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Water Quality Goals and Operational Criteria for Optimization of Low-Pressure Membrane Filtration

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Contents

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Membrane Filtration Terminology and Definitions

Term	Definition
MF	Microfiltration
AWOP	Area-Wide Optimization Program
UF	Ultrafiltration
DIT	Direct integrity test
IFE	Individual Filter Effluent
NTU	Nephelometric turbidity unit
SCADA	Supervisory control and data acquisition
LRV	Log-removal value
LRV_{DIT}	Minimum DIT LRV sensitivity
$LRV_{ambient}$	Real-time LRV calculated from DIT and real-time parameters
TMP	Transmembrane pressure
LRC	Log removal credit
Low-pressure membrane	Micro- or ultrafiltration
Flux	Flow rate per unit area through membrane
CIP	Clean-in-place
HMI	Human-machine interface
MFGM	Membrane Filtration Guidance Manual
VCF	Volumetric concentration factor
ALCR	Air-to-liquid conversion ratio
CFR	Code of Federal Regulations
P_{test}	Minimum DIT pressure
ΔP_{test}	PDR from last DIT ($LRV_{ambient}$) or smallest PDR that can be reliably measured and associated with a known integrity breach during the DIT (LRV_{DIT}, test sensitivity)
BP	Back pressure
D_{base}	Baseline pressure decay
K	Dimensionless flow resistance coefficient
σ	Surface tension
Θ	Liquid-membrane contact angle
Q_p	Design flow rate capacity
Q_{air}	Flow of air through membrane fiber breach
V_{sys}	System volume
T	Water temperature
gfd	Gallons per square foot per day (flux)
psi	Pounds per square inch (pressure)
P_{atm}	Atmospheric pressure
M_{20}	Temperature & pressure normalized permeability, or “specific flux” (20°C, normalized at TMP)
J_{20}	Temperature normalized flux at 20°C
F	Friction factor
Y	Dimensionless net expansion factor for compressible flow through a pipe to a larger area
κ	Dimensionless pore shape correction factor (=1)

1.0 Introduction

The purpose of this document is to present water quality performance goals for low-pressure membrane filtration systems (i.e., microfiltration [MF] and ultrafiltration [UF]). These goals are intended to be applied by operators in daily operations and to reduce uncertainty in performance data developed at membrane plants. Reliable performance data can be used in conjunction with the optimization goals to assess the status of membrane performance. Installation of membrane filtration systems is increasing along with the industry perception of ease of use for operations. Despite membrane filtration being perceived as less labor intensive and more automated, monitoring and trending of performance data is crucial to ensure optimal performance of the system.

The Area-Wide Optimization Program (AWOP) was established in the 1990s by the U.S. Environmental Protection Agency (EPA) and is coordinated by the EPA's Technical Support Branch of the Standards and Risk Management Division in Cincinnati, Ohio. The program was developed to optimize conventional surface water treatment plant performance against microbial contaminants but has since expanded to optimize various other drinking water treatment processes, including low-pressure membrane filtration. Microbial pathogens can be physically removed as particles and chemically inactivated by disinfection during the water treatment process. Therefore, public health protection can be maximized by optimizing both the particle removal and disinfection process(es) (EPA, 2004).

These goals were developed through consultation with industry experts and field events to test their applicability at eight water systems. During these field evaluations, data availability and verification challenges became evident and made the goal development process more complex. It is important to note that although log-removal value (LRV) results could be verified during some of the field evaluations, a significant amount of time and correspondence with the system owner, engineer, membrane and supervisory control and data acquisition (SCADA) system vendors was necessary prior to and after the workshop to achieve these verifications. A summary of key findings from membrane optimization workshops is included in Appendix A.

2.0 Goals Defining Optimal MF/UF Membrane Performance

It is important to assess treatment performance in relation to water quality goals. Table 1, below, presents a summary of the proposed membrane filtration optimization performance and monitoring goals. To facilitate performance data collection and trending, it is also recommended that these goals be incorporated into SCADA programming, with parameters and calculations clearly displayed, particularly for LRV determination, to facilitate process control evaluation.

Table 1. Membrane optimization goals summary

Indirect Integrity Goals:

Performance	***Monitoring***
IFE turbidity ≤ 0.05 NTU, or	Measured continuously (≤ 1-minute intervals)
Particle counts (1.0 – 3.0 µm) ≤ 10 particles / mL	Measured continuously (≤ 1-minute intervals)

Direct Integrity Goal:

Performance	***Monitoring***
$LRV_{ambient}$ ≥ 4.0 log AND ≥ LRC awarded by regulating agency	Determined after every DIT

Operational Goal:

Performance	***Monitoring***
Post-CIP normalized permeability / specific flux (M_{20}) ≥ 90% of Reference Permeability	Determined after every CIP

Since there are many ways some of these metrics can be calculated (e.g., LRV and permeability), a well-designed membrane SCADA human-machine interface (HMI) should incorporate displays of the equations and real-time variables used in these calculations. This would greatly facilitate re-programming and regulatory approvals often needed during plant upgrades and changes in membrane modules. A well-developed, transparent membrane HMI can improve efficiency by reducing programming costs, increase operator productivity, and allow faster responses to production changes, expansion, and conditions that may have an adverse impact to public health. Easy retrieval and trending of historical data can improve maintenance and optimize production capability, leading to fewer complaints and improved customer satisfaction.

3.0 Indirect Integrity Goals

Indirect integrity monitoring refers to some aspect of filtrate water quality that is indicative of particulate removal performance of the membrane system. DITs are only conducted periodically during normal operation (e.g., daily). This is because currently available direct integrity test (DIT) methods require the membrane unit to be temporarily taken out of service, therefore can be too costly or infeasible to apply continuously. Typically, indirect integrity monitoring is conducted continuously (i.e., ≤ 1-minute intervals) but are not as sensitive as DITs for detecting a loss of membrane integrity. However, indirect monitoring does provide an assessment of performance between DITs and can serve as an early indicator of a performance problem.

These indirect integrity testing goals are applicable to systems conducting indirect integrity testing on each membrane unit using on-line monitoring of turbidity or particle counts (1.0 – 3.0 µm range) with a data acquisition frequency of ≤ 1-minute.

Indirect Integrity Water Quality Performance Monitoring Goals:

1. Individual filter effluent (IFE) turbidity should always be ≤ 0.05 NTU, as determined from online continuous turbidity monitoring (i.e., ≤ 1-minute interval), or
2. Particle counts should always be ≤ 10 particles/mL in the 1.0 – 3.0 µm range, as measured from online continuous particle count monitoring (i.e., ≤ 1-minute interval).

Membrane filtration systems are well-documented to consistently produce filtered water below 0.05 NTU (MFGM, p. A13). In addition, modern turbidimeters have the accuracy to measure turbidity at this level and below. This goal is intended to primarily identify gross integrity breaches but allows for some assurance of integrity between direct integrity testing, without compromising membrane recovery and production efficiency.

If these indirect integrity monitoring goals are exceeded, a DIT should be conducted as soon as practical to ensure optimized performance. Ensure that the DIT is also conducted in accordance with the regulatory requirements. See the following section on DIT goals below.

4.0 Direct Integrity Testing (DIT) Goals

Direct integrity testing (or DITs, which may also be called membrane integrity tests, integrity tests, or air hold tests) assesses a membrane unit's ability to hold a pre-defined pressure to identify and isolate integrity breaches that could allow pathogen passage. These operational goals are applicable to membrane systems using a pressure decay or "air hold" DIT on each membrane unit.

A membrane unit may be defined as a group of membrane modules that can be isolated and monitored for the purpose of conducting a DIT. See Figure 1.

Figure 1. Two membrane units (also sometimes referred to as "racks", "skids", or "trains").

DITs must be performed daily, or more frequently if indirect integrity turbidity or particle count monitoring goals or regulations are exceeded (40 CFR 141.719). This means conducting a DIT daily or more frequently whenever individual membrane unit turbidity > 0.05 NTU or particle counts [1-3 µm range] > 10 / mL. Membrane units that fail a DIT must be removed from service, inspected, repaired if necessary, and then pass a DIT before returning to service (40 CFR 141.719). See Figure 2 for an example of how damaged membrane fibers are "pinned" or removed from service.

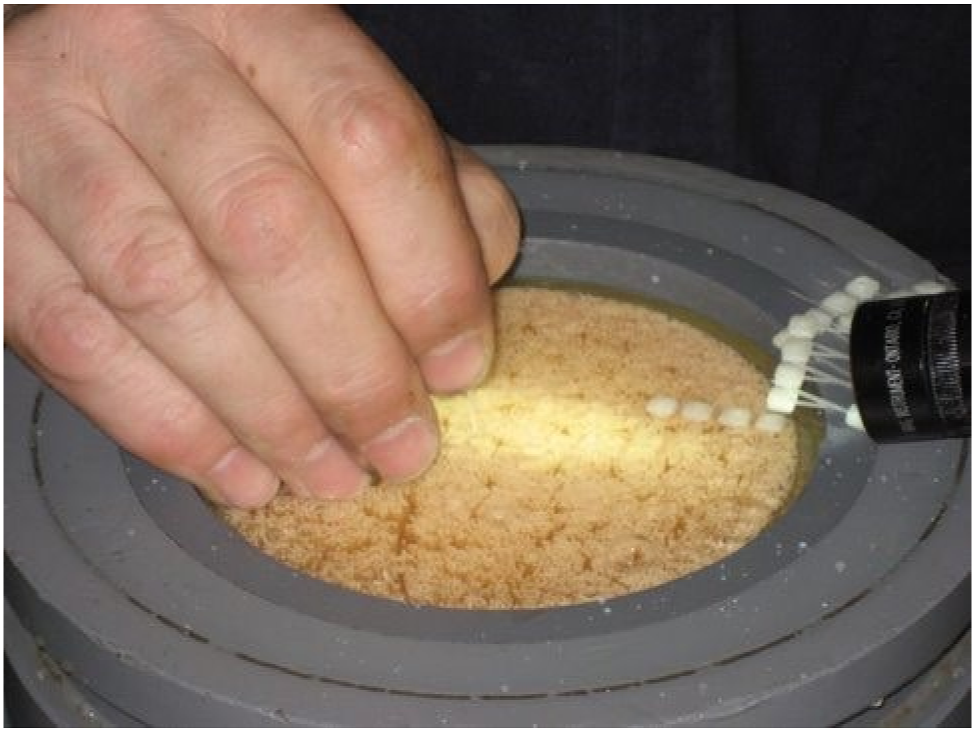

Figure 2. "Pinning" broken membrane fibers.

$LRV_{ambient}$ is the water quality optimization parameter associated with a successful DIT. $LRV_{ambient}$ is calculated using the U.S. EPA Membrane Filtration Guidance Manual (MFGM) Equation 4.9, using the current flow rate just prior to running the DIT, instead of the maximum design flow rate used to calculate the test sensitivity (LRV_{DIT}).

4.1 DIT Conditions Necessary for Accurate Testing

To be an accurate representation of membrane filtration performance, a DIT must be able to detect a breach in a membrane fiber that is large enough to pass a *Cryptosporidium* oocyst, which is less than or equal to 3 µm. This is called the DIT's resolution. The theoretical breach could be from either a single 3 µm hole, or it could be from several smaller holes.

The DIT must also be sensitive enough to verify that the membrane unit is achieving the log removal credit awarded by the primacy agency. This is called the DIT's sensitivity. In this section, the conditions necessary to achieve the required resolution and sensitivity will be discussed.

If the required DIT resolution and sensitivity are achieved, operators can have confidence in the calculated $LRV_{ambient}$ values determined from the DIT to assess membrane unit performance against, not only the regulations, but also the optimization goal of greater than or equal to 4.0-log removal.

4.1.1. Test Resolution: Determining minimum DIT pressure to achieve necessary resolution

The DIT shall have a resolution of $\leq$ 3 µm, where resolution is defined as the size of the smallest integrity breach that contributes to a response from the DIT (40 CFR 141.719). For pressure-based DITs discussed in this document, this resolution is usually expressed in terms of the minimum test pressure, P_{test}, such that the pressure-driven flow through a theoretical 3 µm breach in the membrane could pass a pathogen of that size or smaller. The theoretical breach could be from either a single 3 µm hole or it could be from several smaller holes.

In order to achieve this resolution for a pressure-based test, the net pressure applied during the test, which is the minimum test pressure (P_{test}), must account for the back pressure (BP_{max}) at the pressure monitoring point and must be great enough to overcome the capillary forces in a 3 µm breach throughout the duration of the test, calculated empirically with the expression below. Any baseline decay (D_{base}) must also be accounted for in the minimum test pressure.

- **Back Pressure (BP_{max})**: Because the back pressure acts in opposition to the applied test pressure, the test pressure must be increased by this same amount. The back pressure can be field verified by measuring the height of the water column above the pressure sensor that is used to measure the pressure decay rate and then converting that distance to a static head in pounds per square inch (psi).
- **Capillary forces in a 3 µm breach:** This is calculated empirically with the following expression using the parameters as defined below:

$$0.193 * \kappa * \sigma * cos\theta$$

- **D_{base}**: Any baseline diffusive pressure decay for an intact membrane unit must also be accounted for in the DIT applied test pressure. For example, if the P_{test} is 15 psi for a membrane unit with a baseline decay of 0.25 psi/min over the course of a 2-minute test duration is known, then the applied test pressure must be at least 15.5 psi.

Combining these considerations, the minimum DIT test pressure can be determined by adding:

$$P_{test} = \text{back pressure} + \text{capillary forces} + \text{baseline decay}$$

Therefore, using the expressions introduced above, P_{test}, the minimum applied pressure throughout the duration of a DIT (psi) can be determined as follows in Equation 1:

$$P_{test} = BP_{max} + [0.193 * \kappa * \sigma * cos\theta] + [t * D_{base}] \quad \text{(Equation 1)}$$

Where:

- P_{test} = The minimum applied pressure throughout the duration of a DIT (psi)
- BP_{max} = maximum backpressure on the system during the DIT (psi)
- 0.193 = a factor that incorporates the 3µm defect diameter
- κ = pore shape correction factor (dimensionless) = **1** for the purpose of meeting this goal
- σ = surface tension at the air-liquid interface = **74.9 dynes/cm** at 5°C water temperature for the purpose of meeting this goal
- Θ = liquid-membrane contact angle = **0 degrees**
- t = duration of the DIT (minutes)

- D_{base} = Baseline decay (if known) of the unit, fully intact without integrity breaches, over the duration of the DIT = **assume 0 psi/min** unless provided by the manufacturer

Given the substitutions above, the equation for the applied test pressure simplifies to the following form:

$$P_{test}\ [psi] = 14.5 + BP_{max} \quad \text{(Equation 2)}$$

Equation 2 indicates that the minimum test pressure necessary to achieve a 3 µm resolution is 14.5 psi plus the maximum backpressure on the system during application of a pressure-based DIT, at a conservative temperature of 5°C. For a pressure-based DIT, a water system must have an applied pressure equal to or greater than that provided in Equation 2 to meet the DIT resolution requirement (40 CFR 141.719).

4.1.2 Test Sensitivity: Determining the Minimum Sensitivity of the DIT (LRV_{DIT})

Per 40 CFR 141.719, the DIT must be able to have a sensitivity sufficient to verify the log removal credit awarded by the primacy agency. For optimization, the DIT must be capable of verifying greater than or equal to 4.0-log removal since that is the optimization goal for DITs. Because DITs do not directly measure the flow through a membrane fiber breach, it is necessary to correlate the DIT's pressure-decay-based response to the potential flow of water through a theoretical break during system operation. This is the minimum sensitivity of the DIT and can be determined from Equation 3 below:

$$LRV_{DIT} = \log \frac{Q_p * ALCR}{Q_{air} * VCF} \quad \text{(Equation 3)}$$

Where:

- LRV_{DIT} = minimum test sensitivity of the DIT (as expressed as a log-removal value, or LRV)
- Q_p = membrane unit design capacity flow (L/min)
- Q_{air} = flow of air through the critical breach (L/min) (see below for equation)
- VCF = volumetric concentration factor (dimensionless)
- ALCR = air-to-liquid conversion ratio (dimensionless). In many DITs, including pressure and vacuum-decay tests, air is applied to the drained side of a membrane and subsequently flows through any integrity breaches that exceed the test resolution. To relate air pressure decay determined from the DIT to the flow through a potential breach, a relationship between airflow and liquid flow, known as the ALCR, is necessary. The ALCR is defined as the ratio of air that would flow through a breach during a DIT to the amount of water that would flow through the breach during filtration.

  ALCR is calculated using Equation 4, assuming hollow-fiber modules and turbulent defect flow regime (Darcy pipe flow model) and used for both LRV_{DIT} and $LRV_{ambient}$ (see Section 4.2, below).

$$\text{ALCR} = 170 * Y * \sqrt{\frac{(P_{test} - BP)(P_{test} + P_{atm})}{TMP(460 + T)}}$$

(Equation 4)

Where:

- ALCR = Air to Liquid Conversion Ratio (dimensionless)
- *Y* = Net expansion factor for compressible flow through a pipe to a larger area (dimensionless). The net expansion factor is obtained from charts in various hydraulics references, such as Crane (1988) page A-22. To be conservative, use 0.588, which is the lowest value from Crane, p. A-22 (see Appendix B: Determining the Net Expansion Factor)
- P_{test} = DIT starting pressure (psi) (i.e., ≥ minimum test pressure determined in Section 3.1.1)
- BP = backpressure on the system during the integrity test (psi) (use maximum anticipated back pressure to be conservative)
- P_{atm} = atmospheric pressure (psia)
- T = Water Temperature (°F)
- TMP = Transmembrane pressure during normal operation (psi) (use maximum anticipated TMP during normal operation to be conservative)

Furthermore, Q_{air} can be determined from the DIT, such as in Equation 5 below:

$$Q_{air} = \frac{\Delta P_{test} * V_{sys}}{P_{atm}} \quad \text{(Equation 5)}$$

Where:

- Q_{air} = flow of air through a theoretical 3 µm breach (L/min)
- ΔP_{test} = pressure decay rate determined during the last DIT (psi/min) = P_{test} – final test pressure
- V_{sys} = volume of pressurized air in the system during the test (L)
- P_{atm} = atmospheric pressure (psi)

Replacing Q_{air} in Equation 3 with the expression shown in Equation 5 results in the following expression for LRV_{DIT}

$$LRV_{DIT} = \log \frac{Q_p * ALCR * P_{atm}}{\Delta P_{test} * V_{sys} * VCF} \quad \text{(Equation 6)}$$

4.2 Determining the "Ambient" Log Removal Value ($LRV_{ambient}$) from a DIT

The "ambient" LRV ($LRV_{ambient}$) indicates the membrane module's performance status just prior to taking the module offline for the DIT, using real-time parameters such as TMP and flow rate. $LRV_{ambient}$ intends to indicate real-time performance, opposed to LRV_{DIT} (determined in Section 4.1), which is the DIT's maximum sensitivity, expressed as a log removal value, and uses design capacity flow rate and maximum TMP. For optimization purposes, the $LRV_{ambient}$ should always be greater than or equal to 4.0-log and greater than or equal to the log removal credit (LRC) awarded by the regulating agency.

To determine the $LRV_{ambient}$ using the results of the DIT, the DIT must be conducted with an applied pressure greater than or equal to P_{test}, as determined using Equation 2.

For this goal, $LRV_{ambient}$ must be calculated using Equation 7 below (i.e., MFGM Equation 4.9), with the exception that the design flow, Q_p is substituted with the operating flow, Q, just prior to the DIT. Therefore, $LRV_{ambient}$ is determined as follows:

$$LRV_{ambient} = \log \frac{Q * ALCR * P_{atm}}{\Delta P_{test} * V_{sys} * VCF} \quad \text{(Equation 7)}$$

Where:

- $LRV_{ambient}$ = Log removal value verified by the most recent DIT (log)
- Q = Membrane unit filtrate flow just prior to the DIT (L/min)
- ALCR = air-to-liquid conversion ratio (dimensionless), see Equation 6, but use TMP just prior to DIT.
- P_{atm} = Atmospheric pressure (psia)
- ΔP_{test} = DIT pressure decay rate (psi/min)
- V_{sys} = Volume of pressurized piping/modules during the DIT (liters)
- VCF = Volumetric Concentration Factor (dimensionless) = 1.0 unless an alternative VCF has been verified by a third party.

4.3 Operational Considerations for DITs

4.3.1 DIT Failure Alarms

DITs are the most important monitoring requirement for low-pressure membrane filters. When a membrane unit passes a properly conducted DIT, it demonstrates that adequate filtration of the target pathogens is occurring. DIT results are a better indication of performance than turbidity results for low-pressure membranes. Observe the control systems' responses to a failed DIT. Ensure that DIT alarms and shutdown settings are appropriate, and that the membrane unit is automatically taken out of service if it fails a DIT.

4.3.2 Pressure Sensor Maintenance

LRV_{DIT} represents the maximum log removal value that can be verified for that specific membrane module. Because the sensitivity is logarithmic, a test with a LRV_{DIT} of 5-log is 100 times more sensitive than a test with a LRV_{DIT} of 3-log. This means that equipment for the 5-log test must be capable of detecting very small changes in the integrity response and distinguishing these from background or baseline data. Due to their criticality, pressure sensors used in the detection of pressure/vacuum decay rates should be checked quarterly and calibrated at least once a year, or as recommended by the manufacturer.

Figure 3. Pressure sensor on membrane unit

4.3.3 Flow Mode

Low-pressure membrane filters are operated in one of two modes: deposition (dead-end) mode or crossflow (suspension) mode. If the membrane modules are not operating in the mode for which they are approved by the regulatory agency, this could invalidate the DIT results because initial test parameters, such as the VCF, may be incorrect.

Deposition mode operation is where all the water that is sent to the upstream side of the membrane passes through the membrane and all solid particles larger than the pore size in the membranes are deposited on the upstream side of the membranes. See Figure 1.

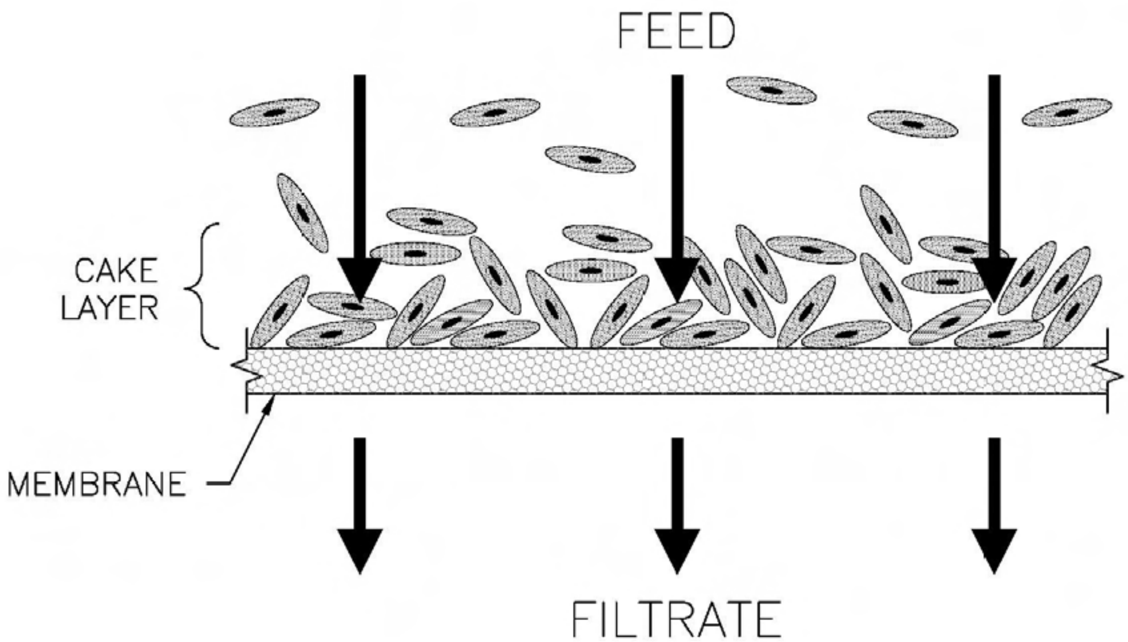

Figure 4. Conceptual Illustration of Deposition Mode Operation (from MFGM Figure 2.14, p. 2-32)

Crossflow (suspension) mode can be created in a variety of ways. One common method is where a portion of the water sent to the upstream side of the membrane does not pass through the membrane but flows across the upstream side of the membrane. The unfiltered water may be sent to waste, recycled back into the feed water of the same membrane unit, or sent for further treatment by a new membrane unit. This crossflow scours and removes some particles that have deposited on the upstream side of the membrane, extending the time between backwashes. Other variations of crossflow (suspension) mode include:

- Flow opposite to the direction of the feed water during filtration; or
- Pumping air or vibrations into the modules or unit (when using membranes that are suspended in a tank).

See Figure 2 for a depiction of crossflow mode.

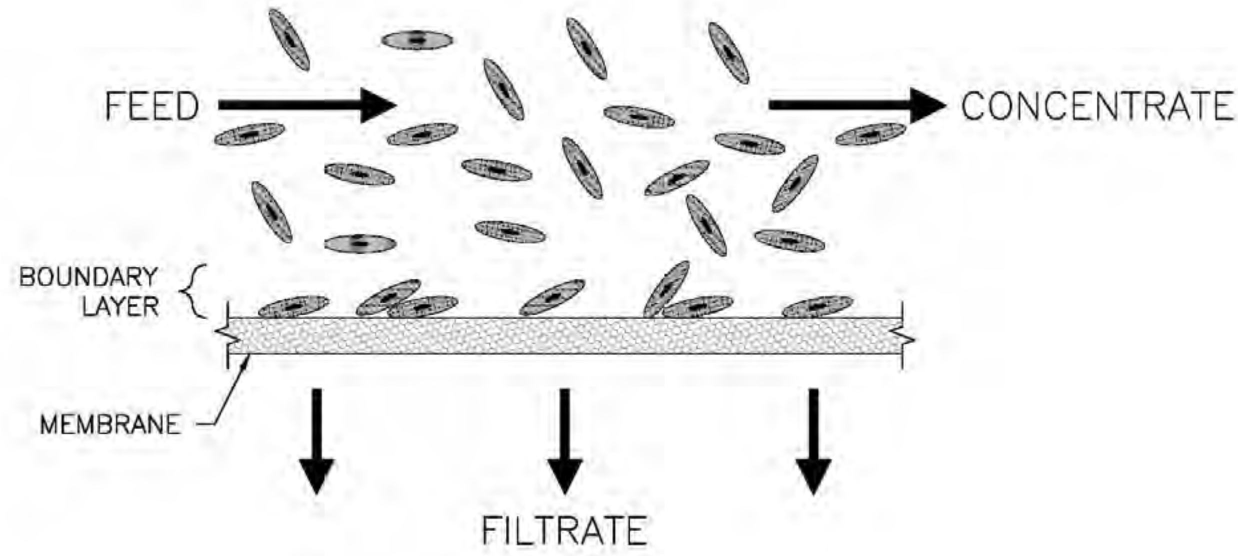

Figure 5. Conceptual Illustration of Suspension Mode Operation (MFGM Figure 2.15, p. 2-33)

Many membrane units are designed with the capability to operate in both deposition and crossflow modes. Occasionally, a membrane manufacturer may state that the membrane units are operating in one mode, but a close inspection of the units reveals the opposite. This is not always easy to detect. If there is any flow sent to the upstream side of the membranes that does not pass through to the filtered side of the membranes, the unit is operating in some kind of crossflow (suspension) mode.

4.3.4 SCADA Status Display

For operations staff to be able to evaluate membrane performance indicators, it is important to have a well-designed HMI display. Options to display every variable used in LRV and permeability calculations should be readily accessible to the operator. The same concept of providing transparency to operations staff should be applied for manufacturer specified performance indicators like resistance, feed fouling index, normalized TMP and normalized flux.

In addition to viewing the available instantaneous data, options should exist to export historical data for more detailed analyses and to be able to view performance trends over a user-specified period. This functionality would be based upon the historian data files containing continuous data for all relevant parameters.

5.0 Membrane Permeability Recovery Operational Goal

Operators of optimized low-pressure membrane systems understand that effective cleaning procedures can help extend the life of the membranes and maintain high quality filtered water. After each clean-in-place (CIP) procedure, normalized membrane permeability should recover to greater than or equal to 90% of the reference permeability. Normalized permeability and reference permeability are described below. These parameters are used to determine the membrane permeability recovery.

5.1 Normalized Permeability:

Normalized permeability (M_{20}) is permeability normalized to 20°C. A baseline or "reference permeability" should be determined for each membrane unit upon initial module installation and after a period of conditioning. Normalized permeability should also be determined prior to and after each CIP to determine the impact of the CIP process on the membranes.

Normalized permeability (or "specific flux") is based on Equation 8 as shown below:

$$M_{20} = \frac{J_{20}}{TMP} \quad \text{Equation 8}$$

Where M_{20} = temperature and pressure-normalized flux (gallons per square foot per day [gfd]/psi)

TMP = transmembrane pressure (psi)

J_{20} = normalized flux at 20°C (gfd), calculated as follows based on Equation 9:

$$J_{20} = J_T * (1.784 - [0.0575 * T] + [0.0011 + T^2] - [10^{-5} * T^3]) \quad \text{Equation 9}$$

Where:

- J_T = actual flux at temperature T (gfd)
- T = water temperature (°C)

5.2 Reference Permeability:

The reference permeability should be determined using the equations for normalized permeability and as follows:

1) After a new membrane unit is installed;

2) After each module replacement (a new reference permeability needs to be established); and

3) For newly installed membrane units or module replacements, recalculate reference permeability after the new modules have been conditioned with at least two weeks of filtering using the raw source water (with pre-treatment prior to the membranes if applicable) and after the first production CIP, in accordance with manufacturer recommendations.

5.3 Membrane Permeability Recovery:

Membrane permeability recovery is a measure of how effectively the CIP procedure restores normalized permeability (M_{20}) back to its original state and should be determined after each CIP. For optimal operation, a permeability recovery of ≥ 90% is suggested.

Membrane permeability recovery is determined as shown in Equation 10:

$$Membrane\ Permeability\ Recovery\ [\%] = \frac{[Post{-}CIP\ Normalized\ Permeability]}{[Reference\ Permeability]} x\ 100 \quad \text{Equation 10}$$

References

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U.S. EPA. 2004. Optimizing Water Treatment Plant Performance Using the Composite Correction Program. EPA 625/9-91-027. Office of Water, Office of Research and Development. Cincinnati, OH.

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Appendix A: Key Findings from Membrane Optimization Workshops and Data Integrity Recommendations

Location	Date	Findings
Oregon	October 26, 2011	• The assessment team was unable to verify LRV reported on SCADA screen, even with assistance from operators. • Routine verification of pressure sensors used to measure the pressure decay rate during the direct integrity test was not conducted according to manufacturer's recommendations. • Laser turbidimeter detected turbidity spikes with each backwash rising from 0.012 NTU to up to 0.02 NTU.
Ontario, Canada	December 2012 – On-going	• Conducted special studies on use of laser turbidimeter and particle counter to assess membrane plant performance. • Use of laser turbidimeter readings (i.e., turbidity, relative standard deviation of turbidity signal) was not as sensitive as particle counting results. • Membrane performance as indicated by particle counts supports an optimization goal of ≤ 10 particles per mL in the 1 to 3 µm range. A plant-specific goal of ≤ 5 particles per mL may be achievable with routine membrane fiber inspection and repair. • Membrane performance as indicated by turbidity supports an optimization goal of ≤ 0.05 NTU 95 percent of the time. A lower goal is likely achievable when using laser turbidimeters. • Assessment of membrane performance should be based on data generated only during production mode (flow forward). SCADA programming needed to provide only performance data when a flow rate is indicated through the membrane.
Oregon	February 21, 2013	• Flow used in the programmed LRV equation was based on the design flow rate and not the flow rate just prior to the DIT. • Data required to verify LRV calculations was stored in several folders and csv files making it difficult to interpret. • The assessment team was able to approximate the onsite LRV calculations; however, this required effort over several months. An exact match to the LRV values calculated by the programming could not be obtained because some of the instantaneous data used to calculate LRV was not stored in the historian files
Idaho	July 23, 2014	• The system volume could not be verified onsite with the engineer or membrane vendor; consequently, it was estimated based on site measurements and module fiber information. • The assessment team was not able to verify the onsite LRV calculations.
Texas	October 29, 2014	• DIT results (LRV, pressure decay) were not being archived into the historian correctly; consequently, performance data trends could not be developed. The same values were shown in the historian for each day going back to at least January 2014. • The LRV equation may not have included the correct system volume. Correspondence between the plant engineer and membrane manufacturer highlighted confusion on the size of system piping used to determine system volume and which equations to calculate LRV. • Recent changes to the DIT duration by the operators may have impacted the test results (two tests conducted during the workshop failed). • The assessment team was not able to verify the onsite LRV calculations.
Idaho	April 29, 2015	• Assumptions were made on TMP and water flow values used in the LRV equations (the values immediately before the DIT were used). • The system volume was obtained from the membrane vendor; however, specific volume calculations were not provided. • The basis for determining the system back pressure could not be verified on site (follow-up needed). • The assessment team was able to verify the onsite LRV calculations; however, follow-up questions were identified.
Washington	May 19, 2015	• The plant had two different types of membrane modules from the same vendor, but different LRV equations were used for each. The LRV equation for the older modules could not be verified on site. • Assumptions were made on TMP and water flow values used in the LRV equations (the values immediately before the DIT were used). • Documentation on all the LRV related input parameters was difficult to obtain; consequently, review of the control screens was necessary to confirm the basis for some parameters. A video of the ladder logic as it calculated LRV during the DIT showed that the effective integrity test pressure, P_{test}, used for determining the Air to Liquid Conversion Ratio (ALCR) was a fixed value, even though it was previously believed to be calculated based upon the ending test pressure of the most recent direct integrity test. • Assessment team was able to verify the onsite LRV calculations.
Missouri	May 17, 2016	• The assessment team was able to validate the LRV equations provided by the system vendor; however, the DIT start pressure was lower than the minimum allowable start pressure for the system design, thus invalidating the testing protocol. • A review of historical turbidity data from the membrane skids required extensive resources to determine performance data for only the production mode (i.e., performance data for both production and off-line modes was sent to SCADA). • Although the system was recently upgraded, LRV programming was not provided at the local PLC or SCADA. The vendor did provide a spreadsheet for the operator to determine LRV based the test results.

In addition to the specific findings presented in the table above, the following general findings were also observed:

1. Differences between LRV determined in a DIT, in which some systems calculate the test sensitivity (abbreviated as LRV_{DIT} throughout this document) using the maximum design flow, while other systems calculate an ambient LRV determined real-time with varying flow rate and TMP (referred to as $LRV_{ambient}$, in this document). In both instances, the data is typically presented simply as LRV, however this distinction is important for optimization.
2. Difficulty locating and verifying the sources of multiple variables used to determine LRV and other performance indicators.
3. Lack of information on how variables are determined or calculated by the manufacturer or SCADA program, or errors in how LRV is calculated.
4. Varying LRV determination and reporting required by states.
5. Lack of documentation for older membrane systems.
6. HMI and SCADA systems that lack sufficient detail to clarify or validate reported results.
7. Insufficient minimum test pressures.
8. Errors or discrepancies found in challenge study documentation translating to membrane installations in the field. One example is with older membrane modules that are changed out with newer modules without notification to regulators and without undergoing a thorough review by regulators to evaluate the impact on pre-existing LRV programming.

Therefore, to standardize the optimization goals and improve availability of reliable data to evaluate membrane plant performance against those goals, the following best practices are suggested:

1. Adopt the optimization goals presented in this document and begin implementation to determine any need for revisions.
2. For optimization purposes, the $LRV_{ambient}$ is determined at least after each DIT and compared to the LRV optimization goal of greater than or equal to 4.0 log.
3. $LRV_{ambient}$ is determined using the same factors as LRV_{DIT} but using the plant flow rate just prior to the DIT test and other parameters determined from the DIT test. Further, it is recommended that the Darcy Pipe Flow model (MFGM equation C.4) to determine the ALCR due to its more conservative nature, unless laminar flow is expected at all flow rates.
4. The LRV equation (MFGM equation 4.9, Chapter 4) should be used to determine $LRV_{ambient}$ for the purposes of comparing performance with the 4.0 log LRV goal.
5. Improve the transparency of how LRV and other performance indicators are determined for membrane systems.

Appendix B: Determining the Net Expansion Factor

The net expansion factor for compressible flow (Y) for use in the Darcy pipe flow model of calculating ALCR (shown as MFGM Equation C.4 below) may be obtained from charts in various hydraulics references, such as page A-22 (Crane, 1988) and using MFGM Equation C.5.

$$\text{ALCR} = 170 * Y * \sqrt{\frac{(P_{test} - BP)(P_{test} + P_{atm})}{TMP(460 + T)}}$$

MFGM Eq. C.4

Where:

- ALCR = Air to Liquid Conversion Ratio (dimensionless)
- *Y* = Net expansion factor for compressible flow through a pipe to a larger area (dimensionless). The net expansion factor is obtained from charts in various hydraulics references, such as Crane (1988) page A-22.
- P_{test} = DIT minimum pressure (psi)
- BP = backpressure on the system during the DIT (psi)
- P_{atm} = atmospheric pressure (psia)
- T = Water Temperature (°F)
- TMP = Transmembrane pressure during normal operation (psi)

The net expansion factor, Y, is a function of the applied test pressure (P_{test}), the system backpressure during the test (BP), atmospheric pressure (P_{atm}), and a flow resistance coefficient (K).

The flow resistance coefficient, K, is a common fluid flow parameter described by most hydraulics texts and is defined as shown in MFGM Equation C.6:

$$K = f * \frac{L}{d_{fiber}}$$

Where:

- *K* = flow resistance coefficient (dimensionless, use consistent units for L and d_{fiber}).
- *f* = friction factor (dimensionless), estimated from a Moody diagram (e.g., from Crane p. A-25) or corresponding tabulated values. See Appendix C of the MFGM for more information.
- L = length of the defect (in), which is typically the depth of the potting material to demonstrate the conservative scenario of a fiber break at the point where the fiber enters the pot.
- d_{fiber} = fiber diameter (in), which is the inside diameter of the fiber lumen.

With a flow resistance coefficient calculated, and the pressure-based expression determined as follows,

$$\frac{P_{test} - BP}{P_{test} + P_{atm}}$$

the net expansion factor, Y, can be determined from an empirical chart such as Crane 1988, page A-22. See the following example.

Example:

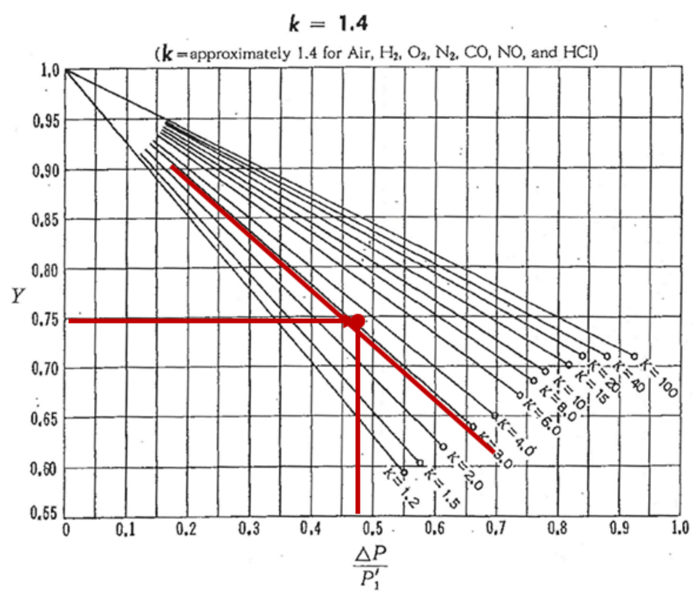
Given:

- P_{test} = 19.7 psi
- BP = 3.32 psi
- P_{atm} = 14.7 psi
- f = 0.027 mm
- L = 95 mm
- d_{fiber} = 0.9 mm

$$K = f \cdot \frac{L}{d_{fiber}} = 0.027\ mm \cdot \frac{95\ mm}{0.9\ mm} = 2.85$$

$$\frac{P_{test} - BP}{P_{test} + P_{atm}} = \frac{19.7 - 3.32}{19.7 + 14.7} = 0.476$$

Using the chart for air in Crane A-22 with K = 2.85 and $\frac{\Delta P}{P'_1} = 0.476$, yields Y = 0.74



Limiting Factors For Sonic Velocity
$k = 1.4$

K	$\frac{\Delta P}{P'_1}$	Y
1.2	.552	.588
1.5	.576	.606
2.0	.612	.622
3	.662	.639
4	.697	.649
6	.737	.671
8	.762	.685
10	.784	.695
15	.818	.702
20	.839	.710
40	.883	.710
100	.926	.710