INTEGRITY MANAGEMENT FOR LOW PRESSURE MEMBRANE PLANTS: IMPACT OF LOG REMOVAL VALUE(LRV) PARAMETER SELECTION

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ABSTRACT

Water quality and monitoring is of the utmost importance in drinking water systems. In terms of pathogen removal quantification, conventional systems are only able to rely on turbidity for this monitoring. Membrane facilities, on the other hand, can and are therefore also asked to also monitor and estimate the Log Removal Values (LRV) of the filtration units through the use of pressure decay tests. Correlating the results of the pressure decay test to obtain an estimate of the membranes' pathogen removal performance is accomplished through a set of calculations. In North America, the USEPA has led both the development and implementation of the LRV concept for membranes with the introduction of the Membrane Filtration Guidance Manual (MFGM) back in November 2005. The use of the LRV to demonstrate pathogen removal has become widespread as utilities upgrade their facilities to comply with more stringent regulatory requirements worldwide. Managing LRV has now become a crucial part in the design, permitting and operation of membrane facilities.

The multiple equations involved to compute the LRV on membrane systems require multiple raw and derived parameter inputs. Proper selection of the operating data is crucial to obtaining representative LRV values that can be used by the operations staff to properly assess the plant integrity. Several theoretical models and options are currently available for the end user to choose from. With the increase in the number of facilities utilizing LRV calculation for integrity management, the calculations and assumptions used have come under frequent scrutiny by the regulatory agencies.

This paper will examine key LRV parameters and present evidence comparing empirical data with theoretical calculations and relate the differences to the recommendations of the Membrane Filtration Guidance Manual. An overview of the different options available for parameters such as flow rate, transmembrane pressure, flow regime, and temperature will be provided. The timing of the integrity test and its relationship with the plant operation will also be reviewed since its impact can be significant on the outcome of the test. Lastly, due to its significant influence on the LRV calculations, a comparison between the theoretical model and experimental data will be presented on the Volumetric Concentration Factor.

KEYWORDS

Membrane Integrity; Microfiltration; Log Removal Value; Pressure Decay Test; Ultrafiltration

1 INTRODUCTION

Regulators, manufacturers, consultants, and utilities have embarked on a journey to implement LRV calculations over the last few years. In North America, the framework has been provided by the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR). Under this rule, systems in Schedule 1 (serving more than 100,000 people) need to be compliant with the new rule by March 2012. Smaller systems can have until September 2015 to be ready. The Drinking Water Standards for New Zealand 2005 (revised 2008) references the USEPA drinking water regulations to provide a framework around the LRV requirements. These requirements are structured around the final LT2ESWTR (Jan 2006) and the EPA Membrane Filtration Guidance Manual (Nov 2005). Questions and discussion points encountered by actors in the drinking water industry stem from the comprehensive implementation of the overall guidelines, and how to translate the requirements into detailed actions. Many options are available with different degrees of field verification, conservatism and parameter selection methods. This review will provide an overview of the impact of several parameter selection methods on the key LRV parameters

2 ESTABLISHING THE QUALITY CONTROL RELEASE VALUE (QCRV)

The Membrane Filtration Guidance Manual defines a Quality Control Release Value (QCRV) for membrane systems as the passing criterion for the NDPT (Non Destructive Performance Test). This is done to ensure an adequate correlation between the challenge test results obtained on a select number of modules, and modules installed at full-scale plants. For challenge testing, the recommendationis to select modules *"that are near the lower end of the statistical distribution of acceptable Non Destructive Performance Test results (NDPT)"* obtained during manufacturing. This approach yield several questions that have to be answered routinely:

- What does "near the lower end" mean? Is it a 90th percentile, a 95th percentile?
- How is the link between the selection of the QCRV at manufacturing and the challenge test results to be established?
- How many modules should be used to establish the "lower end of the statistical distribution"? What is an acceptable sample size?
- How are new module generations going to be handled? The statistical distribution won't exist initially until a significant number of modules have been produced for several projects. How can a QCRV be forecasted based on future production data yet to be obtained?

As can be seen, the overview of the QCRV generates a series of crucial questions for the manufacturer, regulator and water utility. The fundamental questions are how to correlate the challenge test to the QCRV, and whether averaging can be used. As an example, let's assume that a PDT is used as the manufacturing NDPT and the modules challenge-tested have an average Pressure Decay Rate (PDR)of 3.5 kPa/min,with the worst moduletested at 5 kPa/min. A QCRV of 3.5 kPa/mincould be selected in this example based on the average PDR value. In this case, aplant could therefore be installed with modules averaging a PDR less than 3.5 kPa/min but where many individual modules had a manufacturing NDPT higher than the worst module challenge tested (5 kPa/min in this example). The performance of the modules whose PDR is higher than 5 kPa/min is unknown in terms of pathogen removal because they have not been challenge tested.However, in the definition of the QCRV presented here, they are installed in an operating plant because the QCRV is defined as an average.

If the modules with a PDR higher than the maximum used in challenge tests are randomly consolidated in a rack or train, the average quality of this particular unit could be below the QCRV. In light of these potential issues, the argument could be made to select "defective" modules for the challenge testing under the LT2ESWTR frame work. For instance, if the manufacturing plant has established a QCRV of 3.5 kPa/min decay for a particular type of modules, the modules sent for challenge testing should all have decays greater than 3.5 kPa/min. This conservative module selection ensures that all the modules shipped to full-scale drinking water plants are better than those used during challenge testing and that their pathogenic removal capabilities are equal to or greater than the results obtained during the challenge testing, regardless of the facility's configuration.

3 SELECTING A VOLUMETRIC CONCENTRATION FACTOR (VCF)

Early LRV calculations were done without accounting for the impact of the Volumetric Concentration Factor (VCF). However, its contribution is now spanning almost 10 years. Indeed, the draft of the Membrane Filtration Guidance Manual released in June 2003 provided extensive details on how to account for the VCF in the LRV calculations. Its impact has then been refined in the final November 2005 version of the MFGM. The *VCF* is a dimensionless parameter representing the ratio of the concentration of suspended solids on the feed side of the membrane relative to that of the influent feed to the membrane filtration process. In theory, a system operating in dead-end filtration or deposition mode has a theoretical VCF of 1.0. In this concept, a broken fiber inside a tank or pressure vessel would allow non-concentrated raw water to enter the permeate through its broken end.

However, in real life situations the efficiency of the backwash procedure on membrane systems cannot be 100 percent. Once solids have accumulated around the fibers and within the fiber bundle, the air scour (if present) and permeate backpulse cannot return the modules to pristine, like-new conditions where all the solids have been flushed out into the waste stream. There will invariably be solids comprised of silt, coagulated matter that will remain inside the module. Therefore, the concentration of solids around the fibers is not exactly that of the raw water even in deposition mode. Experimental data was gathered in a pilot with one pressurized module to quantify the impact of the actual backwash efficiency on the VCF. Based on the expected error associated with low concentration TSS samples, as defined in Standard Methods for the Examination of Water and Wastewaters (APHA 1998), and the results the preliminary sampling event, turbidity analysis was chosen as the means to determine the VCF. The feed water turbidity was low, around 1-2 NTU, and it was assumed that the Turbidity/TSS ratio would hold constant within the range studied. As shown in Figure 1 below, five locations were sampled within the membrane module (Sample locations 2 through 6) in addition to the feed water sample (location 1).

Turbidity was measured continuously with five Hach Model 1720E online turbidimeters on the five locations in the membrane module (locations 2 to 6). One Hach FilterTrak 660 online turbidimeter was used to measure the pilot feed water turbidity (location 1). Data was collected every thirty seconds from all turbidimeters. All turbidimeters were calibrated in accordance to the manufacturers' protocols. To avoid introducing backwash waste into the turbidity sampling lines, sample pumps for locations 2 through 6 were turned off 30 seconds before the end of the filtration cycle and during the backwash, and turned back on at the beginning of the next filtration cycle.

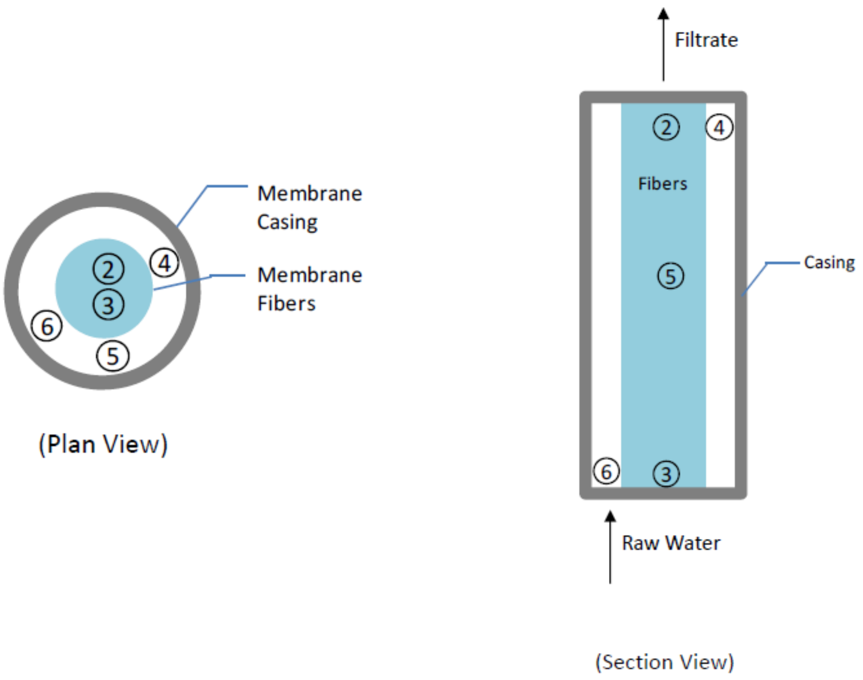

Figure 1: Plan view and section of turbidity sampling inside pressurized module

The experiments were conducted on a full-scale ZeeWeed® 1500 module (550 ft^2 or 51 m^2) operated at a flux of 102 lmh (temperature corrected at 20°C) and a transmembrane pressure (TMP) between approximately 180 and 220 kPa. The system operated with a filtration cycle of 30 minutes in dead end, yielding 100% feed water recovery using the definition of recovery given in Guidance Manual, Section 2.4.1. The overall recovery of the system was 98% when accounting for the backwash waste. The feed water temperature varied between 13.6°C and 14.2°C. The durations for pre-backpulse aeration and backpulse were 30 and 60 seconds respectively, and each backwash generated approximately 85-90 liters of backwash waste.

As discussed previously, the impact of a residual of solids is expected to be seen in the data due to the inherent operational efficiency of the backwash. This effect can be clearly seen on Figure 2below. Each backwash is identified by a spike in the average turbidity of the water inside the module casing. These spikes reached approximately 2.5 to 3.3 NTU.

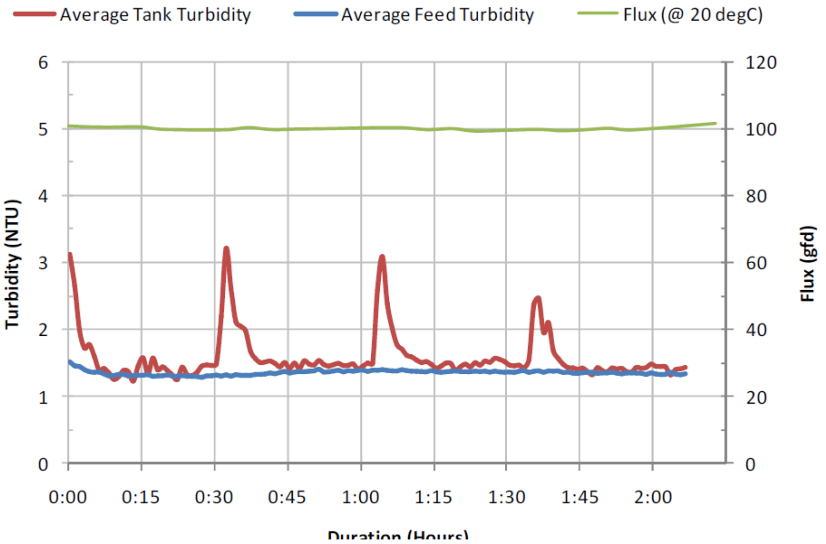

Figure 2: Continuous turbidity monitoring results

The results of the testing campaign are summarized in Table 1 below.The average and median VCF measured using continuous samplings are 1.2 and 1.1 respectively.

	Turbidimeter (NTU)						Mean of 2,3,4,5,6	VCF
	Feed	Location 2	Location 3	Location 4	Location 5	Location 6		
Average	1.4	1.6	1.8	1.7	1.4	1.5	1.6	1.2
Median	1.4	1.6	1.6	1.5	1.4	1.3	1.5	1.1

Table 1: Volumetric Concentration Factor results

This leaves us with an interesting scenario and decisions to make with five possible ways of accounting for the VCF:

- Use a VCF of 1.0 because it is the theoretical value in the MFGM.
- Use the Average VCF of 1.2
- Use the Median VCF of 1.1
- Use the maximum VCF measured right after a backwash
- Not rely on these values and redo the VCF testing at each full-scale plant site

Which of these values should be used? Experience so far has revealed that, depending on the jurisdiction, options 1, 2, 4 and 5 have all been requested by different regulatory agencies. This creates significant issues to drive a consistent approach and reduce variability. The data demonstrated that steady state operation yields a VCF of 1.0

as exemplified in Figure 2 where the feed and average turbidities in the modules reach the same values during the filtration cycle (red and blue lines overlap). This is an argument to use a VCF of 1.0. On the other hand, why not using a value of 1.2 that represents the average VCF? Other agencies have argued that the worst case scenario should be used. In this case, the spike observed for 30 to 60 seconds after a backwash should drive the VCF selection. In this particular case this would yield a VCF of approximately 3 for a system operating in deposition mode.

It is also important to note the impact of the VCF on two-stage plants. The VCF for the second stage has to take into account the concentration effect of the first stage. Irrespective of the first stage operating mode, its backwash waste (feed water to the second stage) is concentrated by $1/(1\text{-Recovery}_{1\text{st Stage}})$. For a typical first stage recovery of 95%, the second stage VCF is therefore 20 even if it operates in deposition mode. In this scenario, the LRV is reduced by 1.3 units (Log 20). For second stage systems operating in suspension mode the VCF would be directly linked to the recovery and a plant at 99.5% would have a VCF of 200 (1/(1-0.995)). This would yield a penalty of 2.3 Log (Log 200).

4 USING THE UPPER CONTROL LIMIT

Two approaches coexist in terms of integrity management: perform a pressure decay test and calculate the corresponding the LRV based on operating conditions, or pre-calculate a failure criterion and establish a not-to-exceed pressure decay rate. This latter method is called the Upper Control Limit (UCL) and defines the highest possible pressure decay rate allowed while still meeting the established LRV requirement. For reference, the definition of the UCL is presented in the Membrane Filtration Guidance Manual in equations 4.16 and 4.17 on page 4-22.

The UCL is defined using Q_p, the membrane unit design flow rate. In the definitions included, the recommendation for the Air-Liquid Conversion Ratio (ALCR) is to use a conservative value, and therefore calculate it with the maximum transmembrane pressure for the system (see pages C.4 and C.8 in the Membrane Filtration Guidance Manual). If one replaces the Hagen Poiseuille ALCR expression (Equation C.14 in MFGM) into the main UCL calculation (Equation 4.17 in MFGM), the following is obtained:

$$UCL = \frac{Q_P}{TMP} \bullet \frac{527 \bullet \Delta P_{Eff} \bullet \mu_w \bullet P_{atm}}{\mu_{air} \bullet (460 + T) \bullet 10^{LRC} \bullet V_{Sys} \bullet VCF}$$

Where

UCL = upper control limit in terms of pressure decay rate (psi/min)
Qp = membrane unit design capacity filtrate flow (L/min)
TMP = transmembrane pressure during normal operation (psi)
P_{atm} = atmospheric pressure (psia)
LRC = log removal credit (dimensionless)
V_{sys} = volume of pressurized air in the system during the test (L)
VCF = volumetric concentration factor (dimensionless)
ΔP_{eff} = effective integrity test pressure (psi)
μ_w = viscosity of water (lbs/ft-s)
μ_{air} = viscosity of air (lbs/ft-s)
T = water temperature (°F)

Membrane permeability (lmh/bar) is directly proportional to a flow in m^3/s/bar corrected for the membrane surface area (Q_p/TMP term). The rearranged equation above shows that the UCL calculation has an embedded permeability term and that the UCL, as well as the LRV, are proportional to the membrane permeability using the Hagen-Poiseuille model. Under the Darcy model, the UCL and LRV are proportional to $Q_p/\sqrt{TMP}$. Using a fixed design filtrate flow and the maximum Transmembrane Pressure (TMP) locks the UCL calculation to a specific "design" membrane permeability.

Under these constraints, a system designed at a flux of 70 lmh and a maximum TMP of 100 kPa would always use a flow rate corresponding to a flux of 70 lmh in the UCL calculation. With a max TMP of 100 kPa, the calculations always assume a membrane permeability of 70 lmh/bar. However, there is nothing preventing operation at a flux of 35 lmh and a TMP of 70 kPa for instance. In this scenario the membranes are more fouled than the "design" case but the plant can still operate well within its maximum allowed flux and below the maximum TMP limit. However, under this scenario the UCL value calculated is overestimated because it is based on a permeability of 70 lmh/bar while the system operates at 50 lmh/bar. The UCL calculated will therefore be double the correct value to guarantee the desired LRV requirement (likely 3 or 4 Log). The UCL calculated by the Membrane Filtration Guidance Manual would for instance be 5 kPa/min to guarantee 3 Log. In actuality, with the 1 to 2 ratio of permeability shown in this example, the UCL should be 2.5 kPa/min. The constant UCL of 5 kPa/min in this example would only guarantee an LRV of 2.7 Log (3 - Log(5/2.5)), instead of the intended 3 Log.

To properly be able to rely on the UCL method or to always obtain a conservative LRV estimate with a locked ratio between flow and TMP requires using the minimum flow achievable by the suction (immersed systems) or feed pump (pressure systems) to the train or skid. This would lock the calculations with the minimum permeability physically achievable in the facility with the equipment and membranes supplied. For centrifugal pumps, a turn down ratio of 1 to 3 is typical. Using this assumption, and a base line using the design flow, the UCL would be three times smaller. Another option would be to monitor online the system's permeability and not allow it to go below the pre-defined limit used in the UCL calculations. This would raise another set of questions such as what defines continuous monitoring and how much filtering on the data would be allowed. It would also impose another operational constraint on the operating staff of water plants unrelated to the ability of the plant's integrity at the time of the pressure decay tests. These approaches do not however appear practical in light of potential operational problems, the drop in LRV, and lowerallowable pressure decay rates for the UCL.

5 TIMINGOF INTEGRITY TEST AND IMPACT OF FOULING

The timing of the MIT sequence impacts LRV results. Since calculations are linked to membrane permeability, unit operations affecting permeability (backwash and cleans) have an effect on the LRV. The MFGM recommends performing MITs after backwashes and cleans to provide the most conservative LRV estimate (see page A-7). Using actual operating parameters, the outcome is however uncertain. The cleaning process exposes pin holes and defects that would have been previously blocked by the fouling layer. The PDR values are then likely to increase after the cleans and therefore decrease the LRV. However, backwashes and cleans increase membrane permeability, which would increase the LRV. The question is then: "Did the clean proportionally increase the permeability more than it proportionally increased the pressure decay value?" In that case, performing a PDT after a clean would yield a higher and not a lower, more conservative, LRV value.

Data has been gathered on several sites to look at the impact of recovery cleans on the LRV. Results are summarized inTable 2. The PDT and permeability multiplication factors (A and B respectively) are obtained by dividing the PDT and permeability values after the recovery clean by the ones before the recovery clean.

	Before Recovery Clean		After Recovery Clean		PDT multiplication factor (A)	Permeability multiplication factor (B)	MIT after recovery clean conservative?
	PDT (psi/min)	Permeability (gfd/psi)	PDT (psi/min)	Permeability (gfd/psi)			
Site 1 – Clean 1	0.16	9.44	0.33	15.2	2.06	1.61	Yes (A>B)
Site 1 – Clean 2	0.13	10.6	0.13	15.6	1	1.47	No (B>A)
Site 2 – Clean 1	0.11	3.5	0.13	12	1.18	3.43	No (B>A)
Site 2 – Clean 2	0.11	2.77	0.19	12.37	1.72	4.46	No (B>A)

Table 2: Impact of cleaning cycles on LRV results

As can be seen, the impact on LRV can be estimated based on the multiplier for the PDT and permeability before and after the clean. One can notice from the data set provided in Table 2that pressure decay rates are the same or greater after the clean. This is expected as the presence of a fouling or cake layer acts as a secondary barrier whose removal through the cleaning process increases the loss of pressure during the integrity test. The permeabilities also logically increased after the clean. In the end, one sees that the LRVs can improve since the permeability can proportionally increase more than the pressure decay rate. The first reaction would be to think that membrane rejection capabilities are always reduced after recovery cleans. This intuitive conclusion is not necessarily true as demonstrated here.

Further data needs to be gathered around the backwash procedure to study the influence of this unit operation on membranes rejection capabilities. One would expect an attenuated effect as the amount of fouling layer removed would be much less significant than during recovery cleans. The impact on the permeability and PDT value would therefore be reduced, but it is still unknown which parameter benefits the most from the backwash. It remains to be seen if doing an MIT after a backwash is conservative or aggressive when compared to the pre-backwash membrane integrity.

The link between permeability and LRV is exemplified by replacing the expression of the Hagen Poiseuille ALCR (Equation C.14 in MFGM) into the main LRV equation:

$$LRV = Log\left(\frac{Q_P}{TMP} \bullet \frac{P_{atm}}{\Delta P_{Test} \bullet V_{Sys} \bullet VCF}\,\frac{527 \bullet \Delta P_{Eff} \bullet \mu_w}{\mu_{air} \bullet (460+T)}\right)$$

Like the UCL, LRVs are proportional to permeability (Q_p/TMP). Therefore, this formula calculates lower LRVs as the permeability decreases. However, experimental results presented below show the opposite relationship. This behavior has been repeatedly confirmed on several challenge test campaigns on both the immersed and pressurized configurations.

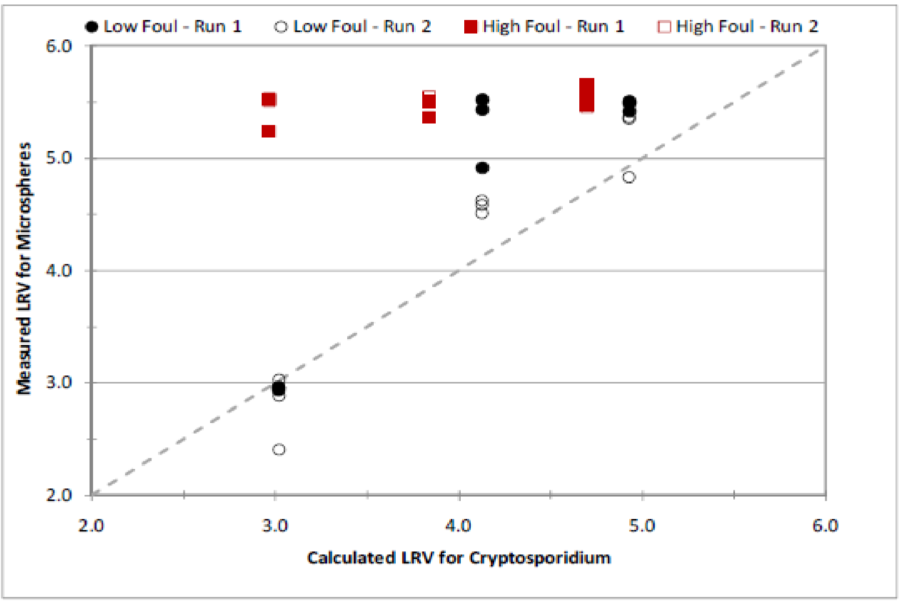

FIGURE 4
MICROSPHERES CORRELATION RESULTS

Figure 3: Impact of fouling on calculated versus measured LRV values

The data in Figure 3show the calculated versus measured LRV for 0.5 m glass microspheres used as a surrogate for Cryptosporidium. The experiments were carried out on a full-scale, 51 m^2, ZeeWeed®-1000 module operating according to full-scale conditions. The black circles show results obtained on clean conditions (15-20 kPa) while the red squares show the results obtained under the same flux and operating conditions when modules are fouled (85-90 kPa). These results are likely attributable to the extra filtration layer created by the fouling material and whose impacts are not modeled by the LRV calculations.

6 COMBINING PARAMETERS - IMPACT OF ASSUMPTIONS

Even though the LRVs are on a logarithmic scale, the decisions made in the selection of the parameters listed above based on the different scenarios available have a great influence on the results. Table 3compares the LRV obtained based on actual operational data to the values obtained using conservative parameter selections. The calculations were performed using formula 4.9 from the Membrane Filtration Guidance Manual. In the table, each effect presented on the LRV is cumulative. For instance, the LRV value of 4.30 is obtained if the base case assumption is updated to reflect a diffusion rate of zero, a maximum TMP of 90 kPa, and the maximum temperature of 25°C. In this case, the pressure decay rate would have to be 5 times smaller to be able to obtain an LRV value of 5 Log (Multiplier column).

	LRV result	Pressure decay Multiplier to calculate 5 Log
Base case - System is one ZeeWeed 1000 cassette populated with 90 modules. 50 lmh (assumed max flux), 2°C, TMP of 50 kPa, start MIT test pressure of 70 kPa, end test pressure of 67 kPa, Diffusion rate of 3.69e-12 mol/s/Pa/m^2, 5 min test, VCF =1 (theoretical)	5.00	1
Diffusion rate = 0	4.88	1.6
Max TMP (90 kPa)	4.64	2.3
Max Temp 25C	4.30	5
VCF = 1.5 in deposition mode	4.13	7.5
Switching from Hagen Poiseuille to Darcy ALCR	3.93	12

Table 3: Impact of parameter selection on the calculated LRV

As shown in the table, the selection of the LRV parameters has a very significant impact on the assessment the plant operating staff will make of the results. In the example above, for the same pressure decay rate the calculated membrane integrity goes from 5 Log to 3.93 Log with the elimination of the diffusion component, the use of the maximum TMP and temperature, the use of a VCF of 1.5 (average VCF value measured experimentally), and the use of the Darcy-modeled ALCR. The 23°C temperature range chosen between summer and winter would be typical of most systems.

It is easy to lose 1 or more calculated Log units depending on the assumptions made on the parameters going into the calculations. Attention must therefore be paid to maintaining a balance between the representativeness of the data, and the desired degree of conservatism in the LRV calculations.

7 CONCLUSION

Even though LRV calculations are globally defined, their detailed implementation is not straightforward and raises multipleparameter selection questions. Therefore, communication should be established early between all parties to define the calculations to be used for a specific project. Ideally, standard requirements can be established at the regulatory level to simplify the implementation of uniform LRV calculations with a consistent approach. Based on the limitations of the UCL model it is hereby suggested that standardization be looked at assuming actual flow, TMP and temperature as input for each integrity test, with the Hagen Poiseuille model when data is available to show its applicability. This would ensure that the LRVs calculated at the drinking water facility are representative of the plant's conditions and provide the necessary feedback to the operation staff.

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