Membrane bioreactor

Validation protocol
About Australian WaterSecure Innovations Ltd

Australian WaterSecure Innovations Ltd (trading as WaterSecure) was established in 2016 to oversee the implementation of national research outcomes, including the WaterVal™ program, one of the flagship outcomes developed by the Australian Water Recycling Centre of Excellence (the Centre), an independent research organisation established in 2009 by Commonwealth funding.

About WaterVal™

WaterVal™ is a framework that provides national consistency in the validation of water treatment technologies for the water industry. The framework, jointly developed by the Centre, regulators, water utilities, researchers and the private sector, is underpinned by protocols and agreed methods to validate pathogen removal by treatment technologies. The framework and protocols are applicable to a broad range of water sources, and give effect to key objectives of the Australian guidelines for water recycling and the Australian drinking water guidelines.

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1. Background and scope

Membrane bioreactors (MBRs) combine biological treatment (activated sludge) and membrane filtration, such as microfiltration or ultrafiltration, to reduce the concentration of pathogens in wastewater. A number of influencing factors contribute to the efficiency of the system, resulting in a complex validation approach.

This protocol has been prepared as part of WaterVal to provide guidance for the validation of MBRs. It proposes a tiered approach that allows for a simplified process where conservative log reduction values (LRVs) are claimed, as follows:

- **Tier 1** – adopting predefined, conservative LRVs based on the statistical analysis of historical MBR performance data and associated operating conditions.
- **Tier 2** – conducting challenge testing under the most conservative operating conditions expected for the specific system being validated to determine the minimum expected LRV, and implementing regular testing of target pathogens or surrogates.

Tier 1 or tier 2 approaches are not considered to strictly meet validation objectives as defined under the *Australian guidelines for water recycling (Phase 1)* (NRMMC et al. 2006); however, in the absence of a more appropriate validation method, these two approaches are recommended to allow implementation of MBR technologies while managing the public health risk. In addition, a proposed tier 3 approach is described in Appendix A which is more closely aligned with the definition of validation. Under this approach an investigation is undertaken incorporating challenge testing to demonstrate the correlation between online parameter(s) and the pathogen removal performance of the MBR. This allows critical limits to be established that are specific to the LRVs claimed. Until it can be further tested, this new method remains hypothetical and does not form part of the validation protocol.

Microfiltration and ultrafiltration membrane systems can be validated through use of direct integrity testing (DIT), also known as pressure decay testing. Although MBRs use microfiltration or ultrafiltration membranes, most MBR systems are not equipped for DIT. If DIT is available, the MBR may be validated as a microfiltration or ultrafiltration system according to validation protocols for direct membrane filtration. Detailed guidance for undertaking direct integrity tests is given in the *Membrane filtration guidance manual* (US EPA 2005). This validation protocol details the approach for validating MBRs without using DIT.

This document is consistent with the WaterVal validation *Protocol template* (AWRCE 2015), which provides a recommended approach to validation that is based on nine elements:

- identification of the mechanisms of pathogen removal by the treatment process unit
- identification of target pathogens and/or surrogates that are the subject of the validation study
- identification of factors that affect the efficacy of the treatment process unit in reducing the target pathogen
- identification of operational monitoring parameters that can be measured continually and are related to the reduction of the target pathogen
- identification of the validation method to demonstrate the capability of the treatment process unit
- description of a method to collect and analyse data to formulate evidence-based conclusions
- description of a method to determine the critical limits, as well as an operational monitoring and control strategy
- description of a method to determine the LRV for each pathogen group in each specific treatment process unit performing within defined critical limits
- provision of a means for revalidation or additional onsite validation where proposed modifications are inconsistent with the previous validation test conditions.

This protocol focuses on the validation of LRVs for microbiological pathogens and does not include validation of chemical removal.
2. Identification of pathogen removal mechanisms

No single mechanism is responsible for reduction of pathogens through an MBR. Depending on the target pathogen, a combination of size exclusion, adsorption and biodegradation will be responsible for inactivating or removing pathogens.

Previous studies have indicated the importance of the fouling layer and entrainment in sludge flocs in helping to remove viruses (0.01–0.1 µm), which are smaller than the typical membrane pore size (0.04–0.4 µm) in MBRs (Hai et al. 2014). Protozoa and bacteria, typically larger than the membrane pores, are removed mainly by size exclusion, regardless of the level of fouling. The relative contribution of each of the removal mechanisms to the overall LRV is known to be pathogen or indicator specific.

2.1. Physical removal

2.1.1. Size exclusion

Size exclusion is the main way that organisms bigger than the nominal pore size of the membrane are removed. Microfiltration and ultrafiltration remove suspended or colloidal particles via a sieving mechanism, based on the size of the membrane pores relative to that of the particulate matter (US EPA 2005). Bacteria (e.g. Escherichia coli) are between 0.5 and 10 µm, whereas viruses (e.g. enterovirus and adenovirus) are typically 0.01–0.1 µm (Antony et al. 2011). Ultrafiltration and microfiltration membranes have pore sizes of 0.002–0.05 µm and > 0.05 µm, respectively (Judd 2011). An overview of pathogen sizes and the pore size of different membrane categories is provided in Figure 1.

![Figure 1 Pathogen size and membrane pore size summary](image_url)

MCF = membrane cartridge filtration; MF = microfiltration; NF = nanofiltration; RO = reverse osmosis; UF = ultrafiltration
Source: US EPA (2005)

2.1.2. Adsorption to membrane

Adsorption of pathogens to the membrane, the cake layer or the biofilm has been cited as a contributing mechanism to explain rejection of pathogens, such as viruses (Ottoson et al. 2006, Shang et al. 2005, Sima et al. 2011, Ueda & Horan 2000). Adsorption is not permanent and desorption can occur; additionally, once all potential adsorption sites are saturated, no further adsorption is expected.

Given that appropriate time is allowed for its formation, biofilm may be responsible for increased virus rejection. In a study looking at a full scale MBR, permeate norovirus concentrations varied sporadically and did
not correspond with changes in influent and mixed liquor suspended solids (MLSS) concentrations. A reversible biofilm, that could be periodically disturbed, was proposed to explain this phenomenon (Sima et al. 2011).

2.1.3. Adsorption to biomass

The suspended solids component within the activated sludge is another source of sites for adsorption of pathogens. In contrast to adsorption to the membrane, adsorption to MLSS is less reversible. To control solids retention time (SRT), biomass is wasted at a constant rate, while new biomass grows; any pathogens adsorbed to the MLSS are removed as excess sludge, potentially before desorption can occur.

Adsorption of pathogenic viruses smaller than the pore size to MLSS permits rejection by the membrane and removal via the waste-activated sludge.

It is unclear if infectivity is reduced via adsorption. For more biologically resistant microorganisms, adsorption may be more significant than biological predation.

2.2. Biological predation

In activated sludge, biological predation of pathogens by larger protozoa and metazoans is a removal mechanism. In a study of conventional activated sludge, the dominant removal mechanism of bacteria was by predation and the dominant removal mechanism of protozoa was by adsorption to biomass (Wen et al. 2009).

The activated sludge component of MBRs is likely to display a similar behaviour. An LRV of 0.75 was observed for bacteriophages in conventional activated sludge (Rose et al. 1996), and at a laboratory scale a LRV of 0.8 for MS2 bacteriophage was associated with the biomass of an MBR (Shang et al. 2005). During a T4 coliphage spiking experiment, less T4 was detected in the biomass of a laboratory-scale MBR with zero sludge wastage, and it was suggested that a mixture of predation and adsorption to the membrane gel layer was responsible (Lv et al. 2006). Unfortunately, the relative effect of biological predation versus adsorption to biomass was not quantifiable.

Cryptosporidium and Giardia have been shown to accumulate in the activated sludge compartment at about 1-log for a full-scale MBR (Pettigrew et al. 2010).

In the case of viruses, the significance of biological predation as a reduction mechanism is pathogen specific. Adenovirus and enterovirus concentrations in the activated sludge of MBRs were observed to be higher than in influent wastewater by approximately 2-log, indicating limited biological degradation of these viruses (Kuo et al. 2010, Simmons et al. 2011). Conversely, the norovirus GII concentrations were 1 log lower in mixed liquor than in the influent, indicating possible biological degradation (Simmons et al. 2011).
3. Identification of target pathogens and surrogates

The target pathogen is the pathogen that is the subject of the validation study and is the most resistant to the treatment process. Generally, a target pathogen should be selected from each pathogen group.

Direct measurement of pathogenic microorganisms in wastewater is often not feasible because of low and highly variable concentrations, and complex analysis procedures (Antony et al. 2011). As a result, indicator organisms are often chosen as surrogates for pathogens. A suitable indicator organism should display correlated or more conservative removal than the target pathogen (Victorian Department of Health 2013).

Target pathogens and surrogate microorganisms recommended for MBRs are summarised in Table 1 and are discussed further in the following sections.

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Target pathogen</th>
<th>Surrogate microorganism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viruses</td>
<td>Enteroviruses</td>
<td>Somatic coliphages and F-specific RNA bacteriophages</td>
</tr>
<tr>
<td>Bacteria</td>
<td>Campylobacter</td>
<td>Escherichia coli</td>
</tr>
<tr>
<td>Protozoa</td>
<td>Cryptosporidium parvum</td>
<td>Clostridium perfringens</td>
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3.1. Viruses

MBR is based on the combination of biological treatment and membrane filtration and the selection of target pathogens or surrogate microorganisms should be conservative and take into account both processes.


FRNA bacteriophages were selected as indicators of virus removal performance because of their small size and low isoelectric point (IEP) of 3.9 (Michen et al. 2010). With a diameter of 0.025 μm (Antony et al. 2012), it was a challenge to remove MS2 bacteriophage via size exclusion by the membrane (pore diameter generally larger than 0.04 μm) and it was chosen to model the behaviour of similarly sized enteroviruses present in wastewater. The low IEP relative to the typical operating pH of MBR (7–8) (Michen et al. 2010, Judd 2011) reduced the likelihood of adsorption of FRNA bacteriophages to the membrane, since the virus particles carry a net negative charge (Antony et al. 2012). Indigenous somatic coliphages can vary in size from 0.027 to 0.2 μm, which overlaps significantly with the MBR pore size range of 0.04 to 0.4 μm; consequently, somatic coliphages are less conservative indicators than FRNA bacteriophages for the membrane filtration component.

When comparing removals of virus surrogates across MBRs, somatic coliphages demonstrated higher resistance than FRNA bacteriophages. The higher resistance of somatic coliphages to MBR treatment seems to be linked to the fact that it is poorly deactivated by the activated sludge. As a result, higher densities of somatic coliphages reach the membrane surface, increasing the likelihood of passage into the permeate. For FRNA bacteriophages, log reductions of up to 2.1-log have been shown within the activated sludge before reaching the membrane, making passage across the membrane and detection in permeate unlikely, given already low influent concentrations. Consequently, somatic coliphages are more conservative indicators than FRNA bacteriophages for the activated sludge component.

While both somatic coliphages and FRNA bacteriophages present limitations as virus surrogates, given their well-documented previous use and conservative nature as surrogates, both should be used to validate a MBR.
3.2. Bacteria

*Escherichia coli* is recommended as the surrogate microorganism because of its extensive historical use as an indicator of faecal contamination and as a challenge organism for membrane systems.

While it can be assumed that treatment processes that are validated for protozoa and virus removal will also satisfy reduction requirements for bacterial pathogens, monitoring a bacterial indicator such as *E. coli* is recommended to provide a complete picture of reduction of the three pathogen groups.

3.3. Protozoa

*Clostridium perfringens* is recommended as a surrogate for protozoa. The diameter of *C. perfringens* spores ranges from 0.6 to 1.0 μm (Orsburn et al. 2008) and their relatively small size compared with protozoa (5–10 μm) (Antony et al. 2011) supports their use as a conservative indicator in membrane challenge testing. *C. perfringens* has been used as a challenge organism to represent protozoan removal in previous MBR studies (Marti et al. 2011, Ottoson et al. 2006, Van den Akker et al. 2014).
4. Influencing factors

The principal factors that influence MBR treatment efficiency can be identified, based on the mechanisms of pathogen removal. Typically, factors that can influence the biological treatment (predation or adsorption) or the filtration step include temperature, hydraulic retention time (HRT), SRT, MLSS, membrane fouling and cleaning, membrane ageing and integrity failures.

In contrast, the membrane pore size (between 0.04 and 0.4 μm) does not appear to impact virus rejection significantly under steady state conditions (Branch & Le-Clech 2015). In addition, both the zeta potential and hydrodynamic radii of viral indicators T4 coliphage and MS2 bacteriophage are affected by pH (Arkhangelsky et al. 2007). Extreme pH changes may affect particle-to-particle and particle-to-sludge adsorption, and a decrease in pH below the pathogen IEP of around 3–5 may improve rejection. However, these extreme conditions do not fall within the typical operating envelope of MBRs (pH 6–8). Although temperature is expected to affect pathogen removal by activated sludge, a previous study showed that temperature variations between 16 °C and 30 °C did not significantly impact overall LRVs (Branch & Le-Clech 2015).

4.1. SRT and MLSS

High concentrations of MLSS is assumed to result in a greater level of deposition on the membrane and consequently higher rejection. It has been suggested that the amount and composition of extracellular polymeric substances are more likely related to the formation of the biofilm and that occurrence of these substances was dependent on the food to microorganism ratio (F/M ratio) (Shang et al. 2005). In a system with constant feed concentration, increase in MLSS results in a reduced F/M ratio. For smaller organisms, a higher MLSS may present more adsorption sites. An increase in MLSS is therefore expected to result in higher removal due to 1) an increased rate of biological predation, 2) increased fouling (physical deposition and biofilm) and 3) an increase in adsorption sites for small organisms such as viruses.

A longer SRT is expected to result in greater accumulation of organisms (rejected by size exclusion and resistant to biodegradation) and therefore to a higher concentration challenging the membrane.

4.2. Hydraulic retention time

Although the effectiveness of biological predation is expected to be microorganism specific, processes involved in this removal mechanism are generally time dependent, and a longer HRT is expected to lead to an increase in the removal of pathogens by the activated sludge component.

4.3. Fouling

Fouling can be defined as ‘the inevitable coverage of the membrane surface (external and internal) by deposits which adsorb or accumulate during operation (Drews 2010). This complex phenomenon can be characterised by a sequence of different stages, occurring in MBRs at various rates and timescales.

The different stages of fouling can be defined according to the cleaning strategy necessary to remove the corresponding fouling phenomena as follows:

- Reversible fouling (cake filtration) occurs within 10 minutes of MBR operation, with an indicative associated transmembrane pressure (TMP) increase of 0.01–0.1 kPa/min. Reversible fouling refers to fouling that can be removed by physical means such as backflushing, aeration or relaxation.
- Residual fouling occurs within 1–2 weeks of operation at an indicative rate of 0.001–0.01 kPa/min, and requires maintenance cleans, such as hosing or chemically assisted backwash (Brepols et al. 2008).
• Irreversible fouling is defined as fouling requiring ‘main cleans’ which may include removing membranes and soaking them in cleaning solution.

• Finally, the term irreversible fouling is used to describe the long-term membrane permeability loss that cannot be recovered; it corresponds to an indicative fouling rate of 0.00001–0.0001 kPa/min and a timeframe of more than one year (Drews 2010).

Increased rejection of viruses due to formation of a biofilm is plausible, but the biofilm takes time to form. Initial change in rejection may be as a result of the more rapid formation of the reversible cake layer. Adsorption to biofilm and cake filtration are expected to enhance pathogen rejection when the pathogen is smaller than the membrane pore size. Furthermore, the cake fouling layer may shield integrity defects larger than the nominal membrane pore size.

4.4. Membrane cleaning

MBR cleaning practices can affect pathogen filtration by removing the fouling layer and altering the intrinsic properties of the membrane. Polymeric components of membranes can degrade after exposure to cleaning chemicals (Arkhangelskys et al. 2007). Chlorine exposure can reduce the weld strength of the membrane/module connection, which is widely accepted as one of the weakest integrity points of MBR membrane modules (Judd 2011). Ayala et al. (2011) noted a higher likelihood of integrity failure following dosing with sodium hypochlorite, which resulted in a lower welding strength.

After long-term operation, cleaning chemicals used to clean the membrane are expected to alter the properties of membrane material and may increase the likelihood of integrity failure due to embrittlement of module materials and interfaces. However, this effect on treatment performance has not been quantified in full-scale systems.

4.5. Membrane ageing

Membrane life estimates have ultimately been based on integrity failure, loss of mechanical strength or production decline. Limited scientific literature is available on long-term trends in MBR pathogen removal performance. Membrane and MBR suppliers offer specific lifetime guarantees of three to eight years (Le-Clech 2010). Based on a rigorous assessment of North American sales data for MBRs with a specific type of membrane and the classification of the type of sale (replacement or new), an empirical model yielded a membrane/module life of eight years (Cote et al. 2012). It was also stated that most failures were attributed to early generation module issues, which were no longer observed with the later generation; hence, the eight-year estimate was probably conservative (Cote et al. 2012). Through extrapolation of permeability (i.e. production capacity) decline to an unacceptable level, a lifetime estimate of 8 to 10 years was made.

The pathogen removal performance of ageing systems has been assessed over 10 years (Nishimori et al. 2010), and average LRVs for faecal coliforms and FRNA bacteriophages were reported above 5 and 4, respectively. In a system that had been operating for five years, LRVs of 5–7 and 4–6 were reported for E. coli and FRNA bacteriophages, respectively (Pettigrew et al. 2010).

4.6. Membrane and module integrity failures

Integrity failures of modules or of the membranes themselves can lead to a breach of containment of the activated sludge and a reduction in pathogen removal.

Membranes can exhibit manufacturing defects, but solid particles and foreign bodies within the bioreactor can also breach or damage membranes. Inappropriately high dosing of cleaning chemicals and pressure shock (associated with integrity testing or pump start-up) are expected to increase the likelihood of membrane integrity failure (Beauchamp et al. 2010). Integrity failure can be induced by high-pressure hosing during maintenance cleans (Le-Clech et al. 2005).
Failure of the module integrity results in short circuiting of membranes by constituents present in the mixed liquor. Module weak points include seal couplings and the membrane frame/pot interface. The likelihood of failure is increased with poor seal quality or an inappropriate replacement regime. Coupling failure of MBR cassettes has been attributed to the strong mechanical forces in the module header associated with air-cycling fouling mitigation systems (Van Betem et al. 2007).
5. Operational monitoring parameters

Operational monitoring parameters are used to measure the performance of the treatment process unit, and relate to the reduction performance of the target pathogen (treatment efficacy). Continuous monitoring of operational parameters provides assurance that the system is under control and indicates when treatment efficacy is reduced to an unacceptable level.

In theory, every factor that may affect the efficacy of the treatment process should have an associated operational monitoring parameter. However, in practice, it is often possible to select a few key operational monitoring parameters that effectively demonstrate efficacy.

In ideal situations, it would be possible to continuously monitor a surrogate in permeate and to correlate the concentration of the surrogate to the pathogen removal performance of the MBR. This validation protocol provides guidance on the type of surrogates that may be considered; however, based on the existing scientific literature, no generic surrogate can be recommended. Also, because of the complex mechanisms involved in pathogen removal by MBR, no single operating parameter that would demonstrate the removal performance in real time can be identified. Operational monitoring should target both confirmation of membrane integrity and activated sludge treatment performance. Different multivariate methods can be applied to identify a set of operational monitoring parameters that can be related to treatment performance, including artificial neural networks, Bayesian belief networks and principal component analysis. Branch & Le-Clech (2015) used Bayesian belief networks to identify the key operating parameters described in this protocol.

LRVs achieved by membrane filtration alone are typically two to five times higher than those achieved by activated sludge (Van den Akker et al. 2014). As a result, priority should be given to monitoring membrane integrity over bioreactor performance.

DIT cannot be considered as an online monitoring technique because it is only applicable to certain configurations of MBR, and, as such, is not considered in this guidance document. When DIT is applicable, the MBR filtration component can be validated according to validation protocols for direct membrane filtration. Detailed guidance for undertaking direct integrity tests is given in the Membrane filtration guidance manual (US EPA 2005).

5.1. Continuous indirect integrity monitoring

Continuous indirect integrity testing is based on measuring water quality parameters such as turbidity or particle count as a surrogate measure of membrane integrity. It relies on the assumption that compromised membrane integrity will result in an excursion from defined limits. These limits are used as a general indication of the presence of an integrity breach to the system, rather than as a definitive measure of performance (Victorian Department of Health 2013).

The sensitivity of continuous indirect integrity monitoring to breaches is a key factor to consider. Turbidity may not be sensitive enough to detect noncatastrophic integrity breaches. Turbidity sensitivity is improved in MBRs because the reactor turbidity, challenging the membrane filtration component, is much higher than in direct membrane filtration applications. Particle counting, although considered a more complex and more expensive monitoring strategy, is more selective than turbidity and is independent of particle properties, which impact turbidity monitoring.

Turbidity and particle counting are applicable for online monitoring of membrane integrity for all configurations of MBRs; however, the limit of detection of these techniques with regards to pathogen breakthrough is unknown. In particular, the ability of these methods to detect the uncontrolled passage of small size pathogens such as viruses associated with minor integrity breaches needs to be demonstrated. The scientific literature suggests that a majority of virus particles are associated with activated sludge flocs (Xagoraraki et al. 2014) and suspended solids (Oota et al. 2005; Sima et al. 2011; Simmons et al. 2011).
integrity monitoring using turbidity or particle counting may therefore be appropriate, although this would have to be demonstrated for the specific system being validated.

Independently of the ability to establish a direct correlation with pathogen LRVs, this protocol recommends that online turbidity monitoring or particle counting with a suitable system design and controls be systematically implemented on MBRs and that critical limits be established to detect catastrophic breaches of integrity.

5.2. Operational monitoring

Operational parameters that affect the performance of the activated sludge and the membrane filtration components need to be continuously monitored in MBRs to ensure that operation stays within the validated envelope. The minimum set of parameters recommended to be monitored is:

- MLSS
- HRT
- membrane flux
- permeability
- temperature
- permeate turbidity.

Critical limits should be set for each operational parameter, indicating when the treatment process is outside the validated range and appropriate corrective actions are required to bring the system back into the validated range, and/or when to cease supply of potentially inadequately treated water.

Control systems may provide access to a broader range of operating parameters; the recommended set above is considered a minimal requirement.

5.2.1. Bioreactor performance

As discussed in Section 4.1, the suspended solid concentration in the mixed liquor is a key influencing factor, and low densities will lead to reduced LRVs. MLSS is therefore considered a critical operating parameter to control and monitor.

Similarly, HRT is an influencing factor and is considered a critical operating parameter to control and monitor as part of an MBR operation.

A high concentration of dissolved oxygen can appear to be related to pathogen removal with a reduced LRV (Branch & Le-Clech 2015); however, this probably reflects the impact associated with subjecting the biomass flocs to an increased level of shear during aeration. Other parameters related to the bioreactor component such as dissolved organic carbon concentration, pH and capillary suction time (filterability) did not significantly influence overall LRVs (Branch & Le-Clech 2015).

5.2.2. Membrane filtration performance

Membrane flux, TMP and permeability are standard parameters to monitor when operating an ultrafiltration system. These reflect the integrity status, with significant breaches (fibre breakage, module integrity failure) eventually leading to abnormally low TMP and high permeability. These parameters also provide some indication of the fouling status of the membranes, with increasing fouling leading to higher TMP, lower permeability and reduced flux.

Operators rely on these parameters to adjust their cleaning program in terms of type and frequency so that they maintain the required production rate. As discussed in Section 4.4, membrane cleaning reduces
membrane fouling, which, in turn, can lower the removal rate of small pathogens. The monitoring of flux and TMP ensures that cleaning cycles do not lead to the MBR system operating outside its validated envelope.

Flux, TMP and permeability are not independent, and monitoring flux and TMP is sufficient to define the operating envelope and ensure that the MBR system is operating within such an envelope.

It is worthwhile noting that the bioreactor and membrane filtration components are not independent of each other, since a reduced flux and higher TMP will lead to an increased HRT.
6. Validation method

The objective of validation is to demonstrate the pathogen log reduction capability of the treatment process. It proposes a tiered approach (Figure 2) that allows for a simplified process where conservative log reduction values (LRVs) are claimed, as follows:

- Tier 1 – adopting predefined, conservative LRVs based on the statistical analysis of historical MBR performance data and associated operating conditions.
- Tier 2 – conducting challenge testing under the most conservative operating conditions expected for the specific system being validated to determine the minimum expected LRV, and implementing regular testing of target pathogens or surrogates.

Tier 1 or tier 2 approaches are not considered to strictly meet validation objectives as defined under the Australian guidelines for water recycling (Phase 1) (NRMMC et al. 2006); however, in the absence of a more appropriate validation method, these two approaches are recommended to allow implementation of MBR technologies while managing the public health risk. In addition, a proposed tier 3 approach is described in Appendix A which is more closely aligned with the definition of validation. Under this approach an investigation is undertaken incorporating challenge testing to demonstrate the correlation between online parameter(s) and the pathogen removal performance of the MBR. This allows critical limits to be established that are specific to the LRVs claimed. Until it can be further tested, this new method remains hypothetical and does not form part of the validation protocol.
6.1. Tier 1

A wide-ranging review of MBR industry data and specific investigations of full-scale facilities (Branch & Le-Clech 2015) led to the establishment of default LRVs for viruses, protozoa and bacteria of 1.5, 2 and 4, respectively. These default values can only be applied to submerged MBR systems that have nominal pore sizes of 0.04–0.1 µm, are operated in accordance with design specifications, and under the conservative operating conditions described in Table 2.
This study incorporated removal data for both target pathogens and indicators, and selected the most conservative data that were considered representative. LRV probability density functions were fitted to data obtained from literature, site visits and validation reports.

The operating envelope was based on the investigation of full-scale facilities (both flat sheet and hollow fibre membrane systems with pore sizes ranging from 0.04 µm to 0.4 µm) and involved approximately 200–300 data points for each operating parameter. Operating boundaries were established based on observed distributions, using 5th percentile values or more conservative values.

For viruses and protozoa indicators, data were more representative (larger dataset and fewer ‘nondetect’ results in permeate) and LRVs were generally more conservative than those based on pathogen data. The 5th percentile for the combined dataset on virus LRV extracted from literature was 1.7, identical to the value determined for somatic coliphages from full-scale site data, but more conservative than the >3.3 observed as the minimum enterovirus LRV. The 5th percentile protozoan LRV indicated by *Clostridium perfringens* was approximately 2.5, lower than the minimum *Cryptosporidium* LRV of >3.1.

For bacteria, 5th percentile LRVs for *Escherichia coli* and other bacteria were generally above 4, which is the maximum LRV recommended for a single treatment process.

In addition to the use of 5th percentile LRVs, resulting values obtained for each pathogen category were rounded down to the nearest half log, leading to conservative recommendations of default LRVs in Table 3.

**Table 3** Tier 1 default LRV for each type of pathogen

<table>
<thead>
<tr>
<th>Pathogen type</th>
<th>Default LRV</th>
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<tbody>
<tr>
<td>Viruses</td>
<td>1.5</td>
</tr>
<tr>
<td>Protozoa</td>
<td>2</td>
</tr>
<tr>
<td>Bacteria</td>
<td>4</td>
</tr>
</tbody>
</table>

Default LRVs cannot be applied and tier 2 should be followed for MBR systems that operate outside the tier 1 envelope in Table 2, with the exception of bioreactor temperature which may require further consideration. The investigation which led to the establishment of the tier 1 envelope included limited data at low bioreactor temperatures (from 12°C to 15°C), at which MBR systems can potentially operate effectively. If the bioreactor is expected to operate at temperatures below the tier 1 lower limit for extended periods of time (for example during winter), the proponent should engage with the regulator to review the applicability of default LRVs. The tier 1 operating envelope and default LRVs will be reviewed over time as more data become available.
6.2. Tier 2

Tier 2 is designed to validate a specific MBR installation when a proponent considers that LRVs above default values (presented in tier 1) can be demonstrated within a specific operating envelope. The approach relies on initial challenge testing to demonstrate the base performance of the MBR system pre-installation, followed by confirming pathogen reduction performance by analysing paired feedwater, mixed liquor and permeate samples during commissioning and post-commissioning. The system is to be operated within the validated envelope at all times for the validated LRVs to remain applicable.

Tier 2 contemplates the use of pre-validation data for systems which have been validated previously and for which it can be demonstrated that the previous validation results apply to the specific circumstances considered. This only applies to the commissioning validation step.

Depending on the specific MBR influent water quality, any of the tier 2 microorganism sampling and analysis components (challenge testing, commissioning validation and ongoing LRV confirmation) can use indigenous or spiked microorganisms provided they are present at high enough concentrations to challenge the system and allow LRVs to be calculated.

Recommended target and surrogate microorganisms are defined in Table 1.

6.2.1. Pre-installation challenge testing

This step is usually carried out by manufacturers in pilot facilities to demonstrate the pathogen reduction capability of the system when operating under design conditions. To be recognised under this protocol, the testing should have been conducted in accordance with principles in this section. If this information is not available from the manufacturer prior to installation, pilot testing should be conducted in accordance with the principles listed in this section in order to collect this information.

The membrane filtration component of an MBR is the main removal mechanism. The challenge testing should accord with principles described in the Membrane filtration guidance manual (US EPA 2005), with the exception of the feedwater to be used during testing. The challenge testing can be carried out in dedicated pilot facilities, provided the operating and feedwater quality conditions are representative of the proposed application.

Challenge testing reagents and membranes

Feedwater at the lowest MLSS expected during operation should be used as the matrix for the challenge testing solution. No oxidants, disinfectants, or other pre-treatment chemicals should be added to the test solution, unless necessitated by process requirements. The challenge test solution should be characterised on basic water quality parameters and any others that are critical to the test or interpretation of the results.

Target microorganisms may be indigenous or spiked where influent concentration is too low. To avoid interferences due to interactions between high concentrations of target microorganisms, this protocol recommends that no more than \(3.16 \times 10^6\) multiplied by the permeate level of detection, of the spiked target microorganism, is used as the feedwater challenge concentration, in accordance with the Membrane filtration guidance manual (US EPA 2005).

A minimum of five modular units should be tested in accordance with the Membrane filtration guidance manual (US EPA 2005).

Validated operating envelope

The operating envelope is defined as a set of operating limits (minimum, maximum or range where appropriate) for key operating parameters, as defined in Section 5.2. The conditions that will lead to the most
conservative LRV need to be applied during challenge testing. To achieve this validation sampling should be conducted at the lowest expected HRT, at the lowest MLSS and at different stages of the filtration cycle, including at the start of a cycle (after the backwash or cleaning sequence) when permeability is expected to be highest.

In addition to parameters listed as significant, this protocol recommends that other potential influencing factors are documented during the validation study. Membrane parameters, including supplier, model number, configuration, nominal pore size, membrane material, planned chemical cleaning frequency and replacement schedule.

**Sampling location**

Paired grab samples of MBR feedwater and permeate should be taken. Grab (as opposed to composite) samples were previously suggested to capture more process variability within full-scale MBRs (Van den Akker et al. 2012). Triplicate sampling is recommended.

This should occur before any additional disinfection occurs. Sodium hypochlorite is a common membrane cleaning chemical and a strong disinfectant. Adequate time should therefore be allowed for sodium hypochlorite or other cleaning chemicals to dissipate from permeate pipework before sampling. The presence of any oxidant residual should be determined and documented before sampling.

To determine the pathogen concentration factor in the bioreactor, one triplicate sample of the target microorganisms or indicators in the MBR should be taken for each filter cycle. Given the limited number of samples, to conservatively estimate the concentration factor, the ratio of the maximum pathogen concentration in the MBR and the average pathogen concentration in the influent should be used.

**Sampling period and frequency**

An adequate sampling period and frequency is required to generate statistically valid results and allow for intrinsic process variability to be observed. This protocol recommends the sampling plan described in Table 4.

<table>
<thead>
<tr>
<th>Sampling event</th>
<th>Filter cycle&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Number of paired samples per module&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>After backwash</td>
<td>Mid-filter run</td>
</tr>
<tr>
<td>After backwash</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Mid-filter run</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>End of filter run</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

<sup>a</sup> Modules must be flushed and sampled to ensure that no disinfectant residual is present.

<sup>b</sup> Sample analysis quality assurance and quality control must be addressed in the validation method. For each sampling event, triplicate sampling is recommended to achieve statistical robustness and to assess standard deviations.

<sup>c</sup> Any die-off of surrogates in these samples would indicate the presence of an oxidant.

Previous guidelines have recommended that seasonal variation be taken into account and for sampling to occur across seasonal variations or at the worst season for operational performance. However, temperature variation between 16 °C and 30 °C has not been shown not to have a significant influence on LRV (Branch & Le-Clech 2015). High flow events due to seasonal rainfall may force an MBR to operate at higher flux and lower HRT; however, provided the validated operating envelope encompasses potential seasonal variations of permeability and HRT, this protocol does not prescribe carrying out challenge testing across seasonal variations.

In addition if the challenge testing is conducted under the most conservative operating conditions (least fouled membranes), this protocol does not recommend sampling over different membrane fouling regimes.
6.2.2. Commissioning validation

This step aims to characterise the performance of the MBR system after installation by demonstrating that it is operating within the validated operating envelope and confirming that the LRVs achieved are higher than the minimum LRVs calculated as part of pre-installation challenge testing. Commissioning validation sampling involves analysing paired grab samples from feedwater, mixed liquor and permeate twice each week for 12 weeks, with a minimum requirement of 20 valid paired results (Table 5). Each event should include triplicate analysis. Target microorganisms may be indigenous or spiked where influent concentration is too low.

To ensure a conservative LRV, permeate samples should be taken as soon as reasonably practical after normally occurring backwash or relaxation events. Based on operating at the highest permeability during the validation period, this protocol recommends to conduct the commissioning validation when membranes are new or immediately after chemical cleaning for MBRs with used and fouled membranes. In the latter case, the post-cleaning permeability (and HRT) define the validated envelope boundaries. Based on this approach, any potential pre-existing integrity failures would be exposed and the challenge testing would be representative of the performance of the MBR membranes in their current state.

In some instances, proponents may seek to rely on pre-validation data as an alternative to site-specific commissioning validation. Pre-validation, defined as the use of a previous validation report, published literature and/or operational monitoring as evidence of a system LRV, could be considered if it can be demonstrated that the previous validation results apply to the specific circumstances of the system being considered. All parameters listed in Table 2 must be considered when justifying that the previous validation information has been collected under operating conditions which are consistent with the proposed application.

### Table 5. Recommended minimum commissioning validation microbial sampling program

<table>
<thead>
<tr>
<th>Sampling location</th>
<th>Sampling method</th>
<th>Sampling frequency</th>
<th>Sampling duration</th>
<th>Minimum number of samples required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedwater, mixed liquor and permeate</td>
<td>Paired grab samples in triplicates</td>
<td>Twice per week</td>
<td>12 weeks</td>
<td>20</td>
</tr>
</tbody>
</table>
Figure 3 illustrates pre-validation eligibility. Such circumstances may include:

- a packaged plant MBR installed and operated under defined, previously validated conditions
- a new MBR constructed and operated under the same conditions as a previously validated facility
- extensive validation of a specific MBR product by a supplier, including an appropriate validated operating envelope.

### 6.2.3. Ongoing LRV confirmation

As there is no continuous integrity monitoring method under tier 2, this protocol recommends an alternative strategy to verify that the system is achieving the validated LRVs when operating within the validated operating envelope. Following the commissioning validation step during which the proponent has confirmed that the specific MBR has achieved the LRVs under conservative conditions, the MBR system is then submitted to an ongoing LRV confirmation program to ensure that the validated LRVs are still being achieved by the regular, albeit less frequent, analysis of paired feedwater and permeate grab samples. Target microorganisms may be indigenous or spiked where influent concentration is too low.

A sliding scale is proposed with regard to the sampling frequency as per Table 6.
Table 6. Recommended minimal microbial sampling frequency for ongoing LRV confirmation

<table>
<thead>
<tr>
<th>Months 1 – 2</th>
<th>Months 3 – 12</th>
<th>After 12 months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fortnightly</td>
<td>Monthly</td>
<td>Quarterly</td>
</tr>
<tr>
<td>sampling</td>
<td>sampling</td>
<td>sampling</td>
</tr>
</tbody>
</table>

A sampling plan is to be provided detailing testing conditions and methods used for spiking (if applicable), sampling and analysis of relevant microorganisms. The system is to be operated within the validated envelope at all times for the validated LRVs to remain applicable.

6.3. Tier 3

Ideally, validation monitoring as defined under the Australian guidelines for water recycling (Phase 1) (NRMMC et al. 2006) should include the continuous (direct or indirect) monitoring of treatment performance and or integrity – for example, by correlating the concentration of a surrogate in permeate to the pathogen removal performance of the MBR. Based on the existing scientific literature, no generic surrogate can be recommended under this protocol, but a new tier 3 method is proposed in Appendix A. Until tested and peer-reviewed in full scale settings, this new method remains experimental and does not form part of the validation protocol.
7. Data collection and analysis

The data collected during the validation testing program must be representative and reliable. To ensure that quality data are collected:

- appropriate sampling methods and techniques must be consistent with the Standard methods for the examination of water and wastewater (Rice et al. 2012)
- National Association of Testing Authorities (NATA)–accredited methods must be used, where available. Where NATA accredited methods are not available, the laboratory must
  - demonstrate that the method used is consistent with a standard method, where this is available
  - document the method used for the analysis
  - retain documentation and appropriate quality assurance data
  - engage independent expert(s) to peer review and endorse the method
- field and laboratory equipment must be maintained and calibrated
- limits of detection must be appropriately measured
- all procedures must be completed by qualified personnel and be subject to quality assurance or quality control procedures.

The monitoring program for the validation study must ensure that the data collected are relevant and sufficient for a statistically valid analysis. The raw data and their analysis must be appended to the validation report. If data are excluded from the analysis, the rationale must be provided.

In analysing data, validation uncertainty needs to be taken into account, including biases and errors in measurements, laboratory equipment, experimental design and analytical techniques. The measurement of uncertainty must be included, to the extent practicable, when attributing an LRV to the treatment process unit.

Under the ISO standard to which NATA accredits laboratories – ISO/IEC 17025-2005: General requirements for the competence of testing and calibration laboratories – accredited laboratories are required to estimate the uncertainty associated with the results they produce (known as the measurement of uncertainty). Measurement of uncertainty data must be provided when reporting analytical results. This information will show the variability in the analytical data and will assist in formulating evidence-based conclusions.

Furthermore, during validation testing, all equipment must be carefully selected and calibrated to minimise uncertainty. Measurements must be traceable to a registered standard method, where this is available.

Increasing the sample number and/or sample volume, and using more accurate and precise measuring devices will provide the best estimate of the capability of a treatment process unit to remove or inactivate pathogens.
8. Critical limits and operational monitoring

Operational monitoring is necessary to ensure adequate control over the system and to continuously confirm that the system is operating within the validated operational envelope. Where operational parameters are found to be outside the validated operating envelope, the log inactivation may not be achieved, resulting in the supply of water that is not fit for use. Action should be taken to bring the system back into the envelope and/or stop the supply of potentially unsuitable water.

A critical limit is a value that must be met to ensure that a critical control point effectively controls a potential hazard; it is a limit that separates acceptability from unacceptability.

8.1. Tier 1

Under the tier 1 validation method, the critical limits are the operating boundaries described in Table 2. Any deviation from this operating envelope should lead to corrective actions.

8.2. Tier 2

Under the tier 2 validation method, a specific operating envelope and associated boundaries will be defined, with conservative limits on key operating parameters set during challenge testing. Specifically, a critical limit is to be set for turbidity (or particle counting).
9. Method to determine the LRV for each pathogen group

9.1. Tier 1

Under the tier 1 validation method, default LRVs are assigned for viruses, protozoa and bacteria of 1.5, 2 and 4, respectively. These default values can only be applied to common MBR systems operated under the conservative operating conditions described in Table 2.

9.2. Tier 2

The Membrane filtration guidance manual (US EPA 2005) identifies the following equation for calculating LRV:

$$LRV = \log(C_f) - \log(C_p)$$

where:

- $LRV$ = log reduction value demonstrated during a challenge test
- $C_f$ = feedwater concentration of the challenge pathogen or indicator
- $C_p$ = permeate concentration of the challenge pathogen or indicator

Feedwater and permeate concentrations must be expressed in identical units (i.e. based on equivalent volumes) to yield a valid LRV. If the challenge pathogen or indicator is not detected in the permeate, then the term $C_p$ is set equal to the detection limit.

A single LRV is calculated for each paired sampling challenge tested. The overall removal efficiency demonstrated during challenge testing is called $LRV_{C_{test}}$. The approach to determining the LRV results should be consistent with the Membrane filtration guidance manual (US EPA 2005):

- where less than 20 paired samples are tested, the lowest LRV achieved across all membranes will be the adopted as $LRV_{C_{test}}$
- where more than 20 paired samples are tested, the 10th percentile of LRVs will be adopted as $LRV_{C_{test}}$. 
10. Triggers for revalidation

Processes should be revalidated when variations occur that may affect the performance of processes (e.g. impacts of changes to primary or secondary treatment processes on downstream filtration or disinfection). Any new processes should be tested using benchtop, pilot-scale or full-scale experimental studies to confirm that the required results are produced under conditions specific to the individual water supply system.

Significant changes to operations include:

- design modifications
- control philosophy or operating parameters
- membrane replacement with a different model to the one validated
- changes to the intended use requiring a higher water quality (higher LRVs)
- continual breaches of the critical limit
- changes to the operating envelope outside which the process is validated for.
Appendix A: Proposed tier 3 validation method

The innovative tier 3 validation method presented here relies on undertaking a specific investigation to demonstrate the correlation between an online parameter(s) that can be continuously monitored and the MBR pathogen removal performance. This approach is based on artificially varying the system removal performance while simultaneously measuring an online permeate water quality parameter and carrying out challenge testing. The resolution of the chosen online monitoring technique will determine a maximum LRV that can be validated. Until tested and peer reviewed in full-scale settings, this new method remains experimental and does not form part of the validation protocol.

This new tier 3 validation method meets the requirements of the Australian guidelines for water recycling (NRMMC et al. 2006), as opposed to the tier 2 method, which only demonstrates performance at discrete points in time and does not provide current continuous performance monitoring. A possible advantage of the proposed tier 3 approach is operational flexibility. LRVs may be demonstrated within an extended operating range with improved critical control limits. This may result in higher system productivity overall, with less stoppages due to unnecessarily conservative alarms.

Turbidity is used as an example in this section. Previous studies measuring the contribution of activated sludge and membrane filtration on pathogen removal in MBRs demonstrated that most removal occurs across the membrane (Chaudhry et al. 2015, Van den Akker et al. 2014). The activated sludge compartment of an MBR contains between 3 and 14 g/L of suspended solids, and, if a membrane integrity breach were to occur, the transfer of suspended solids into permeate would most likely be detectable by turbidity monitoring. Viruses, typically smaller than the membrane pore size, are predominantly attached to suspended solids within the activated sludge of MBRs (Oota et al. 2005, Sima et al. 2011, Simmons et al. 2011); this tier 3 approach relies on the assumption that the LRV of suspended solids is equal to the LRV of pathogens across the membrane. This implies that turbidity can be correlated to pathogen LRVs provided the relationship between turbidity and suspended solids removal is well established.

The proposed approach to correlate permeate turbidity with LRV follows the steps below:

- **Step 1:** Determine a linear correlation of turbidity and suspended solids. Systematic spiking of activated sludge into MBR permeate should be conducted, the solutions circulated at the design flow through a commercial turbidity meter, the turbidity recorded and suspended solids analysed for each solution. At least six different turbidities should be analysed, covering the proposed operating range of the instrument under field conditions (i.e. 0.1–1.5 NTU). Following this approach, previous correlations have been found where a conversion factor can be determined – for example
  \[ \text{Suspended solids (mg/L)} = (1.3 \text{ to } 4.3) \times \text{Turbidity (NTU)} \]  (Branch & Le-Clech 2015, Zha et al. 2008).

- **Step 2:** Use the conversion factor to calculate LRV across the membrane using the equations
  \[
  LRV_{MBR} = LRV_{Bio} + LRV_{Mem}
  \]
  \[
  \text{with } LRV_{Mem} \approx LRV_{SS}
  \]
  \[
  LRV_{SS} = \log_{10} \left[ \frac{MLSS}{\text{Conversion Factor} \times \frac{SS}{Turbidity} \times \text{Permeate Turbidity}} \right]
  \]

- **Step 3:** Select an appropriate LRV_{bio} from Table 7. Provided MLSS is measured regularly or by an online instrument, LRV_{SS} can represent the removal across the membrane. LRV_{bio} must still be accounted for and is pathogen and operating condition specific. Conservative default values are proposed below, based on the 5th percentile values obtained by Branch and Le-Clech (2015). Note that negative LRVs are possible and account for slow biopredation, resulting in accumulation of organisms within the reactor.

201702_WaterVal_Validation Protocol_Membrane Bio-reactor
Table 7 Conservative default $LRV_{Bio}$ values for MBR

<table>
<thead>
<tr>
<th>Indicator</th>
<th>$LRV_{Bio}$ probability density function parameters</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\mu$</td>
<td>$\sigma$</td>
<td>5th percentile</td>
<td>95th percentile</td>
</tr>
<tr>
<td><em>Clostridium perfringens</em></td>
<td>$-1.4$</td>
<td>$0.4$</td>
<td>$-2.0$</td>
<td>$-0.7$</td>
</tr>
<tr>
<td><em>Escherichia coli</em></td>
<td>$0.9$</td>
<td>$0.7$</td>
<td>$-0.2$</td>
<td>$2.0$</td>
</tr>
<tr>
<td>Somatic coliphages</td>
<td>$0.0$</td>
<td>$1.0$</td>
<td>$-1.7$</td>
<td>$1.6$</td>
</tr>
<tr>
<td>FRNA bacteriophages</td>
<td>$1.1$</td>
<td>$1.0$</td>
<td>$-0.7$</td>
<td>$2.8$</td>
</tr>
</tbody>
</table>

Using the default $LRV_{Bio}$ values, LRV overall can then be calculated as a continuous function for a given MLSS. An example is shown with a conversion factor of 4.3 mg/L/NTU, MLSS of 5000 mg/l and 5th percentile values for $LRV_{Bio}$.

Figure 4 Establishment of correlation between turbidity and LRV and critical limit determination (specimen data)

- Step 4: As an additional step to increase validated LRVs, the site specific values of $LRV_{Bio}$ could be determined. The $LRV_{MBR}$ model is conservative because of the $LRV_{Bio}$ values adopted. To achieve higher LRVs, site-specific values of $LRV_{Bio}$ could be determined. If site-specific values of $LRV_{Bio}$ are to be determined, the same sampling regime specified in tier 2 should be carried out, with additional testing of activated sludge concentrations. Ideally, an online monitoring technique could be correlated with $LRV_{Bio}$ and an overall LRV calculated continuously by measuring both $LRV_{Bio}$ and turbidity. However, no such technique is known.

- Step 5: A turbidity critical control limit (CCL) can then be selected and corresponding LRVs established ($LRV_{CCL}$). Sampling should take place in a range where a measurable turbidity change can be expected; assessing historical turbidity data can help to ascertain a baseline.

To ensure that the LRVs identified are conservative, the sampling program and turbidity correlation should take place under the most conservative conditions: the lowest MLSS concentration and highest permeability within the operating envelope. Independently of the continuous online monitoring and correlation with LRVs, the MBR system needs to be operated and controlled at all time within an envelope that is defined as part of the validation.
## Glossary and abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIT</td>
<td>direct integrity testing</td>
</tr>
<tr>
<td>FRNA bacteriophage</td>
<td>F-specific RNA bacteriophage</td>
</tr>
<tr>
<td>HRT</td>
<td>hydraulic retention time</td>
</tr>
<tr>
<td>IEP</td>
<td>Isoelectric point</td>
</tr>
<tr>
<td>LRV</td>
<td>log reduction value</td>
</tr>
<tr>
<td>LRV&lt;sub&gt;Col&lt;/sub&gt;</td>
<td>The log removal value at a particular critical control limit.</td>
</tr>
<tr>
<td>LRV&lt;sub&gt;Test&lt;/sub&gt;</td>
<td>The log removal value as determined from challenge testing.</td>
</tr>
<tr>
<td>MBR</td>
<td>membrane bioreactor</td>
</tr>
<tr>
<td>MLSS</td>
<td>mixed liquor suspended solids</td>
</tr>
<tr>
<td>NATA</td>
<td>National Association of Testing Authorities</td>
</tr>
<tr>
<td>NTU</td>
<td>nephelometric turbidity units</td>
</tr>
<tr>
<td>SRT</td>
<td>solids retention time</td>
</tr>
<tr>
<td>TMP</td>
<td>transmembrane pressure</td>
</tr>
<tr>
<td>US EPA</td>
<td>United States Environmental Protection Agency</td>
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</tbody>
</table>
References


