore, is considered as the standard form of chlorine residual. Total chlorine residual includes chloroorganics and chloramines, both of which are less powerful oxidising agents than free chlorine residual. However, the disinfection action of chloramines persists longer that of free chlorine.

The optimum chlorine residual, free or combined, is those sufficient to produce effluent with the required microbiological quality.

9.2.2 Indicator bacteria concentration in disinfected effluent

Regardless the chlorine residual method employed, enough chlorine solution must be injected to sufficiently destroy or inactivate indicator bacteria that signal the likely presence of pathogens.

As a rule, **regular monitoring of coliform bacteria** in disinfected effluent is required to control chlorination efficiency. The target indicator organisms (*E.coli*, total or fecal coliforms, *Streptococci*), their concentration and frequency of sampling are defined by plant permit.

9.2.3 Influence of wastewater quality on chlorine dose

Wastewater chlorine requirements vary considerably depending on effluent quality. Lower disinfection doses and contact time are characteristic for good-quality effluent, for example filtered activated sludge effluent. Organic and humic compounds or nitrite increase chlorine demand. Suspended solids also affect chlorine disinfection efficiency, because microorganisms are shielded by or embedded in particles.

Typical chlorine doses for municipal wastewater disinfection are about 5-20 mg/l and 30-60 minutes contact time, and usually allow for compliance with permits on conventional bacterial indicators (coliforms, *E.coli*). Higher doses are required for low quality wastewater such as primary or trickling filter effluents. Typical chlorine doses vary in the following ranges[1,3]:

- Primary effluents: 5-20 mg/L
- Chemical precipitation: 2-6 mg/L
- Trickling filter effluents: 10-15 mg/L
- Activated sludge plants: 2-9 mg/L
- Nitrified effluents: 2-6 mg/L
- Tertiary filtered effluents: 1-6 mg/L
- MF or UF effluents: 0.1-0.5 mg/L

9.2.4 Contact time

Facilities are normally designed to provide a minimum of 15-30 min contact time at peak flow. According to some US recommendations (EPA, Title 22), the required contact time can be up to 90-120 min. Under these conditions, a good inactivation of total and fecal coliforms occurs (4 to 6 log removal), and also of viruses. Lower contact time is characteristic for good-quality effluent, for example filtered activated sludge effluent.

9.3 Safety of handling and operation of chlorine products

Chlorine gas has a detectable odour at low levels of concentration (>0.1 ppm) and has a greenish yellow colour at high levels of concentration[13]. The maximum allowed exposition level is 1 ppm (3 mg/m^3). Harmful effects of chlorine gas exposure begin to manifest at concentrations above 5 ppm, temporary at the beginning, and more lasting (>10 ppm), and can result in death.

All of the commonly used forms of chlorine are hazardous chemicals. The precautions necessary for each chemical are different and require the implementation of specific safety procedures.

Depending on the type of chlorine product and equipment, specific care must be taken for handling of chlorine containers[13]. All handling facilities must be designed according to the following safety requirements:

- Specifically designed building with equipment resistant to corrosion
- Adequate space for loading and underloading of cylinders or containers
- Well accessible valves
- Separated storage and operation rooms with panic or escape hardware on all doors
- Adequate ventilation
- Gas detectors
- Eye washing showers
- Self-contained breathing apparatus
- Fire protection

For each operational task, specific operational procedure must be implemented, including:

- Transportation
- Loading and underloading of cylinders or containers
- Exchange of operational cylinders or containers
- Inspection and maintenance procedures with individual protection equipment
- Safety procedures

Figure 17. View of chlorine storage and handling in small facilities

9.4 Operational problems and solutions

A comprehensive maintenance program, with inspection frequencies as recommended by each equipment manufacturer, is critical to plant safety and process efficiency. Table 15 lists routine operational checks of chlorination equipment and remedies if checks indicates potential problems.

Table 15

Some common operational problems of chlorination and possible solutions

Indicator	Probable cause	Solutions
Low or high reading of chlorine residual	Problem of electric positioners	Check that power is on On position and adjust dosage potentiometer Check 4 to 20 mA signal from flow meter and chlorine residual analyser
Poor disinfection efficiency	Low chlorine dosage Poor water quality Short-circuiting	Check chlorine dosage and demand Inspect for flow pattern and existence of short-circuiting, repair if necessary Conduct tracer tests Adjust chlorine dose
Sharp increase of chlorine consumption	Poor influent quality with high ammonia and nitrite	Monitor dosage and demand Adjust process to improve influent quality
Chlorinator failures	Rotameter moving from setpoint Presence of water in rotameter	Check and properly reactivate chlorine supply Check and replace o-ring
Chlorine lines, valves, gauges	Check for leaks Iced container or other equipment Check evaporator pressure, injector vacuum	Repair and correct potential problems immediately

Source: Adapted from [4,13] and feed-back from operators

*Any decision following a process failure or any troubleshooting should be taken only after verification of the correct power supply of all electrical devices

10. CONCLUSIONS AND SUMMARY TABLE OF OPERATIONAL INDICATORS, CONTROL PARAMETERS AND TROUBLESHOOTING

As shown in the previous chapters, **effective operation** of wastewater treatment plants and maintaining of water quality compliance **require** from operators **the following skills and actions**:

- Regular checking of the main operational indicators of each specific process (daily in most cases)
- Good knowledge of the composition of the influent, effluent and internal process streams by regular monitoring of wastewater quality and representative sampling
- Good training on each process operation and knowledge of basic process principles
- Follow-up of good operational practices
- Strong follow-up of recommended preventive maintenance of each specific wastewater treatment process
- On-line monitoring of water quality (turbidity) if stringent water reuse regulations must be consistently achieved

However, even with the best efforts for good operation it is impossible, however, to eliminate disturbances completely. Hence, to maintain optimum process efficiency and reliability, it is necessary to compensate for disturbances by changing some of the process parameters. Process parameters that are to be kept at target values, named operational indicators, are summarised in Table 16.

Table 16In addition, the main process parameters that can be checked or changed to maintain the main operational indicators, named also **operational control parameters** (manipulated parameters) are also indicated.

Based on the operational experience of numerous wastewater treatment plants, **automatic control systems** allow not only for **more precise control of process parameters**, but also to reduce workload. For example automation of DO and SRT improves significantly activated sludge process efficiency with additional benefits for improved sludge settleability and easier sludge dewatering. As a rule, advanced wastewater treatment processes such as MBR or UV disinfection are fully automated.

Failure of any element of an automatic control system (instruments, pumps or valves) may lead to serious operational problems. For this reason, the **process control software**, named Supervisory Control And Data Acquisition (SCADA) and Programmable Logic Controllers (PLC) are very important for the reliable process operation. The complexity of these systems increases for innovative membrane processes such as MBR compared to conventional wastewater treatment processes (activated sludge, filtration, high rate clarification).

To help operators to take the right decision, Table 16 also indicates the **most common operational problems** and recommended solutions. Troubleshooting of each specific process is described in more details in dedicated chapters. It is very important to stress that **all decision following a process failure or any troubleshooting should be taken only after preliminary checking of**:

(1) Correct power supply of all electrical devices
(2) Separate inspection of all the fuses with verification that no circuit breaker has been installed
(3) Checking of the three phases power supply, which have to be at the right voltage and in good rotation order

In summary, successful and reliable operation of more complex processes, such as activated sludge, MBR, high rate clarification or UV disinfection, can be achieved only if each operator is able to recognise system changes and trends, and makes the proper decision to successfully counteract potential harmful events. **These decisions should reflect a judgment gained from a good understanding of the biological and chemical principles at work and from a strong past experience of the system, rather than being based on rigid application of general rules.**

Table 16

Summary of the main operational performance indicators and operational control parameters of the most common wastewater treatment processes

Water Quality Control Parameters	Main Operational Indicators	Main Operational Control Parameters	Main Operational Problems
1. Characterisation and Sampling of Wastewater			
Depending on process: Flow rate, T°C, pH, TSS, BOD_5, COD, turbidity, coliforms or other microbial indicators, N and P forms, chlorine residual	**Representative samples**, adequate equipment; good sample preservation **Consistent monitoring**	**Flow-proportioned composite samples**: the most representative and required by regulations; **Grab samples**: discrete samples for unstable parameters (T°C, pH, bacteria);	Problems of calibration of sensors Inadequate choice of sampling location (poor mixing, sediments) Use of time composite sample on the place of flow-proportioned composite samples
2. Primary Settling			
Suspended and settlable solids, total and volatile solids, COD, BOD5, pH, oil and grease concentration Sludge monitoring	**Sludge Thickness**: <1% (5-10 g/L) **Detention time**: 1 to 2 hours **Hydraulic loading**	Continuous desludging Equal flow distribution among multiple tanks Consistent removal of skimming of floatable solids Odour control	Fermentation of settled sludge (floating sludge, black sludge or wastewater, gas bubbling, odours) Hydraulic overloading with low concentration of sludge
3. Activated Sludge			
F:M ratio (BOD, COD) Sludge retention time SRT Mixed liquor concentration: MLSS and MLVSS, TKN loading, BOD/TKN ratio and nitrification rate Removal efficiency of BOD, TKN	**Dissolved oxygen**: >2 mg/L **Return activated sludge rate**: 50 to 100% **Waste activated sludge rate**: to achieve constant SRT or MLSS	**Microscopic exam** of activated sludge **Sludge volume index** SVI **Control of sludge blanket** depth of clarifiers Mixed liquor **respiration rate** or nitrification rate	Problems of aeration system including low DO, poor mixing and foaming. Problems of clarifiers that include solids loss, bulking sludge, rising sludge, etc. Filamentous foaming and bulking
4. Membrane Bioreactors (MBR)			
Idem as §3 plus Rags, grease & oils, surfactants, monomers (inducing membrane fouling)	**Dissolved oxygen**: >2-3 mg/L **Membrane permeability** no less than 50% of the initial value **Membrane integrity** by means of on-line turbidity monitoring	**Settling test** with examination of supernatant **Microscopic examination** of activated sludge Control of **membrane integrity** periodical air bubbling or on-line turbidity measurement) Control of **membrane filterability** (optional)	Faulty pretreatment (rags, grease) Poor insufficient aeration (anaerobic fermentation, turbid black supernatant) Loss of membrane permeability (membrane fouling) Loss of suspended sludge (leakage or membrane damage)
5. High Rate Clarification			
Suspended solids Turbidity Phosphorus contents Indicator microorganisms Heavy metals Temperature, pH	**Coagulant dosage** **Polymer dosage** Chemical sludge **recirculation rate** Effluent **turbidity**	Optimisation of **chemical dosage** by jar tests Control of chemical **sludge recycling** and **sludge blanket level** Control of **sedimentation** Control of **mixing**	Faulty dosage of coagulant or polymer Sludge fermentation and/or high sludge blanket level Too low or too high recirculation rate Faulty mechanical equipment

6. TERTIARY DEPTH FILTRATION			
Flow rate, T°C TSS, turbidity Indicator microorganisms	Filter **headloss**: critical parameter with a predetermined setpoint to start backwashing	**Hydraulic loading** **Turbidity** on-line control: to prevent solids backtrough **Chemical dosage** to improve filter performance	Filter bed clogging Poor backwashing High effluent turbidity (overloading, poor backwashing)
7. ULTRAVIOLET IRRADIATION			
Flow rate UV intensity UV transmittance Turbidity (optional) Indicator microorganisms	**UV intensity**: by monitoring UV Intensity, UV intensity plus transmittance or calculated UV dose **Flow rate**	**Power supply** **Lamp aging** (control of operating hours) **On-line cleaning** systems	Excessive lamp fouling Low UV intensity and related poor disinfection efficiency Ballast card failure Too frequent lamp replacement
8. CHLORINATION			
Total chlorine residual Residual indicator microorganisms	**Chlorine residual** Residual **indicator microorganisms**	**Chlorine dose** **Contact time** **Handling** of chlorine products	Failures of chlorine equipment Poor disinfection efficiency due to poor wastewater quality

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GLOSSARY

Advanced wastewater treatment: Additional treatment provided to remove suspended and dissolved substances after conventional secondary treatment. Often this term is used to mean additional treatment after tertiary treatment for the purpose of further removing contaminants of concern to public health. This may include membrane filtration, reverse osmosis (RO), advanced oxidation, and disinfection with ultraviolet light (UV) and hydrogen peroxide (H_2O_2).

Aeration: The process of exposing to circulating air.

Aerobic: Living or occurring in the presence of oxygen.

Alternative: A chance to choose between two or more possibilities; one of the two or more possible choices.

Biochemical oxygen demand (BOD) : A measurement of the amount of oxygen utilized by the decomposition of organic material, over a specified time period (usually 5 days) in a wastewater sample; it is used as a measurement of the readily decomposable organic content of a wastewater.

Biodegradable: Capable of being decomposed (broken down) by natural biological processes.

Biofuling : The formation of bacterial film (biofilm) on membrane surfaces.

Biological wastewater treatment: Processes, which employ aerobic or anaerobic microorganisms and result in decanted effluents and separated sludge containing microbial mass together with pollutants. Biological treatment processes are also used in combination and/or in conjunction with mechanical and advanced unit operations. Similar to secondary treatment.

Biosolids: Solid materials resulting from wastewater treatment that meet government criteria for beneficial use, such as for fertilizer.

Chemical oxygen demand (COD): A measure of the oxygen-consuming capacity of inorganic and organic matter present in wastewater. COD is expressed as the amount of oxygen consumed in mg/l. Results do not necessarily correlate to the biochemical oxygen demand (BOD) because the chemical oxidant may react with substances that bacteria do not stabilize.

Chlorination: water disinfection by chlorine gas or hypochlorite.

Coliforms: Bacteria found in the intestinal tract of warm-blooded animals; used as indicators of fecal contamination in water.

Contaminant: An impurity, that causes air, soil, or water to be harmful to human health or the environment.

Constituents: Individual and aggregate components, elements, or biological entities such as total suspended solids (TSS), biochemical oxygen demand (BOD), E. coli, and ammonia nitrogen present and quantifiable in wastewater.

Conventional secondary treatment: Activated sludge treatment, commonly with nitrification, used for the removal of soluble organic matter and particulate constituents.

Discharge: In the simplest form, discharge means outflow of water. The use of this term is not restricted as to course or location and it can be applied to describe the flow of water from a pipe or from a drainage basin. If the discharge occurs in a course or channel, it is correct to speak of the discharge of a canal or of a river. It is also correct to speak of the discharge of a canal or stream into a lake, stream or ocean. Discharge is a comprehensive outflow term. Other words related to it are runoff, stream flow and yield.

Disinfection: Water treatment which destroys potentially harmful bacteria, viruses or protozoa.

Effluent: The water leaving a water or wastewater treatment plant. If effluent has been treated to a high enough standard, it may be considered reclaimed or recycled.

Filtration: A process that separates small particles from water by using a porous barrier to trap the particles and allowing the water through.

Flocculation: The process of forming aggregated or compound masses of particles, such as a cloud or a precipitate.

Fresh water: Water containing an insignificant amount of salts, such as in inland rivers and lakes.

Membrane Bioreactor (MBR): A process that combines a suspended growth activated sludge reactor with a membrane separation system; membrane separation is accomplished by either microfiltration or ultrafiltration and used in place of conventional gravity sedimentation.

Monitoring: Testing that water systems must perform to detect and measure contaminants.

Municipal wastewater: Discharge of effluent from wastewater treatment plants which receive wastewater from households, commercial establishments, and industries. Combined sewer/separate storm overflows are included in this category.

Nutrient: Chemical elements which are involved in the construction of living tissue and which are needed by both plant and animal. The most important in terms of bulk are carbon, hydrogen and oxygen, with other essential ones including nitrogen, potassium, calcium, sulphur and phosphorus.

Nutrient removal: Elimination of nutrients from wastewater in order to prevent water eutrophication.

Population equivalent: One population equivalent (p.e.) means the organic biodegradable load having a five-day biochemical oxygen demand (BOD5) of 60 g of oxygen per day.

Pre-treatment: A process in wastewater treatment where metal screens are used to remove large objects and chunks of debris.

Primary wastewater treatment: A process in wastewater treatment where metal screens are used to remove large objects and chunks of debris.

Process reliability: The level of assurance that a process will achieve consistently the needed degree of constituent removal over the expected range of operating conditions.

Raw wastewater: Wastewater without any wastewater treatment.

Reclaimed wastewater: Municipal wastewater that has gone through various treatment processes to meet specific water quality criteria with the intent of being used in a beneficial manner (e.g. irrigation). The term recycled water is used synonymously with reclaimed water, particularly in California.

Recycled water: See Reclaimed water.

Regulation: A governmental order having the force of law.

Reuse : To use again; recycle; to intercept, either directly or by exchange, water that would otherwise return to the natural hydrologic (water) system, for subsequent beneficial use.

Sanitation: The application of measures and techniques aimed at ensuring and improving general hygiene in the community, including the collection, evacuation and disposal of liquid and solid wastes, as well as measures for creating favourable environmental conditions for health and disease prevention.

Sensitive area: Areas of a country where special measures may be given to protect the natural habitats, which present a high level of vulnerability.

Secondary effluent: Treated wastewater from a conventional biological treatment plant that typically meets average concentrations of 30 mg/L TSS and 30 mg/L BOD.

Secondary treatment: see also biological wastewater treatment. Secondary wastewater treatment may be accomplished by biological or chemical-physical methods. Activated sludge and trickling filters are two of the most common means of secondary treatment. It is accomplished by bringing together waste, bacteria, and oxygen in trickling filters or in the activated sludge process. This treatment removes floating and settleable solids and about 90 percent of the oxygen-demanding substances and suspended solids.

Sewage: Wastewater produced by residential and commercial establishments and discharged into sewers.

Sewage sludge: The accumulated settled solids separated from various types of water either moist or mixed with liquid component as a result of natural or artificial processes.

Sewage sludge directive: Council directive 86/278/EEC on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture. The purpose of this Directive is to regulate the use of sewage sludge in agriculture in such a way as to prevent harmful effects on soil, vegetation, animals and man, thereby encouraging the correct use of such sewage sludge.

Sewage treatment plant: see wastewater treatment plant.

Sludge: A semi fluid mass of sediment resulting from treatment of water, sewage and/or other wastes.

Solids retention time (SRT): The average period of time that biosolids remain in the activated sludge aeration tank.

Treatment: A substance with which to treat water or a method of treating water to clean it.

Treatment plant: Facility for cleaning and treating fresh water for drinking, or cleaning and treating wastewater before discharging into a water body.

Tertiary treatment: See also advanced wastewater treatment. Selected biological, physical, and chemical separation processes to remove organic and inorganic substances that resist conventional treatment practices; the additional treatment of effluent beyond that of primary and secondary treatment methods to obtain a very high quality of effluent. Commonly, the tertiary wastewater treatment process consists of flocculation basins, clarifiers, filters, and chlorine basins or ozone or ultraviolet radiation processes.

Ultraviolet light: Similar to light produced by the sun; produced by special lamps. As organisms are exposed to this light, they are damaged or killed.

Unit operation: Method of treatment in which the application of physical forces predominates. Gravity sedimentation and sedimentation are common examples.

Unit process: Method of treatment in which constituent removal is brought about by chemical or biological reactions.

Wastewater: Used water discharged form homes, businesses, cities, industry, and agriculture. Various synonymous uses such as municipal wastewater (sewage), industrial wastewater, and stormwater.

Wastewater treatment: Physical, chemical, and biological processes used to remove pollutants from wastewater before discharging it into a water body.

Wastewater treatment plant: Plant where, through physical-chemical and biological processes, organic matter, bacteria, viruses and solids are removed from residential, commercial and industrial wastewaters before they are discharged in rivers, lakes and seas.

Water quality: The condition of water with respect to the amount of impurities in it. This term is used to describe the chemical, physical, and biological characteristics of water, usually in respect to its suitability for a particular purpose.

Water reuse: The use of treated wastewater for a beneficial use, such as agricultural irrigation and industrial cooling.

Water use: Water that is used for a specific purpose, such as for domestic use, irrigation, or industrial processing. Water use pertains to human's interaction with and influence on the hydrologic cycle, and includes elements, such as water withdrawal from surface- and ground-water sources, water delivery to homes and businesses, consumptive use of water, water released from wastewater-treatment plants, water returned to the environment, and in stream uses, such as using water to produce hydroelectric power.