Chapter 8

Industrial Water Reuse Technologies

8.1 Introduction

'Water reuse' and 'recycled water' are terms that are often confused with each other. In order to clarify the difference, water reuse as defined in this book is on-site water reuse. The process water or effluent is used within the site – with or without further treatment. Recycled water or reclaimed water, on the other hand, is the water available from a sewage-treatment plant after undergoing secondary, tertiary or advanced treatment. Figure 8.1 shows graphically the two types of systems.

There is sufficient information available on reclaimed water applications. The most common application of reclaimed water use is in power plant and industrial cooling water systems, irrigation of golf courses, parks and agricultural crops. This chapter focuses on industrial water reuse.

Traditionally, industrial wastewater treatment is undertaken to meet regulatory compliance. Consequently, the treatment of wastewater effluent has been seen more as *the cost of doing business* rather than as a valuable resource. Therefore, the minimum treatment required to comply with a regulatory requirement is fulfilled. In recent years this view is changing. There is the realisation that security of water supply, drought, scarcity of water and increased costs for potable water and sewer discharge are forcing some companies to rethink this minimalist strategy. As a result of this new thinking, some organisations have embraced the notion of *zero discharge*. While the notion of zero discharge is appealing, in practice, achieving it is far from simple. High upfront capital costs can make zero discharge unviable except in some rare cases. The end of pipe treatment is always costlier than reuse at the source. For a project to be feasible, the proposed treatment technologies need to be reliable, economical, meet water-quality specifications and be safe to use, as determined by regulatory authorities.

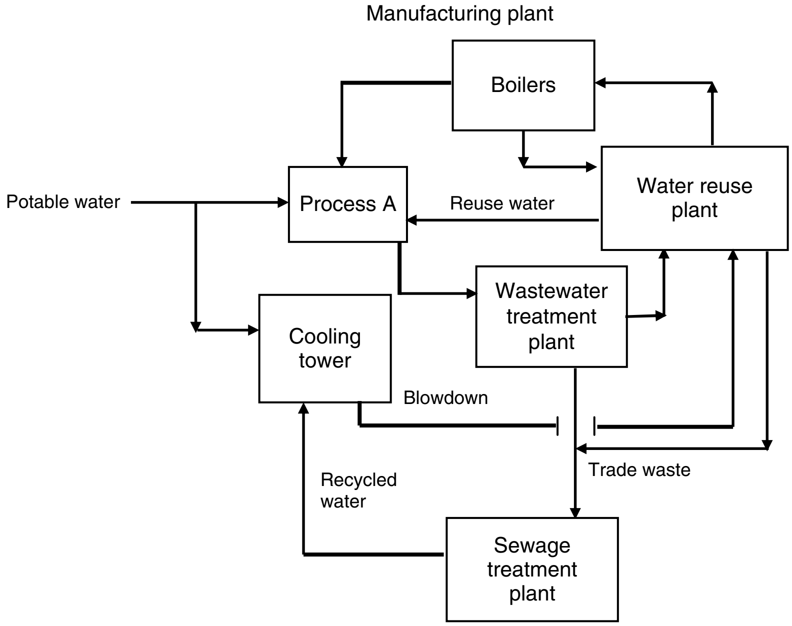


Figure 8.1 A schematic of water reuse and recycling in a manufacturing plant

Two questions always arise when the topic of water reuse comes up. They are

1. What water quality is acceptable?
2. What volume of water is available for reuse?

'Acceptable' water quality is dictated by end use. The potential volume of water available for reuse is dictated by the type of industry sector, the achievable cost savings and the prevailing regulatory environment that enables the reuse of water. For instance, in Japan [1] water recovery from industry is significant. The recovery rates fall into three distinct groups. Over 80% of water used is recovered in the steel, chemical and transport machinery sectors.

Table 8.1 shows the water recovery rates in Japan.

In some industries such as in the pulp and paper industry technological advances such as alkaline sizing are enabling greater mill closure with consequent higher recovery levels of water and fibre.

Another way to look at it is how much water is discharged to the sewer from an industry sector? For example, in the food and beverage processing sector 50–89% of the water is discharged to the sewer.

This chapter provides a step-by-step approach to water reuse and examines the current technologies for water reuse applications.

Table 8.1 Recovery rates for Japanese industries [1]

Industry	Feed ML/day	Recovered water ML/day	Total consumption ML/day	% Recovery rate
Food	2,586	1,527	4,113	37.1
Drink	810	366	1,175	31.1
Textile and dyeing	2,358	61	3,020	21.9
Pulp and paper	8,935	6,591	15,526	42.5
Chemicals	8,761	40,140	48,901	82.1
Plastics	835	1,757	2,592	67.8
Ceramics	1,223	2,660	3,883	68.5
Iron and Steel	3,917	34,460	38,377	89.8
Non-ferrous metals	891	2,447	3,338	73.3
Metal products	525	478	1,003	47.6
Electrical machinery	1,544	3,763	5,307	70.9
Transport machinery	932	11,290	12,222	92.4

8.2 A Step-by-Step Approach to Water Reuse

In general, water reuse is an integral part of a holistic water management philosophy. The following points need to be considered when conceptualising a water reuse project:

- Follow the principles of resource minimisation hierarchy – *avoid, reduce, reuse and recycle* as shown in Figure 8.2. By avoiding the use of water and reducing the pollutant load, the need for subsequent disposal is eliminated. Reducing water use is cheaper than water reuse.
- Consider source reduction first. End-of-pipe treatment is a more expensive option.

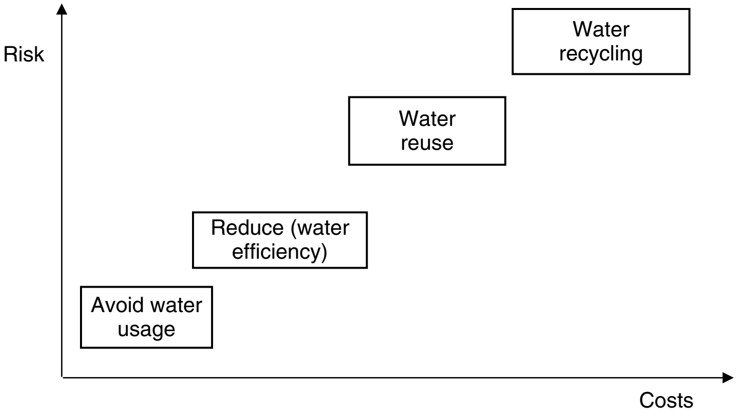


Figure 8.2 Water minimisation hierarchy

- Address the easy options before tackling the more expensive options.
- Segregate the more contaminated streams from the diluted streams and treat them separately.

A step-by-step guide for water reuse projects is summarised below:

1. Establish the goals of the project.
2. Define the project boundaries.
3. Gather data.
4. Identify and evaluate the water reuse projects – relative to goals.
5. Conduct a water reuse technical assessment – desk top as well as a pilot study.
6. Implement the new water-reuse model or design.
7. Commission new system.
8. Monitor operation.
9. Review and update the model or design as needed.

8.2.1 Establishing the Goals of the Study

Clearly specify the goals of the study, the business drivers and alignment with corporate strategy.

8.2.1.1 Goals

Goals of water reuse can be

- meeting EPA or local water authority trade waste regulatory compliance as a condition of operation
- cost savings
- environmental considerations
- good corporate citizenship.

The drivers will dictate the priority and the financial backing at the time of project approval. For instance, if the goal was trade waste compliance then the financial considerations will not be that important, since without achieving trade waste requirements it is difficult to discharge effluent to the sewer.

8.2.1.2 Project Boundaries

What are the boundaries of the study? Is the water reuse study to be undertaken site wide or be limited to a specific area? If the study is undertaken too narrowly then other potential options may be overlooked making the financial justification of the project difficult.

What is the time frame to carry out the study?

8.2.2 Gather Data

Before embarking on a water reuse project it is essential to gather all relevant information. This includes

- Developing a water balance of the site to identify the water sources and water users.
- Analyse the water streams in order to have a general idea of water quality such as conductivity, suspended solids, oil and grease and other contaminants.
- Understand the production process specific to the plant.
- Locate past plant drawings and any changes made to the plant.
- Understand the water-quality requirements acceptable to the plant. Table 8.2 shows industrial process water-quality requirements [2].
- If there are any health and safety standards that need to be achieved in terms of pathogens such as *Legionella*, *Listeria* and *Campylobacter* then these need to be listed. For instance, the pharmaceutical industry must comply with the *Good Manufacturing Practice code (GMP)*. Similarly, the food industry needs to comply with local and international food regulatory standards and HACCP Guidelines (refer to Chapter 13 for details on HACCP).
- List the trade waste standards applicable to the site.
- List if there are any other regulatory approvals that need to be considered such as local council building approvals and so on.
- Determine the current cost of water, wastewater, trade waste charges for pollutants and what the likelihood might be of these charges increasing.
- What is the typical financial justification hurdle rate applied by the organisation? Typically this varies from 2–5 year payback. Some organisations dictate an internal rate of return (IRR) better than 25% for a project to proceed. For details on IRR, refer to Chapter 9.
- Are plant expansions or contractions likely? Will these plans dictate more or less water use?
- Is any large water using equipment earmarked to be upgraded or become more water efficient?
- Are environmental considerations given a lower hurdle rate? That is, an extended payback period.
- Are there any other considerations that would make it more attractive?

8.2.3 Identify the Project

All personnel who could have knowledge of the water systems need to be invited to a preliminary brainstorming meeting to discuss, identify and prioritise the water reuse options. The facilitator needs to list all

Table 8.2 **Typical Industrial Process Water-Quality Requirements [2]**

Parameter*	Pulp & Paper					Textiles		Cement
	Mechanical Piping	Chemical Unbleached	Bleached	Chemical	Petrochemical and Coal	Sizing Suspension	Scouring Bleach & Dye	
Copper	–	–	–	–	0.05	0.01	–	–
Iron	0.3	1.0	0.1	0.1	1.0	0.3	0.1	2.5
Manganese	0.1	0.5	0.05	0.1	–	0.05	0.01	0.5
Calcium	–	20	20	68	75	–	–	–
Magnesium	–	12	12	19	30	–	–	–
Chlorides	1,000	200	200	500	300	–	–	250
Bicarbonate	–	–	−128	–	–	–	–	–
Nitrate	–	–	–	5	–	–	–	–
Sulphate	–	–	–	100	–	–	–	250
Silica	–	50	50	50	–	–	–	35
Hardness	–	100	100	250	350	25	25	–
Alkalinity	–	–	–	125	–	–	–	400
Total Dissolved Solids	–	–	–	1,000	1,000	100	100	600
Total Suspended Solids	–	10	10	5	10	5	5	500
Colour	30	30	10	20	–	5	5	–
pH	6–10	6–10	6–10	6.2–8.3	6–9	–	–	6.5–8.5

* All values in mg/L except colour and pH.

the possible options. Then prioritise the options for further investigation based on

- Water-saving potential
- Cost saving potential
- Technical feasibility
- Technical risk
- Operator complexity
- Time frame – short-term or long-term projects.
- Capital expenditure required
- Return on Investment
- Meeting other organisational drivers.

Carry out a detailed technical review of the selected project(s).
Some examples of water reuse projects include

1. Reuse of wastewater effluent as cooling water make-up – quite common in petrochemical and oil refineries where the cooling water make-up needs are large with stringent wastewater discharge requirements. Challenges are in ensuring that the water is not corrosive to the system and is safe for use.
2. Use of wastewater in boilers – not a common practice but technically feasible. Requires capital expenditure to pre-treat the wastewater to meet boiler feedwater specifications.
3. Reuse of effluent for toilet flushing and washing of floors – challenges are in ensuring that the water is safe for accidental contact through aerosols.
4. Reuse of textile effluent in dye houses – reduces water usage, chemicals and energy usage. Technical challenges are in the removal of oil, colour, dissolved solids, salt and fibre.

Case Study: DPK Australia Pty Ltd – Clean Water Project

The Australian textile industry has been devastated by imports from China. Those left behind are those that have the entrepreneurial vision to compete in niche markets and are very cost conscious. DPK Australia, a family-owned company established in 1981 manufactures and supplies innovative knitted fabrics using Australian Merino wool and other luxury fibres. It partnered with Sydney Water's Every Drop Counts Business Program, to reuse 75% of the wastewater approximately 175 million litres per year that is currently going to waste. In February 2006, DPK was successful in receiving A$525 000 from the NSW government towards a A$1.25 million project to install an innovative vibrating membrane technology for its reuse project.

5. Use of boiler blowdown as cooling water makeup – despite the high heat content, boiler blowdown is a source of good-quality water. However, boiler water polymers can interfere with cooling water treatment chemical programmes.

8.2.4 Technical Assessment

Technical reviews can be conducted as

- desktop technical and financial reviews
- pilot plant trials.

Desktop technical reviews are a screening process to quickly eliminate the non-feasible projects. This assessment can be done at low cost.

Once the options have been identified it is always preferable to carry out an on-site trial or a pilot plant assessment especially when the capital cost is high – to validate the results of the desk top review. Even though pilot plant trials are costly it is only a fraction of the actual plant costs and well worth the expenditure to minimise the risk of equipment non-performance. On-site pilot plant trials give the organisation a higher degree of confidence of potential plant performance and a more realistic assessment of savings and costs. The scope of the trial needs to be developed with the aforementioned needs in mind.

8.2.5 Implementation

Once a firm cost has been received from the contractor, then it is possible to do a sensitivity analysis. If the sensitivity tests show that the project is sensitive to interest rates, capital costs, operational savings, production schedule or some other factor then they need to be examined closely.

Once all of these factors have been examined then a business case needs to be written justifying the project as per the original goals.

A new water balance of the site based on the reuse project can be drawn up.

8.3 Pollutants Found in Reuse Streams

Pollutants found in industrial effluent streams can be segregated as follows:

- inorganic
- organic
- dissolved
- suspended
- gaseous

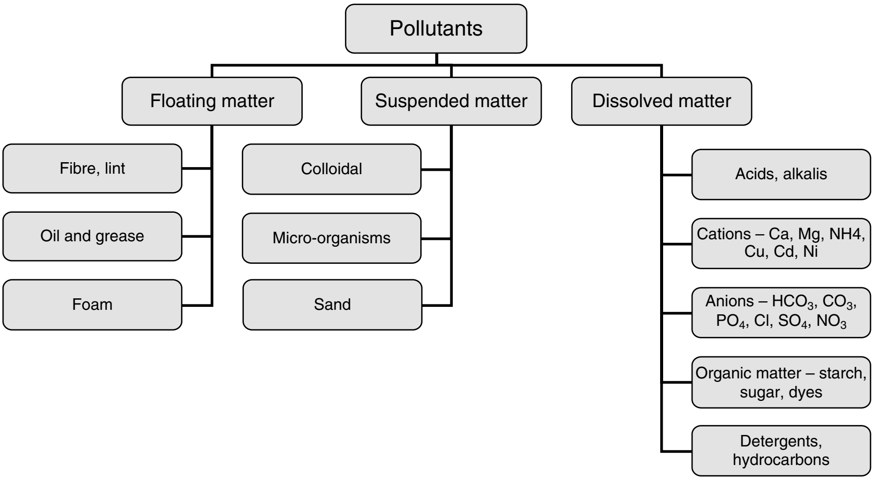


Figure 8.3 Classification of pollutants

- non-ionic
- biological
- pH.

Classification of pollutants is shown in Figure 8.3.

Wastewater quality in industrial effluent is varied. A useful measure of organic loading is the measurement of biological oxygen demand (BOD) and chemical oxygen demand (COD). Refer to Chapter 2 for more details.

The biodegradability of a solution is a measure of the breakdown of chemicals contained in the solution by bacteria. The ratio of BOD/COD determines the theoretical biodegradability of a chemical mixture. If the ratio is greater than 0.4 it is considered to be readily biodegradable. Table 8.3 shows industries where these contaminants are commonly found and their methods of treatment.

8.4 Removal of Pollutants

As Table 8.3 shows, the technologies to remove these pollutants from industrial wastewater streams are diverse and range from

- simple screening, settling and filtration
- chemical and biological treatment
- ion exchange
- reverse osmosis
- electrodialysis and brine concentration.

This section examines these technologies briefly.

Table 8.3 Wastewater contaminants by industry

Industry	Characteristics of wastewater	Treatment options
Food processing Dairy	High in dissolved organics – mainly protein, butterfat and lactose. BOD 2,700; COD 4700. BOD/COD = 0.57	Equalisation, dissolved air flotation, aerobic or anaerobic biological treatment
Meat and poultry processing	High in dissolved and suspended organics including protein, blood, greases, fats and manure. BOD 1430. COD 2746. BOD/COD = 0.52–0.83	Screening, gravity separation, neutralisation, DAF, biological treatment, coagulation and precipitation
Vegetable and fruit canneries	High in dissolved and suspended organics from natural products Jams, jellies BOD 2400; COD 4000. BOD/COD = 0.60	Screening, equalisation, gravity separation, neutralisation, biological treatment
Bakery products	BOD 3200, COD 7000 BOD/COD = 0.46	Biological treatment
Iron and Steel	Phenol, tars, free ammonia, cyanide, iron, suspended solids, oil and grease, mill scale, heavy metals	Equalisation, neutralisation, coagulation
Organic chemicals	Dissolved organics, including acids, aldehydes, phenolics and free and emulsified oils	Gravity separation, flotation, equalisation, neutralisation, coagulation, chemical oxidation, biological treatment, adsorption
Petroleum refining	Phenolics, free and emulsified oils and other dissolved organics	Gravity separation, flotation, equalisation, coagulation, chemical oxidation, biological treatment and membrane technology
Pulp and paper	Fibres, dissolved and suspended organics, high BOD and COD	Screening, gravity separation, biological treatment, chemical oxidation and membrane technology
Plastics and resins	Dissolved organics, including acids, aldehydes, phenolics, cellulose, poly vinyl alcohol, surfactants and oils	Gravity separation, flotation, coagulation, chemical oxidation, solvent extraction, adsorption, biological treatment
Textiles	Dissolved and suspended organics, salt, heavy metals, sulphides, dyes, BOD 80–6000 and COD 800–30,000. Total Suspended Solids – 15–8,000; Cl 1,000–1,600; heavy metals; BOD/COD = 0.2–0.54	Equalisation, neutralisation, coagulation, adsorption biological treatment, membrane technology and ozonation

Table 8.3 (*Continued*)

Industry	Characteristics of wastewater	Treatment options
Coke and gas	High in phenolics, benzene, CN, oil and grease, volatile organics, polynuclear aromatic hydrocarbons, Se, Hg, ammonia and other dissolved organics	Equalisation, flotation, adsorption, biological and chemical oxidation, granular activated carbon, solvent extraction
Landfill leachate	High in BOD, COD, Cd, Pb, Zn, Cl, Fe, Ammonia, P BOD/COD – 0.05–0.49	Biological, ozonation, ammonia stripping, ion exchange and membrane treatment

8.4.1 Order of Removal

The order of removal is given below:

- Primary treatment – adjustment of pH and temperature, removal of suspended solids, oils and fats and heavy metals.

  Technologies used in primary treatment consist of screening, sedimentation, hydrocyclones, settling, filtration, dissolved air flotation and centrifugation.
- Secondary treatment – Biodegradable carbon compounds, nutrients (nitrogen and phosphorus).
- Tertiary treatment – Removal of dissolved solids and disinfection to eliminate pathogens.

These treatment methods will be discussed in the ensuing sections.

8.5 Removal of Suspended Solids

Suspended solids in wastewater can be classified as shown in Table 8.4. Knowledge of the *particle diameter and settling time* allows us to select the most appropriate removal technique.

Table 8.4 Classification of suspended solids

Solids greater than 25 mm (1 in.) in diameter. These can obstruct and damage downstream treatment operations.

Solids in the range 10–25 mm in diameter. Examples are sand gravel and are classified as grit.

Settleable solids with diameters between 10^{-3} mm(1 μm) and 10 mm in diameter.

Colloidal substances. Substances in diameter greater than 10^{-6} mm -10^{-3} mm (10^{-3} μm to 1 μm).

8.5.1 Screening

Screening is the simplest way to remove suspended matter and oversized material which might damage equipment or disrupt the treatment process. Basically, it involves placing a screen or plate with fixed openings in the path of the wastewater flow. All suspended solids larger than these openings are trapped on the upstream side and removed by mechanical cleaning devices. The opening size required for a specific application is governed by the purpose of the screen, the downstream unit operation and the particle size that the screen can effectively remove.

The screens can be classified as follows:

A) Coarse screening – for a spacing of over 3 mm (0.118 in.) or larger (up to 50 mm). For an example in the vegetable canning industry screens sizes do not exceed 5 mm.
B) Fine screens – Openings of 3 mm or less are classified as fine screens. Fine screens are more applicable to industrial wastewater treatment.

Coarse screens. The most commonly used coarse screens are bar screens and these are typically mounted at an angle of 10–90 degrees to the flow.

Fine screens. The main types of screens are

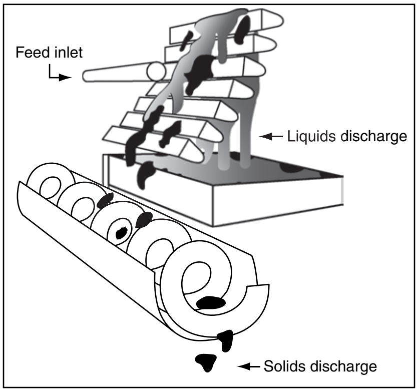
- Static
- Rotary
- Vibrating.

Static screens are brushed or rundown with vertical bars or perforated plates. Static wedge/curved screens are used to minimise blockage of screens such as in the poultry, meat and other food-processing industries where the particles are sticky and tend to clog the screen. The feed inlet is perpendicular or flows by gravity to the top of the screen and then runs down the side of the screens. The screens have openings of about 1 mm. The liquid drains through the side of the screen. Cleaning nozzles or oscillating sprays are installed to rinse the screens. Removal rates can be in the order of 40–75%.

Figure 8.4 shows a schematic of common curved wire screen.

Rotating screens are more complex but popular within the municipal, poultry and meat industry. They consist of a drum which rotates along its axis, and the effluent enters through an opening at one end. Screened wastewater flows outside the drum. The retained solids are washed out from the screen into a collector in the upper part of the drum by a spray of the wastewater.

The screening media used in these devices is generally of stainless material, with openings varying from 0.7 to 1.5 mm. Materials that dissolve with time such as fish solids need to be screened as soon as possible. By the same token, high-intensity agitation of waste streams (such as pumping or flow-through valves) should be minimized before screening or even settling, since they cause breakdown of solids rendering them more difficult to separate.



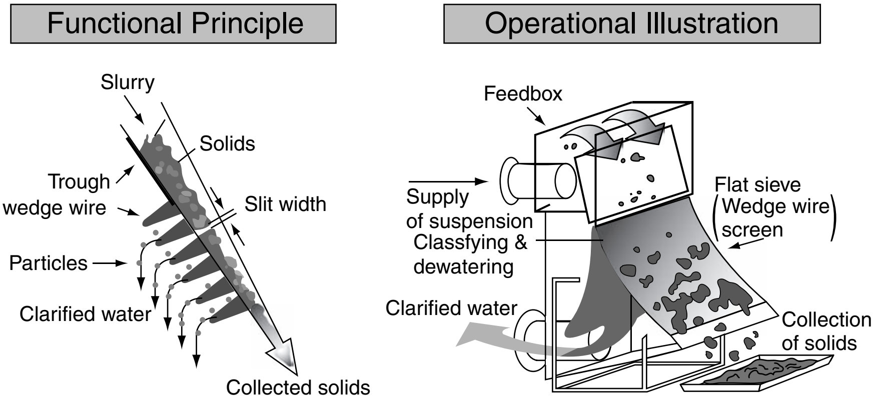


Figure 8.4 A Schematic of a curved screen

Courtesy of Environmental Technology Best Practice Programme, UK

In the Contra-shear design the screens are fed internally to a rotating screen at a tangent. Given the counter-flow direction, higher flow rates than externally fed screens can be achieved. The screens are washed both internally and externally by hot water sprays to remove built up fat and grease. They are suitable for applications with high solids content.

Vibrating screens are used in applications where the moisture content of the solids is low and the wastewater is low in grease content. Typically vibrating screens vibrate at 900–1800 rpm (revolutions per minute).

Weave wire screens such as the on-line self-cleaning filters are able to filter particles up to 5 μm in diameter, that is the maximum particle size required for membrane filtration systems. Refer to Chapter 5 where the application of self-cleaning filters is used in cooling water systems to remove suspended solids.

In the food industry, screens typically achieve a 15–50% reduction in BOD. Capital costs average around A$35 000–150 000.

8.5.2 Sedimentation

Suspended solids may also be removed by settling. Settling is based on the density difference between the suspended particle and the bulk of the liquid which results in the settling of the suspended solids. When the suspended solids are discrete particles (particles do not interact with each other nor bound together) we call this type of settling *sedimentation*.

The terminal or critical velocity (v_c) of discrete particles is a vector between the downward movement of the settling particles and the flow velocity. The particles that reach the bottom of the tank before the outlet will be separated. For discrete settling, calculations can be made on the settling velocity of individual particles. In a settling tank, these move both downwards (settling) and towards the outlet zone with the waterflow as shown in Figure 8.5. v_c can be calculated if the depth of liquid (d) in the tank, the volume of the tank (V) and the flow rate (Q) are known:

$$v_c = d/(V/Q) \tag{8.1}$$

The ratio of V/Q is also known as the residence time of the liquid in the tank. It is called the overflow rate when v_c is expressed in terms of volume of effluent per unit surface area of the tank per unit of time.

Sedimentation is used for the removal of sand, gravel and other dense inert material (specific gravity 2.65) commonly known as grit. Grit is particularly a problem in some wastewaters such as in the fruit and vegetable canning industry.

Surface loading rate is the rate of wastewater flow over the surface area of the sedimentation unit. Typical values are approximately 80–120 m^3/m^2d (2000–3000 US gpd/ft^2). Primary sedimentation tanks generally provide detention times of 90–150 minutes at average flow rates.

Instead of a settling tank, hydrocyclones can be used for the removal of grit for particles diameter ranging from 5 to 400 μm (0.0002–0.016 in.) [3]. Hydrocyclones utilise specific gravity differentials, tangential flow, angular acceleration to separate particles. The feed enters at the side, at a tangent, the heavier particles spiral down to the bottom of the cone due to centrifugal action. The filtrate and the smaller particles migrate towards the centre, spiral upwards and out through the vortex finder discharging through the overflow pipe. The advantage in hydrocyclones is that they have no moving parts, no extra mechanical energy is required, and unlike screens no clogging

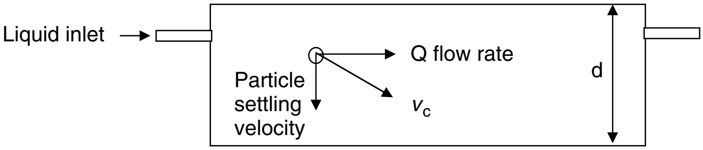


Figure 8.5 A Schematic of discrete settling

takes place. Hydrocyclones can be made from plastic and erosion-resistant materials. However, each cyclone performs only within a narrow band of flow rate. Hydrocyclones are used extensively in the food, mining and pulp and paper industries.

Figure 8.6 shows a graphical illustration of hydrocyclones.

The efficiency with which a hydrocyclone separates at a certain size depends on several design parameters, including [4]:

- diameter of the chamber (D)
- area of the point of entry into the feed chamber ($0.05 \times D^2$)
- area of vortex finder ($0.35 \times D^2$)
- length of the chamber
- angle of the conical section (10° and 20°)
- on operating parameters such as the flow rate of the input material.

As a general rule, the smaller the diameter of the hydrocyclone, the better it is at separating smaller particles.

Table 8.5 shows the separation of suspended solids in a food-processing plant.

8.5.3 Settling

For solids having a specific gravity less than grit, a longer time is required in settling tanks. Particles that would not settle unaided are referred to as *colloids* and typically measure between 10^{-3} and 1 μm (4×10^{-8} and 4×10^{-5} in.) in diameter.

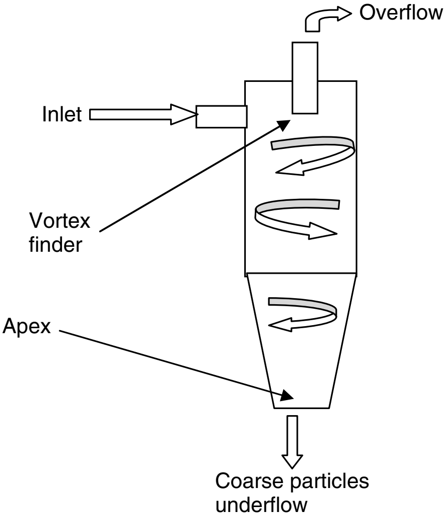


Figure 8.6 A schematic of a hydrocyclone

Table 8.5 Separation efficiency of suspended solids using a hydrocyclone in a food-processing plant

Test	Feed TSS mg/L	Overflow TSS mg/L	Underflow TSS mg/L	Removal efficiency (%)
Run 1	376	37	3,480	90
Run 2	436	51	1,348	88
Run 3	230	73	1,160	68
Run 4	270	12	1,810	96
Run 5	284	16	1,360	94

Courtesy of the Water Management Group Pty Ltd.

For removal of colloidal materials the type of equipment used can be

- conventional horizontal-flow tanks
- tube settlers
- inclined plate settlers
- circular or rectangular clarifiers.

The key design criteria are

- the surface area of the settling tank
- detention time
- tank depth
- surface overflow rate
- weir overflow rate.

Given the inability for laboratory results to exactly mirror actual conditions, settling time is normally doubled and overflow rate is multiplied by 1.5. Typical settling times are around 1–4 hrs. Tank depth is normally around 4 m but can range from 2 to 5 m. After settling the water might of sufficient quality to be reused elsewhere.

8.5.4 Chemically Aided Settling – Coagulation

Otherwise known as coagulation, it is used when colloidal particles do not settle by themselves within a reasonable time and require chemicals to aid in settling. Colloidal particles do not settle because there is an electrical outer layer of negative charge that repel colloids from attaching to one another. To neutralise the outer static charge, chemicals having a high positive charge to mass ratio such as aluminium sulphate, ferric chloride or synthetic coagulants are added. Important polymer properties are polymer type (cationic, anionic and non-ionic), charge density, molecular weight and functional group chemistry. Functional groups can be polyamines or acrylamides. The molecular weight of polymers can range from 10^4 to 10^7.

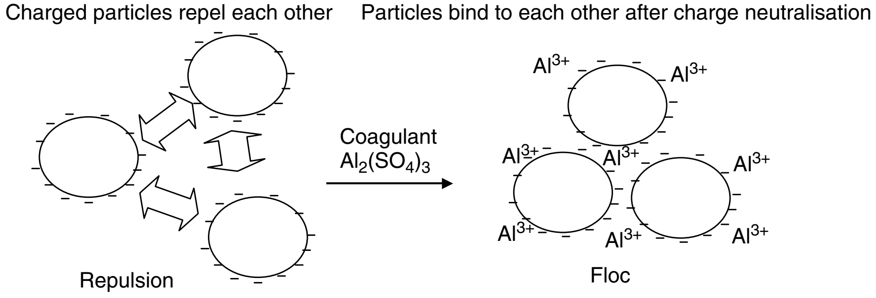


Figure 8.7 How coagulants bind to colloidal particles

Figure 8.7 shows the effect of inorganic coagulants and polymers on colloidal particles. To further aid the process, high molecular polymers or bentonite clay known as flocculants or coagulant aids are added. As Figure 8.7 shows, once the charge is removed the particles are free to collide and stick together forming larger and larger flocs that ultimately become visible to the naked eye and settle quickly. The coagulant aluminium ion precipitates as the $Al(OH)_3$ between pH 6 and 8. The process of chemical coagulation also precipitates metal hydroxides. The resulting jelly-like mass known as *floc* settles to the bottom of the clarifier. The choice of coagulant, coagulant dosage, coagulant aid and pH depends on the wastewater analysis, water temperature, types of clarification equipment and the end use of the treated effluent.

8.5.5 Filtration

Filtration is a separation process that consists in passing a solid–liquid mixture through a porous material (filter) which retains the solids and allows the liquid (filtrate) to pass through. Granular media polishing filters are used for the removal of suspended solids in the 5–50 mg/l range.

The most common example is the conventional sand filter. Table 8.6 shows typical dimensions of filter media. Filters can be classified as

- Single media – sand or anthracite
- Dual media – sand and anthracite
- Multimedia – garnet, sand and anthracite.

Table 8.6 Typical dimensions of multimedia filters

Filter media (Layers arranged from top to bottom)	Specific Gravity	Diameter mm	Height of typical filter layer*
Anthracite	1.6	1–1.5	4.5x
Silica sand	2.65	0.5	2x
Garnet	4.5	0.2–0.4	1x

* Total height of filter media layers – 76 cm (30 in.).

Single-media filters have fine-to-coarse gradation in the direction of flow. After backwashing a single media filter the granular media settles back into place with the coarse materials (largest diameter) on the bottom, fine materials (smallest diameter) on the surface. This natural distribution causes solids to rapidly accumulate at the surface causing increased headloss and short filter runs. It is preferable to have trapped material accumulate more evenly through the depth of the bed to allow longer filter runs.

Multimedia filters employ two or more filter media with different grain size and densities. The media are selected such that the smaller particles are the most dense (e.g. garnet with a specific gravity of 4.5 and particle size of 0.2–0.4 mm), the medium-sized particles have an average density (e.g. sand grains with a specific gravity of 2.65 and a grain size of 0.5 mm) and the largest particles are the least dense (e.g. anthracite grains with a specific gravity of 1.6 and a grain size of 1.0 mm). When mixed and permitted to settle, the multimedia bed will grade itself according to the density of the material. Therefore, the garnet being the densest will settle at the bottom and the anthracite being the least dense will be at the top and sand will be in the middle. When the feed stream flows from top to bottom, the courser-suspended solids will be removed in the upper layers of the filter and the smaller suspended solids near the bottom. Backwashing is performed in the opposite direction. The cost of backwash water and replacement media are the primary expenses of a multimedia filter. Backwash flow rates for multimedia filters are in the order of 24.5–36.5 $m^3/hr/m^2$ (10–15 US gpm/ft^2).

Filter performance is dependent on the amount of turbidity to be removed, the size of the suspended particles and filtration flow rate. With feedwaters of 30 NTU, a multimedia filter is capable of producing effluent with turbidity of 1 NTU and a particulate size in the range of 5–10 μm (0.0002–0.0004 in.). Filtration also reduces insoluble BOD.

Typical filtration flow rates are shown in Table 8.7.

Other filtration methods are cartridge filtration, online filtration (refer to Chapter 5) and membrane filtration. Membrane filtration will be discussed later in this chapter.

Table 8.7 Typical filtration flow rates

Filter rate	Flow rate	
	$m^3/hr/m^2$	US gpm/ft^2
Single	7.4–9.8	3–4
Dual	14.7	6
Multimedia	14.7–36.5	6–15

8.6 Removal of Fats, Oils and Greases

8.6.1 Sources of Fats, Oil and Grease

Fats, oil and grease (FOG) can be of hydrocarbon, vegetable or mineral based and are found in

- laundry effluent
- food retailing
- processing of vegetables and production of margarine
- metal-finishing and metal-cutting industries
- petroleum refining and petrochemical industries.

Emulsions are defined as the dispersion of liquid in an aqueous medium.

The FOG may be present in these streams as either *free floating* or an emulsion. Emulsions occur when oil droplets are stabilised by contaminants or surfactants giving them a electrical charge that will repel each other, for example mayonnaise. The colour of the emulsion is an indication of the particle size of the oil globules. Table 8.8 shows the relationship between particle size and the colour of the emulsion. Unstable emulsions occur if the droplets coalesce spontaneously at a reasonably rapid rate such as that for oil and vinegar salad dressing. Microemulsions are when the emulsion droplet size is less than 0.05 μm.

Methods for separating FOG include physical and chemical separation. When both free and emulsified FOG are present, the most economical solution is to first remove as much free oil or fat as possible.

Physical separation can take the form of

- skimming
- plate-type separators
- API (named after the American Petroleum Institute)
- dissolved air flotation system
- membrane systems.

Table 8.8 The relationship between particle size and emulsion colour

Particle size (μm)	Emulsion appearance
Macro globules >150	Two phases may be distinguished – free oil
10–150	Milky white emulsion
10–1.0	Blue-white emulsion
1.0–0.5	Grey semitransparent
< 0.5	Transparent microemulsion, with three or more phases. Stable emulsion. Droplet rise velocity too long for gravity separation.

In chemical separation the dispersed water droplets and solids are destabilised through the use of coagulants to some of these processes to enhance separation and improve quality of the end product.

8.6.2 Free FOG Removal – Skimming

Free oil droplets greater than 150 μm (0.006 in.) separate easily from water by gravity due to differences in specific gravity such as in plate systems, centrifuges as per Stokes Law or differences in surface tension phenomena such as in oil skimmers.

Gravity oil separators are usually rectangular or circular in shape. Basic elements include an inlet distributor, internal baffles and an oil-collecting or skimming device. Size is determined on the basis of rise rate for a critical size oil globule, velocity through the unit and detention time.

The simplest form of gravity separation is the oil and fat interceptor, otherwise known as a *grease trap*. They are commonly found in shopping malls, restaurants and in the food-processing industries where the requirement is only to skim the fat before the effluent is discharged to the sewer. Grease traps are equipped with baffles to enable the grease or fat to float to the surface so that it can be pumped out.

In the petroleum refining industry the API separators are used to capture free oil. The API separators allow the free oil to rise to the surface, allowing it to be collected and sent back to the desalters as *slop oil* for further processing. The API separators are rectangular tanks with a minimum length to width ratio of 5:1 to minimise potential for short circuiting.

A variant of the API separator is the corrugated plate separator (CPI). The CPI is similar to the lamellar clarification for solids removal. Corrugated metal or plastic plates (12–48 plates) are assembled inclined in parallel to each other at distances 2–4 cm (0.75–1.5 in.). The inclined plates allow for coalescence of oil droplets to large oil globules and migrate to the surface and the settled solids migrate downwards. The large oil globules rise to the surface where it is skimmed off. The CPI is considered to be more effective than API units for oil separation.

Hydrocyclones are also effective for oil removal. The principles of operation were discussed under sedimentation.

Skimming of FOG from the surface of separation vessels can be performed on a manual or continuous basis. Suction skimmers and belt skimmers are used for this purpose. Suction skimmers are being replaced by belt skimmers, which are more reliable with low maintenance.

As mentioned earlier, gravity separators are ineffective for oil droplets smaller than 150 μm (0.006 in.).

8.6.3 Emulsified FOG Removal

The removal of emulsified FOG is more difficult. It is the major contributor to high oil concentrations in the effluent streams. For an example, in spent metal-cutting fluid the free oil can be 5–10% whereas the emulsified oil fraction can be 80–90% of the total. Emulsified oil separation technologies include air flotation, membrane and adsorption processes.

8.6.3.1 Air Flotation

Flotation is basically sedimentation in reverse, to remove floatable materials and solids by increasing the density difference between the oil emulsion and the water phases. In the air flotation process, the feed water is saturated with air under pressure and then expanded through a restriction to atmospheric pressure. The sudden expansion forms microscopic air bubbles, which attach to oil droplets. The air/oil droplets have a lower density than oil micelles and micro-emulsions causing them to rise to the surface much more quickly where they are continuously skimmed off and removed. Air flotation is particularly useful when treating waters which are high in total suspended solids (TSS) or have highly variable suspended solids content.

There are two types of air flotation systems in use:

1. induced air flotation (IAF)
2. dissolved air flotation (DAF).

In IAF systems, air is introduced into the wastewater by an aspirator device or by a fine hole diffuser to form bubbles up to 1000 μm (0.04 in.) in diameter. Since the air/water contact occurs essentially at atmospheric pressure, air bubbles are entrained in the water rather than being formed in the water. Even though the removal efficiencies are less effective than for DAF it is cheaper since no air pressurisation is required and can remove larger amounts of oil/solid flocs which are brought to the surface.

The DAF process is more common than the IAF process. Figure 8.8 shows a schematic of a DAF process. In the DAF process, due to the air bubbles being formed inside the pressurised chamber and after the pressure control valve (expansion valve), microscopic air bubbles and air/oil bubbles 30–120 μm (0.0012–0.048 in.) in size are formed. The air/water stream enters the bottom of the tank. Initial separation occurs at this point. Typical air pressures are 300–600 kPa (44–85 psig). Chemical coagulants such as ferric chloride ($FeCl_3$) or synthetic proprietary products known as reverse emulsion breakers are added to enhance the separation process. However, in food-processing plants, the addition of synthetic coagulants renders the sludge unsuitable as animal stock feed.

There are three methods of aeration:

1. aeration of the main stream
2. aeration of the side stream
3. aeration and recycling a slip stream of clean effluent.

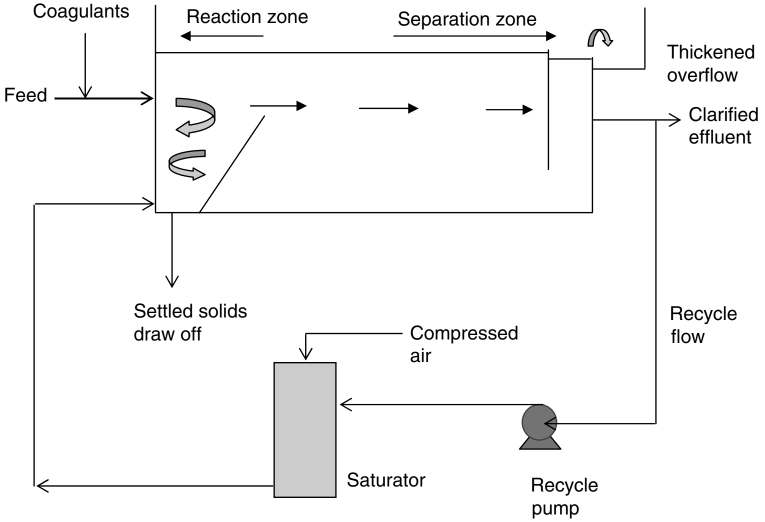


Figure 8.8 A schematic of a dissolved air flotation process

Aeration of the main stream is not common practice. It is generally used when chemical treatment is not required since the floc formed will be destroyed when it goes through the expansion chamber.

In the aeration of a recycled stream, 15–50% of clean effluent is more advantageous than aeration of slip stream, since it does not contribute to dilution of the feed water (if potable water used as the slip stream) and allows for the total influent flow to be flocculated.

There are essentially three types of flotation designs:

1. rectangular
2. circular
3. corrugated plate pack.

Circular flotation tanks and corrugated plate designs are preferred when treating water with high suspended solids concentrations for a given unit capacity.

The DAF units can reduce oil concentrations to 10–25 mg/L in the effluent as long as the influent oil concentrations are less than 160 mg/L [5, 6]. The DAF systems operate at higher hydraulic loading rates (5–15 m/h [2–6 gpm/ft^2]) than gravity sedimentation equipment and consequently detention times are shorter (about 15–30 minutes). Therefore DAF systems require less space.

The key design and operating figures are given in Table 8.9. Performance of DAF systems are dependent on several factors including:

- the solids concentration – higher solids content usually gives higher removal efficiencies

Table 8.9 Key design and operating parameters of DAF systems

Parameter	Metric	US units
Detention time	15–30 minutes	15–30 minutes
Solids loading rate (determines the size of the unit)	2–25 $kg/m^2\,h$	0.5–5.0 $lb/h\,ft^2$
Overflow rate (surface hydsraulic loading rate)	5–12*	2–5*
Recycle Ratio	15–50%	15–50%
Saturator pressure	450–600 kPa	44–85 psig
Air to solids ratio	0.005–0.06 mL/mg	0.005–0.06 mL/mg

* A key consideration with regard to this design parameter is whether the loading rate includes the recycled volume as well as the influent wastewater volume being applied per unit area of the system.

- air to solids (A/S) defined as the amount of air released after pressure reduction and the amount of solids present in the wastewater. There is usually an optimum A/S which is determined by bench scale tests.

Key factors in the successful operation of DAF units are the maintenance of proper pH (usually between 4.5 and 6, with 5 being most common to minimise protein solubility and break-up emulsions), proper flow rates and the continuous presence of trained operators.

8.6.3.2 Ultrafiltration

Membrane processes, especially ultrafiltration (UF) membranes, can be used for the removal of emulsified oil. Ultrafiltration is a low pressure membrane process (100–1000 kPa [14.5–145 psig]) that separates suspended solids and high molecular weight dissolved solids from liquid. The separation is performed by a semipermeable membrane. Low molecular weight dissolved solids such as salts and surfactants pass through the membrane and are discharged with the permeate while high molecular weight dissolved solids >3000 molecular weight (oil, colloidal solids and suspended solids) are concentrated and rejected. Recovery rates of 75% can be achieved with oil concentrations reduced from 3500–30 mg/L, a 99% reduction in the concentration of oil.

Aside from UF, other membranes such as microfiltration and nanofiltration can also be used to separate emulsions. Table 8.10 shows a specific type of plate membrane process known as VSEP (vibratory shear enhanced membrane process) [7] which has achieved high removal efficiencies.

Other methods of treatment are

- biological treatment
- centrifugation
- evaporation
- activated carbon

Biological treatment will be discussed in the next section.

Table 8.10 Oil removal efficiencies using the VSEP process

Process	Membrane	% Recovery	Initial concentration solids %	Final % solids in reject stream
Lubricant wastewater	100,000 MWCO* UF	60	10.33	25.82
Lubricant wastewater	Nanofiltration	75	2.37	37.02
Machine coolant	7,000 MWCO UF	75	2.89	13.82
Oily wastewater	Nanofiltration	80	0.07	0.81
Oily wastewater	70,000 MWCO UF	60	0.15	1.47
Oily wastewater	Nanofiltration	90	0.61	6.64
Produced water/Silt	100 k MWCO UF	70	22.69	84.19
Washwater degreaser	Reverse Osmosis	60	3.02	9.59

Adapted from New Logic Research Inc. *Using Vibrating Membranes to treat oily wastewater*.
* MWCO refers to molecular weight cut off which is a unit to measure the porosity of the UF membrane. The higher the MWCO, the greater the diameter of the pore. These aspects will be discussed under membranes.

Centrifugation and evaporation are energy-intensive processes. Evaporation is suitable for small volumes of poorly emulsified oils.

Evaporators work on the principle that by raising the temperature to of the wastewater 70° C–80° C (160–176° F), the emulsion will be broken. Water will evaporate while oil is left behind. This method is not effective if solids are too high or if the emulsion cannot be broken by heat.

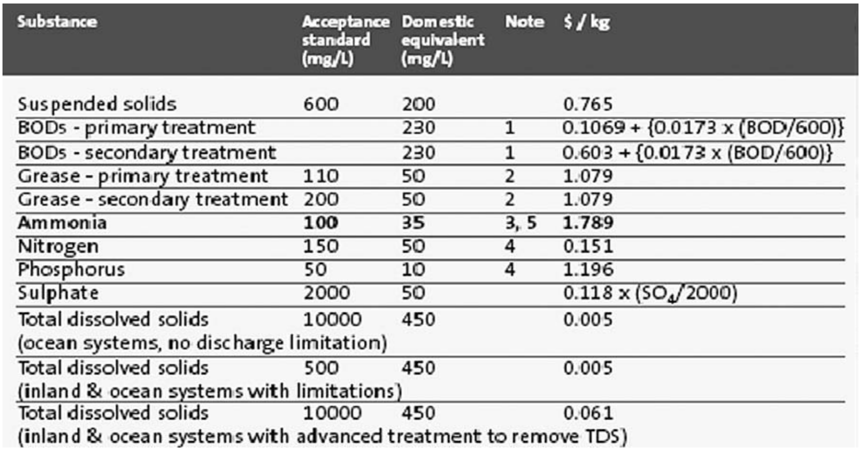
Activated carbon is used to remove traces of oil (1 mg/L or less), to achieve ultrapure water or to remove the surfactants in the wastewater. Activated carbon will be discussed under adsorption.

8.7 Removal of Biodegradable Organics

For the vast majority of industries, removal of biodegradable organics (BOD) is a prerequisite before the effluent streams can be reused. Their removal is also important if discharging to the public sewer, and in the food industries high BOD can indicate product losses.

Many water utilities accept trade waste discharges subject to concentrations and mass loadings being lower than the acceptance standard or as specified in the trade waste agreement. The BOD concentrations higher than the acceptance standard are charged at higher rates since high BOD concentrations in the sewer contribute to rapid corrosion of sewer.

Figure 8.9 shows Sydney Water's trade waste acceptance standards, domestic equivalents and charging rates for domestic substances. In the UK the Mogden formula is used to calculate trade waste strengths.



Substance	Acceptance standard (mg/L)	Domestic equivalent (mg/L)	Note	$ / kg
Suspended solids	600	200		0.765
BODs - primary treatment		230	1	0.1069 + {0.0173 x (BOD/600)}
BODs - secondary treatment		230	1	0.603 + {0.0173 x (BOD/600)}
Grease - primary treatment	110	50	2	1.079
Grease - secondary treatment	200	50	2	1.079
Ammonia	**100**	**35**	**3, 5**	**1.789**
Nitrogen	150	50	4	0.151
Phosphorus	50	10	4	1.196
Sulphate	2000	50		0.118 x (SO_4/2000)
Total dissolved solids (ocean systems, no discharge limitation)	10000	450		0.005
Total dissolved solids (inland & ocean systems with limitations)	500	450		0.005
Total dissolved solids (inland & ocean systems with advanced treatment to remove TDS)	10000	450		0.061

Figure 8.9 Trade waste acceptance standards, domestic equivalents and charging rates for domestic substances

Courtesy of Sydney Water – Trade Waste Industrial Customers – Acceptance Standards and Charging Rates 2006–2007.

In many food-processing plants, high BOD discharges represent product loss to the sewer. For instance, in the dairy industry 1 kg of BOD represents 9 kg of milk. Therefore, minimising product losses will reduce trade waste charges while increasing profits. The following example illustrates the point.

Worked example

A dairy producing 500 000 L milk/day has a sewer usage discharge factor of 0.88 and discharges 440 kL/day. The BOD of the trade waste is 2500 mg/L. The BOD of raw milk is 104 600 mg/L. What are the trade waste charges and value of lost milk? If the BOD was reduced to 1000 mg/L what are the new charges? Assume that raw milk costs $0.10/L and the trade waste is discharged to a secondary treatment plant. Use the values in Figure 8.9 for acceptance standards and charging rates.

	Before waste minimisation	After waste minimisation
Loss of raw material, kg/annum	2,500 × 440 × 1,000/ 104,600 = 10,516 kg/ day × 365 days = 3,838,432 kg. = 2.1% loss	1,000 × 440 × 1,000/ 104,600 = 4206.5 kg/ day × 365 days = 1,535,373 kg = 0.8% loss

Cost of lost raw, material/annum	$ 383,843	$153,573
BOD, $/kg	$0.603 + (0.0173 × 2500/600) = $0.675/kg	$0.603 + (0.0173 × 1000/600) = $0.632/kg
Annual trade waste charges	= $1100/day = $401,500	= $440/day = $160,600

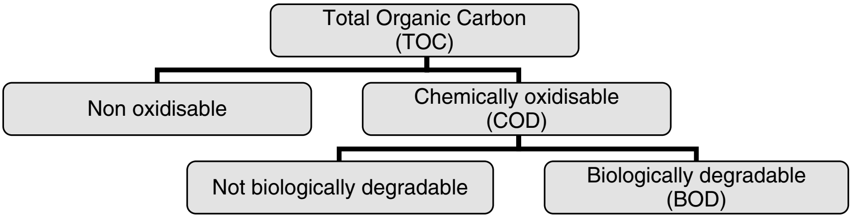


Figure 8.10 The relationship between the organic carbon fractions in wastewater

Organic matter can be classified as shown Figure 8.10.

As Table 8.3 illustrated, when the BOD/COD ratio is greater than 0.4 then the effluent is generally biodegradable, provided that there are no toxins present.

Microbes degrade organics in nature and these principles form the basis of biological treatment albeit, at very high concentrations. Some inorganic compounds such as ammonia, cyanide, sulphide, sulphate and thiocyanate are also biodegradable.

Biological treatment methods can be classified as

- aerobic (using oxygen as the electron acceptor)
- anaerobic (using other electron acceptors such as sulphate, phosphate or other organics other than oxygen).
- hybrid (*combination of aerobic and anaerobic processes*).

The aerobic and anaerobic processes as shown graphically in Figure 8.11 produce different end products. Aerobic processes produces sludge and heat while the anaerobic process produces sludge and methane gas, which can be utilised to generate renewable energy.

The various types of biological processes are shown in the table below. Many of these processes are discussed in wastewater treatment literature and therefore, in the interest of space, will be discussed only briefly in this chapter.

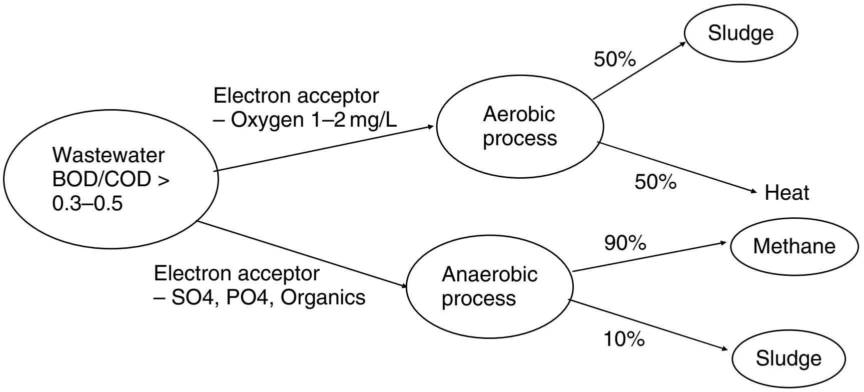


Figure 8.11 An illustration of aerobic and anaerobic processes

Aerobic	Anaerobic	Hybrid
Biological filtration	Anaerobic digestion	Facultative lagoon
Activated sludge (ASP)	Hybrid anaerobic	
Oxidation ditch	Anaerobic lagoon	
Sequencing batch reactor (SBR)	UASB	
Spray irrigation	Anaerobic filters	
Rotating biological discs	Continuous stirred tank reactor (CSTR)	
Submerged Membrane bioreactor		

Facultative lagoons are the most common form of aquatic treatment-lagoon technology currently in use. The water layer near the surface is aerobic while the bottom layer, which includes sludge deposits, is anaerobic. They are applicable when there is sufficient land area.

Aerobic processes can be divided into two groups. These are

1. *suspended growth system*
2. *attached growth system.*

In the suspended growth systems the biomass is maintained in suspension in an aqueous environment. Oxygen transfer occurs directly as dissolved oxygen – from the aqueous phase to the biomass. The most representative and flexible of these processes is the **activated sludge process** (ASP). It must be noted that not all biological matter is digested by the bacteria and these are called 'hard' BOD. It may take days for hard BOD to be digested.

In the attached growth systems the biomass is supported by a solid phase on which it grows. Oxygen is transferred directly to the biomass from the gaseous phase, that is air. The **trickling filter** is the best example of this class.

Trickling filters consist of a fixed film biological reactor, which is followed by a secondary settling tank.

The ASP will be examined, given its ability to handle a variety of industrial wastewater streams. For this reason, it is quite common in industry.

8.7.1 Activated Sludge Process

The ASP was developed in the United Kingdom in the early years of the twentieth century and now forms the centrepiece of the biological treatment processes worldwide.

The ASP as shown in Figure 8.12 consists of a balancing tank to equalise flow and homogenise effluent loads, a fluid bed reactor known as the *aeration tank* where the organic load is stabilised, a secondary settling tank called the *clarifier* where the biological mass is allowed to settle to the bottom of the clarifier while the clear liquid above it is filtered and discharged to the sewer or to the receiving waters. To maintain the bacterial population in the aeration tank in sufficient concentration, a portion of the settled activated sludge (about 25–50%) is pumped or recycled back to the aeration tank. The rest of the sludge is sent to a thickener for dewatering.

The heart of the process is the aeration basin, which is a complex ecosystem of competing organisms. The dominant organisms are the 300 species of unicellular bacteria [8]. Bacteria can be classified as per Table 8.11 by shape and function.

The other organisms present in settleable solids are fungi, protozoa (also single cell organisms), rotifers and sometimes nematodes (worms). Common types of protozoa found in activated sludge mass are the free swimming variant known as ‘ciliates’, amoeba and flagellates. Rotifers are multi-cellular animals having a digestive system and rotating cilia around their head and hence the name. Nematodes can be 0.2–1 mm in length.

Their presence or absence is indicative of the state of the biomass and age. For example, the presence of filamentous bacteria indicates bulking sludge. Similarly, the presence of free swimming protozoa (ciliates) is a sign of a healthy biomass with adequate oxygen supply and the presence of nematodes and rotifers in large numbers is a sign of long and mature sludge.

The process requirements for ASPs are similar to other natural biological processes. The ASPs are capable of reducing organic load by 85–95% with an aeration time of about 6 hrs. However, successful operation of these systems requires trained manpower and the conditions conducive to biological growth. These are

- nutrient loading
- dissolved oxygen (DO)

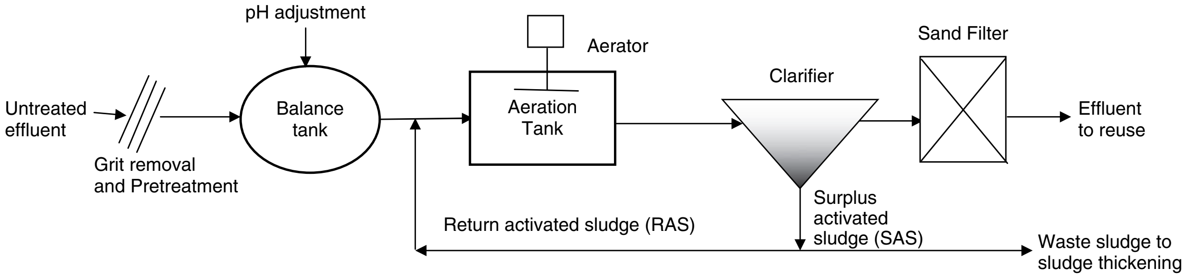


Figure 8.12 A schematic of a typical activated sludge process

Table 8.11 Classification of Bacteria

By shape	By function	Comments
Spherical	Floc formers	Majority. Floc formers are desirable and required for biodegradation to establish a stable flow with good settling characteristics. Size is about 0.5–2 μm (0.00002–0.00008 in.).
Rod	Filamentous	Undesirable. Cause of bulking and foaming in aeration tanks. They comprise of long chains of small bacterial cells and can reach lengths of 100 μm(0.004 in.).
Spiral	Nitrifiers	Desirable. Bacteria to convert ammoniacal nitrogen to nitrate through a two-step process. First step is the conversion of ammonia to nitrite and then the nitrite is converted to nitrate.

- pH
- temperature
- the presence of toxic or inhibitory materials.

Nutrient loading – ASPs operate best when the organic load and flow is relatively constant. Unfavourable conditions can be tolerated as long as there are no sudden fluctuations in flow and organic loading which lead to unsteady state biomass conditions in ASPs. For example, after a rain the stormwater oil concentrations in oil refineries can exceed several thousand mg/L. This quantity of oil entering the ASP can kill the bacteria. Therefore, a balancing tank is a prerequisite in an ASP to even out the flow and organic loading.

The BOD/COD ratio gives an indication of its biodegradability and nutrient requirements. F:M ratio is one of the most important parameters to monitor the relationship between the influent nutrient quantity (equal to the pollutant quantity) and the existing mass of micro-organisms in the aeration tank available to treat the incoming BOD.

For conventional plants the F:M is around 0.2–0.5. At higher values while the rate of treatment increases, the sludge has poor settling characteristics. F:M values below 0.2 are associated with slow BOD removal rates, but with very good sludge settlement.

High load	0.8–1.5	F:M per day
Normal load	0.3–0.7	F:M per day
Low load	0.05–0.2	F:M per day

Once the BOD/COD ratio for the wastewater has been established, then COD values can be used to calculate F:M ratios.

Sludge age is an indication of the F:M ratio. Shorter times are indicative of high growth rate and conversely a longer time is indicative of low growth rates. For instance, at high BOD loading the sludge age will be less than

2 days. For plants requiring nitrogen removal sludge age is normally around 10–15 days [9].

Besides carbon, hydrogen and oxygen the biomass requires nitrogen (N), phosphorous (P) and micronutrients such as iron, calcium, magnesium, copper, zinc and so on. Unlike domestic sewage which has a C:N:P = 100:17:5–100:19:6, most industrial wastewaters such as paper mill effluent, brewery effluent lack N and P which should be added (in the form of urea, superphosphate or ammonium phosphate) to maintain optimal conditions. The minimum BOD to N and P ratio required for optimal microbial growth in the aeration tank is given as:

$$\mathrm{BOD:N:P} \quad = \quad 100:5:1 \tag{8.2}$$

Brewing and some food-processing industries are particularly conducive to sludge bulking probably due to nutrient imbalance.

Dissolved oxygen (DO) – As mentioned earlier aerobic bacteria require DO to produce energy. The minimum DO concentration required for ASP is 0.5 mg/L. Therefore, oxygen is controlled at 1–2 mg/L.

The DO consumption depends on various factors, including the F:M (sludge loading). For a given BOD, more DO is required as the sludge loading decreases. At a low sludge loading, large quantities of DO are required in order to break down the activated sludge.

Nitrification also occurs at low sludge loading, considerably increasing the DO demand. For satisfactory nitrification, the DO needs to be maintained at around 4 mg/L.

The DO is supplied by mechanical or diffused aeration systems such as surface aerators, motor-driven turbine, spargers, swing diffusers, through dispersed aeration and pure oxygen injection. Typically 0.5–2.0 kg of DO is produced per kWh. Aeration is the most expensive operating cost in an ASP and needs to be optimised by monitoring the oxygen concentration.

pH – The optimum pH for ASP is within 6.5–9.5 and for nitrification 7.0–8.5.

Temperature – The typical temperatures for operation of ASPs are 5° C–30° C. But some thermophilic species of bacteria can operate at higher temperatures as high as 60° C. For every 10° C rise in temperature the growth rate doubles (Arrhenius rule). Higher the temperature, the critical oxygen concentration also increases.

Common problems in ASPs are shown in Table 8.12.

There are other variations of this, such as step variation, contact stabilisation, high rate, extended aeration and pure oxygen systems. These are well documented in literature.

For wastewater streams with *non-steady-state* conditions or when the available foot print is limited, the Sequencing Batch Reactor (SBR) process is a viable option. It is an activated sludge process designed to operate under

Table 8.12 Common problems in ASPs.

Problem	Possible cause
High solids content in clarified effluent	1. Too high or too low solids retention time 2. Presence of large number of filamentous bacteria. Treat with biocides.
Settled sludge rises back again	Denitrification produces nitrogen gas that becomes trapped in the sludge causing it to float.
Bulking sludge does not settle quickly	Presence of filamentous micro-organisms. Treat with biocides.
Poor organic load reduction	1. High sludge wastage 2. Lack of N and P 3. Short circuiting in the clarifier 4. Low DO 5. Presence of toxic substances.
Odour	Anaerobic conditions present in the clarifier or low DO.
Foaming (mouse like)	Presence of a particular type of filamentous bacteria called *Nocardia*. Treat with biocides.

non-steady-state conditions. An SBR operates in a true batch mode with equalisation, aeration and sludge settlement occurring in the same tank. To optimise the operation, two or more batch reactors are used in a predetermined sequence. The SBR system can be designed with the ability to treat a wide range of low to intermittent influent volumes, whereas the continuous system is based upon a fixed influent flow rate. Once the reactor is full, the flow is discontinued and the aeration and mixing is discontinued after the biological reactions are complete. The biomass settles and the treated supernatant is removed. Excess biomass is wasted at any time during the cycle. Thus, there is a degree of flexibility associated with working in a time rather than in a space sequence. The SBRs produce a BOD removal efficiency of 85% depending on the mode of operation. Additional advantage of SBRs are that the cost of clarification equipment is avoided. The negatives of SBRs are that the control mechanisms are more complicated than conventional activated sludge systems.

Typical SBR effluent water quality parameters are

TSS	<10 mg/L
BOD	<10 mg/L
Total N	5–8 mg/L
Total P	1–2 mg/L

8.7.2 Anaerobic Processes

Anaerobic processes are best suited to treat high concentrations of BOD such as wastewater from olive oil processing which can contain BOD concentrations as high as 30 600 mg/L and COD concentrations of 97 000 mg/L, beer and wine distillery effluent, textile mill effluent–containing azo dyes, fish-processing effluent and other hard-to-process effluent. Aerobic systems are unsuitable under these high BOD conditions.

Anaerobic processes contain large numbers of highly specialised bacteria which, in the absence of oxygen, convert the concentrated organics into methane gas (CH_4) and carbon dioxide (CO_2) rather than to new cell growth.

One of the most popular anaerobic processes is *The Upflow Anaerobic Sludge Blanket* (UASB). In the UASB reactor, the wastewater enters a vertical tank at the bottom. The wastewater passes upwards through an anaerobic sludge bed where the micro-organisms in the sludge come into contact with wastewater-substrates. The sludge bed which occupies 30–60% of the reactor volume is composed of micro-organisms that naturally form granules (pellets) of 0.5–2 mm diameter that have a high sedimentation velocity and thus resist wash-out from the system – even at high hydraulic loads.

Figure 8.13 shows a graphical illustration of the UASB process.

The gas produced from a well-functioning anaerobic plant contains 60–70% methane. The rest is CO_2 and insignificant amounts of nitrogen and hydrogen gas. The upward motion of released gas bubbles causes hydraulic turbulence that provides reactor mixing without any mechanical parts. At the top of the reactor, the water phase is separated from sludge solids and gas in a three-phase separator – also known the *gas–liquid–solids separator*.

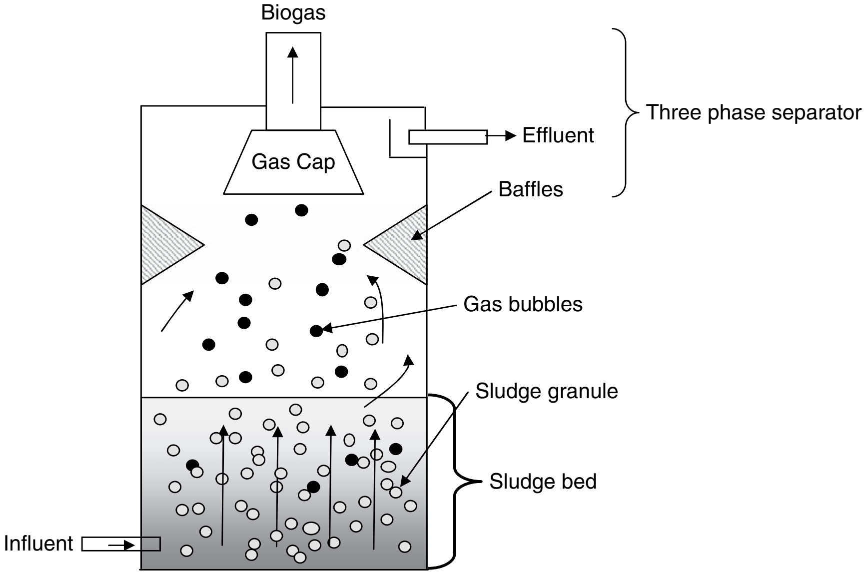


Figure 8.13 UASB Anaerobic process

8.7.2.1 Performance

Operational performance indicators for the UASB process is as follows:

COD removal efficiencies	80–95%
Hydraulic loading rate (HRT)	0.25–1.25 days
Solid retention time	50–100 days or more.
Energy production	1.27×10^7 J/kg (5470 Btu/lb COD) [10]

Operational costs are reported as low as US$0.10/kg COD (due to the generation of own power).

The advantages of anaerobic processes over aerobic processes are summarised in Table 8.13.

Table 8.13 Comparison of Aerobic (ASP) and Anaerobic Treatment (UASB) processes

Criteria	ASP	UASB
Applicability	Limited to BOD loadings less than 2000 mg/L. High strength wastes >2000 mg/L requires dilution [10].	Ideal for high organic strength wastewater. 5–20 kg COD/m^3.d as against 0.5–3 kg/m^3.d for aerobic systems [11]
	Suitable for cold weather operation. Not suitable for high temperatures.	More suited for temperatures above 22° C. Can operate at temperatures as high as 57° C.
	Tolerates a reasonable amount of toxic substances	Cannot tolerate toxic substances
	High nutrient requirements C : N : P = 100 : 5 : 1	Low nutrient requirement C : N : P = 250–350 : 5 : 1
	Continuous operation. Does not tolerate long shutdowns	Applicable to plants with seasonal production.
	High space requirements. Requires a number of tanks.	Low space requirements due to high strength of organic waste.
	Small plants are economically feasible	Small plants not economically viable.
Treatment efficacy	Relatively short sludge retention time is required	Long sludge retention time is required
	N and P removal achieved	Little Nor P is removed.
	Start up time is short	A slow process. Can take months for start up.
	High sludge volumes are produced	Low sludge volumes are produced.
	No flaring of gas is required	Flaring or combustion of methane gas is required.
Costs	Medium to high capital cost. High operational costs. High energy costs for aeration, maintenance of aerators, transport costs for sludge disposal and nutrients costs.	Medium to high capital cost Low operational costs. Low power costs due to generation of methane gas. Low nutrient costs. Low sludge disposal transport costs.

8.7.3 Membrane Bioreactors

Membrane bioreactors (MBR) were originally conceived in the 1960s. MBRs are now becoming popular in domestic and industrial wastewater treatment plants with BOD levels as high as 18 000 mg/L. MBRs are ideal for users who have space constraints, require a consistent quality of low BOD and TSS effluent.

In an aerobic ASP plant, the rate limiting stage is the settling process in secondary clarifier. It limits the solids in the aeration tank to 1500–5000 mg/L (mixed liquor suspended solids (MLSS)). Since the MBR process does not rely on gravitational settling for separation of solids from the liquid, it can operate at significantly higher MLSS concentrations. It relies on filtration performance of microfiltration and ultrafiltration membranes to separate the solids greater than 0.4 μm (0.00016 in.) which includes many types of bacteria and viruses. Therefore, the effluent quality is independent of the settling characteristics of the sludge but MBRs are limited by the fluid dynamics of high-strength suspended solids and oxygen transfer. Typical MLSS strengths are in the order of 10 000–12 000 mg/L. The secret to the capability of the membranes to perform in a biological reactor in a high solids environment is due to the fact that the membranes are used to contain the biomass in the reactor while discharging a purified stream.

The MBR systems are of two designs – submerged and external recirculation. Figure 8.14 shows a schematic of a submerged MBR process.

In the submerged MBR, the microfiltration or ultrafiltration membranes are submerged in the aeration tank. As illustrated, pumps draw product water and sludge. A portion of the sludge is recycled. Air blowers supply air to scour the membranes and for uniform distribution of suspended solids. In the external MBR, the membranes are external to the aeration tank.

The foot print of the bioreactor in an MBR is one-third to one-fifth of that of a conventional ASP. Hydraulic retention times are typically 4–20 hrs with sludge retention times in the order of 15–45 days and recovery is 99%. The long sludge age provides adequate time to reduce excess biomass

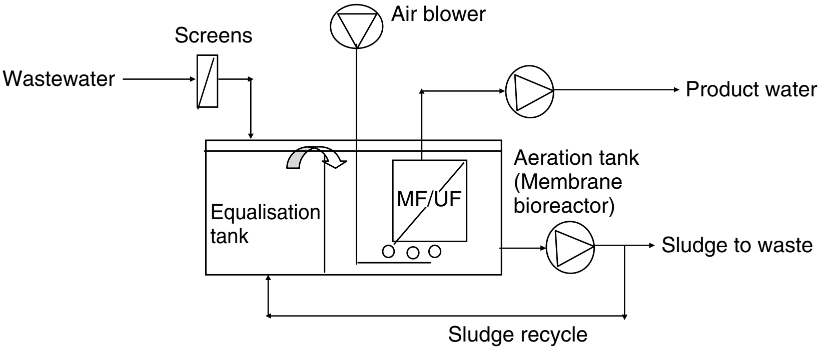


Figure 8.14 A schematic of a submerged MBR

production. The disadvantages of MBRs are that they are prone to intensive fouling and therefore need to be cleaned frequently. Cleaning is normally accomplished by air scouring every 13–15 minutes and cleaning with high concentrations of sodium hypochlorite solutions is carried out once every 2–3 months.

The immersed membranes are less energy intensive compared to external MBRs. However, they use more membrane area and operate at lower flux levels. These terms are explained later in this chapter.

The effluent can be used as reverse osmosis feed water without further treatment.

Case Study: MBR Application in a Dairy

A dairy installed an MBR plant to treat their wastewater effluent from the processing of milk powder, whey, cheese and bacon. The plant has a flow rate of 2000 m^3/d (367 US gpm)

Process Data

		Inlet	**Outlet**
COD	mg/L	3,600	<50
BOD	mg/L	2,250	<3
Ammonia	mg/L	75	<1
TKN	mg/L		<15
Total P	mg/L		< 0.5

8.8 Removal of Heavy Metals

Heavy metals are present in natural waters as well as in industrial wastewaters. Metals such as cadmium, arsenic (not a metal but categorised as one), nickel, copper, lead, chromium discharges to receiving waters are heavily regulated to ensure that concentrations in the receiving waters do not exceed safe limits set by regulatory authorities – such as the US EPA regulations (Federal Hazardous Waste Regulations 40 CFR 261). While chromium is the most widely used heavy metal that is discharged to the environment, *cadmium, lead and mercury* are the most toxic metals to living organisms. Arsenic is found in many well waters in countries such as in Bangladesh. For these reasons, water authorities also impose strict acceptance standards at the entry point to the sewer for the same reason. The sample of metals, the industries where they are typically found, and their acceptance standards to the public sewer are shown in Table 8.14.

Table 8.14 A sample of industries discharging heavy metals

Metal	Industry	Acceptance standards* mg/L
Cadmium	Plating, glassware	1
Chromium	Plating, chrome tanning, alum anodising, ceramics, porcelain, textile dyeing	3
Cobalt	Metal plating, foundries	5
Copper	Foundries, copper plating, automotive industry	5
Iron	Foundries, metal plating, dye manufacture	50
Lead	Ceramics, metallurgical industry, nonferrous smelting, mining, chemicals industry	2
Mercury	Metallurgical industry, alloying, wood preservative, chlorine manufacturing	0.03
Nickel	Plating, oil refining	3
Selenium	Paint manufacture, carpet manufacture, electronics production	5
Uranium	Nuclear industry	10
Zinc	Galvanising zinc plating, metal mining, foundries, porcelain, paint manufacture	5

* Adapted from Sydney Water's Trade Waste Policy. www.sydneywater.com.au. Courtesy of Sydney Water.

8.8.1 Chemical Precipitation

The principal method used to remove heavy metals is by precipitation of the metal ion as the metal hydroxide by the addition of lime or caustic to adjust the pH to reduce the solubility of the dissolved metals. Figure 8.15 shows the metal hydroxide solubility curve showing the solubility of the common heavy metal ions and their solubility versus pH.

Removal of metals by precipitation consists of the following steps:

1. Pretreatment
2. Precipitation
3. Flocculation
4. Settling.

1. Pretreatment step

To aid the precipitation process and achieve even lower concentrations than the predicted theoretical values, alum (aluminium sulphate) or ferric chloride is added to co-precipitate with the heavy metals as aluminium hydroxide [$Al(OH)_3$] or ferric hydroxide [$Fe(OH)_3$].

Chromium is present in both the trivalent (Cr^{3+}) and the hexavalent Cr^{6+} state. In process solutions and wastes, the dominant species is Cr^{6+}. Reducing agents are added to convert hexavalent Cr^{6+} to Cr^{3+}. Unlike most heavy metals which are precipitated readily as insoluble hydroxides by pH adjustment, Cr^{6+} must first be reduced to Cr^{3+} because it forms the chromate complex which behaves as an anion and cannot form an insoluble hydroxide. The

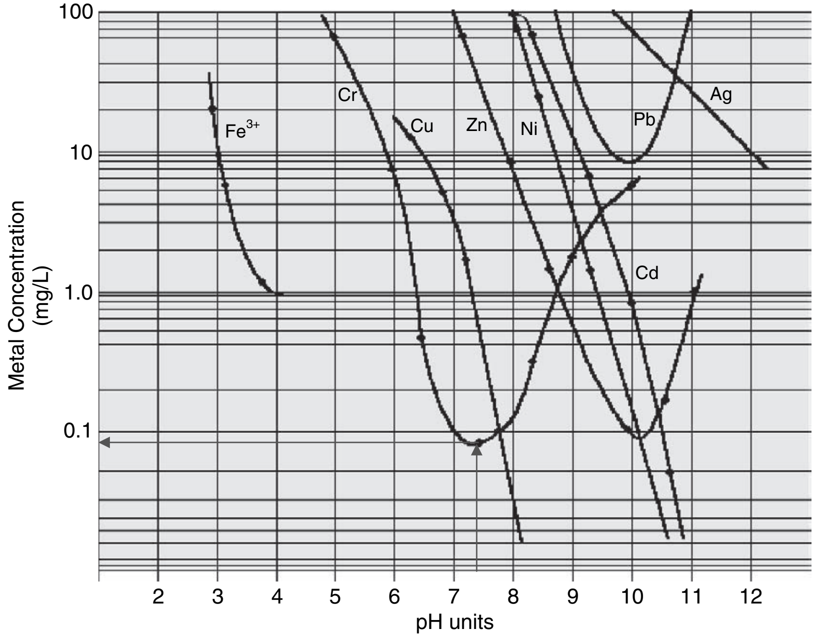


Figure 8.15 Metal hydroxide solubility curve

most commonly used reducing agents are sulphur dioxide gas and sodium metabisulphite (dry granular power).

Amphoteric metals such as copper, cadmium and zinc readily form ammoniacal complexes and under these circumstances the metal hydroxide method is ineffective. Ammonia complexes may be destroyed by oxidation, co-precipitation with ferrous or ferric chloride or one of the most cost-effective methods is to break the ammoniacal complex by the addition of sodium sulphide.

2. Precipitation step

This is carried out by the addition of alkalis sodium hydroxide (NaOH), calcium hydroxide or hydrated lime, [$Ca(OH)_2$]. Other alkalis used are magnesium hydroxide [$Mg(OH)_2$], calcium chloride [$Ca(Cl_2)$], sodium carbonate (Na_2CO_3) and sodium bicarbonate ($NaHCO_3$). Hydrated lime is cheaper than NaOH and produces a metal hydroxide precipitate with faster settling rates and more amenable to dewatering. On the other hand, NaOH reacts faster, has a simpler dosing system and produces less sludge. The disadvantage of the hydroxide method is that ammoniacal complexes and highly chelated metal complexes are not precipitated.

Sulphide precipitation is an alternative method to hydroxide precipitation which precipitates metals as sulphides instead of hydroxides. As Table 8.15 shows metal sulphides have a significantly lower solubility than the corresponding hydroxide.

Table 8.15 Metal hydroxide and sulphide solubilities in mg/L

Metal	Valency	As Hydroxide	As Sulphide
Cd	2+	2.3×10^{-5}	6.7×10^{-10}
Cr	3+	8.4×10^{-4}	No precipitate
Co	2+	2.2×10^{-1}	1.0×10^{-8}
Cu	2+	2.2×10^{-2}	5.8×10^{-18}
Iron	2+	8.9×10^{-1}	3.4×10^{-5}
Lead	2+	2.1	3.8×10^{-9}
Mn	2+	1.2	2.1×10^{-3}
Mercury	2+	3.9×10^{-4}	9×10^{-20}
Ni	2+	6.9×10^{-3}	6.9×10^{-8}
Ag		13.3	7.4×10^{-12}
Tin	2+	1.1×10^{-4}	3.8×10^{-4}
Zinc	2+	1.1	2.3×10^{-7}

In well-designed chlor-alkali plants this method reportedly achieves mercury removal efficiencies of 95–99% [12]. Therefore sulphide precipitation is one way to meet strict limits on dissolved metal concentrations even in the presence of chelating agents. Sulphide precipitates also tend to be less hydrated and therefore less voluminous than hydroxides. Even in the presence of 100 mg/L of EDTA, a chelating agent, copper can be reduced to 1 mg/L with sulphide precipitation. The drawbacks of this method are that hydrogen sulphide can be generated at low pH, excess sulphide is a pollutant and that metal sulphides produce a floc which is more difficult to dewater. Also the metals may leach out from the sludge. For these reasons, sulphide precipitation is used more as a polishing step after hydroxide precipitation [3] Two processes are used for sulphide precipitation: the soluble sulphide process uses sodium sulphide as the treatment reagent, and the insoluble sulphide process uses ferrous sulphide. The sparingly soluble ferrous sulphide overcomes the problem of excess sulphide dosage.

Common target for metal precipitation is a pH between 8.5 and 10. In practice the pH rarely exceeds 9.2. As Figure 8.16 shows the metal hydroxide solubilities, the lowest point of each curve corresponds to the pH at which that metal species will be removed to its minimum solubility point. For an example, as Figure 8.16 shows, the lowest solubility for chromium (Cr^{3+}) is at a pH of 7.5 where the theoretical solubility is 0.08 mg/L. Chromium being an amphoteric metal at pH values below or higher than 7.5 is more soluble.

When two or more metals are present and have different pH at which the minimum solubility occurs, an optimum pH is selected. For example, if both chromium and nickel are present then the optimum pH value to precipitate both metals are at a pH of 9.0–9.5 even though nickel has a minimum solubility at pH 10.2 and chromium at 7.5. Another solution is to use a class of compounds known as dithiocarbamates or trithiocarbamates. These provide precipitation even in the presence of chelating agents such as EDTA.

Barium is an exception where it is commonly precipitated as the sulphate ($BaSO_4$).

3. Flocculation
For faster precipitation polyelectrolytes consisting of organic chemical flocculants are added. These are similar to the ones discussed previously under chemical settling.

4. Clarification
Clarifiers and plate separators are used to settle the sludge followed by media filtration as a polishing step.

Disadvantages of metals precipitation may include the following.

- The presence of multiple metal species may lead to removal difficulties as a result of amphoteric natures of different compounds (i.e. optimisation on one metal species may prevent removal of another).
- As discharge standards become more stringent, further treatment may be required.
- Metal hydroxide sludges must pass EPA requirements prior to land disposal.
- Soluble hexavalent chrome requires extra treatment prior to coagulation and flocculation.
- Reagent addition must be carefully controlled to preclude unacceptable concentrations in treatment effluent.
- Efficacy of the system relies on adequate solids separation techniques (e.g. clarification, flocculation and/or filtration).
- Process may generate toxic sludge requiring proper disposal.
- Process can be costly, depending on reagents used, required system controls, and required operator involvement in system operation.
- Dissolved salts are added to the treated water as a result of pH adjustment.
- Polymer may need to be added to the water to achieve adequate settling of solids.
- Treated water will often require pH adjustment.
- Metals held in solution by complexing agents (e.g. cyanide or EDTA) are difficult to precipitate requiring more expensive solutions.

8.8.2 Ion Exchange

Another method used for removal of heavy metals is ion exchange. Ion exchange is used widely in the metal finishing industry to remove dissolved heavy metals from the rinse water such as for the removal of nickel, copper, tin, aluminium anodising and zinc ions.

Ion exchange principles are discussed in Chapter 7.

In most plating processes, water is used to cleanse the surface of the parts after each process bath. To maintain quality standards, the level of dissolved solids in the rinse water must be controlled. Fresh water added to the rinse tank accomplishes this purpose, and the overflow water is treated to remove pollutants and then discharged. As the metal salts, acids and bases used in metal finishing are primarily inorganic compounds, they are ionised in water and could be removed by contact with ion exchange resins.

Selectivity of ion exchange resins in order of decreasing preference

Strong acid cation exchanger
$Ba^{2+} > Pb^{2+} > Sr^{2+} > Ca^{2+} > Ni^{2+} > Cd^{2+} > Cu^{2+} > Co^{2+} > Zn^{2+} > Mg^{2+} > Ag^{+} > Cs^{+} > K^{+} > NH_4{}^{+} > H^{+}$

Strong base anion exchanger
$I^{-} > NO_3{}^{-} > Cl^{-} > CN^{-} > HCO_3{}^{-} > OH^{-} > F^{-} > SO_4{}^{2-}$

There are synthetic resins that can remove specific ions from the wastewater stream. One such resin cited in literature is iminodiacetic acid [12, 13]. These compounds bond the metal ions into a ring otherwise known as *chelation*. Chelating resins are an order of magnitude more expensive than other resins. The concentrated metal can be recovered to reuse the metal back in the process.

The advantages of ion exchange methods are

- it can operate on demand
- achieves essentially zero level of effluent contamination
- there are a large variety of specific resins available.

The main costs of ion exchange processes are in the cost of regeneration, which is dependent on the type of resin employed, feed-stream quality and the operating arrangement.

The efficiency of ion exchange systems are subject to

- influent quality – higher suspended solids loading increases the pressure drop requiring frequent backwashes and regenerations and leakage of heavy metals
- irreversible fouling of resins due to precipitation of calcium sulphate or other dissolved substances within the resin or adsorption of large organic molecules blocking resin sites
- inlet concentration of the substance being removed
- concentration of regenerant, frequency of regeneration and disposal of spent brine solutions
- variable effluent quality
- resin loss, ageing of resin resulting in loss of active ion exchange sites.

8.9 Adsorption

Adsorption using granular activated carbon (GAC) is a reliable and effective way of removing small quantities of soluble organic impurities in water and wastewater streams particularly those substances that are not readily biodegradable. Activated carbon adsorbs aromatic solvents such as benzene, toluene and xylene; chlorinated aromatics such as chlorobenzene; surfactants such as detergents; textile dyes aromatic and high molecular weight amines; hydrocarbons such as kerosene; pesticides and herbicides; viruses and many other pollutants. They are frequently used as a pretreatment step before RO membrane systems. Wastewater treatment applications include effluent water treatment in the remediation of contaminated ground water, colour removal in textile effluents, car wash facilities and landfill leachate treatment.

Activated carbon is made from bituminous and lignite coal, bone as well as from coconut shells. They all have different properties.

Activated carbon removes organics by adsorbing them onto its microporous surface. The adsorption capability and the rate of adsorption of activated carbon is determined by surface area, pore size, method of manufacture, and characteristics of the solute such as molecular weight, polarity, concentration, pH and temperature. It is available as Powdered Activated carbon (PAC) with a particle size less than 100 μm and GAC which has a particle size of 1–3 mm. GAC is the more common application in industrial wastewater treatment applications. PAC is used as an additive in the activated sludge process by mixing powdered activated carbon into the aeration basin. In general, GAC can remove over 90% of the organics in many industrial wastewaters [14] and usually used when the dissolved organics concentration is less than 10 mg/L [15]. The effluent stream concentration will often be less than <1 μg/L. However, activated carbon is not effective on organics such as alcohols and aldehydes [15].

GAC is housed in pressure vessels similar to sand filtration.

Problems with GAC units are that the carbon particles can break off and plug RO prefilters. It can also change the characteristics of the water raising the hardness level and in some cases pH. Being softer lignite-based activated carbon in particular is prone to greater attrition. Activated carbon is also an excellent environment for bacterial growth. Chlorine may not be effective in such cases. The disposal of spent GAC is another issue. Some sites have steam regeneration facilities to remove the organics and recover the GAC. Therefore careful consideration needs to be given to these issues before making a decision to install GAC units.

8.10 Membranes for Removal of Dissolved Ions

8.10.1 Overview

Since their advent in the 1960s, membrane processes are the preferred option for the treatment of water and wastewater. Costs of membrane systems have reduced dramatically and, coupled with technological advances in membrane design, membrane options and operating limits, the range of applications in water and wastewater treatment is increasing rapidly.

In membrane filtration, membranes separate the components of a fluid under pressure. The membrane pores, being extremely small, allow the selective passage of solutes. This section will briefly discuss membrane systems.

The popularity of membrane processes arise from the fact that they are effective in the removal of both dissolved and suspended solids. Their advantages are

- ability to recover both the clean water (permeate) and concentrated streams (reject) without chemically modifying them
- applicable to a wide range of processes
- contain relatively few moving parts
- modular construction enables scaling up or down.
- membranes can be custom selected to achieve the desired water quality.
- compact design – means reduced foot print
- short start up times compared to biological systems
- minimal chemical pre-treatment
- low energy requirements.

Their disadvantages are

- upfront capital costs can be significant
- finite membrane life requires periodic membrane replacement
- prone to irreversible fouling requiring more frequent membrane replacement
- strong oxidising chemicals, solvent and extreme pH can degrade certain membrane elements
- limited application at high temperatures
- limited options for the disposal of concentrated brine stream.

This section will be devoted to a brief discussion of pressure-driven membranes such as

- microfiltration (MF)
- ultrafiltration (UF)
- nanofiltration (NF)
- reverse osmosis (RO) membrane applications for water reuse.

Electrodialysis (ED) and electrodialysis reversal (EDR) will only be mentioned briefly.

Figure 8.16 shows filtration chart with the sizes of common particles, membrane types, approximate molecular weight and their ability to remove particles.

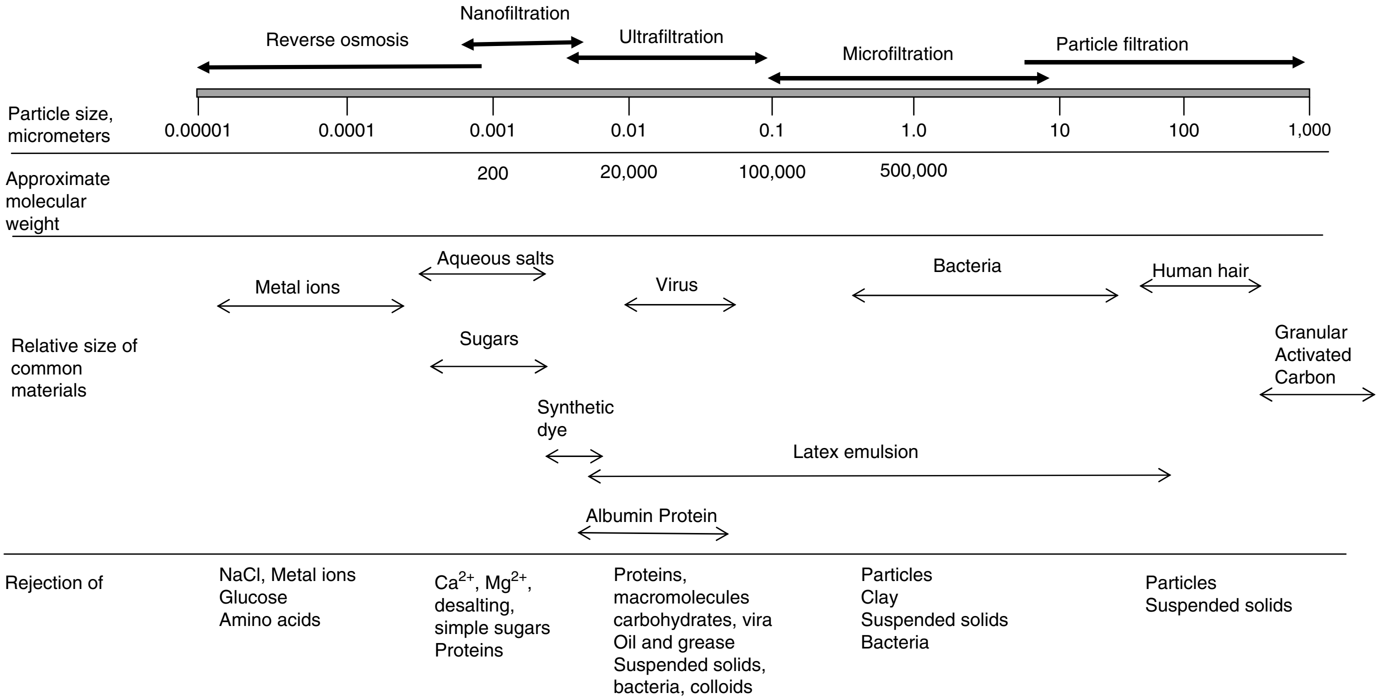


Figure 8.16 Tangential Filtration Chart

8.10.2 Dead-End and Cross-Flow Filtration

Filtration separation is based on the particle size and the volumetric throughput of a filter. Volumetric throughput is proportional to the area and pressure and inversely proportional to the thickness of the filter cake and dynamic viscosity of the fluid.

$$\text{Volumetric throughput} \propto \frac{\text{Area} \times \text{Applied pressure}}{\text{dynamic viscosity} \times \text{thickness of filter cake}} \tag{8.3}$$

Everything being equal, the volumetric throughput will be a function of the thickness of the filter cake. The two types of membrane filtration are based on this principle. They can be classified as

1. Dead-end filtration
2. Cross-flow filtration.

8.10.2.1 Dead-end Filtration

In conventional dead-end filtration, the flow is perpendicular to the membrane surface. There are only two streams present – feed and permeate streams. The fluid passes through the membrane and all particles larger than the pore sizes of the membrane concentrate at the membrane surface. The trapped particles gradually build up a *filter cake* on the surface of the medium, creating a barrier for the solutes which results in increased resistance to the filtration process. Consequently, dead-end membranes systems are limited to low solids applications or to a few types of applications – such as cartridge filtration of boiler feedwater, microfiltration, or ultrafiltration of municipal treatment [16]. Figure 8.17 shows a graphical illustration of dead-end filtration.

8.10.2.2 Cross-flow Filtration

The limitations of dead-end filtration are overcome in cross-flow filtration. In cross-flow filtration there are three streams. The feed stream flows parallel to the membrane surface (tangential) creating a pressure differential across the membrane surface. Consequently some of the particles pass through the membrane which is known as the *permeate* stream. The rest of the solids flow across the membrane scouring the surface and cleaning it in the process – this stream is known as the *reject* stream. Since the solids are continuously removed it minimises the filter cake thickness to a few microns on the membrane surface and facilitates the continuous operation of the system. Therein lies the advantage of cross-flow filtration to effectively separate micron, submicron, molecular and ionic range particles. Figure 8.17 shows these two different filtration mechanisms.

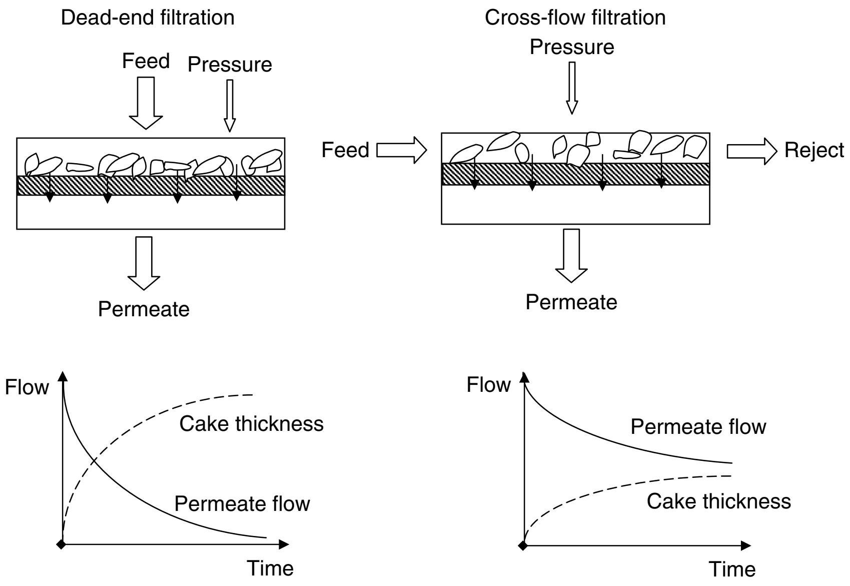


Figure 8.17 Dead-end and cross-flow filtration mechanisms.

8.10.3 Membrane Types

There are four basic types of membranes based on pore size and rejection characteristics. These are

1. Microfiltration (MF)
2. Ultrafiltration (UF)
3. Nanofiltration (NF)
4. Reverse Osmosis (RO).

8.10.3.1 Microfiltration

Microfiltration (MF) is the most open media with pore sizes ranging from 0.01 to 1 μm. Microfiltration membranes are used to separate suspended solids, bacteria, algae and cysts and it is capable of being operated in the dead-end and cross-flow filtration modes. Given the relatively large pores, the operating pressure of MF membranes is the lowest of all membrane processes. Typically applied pressure varies from 21 kPa to 345 kPa (3–50 psig). A wide variety of materials can be used to make microfiltration membranes as shown in Table 8.16. Common applications are in the removal of *Giardia, Cryptosporidium*, viruses, as pre-treatment for reverse osmosis membranes, degreasing, metal recovery and in membrane bioreactors (MBR). Figure 8.18 shows a photo of microfiltration membranes.

Table 8.16 Comparison of membranes

	MF	UF	NF	RO
Pore size, µm	0.01–1	0.005–0.01	0.0001–0.001	<0.0001
Molecular weight cutoff (MWCO)	>100, 000	1,000–500,000 [17]	300–1,000	100–300
Suspended solids removal	Yes	Yes	Yes	Yes
Micoroorganisms removal	Limited. Protozoa, cysts, Bacteria and algae	Limited. Protozoa, cysts, Bacteria algae and viruses	All	All
Dissolved Organics removal	None Only large compounds > 100,000 MW retained.	Yes Insoluble BOD, COD and large organic molecules Macro-molecules, proteins, mono and polysaccharides > 2500 MW	Yes Organics > 300 MW. Simple sugars and Trihalomethane compounds.	Yes Organics > 100 MW
Dissolved inorganics removal	None	None	20–85% rejection	All dissolved salts to 95–99% rejection.
Common applications	Suitable for suspended solids removal. Used as pre-treatment for RO units in treatment of sewage effluent, metal finishing, metal plating and printed circuit board applications.	Reduces turbidity by 99%. Pretreatment for other purification systems. Performs well in oily wastewater, in metal finishing applications, laundry and textile industries.	Has water softening capabilities, i.e. Rejection of divalent salts (Ca and Mg) and some rejection of monovalent salts such NaCl. decolourising. Used to separate sugars	Used as pre-treatment for demineralisation ion exchange and where low dissolved solids effluent is required.

(*Continued*)

Table 8.16 (*Continued*)

	MF	UF	NF	RO
Disadvantages	Certain materials fouled by oily wastewater. No reduction in dissolved solids.	No reduction in dissolved salts or removal of hardness.	Prone to fouling by colloidal materials and water-treatment polymers. Pretreatment required.	Fouled by colloidal materials, water-treatment polymers and sparingly soluble salts. Pretreatment required. Generally SDI* < 3
Recovery rate	~100%	~75%	~70–85%	~50–85%.
Membrane structure	Polyvinylidiene fluoride (PVDF), Polysulfones (PSO), polypropylene, polyacrylonitrile, ceramics	PVDF, PSO, Cellulose acetate, thin film	Cellulose acetate, Thin Film composites	Cellulose acetate, Thin Film composites, polysulfones
Membrane module	Tubular, hollow fiber, plate-and-frame and spiral wound	Tubular, plate-and-frame, spiral wound, hollow fibre	Tubular, plate-and-frame, spiral wound	Tubular, spiral wound, plate-and-frame
Operating Pressure, kPa (psig)	20–345 (3–50)	100–1000 (14.5–145)	338–2028 (50–300)	1,500–6760 (225–1000)
FluxL/m^2/hr (USgal/ft^2/day)	34–680 (20–401)	34–680 (20–401)	8.5–60 (5.0–35)	10–35 (6–21)
Energy usage kWh/m^3	2–20	1–10		

* Silt density index

Figure 8.18 Photo of microfiltration membranes

Courtesy of Pall Corporation.

8.10.3.2 Ultrafiltration

Ultrafiltration (UF) membranes have pore sizes ranging from 0.005 to 0.01 μm. They are usually classified based on their *molecular weight cut-off* (MWCO), which is another method used to categorise membranes. The MWCO is defined as the molecular weight of the smallest molecule, 90% of which is retained by the membrane. The units are expressed in Daltons (grams per mole). The UF membranes have MWCO ranging from 1000 to 500 000 Daltons. For an example, if a membrane has an MWCO of 100 000, then it means that 90% of molecules with a molecular weight of 100 000 will be retained by the membrane. A 100 000-MWCO membrane would have a pore size of 0.01 μm [17].

Given that UF membranes have smaller pores than MF, the operating pressures are higher ranging from 100 to 1000 kPa (14.5–145 psig.).

Common UF wastewater applications include the separation of high molecular weight compounds with a MWCO greater than 1000 such as carbohydrates, proteins, paints and dyes; segregation of oil/water emulsions and separation of heavy metals. The UF is also used as pre-treatment for RO membranes. The UF cannot separate dissolved salts, simple sugars salts, sodium hydroxide or amino acids and consequently no appreciable reduction in conductivity of the permeate stream.

8.10.3.3 Nanofiltration

Nanofiltration (NF) membranes have pore sizes smaller than UF with a MWCO in the range of 150–1000 Daltons. The actual pore size is of little significance for NF and RO membranes. Their solids rejection capabilities are based not on pore size but on selectivity towards ionic charge and molecular weight. Thus, NF is more selective towards divalent ions such as Ca^{2+} and Mg^{2+} and simple and complex sugars. Therefore, these membranes have water-softening capability as well as the ability to reduce total dissolved solids. However, monovalent ions such as Na^{+} and Cl^{-} will pass through more freely. Their rejection rate varies between 0 and 50%. This means that NF has an edge over RO when only partial salt reduction capacity is required.

8.10.3.4 Reverse Osmosis

The RO is the tightest possible membrane process in liquid/liquid separation and therefore produces the highest water quality of any pressure driven membrane process. The RO membranes are classified by percentage rejection of NaCl and ranges from 95 to 99.5%. The MWCO is less than 200 Daltons. The operating pressures are highest in RO membrane applications reaching 6760 kPa (1000 psig) or more and it has also the lowest throughput per unit area (flux).

The four separation processes are summarised in Table 8.16.

8.10.4 Membrane Structure

Membranes can be classified according to their material of construction. Membrane materials can be organic polymers (cellulose acetate, polyamides, polypropylene, polysulfones) or inorganic (e.g. ceramic, zirconia). The membrane material composition determines their ability to be used in harsh wastewater environments. These are

- low or high pH
- high temperature > 50° C
- chemical oxidants – Chlorine
- organic solvents
- abrasive metals.

For instance, most polymeric materials are resistant to moderate pH swings except cellulose acetate (CA) membranes which cannot be operated above pH of 8 nor can they tolerate temperatures above 35° C but can tolerate chlorine residuals. On the other hand, polyamide membranes (PA) are susceptible to chlorine but can operate across a wide pH range. Polysulfone (PSO) have exceptional temperature and pH resistance but are more expensive. Polyvinylidiene fluoride PVDF membranes have the advantage that they can be cleaned with strong acids, caustic soda and bleaches. Ceramic membranes are employed in heavy metal removal applications due to their abrasion resistance but are extremely expensive.

8.10.5 Membrane Configurations

Membranes can be classified according to their configuration which are

- Spiral wound
- Hollow fibre
- Tubular
- Plate and frame.

These are described briefly below.

8.10.5.1 Spiral Wound

Spiral wound membranes dominate the market. Its advantages are its compact design and low price per square area and adequate membrane area per unit volume (300–1000 m^2/m^3). These membranes are commonly used in RO and NF systems.

A spiral wound membrane is constructed from two layers of membrane material separated from each other and are glued to a permeate collector fabric. Plastic mesh is used to form a feedwater channel. The membrane layers, permeate collector and feedwater spacer are rolled around a hollow, perforated centre tube that collects the product water. The membrane module is then inserted into a pressure vessel housing. Typically 6–8 membrane elements are linked inside a single pressure vessel. High-pressure feedwater is directed into one end of the element, the permeate is collected in the permeate channel and flows towards the centre tube, and the concentrate exits at the other end of the element. A conventional single element is approximately 100–200 mm (4–8 in.) in diameter and 1000 mm (40 in.) in length. They contain 7–28 m^2 (80–300 ft^2) of membrane area respectively.

Due to their close spacing design, spiral wound membranes are susceptible to fouling and therefore adequate pre-treatment is a prerequisite. Wastewater temperatures are kept below 45° C. Figure 8.19 shows a graphical illustration of a spiral wound membrane module.

8.10.5.2 Hollow Fibre

Hollow-fibre membrane modules incorporate a bundle of hollow-fibre membranes in a single element. Feedwater enters the inside of the hollow fibre, permeates through the tube wall and is collected in a perforated centre tube. Their distinct advantage is having a very high surface area per unit volume (600–1200 m^2/m^3). Given their very small diameter (0.5 mm typical to 10 μm [16]), they are prone to blockages and fouling. A good pre-treatment system is a prerequisite and they need to operate at low pressures. The design also allows for backflushing of membranes

Figure 8.20 shows photos of an MF symmetric and asymmetric hollow fibre membranes.

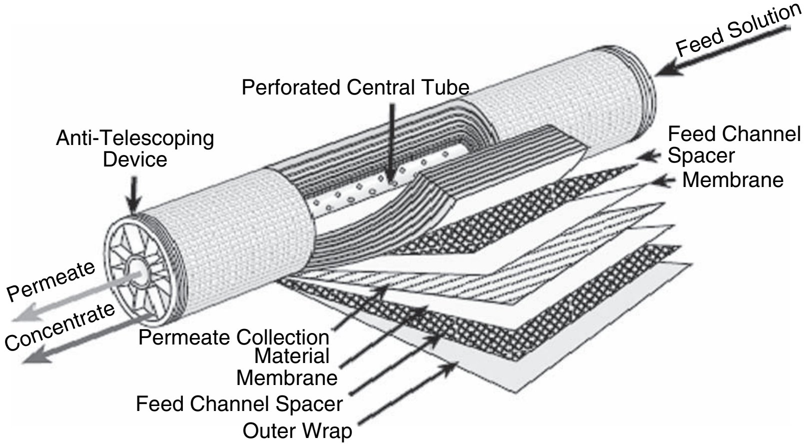


Figure 8.19 A graphical illustration of a spiral wound membrane module

Courtesy of GE Water and Process Technologies.

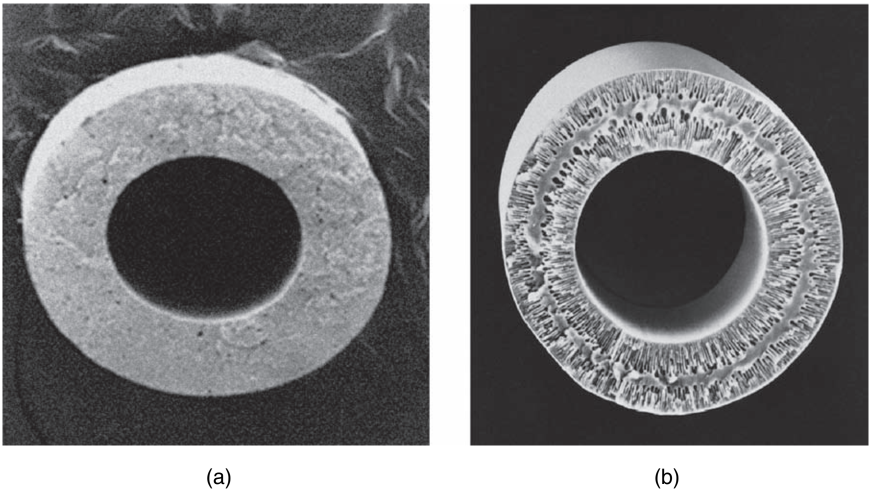

(a) (b)

Figure 8.20 Photo micrographs of hollow-fibre membranes

Courtesy of Pall Corporation.

8.10.5.3 Tubular

Tubular membranes have a lower surface area than hollow-fibre units ($<100\,m^2/m^3$) and a larger diameter – up to 25 mm (1 in.). The advantage of this type of membrane is that they can operate at higher pressures, are less susceptible to fouling and are more robust than spiral wound membranes. Ceramic membranes are used in this configuration. However, they have several disadvantages. They require more space, and therefore have the highest cost per unit area of all the cylindrical membrane configurations. It is time consuming and cumbersome to change membranes and chemical cleaning costs are high. However, the design allows for backflushing of membranes.

8.10.5.4 Plate and Frame

These modules are rectangular or circular flat sheet systems separated by separators and/or support plates. Cassettes allow membrane modules to be removed individually. Given the low packing density (100–600 m^2/m^3), plate and frame membranes are suitable for specialist high fouling applications. The design allows for backflushing of membranes. Figure 8.21 shows a stack of plate-type membranes.

All membranes suffer from fouling. Physical fouling occurs due primarily to the formation of a boundary layer that builds up naturally on the membranes surface during the filtration process. Traditional cross-flow membranes systems such as spiral wound membranes have very fine clearances. These fine tolerances limit their use to low solids waters or require extensive pretreatment to handle high fouling applications such as landfill leachate. As explained previously cross-flow filtration relies on high velocity fluid flow, pumped across the membranes surface as a means of reducing the boundary layer effect. In cross-flow designs, it is not economic to create shear forces in excess of 15 000 inverse seconds [16, 18–20], thus limiting the use of cross-flow to low-viscosity (watery) fluids. In addition, increased cross-flow velocities result in a significant pressure drop from the inlet (high pressure) to the outlet (lower pressure) end of the device, which leads to premature fouling of the membrane.

Some recent breakthroughs in membrane filtration technology have now made it possible for the treatment of some previously difficult separation applications. New "plate and frame" type membrane modules can tolerate very high levels of TSS, organics and COD. These overcome the limitations of conventional membrane modules and are better able to handle the high fouling and plugging applications like landfill leachate.

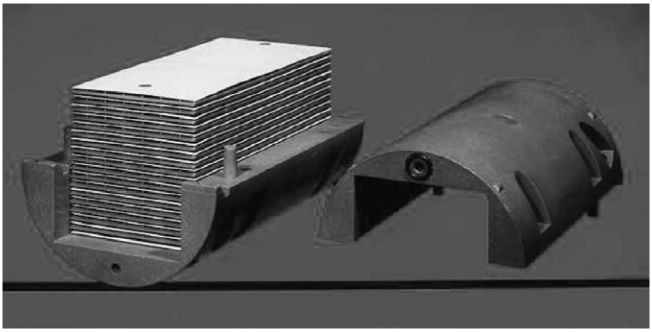


Figure 8.21 A photo of a stack of plate-type membranes

Courtesy of Pall Corporation.

To alleviate the limitations on solids entering a membrane system, new open channel type plate and frame membrane modules have been developed. Two leading designs include the VSEP by New Logic Research Inc. and Disc Tube™ Module by Rochem Separation Systems.

1. Vibratory Shear Enhanced Processing (VSEP) system

The Vibratory Shear Enhanced Processing (VSEP) system is one such technology. VSEP system is able to generate high crossflow and turbulence through torsional oscillation, which keeps the feed liquid homogenous and evenly concentrated. The membranes are vibrated in resonance at a frequency of about 53 Hz (times per second) with an amplitude of 3.2 cm (11/4 in.) to the membrane and the membrane displacement is equal to 1.9 cm (3/4 in.) peak to peak at the perimeter imparting a shear force of 120 000–150 000 inverse seconds [16, 18–20]. Figure 8.22 shows a comparison of the flow dynamics. Consequently, VSEP system can be used in high fouling and high dissolved solid applications such as in black liquor recovery (pulp mills), desalter effluent (oil refining), oil/water emulsions, mine water and landfill leachate with minimum pretreatment. New Logic claims the ability to concentrate the reject stream up to 50% solids (500 000 mg/L). The VSEP system also tolerates high temperatures up to 70–90° C.

Since VSEP is not limited by solubility of minerals or by presence of suspended solids, it can be used to treat the RO reject of conventional spiral wound membranes.

The industrial VSEP machine contains many sheets of membrane, which are arrayed as parallel disks separated by gaskets. The disk stack is contained within a Fiberglass Reinforced Plastic (FRP) cylinder. A 185 m^2 (2000 ft^2) membrane is contained in one VSEP module with a footprint of only 100 × 100 (4 ft × 4 ft) [19]. The result is that the horizontal footprint is very small. Figure 8.23 shows VSEP system.

Case Study: Removal of Calcium Carbonate ($CaCO_3$) Slurry water using a VSEP microfiltration system [19]

The customer required equipment to dewater $CaCO_3$ slurry as part of a manufacturing process. Pilot testing of spiral wound membranes, centrifugal separators and rotary drum filters failed, due to technical limits, high capital and operating costs. The VSEP system was trialled where a hot 7% solution of $CaCO_3$ is fed into a VSEP at 3.8 m^3/hr (17 US gpm). The concentrated stream is at 30% solids. A second pass unit concentrates this to 50% – solids approaching the limits of 'pumpability'.

The biggest advantage of the VSEP in this application was energy savings, reducing pre-treatment equipment costs and labour costs. The system has a payback period of less than one year.

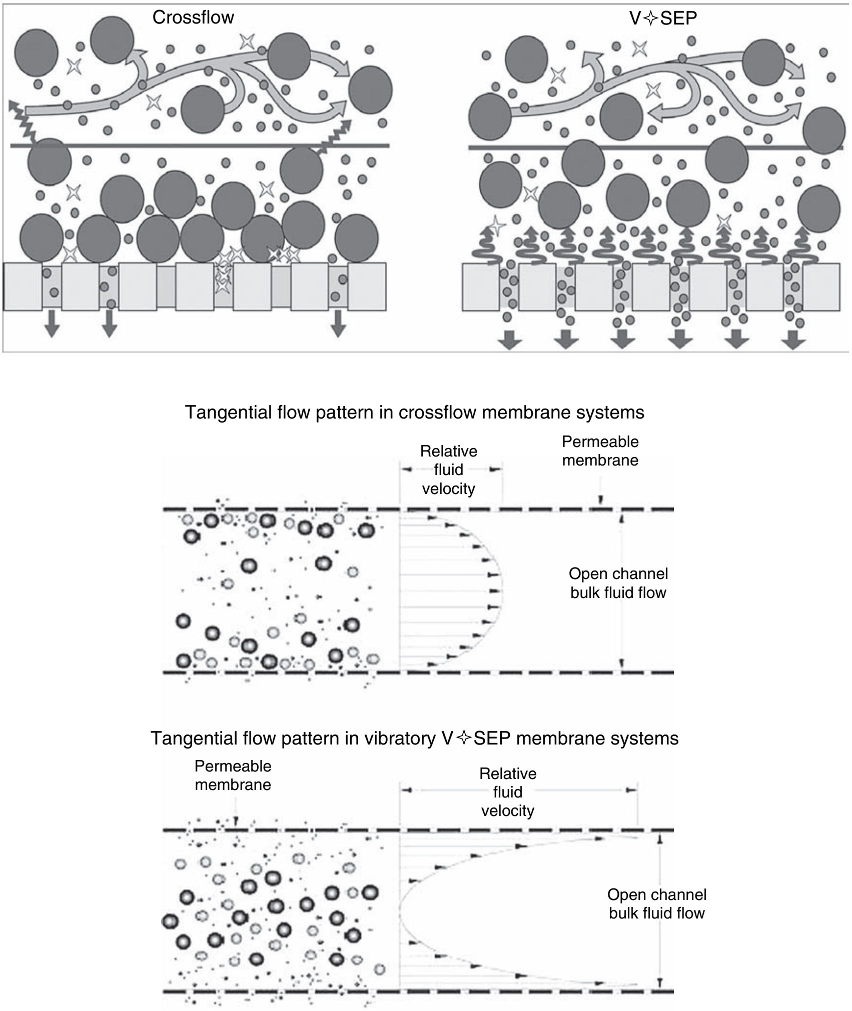


Figure 8.22 A fluid dynamics comparison between VSEP and conventional cross-flow filtration Courtesy of New Logic Research Inc.

2. Disc Tube technology

Pall Rochem's Disc Tube™ Module (DTM) technology was first developed in Germany and contains multiple leaf layers of membranes stacked in a column with spacer setting the gap between them. The Disc Tube™ modules are a tangential flow separation system. This tangential flushing action and the optimised hydrodynamics in the module are the primary factors in keeping the membrane clean and operating properly, which means that the modules rely on high turbulence and high cross-flow to keep the membrane surface clear of suspended solids cakes and other formations that would blind

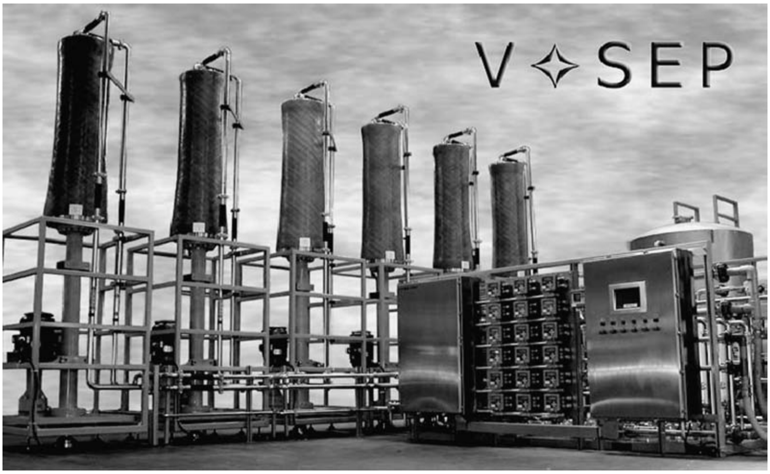


Figure 8.23 A photo of VSEP system showing the small footprint

Courtesy of New Logic Research Inc.

Figure 8.24 Photo of Pall Rochem Disc Tube^{TM} module

Courtesy of Pall Corporation.

the membrane. Unlike VSEP these do not have the vibration capabilities. Figure 8.24 shows a photo of Disc Tube^{TM} module.

Membrane systems can be arranged in a number of ways. The simplest design consists of a feed tank, a feed pump, membrane system and tanks to hold the permeate flow and the reject stream. The permeate quality may be adequate to the need or may require another set or a different type

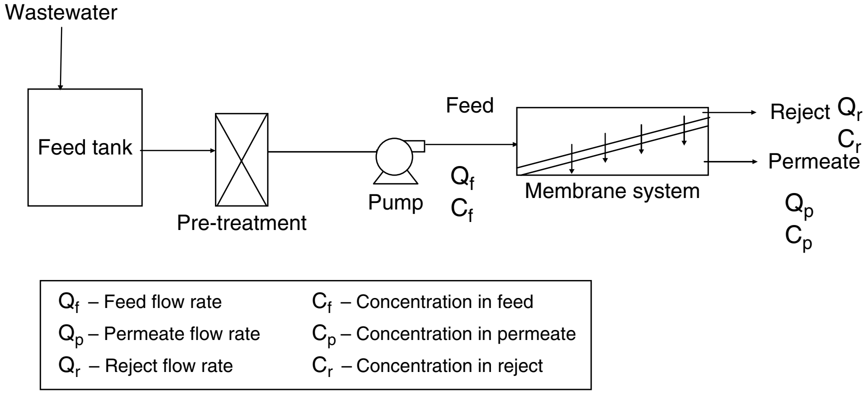


Figure 8.25 Schematic of a single stage membrane plant

of membrane to reach the desired water quality. Cleaning chemicals and sanitisers also require holding tanks and ancillary piping for regular cleaning of membranes.

A simplified schematic of a membrane system is shown in Figure 8.25.

8.10.6 Membrane Performance Monitoring

Membranes are expensive to replace and therefore lengthening membrane life reduces operating costs. The performance of membranes decline with time and therefore membrane performance monitoring helps to detect product quality, permeate flow and onset of membrane failure.

Membrane fouling is one of the main reasons for premature membrane replacement and product quality issues. Membrane fouling results in decreased product quality, reduced flux and an increase in pressure drop across the membrane. Fouling can be either reversible or irreversible. Fouling can be due to inherent system conditions, inadequate pretreatment and/or improper operation.

Fouling can occur due to

- physical blockage of the membrane surface
- chemical scaling of membrane surface, due to a mechanism known as *concentration polarisation*, when salts precipitate on the membrane surface.
- biofilm formation on membrane surface
- *solute absorption*, where adsorption of small molecules makes the pores smaller. For example, in ultrafiltration membranes this is a common cause for a decline in performance, when protein molecules get absorbed into pore walls.

There are other reasons for membrane failure such as: thermal shocks, operating at low or high pH, membrane compaction or improper use of

Table 8.17 Common failure mechanisms

Type of failure	Cause	Remedial measure
Fouling – physical blockage	Inadequate pre-treatment.	Install cartridge filtration, MF/UF before RO. Back flushing, back pulsing, increasing turbulence and cleaning generally restores originally capacity. Cleaners are acids, alkalis, enzymes and detergents.
Fouling – precipitation of sparingly soluble salts	Inadequate pre-treatment. Too high permeate recovery can lead to precipitation of sparingly soluble salts. More of a problem in NF and RO plants	Reduce pH; add ion exchange upstream of membrane plant; inject chemical inhibitors; reduce permeate recovery rates. Can result in irreversible decline in performance.
Fouling – microbiological	Biofilm formation due to inadequate disinfection during operation and/or poor storage practices.	Disinfect with approved products. Use recommended storage practices. Generally reversible except in the case of cellulose acetate (CA) membranes.
Fouling – adsorption of macromolecules in to the membrane	Inadequate pre-treatment. Certain surface active macro-molecules or iron can cause irreversible blockage.	Pre-treatment, eliminate cationic coagulants if it is the cause and or use a different membrane material which is less prone to the particular fouling type.
Membrane degradation due to chemicals.	Operations at high or low pH. Oxidants and organic solvents can damage membranes.	Follow manufacturer's recommendations. Use an appropriate membrane material. Dechlorinate.
Mechanical failure	Hydraulic shocks, high temperature, drying out of membranes due to poor storage practices.	Follow manufacturer's recommendations. Use an appropriate membrane material.

oxidants. The common causes and their remedial measures are listed in Table 8.17.

Silt density index is a filtration test to determine pretreatment requirements to guard against physical fouling of membranes. Scaling gives the potential for chemical fouling and Flux determines the product flow rate per unit area of membrane surface.

8.10.6.1 Silt Density Index

The Silt Density Index (SDI) is a simple filtration test, which measures the fouling tendency of the water. The SDI indicates the rate at which membrane's pores plug. ASTM D4189 describes the procedure. An SDI of 0 is very clean water. An SDI of 6.67 is dirty water. Most equipment vendors of RO and NF equipment specify SDI to be less than 5. However, for conventional spiral wound RO membrane systems, SDI of less than 3 is preferred to minimise problems caused by suspended solids blocking the brine spacers in a RO membrane module. Waters of higher SDI values needs to be filtered using multimedia filters followed by $5\,\mu$ cartridge filters, chemical treatment, or using MF/UF prior to RO/NF membranes. The MF membranes will guarantee an SDI of less than 3 and UF usually achieves SDI of below 2 and frequently below 1. In operation, any increase in SDI needs to be investigated because it means that either the feed quality has changed or a there is a failure in the pre-treatment equipment.

8.10.6.2 Assessment of Scaling Tendencies

Scaling is more of a problem in NF and RO membranes because these membranes convert 75–90% of the feedwater into product water and in the process they reject dissolved ions. As discussed previously, as RO membranes produce pure water, the feed water becomes concentrated. Some of the chemical compounds that are soluble in the RO feed water may no longer be soluble. More importantly, at the membrane surface the concentration of the mineral ions can be several fold higher than what is in the bulk feed water due to a phenomenon known as *concentration polarisation*. The higher the permeate recovery, the greater the concentration of the minerals such as Ca^{2+} in the reject stream which can lead to scaling of the membrane surface resulting in increased energy consumption and chemical cleaning frequency. Therefore, it is important to determine the solubility potential of sparingly soluble compounds at the membrane surface. The Langelier Saturation Index (LSI) or the Stiff Davis Saturation Index (SDSI) is used to evaluate scaling tendencies of calcium carbonate. Chapter 5 gives a description of LSI. The SDSI is a variation of LSI. When the TDS is greater than 5000 mg/L, SDSI is recommended to be used. [5] It is important to maintain a negative LSI of the RO concentrate to ensure no scaling on the membrane surface occurs. This is achieved by acid addition. Use of a weak acid cation exchanger can also be used to remove carbonate hardness, followed by a degassing unit to remove CO_2.

8.10.6.3 Membrane flux

Generally, there is a correlation between pore size and flow rate. The smaller the pore size (more accurately membrane resistance) the lower the flow rate per unit area of membrane – otherwise known as *flux*. It is expressed as m^3 $/m^2$ s (SI units). The more common units are $L/m^2/hr$ (LMH) or gal.ft^2 day (GFD). For a given membrane and feed water quality, flux is a function of applied pressure and water temperature. Generally, the better the feed water quality, the higher the flux. Flux increases with temperature and pressure. However higher the temperature the higher the salt passage through the membrane.

The higher the design flux rate the lower the capital cost and size of the membrane plant. Pretreatment of RO membranes with MF or UF membranes typically increases the flux rate of RO elements.

8.10.6.4 Permeate Recovery

Permeate recovery is defined as the ratio of permeate flow (Q_p) to feed flow (Q_f), usually expressed as a percentage. This is shown in Equation (8.4). It is an expression used to describe how efficiently the system is being operated, and is also used to determine the extent of concentration of the fluid solutes.

$$\text{Permeate recovery (R\%)} = \frac{Q_p}{Q_f} \times 100 \tag{8.4}$$

From formula 8.4 it follows that, the higher the permeate recovery, the higher the permeate flow, the less the reject flow rate. On the other hand, the higher the permeate recovery, the poorer the permeate quality and the more concentrated the reject stream – increasing scaling potential of the membrane surface. Typically, for naturally occurring surface waters, permeate recovery more than 75–80% is not recommended even with good pretreatment. A 5% increase in permeate recovery means that at 75% the feed water concentrates four times at the concentrate outlet and at 80% recovery it concentrates 5 times. The permeate quality will decrease by approximately 25% as permeate recovery moves from 75 to 80%. For wastewater reuse permeate recovery is normally around 70–80%. Reject streams can serve as feed for subsequent modules and this arrangement is known as '*reject staging*' and produces higher recovery rates than the single pass arrangement.

The concentration in the reject stream can be approximated by multiplying the feed concentration by the concentration factor (X) as shown in formula 12.

$$C_r = \frac{C_f}{(1 - R\%)} = XC_f \tag{8.5}$$

where

C_f, C_r given in concentration in mg/L

Worked example

If silica concentration in the feed is 20 ppm, what is the concentration of the reject stream at R = 50, 70, 80 and 90%? What is the desirable R%? Refer to Table 8.18

At 80% recovery the concentration factor X is five times. That means, the concentration at the membrane surface is five times the feed concentration. Increasing permeate recovery rates reduce permeate quality. A 5% increase in permeate recovery from 80–85% increases the concentration in the reject stream by 33%. Silica is typically controlled in the range below 100 mg/L, the permeate recovery R is set at a maximum of 80% (higher silica rejection levels can be achieved by increasing the pH > 10).

Table 8.18 Concentration factor vs System Recovery

Recovery Rate (R%)	Concentration Factor (X)	Permeate Flow (%)	Reject Flow (%)	Silica concentration in the reject stream (mg/L)
0 (Feed water)	1	0	100	20
50	2	50	50	40
70	3.3	70	30	67
75	4.0	75	25	80
80	5.0	80	20	100
85	6.67	85	15	133
90	10	90	10	200

8.10.7 Disposal of Brine Streams

Membrane plants produce a reject stream which needs to be disposed of. The common disposal options are to:

(i) discharge to the public utility's sewer if the concentrations are acceptable to water utility.
(ii) To discharge to the sea or other external water source if approval is granted. Increases transport costs if located inland.
(iii) Concentrate the reject stream further using another membrane system
(iv) Evaporate the water to dryness in sludge drying beds
(v) Evaporate the water and recover more distillate using mechanical vapour compression technologies, brine concentration and crystallisers. These options consume power and requires extra capital.
(vi) Recover saleable materials.

8.10.8 Considerations When Selecting Membrane Systems

Membrane systems require upfront financial costs. The penalty for not getting it right is prohibitive. Quite often the unforseen problems occur at the time of commissioning but by then it is too late (and costly) to change the design and the blame game starts between the vendor and the customer.

Therefore, before purchasing a membrane system the more detailed the analysis is, the lower the risk. It is always preferable to do on-site plant trials – even though the application may be quite common. Spending 10% of the capital costs on a pilot trial will minimise the risk of not getting it right later on.

In selecting and designing a membrane system the considerations include the following.

1. What permeate water quality is desired?
2. What is the feed water quality?

3. What is the variability of the feed stream in terms of quality, flow, volume and temperature?
4. What pre-treatment systems are in place for removal of suspended, colloidal, microbiological and dissolved substances such as clarification, activated carbon units, chlorination/ozonation, cartridge filters and/or water softeners for removal of temporary hardness?
5. What type of membrane system best suits the need?
6. What strategies are used to reduce LSI if NF or RO membranes are used and how will this affect downstream equipment such as demineralisers? (If acid injection is used, care needs to be taken not to overload the anion exchanger with high CO_2).
7. Is there a valuable resource to be recovered from the process stream?
8. What are the design flux rates?
9. What is the permeate recovery? What penalties are there for increasing permeate recovery rates? Will a second pass improve recovery rates? What are the financial costs of this option?
10. What is the per cent salt rejection?
11. How is the reject stream disposed of? What are the costs?
12. Can the reject stream concentrated further to reduce disposal costs?
13. What regulatory approvals are required for the use of the permeate and discharge of reject streams?
14. What is the expected membrane life and replacement frequency?
15. What are the operating costs for membrane replacement, energy, cleaning, license charges and labour costs?
16. How are the membrane systems integrated into the existing plant?

The capital cost of a membrane system is dependent on the size of the system. It can be approximated as follows [21, 22]:

• pumps	30%
• replaceable membranes	20%
• membrane modules (housings)	10%
• pipework, valves, framework	20%
• control system	15%
• other	5%

The operating costs for a membrane system consist of [21]:

• membrane replacement	35–50%
• cleaning	12–35%
• energy	15–20%
• maintenance labour	15–18%

8.10.9 Electrodialysis and Electrodialysis Reversal

Electrodialysis (ED) is an electrochemical membrane process that involves the movement of ions through anion and cation selective membranes from a less concentrated solution to a more concentrated solution by the application of a direct current (DC). The difference in these membrane processes is that no pressure is applied. Direct current causes the charged ions to move towards the anode (+) and cations towards the cathode (−). Ion-selective semipermeable membranes placed in between the electrodes alternatively allow the passage of only hydrogen and hydroxyl anions to pass through to the respective electrodes. In the process the impurities are trapped within the membranes and as a result produce a concentrate stream. In the ED process, with time, the membrane process becomes saturated with charged ions reducing the recovery rate.

The Electrodialysis Reversal (EDR) process overcomes this problem by reversing the polarity of the electrodes every 15 minutes. Polarity reversal causes the concentrating and diluting flow streams to switch after every cycle. This results in cleaning of the membranes, by sending high-quality water in the compartment that was previously filled with the reject stream.

The ED/EDR processes is suitable for desalting brackish water with TDS feedwater concentrations of up to 4000 mg/L. After 4000 mg/L the electricity costs start to increase dramatically. It is not suitable for the removal of organics. In wastewater treatment, applications include concentration of RO reject streams, mining water reuse and cooling tower blowdown treatment.

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