filtrate for drinking water or post-filtration treatment rather than for recycling to an upstream point in the treatment process).

4.6 Example: Establishing Direct Integrity Test Parameters

Scenario:

A submerged, vacuum-driven hollow-fiber membrane system that operates in a deposition (i.e., dead-end) mode hydraulic configuration is required to provide a total of at least 3 log removal for *Cryptosporidium* by the State under the LT2ESWTR. A pressure decay test is applied to one of the membrane units in the system. Assume the plant is at sea level. Applicable parameters are as follows:

Operational parameters

- The permitted design capacity of the membrane unit is 1,200 gpm.
- The maximum anticipated water temperature is 75 ^{o}F (24 ^{o}C).
- The minimum anticipated water temperature is 41 ^{o}F (5 ^{o}C).
- The maximum anticipated backpressure that might be exerted on the units during direct integrity testing is 75 inches of water.
- The minimum anticipated backpressure that might be exerted on the units during direct integrity testing is 60 inches of water.
- The backpressure measured prior to the most recent pressure decay test was 65 inches of water.
- The filtrate flow measured prior to the most recent pressure decay test was 1,000 gpm.
- The TMP measured prior to the most recent pressure decay test was 10 psi.

Direct integrity test parameters

- The volume of pressurized piping during the test is 285 L.
- The initial applied test pressure is 16 psi.
- The duration of the pressure decay test is 10 minutes.
- Baseline (i.e., diffusive) decay is negligible over the duration of the test.
- The smallest verifiable rate of pressure decay under known compromised conditions is 0.10 psi/min.
- The most recent pressure decay test yielded a result of 0.13 psi/min.
- The temperature of both the water and the applied air were 68 ^{o}F (20 ^{o}C) during the most recent pressure decay test.

Unit and membrane characteristics

- The maximum rated TMP is 30 psi.
- The pore shape correction factor (κ) for the membrane material was not determined experimentally, and thus a conservative value of one is assumed.
- The membrane material is relatively hydrophilic and has a liquid-membrane contact angle (i.e., "wetting angle") of 30^{o}, as determined using a method acceptable to the State.
- The membrane surface variation (i.e., roughness) is 0.3 μm, as provided by the manufacturer.

- The hollow-fiber lumen diameter is 500 μm.
- The depth of the membrane into the potting material is 50 mm.
- All flow through any integrity breach that may be present is assumed to be turbulent.

Calculate:

1. The minimum direct integrity test pressure commensurate with the required resolution of 3 μm for the removal of *Cryptosporidium*

2. The sensitivity of the direct integrity test

3. The UCL for this system

4. The LRV verified by the most recent direct integrity test

Solution:

1. Calculate the minimum direct integrity test pressure commensurate with the required resolution of 3 μm for the removal of *Cryptosporidium*.

$$P_{test} = (0.193 \bullet \kappa \bullet \sigma \bullet \cos\theta) + BP_{\max} \qquad \text{Equation 4.1}$$

$\kappa = 1$ — from given information

$\sigma = 74.9$ dynes/cm — the surface tension of water at 5 °C

$\theta = 30^o$ — from given information

$BP_{max} = 75$ inches (of water column) — from given information

$$P_{test} = \left(0.193 \frac{psi \cdot cm}{dyne} \bullet 1.0 \bullet 74.9 \frac{dynes}{cm} \bullet \cos(30^o)\right) + \frac{75\ inches \cdot H_2O}{27.7\ \frac{inches \cdot H_2O}{psi}}$$

$$P_{test} = 12.5\ psi + 2.7\ psi$$

$$P_{test} = 15.2\ psi$$

Because the problem scenario states that baseline diffusive losses are negligible, the pressure calculated above represents the lowest permissible initial applied test pressure. If diffusive losses could not be neglected, P_{test} would represent the lower bound above which the pressure must be maintained to ensure that the resolution is maintained throughout the duration of the test. If this were the case, the applied pressure would have to be increased over P_{test} by the total anticipated pressure decay over the duration of the test. In this particular example, since the applied test pressure is given as 16 psi, the resolution requirement of the LT2ESWTR is satisfied.

2. Calculate the sensitivity of the direct integrity test.

$$LRV_{DIT} = \log\left(\frac{Q_p \bullet ALCR \bullet P_{atm}}{\Delta P_{test} \bullet V_{sys} \bullet VCF}\right)$$ Equation 4.9

Q_p = 1,200 gpm	design capacity filtrate flow (from given information)
P_{atm} = 14.7 psia	atmospheric pressure at sea level (from given information)

The minimum backpressure that might be exerted during direct integrity testing is used to establish a conservative value for sensitivity.

ΔP_{test} = 0.10 psi/min	smallest verifiable decay rate (from given information)
V_{sys} = 285 L	from given information
VCF = 1	standard for deposition mode hydraulic configuration
ALCR = ?	to be determined

Consult Table 4.1 and Appendix C – use Darcy pipe flow model for a hollow-fiber membrane filtration system under conditions of turbulent flow (as specified):

$$ALCR = 170 \bullet Y \bullet \sqrt{\frac{(P_{test} - BP) \bullet (P_{test} + P_{atm})}{(460 + T) \bullet TMP}}$$ Equation C.4

P_{test} = 16 psi	initial applied test pressure (from given information)

If diffusion through an integral membrane unit (i.e., baseline pressure decay was significant, the cumulative decay over the duration of the test would be subtracted from the initial test pressure before applying this parameter to Equation C.4 to yield a conservative result for the ALCR.

BP = 60 inches of water	minimum backpressure (from given information)

P_{atm} = 14.7 psia	atmospheric pressure at sea level (from given information)
T = 75 ^{o}F	maximum anticipated temperature (from given information)
TMP = 30 psi	maximum allowable TMP (from given information)

The values for system backpressure, temperature, and transmembrane pressure (TMP) were selected to establish a conservative (i.e., lower) value for the ALCR, which in turn yields a conservative value for sensitivity.

Y = ?	net expansion factor (to be determined)

As indicated in Equation C.5 in Appendix C, the gas compressibility 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), as follows:

$$Y \propto \left[\frac{1}{\left(\frac{P_{test} - BP}{P_{test} + P_{atm}} \right)}, K \right] \qquad \text{Equation C.5}$$

Smaller values for Y are generated with larger values of the first parameter in Equation C.5 and smaller values for K. Thus, values for these variables should be selected to produce smaller values of Y, which in turn yield smaller values for the ALCR and a more conservative value for the test sensitivity.

Quantifying the first parameter in Equation C.5:

P_{test} = 16 psi

BP = 75 inches (of water column)

P_{atm} = 14.7 psia

$$\left(\frac{P_{test} - BP}{P_{test} + P_{atm}}\right) = \left(\frac{16\,psi - \dfrac{75\ inches \cdot H_2O}{27.7\ \dfrac{inches \cdot H_2O}{psi}}}{16\,psi + 14.7\,psi}\right) = 0.43$$

The flow resistance coefficient is defined by Equation C.6, as described in Appendix C:

$$K = f \bullet \frac{L}{d_{fiber}} \qquad \text{Equation C.6}$$

L = 50 mm	potting depth (from given information)
d_{fiber} = 0.5 mm	fiber diameter (from given information)
f = ?	friction factor (to be determined)

The friction factor can be obtained using the iterative method described in Appendix C.

f = 0.037	friction factor (from iterative method)

$$K = f \bullet \frac{L}{d_{fiber}} = (0.037) * \left(\frac{50mm}{0.5mm}\right) = 3.7$$

Using the appropriate chart on page A-22 from Crane (1988) with the values calculated above:

$$\left(\frac{P_{test} - BP}{P_{test} + P_{atm}}\right) = 0.43, \qquad K = 3.7$$

…yields a value for Y as shown below.

Y = 0.78

Having determined a value for Y, the ALCR can be calculated follows:

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

$$ALCR = 170 \bullet (0.78) \bullet \left(\frac{\left(16\,psi - \dfrac{75\ inches \cdot H_2O}{27.7\ \dfrac{inches \cdot H_2O}{psi}} \right) \bullet (16\,psi + 14.7\,psi)}{(460^oF + 75^oF) \bullet 30\,psi} \right)^{0.5}$$

ALCR = 21.1

Substituting values into Equation 4.9 for sensitivity:

$$LRV_{DIT} = \log \left(\frac{\left(1{,}200\,gpm \bullet 3.785 \dfrac{L}{gal} \right) \bullet 21.1 \bullet (14.7\,psi)}{0.10 \dfrac{psi}{\min} \bullet 285L \bullet 1} \right)$$

LRV_{DIT} = 4.7

Therefore, the maximum removal value that this membrane filtration system is capable of verifying is 4.7 log.

3. <u>Calculate the UCL for this system</u>.

$$UCL = \frac{Q_p \bullet ALCR \bullet P_{atm}}{10^{LRC} \bullet V_{sys} \bullet VCF}$$ Equation 4.17

Q_p = 1,200 gpm — design capacity filtrate flow (from given information)

ALCR = 21.1 — as determined in Part 2 of this example, above

P_{atm} = 14.7 psia	atmospheric pressure at sea level (from given information)
LRC = 3	from given information
V_{sys} = 285 L	from given information
VCF = 1	standard for deposition mode hydraulic configuration

$$UCL = \frac{\left(1{,}200\,gpm \bullet 3.785\frac{L}{gal}\right) \bullet 21.1 \bullet (14.7\,psi)}{10^3 \bullet 285L \bullet 1}$$

UCL = 4.9 psi/min

4. <u>Calculate the LRV verified by the most recent integrity test</u>.

In addition to calculating the sensitivity, Equation 4.9 can also be used to determine the LRV verified by the most recent direct integrity test via applying values for the variables specific to this test event.

$$LRV = \log\left(\frac{Q_p \bullet ALCR \bullet P_{atm}}{\Delta P_{test} \bullet V_{sys} \bullet VCF}\right) \qquad \text{Equation 4.9}$$

Q_p = 1,000 gpm	flow measured prior to testing (from given information)
P_{atm} = 14.7 psia	atmospheric pressure at sea level (from given information)
ΔP_{test} = 0.13 psi/min	measured test decay rate (from given information)
V_{sys} = 285 L	from given information
VCF = 1	standard for deposition mode hydraulic configuration
ALCR = 21.1	as determined in part 2, above

Note that because the ALCR is designed to be a conservative value, it is not necessary to recalculate the ALCR for a specific pressure decay test in order to use Equation 4.9 for the purpose of determining the LRV verified by that test.

Substituting values into Equation 4.9 for sensitivity:

$$LRV = \log\left(\frac{\left(1{,}000\,gpm \bullet 3.785\,\frac{L}{gal}\right) \bullet 21.1 \bullet (14.7\,psi)}{0.13\,\frac{psi}{\min} \bullet 285L \bullet 1}\right)$$

LRV = 4.5

The above result of part 4 of this example demonstrates the effect that the membrane unit filtrate flow and integrity test response can have on the verifiable LRV at any point during operation. Although the sensitivity of this direct integrity test for this particular system under typical membrane unit operating conditions was determined to be an LRV of 4.7 in part 2, operating the unit at about 83 percent of the design flow, coupled with a measured pressure decay rate somewhat higher than the baseline detectable value under known compromised conditions, reduced the verifiable LRV to 4.5. Because this reduction still results in a verifiable LRV that is significantly higher than the required LRC of 3.0, operation under these conditions would still allow the system to maintain compliance with the LT2ESWTR.

4.7 Test Methods

The LT2ESWTR does not specify a particular type of direct integrity test for rule compliance, but instead allows the use of any test that meets the requirements of the rule (40 CFR 141.719(b)(3)). The two general classes of tests currently employed in municipal water treatment applications are pressure- and marker-based tests. Within these two categories, the particular types of tests most commonly used are described in the following subsections, including the pressure and vacuum decay tests, the diffusive airflow test, the water displacement test, and particulate and molecular marker tests. General procedures for conducting each of these tests are provided, along with a listing of some of the advantages and disadvantages of each method. The particular manner in which each of these tests is applied may vary according to manufacturer or site- or system-specific conditions.

The specific tests addressed in this guidance manual are not intended to represent a comprehensive list of all types of direct integrity tests that could be used to comply with the requirements of the LT2ESWTR. Any method that is both consistent with the definition of a direct integrity test under the rule and capable of meeting the specified resolution, sensitivity, and frequency requirements could be used for rule compliance at the discretion of the State.