

Chapter 14: Treatment processes, filtration and adsorption

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14.1 Introduction

Chapter 13 discusses issues relating to the operation of water treatment plants using a chemical coagulant such as alum or polyaluminium chloride followed by rapid granular media filtration. This process may also include sedimentation (ie, clarification) or dissolved air flotation. Filters following coagulation processes operate mainly by adsorption processes rather than straining or entrapment. Chapter 13 also briefly describes water softening using lime (followed by sand filtration) because it is a process that the USEPA and the DWSNZ considers capable of removing protozoa.

This chapter discusses diatomaceous earth filtration, slow sand filtration, membrane filtration, cartridge filtration, and bag filtration. These are the other water treatment processes that can remove *Cryptosporidium* oocysts effectively enough to be considered for protozoa log credits. Their filtration process operates by straining or entrapment.

This chapter also discusses adsorption processes that do not need to follow coagulation processes. These can remove some of the chemical determinands with MAVs. Adsorption processes are also discussed in Chapter 18 with reference to taste and odour control, and in Chapter 19, mainly related to point-of-use and point-of-entry treatment systems. Activated carbon is also mentioned throughout Chapter 9, as a means of adsorbing cyanotoxins from water.

No other filtration processes are discussed in this chapter. Chapter 12, on pretreatment processes, includes some commentary on screens and other coarse filtering processes. These do not qualify for any protozoa log credits.

The 2008 DWSNZ include a new section, section 5.17: Alternative processes: treatment compliance criteria, whereby water suppliers may apply to the Ministry of Health to have other treatment processes assessed for a log credit rating. This approach, which is explained more fully in section 8.4.5 of the Guidelines, allows water suppliers to apply for a log credit rating (or a variation to the prescribed log credits) for a treatment plant or process:

- a) not covered in sections 5.1–5.16 of the DWSNZ
- b) that performs demonstrably better than its compliance criteria
- c) that performs to a lesser, but reliable, level than specified in its compliance criteria.

This chapter concentrates on the operations and management of the processes; Chapter 8 discusses their compliance issues with respect to protozoa removal.

The bag and cartridge filtration sections have been expanded because they are being used more often since when the 1995 Guidelines were produced, and because more experience has been accumulated in recent years regarding their use.

The membrane filtration section in the 1995 edition of the Guidelines was just one paragraph. Technological advances have resulted in the process being used much more often today. Consequently, this section is now quite large.

The other treatments, slow sand and diatomaceous earth filtration, have been expanded because they may be attractive processes for smaller supplies for protozoa removal.

Some process variation is normal and expected; however, too much variability can result in filtration failures, leading to waterborne disease outbreaks. An objective of the DWSNZ, therefore, is to keep process variability within acceptable limits. Understanding the causes of process variations should prevent recurrences. An important design feature is to include sufficient final water storage so the water treatment rate is as near constant as possible; plant using stop/start should be avoided whenever possible.

The AWWA has produced manuals on precoat filtration and on reverse osmosis/nanofiltration, see references. The full list of AWWA manuals and standards appears on <http://www.awwa.org/files/Resources/Standards/StandardsSpreadsheet.xls>.

Risk management issues related to the filtration processes in this chapter are discussed in the:

- MoH Public Health Risk Management Plan Guide PHRMP, Ref: P6.2. Filtration – Slow Sand Filtration
- MoH Public Health Risk Management Plan Guide PHRMP, Ref: P6.3. Treatment Processes – Cartridge Filtration
- MoH Public Health Risk Management Plan Guide PHRMP, Ref: 6.4. Filtration – Diatomaceous Earth

- MoH Public Health Risk Management Plan Guide PHRMP, Ref: P6.5. Treatment Processes – Membrane
- MoH Public Health Risk Management Plan Guide PHRMP, Ref: P10. Treatment Processes – Pump Operation
- MoH Public Health Risk Management Plan Guide PHRMP, Ref: P11. Treatment Processes – Plant Construction and Operation.

DWI (2011) has prepared a list of products that are approved for use in UK water supplies.

A section on desalination has been added because this chapter appears to be the most appropriate. Desalination is not used yet in New Zealand, and has not been considered directly for protozoal compliance.

14.2 Diatomaceous earth filtration

Diatomaceous earth filtration uses a mobile material to build up a filter wall on a membrane. Diatomaceous earth (DE) is a fine, powdery substance comprising the skeletons of diatoms (microscopic algae). It occurs as natural deposits, which are mined, dried, graded and bagged. The usual source is the USA.

DE has been used in New Zealand commonly for swimming pool filtration and in the food industry; for example, most breweries use it to ensure that no yeast is carried over. DE filtration does not remove much colloidal colour or soluble organic matter. These materials are too small to be captured by the mechanical filtration process of DE. They require much finer filtration, or coagulation to allow them to be agglomerated into a floc. DE filtration is mainly used to treat clean stream waters and springs and is accepted in the DWSNZ (Ministry of Health 2005, revised 2008) as being capable of earning 2.5 log credits for protozoa removal.

As at 2005, four water supplies (Ohakune, Woodville, Mokau and Benneydale) have been using a DE process for municipal supply. Bonny and Cameron (1998) described the Woodville plant.

The DE material varies in size. Larger diameter material causes less headloss through the filter layer but offers less protection against protozoal (oo)cysts or other particulate matter. ANSI/AWWA B101-12 covers precoat filter media.

Typically, the finer DE material is around 15–20 microns median size and the coarser material is around 35–40 microns. Both contain a wide range of sizes, but the uniformity coefficient is normally about 5. The uniformity coefficient, or UC, is the ratio between the material's d_{60} and its d_{10} with the d_{60} being the particle size that 60 percent of the material is smaller than, and d_{10} having a corresponding meaning. The pore sizes (the holes between the DE particles) range from about 5 to about 12 microns. The DWSNZ do not specify a maximum median size; compliance is based on performance, as measured by turbidity. Ogilvie (1998) described diatomaceous earth and its use in filtration.

Ongerth and Hutton (1997) found that at least 3 log removal of *Cryptosporidium* was achieved using the coarser media at low flow rates (2.4 m/h). Finer media and higher flow rates (4.9 m/h) improved the results to around 6 log. The improved filtration at higher filtration rates is due to compression of the filter cake. Local practice is to operate at about 4.3 m/h using DE that is rated to remove particles down to 1.2 microns.

WHO (2004a) calls this process 'precoat filtration', and reports some interesting developments:

Precoat filters remove smaller microbial particles (eg, bacteria and viruses) less effectively than they do parasites, unless the coating materials are chemically pretreated; for example, with aluminium or iron coagulants, or with cationic polymers. In a pilot study by Schuler and Ghosh (1990), removal of coliforms with untreated DE was about 0.36 logs, increasing to 0.82 logs with a coating of alum at 1 mg/g DE, and to 2 logs at 3 mg/g DE. This increase was probably due to the trapping of bacteria by the alum. A similar beneficial effect was observed using cationic polymers; at 3.5 mg/g DE, removal of coliforms increased to 3.3 logs. The authors concluded that this increase in removal could be due to an increased site density on the polymer-coated DE for adsorption of negatively charged coliform cells. A similar improvement in removal of bacteria was reported for the pilot study conducted by Lang et al (1986). Alum coating of DE increased removal of total coliforms from 0.16 logs to 1.40 logs, and of HPC bacteria from 0.36 logs to 2.30 logs. Removal of viruses also increased with chemical pretreatment of filter cake (Brown, Malina and Moore 1974). The removal of bacteriophage T2 and poliovirus was about 90 percent (1 log) for an uncoated filter, but increased to more than 98 percent (1.7 logs) when the filter cake was coated with ferric hydrate or polyelectrolytes.

14.2.1 Vacuum or standard DE filtration

The DE is introduced into the water stream by a dosing pump drawing from a stirred DE slurry tank. The concept is to capture the DE particles on a membrane and use them to build up a filter wall. The membrane, a heavy linen type of material, surrounds a solid base called a septum. This usually consists of ABS or PVC tubes with 2–3 mm holes in the walls that allow the filtered water to enter, where it is collected and passed to the next stage.

To create a DE coat on the membrane, a high initial dose is applied, which quickly (say in 20 minutes) builds up a layer of perhaps 2–3 mm thick. This stage is known as the precoat stage and the water during this stage needs to be recirculated until full filtration is established. The amount of precoat applied depends on the filtering surface area. The precoat is measured in kg/m²; the normal precoat dose is about 1 kg/m².

During the filter run (ie, the time the filter operates before the DE must be washed off and the septum recoated), a small maintenance dose of DE is added to the incoming water. This is called the body feed. Its dose rate is based on the turbidity of the raw water and filtration rate, and must be determined by experience. As a guide, fairly clean raw water can be dosed at about 0.15 kg/m²/day. This needs to be increased as the turbidity increases. The filtered water should (in theory) contain no particles larger than

about 2–3 microns (micrometres). DE therefore provides an effective barrier against the (oo)cysts of *Giardia* and *Cryptosporidium*.

The optimum filtration rate is about 0.8 L/s/m² (2.9 m/h) with a maximum of 1.2 L/s/m² (4.3 m/h).

14.2.2 Pressure or modified DE filtration

Many newer DE plants are contained inside a pressure vessel. The concept is similar to that of vacuum DE systems but varies in that:

- the precoat can be applied as quickly as five minutes; again to a thickness of 2–3 mm
- there may be no body feed, although if there is any suspicion of cracking or shrinkage of the cake, body feed should be used
- the filter run time is usually shorter than vacuum filtration due to the higher filtration rate. The optimum filtration rate is about 1.25 L/s/m² (4.5 m/h) with a maximum of 1.6 L/s/m² (5.8 m/h)
- there may be provision for a drop coat procedure, where the DE coat is backwashed off and then re-applied, without removing it from the vessel. This technique increases the risk of recycling previously trapped protozoa, thereby lowering drinking-water quality. Another reason for not using the drop coat technique is because fine clays etc become embedded in the filter support or element cloth, shortening filter runs, and requiring more frequent overhauls. Overhauls involve taking the top off the filter, removing the elements, waterblasting them, and reassembling the unit.

Figure 14.1: Diatomaceous earth pressure plant at Mokau, Waitomo District



Courtesy of Filtration & Commercial Pumping Ltd.

14.2.3 Some operating issues with DE filtration

- **Establishing the pre-coat:** During this time filtered water must be recycled.
- **Body feed:** The idea behind a continuous body feed is to supply loose DE to plaster over any cracks that develop in the pre-coat. These cracks are possible, given the flexible substrate of the membrane. The continuous feed also ensures that the porosity is maintained.
- **Filter run time:** Limitations on the filter run time are usually caused by accumulated headloss. With clean feed water (say, under 2 NTU), headloss will build up at between 0.06 and 6 m/day. For example, where the maximum headloss allowed is 4 metres, the filter run time may be between one day and several weeks.
- **DE handling and disposal:** DE is a siliceous material and can cause respiratory problems if inhaled in dry form. Care must be taken with handling procedures, including removal and disposal (normally to landfill) of spent material.

14.2.4 Monitoring

The DWSNZ use turbidity as an operational requirement in place of monitoring for protozoa against the MAV and the monitoring requirements are described in the DWSNZ. Should the turbidity exceed these requirements the operator should check whether:

- the DE dose is appropriate for the raw water conditions
- the cake has built up enough before drinking-water is produced
- the treatment rate through each filter is within specification
- the filter cake has shrunk or cracked, ie, whether the body feed is appropriate
- there is any short-circuiting
- the raw water quality has changed.

It is recommended that water suppliers establish a control limit for each MAV or operational requirement. Control limits are discussed in Chapter 17: Monitoring. The preventive actions that are to be considered when a control limit is reached are to be documented in the WSP. The purpose of control limits and the preventive actions is to avoid reaching any transgression levels or operational requirements. For example, a control limit for turbidity of the water leaving each filter set at about 0.25 NTU may be advisable.

14.3 Slow sand filtration

The World Health Organization published *Slow Sand Filtration* in 1974. It is still in demand and much of its content remains valid so they continue to make it available electronically. WHO (1974) states that under suitable circumstances, slow sand filtration may be not only the cheapest and simplest but also the most efficient method of water treatment. The process requires a lot of land.

Slow sand filtration began in the early 1800s and was developed at regular intervals throughout that century. Its history, purification mechanisms, design, operation and maintenance requirements and other details are described extensively in a report *Slow Sand Filtration*, published in 1991 (in a period when renewed interest was being taken in the process) by the American Society of Civil Engineers, and in WHO (1974). Also refer to WHO (2004a).

Slow sand filters are not widely used in New Zealand. Examples have included Little River in Banks Peninsula District and Linton Army Camp near Palmerston North. The process produces drinking-water in Apia (Samoa). The Paris water supply (from the River Seine) is treated by slow sand filtration (and other processes) at the Ivry sur Seine plant. It is used there as an organic barrier, particularly to phenols and similar contaminants.

Slow sand filtration (sometimes called biological filtration) operates by two methods:

- a surface filter, which processes the water biologically
- a deep sand bed, which purifies the water by adsorption and some straining.

Slow sand filters comprise a relatively deep sand bed supported on a layer of graded gravel over underdrains (the sand typically 0.9–1.2 m deep on start-up and not to reduce below 0.6 m before resanding). The sand is finer than the 0.6–2 mm range that is typical in the more common rapid granular media filters, having, typically, a mean particle size in the range of 0.15–0.4 mm. This is similar in size to most beach sand. The water takes several hours to pass through the sand, providing ample time for purification by adsorption of microscopic particles adhering to sand grains; 1 m³ of sand has a surface area of about 15,000 m²!

The filters should operate with a head of 1–1.5 m of unfiltered water above the sand. It is most undesirable that the water level in the filter box should drop below the surface of the filter medium during operation. To eliminate the possibility of this happening, a weir is incorporated in the outlet pipe system. The water sits above the sand for 3–12 hours.

The surface of the sand ripens; that is, a biologically active layer, primarily of algae and bacteria, develops on it, adding a biological process to the sand filtering. Ammonia and nitrite can be oxidised in this layer and the organisms living there strip nutrients from the water too. This surface layer is called *schmutzdecke*, a German term meaning dirt layer or filter skin. It takes a day or so to develop and, until it does, the filter will not present a proper barrier to microbial pathogens. This layer does not develop on rapid granular media filters because they are backwashed before any significant amount *schmutzdecke* has had time to develop.

The loading rate (the flow per square metre of filter bed surface area) is low, usually at a constant flow of 100–300 litres per second per square metre per hour, which equates to an equivalent velocity of 0.1–0.3 m/h. The rate may also be expressed as mm/s or m/d. A rate of 0.1 mm/s is equivalent to 0.36 m/h. For protozoal compliance, the DWSNZ state that the filtration rate should not exceed 0.35 m/h, and must be constant. Note that rapid granular media filters (after coagulation) can operate successfully at 30–40 times this rate.

Even at this slow rate, the headloss is typically around 0.1 m when the sand is clean, and increases to about 1.2 m when the sand needs cleaning. This initial headloss is due to the fine size of the sand and the depth of the bed.

There is no backwash system, so all solids captured build up on the surface, with a small amount of penetration into the sand. For protozoal compliance (earning 2.5 log credits), the final water turbidity should be below 0.5 NTU (section 5.10, DWSNZ), and some form of post-disinfection will almost certainly be required in order to achieve bacterial compliance (section 4.3, DWSNZ).

Section 3.6 of WHO (2009) discusses a modification of slow sand filters for household use, calling them biosand filters. These can be used intermittently.

14.3.1 Cleaning

When the bed resistance (headloss) has increased to such an extent that the regulating valve is fully open, it is time to clean the filter bed, since any further increase is bound to reduce the filter output. The top 20–30 mm of sand is scraped off and discarded. Sand removal at small plants can be manual but at larger plants it is more common to use a mechanised system to avoid the large amount of labour required. The water is then turned back on and the filter left to ripen so the *schmutzdecke* layer can build up enough to provide effective filtration again. If the scraping has been completed before the bed has dried out, ripening should take only 1–3 days. During ripening, the water is recycled, passed to another filter, or passed to waste during this time.

Ultimately, maybe after 20–30 scrapings, perhaps after several years, and before the sand reaches its minimum design depth, topping up with new sand, or full cleaning, or complete replacement, will be required. To accelerate the ripening process after resanding, some of the residual bottom sand or scrapings from the surface layer can be placed over the new sand.

A new filter must be run continuously for at least several weeks in tropical climates and longer where temperatures are low (WHO 1974). The time also depends on the nature of the raw water: the cleaner it is, the longer the ripening process will take. As ripening proceeds, there will be a slight increase in the headloss across the bed as the organisms build up, and the formation of a *schmutzdecke* will gradually become visible. These are signs that ripening is proceeding satisfactorily, but only after comparative chemical and bacteriological analyses of raw water and effluent have demonstrated that the filter is in full working condition may the effluent be directed to the public supply.

A detailed study in the Netherlands found removal of MS2 bacteriophage and *E. coli* WR1 was strongly dependent on the water temperature and *schmutzdecke* age; Schijven et al (2013). This model is intended to be incorporated into the Dutch 'legislatively required quantitative microbial risk assessment' (QRMA) and reduce the monitoring required for determining removal efficiency of SSF.

Because of the need to ripen cleaned filters, treatment plants need more than one filter, preferably at least four. The weakest point of a sand filter is the edge where raw water may leak past; to minimise this filters should be at least 100 m², preferably double this.

Full records of cleaning operations should be retained.

14.3.2 Monitoring

The primary protozoal compliance monitoring criterion for slow sand filtration is the turbidity of the filtered water. This should remain under 0.5 NTU (section 5.10, DWSNZ). Should it exceed this, the operator should check whether:

- the sand bed has been disturbed; in particular, whether the sand has bound together then cracked, or pulled away from the filter walls
- the *schmutzdecke* layer still appears normal. If it has been poisoned or damaged in some other way, it may have died off and be losing material into the sand
- the raw water quality has changed abruptly; in particular, whether significant turbidity from clay (rather than coarser material) has been present. An increase in turbidity could be due to heavy rain in the catchment
- any operating parameters such as temperature, pH, flow through each bed, headloss, downstream chlorine demand etc has changed significantly. The operator should assess whether this was good or bad news and how it relates to the higher filtrate turbidity. Colder water, for example, should show higher headloss but not necessarily higher turbidity.

If the turbidity of the filtrate from any filter exceeds 0.5 NTU for more than 5 percent of the time, the cause needs to be determined and resolved before the water from that filter can be used. If it is not possible to shut off the supply from the filter during the investigation, boil water notices must be issued. If the filtered water turbidity is greater than the raw water turbidity, there is a real chance that the filter is discharging; if it is not due to a sudden change in raw water quality, shut down the filter, scrape off the top sand and ripen again.

It is recommended that water suppliers establish a control limit for each MAV or operational requirement. Control limits are discussed in Chapter 17: Monitoring. The preventive actions that are to be considered when a control limit is reached are to be documented in the WSP. The purpose of control limits and the preventive actions is to avoid transgressions of the MAV or operational requirement. For example, a control limit for turbidity of the water leaving each filter set at 0.30–0.40 NTU may be prudent.

WHO (1974) considers the following are the basic records that should be kept for each filter:

- the date of commencement of each cleaning
- the date and hour of return to full service after ripening
- daily raw and filtered water levels, and headloss
- the filtration rate

- raw water and filter effluent quality, ie, colour, turbidity, temperature, *E. coli*
- details of incidents, unusual weather etc.

14.3.3 Aeration

The filtered water may become anoxic as it passes through the sand so may need to be aerated to restore the dissolved oxygen level and remove dissolved carbon dioxide. This is achieved by having a simple weir on the outlet, dropping the filtered water about 1 m vertically. The water passes first through the sand, then through the underdrains and is taken back up to the top of the weir, which is on the same level as the sand surface. This arrangement ensures the water level in the sand does not drop below the surface. If this happens, the surface will dry out, killing the biota, and air will blind off some of the flow paths through the bed. The weir also ensures that the filter operates independently of any level fluctuations in the water above the sand.

14.3.4 Some operating issues with slow sand filtration

- **Raw water quality:** The water going on to the filter should not be too turbid or the filter will quickly overload. Experience will show when this level approaches. Although raw waters up to 100 NTU have been treated successfully for brief periods, 50 NTU is a more realistic upper limit, and optimum purification occurs around 10 NTU. Very turbid raw waters should receive some form of pretreatment.
- **Controlling algal growth:** The amount of algal growth on the surface must be limited, but not prevented. Algae require sunlight so the simplest method of controlling their growth is to limit sunlight where necessary. The Little River units (two in parallel) do not have this feature and have not had this problem.
- **Cold weather:** This can reduce the filter's effectiveness in two ways. As well as limiting the biological activity in the *schmutzdecke* layer, low temperatures also increase the headloss by increasing the viscosity of the water. Slow sand filters are recognised as being more suited to, and more efficient in, warm climates. The DWSNZ call for a minimum temperature of 6°C for protozoal (oo)cyst control. If this temperature is likely to be reached, water suppliers may consider covering the filtration area to limit the cooling effect of wind and frost.
- **Disinfectants:** Chlorine, or any other disinfectant or algicide, should not be added before the water is filtered, because it will kill the organisms in the *schmutzdecke* layer. Efficiently operated slow sand filters have been demonstrated to be effective in removing protozoal (oo)cysts, as well as bacterial and viral pathogens. However, dosing chlorine after filtration is strongly recommended.

14.4 Membrane filtration

14.4.1 Introduction

This section aims to provide the reader with a general understanding of the issues related to membrane filtration for drinking-water treatment in New Zealand, and covers:

- the history and current status of the technology
- the fundamentals of microfiltration (MF) and ultrafiltration (UF) for drinking-water applications. Nanofiltration and reverse osmosis (NF and RO) are discussed briefly
- the fundamentals of membrane filtration operations for drinking-water quality management.

The application of membrane filtration for drinking-water applications has increased markedly in recent years, with a membrane option considered for most water treatment applications. The increase in uptake has been driven by a number of factors, from lowering unit capital and operating costs, to the emergence of low-pressure membrane technology (reducing power demands), and a greater emphasis on correct pretreatment selection. In addition, advantages offered by advanced materials and low footprint designs have given membrane options additional weight when compared with more traditional treatment approaches.

Membrane technology is still developing. The cost of treating water through reverse osmosis membranes is approximately one tenth of the cost it was in 1978. Similarly, the energy requirement is approximately one quarter of that used in 1980 to treat the same volume of water through reverse osmosis membranes. As a result in these dramatic reductions in the cost and energy required, the adoption of reverse osmosis globally as a water treatment process has accelerated exponentially over the last few decades.

These recent developments have been aided by the emergence of further, legitimate evidence supporting membrane filtration as a secure means to eliminate pathogenic organisms from the water supply, in particular, the protozoal species *Cryptosporidium* and *Giardia*.

For the *Drinking-water Standards for New Zealand 2005, revised 2008* (DWSNZ), membrane systems may attain log credits in accordance with the system validation. So far most MF plants in New Zealand have been assigned 4 protozoal log credits, however, in special circumstances, this may be as high as 5, or possibly even higher.

14.4.2 Current experience in New Zealand and overseas

As at April 2005 five membrane plants exist in New Zealand for drinking-water treatment. These vary in type and capacity. All are of the UF or MF genre and have been designed and installed since 1999. A number of upgrades and projects are ongoing that may include membrane technology. At present two principal suppliers cover the market in New Zealand; additional suppliers will enter the market in the future.

Overseas, the number of plants adopting membrane technology is increasing, particularly in US, Europe and Asia. In the UK, for example, membranes have been adopted at various water treatment plants to meet the *Cryptosporidium* Regulations (1999). The largest membrane plant in Europe was commissioned in 2001, the Clay Lane WTP (160 ML/d). In 2003, Invercannie WTP (80 ML/d) in Scotland was commissioned to meet Scottish Executive *Cryptosporidium* Regulations.

An interesting application of membrane filtration at the Méry-sur-Oise water treatment plant in Paris was described by Cotte et al (2005). They replaced coagulation, filtration, ozonation, biological granular activated carbon filtration with clarification, ozonation, biological dual media filtration, cartridge filtration, nanofiltration and UV disinfection. Dissolved organic carbon in the distribution system fell from about 1.8 mg/L to 0.75 mg/L, and biodegradable dissolved organic carbon fell from about 0.6 mg/L to 0.1 mg/L. This enabled the chlorine dose to be cut back, which combined with the lower organic matter, reduced the trihalomethane content from about 0.2 mg/L to 0.008 mg/L; bacterial numbers were significantly lower too.

14.4.3 Fundamentals of membrane filtration

There are four principal classes of membrane filtration that apply to drinking-water treatment:

- microfiltration (MF)
- ultrafiltration (UF)
- nanofiltration (NF)
- reverse osmosis (RO).

Of these, MF and UF are most commonly specified for drinking-water applications, with the five existing plants in New Zealand comprising these technologies. RO has been used in industry and household supplies.

Microfiltration and ultrafiltration

MF and UF are characterised by their ability to remove suspended or colloidal particles via a sieving mechanism based on the size of the membrane pores in the membrane, relative to that of the particulate matter. Pretreatment (mainly coagulation, with or without sedimentation) is needed to remove colour and very fine particles. MF and UF are often collectively called low pressure membrane processes. They operate in the 3–50 psi range, or -3–12 psi if using a vacuum system.

Each membrane has a distribution of pores, which will vary according to the membrane material and manufacturing process. There are two ways to represent pore size:

- nominal, the average pore size
- absolute, the maximum pore size.

MF membranes are generally considered to have a pore range of 0.1–0.2 μm (nominally 0.1 μm), although there are exceptions, with some MF membranes marketed with pore sizes up to 10 μm . Without pretreatment, MF membranes will remove most protozoa, many bacteria, but very few viruses.

For UF, pore sizes generally range from 0.01–0.05 μm (nominally 0.01 μm) or less. With UF, classification in terms of pore size becomes inappropriate, due to the other mechanisms/ phenomena that take place at the membrane surface. In terms of pore size, the lower cut off for a UF membrane is approximately 0.005 μm . Without pretreatment, UF membranes will remove probably all protozoa, most bacteria, and many viruses (consistently greater than 3 log removals).

Some UF membranes are categorised in terms of their molecular weight cut-off (MWCO) rather than a particular pore size. The concept of MWCO, expressed in Daltons (a unit of mass) is a measure of the removal characteristic of a membrane in terms of atomic weight (or mass) rather than size. Therefore, UF membranes with a specified MWCO are presumed to act as a barrier to compounds or molecules with a molecular weight exceeding the MWCO.

Typical MWCO levels for UF membranes range from 10,000 to 500,000 Daltons, with most UF membranes for drinking-water treatment at around 100,000 MWCO. Note that these are large molecules. UF membranes for drinking-water treatment are also characterised according to pore size with respect to microbial and particulate removal capability.

A key distinction when considering MF or UF technology for a particular application is whether to select a pressure or submerged configuration. The use of hollow-fibre membranes is normally selected, and this brief explanation assumes the use of this type of membrane. Hollow-fibres are bundled longitudinally and either encased in a pressure vessel or submerged in a basin, or cell.

Modules are contained in housings, or pressure vessels. Operating pressures for such systems vary from 20–280 kPa. Most applications require designated feed pumps to generate the required operating pressure, although some may be operated under gravity if sufficient head can be developed.

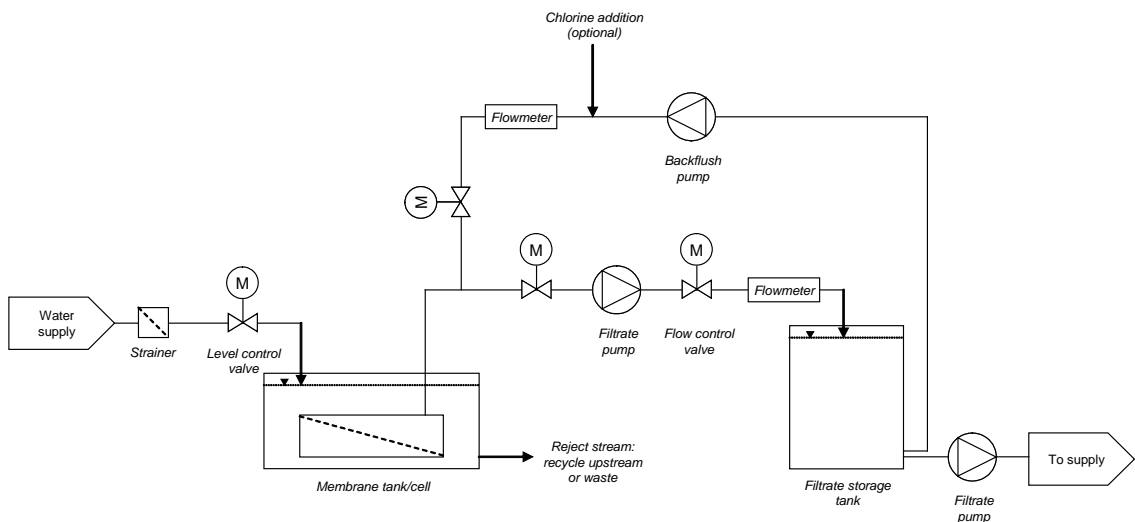
Most systems are referred to as dead-end in as much as all contamination material is trapped on the membrane surface. This is as opposed to generating a continuous reject stream.

While all hollow-fibre systems require pressure as the fundamental driving force, a submerged (or vacuum) driven system is distinguished by its use of negative pressure and is significantly different in terms of design and configuration. Unlike pressure systems, where each membrane module incorporates a pressure vessel, submerged systems use hollow-fibre modules that are driven under vacuum, immersed in an open tank or cell. While the ends are fixed, the lengths of the hollow-fibres are exposed to the feed water in the cell and move freely.

Due to the feed water being contained in an open tank, the outside of the fibres cannot be pressurised above the static head in the cell. Therefore a vacuum, approximately -20 to -90 kPa, is induced at the inside of the fibre walls, where it is filtered outside-in to the lumen (the centre or bore of a hollow-fibre membrane). By design, submerged systems cannot be operated via gravity alone (a common misconception), or in an inside-out mode of filtration. In some circumstances they may be operated by siphon.

Figure 14.2 shows a typical schematic of a submerged membrane system. In this arrangement the vacuum is supplied from the filtrate pump.

Figure 14.2: Typical submerged membrane system



Nanofiltration and reverse osmosis

NF and RO comprise a class of membrane processes that provide a higher degree of removal of contaminants compared with MF/UF. For example, NF systems can remove particles as small as 0.001 to 0.002 μm (microns). Although NF and RO can remove nearly all bacteria and viruses, they are specified less frequently in drinking-water applications, mainly due to the much greater pressure requirements, eg, 800–1,000 psi (say 5,500 to 6,900 kPa or kN/m^2), or even higher for RO where up to 10,000 kPa can be needed in desalination plants.

Removal of viruses by RO membranes may vary significantly and is a function of the membrane itself as well as its condition and the integrity of the entire system, including seals. Removals ranging from 2.7 to more than 6.8 logs, depending on the type of RO membrane, have been reported at bench scale using MS2 bacteriophage as the model virus, and the selection of membranes is an important factor in determining virus removal. Although RO constitutes an excellent barrier to micro-organisms, the maintenance of that barrier depends on the integrity of the system. Breaches of integrity in the membranes or the O-rings could lead to the passage of pathogens into the process water and must be monitored by integrity testing. Effective methods to measure the integrity of RO membranes should be used to achieve target removals. Currently, conductivity measurements are used, but the sensitivity limits their application to about 2 logs of removal. As bacteria have been shown to traverse through membrane defects, membranes cannot be considered as completely effective for disinfection and are commonly succeeded by a disinfection step (WHO 2011a).

Nanofiltration is a high-pressure membrane process that has been used traditionally as a softening process to remove hardness ions. Generally, NF membranes reject divalent ions (eg, Mg^{2+} , Ca^{2+}), but pass monovalent ions (eg, Na^+ , Cl^-). Recently, NF has been used more extensively for removal of DBP precursors and colour. Although NF processes remove nearly all turbidity in feed water, they cannot be used for turbidity removal in the same manner as MF and UF due to the smaller pore sizes. Smaller pore size makes NF membranes more prone to fouling. The application of NF for surface waters is generally not accomplished without extensive pretreatment for particle removal.

NF/RO remove some dissolved contaminants, as represented by measurements of total dissolved solids (TDS) or conductivity ($\mu S/cm$, or mS/m). The typical range of MWCO is less than 100 Daltons for RO membranes, and between 200 and 1,000 for NF membranes. RO is used sometimes for removal of chemical determinands not removed by existing processes. For example, it can be used to remove arsenic. Some point-of-use (POU) units use NF or RO. However RO also removes minerals and according to the WHO, there are very large numbers of people who consume levels of calcium and magnesium that are insufficient to support their physiological needs. Drinking water can contribute considerably to calcium and magnesium intake, depending on the geographical area, and therefore to the overall nutrition. Mineral removal by RO filtration could counteract potential health benefits of DBP removal.

As the majority of drinking-water applications involve MF/UF, these NF and RO technologies are not elaborated upon in the remainder of this section.

14.4.4 Membrane selection

The task of selection of the appropriate membrane will involve consideration of:

- design targets, final water quality, guarantees
- commercial, capital (CAPEX), operating (OPEX) and whole-life costs (WLC)
- site-specific conditions, any process limiting criteria.

One of the major issues to resolve in drinking-water applications is whether to use MF or UF. An outline of their characteristics was given earlier in section 14.4.

A key issue is virus rejection. Although the current DWSNZ do not impose a requirement for viruses, should the water supplier wish to have a higher level of security against virus infiltration using membrane technology, UF should be considered. Future editions of the DWSNZ are likely to address viruses. However, it should be emphasised that not all UF membranes are capable of virus rejection. Studies undertaken in the US in the mid 1990s demonstrated that membranes with a MWCO of 500,000 Daltons were less efficient at virus removal than another with a MWCO of 100,000. The designer should refer to the UF membrane manufacturer for data on their specific virus sized challenge data. It is not advisable to rely on membranes alone to provide primary virus protection; post-chlorination is recommended.

The decision to go with MF or UF technology can be marginal in some cases. In essence a higher degree of separation is returned by UF yet these can be counterweighted with risks. For all applications a risk assessment and cost/benefit analysis should be developed as an aid to the selection process.

Membrane materials

Material properties directly impact performance. The main properties are shown in Table 14.1. Features such as porosity, pore size and shape, are surface roughness are important. Membrane materials can be manufactured in different geometrical configurations, which are then incorporated into a membrane module. Commercially available configurations include hollow fibre, spiral wound, tubular and plate-and-frame. Hollow fibre membranes are the most common form used in community water supplies. The most common membrane materials encountered in drinking-water treatment are:

- polypropylene (PP)
- polyvinylidene fluoride (PVDF)
- polyethersulphone (PES).

Polysulfone and cellulose acetate have been used too.

Table 14.1: Properties of typical membrane materials

	Unit	Polyethersulphone (PES)	Polyvinylidene fluoride (PVDF)	Polypropylene (PP)
Hydrophobicity (water hating)	–	Medium	Medium	High
pH range	–	1 to 13	2 to 10	1 to 13
Chlorine tolerance	–	Good	Excellent	None
Temperature tolerance	°C	High	High	High

14.4.5 Membrane plant operations

The operation modes of a MF/UF system comprise:

- **service:** time which the system is online and generating filtrate
- **backwash:** time which the membrane requires washing to remove entrapped particles and solids. Wastewater is produced during this operation. Operation restores clean head, although not completely
- **clean in place (CIP):** time which the membrane system requires chemicals applied to eliminate foulants not removed by backwashing. For example, natural organic matter or micro-organisms or biofilms adsorbed on the membrane; excess cationic polyelectrolytes need to be controlled carefully too. CIP restores permeability and resistance, although not completely due to some irreversible fouling
- **offline or out of service:** time which backwashing or CIP is taking place, or membrane integrity testing/maintenance procedures are being carried out. Some membrane systems remain in place while back-pulsing.

Service mode

During service the membranes are pressurised, either by positive pressure or vacuum, and generate filtrate. The normal mode of operation is to maintain the flux by increasing the pressure as the filter blocks. In the constant pressure mode, the filtrate output drops as the pores block. Typically the membrane system shall be monitored for the following during the service mode:

- filtrate turbidity or particle count*
- filtrate flow measurement (for measuring plant recovery)^{1*}
- transmembrane pressure² (TMP)*
- cell level (protects membranes)
- filtrate temperature (computed in TMP)
- filtrate pump speed/frequency (if VSD operated).

* Key operating parameter.

Depending on the degree of automatic control, during this mode the membrane plant requires little operator attention other than observation of key operating parameters. Normally a PLC based control system is provided, with an operator interface to observe key operating variables.

The service period should be of the order 98–99 percent of the operating day, accounting for regular backwashing.

¹ The volumetric percent of feedwater that is converted to filtrate in the treatment process over the course of an uninterrupted operating cycle. This excludes losses attributable to backwashing and CIP.

² The difference in pressure from the feed to the filtrate across a membrane barrier.

Should the water quality deteriorate, for example in the case of a membrane plant fed from surface water during a flood event, or a significant decrease in temperature, this should be detected by the upstream instrumentation. This should then be communicated to the operations staff in the form of automatic alarms or flags to adjust the process conditions to maintain performance.

Submerged membrane systems are capable of handling high swings in solids loading or turbidity. The level and duration of such events will impact the permeability of the membrane. Membrane plants fed from surface waters may experience sudden changes in influent raw water quality, particularly in terms of colour, turbidity, organic material and metals. A change in pH may also be experienced depending on the nature of the catchment geology. Should the raw water quality be outside the design criteria of the system, the system may still cope as long as the appropriate operator actions are undertaken. These actions may comprise one or more of the following:

- visual checking of membrane outer surface/colouring. This is straightforward in submerged systems as membranes are exposed
- checking raw water quality and adjusting chemical conditioning if necessary to suit conditions
- checking upstream water quality instrumentation, ensuring still within calibration etc
- checking correct coagulant and/or coagulant aid dose rate. Dose rates should be established at commissioning/performance testing across the range in flows and qualities
- checking the coagulation pH is optimised
- checking hydraulic loading (flow) to membrane units, verification that flux is within design limits. The flux rate will reduce as fouling increases and the membrane manufacturer's minimum flux should be noted
- checking backwash and air scour flows and pressures are set correctly
- checking clean washwater quality/volume to ensure the correct quality and quantity of water is being used. Poor quality washwater should not be used.

Regularity of backwashing and/or CIP may increase temporarily to remove the additional contaminants from the membrane.

Backwashing and clean-in-place (CIP)

During filtration mode, particles and materials that are too large to pass through the membrane pores stay in the raw water or stick to the surface of the membrane. The latter process is known as fouling. Fouling progresses as the membrane system progresses in the service mode and results in decreasing permeability. MF/UF membrane systems typically employ three separate cleaning strategies to alleviate membrane fouling, and these can be automated:

- air scour
- backwash (water)
- combined air scour and backwash
- clean-in-place (CIP).

In the context of a submerged system, air scour is employed continuously or intermittently in each tank. Blowers supply air back to the membrane tank. The bubbles physically agitate the membrane fibres and help to both displace debris that has collected on the membrane surface and to keep the water in the tank mixed.

On a regular basis (can be as frequently as every 15 minutes or even longer than 60 minutes), a backwash is conducted in which filtered water is pumped back through the membranes (inside out) to clean the membrane pores. This action is brief, normally lasting less than one minute. Membrane manufacturers may opt to use a low-concentration chemical solution, such as a dilute chlorine solution, in the backwash water to assist in the cleaning of the membrane pores. This may be favoured to arrest development of organic fouling. The backwash action can be provided by the permeate pumps on some multiple-unit systems through automatic valve switching.

Membranes require periodic chemical cleaning to remove fouling materials that are not displaced by backwashing. The term for the cleaning process is clean-in-place (CIP), since the membrane system(s) are shut down and the membranes are not removed from their locations. During CIP, the membranes are subject to intimate chemical contact through a series of operations. The operations may vary in their degree of automation depending on the nature of the system design. The different chemicals that may be used are proprietary agents, acids, alkalis, oxidants, chlorine and detergents, depending on the composition of the membrane fibres and the nature of the foulant. The membrane manufacturer's guidance should be followed.

The volume of chemical wastewater for CIP operations can be of the order 3 percent of the raw water flow rate during periods of high organic or metal salts loading on the membranes. The required frequency of this CIP will vary based on the raw water characteristics, operating flux³ and the particular membrane material. A frequency of approximately once per month or longer should be attainable. The chemical cleaning solution in the tanks may be reusable if its strength does not deteriorate too significantly, but it is normally neutralised and discarded to waste.

An example of a CIP record sheet applicable to a MF system is presented in Table 14.4.

Types of integrity testing

Integrity testing is required to ensure continuous and repeatable security that the membrane system is performing within its specifications. Integrity testing is also discussed in Chapter 8: Protozoa Compliance, sections 8.4.3.5, 8.6.2.3 and 8.6.2.4.

At present there are two classes of integrity testing:

- **direct integrity testing (DIT):** a physical test applied to a membrane unit in order to identify and/or isolate integrity breaches
- **continuous indirect integrity monitoring (CIIM):** monitoring some aspect of filtrate water quality (ie, turbidity, particle counts) that is indicative of the removal of particulate matter at a frequency of at least once every 15 minutes.

³ The throughput of a pressure-driven membrane filtration system expressed as flow per unit of membrane area (eg, L/m²/h).

Currently there are two general types of DIT that are commercially available for use with membrane filtration plants:

- pressure-based tests (MF/UF)
- molecular marker-based tests (NF/RO).

The test used for a particular system depends upon the type of membrane filtration, target organism(s) and test sensitivity. The DWSNZ specify the compliance requirements within section 5.11 Membrane filtration – treatment compliance criteria, which should be referred to.

In addition to complying with the DWSNZ, the DIT method must be compatible with the particular membrane system. The membrane supplier should confirm whether the system is compliant or non-compliant.

Pressure (vacuum decay) tests are compatible with all the various types of membrane filtration that qualify under DWSNZ. The equipment required to conduct these tests is typically supplied with the proprietary membrane system. However, some types of DIT may not be available from a particular supplier. The test selection may also take account of site or system specific factors. For further details refer to the Membrane Filtration Guidance Manual (USEPA 2005) and the LT2ESWTR Final Rule (USEPA 2006). Membrane filtration is also discussed in Chapter 14 of the review draft LT2ESWTR Toolbox Guidance Manual (USEPA 2009).

Control limits and transgression action guidance

The DWSNZ recommend upper control limits (UCL) set at, as a general rule, two-thirds of the appropriate compliance criterion, or MAV. For example, a membrane filtration system validated and certified to provide 4 log removal of protozoa requires an outlet (filtrate) turbidity of 0.10 NTU. Thus the control limit may be set at 0.07 NTU (and the outlet turbidity must always be less than the inlet turbidity). Turbidimeters must be specified to ensure resolution to this level. The water supplier may elect to specify upper and lower control limits (LCL) to give additional performance control and foresight of deteriorating performance.

Should the control limit be met for a period of 15 minutes, and assuming the backwash TMP trigger has not been met, it is recommended a backwash be initiated manually on the offending units. Should a CIIM instrument be located on each unit's filtrate, the offending unit should be backwashed. If a common instrument is used, each unit that the instrument monitors should be backwashed in a controlled sequence. Should the filtrate turbidity remain in excess of the control limit after the backwash, the unit must be taken out of service for direct integrity testing. This is preventive action as a transgression has not occurred (ie, not greater than 0.10 NTU). Note turbidity can exceed 0.10 NTU, but pass DIT.

Setting the direct integrity test (DIT) test limit

The DIT is the principal means to assess membrane integrity where protozoal removal is the prime function of the membrane system. Test parameters and results can be linked to the particular treatment objectives to give a quantifiable and objective assessment of system performance.

Resolution, sensitivity and frequency needs for DIT are specified in the DWSNZ. For example, the resolution must be that a 3 µm particle (equivalent to the smallest *Cryptosporidium* oocyst) generates a test response. Thus, for pressure based DITs, the applied pressure must be great enough to overcome the capillary static forces that hold water in a breach of 3 µm in diameter in a fully wetted membrane thereby allowing air to escape (through a *Cryptosporidium* sized hole) and thus allowing the loss of air to be detected. A similar concept is applied to marker based tests.

Sensitivity is defined by the particular system performance validation and characteristics of the membrane system itself. The sensitivity must exceed that required to achieve the log credit. For example, 4 log credits must prove repeated 99.99 percent removal of protozoan species tested for. No generic limits can therefore be set.

The DIT limit must be defined and certified before the system enters service. As a minimum the DIT must quote the test threshold specified by the membrane manufacturer. The DIT must be carried out once every 24 hours of operating time.

Interpreting continuous indirect integrity monitoring (CIIM) results

CIIM results are intended to provide an indication of system integrity between direct integrity test applications. The results are compared with the control limit that represents a potential integrity breach.

Caution should be noted as false negative and false positive results are possible with these methods. For example, false positive results may be created by the use of an air scour of the membrane surface as part of the backwash sequence and this may create artificially high results after the unit is returned to service. This may be overcome by running to waste until this known condition is resolved. In practice this may be a period of minutes per unit. Once the performance stabilises below the control limit, the unit is returned to feed forward service. This is more easily accommodated in multiple unit systems than systems with fewer units.

False negative results that arise may be more common than false positives when using CIIM. For example, turbidimeters are less sensitive than monitoring techniques used for direct integrity testing. This may be overcome by using more sensitive instrumentation, eg, laser turbidimetry, although this is more costly. The water supplier could increase the number of CIIM instruments. Each option should be evaluated for each application.

Membrane repair/replacement

This applies to any component of the membrane unit that may allow an integrity breach should it fail, not just the membrane itself. The purpose of repairing the membrane is to prevent integrity breaches that may lead to performance transgressions.

The repair should take place whenever an integrity breach is detected, using DIT or CIIM methods. The source of the integrity breach, for example broken membrane fibre(s), should be located and repaired. The validation of the repair must be by a subsequent DIT, meeting the DIT limit for the system, to prove unit integrity has been restored before the membrane is returned to service.

As outlined previously, depending on the control limit set, integrity breaches leading to membrane repair/DIT may not necessarily represent a transgression. Proactive maintenance can therefore credit the system with maintaining compliance. The repair itself may take the form, for example, of pinning the fibre hole in each end of the membrane module. Thus two pins are inserted per fibre. Should a membrane module be subject to multiple repairs the operator may elect to replace the module itself, or insert a new module immediately to return the unit to service. Here, the repair may take place at the operator's leisure. This may be more cost-effective in terms of minimising plant outage.

The DWSNZ require direct integrity testing in accordance with section 5.11.1.

General operations guidance

The operators should generate plant logs based on the plant operation and maintenance manuals (O&Ms). An example of a monitoring datasheet is presented in Table 14.3. In addition to data recorded online, for example by a SCADA system, this provides essential evidence of operations and plant performance and enables operators to become more knowledgeable of the features of the membrane plant.

The operator should review operational data regularly, such as the TMP, flow rates and the outlet turbidity. The operational staff should aim to detect any anomalies in the data and investigate them. This may lead to early detection of a problem. DIT data should be reviewed continually.

After a CIP, the operational staff should calculate the permeability, record the TMP immediately before and after in order to evaluate the magnitude of fouling that is removed, to determine how frequently cleaning is required and to estimate the long-term impact on membrane life. This information should be recorded in the operation log. Supplier consultation may be required should abnormal results be observed.

The outer colouring of the membrane fibres may be observed on submerged MF systems, however, little is visible on pressure systems. Should membrane change be required prematurely, the membrane supplier may offer biopsy services to help establish the nature of the failure. The end user should note the membrane supplier's warranty conditions as these are generally non-negotiable.

Table 14.2: Typical design/operating criteria for MF/UF systems (guidance only)

Criteria	Typical range for drinking-water application using MF/UF technology
Flux rate – flow per unit of membrane filter area (recovery)	@ <2 NTU feed 50–90 L/m ² /h (94–98%) @ 2–10 NTU feed 40–60 L/m ² /h (92–94%) @ >10 NTU feed <50 L/m ² /h (90% min)
Recovery	95–98%
Flow control, maximum rate of change per minute	1.5–5%
Backwash and chemical clean-in-place (CIP) intervals	Backwash: 15–40 minutes CIP: 30–40 days
Membrane life	>5 years

The calibration of any online instruments, for example turbidimeters, pH meters, should be performed on a weekly basis. If particle counters are used, calibrate in line with manufacturer's recommendations.

Other operational checks should be conducted following the requirements of the validation, the DWSNZ and the manufacturer's instructions.

Membrane plant hydraulics

The membrane system should meet the hydraulic characteristics and constraints of the site and/or interfacing plant. This applies to both gravity (submerged) and pressure systems.

Where submerged systems are being designed, caution should be taken with respect to upstream buffering and lags at varied design flows. A hydraulic model should be constructed across the design envelope, for example, to size channels correctly and to determine if overflows are necessary.

Pressure systems are pumped and this design should default to the membrane supplier. Generally it is recommended that head is broken (filtrate side) from the membrane system, as opposed to feeding the next stage process directly. This avoids possible interference with the downstream process in terms of pressure variance or loss.

The operation sequencing of membrane systems should be considered carefully in terms of operation dynamics as this can be complex. The modes of operation, for example filtration, backwash, CIP, must be balanced to ensure operation risk is low. It is normal to provide standby membrane plant to securely meet the nominal design output. For example, for a submerged system, two standby cells may accompany an array of six operating cells.

Table 14.3: Data log and check sheet

Unit model	Site
Backwash timer setting	
Date	
Time	
Hours run	
TMP ⁽¹⁾ (kPa)	
Temperature (°C)	
pH	
Feed turbidity (NTU)	
Filtrate turbidity (NTU)	
Feed FFI (x 10 ¹² m ⁻²)	
Filtrate flow (L/h)	
Feed flow totaliser (m ³)	
Filtrate flow totaliser (m ³)	

1 TMP = feed pressure – filtrate pressure.

Daily pressure decay test

Perform approximately five minutes after backwash.

Filtrate pressure	
At 0 minutes	_____ kPa
At 2 minutes	_____ kPa
At 4 minutes	_____ kPa

Table 14.4: Chemical cleaning log sheet – provided by membrane supplier

Chemical cleaning report	
Client	Location
Membrane model	Application
Today's date	Date of last cleaning

Parameters	Before cleaning	After cleaning
Flow rate		
Backwash interval		
TMP		
Feed temperature		
pH		
TMP rise between backwash		

Chemical	% conc	pH	Conductivity	Temperature

Cleaning scheme	Duration (minutes)
Recirculation	
Aeration	
Soak	

Comments

14.5 Cartridge filtration

The advantages of bag and cartridge filtration processes include low maintenance requirements, minimal operator skill and attention required, and low space requirements. The only routine maintenance required is filter replacement when a predefined terminal pressure drop or other operating parameter, such as filter age or volume treated, is reached. The operation of these systems is generally straightforward and requires little technical skill. In addition, the filter materials are relatively inexpensive and the housing system is not complex, resulting in relatively low capital costs.

An economic disadvantage of bag and cartridge filtration processes is that the filters must be replaced instead of being regenerated or washed. For larger flows, or water with higher particle loads, frequent filter replacement increases operation and maintenance costs. Additional pumps may be required to provide needed pressure.

A cartridge filtration plant consists of cylinders (or housings) packed with filter cartridges through which the water flows from the outside of the filter into a central collection duct. Cartridge filtration is used in other industries too, so care must be taken to ensure water supply filters are used, ie, the filtration units must comply with NSF/ANSI 53 Standard or similar standards.

A single filter unit or plant comprises the filter medium, its housing, and associated piping and valves. A housing may contain between 1–20 filters.

The particulate loading capacity of cartridge filters is low. Unless the raw water is very clean, these systems usually incorporate some form of pretreatment to remove the bulk of the particulate matter to extend the cartridge filter life. A rule-of-thumb guide is that the water entering the filter should have a turbidity of <3 NTU. If another cartridge filter is to be used upstream, it has been found that a 20–50 micron screening filter is quite effective, see sections 12.3.4 and 12.3.6 in Chapter 12: Treatment Processes, Pretreatment. A filter-to-waste component is recommended for any pretreatment pressure sand filters. At the beginning of each filter cycle and/or after every backwash of the prefilters a set amount of water should be discharged to waste before water flows into the bag/cartridge filter.

Some cartridge filters on the market are claimed to be able to be backwashed. This is not to be done because the washing process can progressively dislodge fibres from the medium, ultimately allowing more and more particles to pass through.

Cartridge types vary widely in size, cost and effectiveness. Testing has shown wide variations between different types. Unlike membrane filtration, there is currently no technique for direct integrity testing. For these reasons, the *Drinking-water Standards for New Zealand 2005, revised 2008* (DWSNZ) require a safety factor over their validated protozoa removal performance. For cartridges that are validated to achieve 3 log removal of *Cryptosporidium*, 2 log credits may be awarded. See Chapter 8: Protozoa Compliance, section 8.4.3.4 for information about validation or certification. Refer also to Chapter 8 of the review draft LT2ESWTR Toolbox Guidance Manual (USEPA 2009) which discusses issues related to cartridge filtration.

Cartridge size

The standard size is 248 mm (9.75 inches) or 254 mm (10 inches) long and 64 mm (2.5 inches) in diameter. This size is used for most small applications. Some suppliers will provide dual housings that will fit two (or more) of these in parallel. Due to seating problems, it is not normally recommended to use cartridge filters in series. For example, instead of joining two cartridges together, it is better to purchase a double length unit, say 19.5 or 20 inches long.

There are larger sizes for applications producing higher volumes. The sizes vary according to the supplier; 150 mm (six inch) diameter is often the next step up. The length also increases in the larger cartridges: 20, 40 and 60 inch options are some common sizes on offer.

Filtration size

Filters are rated on their ability to remove particles of a specific size from a fluid, but the problem is that a variety of very different test methods are applied to specify performance. Because cartridge filters are fixed barriers, their effectiveness is expressed by the size of the smallest holes. This is usually measured in microns or micrometres (1,000 microns being 1 mm). Pore size ratings refer to the size of a specific particle or organism retained by the filter to a specific degree of efficiency. A filter that is marked '10 micron' has some capability to capture particles as small as 10 microns. However, this is meaningless unless there is a description of the test methods and standards used to determine the filter rating. Cartridge filters are often classified by either a nominal or absolute rating.

- **Nominal rating:** is just that, it exists in name only. It is meant to represent the size (or more commonly mean size) of the particles which a filter will exclude, maybe with an efficiency as low as 60 percent! It does not guarantee to remove particles of the same size as the nominal pore rating. It is used only to give a comparison within the same manufacturer's range.

- **Absolute rating:** purports to provide some certainty (usually 100 percent or close to 100 percent) of removing particles of the size quoted. It is meant to represent the actual size of the pores of a filter. However, the material used in the testing may be different (for example, it may be more flexible) than the material being filtered. The test protocol needs to be checked before you can be sure of performance. Filters with an absolute rating are not usually ratified by an outside agency; the rating generally represents the manufacturer's own assessment.

The 'nominal' and 'absolute' ratings are irrelevant for cartridges used for protozoal removal. They vary so much that each filter must pass a challenge test, see Chapter 8: Protozoal Compliance, section 8.4.3.4 Cartridge filtration.

To remove protozoal (oo)cysts such as *Giardia* and *Cryptosporidium*, 3 microns absolute is required, testing to NZS4348 (1995) is required. This size will not remove clays or silts, so most dirty water will remain dirty. To reduce the turbidity due to silt, 0.5 microns absolute is normally needed. For clay turbidity, smaller sizes may be effective. In all cases, it will be necessary to try out different sizes to find the rating required for the material.

Filter cartridge types

How the layers are arranged within the filter will affect how many solids can be held before the cartridge becomes too blocked to pass the flow. Wound or low cost pleated cartridges usually achieve at least 3 log removals in testing; it is usually the design of the physical construction of the housing or its assembly that causes the problems.

- **Pleated cartridges** have a single sheet of filter membrane folded to and fro in a zigzag fashion. These are common in air filters for car motors. A further refinement of these is folded pleats, where the folds overlap each other, as if they were too big to fit up and down only. Pharmaceutical grade cartridge filters are often pleated, usually with a cage around them to make them rigid, ie, less susceptible to damage. Low-cost pleated cartridges can be damaged easily without it being obvious to the user.
- **Depth cartridges** have material of a coarser weave on the outside and finer inside. This allows smaller particles to penetrate further into the filter, allowing more solids to be held before blockage occurs.
- **Wound cartridges** have a continuous thread wound around a core to provide flow paths between the windings. They look a little like oversized bobbins of cotton, and are usually made from polypropylene. The earliest designs used a string material which was decomposed by micro-organisms in the water! Wound cartridges are now less common because they are susceptible to discharging when operating in the stop/start mode.

Filter material

Most cartridges now use polypropylene as the filter medium. Also used are glass fibre (bonded with a resin) and nylon. Various other compounds are also used, polyethersulphone is an example.

Filter housings

The key quality control issue is fitting the cartridges properly into their housings. Most seat on to knife-edge moulded end plates. It is very important to ensure that these are fitted properly into the ends of the cartridge elements, because a leak across this interface will break the whole filtration barrier. Always inspect the filter housing seal and the cartridge seal when changing a cartridge. It is very important to ensure that the cartridge is installed the right way up.

A pressure relief valve should be incorporated into the filter housing, and an automatic air release valve shall be installed on top of the filter housing.

Fitting the cartridge into the housing is covered by the requirements in Chapter 8 of the review draft LT2ESWTR Toolbox Guidance Manual (USEPA 2009) which discusses issues related to cartridge filtration, or the cyst/oocyst reduction conditions of NSF/ANSI 53, or Chapter 4 of EPA/NSF ETV (2002, updated 2005), or a standard formally recognised by the Ministry of Health as being equivalent.

Figure 14.3: Cutaway showing cartridge seal



Picture courtesy of Filtec Ltd.

This picture shows typical cartridge seals: Note there are knife edge seals at both the top and bottom of the cartridge.

Operating issues

- **Commissioning:** verifying the assembly of a certified cartridge filter when it has been installed should be performed by demonstrating that the operating parameters necessary to achieve the specified performance rating, which have been previously established by challenge testing, are being achieved on site. The procedure should be as specified by the supplier.

- **Start-up:** To allow the filtration process to settle down when starting up or restarting, it is strongly recommended to filter to waste for the first five minutes of the filter cycle. Record the initial headloss or pressure differential, and check that it lies within the manufacturer's specification. Note in a log book all relevant information that may help in training and trouble-shooting, especially the date that the new cartridge(s) is installed so that its length of service (preferably volume treated too) is recorded.
- **Pressure testing for leaks:** Correct installation of the cartridge needs to be demonstrated for each cartridge renewal. The most likely failure is a lack of proper seating, allowing flow to leak through the top or bottom seals. Another common cause for failure occurs when the cartridge bursts.

The way to demonstrate that the integrity of the unit has not been breached is to measure the pressure drop across it when operating at the maximum rate.

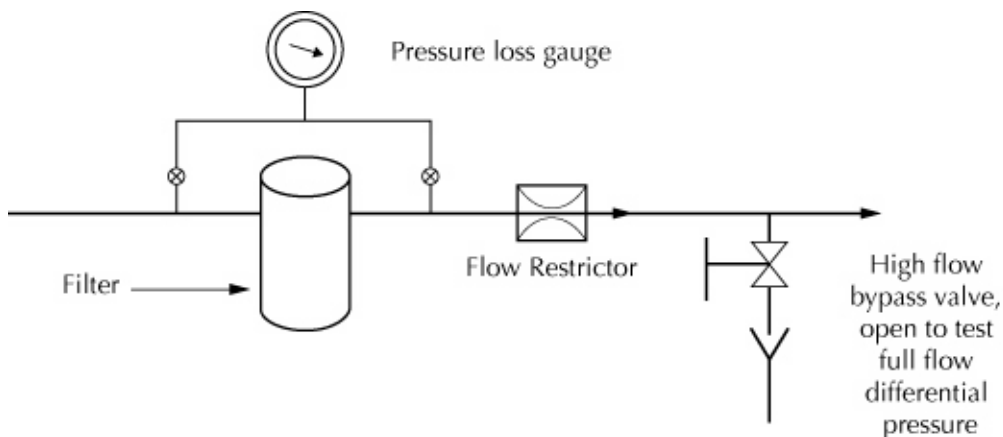
A major difficulty with this is the accuracy of the pressure gauge. Precise gauges are expensive, probably more expensive than the filter unit itself. A simple way to reduce costs is to arrange the pressure sample lines to feed back to the same gauge; this approach also allows the inaccuracy in the gauge to be cancelled out. See Figure 14.4.

The greater the number of cartridge filters in a housing, the more attention must be given to the pressure readings. One faulty cartridge could be passing (oo)cysts, but if it is one of several cartridges in the housing, its effect on the pressure drop may be slight.

The same gauge is used to measure both upstream and downstream pressures. After installation, the upstream pressure is measured by opening that valve and shutting the downstream valve. Then, with the flow unchanged, the downstream pressure is read. The pressure drop should not be greater than that advised by the cartridge supplier. If it is, there is probably a leak through one of the seals.

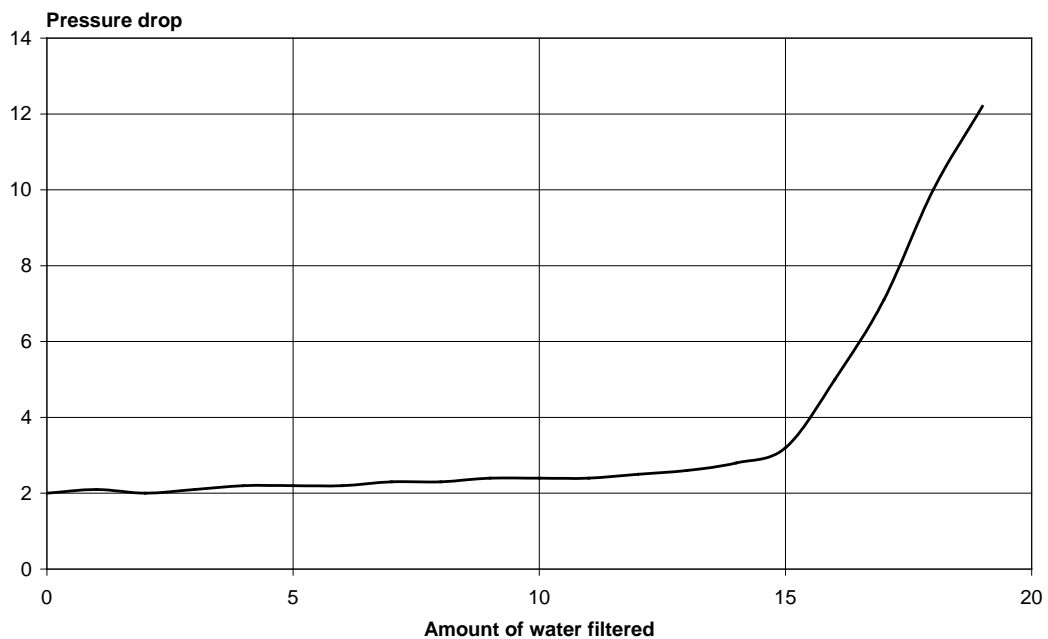
Record as much information on checking and general operation as possible in the log book.

Figure 14.4: Suggested arrangement for reading pressure differential across a cartridge filter



- **Pressure gauge recommendation**
 - Minimum size (4") 100 mm.
 - Accuracy 1 percent of readable scale, as per EN837.1 European standard.
 - Liquid-filled, this helps readability when vibrations are present.
 - Average cost \$150.
 - Maximum readability of 1 kPa cannot be met due to limitations on number of graduations that can be fitted into one 100 mm gauge.
- **Pressure testing for clogging:** If the clean cartridge pressure drop is recorded and the pressure drop is recorded during a filter run, the amount of clogging can be noted. The cartridge should be replaced when the pressure drop reaches or approaches the value advised by the cartridge supplier. Cartridge filters exhibit a knee shape curve of pressure drop over time; see Figure 14.5 (fictitious units). Cartridge filters do not load linearly; additional observation of the filter performance is required near the end of the filter run.

Figure 14.5: Typical pressure drop across a cartridge during a filter run



If a cartridge is not replaced at this point, the flow through it will be reduced. This may not be noticed at first if the flow is discharging into a tank or out through taps, because the change is not sudden or dramatic. Therefore, the pressure drop test should be repeated regularly, along with a simple flow test.

If the differential pressure is ever less than a previous reading, the cartridge must be assumed to have unloaded some of the trapped contaminants, and must be replaced, ie, the integrity of the filter has obviously failed.

- **Guarding against pressure changes:** Cartridges will release particles when bumped, by sudden pressure changes, or as a result of sudden changes in flow. For this reason, the valves connected to the filters should be of the slow opening/closing type such as screw-operated stopcocks, not bar-operated ball valves. Pumps cutting in and out will cause pressure surges so should not be connected directly to cartridges.

- **Flow control:** Cartridge filters must not be operated at flow rates above their stated design rate. If the installation is to meet the DWSNZ, flow control will be needed to limit flows above this. This may be an orifice or similar pressure-loss fitting, or the system may not be capable of excessive flows anyway. A simple flow test will demonstrate whether this is the case. Ideally, cartridge filters should be in continuous operation; restarting after a shutdown produces poorer quality filtrate for at least 30 minutes.

The filter plant should be designed to handle maximum day or maximum instantaneous flow. Prolonged operation at maximum flow clogs the filter faster than operating at lower flows. A minimum of two cartridge filter housings should be provided to ensure continuous water treatment in the event of failure in the filter operation and to allow for filter maintenance and replacement.

The flow through a cartridge filter should be as low as possible to lengthen filter run times and reduce surges. The filtrate should pass to a storage tank sized to cope with maximum demand, thus allowing the filter to operate at a near constant rate. On/off operation is not recommended; to avoid this, consider installing a recirculating pump that pumps treated water back to a point ahead of the cartridge filter. Care must be taken to make sure there is no cross-connection between the finished water and raw water.

- **Disinfection:** if the filter runs are very long, it will be advisable to check whether upstream chlorination is needed to prevent bacteria building up on, and subsequently sloughing off, the filter material and housing.

Monitoring

The compliance monitoring parameters for cartridge filtration are differential pressure, flow and turbidity. The tests and their frequency depend on the population served; see section 5.12 of the DWSNZ and Chapter 8 of the Guidelines.

Very fine particles in the raw water will pass through the cartridge filtration system. If these predominate, the turbidity of the filtered water could be almost the same as the raw water. If the turbidity of the filtered water is greater than the raw or feed water for more than a few minutes, it must be assumed that the cartridge is discharging (unloading) some of its accumulated contaminants, and therefore the operating conditions must be corrected immediately, or the cartridge replaced.

Should any operational requirement be exceeded, the operator should check whether:

- the operating pressure across any one housing exceeded the manufacturer's limit, generally not more than 1.0 Bar (15 psi) difference between inlet to outlet, in which case the filtering medium may have ruptured
- a pressure differential reduction may be the result of damage to or bypass around the seal
- the raw water quality (or prefilter performance) has deteriorated
- there have been any flow surges or sudden pressure changes that may have dislodged particles
- the seals are no longer seated correctly: this could be indicated by the pressure differential no longer increasing.

If the plant experiences turbidity problems following cartridge replacement, consideration should be given to incorporating a flush-to-waste step, five minutes is usually chosen.

14.6 Bag filtration

Bag filters comprise a disposable bag fitted into a filtered water receiver vessel or housing. They can be pressure or open (gravity) versions. They are much like cartridge filters in operation, in that they present a single barrier filter. However, unlike most cartridges, the flow path is from the inside of the bag to the outside.

Bag filters are commonly used in industry to remove dust from air. Care must be taken to use filter bags manufactured for liquid applications only.

A single filter unit comprises the filter medium, housing, and associated piping and valves.

The particulate loading capacity of bag filters is low. Unless the raw water is very clean, these systems usually incorporate some form of pretreatment to remove the bulk of the particulate matter and extend the filter life. A rule-of-thumb guide is that the water entering the filter should have a turbidity of <3 NTU. However, even at the finest mesh size available, bag filters will not remove colloidal colour or dissolved chemicals.

Some bag filters on the market are claimed to be able to be backwashed. This is not to be done because the washing process progressively dislodges fibres from the medium, ultimately allowing more and more particles to pass through. Once the particulate loading capacity has been reached the bag filter is to be discarded.

Bags manufactured from needle felt, made from polyester, polypropylene or nylon, are suitable for pretreatment applications only. The nominal mesh size is from 1,000 microns to less than 1 micron nominal. See section 14.5 for comments on nominal and absolute ratings. Bag filters manufactured from melt blown polymers offer higher efficiencies and test results should be provided to support the supplier's claim of efficiency.

Bag filters may receive up to 1 log credit in the DWSNZ for protozoa removal. See Chapter 8: Protozoa Compliance, section 8.4.3.3 for information about certification requirements. The amount of log credit is less than has been achieved under test conditions because, as with cartridges, the chance of poor fitting and sealing is quite high. Also, as with cartridges, there is usually no continuous direct integrity test (although some have been installed with a turbidity monitor) so this potential loss of quality control has to be allowed for. Refer also to Chapter 8 of the review draft LT2ESWTR Toolbox Guidance Manual (USEPA 2009) which discusses issues related to bag filtration.

Bag filters are relatively common in industrial applications and have been used in some small water treatment plants, but are not common for larger towns. As at 2005 they are in use at Carterton, Pukekohe, and have been trialled at Okato (in Taranaki). The former sites are apparently operating reasonably well; the latter was not successful. Some trials fail due to a heavy load in the 3–10 micron range and low working head, resulting in reduced filter run times.

Operating issues

Integrity and monitoring issues are the same as for cartridges (see section 14.5), and the following issues for cartridges apply also to bags.

- Filter cycling (starting and stopping of the pump or filter operation) can be problematic with bag filtration where the water is pumped directly from the source to the filter, and then out to the distribution system. In these situations, the filters operate on demand and the sudden increase in pressure across the filter causes premature wear and filter failure. Supplies using bag filters should consider the following recommendations for controlling the flow into the filter process to minimise filter cycling:
 - lengthen the filter runs by reducing the flow rate as much as possible through the filter
 - install or divert the flow to a storage facility (eg, pressure or storage tank) after the bag filtration process. The stored water can supply the frequent surges in demand and thus reduce the bag filter cycling
 - until a bag is replaced, the flow through it gradually reduces. This change is not sudden or dramatic; sudden changes indicate rupture or discharge of particles
 - the supplier sets the allowable pressure drop across the bag. If higher pressure drops are set up, the bag may rupture, creating a gap in the filtration barrier. Bag filters do not load linearly; additional observation of the filter performance is required near the end of the filter run
 - bags will release particles when bumped by sudden pressure changes due to sudden flow changes. Therefore, valves connected to the bags should be the slow opening/closing type. Pumps will cause pressure surges and should not be connected directly to bags. A pressure relief valve should be incorporated into the bag filter housing, and an automatic air release valve shall be installed on top of the filter housing
 - if the installation is to comply with the DWSNZ protozoa criteria, flow control is needed in order to limit high flows. This may be an orifice or similar pressure-loss fitting, or the system may not be capable of excessive flows anyway. Bag filters must not be operated at flow rates above their stated design rate. A simple flow test will demonstrate whether this is the case
 - to allow the filtration process to settle down when starting up, it is strongly recommended to filter to waste for the first five minutes of the filter cycle
 - ideally, bag filters should be in continuous operation; restarting after a shutdown produces poorer quality filtrate for at least 30 minutes.
- Very fine particles in the raw water will pass through the bag filter. If these predominate, the turbidity of the filtered water could be almost the same as the raw water. If the turbidity of the filtered water is greater than the raw or feed water for more than a few minutes, it must be assumed that the bag is discharging some of its accumulated contaminants, and therefore the operating conditions must be corrected immediately, or the bag replaced.

- The USEPA (2003d) found that different bags, even with the same stock and lot numbers, could exhibit a wide range of water treatment capacity. Some bags may treat many thousands of gallons of water while others may treat only a few hundred. Pore size gives only a general indication of a bag's capability. Common faults are related to rupture of the seams; gaps in heat welded bags; gasket integrity; and bypass, usually near the lid, typically shown by significant discolouration of the bag. Once a bag begins to foul at 5 to 10 psi differential, the time until the bag must be replaced quickly approaches; bag rupture is more likely near the end of the filter run.

Monitoring

The compliance monitoring parameters for bag filtration are differential pressure, flow and turbidity, see section 14.5 for details. The tests and their frequency depend on the population served; see section 5.13 of the DWSNZ.

Should any operational requirement be exceeded, the operator should check whether:

- the operating pressure across any one housing exceeded the manufacturer's limit, in which case the filtering medium may be approaching rupture
- a pressure differential reduction may be the result of a rupture or bypass
- the raw water quality has deteriorated
- there have been any flow surges or sudden pressure changes that may have dislodged particles
- the seals are no longer seated correctly: this could be indicated by the pressure differential no longer increasing.

14.7 Adsorption processes

14.7.1 Activated alumina

Activated alumina based products have been used historically for the reduction of fluoride, arsenic and selenium. Point-of-use (POU) products using such media have been developed since the USEPA indicated acceptability of POU treatment as an alternative for small communities. Several types of media including unmodified activated alumina, manganese modified or iron modified alumina, and iron based granules are being investigated for use in a manner similar to granular activated carbon (GAC), packed into columns and inserted into housings. Some of these products are being tested for arsenic (V) reduction from 0.05 mg/L per the protocols recently incorporated into NSF/ANSI Standard 53 – Drinking water treatment units – Health effects.

A recent report (NSF 2005) describes the reduction of arsenic (V) from 0.025 mg/L to less than 0.002 mg/L using an activated alumina point-of-use treatment system. The unit shut down automatically after processing 800 gallons. The study found that the cost of POU treatment was less than the cost of operating a central treatment plant. The spent cartridges from the trial were tested for disposal safety according to the California Waste Extraction Test (WET) and EPA Toxicity Characteristics Leaching Procedure (TCLP) test. They passed both tests, indicating that disposal in the household refuse would be acceptable. Currently, there are 20 different products shown as certified for this capability on the NSF website.

While activated alumina primarily removes fluoride and As V (arsenate) and performs better at a lower pH (best between 5.6 and 6), iron-based media generally are more effective at removing both arsenic (III) (arsenite) and arsenic (V), although oxidation of arsenite to arsenate prior to filtration can increase its removal efficiency, depending on pH. In addition, activated alumina is more likely to experience interference affecting arsenic removal from competing ions such as silica, fluoride, phosphate, and sulphate than iron-based media. As with most column treatment systems, the granules can support the growth of micro-organisms. It has been reported that the bacteria can reduce arsenate to arsenite, thereby reducing the efficacy of the activated alumina.

Note that RO devices are certified under NSF/ANSI Standard 58 only for arsenate removal (USEPA 2006).

In New Zealand, geothermal or hydrothermal waters are the most likely to contain excessive fluoride levels; these waters usually contain high silica concentrations too. Arsenic V and silica are preferentially adsorbed by activated alumina media, so fluoride removal may not be very efficient. Fluoride removal is covered in USEPA (1984).

See Chapter 19: Small, Individual and Roof Water Supplies, section 19.3.4, for further discussion on point-of-use and point-of-entry treatment systems.

See USEPA (2003c) for a full discussion on arsenic removal technologies.

14.7.2 Solid block activated carbon (SBAC) filters

All types of carbon filters effect the removal of organic substances by adsorption on to the carbon surface. The filter in this device consists of extremely small particles of activated carbon that are fused together into a solid block with uniform pore size. If the carbon block configuration is constructed properly, the pore size may be uniformly 0.5 micrometre (μm or microns), which would be effective at removing asbestos fibres, protozoal (oo)cysts, and some bacteria. SBAC filters are less prone than GAC filters to channelling and can also be effective at removing organic contaminants such as some pesticides and chlorinated solvents. In addition, some SBAC devices are certified by NSF International for removal of methyl tert-butyl ether and selected disinfection by-products (DBPs) such as total trihalogenated methanes. They can also remove chlorine and can be formulated to remove metals such as mercury and lead.

With regard to limitations, SBAC filters typically will not remove most heavy metals, viruses, small bacteria, arsenic, fluoride, iron, or nitrate. These filters also tend to harbour bacteria that grow on trapped organic matter, and the bacteria can migrate from the filter to the water at a later time.

Most manufacturers recommend that the filters be replaced about every six months, even though the adsorptive capacity may not yet be totally exhausted. However, replacement may be required sooner depending on the quality of the incoming water and the amount of usage (USEPA 2006).

14.7.3 Granular activated carbon (GAC) filters

GAC is extremely porous and can have a surface area of about 1,000 square metres per gram. Many organic compounds, such as chlorinated and non-chlorinated solvents, naturally occurring organic matter, some gasoline components, and trihalomethanes, can be adsorbed on to the GAC surface. However, for some pesticides, such as atrazine and alachlor, GAC has a very low adsorptive ability.

This material is also effective for removal of chlorine and moderately effective for removal of some heavy metals and metals that are bound to organic molecules. Activated carbon processes show promise for removal of biotoxins and other potential organic contaminants of concern.

Regardless of the design, GAC filters are subject to clogging and, like all types of activated carbon filters, provide an environment for bacterial growth (see BAC below) which may present problems. Backwashing can improve long-term effectiveness for removal of organic compounds and provide some control of bacterial growth, but it does not improve radon removal efficiency. ANSI/AWWA (2012) has a Standard (B604-12) for GAC, and B605-13 covers its reactivation.

GAC is not effective at removing fluoride, chloride, nitrate, hardness, or most metal ions, and is not recommended at the point-of-use for removal of radon or VOCs. GAC is not as effective as SBAC, especially with regard to removal of chlorine, taste-causing substances, or halogenated organic compounds (USEPA 2006).

See Chapter 19: Small, Individual and Roof Water Supplies, section 19.3.4, and Chapter 18: Aesthetic Considerations, section 18.3 (under the heading of Taste and Odour), for further discussion on activated carbon treatment systems.

14.7.4 Biologically active filters (BAC)

These are normally granular active carbon filters (GAC) where the bacteria (and some other micro-organisms) are actually encouraged to develop on the granules. The carbon filter also removes some substances by adsorption. BAC filters develop layers of microbes, along with their associated exopolymers, on the surface of or within the granular medium matrix. This biologically active layer, called the *schmutzdecke* in conventional slow sand filters, retains microbes and often leads to their inactivation

and biodegradation. These microbes can also degrade natural organic matter and industrial organic chemicals. Ozone can be effective in partially oxidising organics in the water to biodegradable compounds that can be removed more readily by biological filtration. This increase in the biodegradable fraction of organic carbon occurs as a result of moderate to high levels of ozonation. These ozone levels are typical of the doses commonly applied for disinfection. But ozone may add undesirable compounds such as formaldehyde, NDMA and bromate.

WRF (2016) reported the results of an extensive study on the use of chemically enhanced biological filtration, defined as use of oxidants other than ozone, for increasing biological filtration effectiveness and decreasing disinfection by-product (DBP) formation potential. They trialled nutrient augmentation and a range of potassium permanganate dosages.

Upon start-up, an acclimation period ranging from weeks to months may be necessary for some contaminants. In general, biofiltration is more effective at temperatures greater than 15°C, dissolved oxygen levels greater than 3 mg/L, and within a pH range of 6-9. Increasing empty bed contact time (EBCT) beyond 10 minutes results in marginal improvement for contaminant removal by biofiltration, especially at temperatures greater than 15°C. However, at temperatures below 15°C, greater removal may be obtained with EBCTs longer than 10 minutes.

Adsorption processes are discussed in Chapters 9 and 13 of AWWA (1990). ANSI/AWWA B130-13 covers membrane bioreactor systems. Chapter 3 of USEPA (2004) is the Environmental Technology Verification (ETV) Technology Specific Test Plan for evaluation of drinking water treatment equipment utilising fixed bed adsorptive media for volatile organic chemical (VOC) removal.

14.8 Desalination

Desalination has been included in this section because at least some of the process can include membrane (reverse osmosis or RO) treatment. Distillation can also be used. Chapter 2 of WHO (2005) is titled *Desalination Guidelines Development for Drinking Water*. Chapter 12 is titled *Health Risks from Drinking Demineralised Water*. WHO (2011a) updates these and discusses related safety plans (WSPs).

WHO (2007) states that more than 12,000 desalination plants are in operation throughout the world producing about 40 million m³ of water per day. The number is growing rapidly as the need for fresh water supplies grows more acute and technologies improve and unit costs are reduced. As at 2010, desalinated water provides about 20 percent of Israel's drinking water supply, and major expansions to cope with rising demand are predicted to increase this proportion to around 50 percent by 2020 (taken from WQRA (2011)).

Desalination plants use waters impaired with salts (seawater or brackish water) or other contaminants as their sources. About 50 percent of the capacity exists in the West Asia Gulf region. North America has about 17 percent, Asia apart from the Gulf about 10 percent and North Africa and Europe account for about 8 percent and 7 percent respectively, and Australia a bit over 1 percent.

The principal distillation systems include Multistage Flash (MSF) distillation, Multi-effect Distillation (MED) and Vapour Compression Distillation (VCD). Distillation plants can produce water in the range of 1 to 50 mg/L TDS. As a comparison, RO processes can produce water in the range of 10 to 500 mg/L TDS.

Common membranes are polymeric materials such as cellulose triacetate or more likely polyamides and polysulfones. Membranes are typically layered or thin film composites. The surface contact layer (rejection layer) is adhered to a porous support, which can be produced from the same material as the surface.

In electro dialysis-based treatment systems a direct current is passed through the water, which drives the ions (not the water) through membranes to electrodes of opposite charge. In electro dialysis reversal systems, the polarity of the electrodes is reversed periodically during the treatment process. Ion-transfer (perm-selective) anion and cation membranes separate the ions in the source water. Electro dialysis reversal systems do not provide any barrier against pathogens, and electro dialysis reversal is, therefore, rarely considered to serve as the main treatment barrier for drinking-water production.

Desalinated water is stabilised by adding lime and other chemicals, and/or by blending with other water, both to offer a balanced mineral content and to reduce corrosion effects.

Most of the inorganic components will be significantly removed in the desalination process, either thermal or RO, although some sodium chloride and bromide may be present in the treated water from membrane plants and possibly from some older distillation plants. In terms of key contaminants of direct interest for health and environment, the most important is probably boron, which can be of significance in reverse osmosis plants since the rejection ratio of boron (probably mostly as borate) is less than that for most other inorganic determinands. Bromide is initially present in seawater in relatively large amounts (~70 to 80 mg/L), so even high (eg, >95 percent) percentage removals will allow some bromide of the order of 1 to several mg/L to be present in the finished water.

RO has been shown to remove bacteria and larger pathogens and, depending on the membrane applied, to remove all or a large fraction of viruses. High-quality RO processes are good treatment barriers to pathogens if properly selected and maintained.

Most vegetative pathogens are inactivated under flash pasteurisation conditions (temperature of 72°C for 15 seconds). The condensate is unlikely to contain pathogens after the distillation process because of the killing impact of heat and because pathogens are unlikely to be entrained. However, reduced pressures are used in some desalination processes to reduce the boiling point and reduce energy demand. Temperatures as low as 50°C may be used which might not achieve the required inactivation targets. Inactivation levels expected at temperatures typical of distillation processes are considered sufficient to inactivate most pathogens since they are equivalent or in excess to those used for pasteurisation.

Chlorine in various forms (sodium hypochlorite, chlorine gas) is generally used for disinfection because of its recognised efficiency as a disinfectant and because of the reduced level of disinfection by-product precursors. Protozoa have generally been removed in the desalination process.

Desalinated water is initially more corrosive than many other drinking-water sources, and it is important that the water be stabilised to minimise its corrosive effect on pipes and fittings used in distribution and plumbing systems in buildings, and/or that the materials used in contact with the water be selected with care. The Israeli Ministry of Health has announced that it intends to require water providers to supplement desalinated water with magnesium in order to prevent the potential adverse effects of magnesium deficiency (taken from WQRA 2011). See Spungen et al (2013) for a discussion on health issues related to drinking desalinated water without supplementary calcium and magnesium.

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