
**Water Reuse in Urban Areas —
Guidelines for reclaimed water
treatment: Design principles of a
RO treatment system of municipal
wastewater**

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Foreword

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This document was prepared by Technical Committee ISO/TC 282, *Water reuse*, Subcommittee SC 2, *Water reuse in urban areas*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Over the past decade, with an increasing demand of high-quality reclaimed water, reverse osmosis (RO) has been widely applied as an important option for municipal wastewater reclamation. RO is a water purification technology that uses a semipermeable membrane to remove ions and dissolved organic micropollutants from feed water. In reverse osmosis, an applied pressure is used to overcome osmotic pressure, a colligative property that is driven by chemical potential differences of the solvent, a thermodynamic parameter. The automatic operation, small footprint and consistent high permeate quality are the advantages of an RO process, which make it widely recognized. The reclaimed water produced by an RO system could be used as boiler replenishing water, water for industrial production and so on.

Compared with seawater and industrial wastewater, municipal wastewater has its distinctive features. The total dissolved solid (TDS) concentration in seawater is mainly in the range of 30,000 to 45,000 mg/l^[1], while the TDS concentration in secondary effluent of municipal wastewater ranges from 100 to 3,000 mg/l^[2]. Thus, the RO system of municipal wastewater could achieve higher recovery efficiency with much lower operational pressure compared with that of seawater. However, the dissolved organic matter (DOM) concentration in secondary effluent is in the range of 5 to 20 mg/l as dissolve organic carbon (DOC)^[2], which is much higher than that in seawater (<2 mg/l)^[1]. Furthermore, the components of the DOM in secondary effluent are much more complicated than those in seawater. Long-term operation of the RO system for municipal wastewater reclamation could lead to serious organic and biological fouling. Therefore, in order to provide the stable operation, the distinctive features of municipal wastewater should be taken into consideration in the design of the RO unit as well as the pre-treatment unit. The design experience of the RO system for other water sources (e.g., seawater and industrial wastewater) could not be applied directly to municipal wastewater.

This document provides guidelines for the planning and design of an RO treatment system for water reuse applications in urban areas. This document is applicable to practitioners and regulatory authorities who intend to implement principles and decisions on water reuse in a safe, reliable and sustainable manner.

This document addresses an RO treatment system in its entirety (e.g. reclaimed water sources, pre-treatment process, RO treatment process, post treatment process, performance of RO system, operation and maintenance and monitoring, usage of reclaimed water).

Water Reuse in Urban Areas — Guidelines for reclaimed water treatment: Design principles of a RO treatment system of municipal wastewater

1 Scope

This document provides guidelines for the planning and design of a reverse osmosis (RO) treatment system of municipal wastewater. This document is applicable to practitioners and authorities who intend to implement principles and decisions on RO treatment of municipal wastewater in a safe, reliable and sustainable manner. This document addresses RO treatment systems of municipal wastewater in their entirety and is applicable to any RO treatment system component.

This document provides:

- standard terms and definitions;
- a description of the system components of an RO treatment system of municipal wastewater;
- design principles of an RO treatment system of municipal wastewater;
- statements on the feed water quality and technical requirements of an RO treatment system;
- guidance for operation and maintenance of an RO treatment system;
- specific aspects for consideration and emergency response.

Design parameters and regulatory values of an RO treatment system of municipal wastewater are out of the scope of this document.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 20670:2018, *Water reuse — Vocabulary*

3 Terms and definitions

For the purpose of this document, the terms and definitions given in ISO 20670 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

3.1

assimilable organic carbon (AOC)

organic carbon which can be used by microorganisms for assimilation

3.2

biodegradable dissolved organic carbon (BDOC)

organic carbon which can be used by microorganisms for assimilation as well as catabolism

3.3

concentrate

rejected stream exiting a membrane module under a cross-flow mode

Note 1 to entry: Concentrate stream contains increased concentrations of constituents over the feed stream due to the accumulation of rejected constituents by membranes in the feed stream.

[SOURCE: ASTM D6161-19^[3], modified — Note 1 to entry added.]

3.4

feed

input solution entering the inlet of a membrane module or system

[SOURCE: ASTM D6161-19^[3]]

3.5

ion exchange

process by which certain anions or cations in water are replaced by other ions by passage through a bed of ion-exchange material

[SOURCE: ISO 6107-1:2004, 46^[4]]

3.6

membrane rejection rate

relative measure of how much of the target constituent that was initially in the feed water is separated from the liquid by the membrane

Note 1 to entry: Rejection is generally expressed by $1 - C_2/C_1$, where C_1 is feed concentration and C_2 is permeate concentration. To make the guideline simple, the word “membrane” is frequently omitted depending on the context.

3.7

microfiltration

pressure driven membrane-based separation process designed to remove particles and macromolecules in the approximate range of 0,05 to 2 μm

[SOURCE: ASTM D6161-10^[3]]

3.8

permeate

portion of the feed stream which passes through a membrane

[SOURCE: ASTM D6161-10^[3]]

3.9

pressure drop

pressure change of the influent after the treatment by an RO system

3.10

recovery rate

ratio of the permeate volume to the feed volume

3.11

reverse osmosis

separation process where one component of a solution is removed from another component by flowing the feed stream under pressure across a semipermeable membrane that causes selective movement of solvent against its osmotic pressure difference

[SOURCE: ASTM D6161-10^[3]]

Note 1 to entry: Reverse Osmosis (RO) removes ions based on electrochemical forces, colloids, and organics down to 150 molecular weight. May also be called hyperfiltration.

3.12**silt density index (SDI)**

index for the fouling capacity of water in reverse osmosis systems, measuring the rate at which a 0,45-micrometre filter is plugged when subjected to a constant water pressure of 206,8 kPa (30 psi) ^[5]

[SOURCE: ASTM D4189-07 (2014) ^[5]]

3.13**ultrafiltration**

pressure driven process employing semipermeable membrane under hydraulic pressure gradient for the separation of components in a solution

[SOURCE: ASTM D6161-10 ^[3]]

Note 1 to entry: The pores of the membrane are of a size smaller than 0.1 µm, which allows passage of the solvent(s) but will retain non-ionic solutes based primarily on physical size, not chemical potential.

4 Abbreviated terms

AOC	assimilable organic carbon
BDOC	biodegradable dissolved organic carbon
BOD	biochemical oxygen demand
CA	cellulose acetate
COD	chemical oxygen demand
DOC	dissolved organic carbon
DOM	dissolved organic matter
MF	microfiltration
NPF	normalized permeate flow
ORP	oxidation-reduction potential
RO	reverse osmosis
SDI	silt density index
TOC	total organic carbon
TSS	total suspended solids
UF	ultrafiltration

5 Application of RO treatment systems for reclaimed water**5.1 Overview**

Over the past decade, with an increasing demand for high-quality reclaimed water, reverse osmosis (RO) among other technologies has been widely applied as an important option for municipal wastewater reclamation. RO technology can achieve high removal efficiency of microbes, colloidal matter, dissolved solids, organics and inorganics from feed water. The advantages of an RO process are automatic operation and high stability of RO permeate and this makes the RO process widely accepted ^[6-8].

5.2 Design considerations

Generally, permeate flow rate and permeate quality are used to characterize an RO treatment system under certain feed water quality, recovery rate and operational pressure. Therefore, the main objective of designing an RO treatment system is to meet the specific consideration of permeate flow rate and quality with minimal operational pressure and the considerations about the costs of system components. Furthermore, the cleaning process and maintenance should also be taken into consideration to maintain the stable operation of the system.

5.2.1 Safety considerations

In theory, the reverse osmosis process is driven by pressure. In practice, the pressure is provided by the feed pump of the RO process, and a pressure vessel is used to hold the membrane modules and the pressurized feed water. Therefore, the design and operation of a nRO system shall meet the safety consideration for a pressurized system.

5.2.2 Stability considerations

Stability represents the ability of an RO system to provide stable permeate flow rate and water quality under certain operational conditions. In practice, because of membrane fouling, scaling or other factors which could increase the resistance, in order to maintain a stable rate of permeate flow, the operational pressure keeps increasing. When the operational pressure is too high, it is necessary to clean the RO membranes. As for permeate quality, it might deteriorate because of membrane damage, membrane degradation and membrane fouling. Therefore, the permeate quality shall be diligently monitored.

In order to enhance the stability of an RO system, provision for equalization of feed water flow prior to the pre-treatment stage and/or the RO unit may also be considered. The resultant reduced variability in influent flow rate would also allow for more consistent dosing of chemicals such as antiscalants, reductants and non-oxidizing biocides.

5.2.3 Economy considerations

As for the infrastructure cost of an RO system, it is necessary to meet the considerations of permeate flow rate and quality with a minimal cost of system components. As for the operational cost, it is necessary to maintain the operational stability of the whole system with reasonable operational pressure, cleaning and maintenance.

5.3 RO system components

5.3.1 General

An RO system generally consists of six essential components (see [Figure 1](#)):

- feed water source;
- pre-treatment;
- RO treatment;
- auxiliary equipment;
- post treatment (optional depending of the reclaimed water usage and quality criteria); and
- monitor.

Each part of the system should be characterized and managed with appropriate strategies. See [Annex A](#) for the example of a typical RO treatment system for reclaimed water.

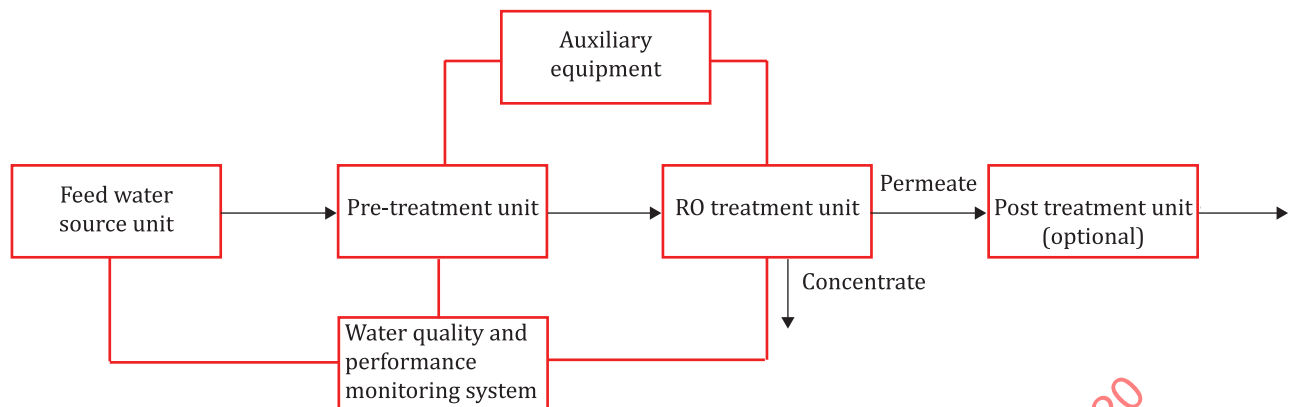


Figure 1 — The essential components of an RO treatment system for reclaimed water

5.3.2 Feed water source

Secondary or tertiary treated municipal wastewater is generally the water source to the RO process stage of the water reclamation plant.

5.3.3 Pre-treatment unit

The pre-treatment unit may include one or more treatment stages such as physico-chemical treatment, oxidation (e.g. ozone/AOPs), media filtration, UF/MF membrane filtration, disinfection.

5.3.4 RO treatment unit

The RO treatment unit generally includes a safety filter, a high-pressure pump, RO equipment and a storage tank for the effluent of RO. It is the key component of the whole RO system.

5.3.5 Auxiliary equipment

The auxiliary equipment may include the dosing and cleaning units. Several kinds of chemicals may be added, including chlorine, cleaning chemicals, antiscalants, reductants and non-oxidizing biocides ([Figure 1](#) and [Figure A.1](#)).

5.3.6 Post treatment unit

According to the specific consideration of the end user, one or more stages shall be needed to attain the desired rejection (e.g. secondary RO, ion exchange, electrodialysis reversal). RO concentrate may require treatment. The post treatment unit will be elaborated on in [Clause 9](#).

5.3.7 Water quality and performance monitoring system

In order to maintain the operational stability and safety of the whole system, monitoring equipment should be installed, including temperature meter, pressure gauge, pH meter, flowmeter, conductivity meter, ORP meter and so on.

6 Technical considerations of pre-treatments

6.1 Quality considerations of feed water

6.1.1 General water quality index

General water quality indices of the feed water for an RO system are listed in [Table 1](#).

Table 1 — General water quality for the feed water of an RO system

Category of water quality index	Detailed water quality index
Inorganic index	Metal cations (calcium, magnesium, iron, aluminum, etc.); Silica; Free chlorine residual; Anions (nitrate, phosphate, etc.)
Organic index	COD, BOD, TOC
Other index to be considered	pH, Silt density index (SDI), Turbidity, Oxidation-reduction potential

Metal ions and silica could be of concern for scaling.

Free chlorine residual is of concern for RO membrane oxidizing damage.

The nutrient availability, such as nitrate and phosphate, could be important factors affecting the biofouling of membranes.

Organic index is related to organic fouling and biofouling, which may become the main fouling problems when secondary or tertiary treated municipal wastewater is used as feed water. These indices are elaborated on in [6.1.3](#).

SDI and turbidity are related to membrane fouling caused by small particles.

6.1.2 Silt density index

Silt density index (SDI) gives the percent drop per minute in the flow rate of the water through the filter, averaged over a period of time such as 15 minutes.

The measurement procedure of silt density index is as follow referring to ASTM D4189-07 (2014)^[5]:

The water sample is filtered through a 0.45 µm membrane with a diameter of 47 mm under a constant pressure of 206.8 kPa (30 psi). At the beginning, the time needed to obtain 500 mL filtrate is t_1 . After time T (generally, 15 min), the time needed to obtain 500 mL filtrate become t_2 . The SDI of the water sample could be calculated with [Formula 1](#):

$$SDI = \frac{\left(1 - \frac{t_1}{t_2}\right) \%}{\frac{t_f}{t_f}} = \frac{\%P}{t_f} \quad (1)$$

where

t_f is the total testing time;

t_1 is the time needed to obtain 500 ml filtrate at the very beginning;

t_2 is the time needed to obtain 500 ml filtrate after the testing time T (generally, 15 min);

$\%P$ is plugging rate if $\%P$ is over 75 %, testing time T should be change to 10, 5 or 2 min.

Feed water with an SDI below 3, is generally considered as adequate feed water.

Other methods or indicators may be used if necessary.

6.1.3 Organic index

Generally, organic indices for an RO system include:

- Total organic carbon (TOC);
- Biochemical oxygen demand (BOD); and
- Chemical oxygen demand (COD).

Compared with seawater, a distinguishing feature of secondary treated municipal wastewater is that the TOC concentration is usually much higher, and therefore close attention should be paid to the membrane fouling caused by the organic matter in the RO process influent for wastewater reclamation.

Besides the TOC concentration, the organic constituents in the secondary treated municipal wastewater are also different from those of seawater. The organic matter might be used by different microorganisms leading to serious membrane fouling. Therefore, the concept of biostability of the feed water should be taken into consideration. The assessment of biostability is generally based on the assimilable organic carbon (AOC) or biodegradable dissolved organic carbon (BDOC)^[9].

AOC is the fraction of DOC that is consumed by microorganisms, resulting in microbial growth and represented by the maximum growth of a pure test microorganism(s) or indigenous bacteria that is correlated with the DOC. BDOC is the consumption of DOC to catabolize organic carbon to CO₂ and new biomass, and represented by the difference between initial DOC and final DOC^[9].

6.1.4 Biological index

Biological index, mainly the bacterial cell number in the feed water, could be used to evaluate the biofouling potential. Besides the amount of microorganisms, the microbial community structure could also show significant effect on the development of biofouling^[10].

6.1.5 Oxidation-reduction potential

Oxidation-reduction potential (ORP) represents the content of oxidizing and reducing substances in water. The oxidizing substances in municipal wastewater usually include free and combined chlorine, ozone and so on. Some RO membrane materials, such as polyamide, are sensitive to these oxidizing substances, and thus pre-treatment units, such as carbon filtration and adding reductants, are used to remove the oxidizing substances.

6.2 Selection of mechanical pre-treatments

Municipal wastewater should be pre-treated before being fed into the RO treatment devices to meet the water quality considerations. The selection of pre-treatment unit(s) should take into account the quality of feed water, influent quality considerations of RO treatment unit(s), technical features, cost and so on. Besides, experimental data or similar engineering experience should also be referred to. Generally, pre-treatment unit(s) consists of processes such as clarification, media filtration, multimedia filtration, microfiltration, ultrafiltration and cartridge filtration. The detailed design of pre-treatment is not included in this document.

6.2.1 Clarification

Clarification is the integration of coagulation, precipitation and sedimentation, and is mainly used to remove total suspended solid (TSS), colloids, organic matter and phosphorus in the feed water. Aluminium and ferric salts can be used as coagulant.

6.2.2 Media/Multimedia filtration

Media/multimedia filtration is mainly used to remove total suspended solid in the feed water. For example, a dual media filter may use anthracite and either quartz sand or silica sand as filtration media.

6.2.3 Activated carbon filtration

Activated carbon filtration can be used to remove colour, odour, residual chlorine and dissolved organic constituents with low molecular weight in the feed water. Single layer filter tank or homogenous media filter tank can be chosen with the use of activated carbon as the media. Activated carbon should be replaced and regenerated periodically.

6.2.4 Microfiltration and ultrafiltration

Microfiltration (MF) and ultrafiltration (UF) can remove, depending on the membrane pore size, several kinds of pollutants in the feed water, including viruses, bacteria, protozoa, TSS, colloids, organics with high molecular weight, etc. Hollow fibre MF/UF membrane is usually used in the pre-treatment unit of an RO treatment system.

6.2.5 Cartridge filtration

Cartridge filtration can mainly remove TSS in the feed water and is usually used as a prefilter prior to the RO device.

6.3 Chemical pre-treatments

6.3.1 Antiscalants

Antiscalants are a series of chemicals that are used to prevent the scaling of the membrane surface. Most of the antiscalants are organic polymers with a molecular weight in the range from 2 000 to 10 000 Da, such as polyacrylic acid, organophosphates, phosphonates, polymaleic acid and so on.

The dosing system should be designed so that the antiscalants are thoroughly mixed before they enter the components of an RO system. The selected antiscalants for an RO system should be compatible with the RO membrane, otherwise damage to the membrane may occur.

6.3.2 Chemical oxidizers for disinfection of the feed

Chemical oxidizers including chlorine, hypochlorite and peracetic acid could be used for disinfection in feed water or at the wastewater treatment plant or both locations. Chlorine is the most commonly used chemical oxidizer to inactivate microorganism in municipal wastewater. Residual chlorine in the feed could inhibit microbial growth significantly. However, under some circumstance chlorine may also fail to control biofouling [10].

6.3.3 Reductants

The chemical oxidizers used for disinfection could damage the RO membrane made of certain materials, such as polyamide and aromatic polyamide. Therefore, reductants are usually added to remove these oxidizers before the RO unit. The most commonly used reductant in an RO system is sodium bisulphite.

6.3.4 Non-oxidizing biocides

Non-oxidizing biocides will not damage the RO membrane and may be added before the RO system to prevent the biological fouling of the RO membrane. The dose should be tracked in order to prevent excessive biocide use.

7 Technical and structural considerations of RO unit

7.1 Components

7.1.1 RO feed pumps

RO feed pumps are sized using the required flow rate and operating pressure. Pump curves are then generated to determine the number of stages, impeller diameter, horsepower required, and the efficiency of the pump. An RO feed pump requires a minimum pressure at the pump suction to prevent pump cavitation.

7.1.2 RO membrane modules

RO membranes for industrial-scale applications are typically modularized using configurations that pack a large surface area of membranes into a relatively small volume. This makes the RO system more economical to use in that the system requires a smaller footprint, and membranes can be replaced in smaller modules rather than system wide.

7.1.3 Pressure vessels

A pressure vessel is the pressure housing for the membrane modules and contains the pressurized feed water. Pressure vessels are made to specially accommodate the diameter of membrane module being used. The length of the pressure vessel can be as short as one membrane module and up to seven membrane modules in series.

Proper installation of membrane modules into a pressure vessel is critical. The membrane modules are guided into the pressure vessel in series. Membranes should be loaded into or removed from pressure vessel in the direction of flow. Therefore, the first module into the vessel, which is the last one in the series, is the first module out.

7.2 Selection of RO membranes

7.2.1 Membrane materials

The performance of an RO unit is directly dependent on the properties of the membrane material. More specifically, the chemical nature of the membrane polymer and the structure of the membrane are what determines the rejection and flux properties of the RO system. Ideally, RO membranes should offer high flux and high rejection rate, as well as high strength and durability. However, in practice, high rejection rate and high flux have been two mutually exclusive goals. Although the last few years has seen an increase in flux rates with no decrease in rejection, most membranes today represent a compromise between high rejection rate and high flux.

The most commonly-used material for RO membranes, based on the type of polymer backbone, is polyamide^[11].

Basically, there are two types of polyamide membranes:

- linear aromatic polyamide membranes
- composite polyamide membranes.

Linear aromatic polyamide membranes were originally fabricated into hollow fibre membranes and used primarily for seawater and brackish water desalination.

Composite membranes are essentially a composite of two polymers cast upon a fabric support.

Currently, cross-lined, fully aromatic polyamide membranes are the most popular RO membranes in use.

[Table 2](#) lists the predominant characteristics of composite polyamide membranes^[12].

Table 2 — The characteristics of polyamide composite RO membranes

Property	Value for polyamide composite membranes
Membrane type	Homogeneous asymmetric, thin-film composite
Salt rejection (%)	>98 @ 25 °C
Silica rejection (%)	>96 @ 25 °C
pH range	2-11
Feed pressure	145-400 psi
Temperature tolerance	Up to 45 °C

Table 2 (continued)

Property	Value for polyamide composite membranes
Surface charge	Negative (anionic)
Chlorine tolerance	<0,02 ppm
Fouling tolerance	Fair
Surface roughness	Rough

Besides polyamide membranes, cellulose acetate (CA) and polyether urea (PEU) are other types of materials for RO membrane. CA membranes were commercially viable because of their relatively high flux due to the extreme thinness of the membrane. However, the high operating pressure and relatively low salt rejection of CA membranes were holding back this material from becoming more commercially acceptable. PEU membranes differ from polyamide membranes in the surface charge and morphology. PEU membranes have a slightly positive charge to them. Furthermore, the surface of a PEU membrane is smooth, similar to a CA membrane, thereby minimizing the potential for fouling.

7.2.2 Membrane modules

There are four basic forms for RO membrane modules: plate-and-frame, tubular, spiral wound and hollow fibre. These four configurations are summarized in [Table 3](#)^[12].

Table 3 — Brief comparison of four basic RO membrane modules

Property	Plate-and-frame	Tubular	Spiral wound	Hollow fibre
Packing density, ft ² /ft ³ (m ² /m ³)	45-150 (148-492)	6-120 (20-374)	150-380 (492-1247)	150-1500 (492-4924)
Potential for fouling	Moderate	Low	High	Very high
Ease of cleaning	Good	Excellent	Poor	Poor
Relative manufacturing cost	High	High	Moderate	Low

Plate-and-frame RO modules are typically used for specialty, high suspended solids applications and are not generally found in water purification facilities. Tubular modules are also used for specialty, high-solids applications typically found in food and biological processing industries. Spiral wound membrane modules are the most common type of module used for RO today due to the fairly high packing density. Some manufacturers also developed hollow fibre RO modules with very high packing density. But these modules are currently vulnerable to fouling and relatively difficult to clean.

7.3 RO unit configuration

The number of the RO membrane modules used in a certain system is related to several factors, including the requirement of the flow rate of the permeate, the recovery rate, the water quality of the feed water and so on. According to the requirements on the water permeate quality and the recovery rate, the design of single stage or multi stage is used, and the number of membrane modules in each stage is determined.

Generally, permeate flux, recovery rate and water temperature fluctuate within ranges. Therefore, the whole design should be optimized considering these factors as well as the membrane fouling caused by different kinds of feed water. The RO membrane supplier can usually provide software to assist with the design process.

8 Operating conditions and maintenance system

8.1 Operating conditions

8.1.1 Pressure

Operating pressure directly affects water flux and indirectly affects salt rejection. Because operating pressure directly affects the driving force for water across the membrane, higher pressure will lead to higher flux. Salt transport, however, is un-affected by pressure. Therefore, the same amount of salt passes through the membrane at low or high feed water pressure. Nevertheless, because more water has passed through the membrane at higher pressure, the absolute salt concentration in the permeate is lower, so it appears as if the salt passage decreases and the salt rejection increases as pressure increases.

8.1.2 Temperature

Temperature influences system flux and rejection performance. Under conditions of constant pressure and at temperature less than 45 °C, water flux is linearly proportional to the water temperature, while salt rejection decreases slightly with increasing temperature. In practice, temperature changes are dealt with by adjusting the operating pressure: lower pressure in the warmer summer months and higher pressure in the colder winter months.

In order to take into account the effect of the temperature onto the membrane performance, and to compare different membrane performances, data are usually given at a standardized temperature of 25 °C.

8.1.3 Feed water flow and permeate flux

The feed water flow through an RO system should be dictated by the water quality of the feed water. The cleaner the water source, the higher the feed water flow may be, resulting in smaller systems and lower overall cost of operation and maintenance. At higher feed water flow rates, contaminants such as colloids and bacteria that may be present in the source water, are sent to the membrane more rapidly, resulting in faster fouling of the membranes. Therefore lower flow rates are recommended for water sources that contain high concentrations of contaminants.

Permeate flux determines the overall size of the RO system in terms of membrane area required to achieve the desired separation. The permeate flux for a given application should be based on the feed water source. Source water with better water quality allows for higher flux, which, in turn, means less membrane area is required to achieve the desired separation.

Permeate flux is affected by several operating variables, as discussed above. In summary:

- Permeate flux is directly proportional to operating pressure.
- Permeate flux is directly proportional to water temperature.
- Permeate flux decreases slightly as recovery increases until the osmotic pressure of the feed water equals the driving pressure, at which point productivity ceases.
- Permeate flux decreases with increasing feed concentration of dissolved solids.
- Permeate flux is relatively constant over a range of pH, although for some newer polyamide membranes, flux is also a function of pH.

8.1.4 Concentrate flow

The recommended concentrate flow rate is related to the feed water quality. The cleaner the water source, the lower the concentrate flow may be, resulting in smaller systems and lower overall cost of

operation. However, at lower concentrate flow rates, contaminants, such as colloids and scale-formers, have a much greater chance of fouling or scaling a membrane.

8.1.5 pH

The stability of polyamide composite membranes is affected by pH. The pH range of nominal application is broad, ranging from as low as 2 to as high as 11, depending on the specific membrane and manufacturer. Acceptable operating pH is a function of temperature, with high temperatures requiring narrower pH ranges of operation.

The rejection capability of polyamide composite membranes is also affected by pH. Rejection of most species is highest at about pH 7,0-7,5. Rejection drops off at higher and lower pH levels, but the drop off is very gradual at lower pH levels. The flux through a polyamide composite RO membrane is relatively constant over the range of suitable pH.

The pH of RO product water is generally lower than the pH of feed water, unless the carbon dioxide is completely removed from the feed water, because carbon dioxide is not rejected by RO membranes, but carbonate and bicarbonate are.

8.2 RO performance parameters

8.2.1 Permeate flow rate

Permeate flow rate is one of the most important parameters to evaluate the performance of an RO system. Generally, normalized permeate flow (NPF) is used to characterize permeate flow rate. Several factors can affect the NPF. Membrane fouling, scaling and compaction can all result in a loss in NPF. On the other hand, an increase in NPF is typically the result of a leak, either due to a breach in the membrane itself or because of problems with the membrane module hardware, or to exposure to oxidizers such as chlorine.

The following formula shows how temperature, in terms of the temperature correction factor, TCF; pressure, P ; and concentration, as osmosis pressure, Π , are used to normalize permeate flow rate^[13]:

$$\text{Normalized flow} = \frac{[(AAP_s - \Delta\Pi_s)] TCF_s}{[(AAP_a - \Delta\Pi_a)] TCF_a} \cdot \text{Actual flow}$$

where

AAP = the average applied transmembrane pressure = $P_{\text{feed}} - \frac{\Delta P}{2} - P_{\text{perm}}$

P_{feed} = applied feed pressure

ΔP = pressure drop from feed inlet to concentrate effluent

P_{perm} = permeate pressure

$\Delta\Pi_n$ = difference between the osmotic pressure on the membrane feed and permeate sides

TCF = temperature correction factor (membrane and manufacturer dependent)

"s" = subscript for "standard" conditions

"a" = subscript for "actual" conditions

Standard condition for an RO system is usually at a given temperature of 25 °C.

8.2.2 Salt rejection

Salt rejection is used to evaluate the purification ability of an RO system. Membrane scaling and degradation can result in a loss in salt rejection as can the breaches of O-rings and permeate tube. Increase in salt rejection is typically due to membrane compaction. As the membrane becomes denser due to compaction, the passage of salts through the membrane is reduced, leading to a loss in salt passage and an increase in salt rejection.

8.2.3 Pressure drop

Pressure drop measures the loss in pressure from the feed to the concentrate. In effect, it measures the loss in driving force for water across the membrane. It is unusual to find a loss in pressure drop under normal operating conditions for most RO systems. If a loss in pressure drop is recorded, it is typically a result of faulty instrumentation. Several factors can lead to high pressure drop, including membrane scaling, colloidal fouling and biofouling. These factors all involve deposition of materials onto the surface of the membrane as well as onto components of the membrane module, such as the feed channel spacer of the spiral wound modules. This causes a disruption in the flow pattern through the membrane module, which, in turn, leads to frictional pressure losses and an increase in pressure drop.

8.3 Automatic chemical dosing system

8.3.1 Dosing point

In order to maintain the stable operation of an RO system, several chemical reagents need to be added at different points of the whole system. Typically, chemical oxidizers (e.g. chlorine) is added to inactivate the microorganism in the feed water in the very front of the whole system or in the municipal wastewater treatment plant before the effluent is pumped to the water reclamation plant. See [Annex B](#) for Information of chlorine disinfection for the influent of an RO system.

Antiscalants and reductants are added in the water tank after the last stage of pre-treatment before RO. Non-oxidizing biocides are added right before the RO device.

Chemical reagents are also added to clean the MF or UF membrane as well as the RO membrane.

8.3.2 Dosing method

Generally, there are two dosing methods: continuous addition and batch addition. Continuous addition is to add the reagents with a low concentration continuously. Batch addition is to add the reagents with a higher concentration at certain time intervals.

Typically, chemical oxidizers, antiscalants and reductants are added continuously at certain locations of the system; while non-oxidizing biocides are added with a much higher concentration at a longer time interval (e.g. once a week or every two weeks).

8.4 Control and monitor system of RO performance

8.4.1 Instrumentation

Instrumentation is the key to operate and monitor an RO system. [Table 4](#) lists the basic instrumentation that should be part of an RO system^[12]. Sometimes, the designing plan does not include the inter-stage (the position between different stages) instrumentation. But this instrumentation is essential during troubleshooting to determine whether problems with an RO system are due to fouling in the first stage, or due to scaling in the last stage. Alarms and emergency shutdown are necessary to prevent damage to RO and pre-treatment equipment and to personnel near the unit.

Table 4 — Basic recommended RO instrumentation

Parameter	Raw feed	Pressurized feed	Inter-stage	Permeate	Concentrate
Pressure	√ ^a		√	√	√
Flow	√		√ ^{*b}	√	
Conductivity	√		√ [*]	√	√ [*]
Turbidity	√	√ [*]			
SDI		√ ^{**c}			
Temperature	√				
ORP	√				
Free chlorine	√				
pH	√				
^a √: should be installed ^b *: Generally not provided ^c **: Typically measured off line sampling					

8.4.2 Control system

The basic function of a control system is to keep the RO system functioning and on-line. At start-up, the control system will automatically open necessary valves and start the feed pump. Typically, the control will automatically adjust the pressure of the feed pump to maintain a designed flow rate through the RO system. If not, a concentrate flow control valve can also be used to maintain a consistent recovery rate. The control system will also automatically turn RO systems on and off according to the demand for product water.

Most RO systems are equipped with a programmable logic controller (PLC) as the main control system.

8.4.3 Monitoring system

An operator interface, otherwise called the human machine interface (HMI), is used to record data gathered by the PLC. The different forms of HMI can be SCADA, touchscreen panel or mimic diagram. The HMI uses process displays with real-time sensor readings so that the operator can quickly assess the status of the system. The operator uses the control panel to adjust alarm settings and to turn on and off process equipment. Once running, however, the PLC controls and runs the system automatically, without further input from the operator.

8.5 Cleaning system

8.5.1 Physical cleaning

Physical cleaning is the method in which the RO membrane is flushed by the feed with high flow rate and low pressure, so that the pollutants attached on the membrane can be washed away quickly. The essential factors of physical cleaning are high flow rate, low pressure and cleaning frequency. It is usually necessary to stop the operation of an RO system and control the flow rate and pressure of the feed carefully to conduct physical cleaning.

8.5.2 Chemical cleaning

In order to select suitable reagents and procedures for chemical cleaning, a series of factors need to be taken into consideration. Firstly, the main components of the pollutants on the membrane should be determined. Information on cleaning methods could come from equipment or RO membrane or reagent suppliers. Depending on the pollutants, specific cleaning reagents can be recommended by suppliers. Instructions from the manufacturers for the reagent use should be followed for health and safety and best results for the cleaning. In the case of serious membrane fouling, one of the contaminated RO membranes could be taken out from the system and cleaning experiments should be conducted on it to

determine suitable reagents and procedures. To achieve superior cleaning, sometimes several cleaning reagents could be used. For example, a contaminated RO membrane is washed with water and then with an alkali solution to remove organics, and finally washed with acid to remove metal deposition. Detergents might be added into the cleaning reagent to remove biological or organic pollutants. Chelant could be used to remove colloids, metals and so on.

Generally, there are two methods for chemical cleaning: on-site and off-site. On-site cleaning is to conduct chemical cleaning while the membrane is still in the system, and it is the main chemical cleaning method used by most RO systems. Off-site cleaning is to take the contaminated RO membrane out of the system and conduct chemical cleaning. Off-site cleaning is usually used to check the effectiveness of the chemical cleaning procedure before the procedure is used to clean the whole RO unit. When the membrane fouling is too serious and the flow rate after on-site cleaning is still very low, off-site cleaning should be used.

8.6 Integrity testing of RO systems

Because of a range of breaches that can develop in the RO system, the integrity of RO membranes may be compromised. Membrane breaches can occur as a result of: damage to the membrane layer as a result of chemical or biological degradation and particulate abrasion; delamination of the skin layer from the supporting layer; telescoping; and failures of O-rings, gaskets, connectors and other fittings.

In order to ensure the quality and safety of permeate produced by an RO system, the integrity of the entire system shall remain intact over the service life of the elements. Furthermore, system operators shall be able to provide evidence of the integrity to satisfy regulatory requirements on a regular basis. Several integrity monitoring techniques have been developed for the RO system. Table 5 summarizes current and emerging integrity monitoring methods^[14].

Table 5 — Current and emerging integrity monitoring methods

Monitoring technique	Mode	Technology maturity	Advantages/Limitations
Existing techniques—Direct monitoring			
Vacuum decay testing	Offline	Laboratory and pilot scale	Applies only to individual elements and not to the entire system
Pressure decay testing	Offline	Laboratory and pilot scale	Not practical for full-scale elements due to drainage requirement; pressurizing permeate side can cause damage to RO membranes
Existing techniques—Indirect monitoring—Naturally occurring substances			
TOC monitoring	Online	Full-scale; can be used for entire stage of RO systems	Used in several installations but equipment to detect very low levels is expensive
Sulphate monitoring	Offline	Full-scale; can be used for entire stage of RO systems	Expensive to monitor continuously using ICP
Conductivity monitoring	Online	Full-scale; can be used for entire stage of RO systems	Low resolution; removal limited to 2 log ₁₀ for water reuse applications; probing more effective than online monitoring
Periodic Testing	Online	Full-scale	Offers multiple, periodic testing; can locate defects but is complex to implement in full scale applications
Existing techniques—Indirect monitoring—Challenge tests			
Dye testing	Online	Pilot and full-scale	Can provide up to 4 log ₁₀ resolution; fouling can be an issue for some dyes
Pulse integrity test	Online	Pilot scale	Can locate defects if calibrated
Microbial surrogates (i.e., MS2, <i>E. coli</i> etc.)	Offline	Pilot and full-scale	Seeding required since MF/UF pretreatment will remove most surrogates; can be expensive
Existing techniques—Integrated and multi-parameter monitoring system			

Table 5 (continued)

Monitoring technique	Mode	Technology maturity	Advantages/Limitations
Monitoring the permeate fluorescence where fluorescent molecules are injected in the feed (For example, the commercial TRASAR® solution)	Online	Full-scale; can be used for entire stage of RO systems	Up to 6 log10 removal reported with non-continuous spikes; up to 2 log10 when used with antiscalants
Emerging Techniques—Pathogen Detection Systems			
Measuring unique bio-optical signals of particles and comparing them to those in the library to identify microbial contaminants (For example, the commercial BioSentry™ Device)	Offline	Laboratory scale	Valid only for particles greater than 0.4 µm
Real-time polymerase chain reaction	Offline	Laboratory scale	Requires specialized personnel, sample preparation and long time periods for results; expensive
Evanescent Wave Fiber Optic Sensor	Online	Laboratory scale	Long detection time (several hours)
Microarray biosensor instrument	Online	Laboratory scale	Laboratory-scale systems common

8.7 System failure

There are mainly two kinds of system failure in an RO system: the decrease of permeate flux and the decrease of rejection rate. Table 6 summarizes common possible causes and locations of system failure of an RO system. In the operation of an RO system, the permeate flux is usually kept stable, and the change in pressure drop, pressure of the feed and the rejection rate could indicate some typical problems in the system.

Operational procedures should be followed under these conditions (Table 6).

Besides, there should be operational procedures to deal with the cases of extreme breaks in membranes (e.g., damage caused by oxidizers, membrane hydrolysis).

Table 6 — Potential causes and locations of system failure of an RO system

Cause of system failure	Possible location of system failure
Contamination caused by metallic oxide	First stage, the membrane at the front
Contamination caused by colloids	First stage, the membrane at the front
Inorganic scaling	The membrane at the back
Sedimentation of SiO ₂	The membrane at the back
Biological fouling	Usually on the front
Organic fouling	All the stages
Antiscalant fouling	The membrane on the back
Damage caused by oxidation	First stage
Hydrolysis of the membrane	All the stages
Abrasion of the membrane	First stage
Leakage of O-rings	Random

Table 6 (continued)

Cause of system failure	Possible location of system failure
Leakage of membrane components	Random

9 Post-treatment unit

Generally, the water quality of the permeate from a stable RO system can meet the standards of most reuse purposes, including low pressure boiler make-up water and recirculating cooling water, industrial water for semiconductor factories and so on. The post-treatment process would be dependent on the final use. Typically, post treatment for RO product water includes secondary RO, ion exchange, electrodialysis reversal, stabilization by alkalinity addition and final disinfection.

10 RO concentrate management

The management and treatment of RO concentrate is an important issue in the operation of RO process. RO concentrate contains concentrated salts and pollutants from the feed, including organics and inorganic nutrients, as well as the chemicals added in the RO system, including antiscalants, non-oxidizing biocides and so on. Therefore, the ecological and health risks of RO concentrate is significant. [Figure 2](#) summarizes the practical treatment modes of the concentrate from the RO system for wastewater reclamation. Eutectic freeze crystallization or thermal evaporation is usually used for the intermediate treatment (Mode A). When the amount of RO concentrate is small, circulation to the municipal wastewater treatment plant (WWTP) is the viable option (Mode B and C). Although some proven processes allow to satisfy the discharge standard (Mode E), the diversification of solutions need to be developed. See [Annex C](#) for the information of technologies for RO concentrate treatment.

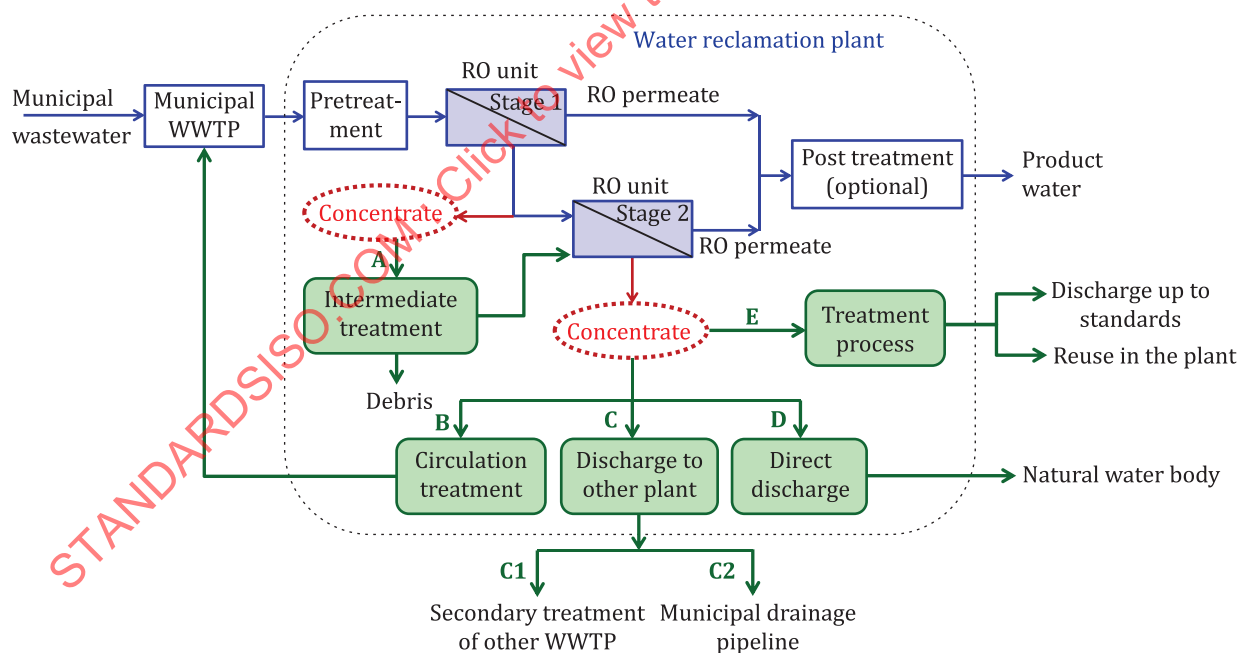


Figure 2 — The treatment modes of the concentrate from the RO treatment system of municipal wastewater

11 Emergency response plan

Emergency response plans should also be put in place to deal with and minimize the impacts of incidents or emergencies that could compromise the water quality of the permeate, such as extreme weather

conditions, natural disasters and illness outbreaks. The development procedures of an emergency response plan should include:

- communication between all relevant agencies and/or local authorities to define potential incidents and emergencies;
- development of an emergency response plan and related document procedures. A risk assessment procedure could be used to identify critical points, potential risk situations and best management options for reducing risk levels, see ISO 20426;
- regular checking of emergency response plans;
- regular plan updating.
- key areas to be addressed in incident and emergency response plans include:
 - predetermined agreements by the leading agencies and/or local authorities to decide on potential health or environmental impacts;
 - communication protocols and strategies, including notification procedures;
 - mechanisms for increased health or environmental surveillance.

Appropriate documentation and reporting of the incident or emergency should also be established. The engineers and operators should learn as much as possible from any incident to improve preventive measures and planning of corrective actions for other failures.