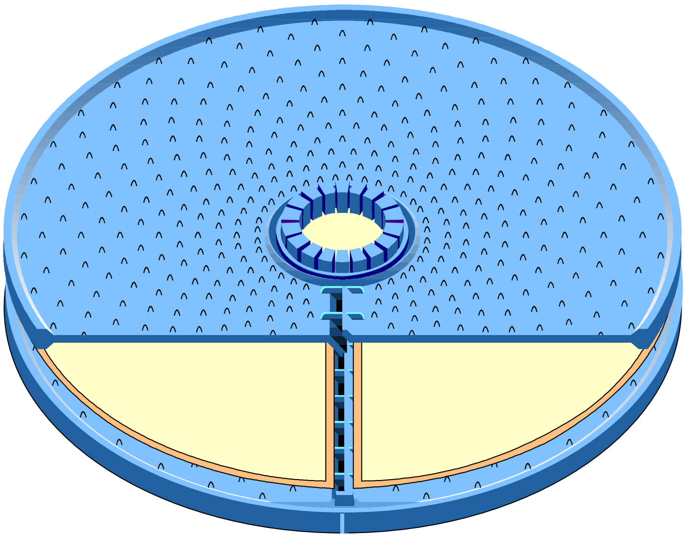
mft CD Module Technical Manual



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1. General safety information

Within this chapter, general safety information to prevent injury to the user or other people, to prevent property damage and to safely use the product are briefly introduced.

This manual does not necessarily cover all precautions that need to be followed when installing, operating and servicing the product. Thus, local regulations, plant regulations, customary rules of technology and all additional security-relevant measures must be observed. Failure to do so may result in danger for the people, for the environment as well as for the product.

1.1 Safety guidelines

This manual contains descriptions and instructions regarding the use of mft CD modules for water and wastewater treatment. Do not use it for any other purposes.

The following general safety guidelines shall always be kept in mind:

- handle CD modules with care;
- when handling CD modules, wear appropriate protective clothing;
- perform regular products inspection and maintenance;
- prevent foreign matter from touching the membrane cushions;
- do not directly touch membrane cushions, use gloves to cover the hands' skin;
- CD modules exposure to fire is strictly prohibited;
- do not treat water or wastewater containing substances which may damage or degrade the membrane cushions and/or other CD module components;
- do not drink and/or shower with treated water unless it is suitable for potable use;
- do not mix alkaline chemicals with acid chemicals under any circumstances;
- prevent any chemical leakage that may damage the CD modules, other treatment plant components and/or may cause environmental pollution.

1.2 Safety symbols

Within this manual, the following safety symbols are used:

Table 1. Safety symbols meaning and description

Symbol	Meaning	Description
	Notice	This symbol is used to indicate a situation that may result in property damages
	Caution	This symbol is used to indicate a situation that may result in injuries or property damages
	Warning	This symbol is used to indicate a situation that may result in serious injuries or death
	Danger	This symbol is used to indicate a situation that will result in serious injuries or death

2. Introduction to nanofiltration and reverse osmosis

In water treatment applications, nanofiltration (NF) and reverse osmosis (RO) are membrane-based separation techniques used to separate dissolved compounds, namely dissolved salts (i.e. ions), inorganic molecules and organic molecules from a water solution. As a result, water and some dissolved compounds pass through the membrane while the bulk of dissolved compounds is retained.

Figure 1 shows how NF/RO membranes selectivity compares to other membrane filtration techniques. Although they are also able to remove particulate matter, NF/RO membranes can rapidly foul when subjected to significant particulate loading.

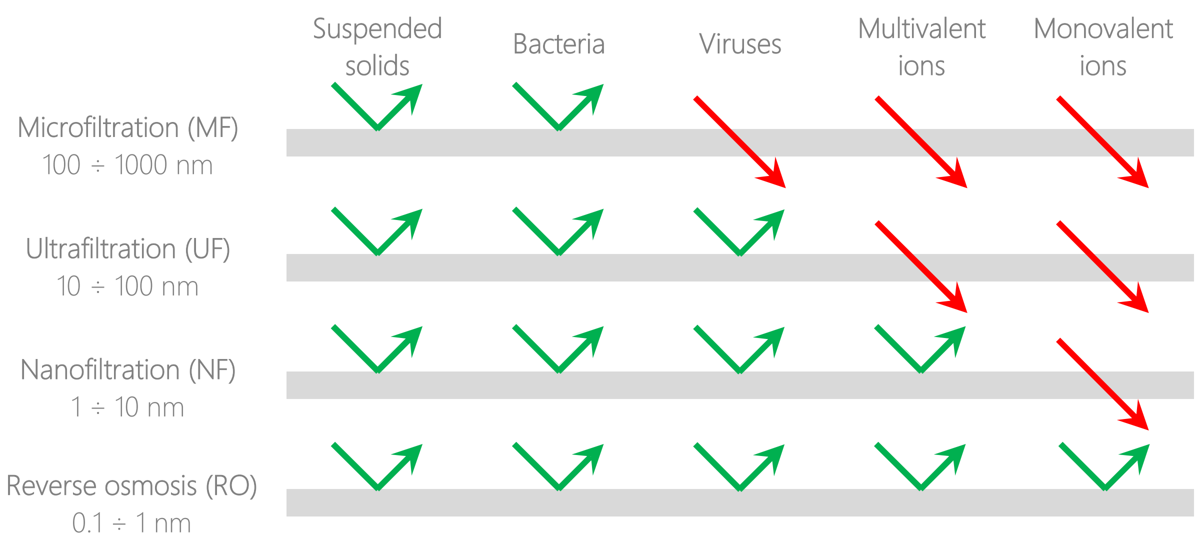

Figure 1. Typical membrane filtration ranges

Membrane selectivity may also be expressed according to molecular weight cut-off (ref. 2.3.10).

2.1 Background

To better understand the reverse osmosis phenomenon, we must first introduce osmosis. This is a natural phenomenon where water flows through a semipermeable membrane (i.e. the reverse osmosis membrane) from a solution with a lower concentration of ions to a solution with a higher concentration of ions. Water continues to flow until the ions concentration on both sides of the membrane is equalized (ref. Figure 2 left). Once the system has reached an equilibrium, we may define the osmotic pressure difference between the two solutions as the pressure corresponding to the water level difference between the two sides of the membrane.

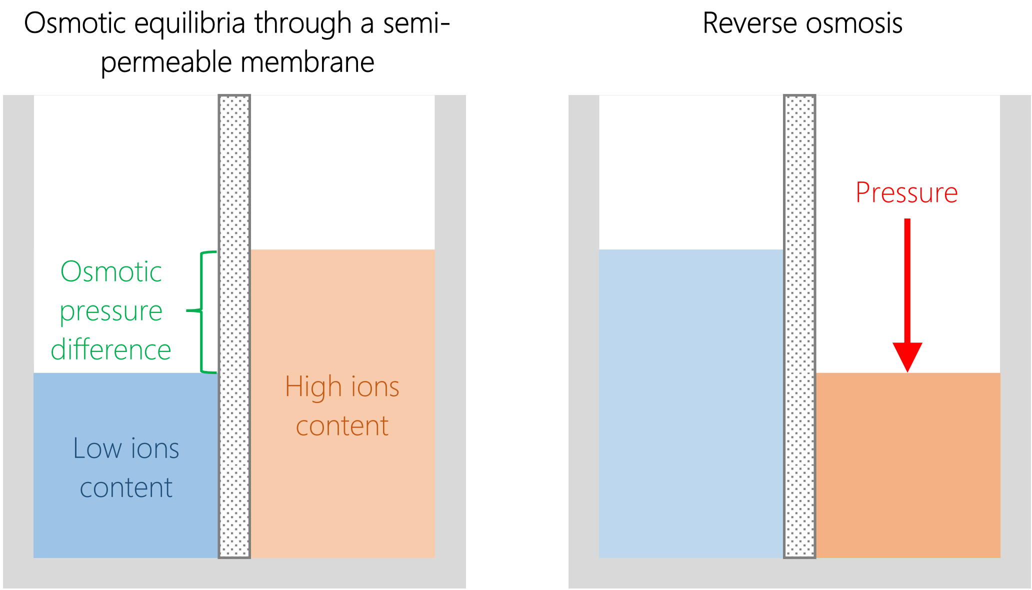

Figure 2. Reverse osmosis working principle

By applying a pressure greater than the osmotic pressure difference on the compartment that once contained the high-concentration ions solution, water is forced to pass through the membrane in the direction reverse to that of osmosis (hence the name "reverse osmosis", ref. Figure 2 right). Although ions also diffuse through the membrane, their mass transfer rate is much slower than that of the water. This way, on one side of the membrane, relatively pure water accumulates while, on the other side of the membrane, dissolved compounds are concentrated. Note that, due to the added resistance of the membrane itself, the applied pressure required to achieve reverse osmosis is significantly higher than the osmotic pressure alone.

Unlike RO membranes, NF membranes are not a complete barrier to dissolved salts and, depending on the type of salts and the type of membrane, the salt rejection and thus the osmotic pressure may be either low or high (up to values of RO membranes).

2.2 Applications

NF/RO membranes can be used to either purify water or to concentrate and recover dissolved solids in the feed water. Common applications include:

- water purification for boiler make-up;
- seawater and brackish water desalination for potable use;
- ultrapure water for the microelectronics industry;
- high-purity water for the pharmaceutical industry;
- process water for beverages;
- dairy products processing;
- process materials recovery (e.g. metals in case of metal finishing industries, dyes in case of textile industries, etc.);
- municipal and industrial wastewaters reuse or concentration;
- Minimum and Zero Liquid Discharge (MLD and ZLD) applications.

2.3 Basic terms and definitions

Filtration is the separation of two or more components inside a fluid stream through the use of a filter media and the application of an appropriate driving force (i.e. a pressure gradient).

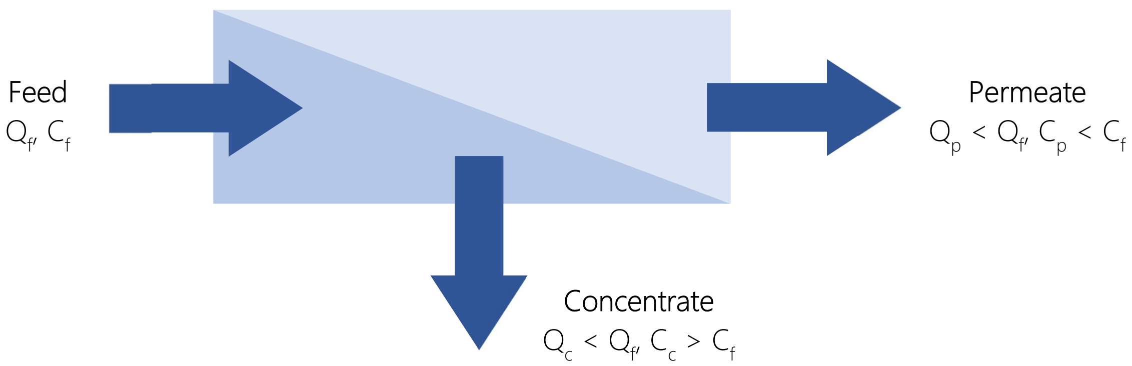

Figure 3. Filtration flow components

In particular, the components in Figure 3 are described as follows:

- feed, the liquid stream entering the filtration unit with a flow labelled Q_f and a solutes concentration labelled C_f;
- permeate (or filtrate), the product of the filtration process with a flow labelled Q_p and a solutes concentration labelled C_p;
- concentrate (or retentate), the waste produced by the filtration process with a flow labelled Q_c and a solutes concentration labelled C_c

where flows are usually expressed in [m^3/h] and solute concentrations in [mg/L].

The key terms used in NF/RO processes are defined within the following sub-paragraphs.

2.3.1 Recovery rate

The recovery rate (R, or conversion) is the fraction of the feed water that is recovered (converted) as permeate:

$$R = \frac{Q_p}{Q_f} = [\%]$$

The recovery rate depends mainly on the feed water characteristics. In particular, the higher feed water quality (i.e. the lower the feed solutes concentration), the higher the achievable recovery rate.

2.3.2 Concentration factor

The concentration factor (CF) describes the concentration increase of solutes from the feed to the concentrate:

$$CF = \frac{C_c}{C_f} = [-]$$

In order to quickly assess its value, the solutes passage through the membrane may be neglected (hence $C_p \approx 0$) to obtain the following expression:

$$CF \approx \frac{1}{1-R} = [-]$$

From the above equation, one gets the following values:

Table 2. Concentration factors as a function of the recovery rate

Recovery rate	Concentration factor
40%	1.7
50%	2.0
60%	2.5
75%	4.0
90%	10
95%	20

I.e., with a recovery rate of 75%, we can concentrate the feed water dissolved compounds by ca. 4 times. Note that higher recovery rates result in less concentrate water to dispose of but also in lower permeate purity and in higher membrane fouling tendency.

2.3.3 Water flux

The water flux (J_w) is the extracted flowrate (Q_p) per unit of membrane area (A_m):

$$J_w = \frac{Q_p}{A_m} = [LMH]$$

The water flux determines the overall size of the NF/RO system in terms of membrane area required to achieve the desired degree of separation.

The following applies:

- the water flux depends on the feed water source. In particular, the higher feed water quality (i.e. the lower the feed solutes concentration), the higher the achievable water flux;
- the higher the operating pressure, the higher the achievable water flux (ref. 2.3.4 and 2.3.6);
- the higher the water temperature, the higher the water flux at constant pressure (ref. 2.3.6);
- the higher the recovery rate, the (slightly) lower the water flux.

In addition, the higher the water flux, the more severe the fouling phenomena (ref. 2.3.12). This results in higher cleaning frequency, which implies higher chemical costs and lower membrane lifetime (and, thus, higher membrane replacement costs).

2.3.4 Net driving pressure

The net driving pressure (NDP) is the pressure available to drive the feed water through the membrane, i.e. the applied pump pressure (p_f, feed pressure) minus all the backpressures:

$$NDP = p_f - \Delta p_{geo} - \Delta p_{piping} - \frac{\Delta p_m}{2} - \Delta \pi_{avg} - p_p = [bar]$$

where:

- Δp_{geo} is the pressure loss due to the geodetic head [bar];
- Δp_{piping} is the pressure loss due to the piping [bar];

- Δp_m is the pressure loss across one module or one module cluster [bar];
- $\Delta\pi_{avg}$ is the average osmotic pressure difference between feed and permeate [bar];
- p_p is the permeate pressure [bar].

2.3.5 Osmotic pressure

The osmotic pressure (π) is the pressure on the membrane created by the naturally occurring process of water flowing across a semipermeable membrane from a pure solvent to a solution (ref. 2.1). Usually, it is expressed as a function of the ions concentration (C):

$$\pi = k \times C = [bar]$$

The osmotic pressure coefficient (k) is calculated as follows:

$$k = \frac{R \times T \times \sum_i m_i}{C} = \left[\frac{bar}{1{,}000\ mg\ TDS/L}\right]$$

where:

- R is the universal gas constant, equal to 0.08314 L·bar/(mol·°K);
- T is the design temperature [°K];
- m_i is the molar concentration of the i-th component [mol/L].

Typically, in most RO applications, the osmotic pressure coefficient is equal to 0.7 ÷ 0.9 bar/1,000 mg TDS/L. As first approximation, a value of 0.8 bar/1,000 mg TDS/L may be assumed.

2.3.6 Water permeability (or specific water flux)

The water permeability (K_w) is the capacity of the membrane to be crossed by the liquid phase. It is calculated as the ratio between the water flux (J_w) and the net driving pressure (NDP):

$$K_w = \frac{J_w}{NDP} = \left[\frac{LMH}{bar}\right]$$

It describes the membranes performances and it depends on the membrane characteristics, operating conditions (i.e. temperature, pH, etc.) and fouling phenomena.

Because the membrane permeability varies from its reference (or normalized) value ($K_{w,ref}$) with water temperature:

$$K_{w,T} = K_{w,ref} \times TCF = \left[\frac{LMH}{bar}\right]$$

the temperature correction factor (TCF) shall be introduced:

$$TCF = e^{k_m \times \left(\frac{1}{T_{ref}} - \frac{1}{T}\right)} = [-]$$

where:

- k_m is the membrane material constant. For CD modules using Filmtec membranes, it is equal to 3,020 for T ≤ 25°C and to 2,640 for T < 25°C (DOW, 2020);
- T is the water temperature [°K];
- T_{ref} is the reference water temperature, equal to 298.15°K.

2.3.7 Concentration polarization factor

The concentration polarization factor (β) is used to evaluate the effect of concentration polarization phenomena, i.e. the accumulation of feed solutes at the membrane surface:

$$\beta = \frac{C_m}{C_{fc}} = K_p \times e^{\frac{Q_p}{Q_c}}$$

where:

- C_m is the feed solutes concentration at the membrane surface [mg/L];
- C_{fc} is the average feed-concentrate concentration [mg/L]:

$$C_{fc} = \frac{C_{fm} + C_c}{2} = \left[\frac{mg}{L}\right]$$

- C_{fm} is the membrane feed solutes concentration. Since concentrate recirculation is needed to ensure enough crossflow (ref. 2.3.11), C_{fm} is equal to:

$$C_{fm} = \frac{C_f \times Q_f + C_c \times Q_r}{Q_f + Q_r} = \left[\frac{mg}{L}\right]$$

  where:

  - Q_{fm} is the membrane feed flow [m^3/h]:

$$Q_{fm} = Q_f + Q_r = \left[\frac{m^3}{h}\right]$$

  - Q_r is the concentrate recirculation flow [m^3/h].

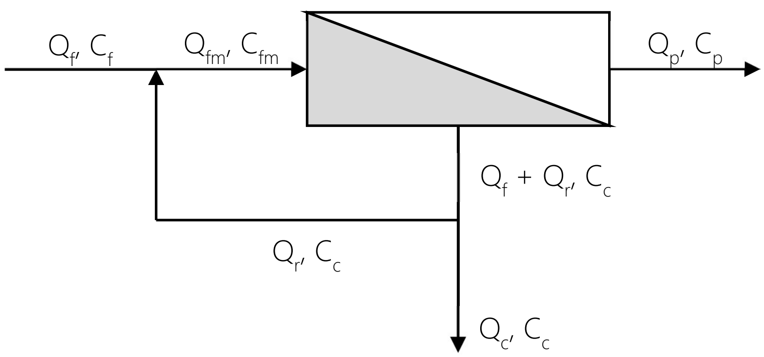

Figure 4. Filtration flow components with concentrate recirculation loop

- K_p is the membrane constant (usually, equal to 0.99).

β values shall be lower than 1.2 in order to minimize fouling phenomena.

2.3.8 Solutes rejection rate

The solutes rejection rate (Rej) is the capacity of the membrane to retain feed solutes:

$$Rej = 1 - \frac{C_p}{\beta \times C_{fc}} \approx 1 - \frac{C_p}{C_{fc}} = [\%]$$

The rejection rate depends both on the influent species properties (molecular weight, polarity, etc.), on the operating conditions (pH, water flux, recovery rate, etc.) and on the NF/RO membrane characteristics.

2.3.9 Solutes passage rate

The solutes passage rate (Pas) is the opposite of the solutes rejection rate, i.e.:

$$Pas = 1 - Rej = [\%]$$

Because it varies from its reference value (Pas_{ref}) with water temperature, the salts temperature correction factor (STCF) shall be introduced:

$$Pas = Pas_{ref} \times \frac{J_{w,ref}}{J_w} \times STCF = [\%]$$

where:

- $J_{w,ref}$ is the water flux at reference conditions [LMH];

- STCF, for sake of simplicity, is usually assumed equal to TCF.

2.3.10 Molecular Weight Cut-Off (MWCO)

MWCO is the molecular weight retained by the membrane expressed in Dalton [Da] with an efficiency of 90%.

DOW Filmtec RO membranes used in CD modules have a MWCO of ca. 100 Da while DOW Filmtec NF membranes used in CD modules have a MWCO of 200 to 400 Da.

2.3.11 Crossflow filtration

In crossflow filtration, the feed water flows tangentially to the membrane surface, the permeate passes through the membrane and the concentrate flows towards its dedicated discharge point. Therefore, crossflow filtration has one influent stream and yields two effluent streams.

The feed flow scours the membrane surface, thus helping to minimize fouling phenomena. Note that a minimum concentrate flow is required to effectively scour the membrane surface.

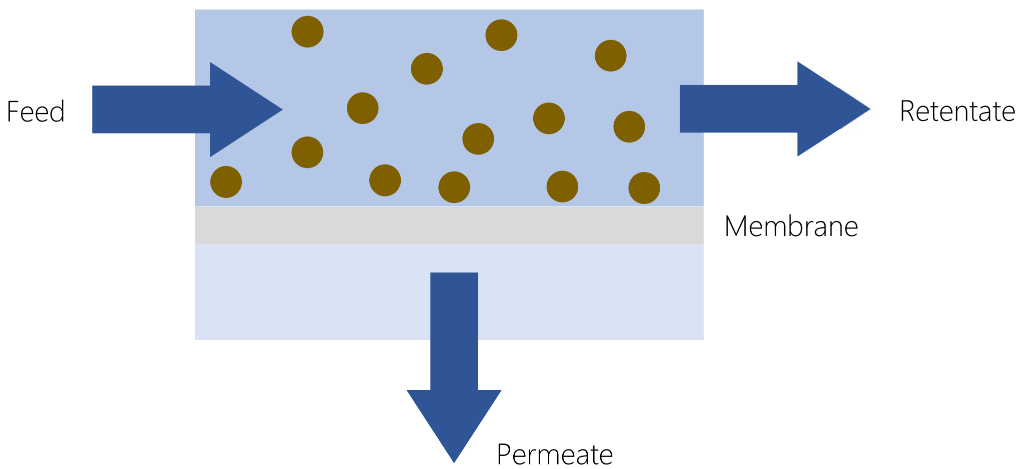

Figure 5. Crossflow filtration schematic

In crossflow configurations, in order to create the backpressure required for permeation, a flow control valve on the concentrate stream is required. Closing said valve results in an increase of the net driving pressure and, thus, of the permeate flowrate and of the recovery rate.

2.3.12 Membrane fouling

Membrane fouling is the deposition, accumulation and/or adsorption of organic and/or inorganic substances on the membrane surface or within membrane pores. It causes the decrease of membrane water permeability over time, which results in lower permeate flowrates and - sometimes - in increased feed solutes passage (the latter is due to concentration polarization phenomena). Also, increased module pressure losses and, thus, higher pumping energy consumption may be experienced.

Fouling may be classified on the basis of the nature of the particles causing it:

- particulate fouling, namely the entrapment of particulate and colloidal matter (e.g. iron flocs, aluminum flocs, clay, silt, colloidal silica, algae, bacteria as such, etc.). This is usually assessed via TSS, turbidity, silt density index (SDI) and/or modified fouling index (MFI) measurements;
- biological fouling (biofouling), namely the growth of a biologically active layer (biofilm) on the membrane surface. This is usually assessed via total bacteria count and assimilable organic carbon (AOC) and extracellular polymeric substances (EPS) measurements;
- organic fouling, namely the adsorption of specific organic compounds (e.g. humic substances, oil and grease, etc.) on the membrane surface;
- inorganic fouling, namely the deposition of dissolved iron Fe(II) and manganese Mn(II);
- scaling, namely the precipitation and deposition of sparingly soluble salts (e.g. calcium-based salts, sulphate-based salts, reactive silica, etc.)

or on the basis of its cleanability:

- physically reversible, amendable with physical cleaning interventions;
- chemically reversible, amendable with chemical cleaning interventions;
- irreversible, not amendable. Note that this determines the membrane lifetime.

Fouling may manifest in three ways:

- feed channels clogging, with higher pressure loss across the module. This results in:
    - lower net driving pressure;
    - damages to membrane cushions due to compression, adsorption and/or membrane drying.

Note that local feed channels clogging phenomena may occur as well, which result in uneven feed flow distribution. This may result in locally high water flux and concentration polarization and, thus, membrane surface fouling;

- membrane hydraulic resistance increase due to fouling directly on the membrane surface. This results in higher feed pressure to maintain the target capacity or in lower capacity whenever the feed pressure is not increased and thus in:
  - possibly higher permeate solutes concentration because of concentration polarization phenomena due to the fouling layer, i.e. the membrane "sees" higher solutes concentrations and thus - despite the actual rejection rate is the same - the apparent rejection rate decreases;
  - increased cleaning frequency, which may result in shorter membrane lifetime.

Upstream CD modules in a cluster (cluster-lead) are generally most affected by particulate, inorganic and organic fouling, while downstream CD modules in a cluster (cluster-end) are generally most affected by scaling. One exception to this is biofouling, which may occur anywhere in the CD modules cluster where conditions favor biofilm growth.

Fouling influencing factors are:

- influent water/wastewater characteristics (ref. 3.1) and their changes;
- membrane characteristics;
- module characteristics (feed channels size, feed channels shape, etc.);
- membrane operating parameters (ref. 8.3.1).

In order to control fouling phenomena, the following shall be evaluated:

- optimal influent water/wastewater pre-treatment design and operation. In fact, feed water pre-treatment units upstream of the membrane filtration unit have the task to reduce membrane fouling phenomena as much as possible;
- optimal membrane filtration unit design and operation:
  - equipment selection (ref. 6.5, 6.6, 6.7, 6.8 and 6.10);
  - process control instrumentation (ref. 6.9) and automation (6.12);
  - operating feed pressure, recovery rate and crossflow (ref. 8.3.1);

- physical (flushing) and chemical cleaning interventions. In particular, flushing interventions following system standby and shutdown (ref. 8.6) as well as periodic cleaning interventions (ref. 9) help in preventing and amending fouling phenomena.

3. Feed water, pre- and post-treatments

Feed water quality and its fouling potential have a significant impact on the design of a NF/RO membrane filtration unit. In fact, selection of the membrane type and of the design water flux as well as the achievable recovery rate and solutes rejection rate are all influenced by the feed water quality.

Within this chapter, the main feed water characteristics and the typical pre- and post-treatments units will be briefly discussed.

3.1 Feed water characteristics

The importance of a complete and accurate feed water analysis cannot be stressed enough since it is critical in determining the required pre-treatments units (if any) and the NF/RO membrane filtration unit design. In fact, as already stated, the performances and the successful operation of a NF/RO membrane filtration unit depend directly on the feed water quality. As discussed in paragraph 2.3.12, the nature of feed water solutes influences membrane performances by promoting membrane fouling and/or degradation phenomena. Table 3 lists feed water and concentrate quality guidelines that must be ensured in this regard.

Table 3. Required feed and concentrate characterization

Parameter	Unit	Value	Location
Temperature	°C	< 45	Feed, concentrate
pH	-	4 to 11	Feed, concentrate
Colloids	SDI_{15}	< 15	Feed
Total Suspended Solids (TSS)	mg/L	30	Feed
Chemical Oxygen Demand (COD)	mg/L	15,000	Feed
Total Dissolved Solids (TDS)	mg/L	130,000	Concentrate
Total iron	mg/L	< 0.05	Feed
Total manganese	mg/L	< 0.05	Feed
Aluminum	mg/L	< 0.05	Feed
Calcium carbonate	LSI	N. A. [1]	Concentrate
Saturation indexes	SI	N. A. [1]	Concentrate
Silica (as SiO_2)	mg/L	N. A. [1]	Concentrate

Parameter	Unit	Value	Location
Hydrogen sulfide	mg/L	< 0.10	Feed
Free chlorine	mg/L	< 0.02	Feed
Fat, Oil and Grease (FOG)	mg/L	< 0.10	Feed
Hydrocarbons	mg/L	Nil	Feed
Cationic polymers	mg/L	Nil	Feed
Solvents, glues and adhesives	mg/L	Nil	Feed
Total bacteria count	CFU/mL	< 1,000	Concentrate

[1] Silica limit concentration depends on the selected anti-scalant. However, it is recommended to avoid exceeding 80 to 90% of the saturation limit after anti-scalant dosing.

The following paragraphs detail the most relevant feed water constituents that affect the performance of NF/RO membranes.

3.1.1 Temperature

Water temperature affects:

- the water viscosity and, thus, the membrane permeability (ref. 2.3.6). In particular, the latter increases by ca. 3% per degree Celsius thanks to the water viscosity decrease. If a NF/RO system is operated at constant pressure, this results in a water flux increase of ca. 3% per degree Celsius;
- the solutes rejection rate and, thus, the permeate quality (ref. 2.3.9). In particular, since NF/RO systems are usually operated at constant water flux, the permeate quality improves by ca. 3% per degree Celsius;
- the required feed pressure. In particular, the higher the temperature, the higher the permeability (and, thus, the lower the required net driving pressure, ref. 2.3.6) and the higher the osmotic pressure. These two are opposing contributions on the feed pressure (ref. 2.3.4). In general, up to ca. 30°C, the higher the temperature, the lower the feed pressure;
- the solubility of sparingly soluble salts. In general, the higher the temperature, the more soluble the sparingly soluble salts and, thus, the lower scaling phenomena occurrence.

If needed, water temperature may be changed via natural heat dissipation, forced heat exchange, etc. Note that lower and upper water temperature limits exist in order to avoid damaging NF/RO membranes (ref. Table 3).

3.1.2 pH

pH affects:

- the stability of NF/RO membranes. In particular, the acceptable operating pH range is a function of water temperature, with higher temperatures requiring narrower pH ranges (ref. Table 7);
- the membrane rejection rate. For most species, it is maximum at pH values between 7.0 and 7.5;
- the solubility of some sparingly soluble salts and, thus, scaling phenomena occurrence;
- the effectiveness of coagulation and flocculation pre-treatment units.

If needed, pH may be adjusted via chemicals dosing (ref. 3.2.4).

3.1.3 Colloids

The higher the colloids concentration, the higher the particulate and organic fouling rate of the membrane (ref. 2.3.12), which results in sensibly lower water flux (and, thus, in sensibly lower productivity) and - sometimes - in lower solutes rejection rate. Unlike suspended solids, colloids are responsible of severe membrane permeability decline due to the formation of a thick, mixed foulants layer with very low water permeability.

Colloids are usually determined via SDI and/or MFI measurements. Note that there is no direct correlation of turbidity to these indexes, other than high turbidity usually means high SDI and MFI (while the opposite is not always true).

Colloids can be reduced via coagulation and flocculation (ref. 3.2.12) and solids-liquid separation units (ref. 3.2.9, 3.2.10, 3.2.11 and 3.2.13).

3.1.4 Total suspended solids (TSS)

The higher the total suspended solids:

- the higher the particulate and organic fouling rate of the membrane (ref. 2.3.12), which results in lower water flux (and, thus, lower productivity) and - sometimes - in lower solutes rejection rate;

- the higher the clogging rate of the membrane (ref. 2.3.12), which results in higher module pressure drop.

TSS can be also measured in terms of turbidity (NTU, Nephelometric Turbidity Units) and can be reduced via coagulation and flocculation (ref. 3.2.12) and solids-liquid separation units (ref. 3.2.9, 3.2.10, 3.2.11 and 3.2.13). Note that TSS and turbidity are aggregate parameters, thus similar values may exhibit very different fouling and clogging behaviors. Therefore, the feed water maximum admissible TSS content (ref. Table 3) varies case-by-case and shall be evaluated via pilot tests.

3.1.5 Chemical oxygen demand (COD)

The higher the chemical oxygen demand, the higher the organic fouling rate (ref. 2.3.12) and, thus, the lower the water flux and the productivity.

Sometimes, in order to measure the feed water organic matter content, also total organic carbon (TOC) may be used. COD/TOC can be reduced via coagulation and flocculation (ref. 3.2.12) and solids-liquid separation units (ref. 3.2.9, 3.2.10, 3.2.11 and 3.2.13), chemical oxidation treatment units (ref. 3.2.15) and/or biological treatment units (ref. 3.2.16). Again, note that COD/TOC are aggregate parameters, thus similar values may exhibit very different fouling behaviors. Therefore, the feed water maximum admissible COD/TOC content (ref. Table 3) varies case-by-case and shall be evaluated via pilot tests.

3.1.6 Total dissolved solids (TDS)

The higher the total dissolved solids, the higher the feed osmotic pressure and, thus, the feed pressure required for a given water flux, i.e. for a given productivity. Generally, depending on their composition, the higher the TDS content, the higher the scaling tendency.

Of particular interest are sparingly soluble salts, namely salts that may precipitate whenever the concentration product of salt-forming ions exceeds its solubility product, which is function of the water temperature and of the ionic strength of the solution.

3.1.7 Iron, manganese and aluminum

The higher the iron, manganese and/or aluminum content:

- the higher the particulate and inorganic fouling rate (ref. 2.3.12) and, thus, the higher the module pressure drop and the lower the productivity;
- the higher the risk of oxidization of the membrane. In fact, iron and manganese are able to catalyze the oxidation of NF/RO membranes, resulting in damage to the membrane itself and - thus - in lower rejection rate and higher productivity.

Note that, by dropping the pH and reducing the oxygen concentration (namely, by keeping the NF/RO membrane filtration unit in anaerobic conditions), higher concentrations of soluble iron can be tolerated. In fact, iron in its ferrous form doesn't pose any particular problem.

Iron and manganese can be removed e.g. via chemical precipitation (ref. 3.2.15) media filtration (ref. 3.2.11) or micro-/ultra-filtration (ref. 3.2.13) or precipitative softening (ref. 3.2.6) followed by clarification (ref. 3.2.9).

Whenever aluminum comes from alum dosing, this is generally addressed by operating at appropriate pH (i.e. 7 to 9) and/or by replacing alum with another coagulant. Aluminum can be removed e.g. via precipitative softening (ref. 3.2.6) or chemical precipitation (ref. 3.2.6 and 3.2.15).

3.1.8 Calcium carbonate, LSI and SDSI

Calcium carbonate scaling potential is expressed via the Langelier saturation index (LSI), whenever the TDS content is up to 5,000 mg/L, or Stiff-Davis saturation index, whenever the TDS content is higher than 5,000 mg/L.

The more positive the LSI or the SDSI value, the higher the scaling potential, the lower the productivity and the lower the solutes rejection rate due to concentration polarization.

Since it is desirable to keep the concentrate LSI or SDSI value near zero in order to minimize calcium carbonate scaling, pH adjustment via acid dosing is a common strategy (ref. 3.2.4). Alternatively, anti-scalants may be used to allow operation at higher LSI or SDSI values (ref. 3.2.5). Note that, even with anti-scalant dosing, the LSI is required to be lower than 1.8.

Calcium may also be removed via precipitative softening (ref. 3.2.6).

Table 4. Recommended pre-treatments against different inorganic compounds. If they are not sufficient, NF/RO membrane filtration unit recovery rate reduction is required

Compound	Pre-treatment
Calcium carbonate	pH adjustment, anti-scalant dosing, lime softening
Calcium phosphate	pH adjustment, anti-scalant dosing, lime softening
Calcium sulphate	Anti-scalant dosing, lime softening
Barium sulphate	Anti-scalant dosing, lime softening
Strontium sulphate	Anti-scalant dosing, lime softening
Calcium fluoride	Anti-scalant dosing, lime softening
Silica	Anti-scalant dosing, lime softening, pH adjustment, temperature increase
Iron	Precipitation and filtration, lime softening
Aluminum	Precipitation and filtration, lime softening

3.1.9 Other saturation indexes

Besides calcium carbonate, there are other calcium-based compounds that cause scaling, i.e. calcium sulphate, calcium phosphate and calcium fluoride. Since LSI and SDSI are not helpful in predicting scaling form these three compounds, calculation of the ionic products and of the solubility constants is required. In addition to the above, calcium also affects the deposition of natural organic matter (NOM) on the membrane. Thus, the higher the calcium concentration, the faster the water flux decreases.

In addition, barium and strontium form sulphate scales that are not readily soluble. Again, calculation of the ionic products and of the solubility constants is required.

Anti-scalants dosing (ref. 3.2.5) and/or precipitative softening units (ref. 3.2.6) help to control calcium-based compounds as well as barium sulphate and strontium sulphate scaling.

3.1.10 Silica

Silica can cause both membrane scaling (reactive silica) and particulate fouling (colloidal and suspended silica), thus increasing the module pressure drop, lowering the productivity and - eventually - decreasing the solutes rejection rate.

In water treatment applications, silica is usually expressed as SiO_2 but, in reality, more than 22 phases of silica have been identified. Therefore, both the chemistry of silica and the scaling and fouling mechanisms with silica are complex.

Silica speciation and concentration depend on water qualitative characteristics and affect silica scaling and fouling phenomena. In particular, the speciation of silica mainly depends on pH and, at the pH values lower than 8 (common to most NF/RO membrane filtration units), the form of silica present is primarily silicic acid. Thus, silica scaling calculations are usually performed considering silicic acid only, whose solubility depends mainly on water temperature. Once the silicic acid concentration exceeds its saturation value, a soft, gel-like substance appears (also called amorphous silica or colloidal silica). The solubility of amorphous silica depends mainly on pH and it is relatively constant below pH values of 8.5 to 9.0, while it rapidly increases at higher pH values.

The presence of hardness, aluminum, iron and manganese may greatly reduce the solubility of silica, forming silicate compounds which precipitate at elevated temperature and pH values. Therefore, it is normally accepted to operate at lower pH values in presence of amorphous silica.

In order to control silica fouling and scaling phenomena, it is possible to inhibit/disperse silica through anti-scalants/dispersants dosing (ref. 3.2.5) and to remove silica via lime softening (ref. 3.2.6), eventually with magnesium chloride or magnesium hydroxide addition.

3.1.11 Hydrogen sulphide

Hydrogen sulphide reacts with oxygen, chlorine and metals (such as iron and manganese) to yield - respectively - solid elemental sulphur and insoluble metal sulphides. Fouling with elemental sulphur and/or metallic sulphides causes a decrease in water flux and in solutes rejection rate.

To deal with hydrogen sulphide, two different approach are possible:

- keeping the feed water at a pH values lower than 5 and free of oxygen or other oxidizers. In this case, it is necessary to scrub the permeate and the concentrate of the hydrogen sulphide gas passing through the NF/RO membrane filtration unit in order to protect from corrosion and/or sulphur precipitation any downstream treatment units;

- oxidizing hydrogen sulphide via aeration or chlorine, potassium permanganate or peroxide dosing (ref. 3.2.15) and removing the insoluble elemental sulphur and metal oxides via media filtration (ref. 3.2.11) or micro-/ultra-filtration (ref. 3.2.13).

3.1.12 Free chlorine

Polyamide composite membranes are very sensitive to free chlorine, with tolerance levels less than 0.1 mg/L. Continuous exposure damages irreversibly the membrane and, thus, shall be avoided. This phenomenon is exacerbated at high pH values and in presence of transition metals (e.g. iron and manganese) that catalyze the membrane oxidation. In particular, polyamide composite membranes exposed to chlorine oxidation show an initial decrease in water flux followed by an increase in water flux and s decrease in solutes rejection rate.

Free chlorine is usually removed via sodium metabisulphite dosing (ref. 3.2.15).

3.1.13 Fat, oil and grease

Even low concentration of fat, oil and grease (FOG) can dramatically decrease the membrane water permeability.

FOG are usually removed via coagulation and flocculation (ref. 3.2.12) and media filtration (ref. 3.2.11), micro-/ultra-filtration (ref. 3.2.13) or dissolved air flotation (ref. 3.2.10).

3.1.14 Microbes

Microorganisms can be regarded as colloids with the ability to reproduce and form a biofilm under favorable conditions, which are the ones found on NF/RO membranes where concentration polarization phenomena ensure high contents of organics and nutrients.

Microbial fouling results in lower membrane water flux (and, thus, productivity), higher operating pressure, higher module pressure drop and - in case of uneven growth of colonies, a phenomenon that leads to localized areas of lower flow velocity wherein scaling phenomena can occur - lower solutes rejection rate.

Microbial fouling is best dealt with before the biofilm becomes mature since it protects the microorganisms from the action of shear forces and biocidal chemicals. Cleaning interventions (ref. 9) are usually sufficient to amend biofouling phenomena in plate-and-frame NF/RO membrane filtration units since they are usually more frequent than in spiral-wound NF/RO membrane filtration units and they are more effective thanks to the enhanced hydraulic regime.

In addition, pre-treatment units such as lime softening (ref. 3.2.6), media filtration (ref. 3.2.11), micro- and ultrafiltration (ref. 3.2.13) and biological reactors followed by clarification or dissolved air flotation (ref. 3.2.16, 3.2.9 and 3.2.10) help in reducing the microorganisms load to the membranes, but they do not help once the biofilm is formed.

3.1.15 Other compounds

Oxidizers (e.g. ozone, hydrogen peroxide, potassium permanganate, etc.) degrade the crosslinking of polyamide thin-film composite NF/RO membranes. In addition, some organic compounds can result in swelling or dissolution of the polysulfone membrane support layer, e.g.:

- solvents such as dimethyl formamide, dimethyl acetamide, n-methyl pyrrolidone, dimethyl sulfoxide, etc.;
- aromatic hydrocarbons such as benzene, toluene, xylene, phenol, diesel fuel and gasoline;
- ketones, aldehydes, esters and strong ethers.

Only low-molecular solvents, i.e. alcohols such as isopropanol and smaller molecules, are acceptable.

Also, overdosing of high molecular-weight cationic polymers used for coagulation (ref. 3.2.12) may result in irreversible fouling phenomena.

3.2Pre-treatments

Preserving membrane integrity through proper pre-treatment of the feed water is essential to minimize fouling phenomena and to maximize the efficiency and the longevity of the NF/RO membrane filtration unit.

The pre-treatments layout depends on the feed water source, on the application and on any local requirement.

In general, NF/RO membrane filtration units with inadequate pre-treatments layout show a very rapid decline of performances that usually cannot be fully recovered even by cleaning the membranes, leading to frequent and harsh cleaning interventions and - thus - to short membranes lifetime.

The aim of this paragraph is to provide a generic understanding of the role of pre-treatment units. For further information, literature and experienced designer shall be consulted.

3.2.1 Scaling potential reduction

In general, the following approach shall be followed:

- check the scaling potential of the water;
- if needed (LSI > 0 or SDSI > 0), add sulfuric acid or - in case of high sulphate scaling potential - hydrochloric acid to lower the pH to 6.3 ÷ 6.5;
- in case of calcium phosphate scaling potential (typical of wastewater applications), add ferric chloride to remove the phosphates;
- if needed, add anti-scalants/dispersants to reach the target recovery rate. To calculate the appropriate type and dosage, an anti-scalant/dispersant supplier's software shall be used. By defining the feed water characteristics, the operating water flux and recovery rate and the membrane solutes rejection rate, an anti-scalant product that ensures saturation indexes lower than 80 to 90% shall be chosen;
- if needed, pre-treat the feed water (e.g. via precipitative softening). For more details, refer to the following paragraphs;
- if needed, lower the solutes recovery rate or choose another technology.

3.2.2 Fouling and clogging potential reduction

If the concentrate TSS, COD and/or FOG contents are higher than the values in Table 3, physico-chemical (i.e. coagulation and flocculation, chemical oxidation, clarification, DAF, media filtration, micro-/ultra-filtration) and/or biological pre-treatment is needed to protect both the subsequent cartridge filtration and NF/RO membrane filtration units. For more details, refer to the following paragraphs.

In general, media filters are used in case the feed TSS content is higher than 30 mg/L in order to reduce the chemical cleaning frequency to amend fouling phenomena. In case the feed TSS are higher than 500 mg/L, then the adoption of a coagulation, flocculation, clarification (with or without lamella) and media filtration shall be evaluated.

Typically, biocides are not used with plate-and-frame modules because they are easier to clean than spiral-wound elements (ref. 3.1.14).

3.2.3 Typical pre-treatments layout

The following pre-treatments layout may be used:

- if needed, TSS, particulate COD and/or FOG reduction via coagulation, flocculation, DAF or clarification (with or without lamella) and media filtration or micro-/ultra-filtration;
- if needed, feed water heating via immersed heaters or heat exchangers;
- if needed, COD, nitrogen and emulsified FOG reduction via biological treatment followed by clarification or micro-/ultra-filtration or coagulation, flocculation and DAF;
- if needed, hardness and/or silica and/or heavy metals reduction via precipitation or decarbonation or softening (with lime or caustic soda and, if needed, soda ash dosing), coagulation and flocculation, lamella clarification and media filtration;
- if needed, anti-scalant/dispersant dosing. It is recommended to always include provisions for anti-scalant/dispersant dosing;
- cartridge filtration.

Careful examination of historical feed water data (if any) and/or pilot testing allow to properly design the required pre-treatments, whose sequencing is always site specific.

3.2.4 pH adjustment

pH shall be within the required range (ref. Table 3). If not, it shall be adjusted via strong alkaline (e.g. caustic soda) or strong acid (e.g. hydrochloric acid or sulphuric acid) dosing.

In addition, strong acid dosing is used in case of calcium carbonate scaling and/or calcium phosphate potential so that LSI or SDSI within the concentrate are negative or, in case anti-scalants/ dispersants are used, are lower than - respectively - 1.8 and 1.0.

In general, food-grade quality alkaline and acids shall be used to avoid impurities that could foul and/or damage the NF/RO membranes.

Despite sulphuric acid is easier to handle and often easier to buy than hydrochloric acid, its use releases sulphate into the feed water, increasing the sulphate scaling potential. Thus, the acid to be used (hydrochloric or sulphuric acid) is to be evaluated by running an anti-scalant/dispersant supplier's software.

3.2.5 Anti-scalant/dispersant dosing

Anti-scalants (or threshold scale inhibitors) are typically proprietary organic synthetic polymers (such as polyacrylates, organo-phosphonates, etc.), which react with the surface of ion clusters in a way to prevent their growth to form crystal scales harmful to NF/RO membranes at significant levels of supersaturation. They allow to control carbonate, sulphate and calcium fluoride scaling phenomena and they replace or are used together with pH adjustment via acid dosing (ref. 3.2.4) to control calcium carbonate scaling phenomena.

Dispersants (or anti-foulants) are typically organic synthetic polymers (such as polyacrylates, organo-phosphonates, etc.) which stabilize supersaturated silica solutions. They also allow to control iron, manganese, aluminum, silica, silt and/or clay fouling phenomena.

Today, proprietary copolymers that act both as anti-scalant and dispersant are available, targeting multiple sparingly soluble salt and colloids.

Anti-scalants/dispersants are completely rejected by NF/RO membranes and, therefore, they don't represent a concern for the permeate quality.

Note that precipitation reactions may occur in case anionic anti-scalants/dispersants are used together with cationic coagulants and flocculants, such as multivalent cations (e.g. iron and aluminum) and cationic polyelectrolytes. The resulting precipitation products are very difficult to clean off from NF/RO membranes.

Optimal anti-scalants/dispersants dosing and maximum allowable scaling and fouling compounds saturation are determined by using the supplier's proprietary software package.

Also, anti-scalants/dispersants must be compatible with the NF/RO membrane being used, which otherwise could be irreversibly fouled or damaged. The chemical supplier shall ensure said compatibility.

Anti-scalants/dispersant shall be properly mixed with feed water before entering the NF/RO membrane filtration unit. Thus, their injection point is usually located upstream of the cartridge filters so that enough residence time and turbulence is provided. In case of feed water acid pH adjustment, the acid shall be properly mixed with feed water before it reaches the anti-scalant/dispersant injection point, otherwise concentrated pockets of low pH acid-water mixture may greatly decrease the efficacy of the anti-scalant/dispersant. In addition, in case of feed dechlorination, the dechlorination chemical shall be properly mixed with feed water before it reaches the anti-scalant/dispersant injection point, otherwise free chlorine may decrease the efficacy of some anti-scalant/dispersant products.

To achieve a reasonable stroking frequency of the dosing pump (i.e. once every 5 seconds), dilution of the anti-scalant/dispersant product may be required. Make-up service water shall be without hardness and free chlorine. The anti-scalant/dispersant feed flow is usually controlled based on the feed flow rate to the NF/RO membrane filtration unit. Anti-scalants/dispersants pre-made solutions shall be stored within the dosing tank for maximum 7 to 10 d in order to keep their quality.

3.2.6 Precipitative softening

Precipitative softening is used to reduce carbonate hardness (via lime or caustic soda only dosing) or total hardness (via lime or caustic soda plus soda ash dosing). In addition, whenever also soda ash is used and if enough magnesium is precipitated (otherwise, sodium aluminate or magnesium oxide must be added as well), silica can be reduced. Other substances that can be reduced as well are iron, manganese, aluminum, barium, strontium, TSS/turbidity and COD/organics.

Precipitative softening is usually preceded by coagulation with ferric chloride and flocculation with anionic or non-ionic polymer (ref. 3.2.12) and it is followed by lamella settling (ref. 3.2.9), media filtration (ref. 3.2.11) and pH adjustment via acid dosing (ref. 3.2.4). The resulting sludge from the lamella settling is partly recirculated to the reaction chamber in order to promote the chemical precipitation reactions.

Precipitative softening may be performed cold, warm (50 to 60°C) or hot (110 to 115°C). In general, the higher the temperature, the faster the precipitation reactions (with very cold waters, reactions may complete even after the solids-liquid separation units if the system is not properly designed), the higher the removal efficiency and - usually - the higher the operating costs (i.e. heating is performed via steam usage).

3.2.7 Chemical oxidation

Chemical oxidation of iron, manganese and/or hydrogen sulphide is typically performed via air injection and/or sodium hypochlorite (NaOCl) or potassium permanganate ($KMnO_4$) dosing. The resulting iron and manganese hydroxides and elemental sulphur may be removed via media filtration (ref. 3.2.11) or micro-/ultra-filtration (ref. 3.2.13).

3.2.8 Screening

Any raw water screening depends on the application and on the selected pre-treatments layout. E.g. in case of media filtration (ref. 3.2.11), 0.5 to 6 mm screening is usually sufficient while, in case of micro-/ultra-filtration (ref. 3.2.13), screening below 100 to 300 µm may be required and, in case of biological treatment (ref. 3.2.16), 1 to 6 mm screening is often needed. Thus, the design and the rating of screens is specified by the pre-treatment units' manufacturers.

3.2.9 Clarification (or settling)

Clarifiers (or settlers) are used to remove large suspended solids and, together with coagulation and flocculation (ref. 3.2.12), colloids. Clarified effluents may be not low enough in turbidity and suspended solids to be fed to the NF/RO unit and media filtration (ref. 3.2.11) or micro-/ultra-filtration (ref. 3.2.13) may be required. Still, clarification is a good bulk removal technology for reducing the majority of suspended solids and turbidity.

Three types of clarifiers are available:

- conventional clarifiers, typically used in wastewater applications due to the lower sensitivity to influent flowrates fluctuations;

- lamella clarifiers, offering the advantage of the lowest footprint at the price of being more sensitive to influent flowrates variations;
- solids-contact clarifiers, offering reduced chemicals demand and often involving proprietary designs.

3.2.10 Dissolved air flotation (DAF)

Dissolved air flotation is more effective than clarification when it comes to remove suspended solids that buoyant and, thus, may not settle well (e.g. organic suspended solids, FOG, algae, etc.).

This process involves the saturation under pressure of a fraction of raw water with air, the injection of air saturated water into the recirculated fraction of treated raw water with subsequent release of air microbubbles, the attachment of particles to the air microbubbles and their rise to the surface and the mechanical collection of floating solids (e.g. via skimmers) and their discharge to the sludge treatment line.

3.2.11 Media filtration

Media filters are used to remove suspended solids and colloids. The filtrate quality depends on the influent particles, on the filtering media and on operational parameters (e.g. temperature, pH, hydraulic loading rate, etc.). In order to increase the removal efficiency, coagulation and flocculation (ref. 3.2.12, inline or within dedicated tanks) may be used to condition the feed water.

Usually, media filters are filled with two (sand and anthracite) or more (usually, sand, anthracite and garnet) different types of media, hence their names (dual- and multi-media filters). Multi-media filters offer finer filtration than dual-media ones thanks to the smaller size of the garnet media particles.

Graduation of the filtration bed from coarse to fine media is achieved by decreasing the media particles dimension and by increasing the media particles density from top to bottom. This allows to maximize the filtration time between two subsequent backwash interventions since larger particles are removed within the top layers, while smaller particles are subsequently removed through the bottom layers (if any).

Many media filter configurations are used in water and wastewater treatment applications. In particular, as a NF/RO membrane filtration unit pre-treatment, down-flow gravity or pressure filters media filters are usually selected.

During operation, the feed water enters at the top of the media filter, percolates through the filter bed and is drawn off through the collector system at the bottom of the media filter. Over time, the pressure losses through the filtration bed increases due to particles accumulation and, thus, a backwash intervention with raw water or filtrate is required to remove said particles. The latter possibility requires a filtrate storage tank and a dedicated pumping station. Whenever difficult-to-backwash influent solids are present and/or coagulants/flocculants are used, air scour during backwash is recommended to increase the backwash efficiency. Before a backwashed media filter is placed back into service, it must be rinsed to drain until the so called first filtrate meets the required qualitative characteristics.

Note that effective backwash requires that the filtering media is fluidized, thus sufficient filtration bed expansion shall be ensured. The required backwash flow rate to do so depends on the water viscosity and, thus, on the water temperature.

3.2.12 Coagulation and flocculation

The use of coagulation and flocculation as pre-treatments to NF/RO membrane filtration units must be approached with caution. Properly designed and operated, these chemicals are very effective in improving the particles settleability and filterability by increasing their size. On the other hand, when overdosed and/or dosed at a non-optimal pH values, their use can cause more problems than it solves. E.g. coagulants overdosing may result in changing the particles net negative charge to a net positive charge, which results in particles repelling each other.

Jar testing and/or pilot plants operation are essential to determine the proper coagulation and flocculation process design (i.e. pH, mixing intensity, flocs hydraulic retention time, etc.) and the dosage of chemicals. In full-scale plants, streaming current detectors or turbidity monitors are recommended to control the chemicals dosing.

Coagulants are used to neutralize the negative surface charge of the colloids and suspended solids in water so that they can agglomerate (destabilization) and, if metal salts are used, to entrap them into the freshly formed, heavier hydroxide micro-flocs. Coagulants commonly used in water and wastewater treatments applications are:

- iron coagulants, such as ferric chloride and ferric sulphate;
- aluminum coagulants, such as polyaluminium chloride and aluminum sulphate. Despite being effective, their use is not recommended because of possible NF/RO membrane fouling phenomena due to residual aluminum. Note that also iron coagulants could cause NF/RO membrane fouling phenomena but iron compounds are easier to remove via upstream solids-liquid separation units (due to the lower iron compounds solubility) and to dissolve during chemical cleaning interventions than aluminum compounds;
- organic compounds such as low-molecular weight, highly-charged cationic polymers. Since cationic polymers have a natural affinity for the negatively-charged polyamide thin-film composite membranes, they may cause membrane fouling (sometimes irreversible). Therefore, it is recommended to avoid their use. In addition, cationic polymers can co-precipitate with anionic anti-scalants, thus fouling the NF/RO membrane further by forming insoluble organic compounds that are difficult to clean.

Note that, during coagulation, metal salts hydrolyze, consuming alkalinity and thus reducing the pH.

Coagulation is a very rapid process, usually requiring just a few second to complete. However, effective coagulation needs intensive mixing to bring the coagulant in contact with the negatively-charged particles to be neutralized in such a short time.

Flocculants are used to conglomerate the charge-neutralized particles into larger ones, called flocs. Flocculants used in water and wastewater treatments applications are very high-molecular weight organic compounds that may be positively charged (cationic polymers), negatively charged (anionic polymers) or close to neutrality (non-ionic polymers). Usually, anionic polymers are the most effective ones, despite the lower weight when compared to non-ionic polymers. Again, overdosing may cause membrane NF/RO fouling phenomena, but anionic and non-ionic polymers can usually be removed whenever addressed in a timely manner.

The so formed flocs are then removed via solids-liquid separation units such as lamella clarification (ref. 3.2.9) and media filtration (ref. 3.2.11) or micro-/ultra-filtration (ref. 3.2.13) and/or DAF (ref. 3.2.10) in order to avoid that downstream NF/RO membranes could be fouled.

Flocculation requires low-intensity mixing to bring the flocculant in contact with the particles to avoid breaking the flocs and, thus, it takes more time than coagulation to complete (usually, from a few minutes to half an hour).

Inline coagulation and flocculation (e.g. by using an in-line static mixer or by injecting the chemical within the suction side of a booster pump) may be used in case of raw waters containing low concentrations of suspended matter. Otherwise, dedicated coagulation and flocculation chambers or solids-contact type clarifiers are to be used.

3.2.13 Micro- and ultra-filtration

Micro- (MF) and ultra-filtration (UF) membranes removes turbidity, suspended solids, bacteria and - in case of UF - also some dissolved organic compounds depending on their molecular mass and on the membrane pore size. Hence, low SDI/MFI values can be achieved with a well-designed and properly maintained MF/UF unit.

MF/UF units could be either pressure or vacuum driven. Pressurized membrane filtration systems consists of encapsulated membrane modules and water is driven through the membrane by the feed pressure delivered by feed pumps. In vacuum membrane filtration system, membrane bundles, that form membrane modules, are immersed within dedicated tanks and water is driven through the membranes by negative pressure (suction) delivered by permeate pumps.

MF/UF membrane backwash plays a similar role as filtration media backwash unit used in media filters. Among the main differences is the use chemicals, mainly chlorine as sodium hypochlorite, in chemical enhanced backwash (CEB) interventions.

MF/UF filtrate quality is but little affected by feed water quality variations. However, with increased feed water suspended solids and colloids concentration, the membrane filtration system has to operate at lower water flux and more frequent backwash and CEB interventions shall be performed, thus lowering both the permeate flowrate and the unit recovery rate. Thus, in this case, coagulation and flocculation (ref. 3.2.12), clarification (ref. 3.2.9) and/or DAF (ref. 3.2.10) may be required upstream of the MF/UF filtration unit. Also, in case of high organics and solids contents, MF/UF units may be combined with suspended biomass biological treatment units (ref. 3.2.16) to have the so-called membrane biological reactors (MBRs), if in anoxic/aerobic conditions, or anaerobic membrane biological reactors (AnMBRs), if in anaerobic conditions.

3.2.14 Cartridge filtration

Cartridge filtration protects the downstream installed equipment, namely the NF/RO membranes from fouling and the high-pressure pumps from erosive material originating from pre-treatments malfunctioning (e.g. media filters breakthrough). Thus, cartridge filters are not intended for bulk removal of suspended solids and organics. Also, whenever dedicated CIP pumps are provided for NF/RO membrane filtration unit cleaning, cartridge filters shall be installed on the CIP feed line. Note that, during chemical cleaning interventions, cartridge filters should be changed out with every new cleaning solution.

Cartridge filtration with an absolute pore size of 10 µm or less is always required. If there is a risk of colloidal silica fouling or piston high-pressure pumps are used (ref. 6.5), cartridge filtration with an absolute pore size of 5 µm or less is recommended.

Cartridge filters shall be made of a synthetic, non-degradable material (e.g. polypropylene) and they are to be installed within dedicated steel pressure vessels which are equipped with pressure gauges to indicate the differential pressure and, thus, the fouling extent of the cartridge filters. Once cartridge filters are fouled, they are to be replaced with new ones.

3.2.15 Oxidation

Oxidation via aeration is performed to oxidize some inorganic compounds (e.g. iron) while oxidation via chemicals dosing (such as sodium hypochlorite, chlorine dioxide, hydrogen peroxide, potassium permanganate, ozone, etc.) is performed to oxidize organic and inorganic compounds (e.g. iron and manganese), to remove color and/or to control microbial growth.

In general, food-grade quality chemicals shall be used to avoid impurities that could foul and/or damage the NF/RO membranes.

It is fundamental to protect NF/RO membranes from chemical oxidants, e.g. by dosing sodium metabisulphite to neutralize any residual free chlorine. Whenever oxidation pre-treatments are in place, chlorine analyzers and/or redox potential meters are used in practice to monitor the presence of chlorine and other oxidants and ensure that appropriate operating strategies are followed, e.g. dumping the feed stream to the NF/RO membrane filtration unit if the measured values are above a maximum set-point value.

Regarding sodium metabisulphite dosing, it shall be fed after cartridge filters to ensure their protection from biofouling phenomena. To ensure all free chlorine has been removed, the measured ORP value shall be lower than ca. 200 mV.

Last but not the least, in presence of heavy metals (such as iron, manganese and cobalt) and excessive oxygen, sodium metabisulphite may be converted to an oxidant, thus damaging the NF/RO membranes instead of protecting them.

3.2.16 Biological treatment

Biological treatment units may be used to reduce high organics and/or nitrogen contents, thus reducing both organic fouling and biofouling phenomena. Aerobic/anoxic biological treatment units (e.g. CAS, MBBR and MBR processes) are used in case of moderately high organics content and any nitrogen content while anaerobic biological treatment units (e.g. UASB, EGSB, AnMBR, etc.) are used in case of very high organics content.

Note that MBR and AnMBR processes combine a biological process with micro-/ultra-filtration membrane filtration technology (ref. 3.2.13) and, thus, they are particularly suitable for use in combination with NF/RO membranes.

3.2.17 Waste streams management

Utilization of clarifiers (ref. 3.2.9), DAF (ref. 3.2.10), media filters (ref. 3.2.11) and micro-/ultra-filtration units (ref. 3.2.13) requires incorporation of the sludge treatment line to handle the resulting waste sludge and/or the backwash streams. The objective of sludge treatment systems is to concentrate and dewater waste sludge and backwash streams to a solids concentration above 15 to 25%, so that they can be easily and conveniently transported off site and disposed to landfill or they can undergo further on-site processing (e.g. thermal treatments).

Usually, this concentration process includes static or dynamic solids thickening and dewatering. Any separated water is usually returned to the head of the pre-treatments and care shall be taken in selecting the proper coagulants and flocculants for sludge thickening and dewatering to minimize NF/RO membrane filtration units fouling phenomena (ref. 3.2.12).

The NF/RO concentrate stream is usually disposed as such as a special waste. In case of ZLD systems, it is sent to crystallization and/or evaporation.

3.3 Post-treatments

In case further ammonia removal is required after the NF/RO membrane filtration unit, a second spiral-wound RO pass may be used. Whenever this is still not enough, a third RO pass is usually not convenient and then ammonia stripping or ion exchange units may be used. Note that ammonia stripping requires the pH to be raised to 12 so that ammonium is converted to ammonia gas, thus afterwards pH adjustment (ref. 3.2.4) may be required to comply with discharge standards.

4. mft Circular-Disc modules

Within this chapter, Circular-Disc (CD) modules description, nomenclature and main characteristics are briefly presented.

4.1 Description

Essentially, CD modules are made of a pressure vessel, of a sealing system and of a stack of support plates and membrane cushions.

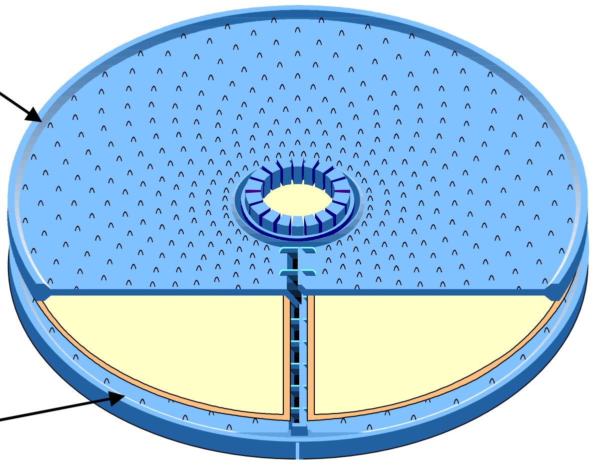

Figure 6. One membrane cushion between two support plates

Each membrane cushion is made of two polyamide thin-film composite NF/RO membrane sheets separated by the polyethersulphone permeate spacer. The outer diameter is sealed via thermal welding. The central hole allows the permeate to flow into the permeate collection pipe, while the external slot allows the feed water to flow from one cushion to the next.

The membrane cushions are placed in between support plates and O-rings separate the permeate from the feed and concentrate water. The support plates are stacked onto the permeate anchor, which collects the permeate and which is installed within the pressure vessel. The pressure vessel is sealed with pressure and end plates and it is connected via hoses to the feed, permeate and concentrate manifolds. All the connections are all placed on the top end of the CD module.

The feed water first flows from the top to the bottom of the CD module within the gap between the pressure vessels and the stack of support plates. Then, it rises along the stack of support plates in a helicoidal pattern, ensuring a steady and well-defined flow regimen on the entire membrane cushions surface. After travelling through the stack of support plates, the feed water is termed as concentrate and it leaves the CD module through the dedicated connection.

The permeate crosses the NF/RO membrane sheets into the permeate spacer and it leaves the membrane cushions to the permeate anchor at the center of the module. Then, the permeate leaves the CD module through the dedicated connection.

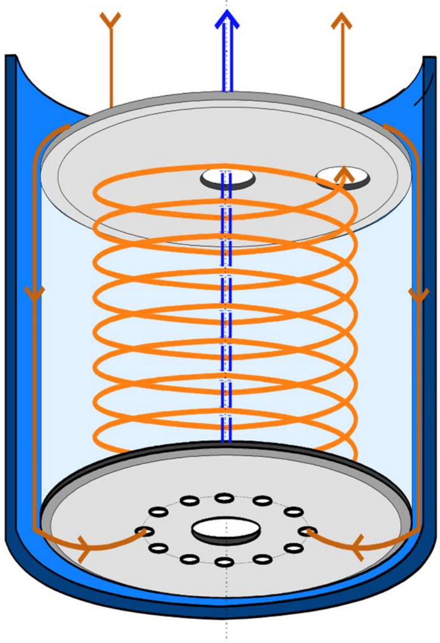

Figure 7. Flow schematic inside the CD modules

4.2Nomenclature

The CD modules nomenclature is as follows:

- the first part of the name indicates the module design and is membrane surface, e.g. CD-9 is a Circular Disc module with 9 m^2 of active membrane surface area;
- the second part of the name indicates the type of installed membrane, i.e. SW stands for high-rejection RO membrane (typically used for seawater) while BW stand for low-rejection RO membrane (typically used for brackish water) and NF stands for a NF membrane;
- the third part of the name indicates the maximum operating pressure, i.e. 140 stands for 140 bar;
- the fourth of the name indicates the CD module year of production;

- the fifth and last part indicates the CD module serial number.

E.g. CD-9-SW-140-2020-00115 indicates a CD module with 9 m^2 of active membrane surface area, equipped with high-rejection RO membrane, able to operate up to 140 bar, produced in year 2020 and having serial number 00115.

All the above information are available within a QR code, which can be easily decoded with a smartphone. This contains also additional details, e.g. the exact type of membrane that has been used to manufacture the membrane cushions.

4.3Characteristics and membrane selection

Within the following table, the main characteristics of mft modules are summarized.

Since NF/RO membrane filtration units are typically designed and operated at a fixed water flux, the higher the NF/RO membrane water permeability the lower the required feed pressure and, thus, the pumping energy consumption. On the other hand, the higher the permeability, the lower the membrane solutes rejection rate. Thus, mft offers different membrane types to optimally address different applications.

Table 5. Main characteristics of CD modules

Parameter	CD-9-SW	CD-9-BW	CD-9-NF	CD-17-SW	CD-17-BW	CD-17-NF
Flow direction	Out-to-in					
Filtration mode	Crossflow					
Membrane manufacturer	DOW FilmTec or equivalent					
Membrane type	SW30HR or SW30XLE	BW30LE	NF270	SW30HR or SW30XLE	BW30LE	NF270
Membrane material	PA					
Spacer material	PES					
Membrane area	9 m^2			17 m^2		
Membrane cushions no.	115			227		
Disc plate material	Glass fiber reinforced ABS					
Casing material	FRP, PVC, coated steel 1.0577 and SS 1.4571					
Feed flow channel width	2.5 mm					
Nominal module pressure drop	2 bar			3 bar		
Minimum feed flow	750 L/h			1,100 L/h		
Maximum feed flow	1,200 L/h			1,500 L/h		
Maximum feed pressure	140 bar			40 bar		
Operating temperature range	5 to 40°C					
Maximum cleaning temperature	45°C					
Operating pH range	4 to 11	4 to 11	4 to 11	4 to 11	4 to 11	4 to 11
Cleaning pH range	2 to 13	2 to 13	2 to 12	2 to 13	2 to 13	2 to 12

Parameter	CD-9-SW	CD-9-BW	CD-9-NF	CD-17-SW	CD-17-BW	CD-17-NF
Module height	1,170 mm			2,005 mm		
Module external diameter	322 mm			322 mm		
Module weight (empty)	120 kg			160 kg		
Module weight (full)	145 kg			210 kg		
Module water volume	25 L			50 L		
Feed connection	G 1/2" F					
Permeate connection	Rp 3/8" F					
Concentrate connection	G 1/2" F					

5. CD module assembly

Within the following paragraphs, the assembly of CD modules is explained.

	Wear adequate personal protective equipment (PPE) when assembling CD modules!
	For reasons of safety, it is strictly forbidden to make any modification to the CD modules!

Step 1. Support plates stack preparation

	Check that the support plates O-rings are not damaged and free of dirt!

- Fit the support plates O-rings on both sides of the support plates within the dedicated slots;

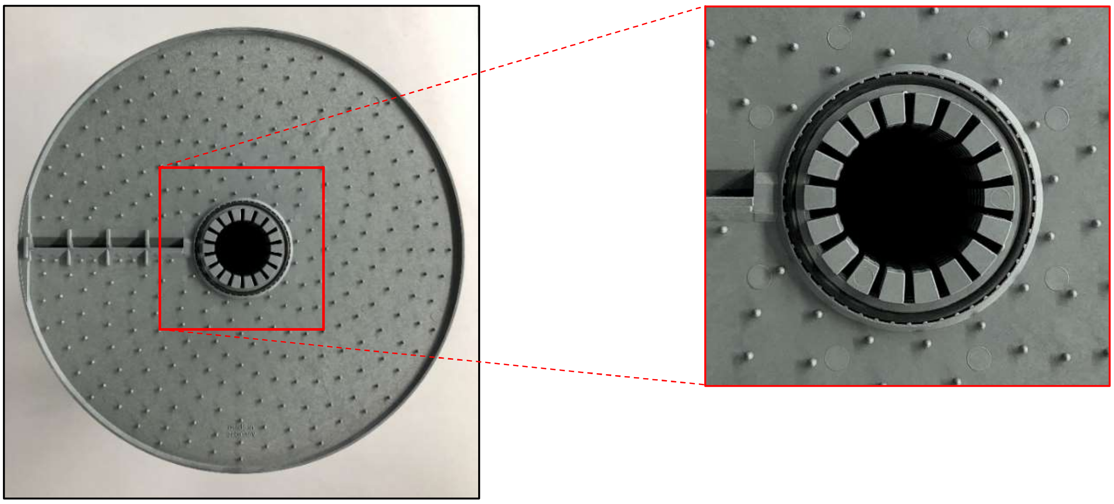

Figure 8. Support plates O-rings installation

	Pay attention that no dirt particles are present within the O-rings slots!

	Avoid any damage to the support plates O-rings!
	Confirm that the support plates O-rings are firmly pressed within the dedicated slots!

- lay the first membrane cushion above the first support plate;

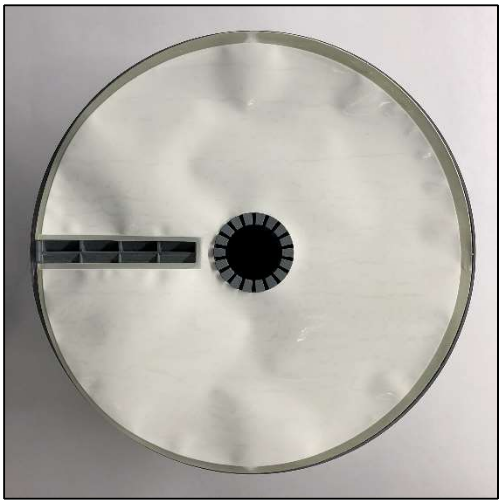

Figure 9. Membrane cushion positioning

	Always wear cloth gloves when handling the membranes and handle them by the welding seam as otherwise they are susceptible to damage!
	Do not firmly press the membrane cushions onto the support plates to avoid damaging the membrane surface!

- lay the second support plate above the first membrane cushion;
- continue to stack support plates and membrane cushions until the required number of membrane cushions has been placed (ref. Table 5). Cover the last membrane cushion with one additional support plate;

	While stacking the support plates, check that their positioning slots are aligned!

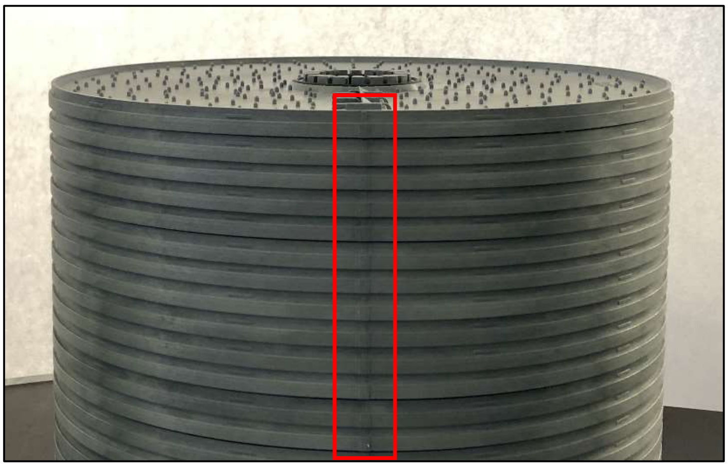

Figure 10. Support plates alignment

Step 2. Support plates stacking onto the permeate anchor

- Place the permeate anchor on a levelled surface;

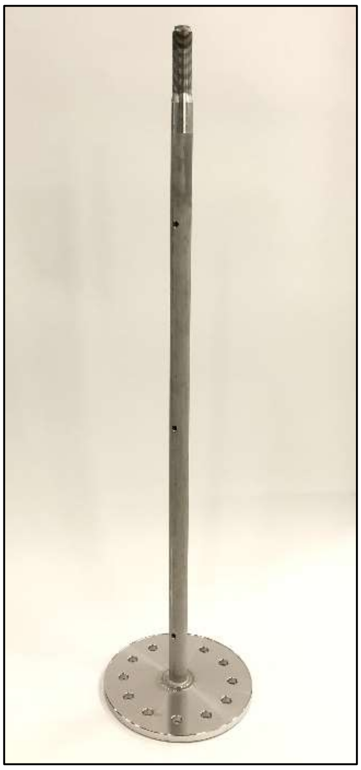

Figure 11. Permeate anchor positioning

- lay the stack of support plates onto the permeate anchor;

Figure 12. Support plates stacking onto the permeate anchor

Check that the support plate positioning slots are aligned!

Step 3. Top plates assembly placement

Check that the top pressure plate O-ring is not damaged and free of dirt!

- Insert the top pressure plate O-ring into the dedicated slot of the top pressure plate, i.e. the PVC plate with two holes through;

Pay attention that no dirt particles are present within the O-rings slot!

	Avoid any damage to the top pressure plate O-ring!

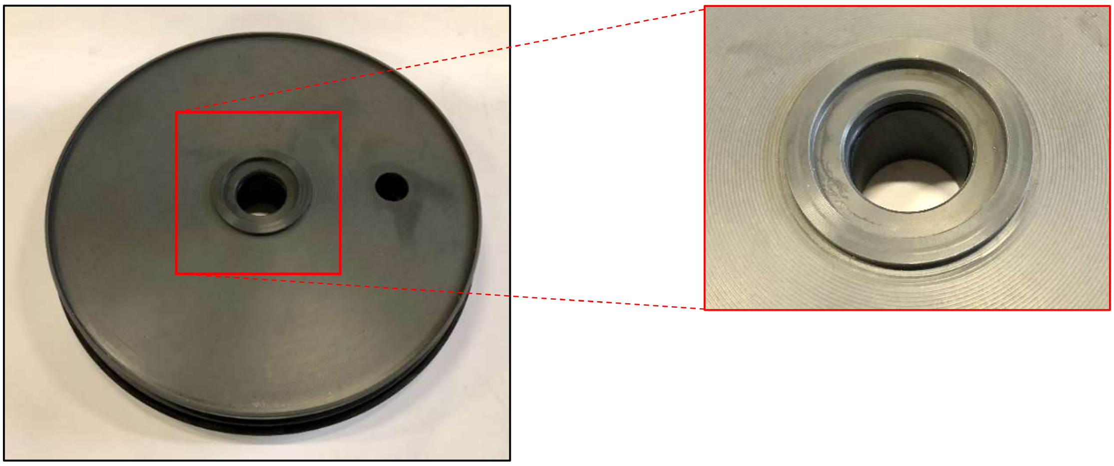

Figure 13. Top pressure plate O-ring installation

	Confirm that the top pressure plate O-ring is firmly pressed within the dedicated slot!

- insert the lip seal into the top pressure plate within the dedicated groove. Orientate the wide side of the lip towards the inner side of the module;

Figure 14. Top pressure plate lip seal installation

	Confirm that the lip seal is firmly pressed into the dedicated groove!

- lay the top end plate, i.e. the metal plate with five holes through, onto the top pressure plate;

	Be sure to align the holes of the two plates!

- screw the two M8 x 50 mm cylinder head screws into the dedicated holes to fix the top end plate to the top pressure plate. Do not tight them yet;

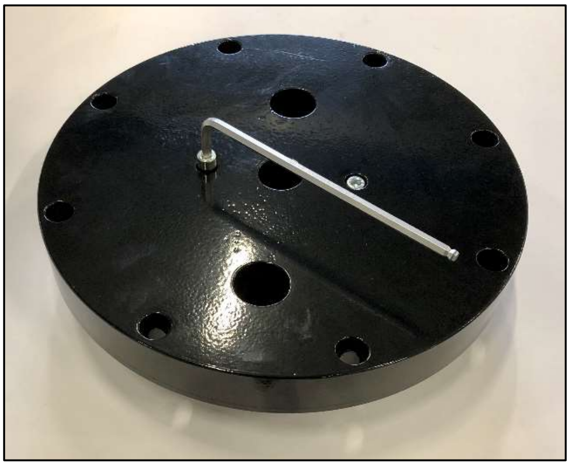

Figure 15. Top end plate to top pressure plate fixing

- insert the O-rings into the dedicated slot of the feed and concentrate adaptors;

	Pay attention that no dirt particles are present within the O-rings slot!
	Avoid any damage to the top pressure plate O-ring!

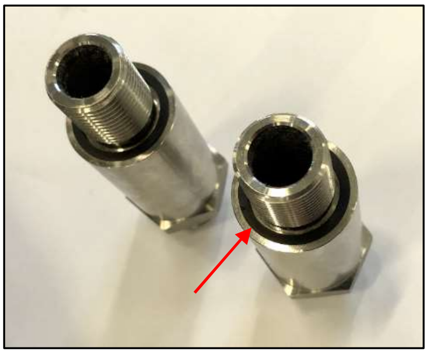

Figure 16. Feed and concentrate adaptors O-rings installation

	Confirm that the feed and concentrate adaptors O-rings are firmly pressed within the dedicated slots!

- insert the feed and concentrate adaptors into the dedicated threads and screw them tightly together with the PVC plate. Now the cylinder head screws can be tightened;

Figure 17. Feed and concentrate adaptors installation

- carefully place the top plates assembly on top of the support plates stack;

Figure 18. Top plates assembly positioning

	Be sure to orientate the top plates assembly so that the feed water inlet is on the opposite side of the support plates ramps!

- carefully push the top plates assembly downwards;

	Be sure that no rotation of the support plates takes place!
	Do not apply too much force to avoid damaging the support plates and the membrane cushions!

- place the plastic washer first and the metal washer second on top of the permeate anchor connection;

Figure 19. Top plates assembly washers positioning

- screw the first nut on top of the permeate anchor connection by using a torque wrench locked at 110 N·m;

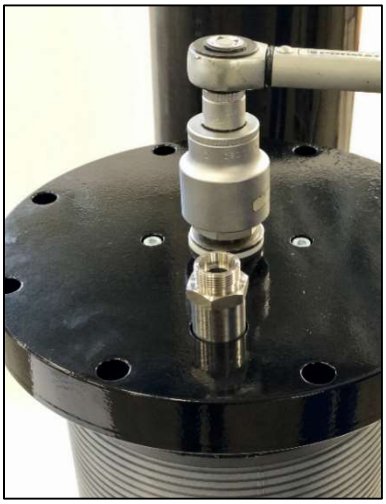

Figure 20. Top plates assembly first nut installation

- screw the second nut on top of the permeate anchor connection by using a torque wrench locked at 110 N·m.

Figure 21. Top plates assembly second nut installation

Step 4. Bottom plates assembly placement

- Insert the lip seal into the dedicated groove of the bottom pressure plate, i.e. the PVC plate with no holes through. Orientate the wide side of the lip towards the inner side of the module;

	Confirm that the lip seal is firmly pressed into the dedicated groove!

- lay the bottom end plate, i.e. the metal plate with two holes through, on the bottom pressure plate;

	Be sure to align the holes of the two plates!

- screw the two M8 x 50 mm cylinder head screws into the dedicated threads to fix the bottom end plate to the bottom pressure plate.

Figure 22. Bottom end plate to bottom pressure plate fixing

Step 5. Module final assembly

- Place the bottom plates on top of two square steel tubes;

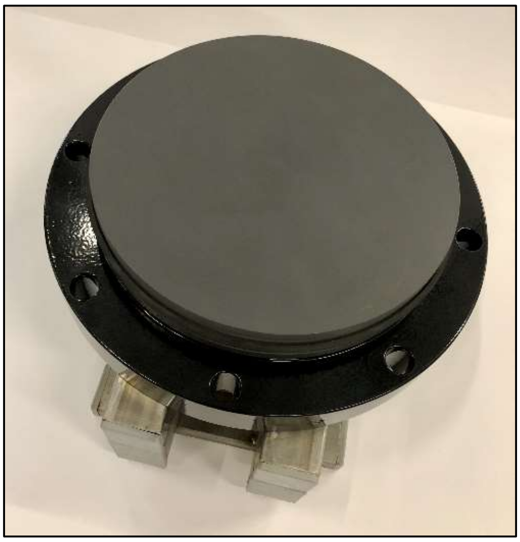

Figure 23. Bottom module assembly positioning

- lubricate the inner part of the upper pressure vessel end with appropriate media such as glycerine or dish soap;

	Do not use fat or vaseline!

- flip the pressure vessel around and carefully insert it onto the bottom plates assembly so that the two parts are firmly connected;

Figure 24. Pressure vessel fitting onto the bottom plates assembly

⚠	Do not use hammers or similar tools!

- screw the lifting tool into the permeate connection;

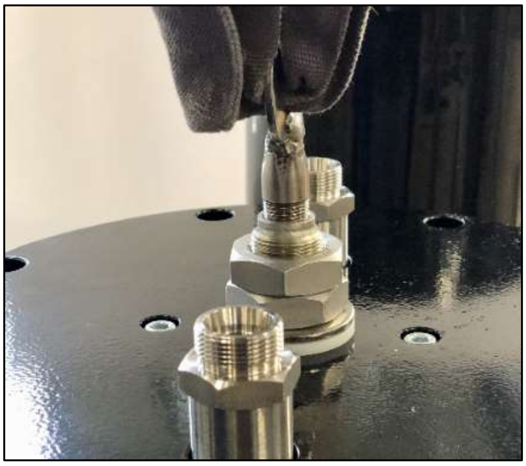

Figure 25. Lifting tool positioning

	Use a suitable lifting device (e.g. jip crane) to move the stack of plates!

- lubricate the top pressure plate lip seal with appropriate media such as glycerin or dish soap;

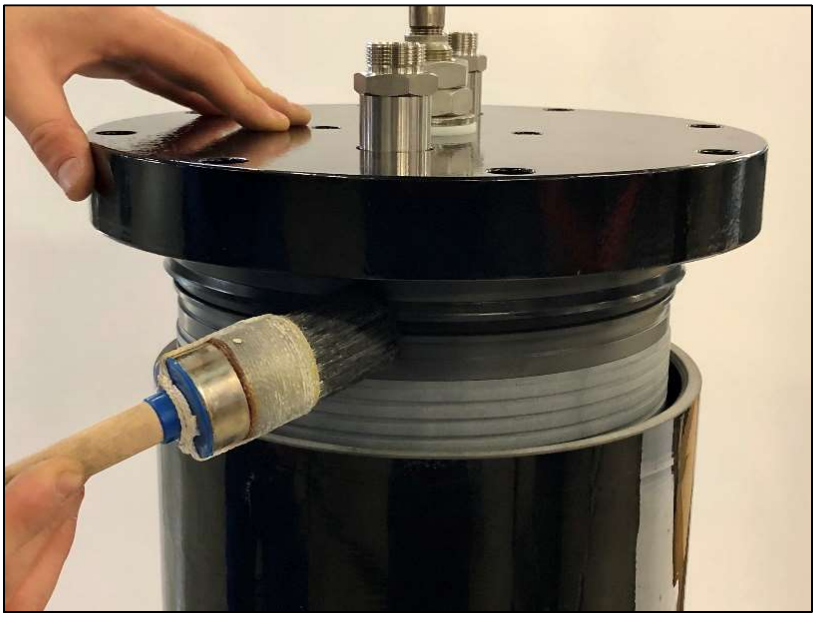

Figure 26. Top pressure plate lip seal lubrication

	Do not use fat or vaseline!

- lubricate the inner part of the upper pressure vessel end with appropriate media such as glycerin or dish soap;

	Do not use fat or vaseline!

- carefully insert the stack of plates and top plates assembly into the pressure vessel so that the two parts are firmly connected;

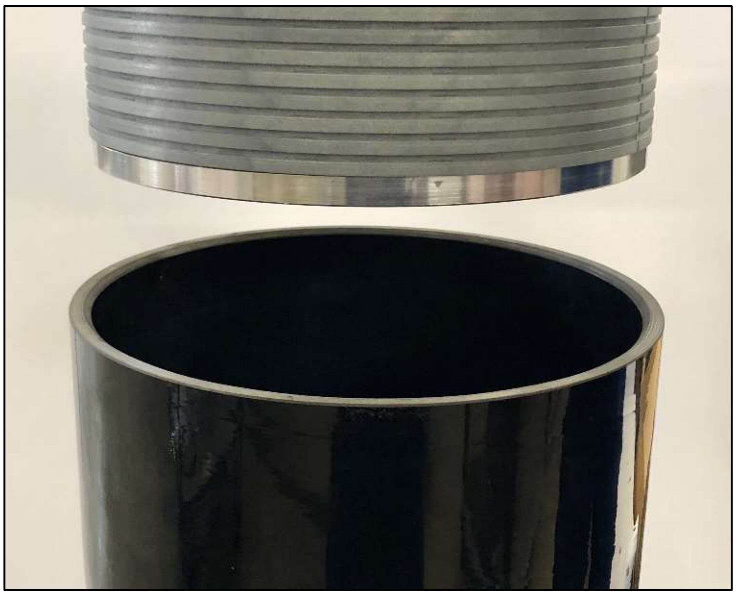

Figure 27. Stack of plates and top plates assembly insertion into the pressure vessel

- place the tension rods top washers onto the top end plate;

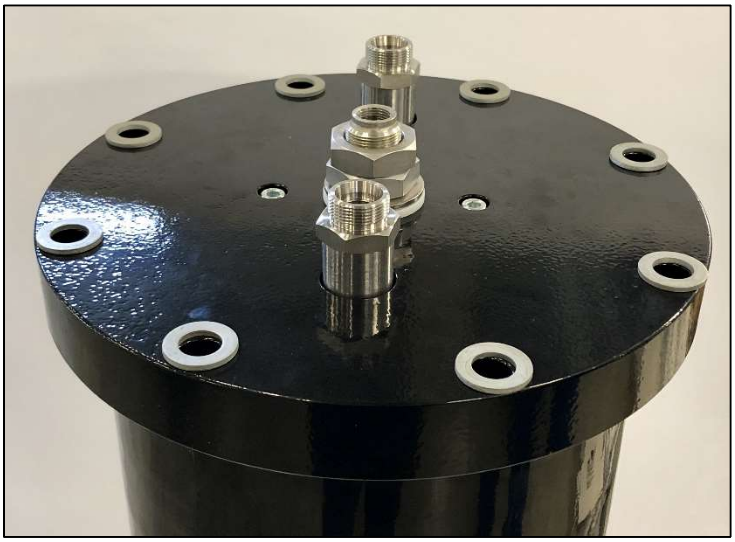

Figure 28. Tension rods top washers placement

- insert the tension rods into the dedicated holes of the top end plate and slide them down into the dedicated holes of the bottom end plate;
- if needed, align the end plates by rotating the top one;

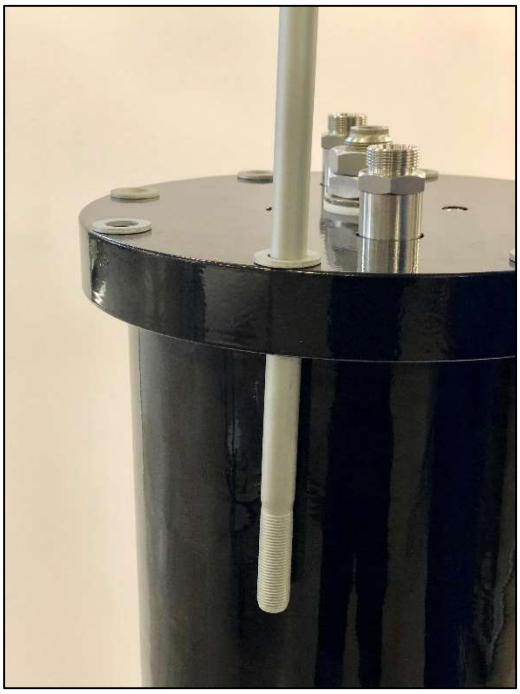

Figure 29. Tension rods insertion

- insert the bottom washers onto the tension rods and screw the cap nuts by using a torque wrench locked at 25 N·m.

Figure 30. Bottom washers and cap nuts installation

Step 6. Module connection

- Identify permeate (in the middle), feed (furthest from the permeate connection) and concentrate connections (closest to the permeate connection);

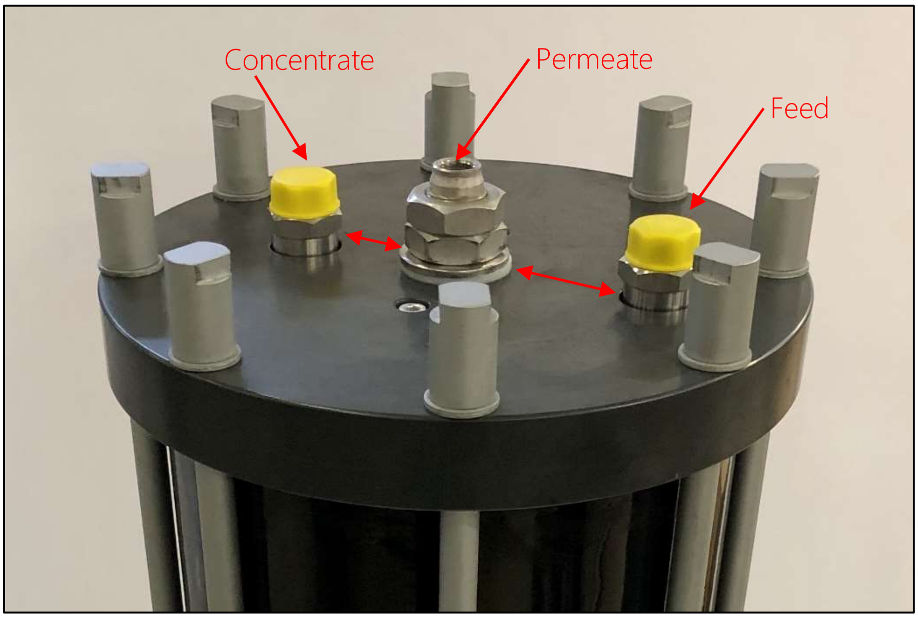

Figure 31. Module connections identification

- use appropriate hoses (out of mft scope of supply) to connect the CD modules to the feed, permeate and concentrate manifolds, e.g. Hansaflex PHD 116 X ... AOLVA for high pressure connections (i.e. feed and concentrate ones).

6. Membrane filtration unit design

In this chapter, simple criteria and recommendations for designing the membrane filtration unit are presented.

6.1 Membrane filtration trains

Membrane filtration units typically have more than one individually controlled membrane skid (or rack) in parallel. Whenever other ancillary equipment is also dedicated to specific membrane skids (e.g. low-pressure pumps, anti-scalant dosing facility, cartridge filters and high-pressure pumps), the entire grouping of components is referred to as a membrane filtration train.

The number of membrane filtration trains depends on the overall capacity of the plant, the required degree of flexibility and the capacity loss that is acceptable when one train is out of service because of membrane cleaning interventions or maintenance works.

In general, the use of dedicated low- and high-pressure pumps for each membrane filtration train is recommended, possibly with a common spare unit. This arrangement, which may also be dictated by the maximum available capacity of plunger and piston pumps (ca. 25 to 30 m^3/h per pump), also minimizes the pumping energy consumption.

6.2 Membrane filtration stages and passes

In the following discussion:

- staging means two membrane filtration units in sequence where the second stage is fed with the concentrate of the first one;
- passing means two membrane filtration units in sequence where the second pass is fed with the permeate of the first one.

An illustrative example is depicted in Figure 32.

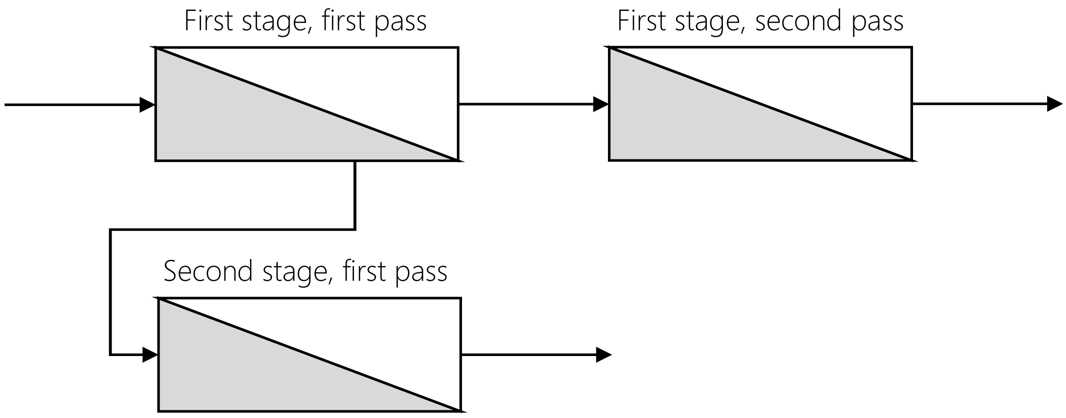

Figure 32. Membrane staging and passing example

6.3CD modules clusters

Whenever two or more CD modules are installed in series, a CD modules cluster is formed to reduce the required crossflow and, thus, the pumping energy consumption. In plate-and-frame NF/RO membrane filtration units, this is a unique feature to CD modules thanks to their optimized hydraulic design, which allows for considerably lower module pressure losses than competitors' solutions.

Generally, it is possible to group 1 to 5 CD modules in series, where the concentrate of the first module becomes the feed to the second module and so on. The number of CD modules in a cluster depends on the last module (cluster-end) concentrate characteristics, which shall comply with the limits listed in Table 3. For the sake of simplicity, a cluster with 2 CD modules in series is termed cluster-2, a cluster with 3 CD modules in series is termed cluster-3, and so on.

Note that all the CD modules within a cluster belong to the same membrane stage/pass and they share the same recirculation loop.

6.4Design procedure

The following procedure involves the design of a single pass/stage membrane filtration unit with cluster-1 to cluster-5 configuration. Permeate and concentrate staging with dedicated concentrate recirculation loops may be easily implemented by considering more than one pass/stage in series.

6.4.1 Membrane filtration unit design

Osmotic pressure (Π):

$$\Pi = 0.08314\ \frac{L \times bar}{°K \times mol} \times (T + 273.15) \times \frac{\sum_i C_{m,i}}{1000\ mmol/mol} = [bar]$$

where:

- T is the water temperature [°C];
- $C_{m,i}$ is the molar concentration of the ionic compound i [mmol/L].

Osmotic pressure coefficient (K_Π):

$$K_\Pi = \frac{1000\ mg/g \times \Pi}{\sum_i C_i} = \left[\frac{bar \times L}{g}\right]$$

where C_i is the concentration of the ionic compound i [mg/L].

Note that:

- for the raw feed water (subscript "in"):
    - the compounds concentrations are given as design data;
    - usually, the pH value, hydrogen ion content (H^+), hydroxide ion content (OH^-) and the bicarbonate ion content (HCO_3^-) are known and, thus, carbonate ion content (CO_3^{2-}) is calculated via carbonate equilibria relationships;
- for the pH-adjusted feed water (subscript "adj"):
    - the compounds concentrations are the same as in the feed water, with the exception of chloride, sulphate and/or sodium increase due to hydrochloric acid, sulfuric acid or sodium hydroxide dosing as pH-adjusting agent;
    - pH value, hydrogen ion and hydroxide ion contents are specified and, thus, bicarbonate ion content and carbonate ion content are calculated via carbonate equilibria relationships by assuming that the total carbonate species content is the same as in the feed water;
- for the feed water (subscript "f"), namely the blend of the pH-adjusted feed water and the recirculation water, the concentration of the compound i ($C_{f,i}$) is calculated as follows:

$$C_{f,i} = \frac{C_{adj,i} \times Q_{adj} + C_{c,i} \times Q_r}{Q_{adj} + Q_r} = \left[\frac{mg}{L}\right]$$

where:

- $C_{adj,i}$ is the pH-adjusted feed water concentration of the compound i [mg/L];
- Q_{adj} is the pH-adjusted feed water flow [m^3/h];
- $C_{c,i}$ is the recirculation concentration of the compound i [mg/L]. Note that the recirculation water has the same qualitative composition of the concentrate, hence the use of the concentrate water subscript to indicate the recirculation water compound i concentration;
- Q_r is the recirculation water flow [m^3/h];

- for the permeate water (subscript "p"):
  - the compounds concentrations are given as design data by running a simulation with DOW WAVE software. This is the most accurate tool to estimate the different ions rejections by DOW Filmtec membranes at the design operating conditions (i.e. temperature, pH, feed composition, water flux, recovery rate and concentrate recirculation ratio). To do so, NF/RO membrane elements that have the same membrane used for the membrane cushions shall be selected and a number of NF/RO elements to have circa the same water flux as in the CD membrane filtration unit (J*) shall be selected;
  - in case of additional compounds not considered by DOW WAVE (e.g. TSS, COD, BOD, iron, manganese, etc.), their concentrations are calculated as follows:

$$C_{p,i} = C_{fc,i} \times (1 - CR_i) = \left[\frac{mg}{L}\right]$$

where:

- $C_{fc,i}$ is the average feed-concentrate concentration of the compound i:

$$C_{fc,i} = \frac{C_{f,i} + C_{c,i}}{2} = \left[\frac{mg}{L}\right]$$

- $C_{f,i}$ is the feed concentration of the compound i [mg/L];
- $C_{c,i}$ is the concentrate concentration of the compound i [mg/L];
- CR_i is the rejection of the compound i at design conditions (from experience or pilot trials) [-].

By performing a mass balance over the membrane filtration stage and by combining it with the two above equations, it is possible to calculate the permeate concentration of the compound i ($C_{p,i}$) as follows:

$$C_{p,i} = C_{adj,i} \times \frac{\frac{Q_{adj}}{2 \times Q_c} \times (1 - CR_i) \times \left(1 + \frac{Q_c + Q_r}{Q_f}\right)}{1 - \frac{Q_p}{2 \times Q_f} \times (1 - CR_i) + \frac{Q_p}{2 \times Q_c} \times (1 - CR_i) \times \left(1 + \frac{Q_c + Q_r}{Q_f}\right)} = \left[\frac{mg}{L}\right]$$

where:

- Q_f is the feed flow to the CD modules:

$$Q_f = Q_{adj} + Q_r = \left[\frac{m^3}{h}\right]$$

- Q_p is the permeate water flow [m^3/h];
- Q_c is the concentrate water flow [m^3/h];

  - bicarbonate ion and carbonate ion contents are defined by the DOW WAVE projection while pH value, hydrogen ion content and hydroxide ion content are calculated via carbonate equilibria relationships;

- for the concentrate water (subscript "c"):
  - by performing a mass balance over the membrane filtration stage, it is possible to calculate the concentration of the compound i ($C_{c,i}$):

$$C_{c,i} = \frac{C_{adj,i} \times Q_{adj} - C_{p,i} \times Q_p}{Q_c} = \left[\frac{mg}{L}\right]$$

  - pH value, hydrogen ion content, hydroxide ion content, bicarbonate ion content and carbonate ion content are calculated via carbonate equilibria relationships by performing a mass balance of the total carbonate species over the membrane filtration stage.

Permeate flow (Q_p):

$$Q_p = Q_{adj} \times R = \left[\frac{m^3}{h}\right]$$

where R is the CD-RO unit recovery rate [-]. This parameter shall be defined by the user such that:

- the maximum allowed operating pressure is not overcome (ref. Table 3);
- the maximum allowed concentrate TSS and COD contents are not overcome (ref. 3.1);
- the scaling phenomena are kept under control. To check this, the use of an anti-scalant/dispersant projection software is required (e.g. Flodose by BWA).

Concentrate flow (Q_c):

$$Q_c = Q_{adj} - Q_p = \left[\frac{m^3}{h}\right]$$

Modules number (N_m):

$$N_m = \frac{1000\ L/m^3 \times Q_p}{J_w \times a_m} = [-]$$

where:

- J_w is the water flux [LMH];
- a_m is the membrane area of one module [m^2], e.g. 9 m^2 in case of a CD-9 module.

The design modules number (N_m*) is specified from the above calculated modules number (N_m) by taking into account the number of modules per cluster ($n_{m,c}$). E.g. if N_m = 11.3 and a cluster-2 configuration is selected, then N_m* = 12.

Design water flux (J^*_w):

$$J_w^* = \frac{1000\ L/m^3 \times Q_p}{N_m^* \times a_m} = [LMH]$$

Considering parallel trains operation, the following quantities may be calculated:

$$q_{adj,t} = \frac{Q_{adj}}{N_t} = \left[\frac{m^3}{h}\right], q_{p,t} = \frac{Q_p}{N_t} = \left[\frac{m^3}{h}\right], q_{c,t} = \frac{Q_c}{N_t} = \left[\frac{m^3}{h}\right], n_{m,t} = \frac{N_m^*}{N_t} = [-], n_{c,t} = \frac{n_{m,t}}{n_{m,c}} = [-]$$

where:

- N_t is the number of parallel trains [-];
- $q_{adj,t}$ is the pH-adjusted feed flow of one train [m^3/h];
- $q_{p,t}$ is the permeate flow ofm one train [m^3/h];
- $q_{c,t}$ is the concentrate flow of one train [m^3/h];
- $n_{m,t}$ is the number of modules per train [-];
- $n_{c,t}$ is the number of clusters per train [-];
- $n_{m,c}$ is the number of modules per cluster [-].

Permeate flow per module ($q_{p,m}$):

$$q_{p,m} = \frac{q_{p,t}}{n_{m,t}} = \left[\frac{m^3}{h}\right]$$

Minimum feed flow per cluster ($q_{cf,c}$):

$$q_{cf,c} = q_{cf,min} + (n_{m,c} - 1) \times q_{p,m} = \left[\frac{m^3}{h}\right]$$

where $q_{cf,min}$ is the minimum crossflow per module [m^3/h]. This is equal to the minimum feed flow per module (ref. Table 5).

Crossflow per train ($q_{cf,t}$):

$$q_{cf,t} = q_{cf,c} \times n_{c,t} = \left[\frac{m^3}{h}\right]$$

Recirculation flow per train ($q_{r,t}$):

$$q_{r,t} = q_{cf,t} - q_{adj,t} = \left[\frac{m^3}{h}\right]$$

Temperature correction factor (TCF):

$$TCF = e^{k_m \times \left(\frac{1}{298.15} - \frac{1}{T+273.15}\right)} = [-]$$

where:

- k_m is the membrane material constant [-] (ref. 2.3.6);
- T is the water temperature [°C].

Water permeability at design conditions (K_w):

$$K_w = K_{w,25} \times TCF = \left[\frac{LMH}{bar}\right]$$

where K_{25} is the water permeability at 25°C [LMH/bar]. This can be inferred from the membrane datasheets provided by DOW Filmtec.

Net driving pressure (NDP):

$$NDP = \frac{J_w^*}{K_w} = [bar]$$

Feed TDS concentration (C_f):

$$C_f = \frac{C_{adj} \times Q_{adj} + C_c \times Q_r}{Q_{adj} + Q_r} = \left[\frac{mg}{L}\right]$$

where:

- C_{adj} is the pH-adjusted feed TDS concentration [mg/L];
- Q_{adj} is the pH-adjusted feed water flow [m^3/h];
- C_c is the concentrate TDS concentration [mg/L];
- Q_r is the recirculation water flow [m^3/h].

Average feed-concentrate TDS concentration (C_{fc}):

$$C_{fc} = \frac{C_f + C_c}{2} = \left[\frac{mg}{L}\right]$$

Note that the feed TDS concentration and the average feed-concentrate TDS concentration are to be calculated via an iterative procedure.

Average feed-concentrate osmotic pressure (Π_{fc}):

$$\Pi_{fc} = \frac{K_{\Pi,\mathrm{fc}} \times C_{fc}}{1000\ mg/g} = [bar]$$

where

- $K_{\Pi,fc}$ is the average feed-concentrate osmotic pressure factor. This may be calculated e.g. by assuming a linear relationship between the pH-adjusted feed and the concentrate osmotic pressure factors:

$$K_{\Pi,\mathrm{fc}} = K_{\Pi,\mathrm{adj}} + C_{fc} \times \frac{K_{\Pi,\mathrm{c}} - K_{\Pi,\mathrm{adj}}}{C_c - C_{adj}} = [-]$$

- $K_{\Pi,c}$ is the concentrate osmotic pressure factor [-];
- $K_{\Pi,adj}$ is the pH-adjusted feed osmotic pressure factor [-].

Permeate osmotic pressure (Π_p):

$$\Pi_p = \frac{K_{\Pi,\mathrm{p}} \times C_p}{1000\ mg/g} = [bar]$$

where $K_{\Pi,p}$ is the permeate osmotic pressure factor [-];

Clean membrane feed pressure ($p_{f,clean}$):

$$p_{f,clean} = NDP + \Pi_{fc} + \Delta p_{geo} + \Delta p_{piping,f} + \frac{\Delta p_{m,max} \times n_{m,c}}{2} + p_p - \Pi_p = [bar]$$

where:

- Δp_{geo} is the geodetic head of the CD-RO unit [bar];
- $\Delta p_{piping,f}$ is the pressure loss due to the feed piping [bar];
- $\Delta p_{m,max}$ is the maximum module pressure loss [bar];
- $n_{m,c}$ is the number of modules per cluster [-];
- p_p is the permeate pressure [bar];
- Π_p is the permeate osmotic pressure [bar].

Unless pilot data are available, the fouled membrane feed pressure ($p_{f,fouled}$) may be estimated as follows:

$$p_{f,fouled} = (1.2 \div 1.3) \times p_{f,clean}$$

where $p_{f,clean}$ is the clean membrane feed pressure [bar].

The design feed pressure (p_f^*) is specified from the above calculated feed pressure (p_f).

6.4.2 Cleaning unit design

CIP tank water volume ($V_{w,tank}$):

$$V_{w,tank} = 1000\ \frac{L}{m^3} \times \frac{Q_{CIP} \times HRT_{tank}}{60\ min/h} = [L]$$

where:

- Q_{CIP} is the CIP flowrate [m^3/h]. This is at least equal to the feed flow ($q_{f,t}$) or, better, to the required crossflow capacity ($q_{cf,t}$);
- HRT_{tank} is the minimum hydraulic retention time of the CIP tank [min]. This is usually equal to 3 to 5 min.

Modules water volume per train ($V_{w,m}$):

$$V_{w,m,t} = v_{w,m} \times n_{m,t} = [L]$$

where $v_{w,m}$ is the water volume of one CD module [L] (ref. Table 5).

CIP cleaning water volume ($V_{w,CIP}$):

$$V_{w,CIP} = (1 + SF) \times \left(V_{w,m,t} + V_{w,piping} + V_{w,tank}\right) = [L]$$

where:

- SF is the security factor (> 1) which accounts for the water volume of pumps, valves, etc.;
- $V_{w,piping}$ is the CIP loop piping water volume [L].

Cleaner volume ($V_{cleaner}$):

$$V_{cleaner} = \frac{C_{cleaner} \times V_{w,CIP}}{f_{cleaner}} = [L]$$

where:

- $C_{cleaner}$ is the target cleaner concentration [% v/v];
- $f_{cleaner}$ is the cleaning principle fraction within the cleaner [%].

Note that the subscript "cleaner" stands for "acid" or "alkaline", depending on the considered cleaner (namely, acid or alkaline).

Cleaner dosing flow ($Q_{d,cleaner}$):

$$Q_{d,cleaner} = \frac{V_{cleaner} \times 60\ min/h}{T_{d,cleaner}} = \left[\frac{L}{h}\right]$$

where $T_{d,cleaner}$ is the cleaner dosing phase duration [min].

Cleaner storage tank volume ($V_{s,cleaner}$):

$$V_{s,cleaner} = N_{cycle\ ,cleaner} \times \frac{Q_{d,cleaner}}{60\ min/h} \times \frac{52\ w/y}{t_{CIP,cleaner}} \times \frac{T_{s,cleaner}}{12\ months/y} = [L]$$

where:

- $N_{cycles,cleaner}$ is the number of cleaning cycles per cleaning intervention [-];
- $t_{CIP,cleaner}$ is the cleaning frequency [1/week];
- $T_{s,cleaner}$ is the cleaner storage time [month].

6.5Pumps

In NF/RO membrane filtration units based on CD module technology, mainly five types of pumps are used:

- centrifugal pumps, as pre-pressure pumps (2 to 4 bar), high-pressure pumps in low-salinity wastewater applications (up to 25 bar) and CIP pumps. Their typical efficiency is equal to 65 to 75%;
- plunger pumps as high-pressure pumps (up to 140 bar). Their typical efficiency is equal to 80% and they require a pre-filtration of 10 μm absolute on the suction side and a pulsation dampener on the pressure side in order to minimize pressure surges;
- piston pumps as high-pressure pumps (up to 140 bar). Their typical efficiency is equal to 90% and they require a pre-filtration of 5 μm absolute on the suction side. In this case, no pulsation dampener on the pressure side is required (but it is strongly recommended);
- booster modules for concentrate recirculation. Their typical efficiency is equal to 70% and they can be used at operating pressures up to 80 bar;
- diaphragm or drum pumps for chemical cleaners dosing.

Note that, since high-pressure pumps require a certain feed water pressure (i.e. 1 to 1.5 bar) in their suction side to avoid cavitation phenomena, low-pressure pumps shall always be installed.

The above pumps are to be sized on the required flowrates and operating pressures. High-pressure pumps shall include an operating pressure premium to account for fouling phenomena over the NF/RO membranes lifetime (ref. 6.4.1).

To regulate the feed flow and thus the operating pressure, the following solutions are available:

- install a throttling valve on the pressure side of the high pressure pump. This may be used only in combination with centrifugal pumps, since they can be throttled;
- provide a dedicated bypass line from the pump discharge to the pump suction with a backpressure valve. This is typically used in combination with piston and plunger pumps, since they cannot be throttled;
- use a variable frequency drive (VFD) on the high-pressure pump motor. This may be used in combination with bot of the above solutions, it is recommended in case of large variations in water temperature (i.e., higher than 5°C) and it allows for energy saving. In fact, lower operating pressures are required at higher water temperatures to produce the same amount of permeate (ref. 2.3.6). Therefore, the VFD will reduce the speed of the high-pressure pump motor to generate a lower discharge pressure. Also, if membranes foul, the VFD automatically adjusts the speed of the high-pressure pump motor to increase the operating

pressure to compensate for membrane fouling pressure loss, which lowers the permeate production. This way, energy costs are minimized until membranes foul.

In addition, on the pressure side, plunger and piston pumps require relief valves to be installed in order to ensure that the maximum allowed pressure will not be exceeded.

Pumps wetted parts materials shall be suitable to the medium to be conveyed, i.e. SS AISI 316Ti or higher grade for metallic components, PVC or HDPE for thermoplastic components, EPDM or PTFE for elastomeric components or ceramic, depending on the feed water or on the chemical solution characteristics.

6.6Valves

As in typical NF/RO membrane filtration units, the following valves are typically installed:

- manual or automatic butterfly or ball inlet valves to isolate the plant for maintenance and preservation;
- in case of centrifugal high-pressure pumps, throttling valves on the pressure side or, in case of plunger high pressure pumps, backpressure valves in dedicated bypass lines from the pumps discharge to the pumps suction to control the feed pressure;
- check valves on the discharge side of low- and high-pressure pumps;
- check valves on the permeate side of every CD module to avoid permeate static backpressure phenomena, which could damage the membrane cushions and the support plates as well the displace O-rings;
- flow control valves on the concentrate manifolds of each membrane filtration train to set the recovery rate. These are designed for a high pressure drop in order to throttle the concentrate flow while minimizing cavitation phenomena;
- if needed (i.e. if the concentrate manifold ends into a drain below the top level of the CD modules pressure vessels), air release valves on the concentrate manifolds of each membrane filtration train at a position higher than the aforementioned level. This allows, after the membrane filtration train has been shut-down, to avoid that CD modules may be emptied due to siphoning effect, which would lead to membrane cushions drying and to water hammer phenomena when restarting the membrane filtration train;

- if needed, check valves on the permeate and concentrate manifolds of each membrane filtration train;
- manual or automatic butterfly or ball valves in the permeate manifolds of each membrane filtration train to enable permeate drain during start-up and cleaning solution recirculation during cleaning phases;
- manual or automatic butterfly or ball valves in the concentrate manifolds of each membrane filtration train to enable cleaning solution recirculation during cleaning phases;
- manual sample ball valves located in multiple positions of each membrane filtration train for water quality monitoring. In particular, sample ports on feed, concentrate and permeate piping of each stage/pass shall be installed to enable system performances assessment and sample ports on each CD module permeate outlet are recommended to facilitate system troubleshooting (ref. 11.2.3).

Regarding valves operation, the following guidelines are to be followed:

- automatic valves shall have adequate actuation time (e.g. 2 s);
- during automatic valves change over, the closed valve shall complete its opening cycle before the open valve closes;
- flow control valves shall fail open;
- flow control valves shall be completely open when pumps are activated.

In particular, the concentrate flow control valves, which set the concentrate pressure and thus the recovery rate of the system, may be:

- manually operated. In this case, a combination of an automatic ball valve, a pressure regulating valve and a needle valve for each membrane filtration train is recommended;
- automatically operated. In this case, one failsafe-open-type valve with pneumatic membrane actuator for each membrane filtration train is recommended.

In general, recommendations on mft P&IDs shall be followed.

Valves materials shall be suitable to the feed water characteristics, i.e. PVC in case of low operating pressures (i.e. up to 10 bar) or AISI 316Ti (e.g. AISI 254SMO) stainless steel in case of high operating pressures (i.e. higher than 10 bar). With the exception of flow control valves, valves size shall match the diameter of the connected piping.

6.7Construction materials

Proper selection of materials of construction is critical for NF/RO membrane filtration units because of the corrosive nature of process streams as well as of cleaning solutions, which can severely limit the equipment useful life. In addition, any equipment located upstream of the membrane filtration unit that undergoes corrosion can release corrosion by-products that could scale and/or damage the NF/RO membranes.

Exterior parts exposed to spillage and/or corrosive atmosphere shall be constructed with suitable materials, i.e. i.e. with a certain corrosion resistance, or coated by painting, galvanizing, rubber coating, etc. Interior parts exposed to process streams, i.e. feed water and/or cleaning solutions, shall be constructed with suitable materials. As well, operating condition (i.e. water temperature, pressure, pH and salinity) shall be accounted for. In addition, suitable maintenance programs shall be established to repair any leakage.

6.8Piping

Low pressure piping (i.e. up to 10 bar) is usually made of schedule 80 PVC-U or HDPE while high-pressure piping (i.e. higher than 10 bar) is usually made of AISI 316Ti or higher grade stainless steel (e.g. AISI 254SMO), depending on the feed water or on the chemical solution characteristics.

Plunger and piston pumps require high-pressure suction and pressure hoses that are usually part of the scope of the supply of the pump's manufacturer. These allow compensating for pulsations and, thus, they are essential for the proper functioning of the system.

In addition, the following general precautions must be taken:

- minimize dead ends;
- size pipes for maximum flow velocities of 2 (plastic pipes) or 3 m/s (metallic pipes);
- in case of metallic pipes, weld by using backing gas in order to minimize crevice corrosion phenomena and ensure a minimum flow velocity of 1.5 m/s to form and maintain a passive film;
- all pressure piping shall be rated at 150% or more than the maximum operating pressure and shall be fully restrained.

In order to avoid excessive foaming phenomena, CIP permeate and concentrate return lines shall extend below the level of the cleaning solution within the CIP tank.

6.9Instrumentation

To ensure proper operation of the membrane filtration unit, a number of control instruments are necessary. These are the same as in spiral-wound NF/RO systems, i.e.:

- flow meters to measure the permeate and concentrate (or feed) flowrates in order to calculate and adjust the recovery rate;
- flow meters to measure the recirculation flowrates in order to verify the membrane crossflow;
- temperature meters to monitor the feed water temperature in order to assess the feed water suitability and to normalize the operating conditions with regard to temperature;
- pressure gauges to monitor the cartridge filters pressure drop, the pumps inlet and discharge pressures and the membrane modules feed, permeate and concentrate pressures. Whenever two or more CD modules are installed in a cluster, one pressure gauge in-between every two subsequent modules shall be provided to help detecting clogging phenomena. Liquid-filled pressure gauges shall contain membrane-compatible fluids (such as water) in place of oils or other water-immiscible liquids;
- pressure switches to monitor the inlet pressure to the high-pressure pump in order to protect it;
- pressure meters to measure the membrane modules feed and concentrate pressures in order to determine the membrane modules pressure drop;
- pH meters to monitor the feed pH in order to assess the feed water suitability and to determine the efficacy of chemical cleaning interventions;
- conductivity meters to measure the feed and permeate conductivity in order to assess permeate quality and salts rejection;
- level meters to measure the water level within the feed, permeate (if any) and concentrate tanks (if any);
- level switches to control the dosing of process reagents (acid, anti-scalant and/or cleaners).

Warning or alarm messages should be automatically activated whenever one or more of the above parameters reach pre-set low-low, low, high and/or high-high values.

Operating conditions (i.e. water temperature, pressure, pH and salinity) shall be considered during selection of the instrumentation equipment. The accuracy of all instruments is also critical. Instruments must be installed and calibrated according to manufacturer recommendations and procedures.

Recommendations on mft P&IDs shall also be followed. Note that inter-stage instrumentation is critical during system troubleshooting. Critical is also the location of sensors, e.g. flow and pressure meters shall be as close as possible to the CD modules and at a sufficient distance from valves or other places of high turbulence.

6.10 Tanks

Storing water in tanks should be generally kept at a minimum. Whenever tanks are used, they shall be protected from dust and microbiological contamination and inlet and outlet connections shall be placed so that no stagnant zones exist. If the latter is not possible, suitable mixing devices shall be installed.

A feed tank is used as a buffer to allow NF/RO membrane filtration units continuous operation in case of discontinuous feed water supply (e.g. during backwash of upstream filters) and/or in case of pH adjustment necessity.

In case of NF/RO membrane filtration units with two stages and/or passes, two possibilities are available:

- directly feed the second membrane stage/pass with a dedicated high-pressure pump;
- use a break tank, followed by dedicated low-pressure and high-pressure pumps. This allows to simplify the plant operation and to reduce the production time loss due to cleaning interventions, but it requires dosing dilute alkaline cleaners via sprinkling system in order to avoid bacteria growth and/or foaming phenomena. This because the first permeate pass quality may quickly deteriorate, thus shortening the life of the second stage/pass NF/RO membranes.

Last but not the least, tanks are needed to perform CIP interventions (ref. 9) and to store process (e.g. acid for pH adjustment and anti-scalant/dispersant) and cleaning chemicals (e.g. acid and alkaline cleaners). Usually, said tanks are made of polypropylene or fiberglass-reinforced plastic (FRP), they allow for complete drainage and they are provided with removable covers.

6.11 Generic layout considerations

Arrangement of equipment on-site shall provide adequate access for maintenance, i.e. removal and replacement of individual equipment items. In particular, fork-lift access shall be provided to process areas, including but not limited to the CD modules skids, CIP units and chemical storage areas.

Adequate clearance on top of the CD modules shall be provided for moving them. Clearance should be at least equal to the length of the CD modules plus a working allowance of 0.50 m.

Feed water, concentrate and permeate manifolds and their connections to the pressure vessels should be designed to facilitate easy access to CD modules. Typically, they are placed above the CD modules skids on a dedicated supporting structure.

No flow restrictions shall be installed within the permeate line from the CD modules to the permeate destination (e.g. permeate buffer tank). Permeate automatic valves may be installed as long as protection measures are in place to avoid that CD modules are brought online without these automatic valves first being opened (ref. 6.12).

Provisions should be made for floor drains near the CD modules skids since cleaning interventions and modules maintenance works may involve the spillage of water.

The location of all valves and instruments should allow their operation, adjustment and maintenance from the normal operating floor level.

Chemical dosing lines shall be as short as possible and without dead-end sections, which may promote micro-organisms growth, and high points, which may become a hazard in case of piping failures. All chemical injection points shall be located at the bottom or at the side of process pipelines. Chemical storage facilities should be located along service roads to make chemical deliveries more convenient.

Service water access, hose connections and hoses shall be provided throughout the plant to ease maintenance operations.

6.12 System automation

Other than electronic instrumentation (ref. 6.9), the operation of NF/RO membrane filtration unit requires a programmable logic controller (PLC) equipped with a human-machine interface (HMI) in order to operate and control a large number of process equipment and subunits. In addition, this control system shall:

- protect the installed equipment;
- keep the sequence and timing of equipment operation;
- operate the installed equipment within the process design limits;
- record and process operational data;
- display relevant information;
- enable controlled intervention by operators.

The main target of the control system is to operate the membrane unit to produce the required permeate flow at the design recovery rate. Two control loops ensure this:

- permeate flow control loop, i.e. regulation of the high-pressure pump motor speed and/or of the throttling/backpressure valve position according to the measured permeate flow rate. The high-pressure pump motor speed and/or valve position shall be changed slowly to prevent water hammer phenomena, which can cause cracks in the supporting plates as well as compaction of the membrane cushions (resulting in lower water fluxes through the membrane cushions at constant pressure). Also, water hammer may wear and/or dislodge O-rings used between membrane cushions and support plates, resulting in leakage of feed water into permeate. Thus, a pressure increase of no more than 0.7 bar/s is recommended;
- recovery rate control loop, i.e. regulation of the concentrate flow control valve position according to the measured permeate and concentrate flow rates (i.e., to the calculated recovery rate).

The control system shall have both manual (i.e. by operators) and automatic control provisions (i.e. by the PLC). At a minimum, the following controls shall be provided:

- membrane unit normal start-up, normal shut-down, emergency shut-down, and cleaning sequence;
- pre-treatment processes (if any);

- low- and high-pressure pumps;
- recirculation pumps (if any);
- ancillary equipment (e.g. automatic valves) and instrumentation;
- chemical dosing systems (acid for pH adjustment and anti-scalant/dispersant) and CIP systems;
- spent cleaning solution neutralization systems (if any).

The control system automatically switches membrane filtration trains on and off according to the capacity demand. This is typically accomplished via level control within the feed tank.

6.12.1 Shutdown conditions

The control system is designed to shut-down all membrane filtration trains whenever operators manually or the PLC automatically initiate(s) a membrane filtration unit shut-down under the following conditions:

- critical common pump failure (pH adjustment dosing pumps, etc.);
- low-low pH-adjustment acid storage tank reagent level (if any);
- feed tank low-low water level;
- feed water temperature and/or pH out of range;
- concentrate and/or permeate holding tank high-high water level;
- service air network low pressure (emergency shutdown condition);
- loss of power.

The control system is also designed to shut down-individual membrane filtration trains whenever the operators manually initiate a membrane train shut-down or automatically under the following conditions:

- critical dedicated pump failure (anti-scalant/dispersant dosing pumps, low-pressure pumps, high-pressure pumps, recirculation pumps, etc.);
- low-low anti-scalant storage tank reagent level (if any);
- high-pressure pump low suction pressure;
- high-high feed pressure (emergency shutdown condition);
- high-high feed electrical conductivity;

- high-high CD modules pressure loss;
- recovery rate out of range;
- permeate flow out of range;
- high-high permeate electrical conductivity;
- train high-high concentrate pressure;
- low-low concentrate flow.

6.12.2 Normal start-up sequence

Generally, the membrane filtration unit normal start-up sequence includes the following phases:

- check if pre-conditions are fulfilled, i.e. if the feed water tank level is higher than low, if feed water temperature and pH are within range, if permeate and concentrate water tanks level is lower than high, etc.;
- if needed, completely open the concentrate flow control valve. This prevents damage from the initial high-pressure pump discharge blast to the installed equipment and CD modules;
- modulate all automatic valves to start-up positions;
- start the low-pressure pump and flush the membrane filtration train with feed water in order to remove any air that could be trapped within piping and CD modules and start chemical dosing pumps (if any, i.e. anti-scalant/dispersant dosing pump). This step usually lasts 3 to 5 min (set-point value adjustable by operators within a specified range), depending on the membrane filtration unit configuration and design;
- start the high-pressure pump with start-up motor speed (if any VFD is provided, set-point value adjustable by operators within a specified range);
- close the concentrate flow control valve to the normal operating position (set-point value adjustable by operators within a specified range);
- start the recirculation pump (if any);
- switch the high-pressure pump into automatic control mode and allow its motor speed and/or throttling/backpressure valve position adjustment according to the permeate flow control loop (ref. 6.12);
- switch the concentrate flow control valve into automatic control mode and allow their position adjustment according to the recovery rate control loop (ref. 6.12). Now the membrane filtration train is operating at nominal conditions.

6.12.3 Normal shut-down sequence

Upon initiation by operators or the PLC, the membrane filtration train normal shut-down sequence includes the following phases:

- remove control loops from automatic control;
- reduce the high-pressure pump motor speed to minimum and/or open the throttling/ backpressure valve to maximum;
- stop the high-pressure pump;
- stop the recirculation pump (if any);
- stop the low-pressure pump and chemical dosing pumps (if any);
- completely open the concentrate flow control valve;
- perform the flushing sequence:
  - fill the CIP tank with chlorine-free service water;
  - modulate all automatic valves to flushing positions;
  - start CIP pumps (if any) or the low-pressure and recirculation pumps;
  - start the flushing timer (set-point value adjustable by operators within a specified range). During this phase, if needed, refill the CIP tank with chlorine-free service water;
  - wait until the CIP tank is empty;
  - stop CIP pumps (if any) or the low-pressure and recirculation pumps;
- completely open the concentrate flow control valves;
- now the membrane train is in offline mode (in case of initiation by operators) or in standby mode (in case of initiation by the PLC).

6.12.4 Emergency shut-down sequence

Upon initiation by operators or the PLC, the membrane filtration train emergency shut-down sequence includes the following phases:

- remove control loops from automatic control;
- stop all pumps;
- completely open the concentrate flow control valve;
- modulate all automatic valves to offline positions;

- now the membrane train is in offline mode.

In case of power outage, all the rotating equipment stops immediately and most of automatic valves open. This means that the operating pressure is suddenly released and water hammer phenomena take place, which may damage CD modules, pumps, valves and sensors. Therefore, the continuity of the energy supply shall ensure at minimum the safe completion of the emergency shut-down procedure (if needed, this may be achieved via the installation of an adequately-sized dedicated UPS unit).

6.12.5 Cleaning sequence

Upon initiation by operators or the PLC, the membrane filtration train cleaning sequence includes the following phases:

- flush the selected membrane filtration train with chlorine-free service water (ref. 6.12.3);
- prepare the cleaning solution within the CIP tank:
    - fill the CIP tank by using chlorine-free service water as make-up water;
    - start the selected cleaning formulation dosing pumps. This step usually lasts up to 15 min (set-point value adjustable by operators within a specified range), depending on the membrane filtration unit configuration and design;
    - if needed, heat the cleaning solution up to the desired temperature value (set-point value adjustable by operators within a specified range);
- modulate the cleaning unit and selected membrane filtration train automatic valves to CIP positions;
- start the CIP pump (if any) or the selected membrane filtration train low-pressure and recirculation pumps;
- start the recirculation timer (set-point value adjustable by operators within a specified range). This step usually lasts 30 to 60 min;
- open the automatic CIP discharge valve;
- close the automatic CIP concentrate recirculation valve;
- wait until the CIP tank is empty;
- stop the CIP pump (if any) or selected membrane train low-pressure and recirculation pumps;

- flush the selected membrane filtration train with chlorine-free service water (ref. 6.12.3);
- if needed, repeat the above nine steps with the next cleaning formulation;
- now the selected membrane train is in offline mode (in case of initiation by operators) or in standby mode (in case of initiation by the PLC).

To automatically initiate a cleaning intervention, the cleaning triggers listed in chapter 9 are commonly used.

6.12.6 Conservation sequence

Conservation (or lay-up) is necessary if the membrane train is in standby or offline mode for more than 2 days. Upon initiation by operators or the PLC, the membrane filtration train conservation sequence includes the following phases:

- perform a complete cleaning sequence (ref. 6.12.5);
- prepare the conservation solution (1% w.t. food-grade SMBS, ref. 10.1.1) within the CIP tank:
    - fill the CIP tank by using chlorine-free service water as make-up water;
    - start the conservation chemical dosing pumps. This step usually lasts up to 15 min (set-point value adjustable by operators within a specified range), depending on the membrane filtration unit configuration and design;
- modulate the cleaning unit and selected membrane filtration train automatic valves to conservation start positions;
- start the CIP pump (if any) or the selected membrane filtration train low-pressure and recirculation pumps;
- start the conservation timer (set-point value adjustable by operators within a specified range). This step usually lasts 30 to 60 min;
- during the above step, ensure that air within the membrane filtration train is minimized after the conservation is completed, e.g. by allowing the conservation solution to overflow through an open valve located higher than the upper end of the highest CD module;
- open the automatic CIP discharge valve;
- close the automatic CIP concentrate recirculation valve;
- wait until the CIP tank is empty;

- stop the CIP pump (if any) or the selected membrane filtration train low-pressure and recirculation pumps;
- modulate the cleaning unit and selected membrane train automatic valves to conservation end positions to prevent air from entering the CD modules;
- now the selected membrane filtration train is in offline mode.

After the completion of the conservation sequence, periodically operators shall perform the checks listed at paragraph 10.1.2.

6.12.7 Alarms and warnings

In addition to the shutdown conditions (ref. 6.12.1) and their corresponding alarms, some common additional warnings and alarms are the following:

- feed tank high water level;
- feed water temperature and/or pH out of range;
- low anti-scalant storage tank reagent level;
- concentrate and/or permeate holding tank high water level;
- high feed pressure;
- low feed electrical conductivity;
- high feed electrical conductivity;
- high modules pressure loss;
- recovery rate out of range;
- permeate flow out of range;
- low permeate electrical conductivity;
- high permeate electrical conductivity;
- high concentrate pressure;
- low concentrate flow.

6.13 Miscellanea

The ability to clean each membrane filtration stage/pass individually is very important. This allows to maximize the cleaning efficiency, by optimizing the cleaning protocol for each stage/pass and by allowing for proper flow rates through the CD modules within each stage/pass. Thus, automatic valves in sufficient number should be installed to allow for cleaning of each membrane stage/pass individually.

Clean, dry service air to actuate automatic pneumatic valves shall be supplied by oil-free compressors equipped with air dryers, air control stations and dedicated piping.

7. Handling and installation

This chapter describes the required handling and installation procedures.

7.1 Preliminary requirements

7.1.1 Documents

Before installing the CD modules, make sure to have the following documents at hand:

- general arrangement plan;
- plot plan;
- process flow diagrams (PFDs);
- process and instrumentation diagrams (P&IDs);
- CD modules arrangement drawings;
- electrical and control schemes;
- membrane filtration unit equipment list.

7.1.2 Site requirements

Ensure that:

- civil engineering works have been completed;
- electricity supply is available for use;
- pre-treatment units have been completed and are available for use;
- feed, permeate and concentrate manifolds as per the installation documentation have been completed;
- feed, permeate and concentrate hoses as per the installation documentation have been installed;
- a reserved lay-down area for proper CD modules unloading is available;
- arrangements have been made for the disposal of flush water, concentrate water, drain water and spent cleaning solutions;
- all chemicals for proper membrane filtration unit operation are available for use;
- any water used for clean water testing is of potable water quality and free of chlorine;

- all connecting pipes have been purged and flushed;
- any debris that falls into tanks is immediately removed;
- service air filtration is performed at compressors inlet in order to protect the compressor themselves and the automatic pneumatic valves.

7.1.3 Personnel requirements

When handling CD modules, minimum 2 qualified millwrights are needed.

During most of the membrane filtration unit assembly, minimum 2 qualified millwrights are needed as well as one or more qualified electricians to verify that all the previously installed equipment and to wire the newly installed equipment.

When commissioning the membrane filtration unit, qualified electricians, pipefitters, millwrights and final operators are required on-site.

7.2 Handling

7.2.1 Packing information

CD modules are packed inside metal transportation skids and weatherproofed by a plastic wrapping. The dimensions of said skids depend on the number of CD modules to be installed.

Wet-shipped CD modules are preserved with a 1% w.t. sodium metabisulphite (SMBS) solution and they are sealed with gas-tight plastic caps on the feed, permeate and concentrate connections. This to prevent biological growth phenomena during storage and shipping. Dry-shipped CD modules are filled with 200 mL of potable water free of chlorine (to maintain the recommended humidity level within the CD module) and they are sealed with gas-tight plastic caps on the feed, permeate and concentrate connections.

	Removal of the gas-tight plastic caps is allowed only if clean water testing or operation starts immediately!

7.2.2 Tools

The following items and equipment should be available on site:

- forklift with forks extensions rated for the transportation skids weight to safely move said skids;
- appropriate protective clothing and equipment;
- laser level to ensure that the required tolerances are achieved;
- digital camera or smartphone to document the transportation skids conditions.

7.2.3 Transportation

To preserve CD modules during transport, the following precautions must be taken:

- keep environmental temperature from 5 to 35°C (optimum 5 to 20°C) and humidity lower than 60%. Use an air-conditioned and/or heated trailer if these requirements can't be guaranteed;
- avoid exposure to rain and/or wind;
- avoid exposure to direct sunlight;
- place transportation skids on a level surface and prevent them from falling or overturning;
- avoid unpaved roads since excessive vibrations may damage the CD modules. If this is unavoidable, drive at sufficiently low speed.

	The CD modules must be transported inside the original transportation skids!

- the CD modules must be transported in an upright, standing position.

7.2.4 Loading and unloading from shipping containers

To preserve the CD modules during loading and unloading operations from shipping containers, the following precautions must be taken:

- do not hoist the transportation skids. Use forklift or cranes and chains or slings rated for the skids weight in order to move them;

- when using forklifts and/or cranes, make sure that all devices are certified and regularly inspected and that all operators are certified;
- place transportation skids on a level surface and prevent them from falling or overturning;
- do not stack transportation skids;
- do not stand or sit on the top of transportation skids;
- do not stand underneath transportation skids.

After unloading the transportation skids, check that:

- all items have been delivered as per the packing list;
- no damage has been caused by the transportation;
- all transportation skids have not been previously opened.

In case of damage observed and/or caused during skids loading, transportation and/or unloading operations, report it immediately to mft.

	Wear adequate personal protective equipment (PPE)!

The Customer has to fill the “CD Module Shipment Status” document, which states the conditions of the transportation skids. This document has to be digitally transmitted to mft within 2 working days from the CD modules delivery. After that period, mft will consider the equipment shipment completed successfully.

7.2.5 Storage

The Customer must provide all the facilities and services required for storage, protection, and security of all the equipment delivered by mft.

To preserve the CD modules during storage, the following precautions must be taken:

- arrange indoor storage with environmental temperature from 5 to 35°C (optimum 5 to 20°C) and humidity lower than 60%. If the CD modules are to be stored outdoor, use a weatherproofed and well-vented shelter;
- avoid exposure to direct sunlight;

- avoid exposure to rain, wet conditions and/or dew condensation;
- ensure protection from extreme heat and winds;
- avoid storage where insects or small animals may enter the transportation skids. If needed, take measures to prevent them from doing so;
- prevent transportation skids from falling or overturning;
- do not put any heavy object on top of transportation skids;
- do not store the CD modules in a laying position, outside of transportation skids;
- avoid excessive vibrations and collision of transportation skids with other objects.

Wet-shipped CD modules may be stored for 3 months: after this time, the conserving solution must be visually inspected for biological growth, i.e. it shall appear clear. Meanwhile, every month, the pH of the conservation solution shall be checked to verify that it never drops below 3. Otherwise, the conserving solution shall be replaced (ref. 10.1). Note that a pH decrease of the conservation solution occurs when bisulphite is oxidized to sulfuric acid.

7.3 Installation

7.3.1 Initial preparation

CD modules unpacking operations must be performed inside designed areas, on a dry level surface.

7.3.2 Tools

The following items and equipment should be available on site:

- forklift with forks extensions rated for the transportation skids weight to safely move said skids;
- hoist or crane with slings and lifting bracket rated for CD modules weight to safely lift said modules out of the transportation skids;
- appropriate protective clothing and equipment;
- no. 1 box cutter to remove the plastic wrapping;
- no. 1 x 13 mm wrench to open the transportation skids;
- no. 1 x 3/8" Rp safety hoist ring rated for the CD modules weight;
- no. 1 laser level to ensure that required tolerances are achieved;

- digital camera or smartphone to document the CD modules conditions.

7.3.3 Unpacking

CD modules are shipped in metal transportation skids (ref. 7.2.1). CD modules must remain packed until the installer is ready to install them within the membrane filtration unit.

Unpack CD modules in presence of an mft representative to monitor the process and to verify that site preparations (ref. 7.1) have been satisfactorily completed. Failure to do so may affect the CD modules warranty.

	At least two people are required to unpack CD modules!

CD modules shall be unpacked by lifting them out of the transportation skids through a hoist or a crane. To lift the CD modules, an adequate lifting device (e.g. 3/8" Rp safety hoist ring rated for the CD modules weight) must be used.

7.3.4 Moving

To preserve the CD modules while being moved, the following precautions must be taken:

- ensure that the necessary planning and precautions have been arranged to safely move the CD modules;
- when using hoists or cranes, make sure that all devices are certified and regularly inspected and that all operators are certified;
- move the CD modules slowly and avoiding interruptions and swings, handling them with extreme care;
- place the CD modules on a level surface and prevent them from falling or overturning;
- do not stand underneath the CD modules;
- do not damage any CD module component.

7.3.5 Initial inspection

Before installing the CD modules, check that:

- all preparatory works have been completed (e.g. painting, coating, metal working, welding, drilling, sand blasting, wiring, etc.);
- all piping, accessories and equipment have been properly installed in accordance with the supplied P&ID and equipment list;
- all piping, accessories and equipment are compatible with design pressures and pH ranges;
- all piping, accessories and equipment are made of corrosion resistant materials;
- installed instrumentation allows proper operation and monitoring both of the pre-treatment units and of the membrane filtration unit;
- pumps are ready for operation (i.e. aligned, lubricated and with proper rotation direction);
- new cartridge filters are properly installed directly upstream of the high-pressure pumps;
- chemical dosing points are properly located;
- chemical dosing lines check valves are properly installed;
- provisions to ensure proper mixing of chemicals exist;
- if chlorine is used, provisions to remove it upstream of the membrane filtration unit exist;
- pressure relief protections are installed;
- all foreign matter inside any process tanks has been removed;
- all connecting pipes have been purged and flushed;
- provisions for sampling raw water, feed, permeate and concentrate streams from each stage exist;
- connections both for normal operation and chemical cleaning exist;
- CD modules are secured to the installation skids;
- provisions for sampling permeate from individual CD modules exist;
- CD modules are protected from temperature extremes (i.e. freezing, direct sunlight, heater exhaust, etc.);
- no leftover parts exist;
- no visible defects are present;
- no loose or missing nuts and/or bolt exist;
- no rust spots are present.

7.3.6 Installation precautions

To preserve the CD modules while being installed, the following precautions must be taken:

- ensure that the necessary planning and precautions to safely move the CD modules have been arranged;
- when using hoists or cranes, make sure that all devices are certified and regularly inspected and that all operators are certified;
- move the CD modules slowly and avoiding interruptions and swings, handling them with extreme care;
- place the CD modules on a level surface and prevent them from falling or overturning;
- do not stand underneath the CD modules;
- use appropriate tools and care for tightening and loosening bolts and/or nuts;
- use a laser level to ensure the required tolerances are achieved;
- be careful not to trap your fingers between the CD module parts;
- do not damage any CD module component.

7.3.7 Installation

To install the CD modules, the following steps shall be taken:

- place the CD modules on the desired positions within the dedicated installation skids;
- check the CD modules levelling. In particular, every CD module shall be installed vertically and perpendicular to the basement of the corresponding installation skid. The maximum allowable levelness error is equal to 3‰ in both longitudinal and transversal directions;
- connect the feed, permeate and concentrate hoses to the CD modules. Refer also to the installation drawings. Before completing said connections, purge and flush feed, permeate and concentrate manifold and hoses at their design flowrate in order to remove any construction residual.

8. System operation

Long-term performance of the membrane filtration unit depends on proper commissioning, operation and maintenance. In fact, fouling phenomena minimization is achieved not only just through proper system design, but also through proper system commissioning, operation and maintenance.

In addition, complete and accurate record keeping and data normalization are required to determine the actual plant performance and, whenever necessary, to enable corrective measures.

8.1 Initial start-up

8.1.1 Required equipment

The following equipment is recommended:

- appropriate protective clothing and equipment;
- portable thermometer;
- portable pH meter;
- portable conductivity meter (with a measuring range from the permeate to the concentrate conductivity values);
- adequate chemicals for membrane filtration unit operation (e.g. anti-scalant/dispersant), cleaning and conservation;
- bottles for water sampling (HDPE, 125 mL at least) in sufficient number to follow the recommended monitoring plan (ref. 8.8.2).

Note that this should also be part of the equipment at the site.

8.1.2 Preliminary checks

After having installed the CD modules and before starting up the membrane filtration unit, make sure that the whole pre-treatment section is working in accordance with the specifications. If pre-treatment units involve raw water chemical conditioning, a full analysis of the water entering the membrane filtration unit must be performed. Furthermore, absence of chlorine must be determined.

The raw water to the membrane filtration unit must be as stable as possible regarding quantitative (i.e. flow) and qualitative (i.e. temperature, pH, electric conductivity, etc.) characteristics.

The following checks are recommended before performing the initial membrane filtration unit start-up:

- retighten the nuts on top of the permeate anchor connection by using a torque wrench locked at 110 N·m
- all pre-treatment units are purged and flushed. If present, multimedia filters are also backwashed;
- the feed water qualitative characterization matches the design data;
- chemical storage tanks are filled with the appropriate chemical solutions (i.e. active chemical principle and dilution);
- feed, permeate and concentrate piping are properly connected;
- instruments are properly working and calibrated;
- pressure relief valves are correctly set;
- set-point values, interlocks and alarms are properly set;
- provisions exist for preventing the membrane filtration unit from operating when the feed water chemical conditioning dosing pumps are inactive;
- provisions exist for preventing the feed water chemical conditioning dosing pumps from operating when the membrane filtration unit is inactive;
- all major equipment (i.e. pumps, compressors, sensors, control systems, etc.) is working properly;
- no leakages of water and/or service air from tanks and/or pipes take place;
- the permeate line is open.

Results of the above checks must be included in the start-up report (ref. 8.8.1).

8.1.3 Initial start-up sequence

Proper start-up of the membrane filtration unit is essential to prevent module and membrane damages due to excessive pressures or flowrates and/or hydraulic shocks. In addition, measurement of the initial performance is important to set benchmark values against which future operating performance will be evaluated.

The typical membrane filtration unit initial start-up sequence is as follows:

- check if pre-conditions are fulfilled, i.e. if the feed water tank level is higher than low, if feed water temperature and pH are within range, if permeate and concentrate water tanks level is lower than high, etc.;
- if any, completely open the feed throttling/backpressure valve and the concentrate flow control valve;
- modulate all automatic and hand valves to start-up positions;
- start the low-pressure pump and flush the membrane train with feed water in order to remove any air that could be trapped within piping and pressure vessels. If needed, open the venting ports and start and stop the flushing procedure several times in order to remove any remaining air pocket to the outlets. In fact, continuous flushing may end up pressurizing air pockets only;
- wait for 30 min and check all pipe and valves connections for leakages. Tighten connections where necessary;
- start the chemical dosing pumps (if any, i.e. anti-scalant/dispersant dosing pump);
- if any, nearly close the feed throttling/backpressure valve (to have a feed pressure lower than 6 bar) or, if any, set the high-pressure pump VFD to operate at minimum allowed frequency;
- start the high-pressure pump;
- start the recirculation pump (if any);
- slowly open the feed throttling/backpressure valve (if any) or increase the high-pressure pump VFD frequency (if any). Do not increase the feed pressure more than 0.7 bar/s to avoid damaging the CD modules;
- slowly close the concentrate flow control valve;
- repeat the two above steps until the permeate and concentrate flowrates operating set-point values are reached;
- compare the feed pressure, the permeate flowrate and the recovery rate with their design values;
- check the chemical dosing effectiveness. If acid dosing is performed, check the feed water pH;

- wait for 60 min and write down all operating parameters in the membrane filtration train log sheet (ref. 8.8.1);
- check the permeate conductivity of every CD module. If this doesn´t meet the expectations, investigate the causes and perform any required corrective action (ref. chapter 11);
- wait for 24 to 48 hours. During this time, every hour, write down all operating parameters in the membrane filtration train log sheet (ref. 8.8.1) and, after 10 hours (and every 200 h), check the CD modules torque loading on the modules (ref. 4). Before measuring this parameter, the membrane filtration train must be switched off and the water pressure must be released;
- review all the measured operating parameters by comparing them to the design values to assess the membrane filtration train performance;
- take samples of feed, permeate and concentrate water for laboratory analyses;
- check all tanks, pipe and valves connections for leakages. If necessary, tighten connections;
- confirm the proper operation of all the major equipment and of all safety devices;
- check all membrane filtration unit process automations, i.e. all control loops and their alarms;
- lock the system into automatic operation mode.

The data obtained during initial start-up serve as a reference for evaluating future system performance. In particular, permeate flow, membrane permeability, salts passage and CD module pressure loss are to be normalized (ref. 8.9).

Also, during this phase, it is advisable to find an empirical correlation between field measured conductivity and laboratory measured TDS contents within feed and permeate streams.

Last but not the least, it is highly recommended to profile the permeate conductivity (ref. 11.2.3) of each membrane filtration train in order to establish a baseline for future evaluations.

8.1.4 Membrane performances

The start-up performance of a NF/RO membrane filtration unit and the time required to reach the stabilized performance depends on the prior membrane storage conditions.

If properly stored, dry- and wet-preserved membranes reach the same stabilized performance after some hours or a few days of operation (up to 2 weeks). Generally, wet-preserved membranes stabilize faster than dry-preserved membranes. A decline in membrane permeability and an increase in solutes rejection rate is observed due to membrane cushions compaction.

8.2 Normal start-up sequence

The normal start-up sequence is similar to the initial start-up one (obviously, leakages control and baseline performance assessment may be avoided) and it is automated through the use of the PLC and automatic valves (ref. 6.12.2).

	Wet-shipped CD modules shall be cleaned with an alkaline cleaner before the membrane filtration unit is started up!

8.3 Normal operation

A membrane filtration unit is designed on the basis of a defined set of data such as the feed water quantitative and qualitative characterization. In reality, its operation has to be flexible enough to respond to the changing feed water characterization.

Note that NF/RO membrane filtration units operate best when flows and recovery rates are held constant since both parameters were selected with attention to other process variables such as the required crossflow. Adjustment of flowrates and recovery rates without considering all the other process variables leads to accelerated fouling, which results in higher cleaning frequencies and - ultimately - in higher membrane replacement rates.

Usually, NF/RO membrane filtration units are operated at constant permeate flowrates. Any change in the water flux, e.g. due to feed water temperature changes or membrane fouling phenomena, is compensated by adjusting the feed pressure. However, the maximum specified feed pressure shall not be exceeded and the excessive build-up of fouling shall be avoided (ref. chapter 9).

If the feed water analyses show an increase of the fouling potential, the recovery rate has to be decreased and/or pre-treatment units performances shall be enhanced.

Normally, the NF/RO membrane filtration unit capacity is designed to meet the peak feed flow. Thus, membrane filtration units adjustment means to shut it down when no feed water is available. Large plants are split up into a number of identical membrane filtration trains (ref. 6.1), therefore the number of membrane filtration trains in service can be adjusted to the needs. Despite this, since a high start/stop frequency can decrease the membranes performance and lifetime, feed water equalization is recommended to ensure a more constant operation. Reducing the feed flow through VDFs on the high-pressure pumps is another possibility. In this case, during low flow operation, attention shall be paid that the minimum required crossflow is maintained.

The aim is to operate the membrane filtration unit in such a way to have stable operation from one cleaning intervention to the next one while meeting the target permeate flowrate and quality. Usually, the longer the operation cycle (i.e. the time interval between two consecutive cleaning interventions), the higher the membrane filtration unit production and the lower the chemical consumption.

In practice, the recovery rate of NF/RO membrane filtration units is adjusted via the concentrate flow control valve. Throttling this valve results in higher operating pressures, which forces more water through the membrane instead of leaving as concentrate. Thus, higher permeate flowrates and recovery rates may be achieved. Exceeding the design recovery rate may result in accelerated membrane fouling. On the other hand, falling below the design recovery rate does not adversely impact membrane fouling but it results in higher concentrate flowrates to be handled.

During normal operation, data shall be collected as per paragraph 8.8.

8.3.1 Membrane performances

Once stabilized, membrane performances vary as follows:

- the higher the feed water quality (i.e. the lower the feed concentrations), the lower the fouling potential and the concentration polarization phenomena and the higher the water flux. Consequently, the higher the permeate flowrate and quality and the lower the concentrate flowrate. Lower feed water quality may be compensated by increasing the operating pressure as long as the maximum pressure set-point is reached and fouling phenomena are within the acceptable limit;

- the higher the water temperature, the higher the water flux and the slightly lower the solutes rejection rate. Consequently, the higher the permeate flowrate and the lower the concentrate flowrate as well as the permeate quality. Usually, changes in water temperature are dealt with by adjusting the operating pressure, i.e. by increasing it when the water temperature decreases. Note that, for increasing water temperatures, the operating pressure may be reduced until the tolerated permeate quality is not exceeded or a number of CD modules shall be taken out of service (ref. 8.4 and 10);
- according to the pH of the feed/concentrate stream, the solutes rejection rate changes (ref. 3.1.2). Note that the permeate pH is usually lower than the feed pH due to carbonate and bicarbonate rejection by the membrane;
- the higher the operating pressure, the higher the water flux and the recovery rate. Consequently, the higher the permeate flowrate and quality and the lower the concentrate flowrate;
- the higher the recovery, the higher the fouling potential and the concentration polarization phenomena and the lower the water flux and the time interval between two subsequent cleaning interventions (and, thus, the membranes lifetime). Note there is a higher limit to recovery rates due to fouling phenomena due to the increase of the feed/concentrate concentrations;
- the higher the crossflow, the lower the fouling potential and the concentration polarization phenomena and the higher the water flux. Consequently, the higher the permeate flowrate and quality and the lower the concentrate flowrate;
- the longer the standby time in presence of feed water within the CD modules, the higher the fouling potential. Hence, the importance of flush interventions and/or membrane conservation in case of membrane filtration unit standby or shutdown (ref. 8.6 and 10).

Given the tendency to increase the permeate flowrate shortly after start-up or after a successful alkaline membrane cleaning intervention (i.e. when membranes are performing their best), if changes are made without taking into account fouling phenomena, this will lead to increased membrane cleaning interventions frequency and, ultimately, to shorter membranes lifetime.

8.4 Normal shut-down

Whenever the membrane filtration unit undergoes normal shut-down (i.e. because of lack of feed flow), it must be flushed preferentially with service water in order to remove the highly fouling water from the feed/concentrate side of the CD modules. The normal shut-down sequence is automated through the use of the PLC and automatic valves (ref. 6.12.3).

⚠	In case multiple membrane filtration trains are running in parallel, the train to be shut-down shall be isolated from common manifolds via check and/or isolation valves!

Whenever the membrane filtration unit must be shut down for less than 48 hours, it shall be flushed (stand-by flushing, ref. 8.6) every 15 minutes to every 24 hours, depending on the operating conditions (i.e. the higher the feed water temperature and solutes concentration, the higher the stand-by flushing frequency).

Whenever the membrane filtration unit must be shut down for more than 48 hours, it shall be put under conservation (ref. 10).

8.5 Emergency shut-down

In case of emergency shut-down, its cause(s) shall be identified and solved (ref. 11). Then, a flushing (ref. 8.6) and/or a cleaning intervention (ref. 9) shall be manually started.

8.6 Flushing

Flushing is typically used:

- when the membrane filtration train goes offline (i.e. normal shut-down, ref. 8.4). The purpose of the offline flushing is to get rid of feed water compounds and chemicals within the feed/concentrate stream, which may promote fouling phenomena and/or equipment deterioration;

- intermittently during the membrane filtration train stand-by time. The stand-by flushing allows to stir up compounds that may have settled on the membrane during the membrane filtration unit downtime and wash them away, thus reducing fouling phenomena;
- during cleaning interventions (ref. 9).

Flushing is performed by using service water, free of any chemical and by using low-pressure pumps or CIP pumps (if any). It is performed at low pressure (ca. 3 to 4 bar) by passing through de-energized high-pressure pumps in order to avoid permeate production, which would increase the solutes concentration within the feed/concentrate water. Flushing is performed at a high flowrate, without exceeding the maximum feed flowrate per CD module (ref. "CD Module Datasheet"), and it shall last long enough to replace 2 to 3 empty volumes of the whole membrane filtration, including piping, valves and pumps in addition to the CD modules (i.e. typically it lasts 5 to 10 minutes). The resulting flushing water is sent to drain and it shall not be recirculated upstream of the membrane filtration unit.

8.7 Pre-treatment units

Following are listed a few recommendations to properly operate the pre-treatment units:

- in case of changing feed water quality, pre-treatment units set-points may have to be adjusted;
- avoid excessive storage times of short shelf-life chemicals (i.e. sodium bisulphite solutions);
- ensure the correct anti-scalant/dispersant dosage. This is of utmost importance since its under-dosage favors scaling phenomena while its over-dosage may lead to the anti-scalant/dispersant deposition on the membrane surface;
- weekly check that cartridge filters are properly seated and change them whenever their pressure losses are higher than 0.8 bar (and minimum every 3 months);
- upon start-up of new cartridge filters, send to drain the initial effluent of the cartridge filtration unit in order to prevent membrane fouling due to the substances used during cartridge filters manufacturing (e.g. textile aides, surfactants, lubricants and/or emulsifiers). Check the published guidelines of the cartridge filters manufacturer.

8.8 Record keeping

In order to track the membrane filtration unit performance evolution over time, it is necessary to monitor and record all relevant data. Note that site-dependent factors are not considered in this document. Thus, please refer also to the O&M manual of your plant.

8.8.1 Membrane filtration unit start-up report

This report shall comprise at minimum the following information:

- description of the entire plant;
- PFD, P&ID and equipment list of the entire plant;
- results of checks as per paragraph 8.1.2;
- calibration data of all gauges and meters based on manufacturers recommendations;
- initial performance of pre-treatment units and membrane filtration unit. In particular, the very same operating data as per normal operation (ref. 8.8.2) as well as feed, concentrate and permeate qualitative characterization via laboratory analyses are needed;
- relevant pictures of the plant during start-up.

8.8.2 Membrane filtration unit operating data

The following table lists the main data that shall be monitored and recorded in order to determine how the membrane filtration unit is operating.

Table 6. Minimum recommended monitoring protocol for the membrane filtration unit. Date and time of data logging shall be indicated as well

Location	Parameter	Frequency
Membrane filtration unit (every stage/pass)	Operating hours	Daily
	Number of CD modules in operation	Daily
Inlet	Temperature	Continuously / Daily
	pH	Continuously / Daily
	Anti-scalant dosage	Daily
Feed (every stage)	Pressure	Continuously / Daily
	Conductivity	Continuously / Daily

Location	Parameter	Frequency
Permeate (every stage)	Flow	Continuously / Daily
	Pressure	Continuously / Daily
	Conductivity	Continuously / Daily
Recirculation (every stage)	Flow	Continuously / Daily
Concentrate (every stage)	Flow	Continuously / Daily
	Pressure	Continuously / Daily
Calculated (every stage/pass)	Module pressure loss	Daily
	Water flux	Daily
	Recovery rate	Daily
	Salts rejection rate	Daily

where the module pressure loss may be approximated as follows:

$$\Delta p_m = p_f - p_c$$

In addition to the above, the feed water quality must be daily assessed with field instrumentation. At least once per month, it is also recommended to perform the following controls:

- laboratory analysis of the project design data (e.g. pH, COD, NH_4^+, etc.) and of the TDS composition within feed and permeate streams. With these data, the empirical relationship between conductivity and TDS content shall also be checked;
- conductivity profiling of each membrane filtration train (ref. 11.2.3).

Also, all relevant operational events shall be recorded for future reference, e.g. if any CD module has been taken out of service because of maintenance interventions.

Last but not the least, when performing cleaning interventions (ref. 9), their relevant parameter shall be recorded as well, i.e. type and concentration of cleaners and cleaning operating conditions (phases duration, temperature, pressures, pH and flowrates). The same applies to conservation interventions (ref. 10), i.e. type and concentration of conserving agents and conservation operating conditions.

8.8.3 Pre-treatments operating data

Since the membrane filtration unit performances depend largely on the proper operation of the pre-treatment units, their operating data shall be monitored and recorded as well.

Typically, the following variables are of interest:

- feed chlorine concentration (if chlorination is performed upstream of the membrane filtration unit);
- pressure drop of all filters (e.g. multi-media and cartridge filters);
- consumption of chemicals;
- periodic calibration of all instruments based on manufacturers recommendations;
- any unusual event (e.g. malfunctioning and/or shutdown).

8.8.4 Maintenance logs

Maintenance logs shall include the following information:

- routine maintenance operations, such as:
    - maintaining the CD modules torque loading on the modules (ref. 5) to avoid damages to membrane cushions and support plates (check every 200 h);
    - checking the accuracy of automatic valves positioning indicators;
    - cleaning and calibrating critical instruments at least monthly, e.g. pH sensor measurements shall be compared with readings from a portable pH meter at least weekly and - in case of deviations greater than 20% - pH electrodes shall be cleaned and calibrated according to the manufacturer instructions;
    - cleaning and calibrating all the other instruments at least yearly;
    - comparing pressure gauges measurements with readings from pressure transmitters at least weekly. In case of deviations greater than 5%, pressure gauges shall be cleaned or replaced and/or pressure transmitters shall be cleaned and calibrated according to the manufacturer instructions;
    - calibrating dosing pumps at least yearly;
    - plant-wide checking via mass balances at least monthly, e.g. properly calibrated flow meters shall have less than 5 to 10% difference between the total flow rate of water

supplied to the plant (i.e. feed flow) and the total flow rate of water leaving the plant (i.e. permeate and concentrate flows);

- mechanical failures and replacements;
- any change of CD modules locations with their serial numbers;
- replacements or additions of the membrane filtration unit ancillary equipment, e.g. high-pressure pumps, by indicating date, brand name and type and nominal relevant characteristics;
- replacement or additions of pre-treatment equipment, e.g. cartridge filters, by indicating date, brand name and type and nominal relevant characteristics;
- chemical cleanings interventions (ref. 9) by recording date, cleaning chemicals type and concentration, cleaning protocol (i.e. recirculation and soaking times, sequences of cleaners, etc.) and measured data (i.e. flowrates, temperatures, pressures and pH values during cleaning, performances after cleaning, etc.).

In particular, the importance of instruments calibration cannot be over emphasized since membrane filtration units operation is highly automated and, thus, dependent on instruments accuracy. Consequently, many operational problems can be avoided by implementing an adequate instrumentation calibration program.

8.9 Data normalization

Membrane filtration unit performances are influenced by the feed water temperature and composition and by the operating pressure and recovery rate. In order to distinguish early enough between such normal factors and fouling phenomena or other problems, the measured membrane permeability, solutes passage and CD module pressure loss have to be normalized to the given reference performance (i.e. during initial start-up, ref. 8.1.3).

The measured membrane filtration unit performance at operating conditions can be transferred to reference (subscript "ref") conditions via the following calculations:

- normalized permeate flow ($q_{p,t,ref}$):

$$q_{p,t,ref} = q_{p,t} \times \frac{N_{m,ref}}{N_m} \times \frac{TCF_{ref}}{TCF} \times \frac{NDP_{ref}}{NDP}$$

where N_m and $N_{m,ref}$ are - respectively - the number of CD modules currently in service and the number of CD modules in service at reference conditions;

- normalized membrane permeability ($K_{w,ref}$):

$$K_{w,ref} = K_w \times \frac{TCF_{ref}}{TCF}$$

- normalized solutes passage (Pas_{ref}):

$$Pas_{ref} = Pas \times \frac{q_{p,t}/N_m}{q_{p,t,ref}/N_{m,ref}} \times \frac{C_{fc,ref}}{C_{fc}} \times \frac{TCF}{TCF_{ref}} \times \frac{C_f}{C_{f,ref}}$$

- normalized CD module pressure loss ($\Delta p_{m,ref}$):

$$\Delta p_{m,ref} = \Delta p_m \times \frac{\left(2 \times q_{c,t,ref} + q_{p,t,ref}\right)^{1.5}}{\left(2 \times q_{c,t} + q_{p,t}\right)^{1.5}}$$

where the CD module pressure loss may be approximated as follows:

$$\Delta p_m = p_f - p_c$$

Refer to paragraphs 2.3 and 6.4 about how to determine the above parameters. For sake of simplicity, to calculate the net driving pressures, the osmotic pressures may be approximated as follows (DOW, 2020):

$$\Pi = [bar] = \begin{cases} \dfrac{C \times (T + 320)}{491{,}000} & if\ C < 20{,}000\ ppm \\ \dfrac{0.0117 \times C - 34}{14.23} \times \dfrac{T + 320}{345} & if\ C > 20{,}000\ ppm \end{cases}$$

where T is the water temperature expressed in [°C].

By graphing the above variables (i.e. normalized membrane permeability, normalized solutes passage and normalized CD module pressure loss) over time, it is possible to compare their values in order to troubleshoot the system, as trends are easier to discern. As shown in Figure 33, normalized membrane permeability (and normalized permeate flowrate) display a typical "saw tooth" pattern due to cleaning interventions.

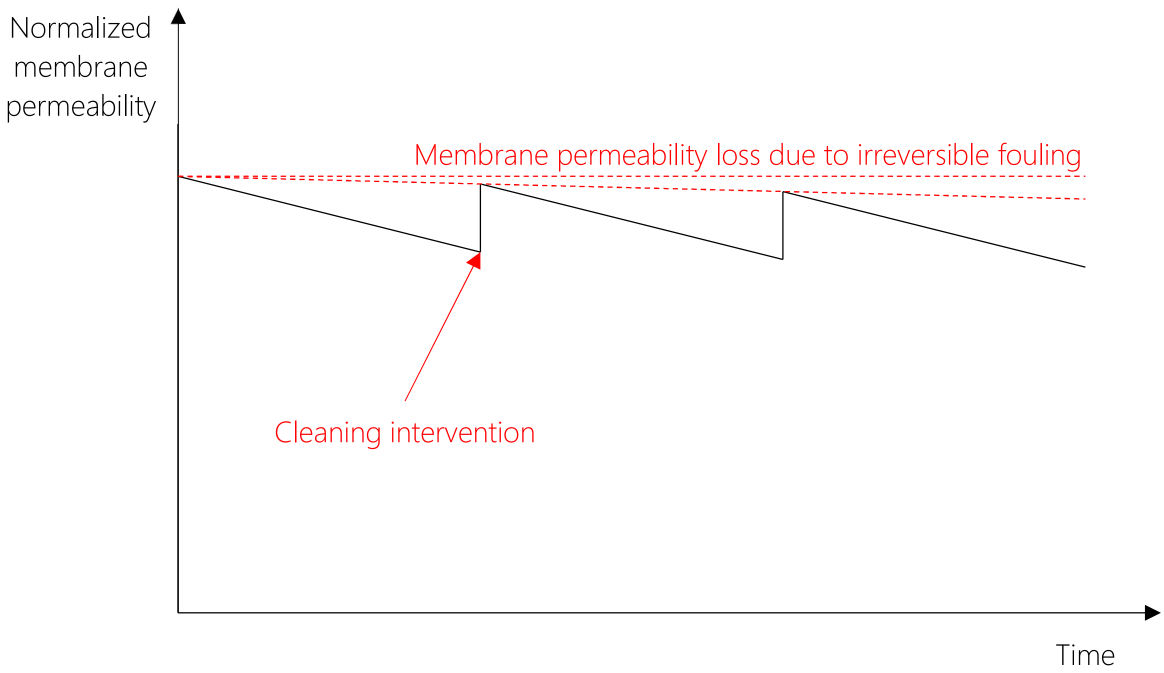

Figure 33. Normalized permeability evolution over time

During the initial start-up phase, normalization shall be performed daily and then, after membrane filtration unit performance stabilization, once per week. It is also recommended to perform operating data normalization before and after any scheduled maintenance intervention to check whether membrane filtration unit operating parameter adjustment is needed.

9. Chemical cleaning

Membrane chemical cleaning (Cleaning In Place, CIP) is more effective when it is tailored to the specific fouling problem. Note that a wrong choice of cleaning chemicals may even worse fouling phenomena. Therefore, before performing any cleaning intervention, the type of foulants on the membrane surface should be determined by:

- analyzing the plant performance data (ref. 8.8.2 and 8.9);
- analyzing the feed water qualitative characteristics via laboratory analyses;
- checking the results of previous chemical cleaning interventions;
- analyzing deposits on cartridge filters and/or membrane cushions (if any):
    - crystalline deposits, which feel like sanding paper to the touch, are typical of inorganic fouling or scaling while sticky deposits, which feel slippery to the touch and may be smelly, are typical of particulate, organic or biological fouling;
    - if reddish-brown crystalline deposits are present, fouling may be due to iron deposits (inorganic fouling);
    - if white/beige crystalline deposits are present, fouling may be due to calcium scales or reactive silica deposits (scaling);
    - if white/beige slimy deposits are present, fouling may be due to organics (organic fouling) or colloidal silica (particulate fouling);
    - if brown-black slimy deposits are present, fouling may be due to biological growth (biofouling).

Chemical cleaning interventions frequency is also fundamental. If they are delayed too long, it could be difficult to completely remove foulants from the membrane surface and, thus, membrane performances may not be restored and may decline even faster. In fact, if foulants are not successfully removed, it is easier for further foulants to deposit on the membrane surface. As a consequence, fouling phenomena are accelerated and cleaning interventions frequency increases, resulting in shorter membranes lifetime and higher operating and maintenance costs. Generally, cleaning is more likely to be effective if performed sooner rather than later.

Compared to baseline values (i.e. the ones collected during initial start-up, ref. 8.1), cleaning interventions are recommended when:

- the normalized membrane permeability drops by 10%;
- the normalized permeate solutes concentration increases by 10%;
- the normalized CD module pressure drop increases by 15%;
- the given time interval is reached. Since membrane fouling phenomena happen continuously, cleaning interventions must be performed at given time intervals in order to prevent irreversible fouling situations;
- the high feed pressure set-point and the low permeate flow set-point are reached at the same time

where the above normalized physical quantities are calculated as shown in paragraph 8.9. The decision about timing, frequency and type of cleaning intervention is usually based on the experience gained during the membrane filtration unit operation and on laboratory analyses of the foulants.

Note that pre-treatment units malfunctioning may result in reduced permeate flowrate and/or in increased solutes passage. If such problems are observed, they shall be addressed on top of cleaning the membrane filtration unit.

9.1 Preliminary requirements

Ensure that:

- accepted safety practices are followed. Also, consult the cleaning chemicals manufacturer for detailed information about safety, handling and disposal;

	Wear adequate personal protective equipment (PPE)!

- when preparing chemical cleaning solutions, ensure that all chemicals are completely dissolved and well-mixed before circulating the cleaning solutions through the CD modules;
- chlorine-free service water shall be used as cleaning solutions make-up water and as flushing water.

9.2 Cleaning chemicals

Acid cleaners are used to remove most of inorganic foulants (e.g. carbonate scales and iron deposits) while alkaline cleaners are used to remove particulate, biological and organic foulants and some inorganic foulants (e.g. sulphate and silica scales). Note that sulphuric acid shall not be used in cleaning interventions because of the risk of calcium sulphate precipitation. In addition to acid or caustic substances, other compounds such as metal chelating agents, surfactants and enzymes are effective in removing foulants from the membrane.

Cleaner may be generic or specific (i.e. the so called specialty cleaners). In the former case, the following formulations are frequently used:

- acid cleaning with a solution made of 0.2% w.t. hydrochloric acid and 2% w.t. citric acid to reach a pH value of 2. This is very effective in removing metal oxides/hydroxides and carbonate deposits;
- alkaline cleaning with a solution made of 0.1% w.t. sodium hydroxide to reach a pH of 12, a chelating agent such as EDTA (1% w.t.) and a surfactant such as SDS (0.025% w.t.). This is very effective in removing organic matter deposits.

Specialty cleaners are advised in case of feed water with high fouling potential, i.e. in case of wastewater applications.

All cleaners used must be suitable for membrane applications and, especially, for use with Filmtec membranes.

Note that, prior to using a cleaning solution containing surfactants, a small scale test should be performed to check if the target surfactant concentration will not result in excessive foaming.

In order to maximize the cleaning efficiency:

- select the correct cleaning chemicals formulation and concentration;
- apply the correct cleaning chemical sequence. Alkaline cleaning is generally recommended as the first cleaning step. Acid cleaning as the first cleaning step should be used only if it is known that calcium carbonate and/or iron oxide/hydroxide are the only foulants present on the membrane surface. In fact, acid cleaners typically react with silica, organics and/or biofilm on the membrane surface, a phenomenon which may cause the membrane performance to decline further (e.g. due to EPS reactions in acid environments). If a combination of

particulate fouling, biofouling, organic fouling, inorganic fouling and/or scaling is present, usually an alkaline-acid-alkaline sequence is recommended;

- select the correct pH. In particular, pH values of 1 to 2 are recommended in case of acid cleaning and pH values of 11 to 12 are recommended in case of alkaline cleaning. Membrane limitations shall be considered (ref. Table 7);
- select the correct cleaning solution temperature. In particular, values below 20°C are not suggested because of the very slow chemical kinetics and to the risk of precipitation of some chemicals (e.g. SLS). Generally, temperatures of 35 to 40°C are recommended because cleaning interventions are more effective at higher temperatures. Again, membrane limitations shall be considered (ref. Table 7);
- select the appropriate flowrate. In particular, flowrates in the range of the required crossflow help in effectively removing cleaning debris from the membrane surface;
- define the appropriate duration of circulation and soaking phases (ref. 9.3) so that the cleaning solution has enough time to penetrate the fouling layers.

The above parameters shall be monitored and, in case of flowrates, temperature and pH values, recorded at 15 min intervals during the entire cleaning process.

Since membrane cleaning is not an exact science, some trial-and-error approach may be necessary. In fact, the effectiveness of cleaning interventions cannot be assessed until after returning the membrane filtration unit to service and monitoring its performances. If these are still not sufficient, the membrane filtration unit must be cleaned again with the same or a different protocol. Therefore, keeping good records of cleaning interventions successes and failures is strongly advised.

Optimized cleaning protocols allow for longer system operating time between two subsequent cleaning interventions and, thus, they minimize operating costs.

If cleaning attempts do not result in sufficient membrane performance improvement, membrane cushions replacement is the only practical solution available.

9.3 Cleaning procedure

Cleaning procedures comprise the following steps (phases):

- cleaning solution preparation. In particular, directly into the CIP tank, make-up water is added to reach the desired dilution and powdered or liquid chemicals are fed;
- if needed, cleaning solution pre-heating (usually, up to 45°C) is performed via immersion heaters or heat exchangers;
- cleaning solution introduction and circulation at low pressure (3 to 4 bar) by switching on the low-pressure pump or the CIP pump (if any). The feed pressure shall be low enough that no or little permeate is produced in order to minimize fouling particles re-deposition on the membrane. Permeate and concentrate streams are recycled back to the CIP tank. During this phase, which usually lasts for 30 to 60 min, the cleaning solution pH shall be monitored and, if it varies more than 0.5 pH units, it shall be adjusted by adding fresh cleaner;
- soaking, i.e. by switching off the low-pressure pump or the CIP pump (if any) and allowing the CD modules to soak. Usually, this phase lasts from 0 (i.e. no soak) to 12 h, depending on the fouling type and intensity. During this phase, the cleaning solution temperature shall be monitored and, if it varies more than 5°C, it shall be adjusted by circulating it and heating it up or it shall be replaced by a fresh cleaning solution in order to avoid precipitation phenomena due to the temperature decrease;
- flushing to extract the foulants removed from the membrane surface and the spent cleaning solutions. During this phase, the minimum recommended water temperature is equal to 20°C;
- if needed, repeat the above five steps with the same or the subsequent cleaning solution;
- restart the membrane filtration unit normal operation.

During all the above phases, the flow direction shall always be the same as during normal operation and the maximum feed flow capacity of each CD module shall always be respected (ref. "CD Module Datasheet"). Allowed temperature and pH ranges (ref. Table 7), overall during the cleaning solutions circulation phases, shall always be respected as well.

Table 7. pH range and temperature limits during cleaning

Membrane type	pH range		
	T < 25°C	T < 35°C	T < 45°C
Filmtec NF270	1 ÷ 12	1 ÷ 11	3 ÷ 10
Filmtec BW30	1 ÷ 13	1 ÷ 12	1 ÷ 10.5

Filmtec SW30	1 ÷ 13	1 ÷ 12	1 ÷ 10.5

Conductivity profiling (ref. 11.2.3) shall be performed after every cleaning intervention.

9.3.1 Cleaning precautions

The following precautions shall be considered when performing chemical cleaning interventions:

- in case of multi-stage/pass systems, each stage/pass should be cleaned separately to avoid that the removed foulants from one stage/pass are pushed to the next one and to maximize the cleaning efficiency. Note that flushing and soaking operations may be done simultaneously in all stages/passes;
- fresh cleaning solutions need to be prepared whenever the cleaning solution becomes turbid and/or discolored.

9.3.2 Membrane performances

After an alkaline cleaning intervention, membrane may temporarily loosen a bit. This results in higher water fluxes and lower solutes rejection rates.

The opposite happens after an acid cleaning intervention. Typically, membrane performances return to nominal within a couple hours to a day.

9.3.3 Emergency chemical cleaning

Whenever cleaning interventions have not been carried out in time (i.e. the normalized membrane permeability drops by more than 10%, the normalized permeate solutes concentration increases by more than 10% and/or the normalized CD module pressure drop increases by more than 15%), the success of the described cleaning processes may be limited and harsher cleaning methods can be tried. However, no warranty can be given on the cleaning efficiency and on the membrane performances after such cleaning attempts.

9.3.4 Spent cleaning solutions disposal

Spent cleaning solutions, depending on their composition, may be discharged into a sanitary sewer system or disposed of with the concentrate. In the former case, a discharge permit shall be available and treatment for pH neutralization is usually required. This may be done within the CIP tank or, better, in a dedicated tank (neutralization tank), whose size depends on the frequency of cleaning/neutralization operations.

Note that spent cleaning solutions shall absolutely not be recirculated upstream of the membrane filtration unit.

10. Conservation, storage, shipping, re-wetting and disposal

Wet-shipped or used CD modules shall be handled in such a way that biological growth and changes in membrane performances are prevented.

10.1 Conservation

Before putting a membrane filtration train out of service for more than 2 days or before removing any used CD module from the membrane filtration unit for storage or shipping, any CD module that has been used shall put under conservation (ref. 6.12.6).

10.1.1 Preliminary requirements

Ensure that:

- accepted safety practices are followed. Also, consult the chemicals manufacturer for detailed information about safety, handling and disposal;

	Wear adequate personal protective equipment (PPE)!

- when preparing conservation solutions, ensure that all chemicals are completely dissolved and well-mixed before circulating the conservation solution through the CD modules;
- food-grade (i.e. not cobalt-activated) sodium meta-bisulphite (SMBS) shall be used as conservation agent;
- chlorine-free service water shall be used as cleaning solutions make-up water;
- an alkaline cleaning intervention (ref. 9) has been performed.

10.1.2 Periodical controls

After the conservation sequence completion (ref. 6.12.6), operators shall:

- ensure that the membrane filtration train under conservation is kept at room temperatures between 5 and 35°C, where the lower-end values are the most desirable;
- check the conservation solution pH once a week. When the pH value becomes 3 or lower, the conservation solution shall be renewed as soon as possible;
- the conservation solution shall be renewed at least once a month if its temperature is lower than 25°C and at least every two weeks if its temperature is equal to or higher than 25°C.

10.2 Used modules storage and shipping

In order to store used CD modules, after the conservation sequence completion, they may be disconnected from feed, permeate and concentrate hoses and their connections shall be sealed with the plastic caps with which they were shipped. Storage conditions for used CD modules are the same as for new wet-shipped CD modules (ref. 7.2.5).

When conserved CD modules are to be shipped, the original packaging or a similar one shall be used in order to protect the CD modules from mechanical damage.

10.3 Membrane re-wetting

CD modules that have dried out after being wet-shipped or used may irreversibly have lost membrane permeability. In order to (partly) restoring the membrane permeability, membrane cushions re-wetting may be achieved with one of the following methods:

- soak the membrane cushions in a 50% ethanol or propanol solution for 15 min;
- soak the membrane cushions in a 1% w.t. hydrochloric acid or a 4% w.t. nitric acid solution up to 100 h;
- pressurize the CD modules at 10 bar and throttle the permeate piping hand valve (if any) so that the permeate pressure is equal to the concentrate pressure for ca. 30 min. Open the permeate hand valve before releasing the feed pressure.

However, no warranty can be given on the membrane performances after such re-wetting attempts.

10.4 Used modules disposal

Used CD modules may be disposed of as solid waste according to local regulations. Be careful of any hazardous liquid or deposit that may be contained within the CD modules.

11. Troubleshooting

While a slow performance decline (i.e. permeate flow and rejection) is due to normal fouling phenomena that can be amended via chemical cleaning interventions, a sudden performance decline is due to defects and/or improper operation of the membrane filtration unit. These problems shall be immediately taken care of in order to maximize the chances of restoring the membrane performances.

11.1 Evaluation of membrane filtration unit performances

If the membrane filtration unit performances are not satisfactory, the normalized operational data, (ref. 8.9) shall be compared against the corresponding start-up values.

In case that the initial membrane filtration unit performances (i.e. at start-up) are not satisfactory, a comparison of the actual performances with the projected values under actual conditions may be helpful. Deviations as large as the specified CD module performances variation (ref. "CD Module Warranty Terms and Conditions") are accepted.

If the normalized actual performances have deteriorated too much compared to the initial performances or if the measured actual performances does not match close enough with the projected performances, check the following:

- all the membrane filtration equipment, instruments and valves as well as all pre-treatment units are properly functioning;
- all set-point values have been properly defined;
- all instruments are calibrated. In case of flow and conductivity meters, this may be verified by performing the following mass balances:

$$q_{f,t} = q_{p,t} + q_{c,t} \qquad \textit{Flow meters}$$
$$q_{f,t} \times EC_{f,t} = q_{p,t} \times EC_{p,t} + q_{c,t} \times EC_{c,t} \qquad \textit{Conductivity meter}$$

  where:

  - $EC_{f,t}$, $EC_{p,t}$ and $EC_{c,t}$ are - respectively - the feed, permeate and concentrate conductivities of the considered membrane filtration train;
  - feed conductivity shall be measured after any chemical additions (e.g. acid for pH adjustment, anti-scalants/dispersants, etc.);

    - tolerances of maximum 5% are admitted;
- the membrane filtration unit has stabilized, i.e. at least 24 to 72 h have passed since the initial start-up;
- normalized data (ref. 8.9) have been used;
- permeate pressure has been considered in operational (ref. 2.3.4) and normalized data (ref. 8.9) calculation;
- start-up (ref. 8.1 and 8.2) and shut-down (ref. 8.4 and 8.5) procedures have been correctly performed, i.e. the membrane filtration unit is protected against hydraulic shocks and permeate back-pressure and back-flow phenomena;
- the types of cleaners used during chemical cleaning interventions are appropriate, i.e. the chemicals are effective in cleaning the membranes without damaging them. In particular, if membranes are cleaned effectively and on time, their performances after cleaning shall return close to the reference values;
- the frequency of chemical cleaning interventions is appropriate, i.e. it shall be compared to design projections;
- the feed water characterization has been performed via laboratory analyses in order to identify all the fouling species. In particular, these shall be compared to design data in order to assess the membrane fouling and degradation potentials;
- the replacement rate of cartridge filters is appropriate. In particular, if it is too high, potential fouling problems may arise while, if it is too low, problems such as cartridge filters sudden collapse may arise;
- the dosing rates of chemicals used within the pre-treatment units are appropriate, e.g. acid for pH adjustment and anti-scalant/dispersant dosing flowrates.

Once all the above has been verified and the observed membrane filtration unit performances still do not meet the expected values, checking and testing shall be performed as described within the following paragraph.

11.2 Membrane filtration unit checking and testing

11.2.1 Visual inspection

Check the following:

- no CD module pressure vessel is leaking. In particular, leaking pressure vessels may suck air whenever the membrane filtration unit is shut-down, causing hydraulic shocks during start-up and accelerated fouling phenomena;
- depending on profiling results (ref. 11.2.3), open the selected CD modules and check for mechanical damages, e.g. damaged or misplaced O-rings. If needed, replace the damaged parts;
- open a cluster-end CD module and inspect its membrane cushions for physical damage (i.e. crumpling or crushing damage that could have occurred due to excessive module pressure drop or water hammer phenomena) and for fouling (ref. 9).

11.2.2 Cleaning interventions checking

Asses the efficacy of cleaning interventions (ref. 9.2). Analyze the spent cleaning solutions for organic and inorganic fouling compounds and compare it with a fresh cleaning solution in order to determine the type of foulants.

11.2.3 Conductivity profiling

Whenever a membrane filtration unit exhibits low salts rejection rates, one of the first steps in troubleshooting is localizing the source of the problem. In order to do so, permeate conductivity of all CD modules are checked with a portable meter (conductivity profiling). All the obtained values within the same membrane filtration skid shall be represented with the aid of a dedicated table and/or a bar graph: this facilitates finding abnormal permeate conductivities values within the same membrane filtration stage/pass, whose corresponding CD modules shall be checked (ref. 11.2.1).

11.3 Modules evaluation

11.3.1 Visual inspection

When the causes of a membrane filtration unit performances loss are not known or when they have to be confirmed, one or more membrane CD modules have to be analyzed individually.

The CD modules to be selected are those showing a steep increase in the conductivity profile (ref. 11.2.3) and/or those at cluster-end.

Visual inspection of membrane cushions provides information about fouling phenomena and visual inspection of O-rings provides information about excessive hydraulic loads.

11.3.2 Performance testing

The CD module standard performance test is used to determine the permeate flowrate and the salts rejection rate of CD modules under standard test conditions. The test results can then be compared with the specification of the CD module. The CD module performances are to be determined before and after any cleaning interventions in order to assess their efficacy as well.

The apparatus for the standard test is built as per the ASTM standard no. D4194-03 (2014) and it consists of the following items:

- a feed holding tank equipped with an immersion heater to maintain the feed solution at 25°C;
- low- and high-pressure pumps to provide the required feed flowrate and pressure;
- cartridge filtration unit;
- all the required piping, valves and instruments;
- the CD module to be tested.

Note that permeate and concentrate streams are recycled back to the feed tank, thus the system works in a closed loop.

A synthetic test solution is used as feed water. In case of NF applications, this is made of magnesium sulphate ($MgSO_4$) or calcium chloride ($CaCl_2$) while, in case of RO applications, it is made of sodium chloride (NaCl). If needed, the feed water pH shall be adjusted to a pH of 8 by adding hydrochloric acid (HCl) or sodium hydroxide (NaOH). The feed salt concentration, the feed pressure, the feed flowrate and the recovery rate are given in the "CD Module Factory Test Certificate" of the relevant CD module.

The following data shall be recorded every 15 min:

- permeate and concentrate flowrate;

- feed, permeate and concentrate pressure;
- permeate temperature;
- feed, permeate and concentrate conductivity.

This shall be continued until four subsequent permeate flowrate values and four salts rejection rate values converge within a 5% error.

In this test, the salts rejection rate is calculated as follows:

$$SR = 1 - \frac{2 \times EC_p}{EC_f + EC_c}$$

where EC_f, EC_p and EC_c are - respectively - the feed, permeate and concentrate conductivity.

11.3.3 Cleaning interventions testing

Whenever the permeate flowrate of the tested CD module is too low compared with the reference value (ref. 11.3.2), cleaning protocols can be tested. Note that cleaning interventions cannot be successful when the membrane cushions are damaged or when they are heavily fouled/scaled (usually, this is highlighted by permeate flowrates lower than 50% of the reference value).

The cleaning intervention testing involved defining and performing different cleaning protocols to evaluate their efficacy. Cleaning interventions are carried on accordingly to the procedure described in chapter 9. Whenever a cleaning protocol has been proven effective, it can be applied to the whole membrane filtration unit.

11.4 Symptoms, causes, testing and corrective measures

Symptoms of troubles are loss of normalized permeate flow, increase of normalized solutes passage and of normalized module pressure drop (ref. 8.9). Depending on their combination and location, different causes of troubles can be identified and further testing on-site may be performed in order to determine the appropriate corrective measures.

Reference troubleshooting charts are presented within Table 8 and Table 9.

Table 8. Simplified membrane filtration unit troubleshooting chart

Observed phenomenon	Possible corrective action
Normalized solutes passage increase	Assess conductivity profiles to find problematic CD modules, shut-down the membrane filtration train, open the problematic CD modules, replace damaged O-rings and/or membrane cushions and reassess conductivity profiles Perform a cleaning intervention
Normalized module pressure drop increase	Check if feed or concentrate flows are higher than reference conditions Confirm that pre-treatment units are properly functioning Shut-down the membrane filtration train, open cluster-lead CD modules for visual inspection Perform a cleaning intervention
Normalized permeate flow increase	Check operating parameters, i.e. water temperature, feed water composition, feed pressure and recovery rate Check permeate water conductivity. Whenever this has worsened, assess conductivity profiles to find problematic CD modules, shut-down the membrane filtration train, open the problematic CD modules, replace damaged O-rings and/or membrane cushions and reassess conductivity profiles
Normalized permeate flow decrease	Check operating parameters, i.e. water temperature, feed water composition, feed pressure and recovery rate Perform a cleaning intervention
Feed pressure required to maintain set permeate flow increase	Check operating parameters, i.e. water temperature, feed water composition, feed pressure and recovery rate Perform a cleaning intervention
Time interval between two cleaning interventions is too short	Check if unnecessary cleaning interventions have been performed Consider cleaning interventions effectiveness and, if necessary, increase the cleaning solution temperature, use more extreme pH values, use higher cleaning agents concentrations, use stronger cleaning agents and/or adopt longer soaking times
Performances don’t return to reference values after performing a cleaning intervention	Consider cleaning interventions effectiveness and, if necessary, increase the cleaning solution temperature, use more extreme pH values, use higher cleaning agents concentrations, use stronger cleaning agents and/or adopt longer soaking times
Increase in feed water concentrations	Check and, if needed, optimize/enhance pre-treatment units

Table 9. Detailed membrane filtration unit troubleshooting chart

Normalized permeate flow	Normalized solutes passage	Normalized module pressure loss	Location	Probable cause(s)	Testing	Corrective measures
Decreasing	Stable, decreasing or increasing	Greatly increasing	Any	Biofouling	Analyze feed water, analyze deposits on membrane cushions (ref. 9)	Alkaline cleaning and sanitization with SMBS of the entire plant, pre-treatments enhancement
Decreasing	Stable	Stable or increasing	Any	Aged conservation solution	-	Alkaline cleaning
Decreasing	Stable	Stable	Any	Incomplete wetting	-	Ref. 10.3
Decreasing	Increasing	Stable or increasing	Lead-cluster CD modules and/or first stage	Metal oxides and/or elemental sulphur fouling	Analyze feed water, check for plant equipment corrosion, analyze deposits on membrane cushions (ref. 9)	Acid cleaning if metal oxides fouling and/or alkaline cleaning with EDTA addition if elemental sulphur fouling, pre-treatments enhancement, retrofit corroded equipment with appropriate materials
Greatly decreasing	Increasing	Stable or increasing	Lead-cluster CD modules and/or first stage	Colloidal fouling	Analyze deposits on cartridge filters and membrane cushions (ref. 9)	Alkaline cleaning, pre-treatments enhancement

Normalized permeate flow	Normalized solutes passage	Normalized module pressure loss	Location	Probable cause(s)	Testing	Corrective measures
Greatly decreasing	Increasing	Stable or increasing	End-cluster CD modules and/or last stage/pass	Scaling	Analyze feed, permeate and concentrate water, check acid and anti-scalants/dispersants dosage, analyze deposits on membrane cushions (ref. 9)	Acid cleaning, optimize type/dosage of acid and/or anti-scalants/dispersants dosing, lower the recovery rate
Greatly decreasing	Greatly decreasing	Stable	Any	Membrane compaction	Check for high feed pressure, high water temperature and/or water hammer phenomena	Replace damaged membrane cushions
Greatly decreasing	Stable, decreasing or increasing	Stable	Any	Organic fouling	Analyze feed water, analyze deposits on cartridge filters and membrane cushions (ref. 9), check coagulant and flocculants dosing	Alkaline cleaning, optimize type/dosage of coagulants and flocculants, pre-treatments enhancement
Stable	Increasing	Stable	Any	Permeate back-pressure	Conductivity profiling and selected CD modules opening, check for permeate back-pressure	Replace damaged membrane cushions and reassess conductivity profiles, investigate causes for permeate back-pressure
Increasing	Greatly increasing	Stable	Any	Leaking O-rings	Conductivity profiling and selected CD modules opening, check for water hammer phenomena	Replace damaged O-rings and reassess conductivity profiles

Normalized permeate flow	Normalized solutes passage	Normalized module pressure loss	Location	Probable cause(s)	Testing	Corrective measures
Increasing	Greatly increasing	Stable	Lead-cluster CD modules and/or first stage	Membrane surface abrasion	Conductivity profiling and selected CD modules opening, check for particles in the feed water, check membrane cushions (if uniform damage)	Replace damaged membrane cushions, correct installation or replace cartridge filters and reassess conductivity profiles
Increasing	Greatly increasing	Stable	Lead-cluster CD modules and/or first stage	Membrane oxidation	Check feed water temperature and pH (if neutral to alkaline), check feed water for metals and oxidizing chemicals, check membrane cushions (if uniform damage)	Replace damaged membrane cushions, pre-treatments enhancement
Stable or decreasing	Stable or increasing	Stable or increasing	Lead-cluster CD modules and/or first stage	Cartridge filters bypass	Check cartridge filters (if improperly installed or defective)	Correct installation or replace cartridge filters
Stable or decreasing	Stable or increasing	Stable or increasing	Lead-cluster CD modules and/or first stage	Multi-media filters breakthrough	Check multi-media filter integrity	Reduce multi-media filter backwash interval, repair multi-media filters (if needed)
Stable or decreasing	Stable or increasing	Stable or increasing	Lead-cluster CD modules and/or first stage	Pump impellers or pistons deterioration	Check pumps discharge pressure	Repair pumps, investigate causes for deterioration

Normalized permeate flow	Normalized solutes passage	Normalized module pressure loss	Location	Probable cause(s)	Testing	Corrective measures
Stable or decreasing	Stable, decreasing or increasing	Stable or increasing	Lead-cluster CD modules and/or first stage	Anti-scalants/ dispersants precipitation	Check feed water for multivalent cations, check coagulants, flocculants and anti-scalants/dispersants dosage	Alkaline cleaning with EDTA addition, optimize type/dosage of coagulants, flocculants and anti-scalants/dispersants

Disclaimer

All information set forth herein are for informational purposes only. This information are generic and may differ from that based on actual conditions.

The Customer is responsible for determining whether information within this document are appropriate for Customer's use and for ensuring that Customer's workplace and disposal practices are in compliance with applicable laws and norms.

While operating conditions stated in this document are intended to lengthen the product lifespan and/or improve the product performance, this will ultimately depend on actual circumstances and it is in no event a guarantee of achieving any specific results.

The product is intended exclusively for use as nanofiltration or reverse osmosis module for processing water solutions. Any other use of the product is not authorized. The correct use of the product includes the observance of all operating, maintenance and repair instructions issued by mft.

mft cannot be held liable for damages to human lives, property and the likes resulting from using improper use of the product.

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