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Subject: Technical Memorandum on Pathogen Crediting Frameworks for Decentralized Non-Potable Water Systems

1 Introduction

Through the efforts of San Francisco Public Utilities Commission (SFPUC) and the San Francisco Department of Public Health (SFDPH), the City and County of San Francisco (CCSF) has been at the forefront of the growing movement to enhance water supply reliability through the onsite reuse of water. Decentralized non-potable water systems (DNWS) are defined as 'systems in which water from local sources is collected, treated, and used for non-potable applications at the building, neighborhood, and/or district scale, generally at a location near the point of generation' (Sharvelle et al. 2017). Given the nascent stage of this concept both in California and at the national scale, multiple hurdles to implementation exist. Key among these are the lack of both public health standards and an established, streamlined permitting process. To address these issues, SFPUC contracted with the National Water Research Institute (NWRI), Water Environment Research Foundation (WERF), WateReuse Research Foundation (WRRF) and Water Research Foundation (WaterRF) to move forward two key goals: (1) the development of recommendations and guidance for treatment requirements that ensure public health protection, and (2) the development of a management framework for the appropriate use of onsite-treated alternate water sources for non-potable applications. To address the first goal, NWRI convened an Expert Panel to establish water quality and monitoring criteria with a focus on pathogen removal targets, monitoring regimes, management, permitting, and applications for the treated water sources. The product of this effort is the final report entitled, "Risk-Based Framework for the Development of Public Health Guidance for Decentralized Non-Potable Water Systems" (Sharvelle et al. 2017).

One of the main outcomes of this report was the creation of water quality standards, particularly related to the minimum degree of pathogen removal required for public health protection. The NWRI panel chose to focus their criteria on pathogens because they considered microbial risks to be "the greatest concern to human health in DNW systems" (Sharvelle et al. 2017). Given that their framework focuses only on non-potable applications, they deemed that "the most important risk is human exposure to pathogens that become airborne or are ingested with small amounts of water." While exposure to chemical contaminants may also occur, they were not considered in their framework. A risk-based approach was used to determine the pathogen removal goals.

These goals are specified in terms of "log reduction targets," or LRTs, where an LRT of 1 represents a 1-log (or 90% reduction), a 2 represents a 2-log (or 99% reduction), and so forth.

To develop the LRTs, the Panel utilized quantitative microbial risk assessment (QMRA) to relate human health risk with the exposure to microbial hazards in the non-potable water supplies. Starting with assumptions about (a) tolerable levels of risk and (b) the concentrations of pathogens in different source waters, they back-calculated the degree of treatment (i.e., LRTs) that would be required to ensure public health protection. The Panel calculated LRTs for two different "tolerable" risk goals:

- 1 in 10,000 (10^{-4}) infections per person per year (ppy) due to exposure to water from a DNWS. This risk goal is often considered the benchmark for potable applications in the U.S.; it underlies the EPA's Surface Water Treatment Rule (EPA 1989, Regli et al. 1991), and is the explicit goal of California's potable reuse regulations for groundwater recharge (CDPH 2014, Hultquist 2016).
- 1 in 100 (10^{-2}) infections ppy due to exposure to water from a DNWS. This second risk goal reflects EPA's recreational water quality guidelines, which specify controlling to a level at or below 10^{-2} illnesses ppy (EPA 2012). The 10^{-2} *infection* ppy goal specified by the Panel is more conservative than EPA's guidelines of 10^{-2} *illnesses* ppy due to the fact that only a fraction of all infections will result in illness. The higher rate of acceptable illness (10^{-2}) compared to the drinking water standards (10^{-4}) is due to the fact that exposure to recreational waters is voluntary.

Given the involuntary exposure associated with DNWS applications, at this time, SFPUC and SFDPH anticipate moving forward utilizing the 10^{-4} infections ppy risk target for CCSF's on-site reuse systems. By choosing this level, the public's exposure to the non-potable DNWS source will present a risk that is no greater than that associated with its consumption of potable sources. Furthermore, given the lack of experience in DNWS, it may be more appropriate to begin implementation with the more stringent risk goal. All further discussions of LRTs and example treatment trains will be based on the 10^{-4} risk goal.

The degree of pathogenic microorganisms present depends on the source water, with the highest concentrations expected in fecally-contaminated waters such as blackwater. Accordingly, a system's LRTs depend on its source water(s). The LRTs for blackwater, graywater, stormwater, and roof runoff water for use in both unrestricted irrigation and indoor use are presented in Table 1. The stormwater LRTs are also applicable to foundation drainage water.

Table 1. Log reduction targets for decentralized non-potable water systems based on source water and end use. LRTs are based on achieving a risk goal of 10^{-4} infections per person per year, per Sharvelle et al. (2017). LRTs corresponding to 10^{-2} risk goal are 2-logs lower than values shown.

Water Use Scenario	Enteric Viruses	Parasitic Protozoa	Enteric Bacteria
Domestic Wastewater/Blackwater			
Unrestricted irrigation	8.0	7.0	6.0
Indoor use	8.5	7.0	6.0
Graywater			
Unrestricted irrigation	5.5	4.5	3.5
Indoor use	6.0	4.5	3.5
Stormwater (10^{-1} dilution[a])			
Unrestricted irrigation	5.0	4.5	4.0
Indoor use	5.5	5.5	5.0
Stormwater (10^{-3} dilution[a])			
Unrestricted irrigation	3.0	2.5	2.0
Indoor use	3.5	3.5	3.0
Roof runoff water			
Unrestricted irrigation	N/A	No data	3.5
Indoor use	N/A	No data	3.5

[a] LRTs are based on the assumption that the dominant contributor of pathogens in stormwater is contamination with municipal wastewater. Stormwater dilutions represent different contributing fractions of municipal wastewater.

1.1 Purpose of this Document

Per the recommendations of the NWRI Panel, DNWS must provide treatment systems that meet or exceed the minimum specified LRTs in order to ensure public health protection. The purpose of this document is to present different unit treatment processes that could be used to achieve the LRTs, and describe the existing regulatory frameworks for crediting these processes with pathogen removal or inactivation (log reduction values or LRVs). The document also provides template treatment trains that could be used to achieve the necessary LRTs for the different types of source water. These trains are not meant to be prescriptive, but to illustrate potential approaches for the design of a DNWS treatment train using existing pathogen crediting frameworks.

2 Pathogen Crediting Frameworks

2.1 Introduction

Water treatment systems consist of a series of unit processes. To meet a wide range of water quality goals, multiple unit processes are often designed in series, with each providing a specific function, e.g., coagulation, filtration, disinfection. The extent of pathogen removal achieved by a unit process is a function of the treatment mechanisms involved (e.g., physical removal in a membrane filter, DNA damage by UV irradiation) and also its design and operation. Multiple studies have been undertaken to quantify pathogen removal and inactivation through various unit processes, often using human pathogens or microbial indicators to assess performance. Because

they use actual microorganisms to assess pathogen control, these challenge studies provide perhaps the best estimate of the "actual" performance of the system. One downside of these challenge studies, however, is the long turnaround between the time when the water is sampled and when performance is quantified. Due to the limitations of current pathogen monitoring methodologies, days to weeks may be needed to evaluate pathogen removal performance. These long delays can be problematic, particularly if the quality of the water needs to be monitored and verified on shorter timescales. Oftentimes, regulations require that unit processes be measured on an interval as frequent as once every 15 minutes, a constraint that limits the applicability of many microbial methods.

For this reason, it is important to differentiate between the "actual" level of pathogen removal and that which can be rapidly and continuously demonstrated. In lieu of direct pathogen measurements, surrogates are frequently used to provide a continuous evaluation of system performance. Examples include the use of turbidity to measure filter performance, or the use of a disinfectant "CT" dose to quantify the degree of inactivation. Oftentimes, these surrogates have lower sensitivity than the microbial methods, and thus cannot demonstrate the same degree of protection as a microbial challenge study. Because they can provide a rapid and continuous demonstration of performance, however, surrogates are frequently used as the basis for the crediting of pathogen barriers. The specifics of the crediting schemes for the various unit processes will be presented in subsequent sections.

When seeking to comply with a given set of LRTs, a treatment train must receive pathogen removal 'credit' equal to or greater than the LRTs. Both the EPA and California Surface Water Treatment Rules emphasize the importance of multiple barrier treatment, that is, the use of a series of treatment processes to provide removal and inactivation of pathogens. The primary types of barriers that will be discussed in this document are those that achieve physical removal through filtration and chemical inactivation through disinfection.

2.2 Elements of Pathogen Crediting Frameworks

Pathogen crediting frameworks generally consist of requirements for validation, field verification, and ongoing monitoring of treatment performance (Sharvelle et al. 2017). Each of these aspects, as described briefly below, will be addressed for each unit process being considered in this document.

- Validation: initial demonstration that a unit process is capable of achieving a certain amount of pathogen removal/inactivation. Validation is typically done at pilot- or demonstration-scale.
- Field verification: demonstration upon system startup that the system is functioning as expected, i.e., in line with the previous validation testing.
- Ongoing monitoring of treatment performance: ongoing demonstration of compliance with influent and effluent water quality standards, dose requirements, and other aspects of a unit process related to treatment performance.

2.3 Available Frameworks

The following sections describe the major frameworks currently in use to credit unit processes for the removal and inactivation of enteric viruses, *Giardia lamblia* cysts, and *Cryptosporidium* oocysts.

2.3.1 Drinking Water

The concept of pathogen crediting originated in the Environmental Protection Agency's (EPA) Surface Water Treatment Rule (SWTR). The original rule and subsequent updates lay out pathogen removal requirements for facilities treating surface waters, specifying minimum log reductions for enteric virus, *Giardia lamblia*, and later, in the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR), *Cryptosporidium*. To help facilities comply with these rules, the EPA has created guidance manuals that lay out approaches for demonstrating and receiving pathogen credit for various types of treatment. The guidance documents referenced here are listed below.

Ultimate authority for enforcing the surface water treatment rules lies with the states[1]. Therefore, this document also references the California drinking water regulations, contained in the California Code of Regulations, Title 22, Division 4, Chapter 17: Surface Water Treatment (CDPH 2013). Additional guidelines for UV disinfection have been published by NWRI. Although these are not regulations, DDW has endorsed them and acknowledged that future regulations may be based on them (SWRCB Division of Drinking Water 2014).

EPA Documents

- Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems using Surface Water Sources (1991)
- Disinfection Profiling and Benchmarking Guidance Manual (1999)
- Alternative Disinfectants and Oxidants Guidance Manual (1999)
- Membrane Filtration Guidance Manual (2005)
- Long Term 2 Enhanced Surface Water Treatment Rule (2006)
- Ultraviolet Disinfection Guidance Manual for the Final Long Term Enhanced Surface Water Treatment Rule (2006)
- Long Term 2 Enhanced Surface Water Treatment Rule Toolbox Guidance Manual (2010)

California Documents

- California Code of Regulations, Title 22, Division 4, Chapter 17: Surface Water Treatment (2013)

Additional Documents

- National Water Resources Institute Ultraviolet Disinfection: Guidelines for Drinking Water and Water Reuse, Third Edition (2012)

[1] If a state has not obtained primacy, i.e., primary enforcement responsibility over public water systems, then the responsibility lies with the EPA (EPA 1991).

2.3.2 Potable Reuse

Pathogen crediting frameworks in potable reuse are generally similar to those used for drinking water. Additional guidance is provided in the California groundwater replenishment regulations.

EPA Documents

- Membrane Filtration Guidance Manual (2005)
- Ultraviolet Disinfection Guidance Manual for the Final Long Term Enhanced Surface Water Treatment Rule (2006)
- Long Term 2 Enhanced Surface Water Treatment Rule Toolbox Guidance Manual (2010)

California Documents

- California Code of Regulations, Title 22, Division 4, Chapter 3: Water Recycling Criteria (2014)
    - Article 5.1: Indirect Potable Reuse: Groundwater Replenishment – Surface Application
    - Article 5.2: Indirect Potable Reuse: Groundwater Replenishment – Subsurface Application

2.3.3 Non-Potable Reuse

The primary pathogen framework referenced here is that used for non-potable reuse in California. Additional information from Australian guidelines was also used.

California Documents

- California Code of Regulations, Title 22, Division 4, Chapter 3: Water Recycling Criteria (2014)

Additional Documents

- National Water Resources Institute Ultraviolet Disinfection: Guidelines for Drinking Water and Water Reuse, Third Edition (2012)
- Australian WaterVal Membrane Bioreactor Validation Protocol (2017)

2.4 Bacteria Crediting

Identifying the link between waterborne pathogens and human disease was a key moment in the history of public health. Once this relationship was understood, the water industry began verifying the microbial safety of treated water through the use of a bacterial standard—the absence of total coliform in drinking waters was used to demonstrate that the water was suitable for human consumption (NRC 2004). With the effluent coliform standard, it was not necessary to quantify the *removal* of pathogens through different unit processes; it was only necessary to show that the final treated water complied with the effluent standard. The actual crediting of processes did not arise until the late 20th century, when the water industry realized that the coliform standard might not provide sufficient protection against more resistant pathogens, such as viruses and protozoa. Consequently, regulatory frameworks in the U.S. and other countries evolved to address three additional pathogens: enteric viruses, *Giardia lamblia* cysts, and *Cryptosporidium* oocysts. Because the "safe" levels of virus and protozoa are below those that can be detected with existing monitoring techniques, effluent monitoring was no longer capable

of demonstrating adequate pathogen control (Macler and Regli 1993, Regli et al. 1991, Trussell et al. 2013). Instead, the new regulations required that a minimum degree of pathogen reduction through the treatment train be demonstrated, such that the final effluent would achieve the low levels considered to be "safe."

One consequence of this approach is that frameworks for establishing bacterial removal credits through unit processes—e.g., CT tables for chlorine and UV disinfection, removal credits for membrane filtration, etc.—have not been developed. This presents a challenge in the DNWS framework, given that specific bacterial LRTs have been recommended. Ideally, bacterial removal and inactivation could be credited using existing frameworks that have been evaluated and accepted by EPA or other recognized authorities. In the absence of such guidance, this report offers two approaches for bacteria. The first is to use the historical model—effluent total coliform monitoring—as an indicator that bacteria levels in the effluent have been sufficiently controlled. This approach is a compromise given one of the goals of the DNWS report is to move toward on-line verification of unit performance and away from effluent monitoring.

Alternatively, efforts could be made to assign bacterial reduction credits based on an understanding of pathogen removal and inactivation through the various unit processes. This report proposes a number of potential bacterial crediting frameworks for unit processes where this relationship might be made. We recommend that additional research efforts further develop and evaluate bacterial crediting frameworks, particularly in light of the fact that a number of guidance documents specify bacterial log reduction targets (Crook et al. 2013, Natural Resource Management Ministerial Council et al. 2008, Sharvelle et al. 2017).

We propose a two-pronged approach for bacterial crediting. Using the proposed unit process crediting frameworks in this document, it is possible to build treatment trains that achieve the bacterial LRTs using on-line surrogate monitoring. Trains that can use surrogate monitoring alone to meet the DNWS bacterial LRTs can consider reducing or eliminating effluent coliform monitoring requirements. However, if a unit process does not have a proposed crediting framework, or the treatment train cannot meet the bacterial LRT using the proposed frameworks, we recommend using effluent total coliform monitoring to verify the bacterial quality of the water. As bacterial crediting frameworks continue to evolve for additional unit processes, the use of these frameworks can replace or reduce the frequency of effluent coliform monitoring.

For systems relying on effluent coliform monitoring, we recommend an adaptive monitoring approach to allow a highly performing system to decrease monitoring frequency over time, assuming the requirements are consistently met. One way to implement the adaptive monitoring approach would be to have the monitoring frequency set in conjunction with the three risk management categories in the NWRI report. The report identifies three broad risk management categories based on the size of the user population, the likelihood of exposure, and the pathogen concentrations in the source water. Category 3 systems might begin with one month of daily sampling (20 samples allows quantification of performance at the 95th percentile value), 5 months of weekly sampling (20 additional samples allows quantification of performance at the 97.5th percentile value), and subsequent monthly sampling. Category 2 system could monitor daily for one week, weekly for three weeks, and then monthly. In all cases, if a system fails to

meet the total coliform goal at any point, the monitoring program should be restarted from the beginning.

3 Principles of Pathogen Control

The unit processes covered in this document remove pathogens via two primary mechanisms: physical removal through filtration and chemical inactivation via disinfection. This section reviews important principles of these types of processes that are necessary background for the crediting approaches.

3.1 Filtration Concepts

Filtration is used for the physical removal of pathogens, which can be accomplished through a variety of mechanisms depending on the form of filtration being used. All filtration processes discussed in this document are pressure-driven membrane processes. The basic principle of this type of process is illustrated in Figure 1. A feed stream is pumped against a membrane, which results in a product stream as well as a waste stream containing the removed constituents. The two commonly used types of pressure-driven membrane processes are membrane filtration and reverse osmosis. The two processes use different types of membranes and removal mechanisms, among other differences. Each will be discussed in further detail in subsequent sections.

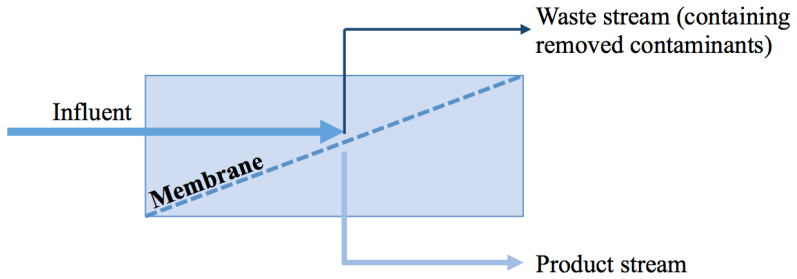


Figure 1. Schematic of membrane-based separation process.

3.2 Disinfection Concepts

Disinfection refers to the destruction and/or inactivation of pathogenic microorganisms by exposure to a chemical agent or physical process. In the context of water treatment, this is generally accomplished in flow-through reactors where a disinfectant is continuously being added. The extent of disinfection achieved by a given process is a function of the susceptibility of a particular pathogen to a disinfectant, the concentration to which it is exposed, and the time of exposure. The most commonly used framework for disinfection is the CT framework. CT refers to the product of the disinfectant residual concentration (C) and the contact time (T). The EPA has compiled CT tables for several disinfectants and pathogen types. An example of the CT table for virus inactivation using free chlorine is shown in Table 2. Using this table, one sees that a 2-log reduction in virus (99% inactivation) would require a CT of 2 mg-min/L at a temperature of 15˚C and pH 7.

Table 2. CT values for virus inactivation by free chlorine, per USEPA (1991). CT values are in units of mg-min/L.

	Log Inactivation					
	2.0 pH		3.0 pH		4.0 pH	
Temperature (C)	6-9	10	6-9	10	6-9	10
0.5	6	45	9	66	12	90
5	4	30	6	44	8	60
10	3	22	4	33	6	45
15	2	15	3	22	4	30
20	1	11	2	16	3	22
25	1	7	1	11	2	15

3.2.1 Disinfection Hydraulics

Disinfection contactors—e.g., tanks, basins, clearwells, etc.—are effectively reactors in which the disinfectant is reacting with pathogens. Because these systems are generally flow-through, it is important to understand how reactor hydraulics impact the way in which these systems are typically credited. Hydraulics are important because they impact the time the water spends in contact with the disinfectant, i.e., the "T" in the CT equation. To illustrate the importance of reactor hydraulics for disinfection performance, consider the two extremes in terms of flow and mixing: the completely stirred tank reactor (CSTR) and the plug flow reactor (PFR). These two reactor types are illustrated in Figure 2 and can be assumed to have the same volume. For any flowrate Q, then, these two reactors have the same average hydraulic retention time (HRT), which is simply the volume of the reactor divided by the flowrate (V/Q).

In the case of the CSTR, the inflow to the reactor is immediately mixed with the entire contents; therefore, some fraction of the water exits immediately after entering the reactor with the remainder spending varying lengths of time in the reactor. In the ideal PFR, there is no mixing in the direction of flow; therefore, every drop of water that enters the reactor spends exactly the same time in the reactor before exiting. In both of these ideal cases, the water spends the same amount of time in the reactor *on average*, since they have identical HRTs. However, in the CSTR the water experiences a distribution of residence times whereas in the PFR all water experiences the same residence time.

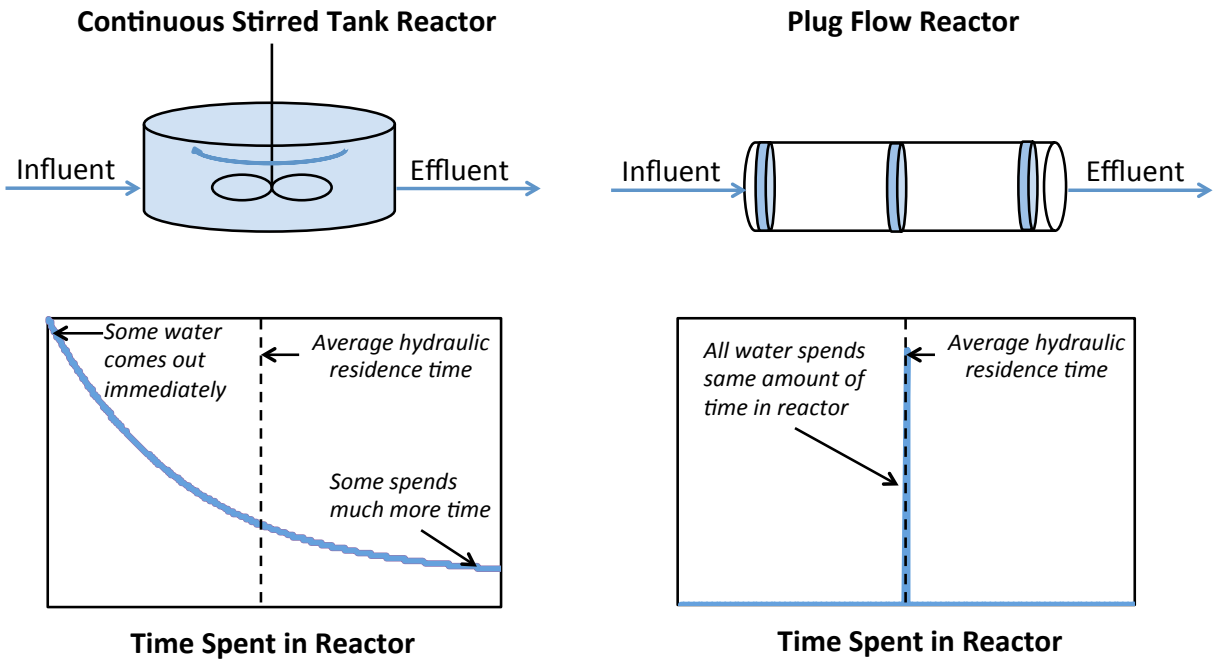


Figure 2. Illustration of reactor hydraulics for two reactor types.

In an ideal PFR, the contact time is straightforward – it is the length of time experienced by all of the water, namely, the HRT. In the CSTR, however, the contact time for disinfection is not as obvious since a distribution of retention times are observed; some water spends very little time, some spends a very long time. Reactors that behave closer to ideal plug flow are more desirable for disinfection since they eliminate the possibility of water spending a very short time in the reactor. In reality, there is always a distribution of time spent by water in the reactor. Characterizing this distribution and using the appropriate contact time is a critical component of disinfection practice.

Reactor hydraulics are generally characterized using a tracer study. The basic methodology of a tracer study involves applying a tracer chemical to the system and subsequently tracking the effluent tracer concentrations over time. These data can then be used to create a profile of the flow distribution exiting a reactor. A sample tracer curve is shown in Figure 3, along with the two most common values used for contact time: T_{10} and T_{Modal}. T_{10} refers to the time it takes for 10% of the tracer to exit the reactor; this provides a measure of the minimum contact time experienced by 90% of the flow through the reactor. T_{Modal} refers to the time it takes for the peak concentration of tracer to exit the reactor and is a more average representation of time spent in the reactor. The application of these different contact times for specific disinfection processes will be discussed further in the relevant unit process sections of Section 4.

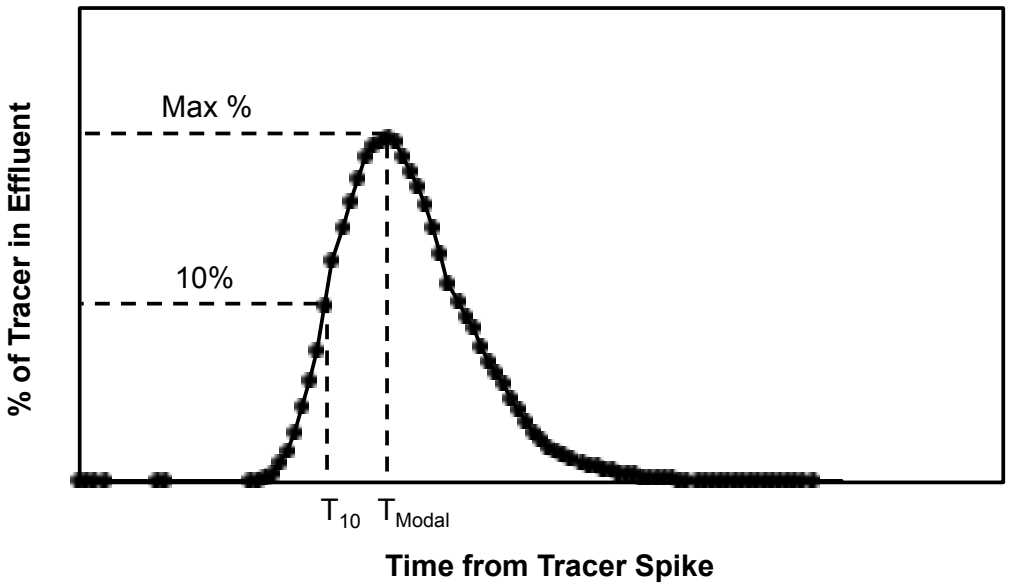


Figure 3. Example data from a tracer study illustrating the T_{10} and the T_{Modal}

3.2.2 Impact of Particles on Disinfection

Particulate matter present in water can provide a surface for interactions with pathogens. The association of pathogens with particles can impact the efficiency of disinfection by shielding the microorganisms from the disinfectant (Hejkal et al. 1979, Herson et al. 1987, Hoff 1978, Hoff and Akin 1986, LeChevallier et al. 1981, Parker and Darby 1995, Stagg et al. 1977). For example, bacteria and viruses associated with particles can exhibit slower disinfection kinetics than when they are free floating, also known as monodisperse (Pecson 2016, Pecson et al. *submitted*). Because the CT tables were developed for surface waters, it may be difficult to extrapolate these values to water with higher organic loading and different types of particulates (e.g., raw wastewater). To avoid the effects of particle shielding in disinfection, filtration is commonly used as pretreatment. In general, if disinfection is practiced after a membrane filtration process, the impact of shielding should be low because membrane filtration is highly effective at removing particulate matter.

4 Unit Process Crediting Frameworks

4.1 Microfiltration/Ultrafiltration

The two forms of low-pressure membrane filtration are microfiltration (MF) and ultrafiltration (UF). Both processes employ the same treatment mechanism, namely, the physical removal of suspended particles via size exclusion, given that the membrane pores are of a sufficiently small size to block the passage of many waterborne particles. The primary difference between MF and UF is pore size, with MF membranes having larger pore sizes (0.1 – 0.2 µm) than UF membranes (0.01 – 0.05 µm) (EPA 2005). As shown in Figure 4, the pore size is directly related

to the types of pathogens that can be removed by the size exclusion mechanism[2]. In general, both MF and UF are effective at removing protozoa and bacteria.

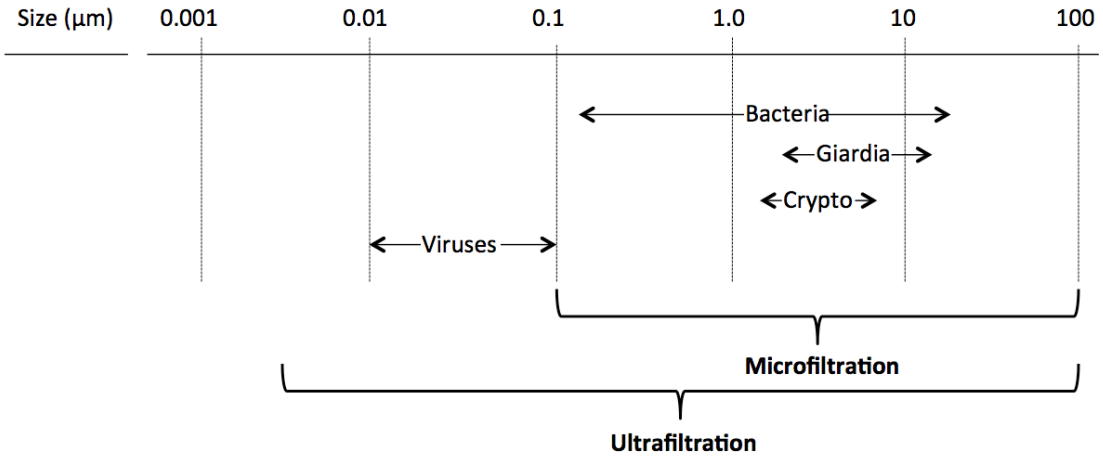


Figure 4. Comparison of pathogen size with typical pore size range of membrane filtration processes. Figure adapted from USEPA (2005).

4.1.1 MF/UF – Drinking Water & Potable Reuse – California

MF and UF have received pathogen removal credit in the context of both drinking water and potable reuse. The primary source of guidance on pathogen crediting through MF and UF is the EPA's Membrane Filtration Guidance Manual (USEPA 2005).

Validation & Field Verification

Current practice in California and the U.S. is to award pathogen credit to systems that can demonstrate their ability to (1) detect a breach of 3 µm or larger with a membrane integrity test, and (2) meet the continuous turbidity requirements (see the following section, Ongoing Monitoring of Treatment Performance). A breach of 3 µm or greater is relevant because it represents the size of *Cryptosporidium* oocysts, the smaller of the two protozoan pathogens. This can be done with pilot testing or upon full-scale system startup; validation with pathogen challenge testing is not required. Although membranes do not currently need to undergo validation testing, a list of technologies that have previously been validated using the guidelines from the Membrane Filtration Guidance Manual is available (CDPH 2011).

Ongoing Monitoring of Treatment Performance

Two types of ongoing monitoring are required: direct and indirect integrity testing. A direct integrity test is defined as "a physical test applied to a membrane unit in order to identify and isolate integrity breaches (i.e., one or more leaks that could result in contamination of the

[2] Additional removal mechanisms exist, such as removal of smaller particles due to the formation of a cake layer on the membrane surface.

filtrate)" (CDPH 2013). The three requirements for a direct integrity test are as follows (USEPA 2005):

- Must be responsive to integrity breach on the order of 3 µm (or less)
- Must verify LRV equal to or greater than the removal credit awarded
- Must be conducted on each membrane unit no less than once per day that the process is operational

Direct integrity testing is typically accomplished with a pressure decay test, in which pressure is applied to membrane units and the subsequent loss in pressure is monitored over time. The rate of pressure loss can be related to the size of holes in the membrane and used to identify significant breaches in the system. In intact systems, the loss of pressure occurs slowly; this rate increases as the system experiences more breaches. As part of the membrane validation process, control limits must be developed for pressure decay tests (or an alternate direct integrity test). These limits indicate the pressure decay rate above which there is a breach of 3 µm or greater. If the PDT on a membrane unit fails to meet this limit, that unit must be taken offline. Because direct integrity testing requires membrane units to be taken offline, it is generally done on a daily basis.

The size of the membrane breach that can be detected is inversely proportional to the amount of pressure required, that is, higher pressures are needed to detect smaller holes. The amount of pressure needed to detect a virus-sized integrity breach is beyond the capacity of any existing MF/UF units to withstand; therefore, although virus removal may be documented during validation testing, it cannot be verified on an ongoing basis and so is generally not credited (EPA 2005).

In addition to periodic direct integrity testing, continuous indirect integrity testing is also required. This consists of monitoring an aspect of filtrate water quality that is reflective of the removal of particulate matter (CDPH 2013). California stipulates the use of turbidity, although they allow for case-by-case approval of alternative parameters. 'Continuous' monitoring is defined as measuring at least once every 15 minutes. If the turbidity is above 0.15 NTU for greater than 15 minutes, a direct integrity test must be triggered. Monthly reporting of all monitoring results that triggered direct integrity testing, along with the corrective action taken in each case, is required.

4.1.2 MF/UF – Non-Potable Reuse – California

The use of MF and UF for non-potable reuse in California is governed by the California Code of Regulations Title 22, Division 4: Environmental Health, Chapter 3: Water Recycling Criteria. In the context of non-potable reuse, membrane filtration is used as pretreatment for disinfection. Title 22 non-potable regulations stipulate requirements for virus reduction and final bacterial quality; there is no requirement for protozoa removal. As a result, MF/UF systems do not receive pathogen credit in the context of non-potable reuse because they (1) cannot demonstrate ongoing virus removal, and (2) they are not required to demonstrate protozoa removal. Although no credit is given, filtration does provide effective pretreatment that removes particulates and prepares the water for subsequent disinfection steps. The following discussion outlines the requirements for membrane filtration processes preceding disinfection steps in non-potable reuse.

Validation

Both MF and UF are already approved filtration technologies for use in non-potable applications, and thus they do not need to undergo product-specific validation (CDPH 2014).

Field Verification

California does not provide any specific pathogen-related requirements to be completed upon system startup. Field verification of performance is achieved through the use of the ongoing monitoring techniques outlined below.

Ongoing Monitoring of Treatment Performance

The monitoring requirement for MF/UF systems is continuous (i.e. at least every 15 minutes) online turbidity measurement. The effluent must meet the following turbidity criteria:

- Less than or equal to 0.2 NTU 95% of the time within a 24-hour period
- Never greater than 0.5 NTU

4.1.3 MF/UF Bacterial Crediting

As discussed, pathogen credit in MF/UF systems is awarded based on a verification of the integrity of the system. In order to receive protozoa credit, MF/UF systems must demonstrate a high degree of system integrity against *Cryptosporidium*, i.e., down to a 3-µm breach size. Because bacteria may be significantly smaller than *Cryptosporidium* oocysts (Figure 4), the direct integrity tests may not provide a conservative representation of bacterial removal through MF/UF. As a result, bacteria removal credit based on protozoa removal is not recommended for MF/UF systems. Additional research in this area is recommended to develop a bacterial crediting framework.

4.1.4 MF/UF Frameworks Overview & Comparison

The pathogen crediting frameworks for MF/UF are summarized in Figure 5. The main difference between these frameworks is that the potable framework grants pathogen (namely, protozoa) removal credits and requires a pressure decay test. Neither of the two frameworks assigns virus removal credit. The effluent turbidity standards are also less stringent for non-potable systems. Both the drinking water and non-potable reuse frameworks could be applied in DNWS. If systems desire to receive credit for protozoa removal through MF/UF, they would apply the drinking water framework; if they only need to achieve sufficient pretreatment for subsequent disinfection, the non-potable framework would enable them to do so with less operational complexity.

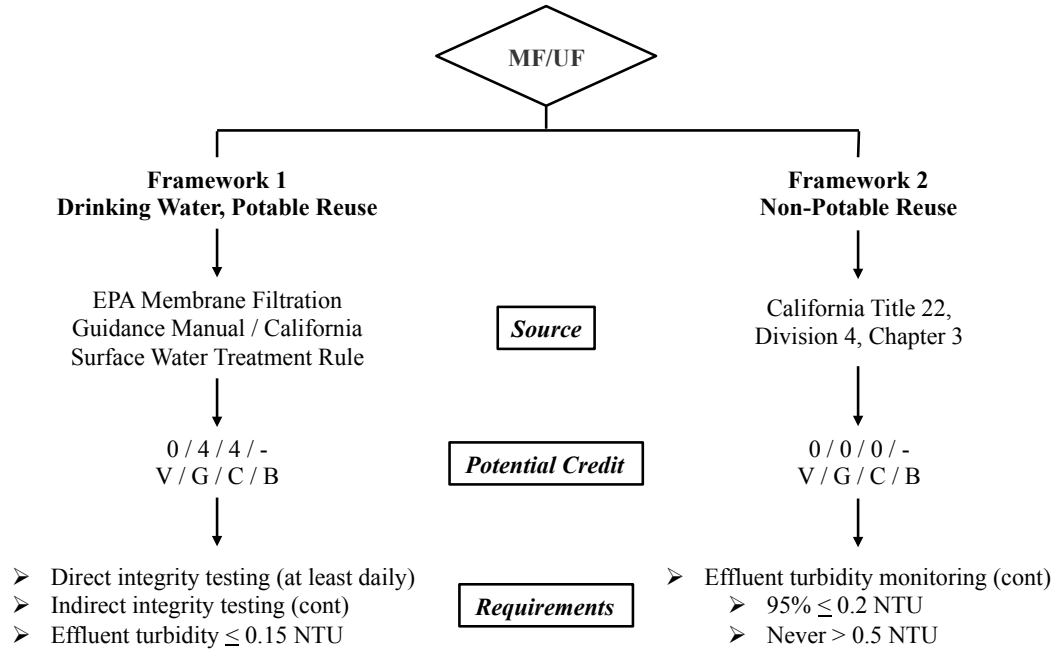


Figure 5. Summary of MF/UF pathogen crediting frameworks, including the framework source, potential pathogen credits, and requirements.

4.2 Membrane Bioreactor

Membrane bioreactors consist of both biological treatment and membrane filtration. The biological treatment is a suspended growth system with a high mixed liquor suspended solids (MLSS) concentration, and the membrane filter is typically an MF or UF membrane. These systems have several pathogen removal mechanisms, including size exclusion, adsorption, and biodegradation. The mechanism of size exclusion by the membrane is the same as for MF/UF systems. There are several sources of adsorption sites in the system, including the suspended solids within the activated sludge and the cake layer that forms on the membrane as it fouls. Biopredation by larger organisms has been shown to reduce the concentrations of some smaller pathogens (Branch and Le-Clech 2015).

MBRs are used in wastewater and non-potable reuse applications, but to date have not been credited with pathogen removal in California. The Australian WaterVal program has recently published an MBR crediting framework that will be discussed in the following section (WaterSecure 2017). DDW has indicated their willingness to accept this framework for pathogen crediting of MBRs in California.

4.2.1 MBR – Non-Potable Reuse – Australia

Validation

The Australian MBR validation protocol specifies three validation tiers. Tier 1 does not require site-specific validation; it allows for default pathogen credits (Table 3) to be awarded if the system is operated within a specified range of operating conditions referred to as the operating

envelope (Table 4). Tier 2 and 3 validation allow for additional pathogen credits, however they both involve extensive challenge testing. The requirements for Tiers 2 and 3 will not be covered here (see WaterSecure (2017) for additional information) under the assumption that on-site systems will likely select the default Tier 1 credits to minimize the complexity of the validation process. The following discussion relates to compliance with Tier 1 requirements.

Table 3. Default MBR pathogen LRVs for Tier 1, per WaterSecure (2017)

Pathogen Type	Default LRV
Virus	1.5
Protozoa	2
Bacteria	4

Field Verification

Field verification must be done to verify the system is operating within the Tier 1 operating envelope (Table 4). Field verification involves operating and monitoring the system to demonstrate that all of the required performance and water quality metrics are met. No additional pathogen testing is required.

Ongoing Monitoring of Treatment Performance

Systems must perform continuous indirect integrity monitoring in the form of effluent turbidity and demonstrate that the system always has effluent turbidity $\leq$ 0.2 NTU. Additional parameters need to be continuously monitored as well to ensure the MBR remains within the operating envelope: mixed liquor suspended solids (MLSS), hydraulic retention time (HRT), membrane flux, permeability, and temperature. The acceptable ranges of operating conditions are summarized in Table 4.

Table 4. Summary of MBR operating envelope for Tier 1 default LRV credits. Adapted from WaterSecure (2017)

Parameter	Units	Minimum	Maximum
Bioreactor pH	pH units	6	8
Bioreactor dissolved oxygen	mg/L	1	7
Bioreactor temperature	C	16	30
Solids retention time	d	11	--
Hydraulic retention time	h	6	--
Mixed liquor suspended solids	g/L	3	--
Transmembrane pressure	kPa	3	--
Flux	$L/m^2/h$	--	30
Turbidity	NTU	--	0.2

4.2.2 MBR – Non-Potable Reuse – California

Validation & Field Verification

No product-specific validation is required for MBRs. A list of previously validated MBRs is available for reference (SWRCB Division of Drinking Water 2014). Currently, an MBR must demonstrate that it meets the California Title 22 turbidity requirements for tertiary filtration. This can be done with pilot testing or upon startup of the full-scale system. If the system does not meet the turbidity requirements it must discharge to the sewer until it can demonstrate compliance.

Ongoing Monitoring of Treatment Performance

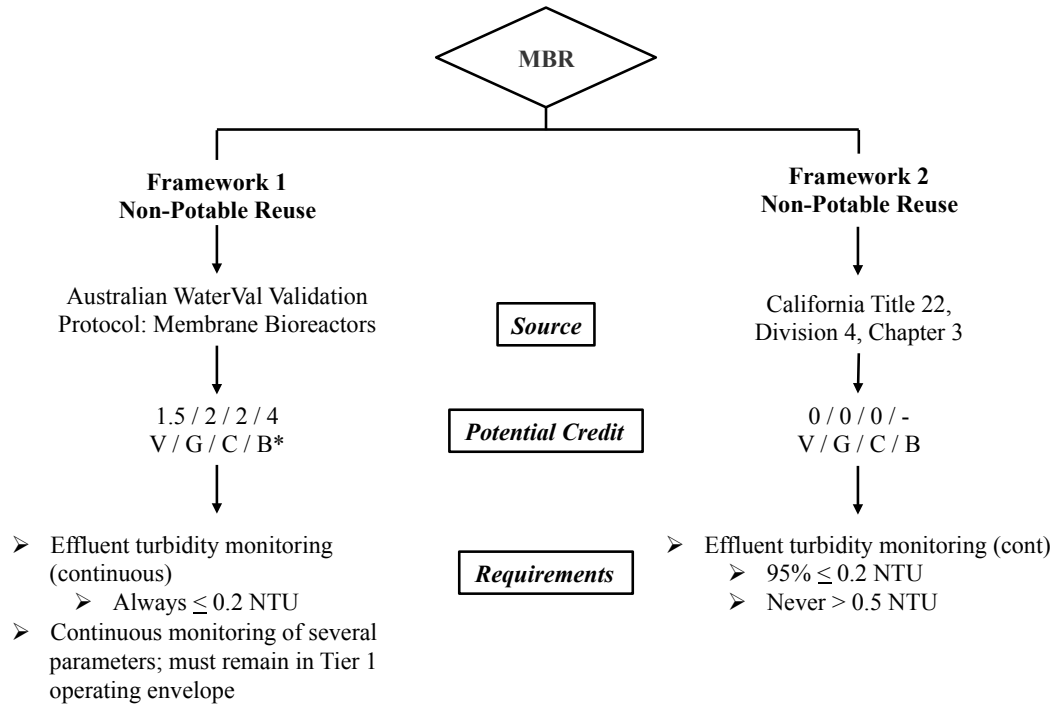
The monitoring requirement for MBR systems is continuous online turbidity measurement. The effluent must meet the following turbidity criteria:

- Less than or equal to 0.2 NTU 95% of the time within a 24-hour period
- Never greater than 0.5 NTU

4.2.3 MBR Frameworks Overview and Comparison

An overview of the available pathogen crediting frameworks for MBRs is provided in Figure 6. As shown, pathogen credit is only available under the Australian guidelines. The Tier 1 operating envelope allows systems to receive default pathogen credits for all pathogen groups, including bacteria. Although the authors have reviewed the validation protocol, the data used to develop the default pathogen credits have not been reviewed. Therefore, if these credits are to be used, we recommend their adoption only after they have received official approval from DDW or through a similar, rigorous independent evaluation. As stated, DDW has indicated their willingness to accept this framework for pathogen crediting.

Even though pathogen credit will not be obtained under the California non-potable reuse framework, MBRs provide a large benefit in the form of organics reduction. This benefit is particularly relevant for blackwater and graywater, which both have high levels of organics that can interfere with downstream unit processes—including chemical and UV disinfection—and lead to issues with both the aesthetics and microbial stability of the finished water.



** Crediting should occur only after evaluation of data used to develop default values, or DDW approval of this framework*

Figure 6. Summary of MBR pathogen crediting frameworks, including the framework source, potential pathogen credits, and requirements.

4.3 Reverse Osmosis

Reverse osmosis (RO) is a membrane process designed to remove dissolved solids. By applying high pressure, water is forced through a semi-permeable membrane that allows the passage of water while rejecting nearly all of the dissolved solids. The ability to remove dissolved species makes RO a more effective barrier for chemical constituents than MF/UF. However, because of the high pressures required, RO is also more energy-intensive. RO has also been shown to provide greater rejection of pathogens than MF/UF membranes; unfortunately, there is not currently a direct integrity test for RO that can demonstrate this high rejection on an ongoing basis. RO is eligible for removal credit for all pathogen groups, but generally receives less protozoa credit than MF/UF because of the lack of a direct integrity test.

4.3.1 RO – Drinking Water – California

Validation

RO membranes are not required to undergo validation with pathogen challenge testing.

Field Verification

Neither EPA nor California provides any specific pathogen-related requirements to be completed upon system startup. Field verification of pathogen removal is achieved through the use of the ongoing monitoring techniques outlined below.

Ongoing Monitoring of Treatment Performance

In the context of drinking water systems, RO is generally only used for desalination of seawater or brackish groundwater. Pathogen credit for desalination is obtained through the use of online monitoring of electrical conductivity (EC)[3] in the influent and effluent; because the EC of seawater is so high, this method typically is able to demonstrate 2-log reduction of all pathogen types. RO systems must have a control limit to indicate when the integrity has been compromised. Alarms and corresponding response procedures must be initiated if the system reaches the established control limit.

4.3.2 RO – Potable Reuse – California

Validation

RO membranes must undergo testing to demonstrate that they meet the following standards (CDPH 2014):

- Minimum sodium chloride rejection of 99%
- Average sodium chloride rejection no less than 99.2%

This testing is generally product-specific[4], with no site-specific validation required.

Field Verification

There are no pathogen-specific field verification requirements for RO systems. Field verification should be conducted using ongoing performance monitoring methods to verify that the system achieves the accepted LRV, and that system alarms are functioning.

Ongoing Monitoring of Treatment Performance

Pathogen credit is most commonly demonstrated through the removal of a surrogate parameter, typically EC or TOC removal. Online monitors are used in both the influent and effluent to continuously demonstrate rejection. TOC monitors are more expensive but have higher sensitivity than EC, allowing for higher log reduction to be demonstrated. RO systems must consistently demonstrate that they are achieving the log reduction for which they are credited. The system must establish control limits that define the acceptable operating range; when operation crosses outside the control limits, corrective actions must be taken. These actions would be defined in the engineering report.

[3] EC rejection is an indirect measurement of total dissolved solids rejection
[4] Rejection must be demonstrated through Method A of ASTM International's method D4194-03 (2008)

Because RO is known to achieve higher levels of pathogen removal than can be demonstrated with either TOC or conductivity, new surrogates are being investigated that can demonstrate higher levels of removal. This is an area of active research, and to date no new surrogates have officially been approved by DDW.

4.3.3 RO – Bacteria Crediting

Given the mechanism of pathogen removal through RO, we recommend awarding the same removal credit for bacteria as is awarded for virus and protozoa. Because viruses are smaller than bacteria, it should be conservative to assume that bacterial rejection is equivalent to virus rejection.

4.3.4 RO – Additional Considerations

RO is highly effective at removing dissolved constituents and pathogens. However, it results in the generation of a concentrated brine stream that requires disposal. It may be possible to dispose of this stream through the sewer.

4.3.5 RO – Frameworks Comparison and Overview

A summary of the RO pathogen crediting frameworks is provided in Figure 7. Either of these frameworks could be used for DNWS.

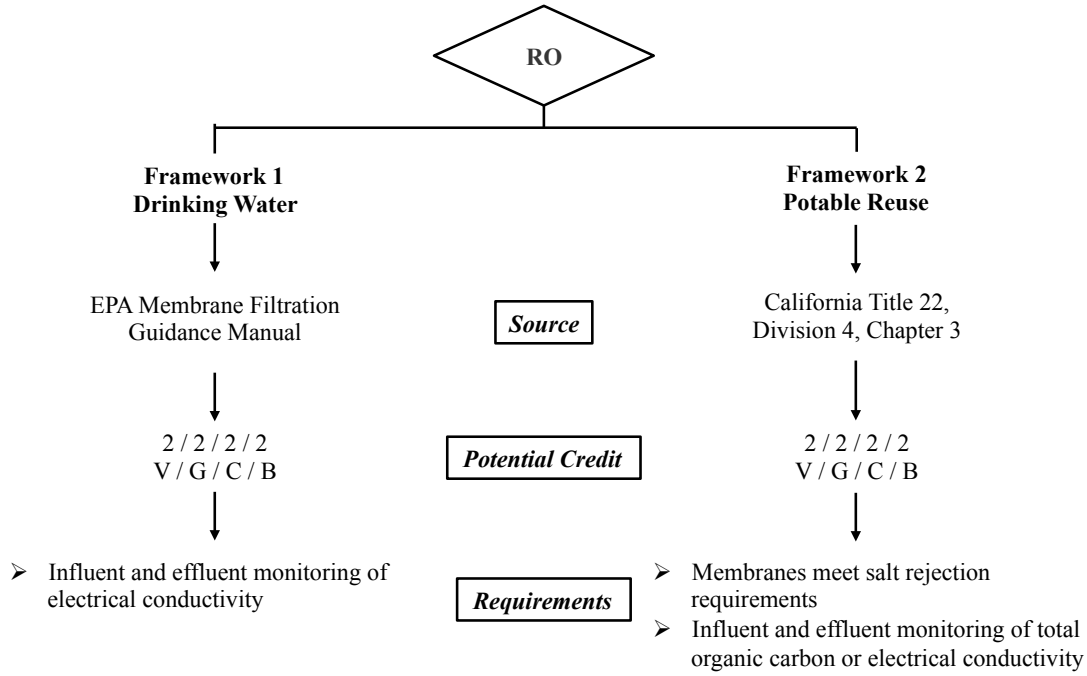


Figure 7. Summary of RO pathogen crediting frameworks, including the framework source, potential pathogen credits, and requirements.

4.4 Ultraviolet Light

Ultraviolet light irradiation (UV) is a commonly used disinfection process that involves generating and transmitting UV light to inactivate pathogens (USEPA 2006). The principle mechanism of disinfection is through damage to nucleic acids, which inhibits pathogen replication. Benefits of UV treatment include its effectiveness against all of the pathogen types, and its low formation of disinfection by-products (DBPs).

UV treatment is used in the drinking water, potable reuse, and non-potable reuse contexts. The CT framework cannot be applied to UV systems because there is no disinfectant residual present, however it does use an analogous crediting scheme. Instead of calculating the product of residual concentration times contact time, UV disinfection is based on the amount of UV light emitted by the system (in mW/cm^2) multiplied by the duration of exposure to the light source (in seconds). The product of these two is a "dose" expressed in millijoules per square centimeter (mJ/cm^2). UV doses have been related to pathogen inactivation for the three main pathogen groups (V/G/C) for both drinking water and non-potable reuse.

4.4.1 UV – Drinking Water – California

Validation

UV reactor validation is required and must follow a state-approved procedure. Currently, two validation frameworks are accepted in California for drinking water reactors: the EPA UV Disinfection Guidance Manual (USEPA 2006) and the German UV Devices for the Disinfection for Drinking Water Supply Standard (commonly known as DVGW) (DVGW 2006). An additional validation framework, the NSF/ANSI 55 Standard for UV Water Treatment Systems, is used for household systems and may also be applicable for DNWS (NSF / ANSI 2016). Reactor validation with these three frameworks is product-specific, and approved reactors can be used without site-specific validation as long as the system is operated within the ranges of validated water quality and operational conditions.

All three validation frameworks involve challenge testing with pathogen surrogates to determine the operating conditions under which the desired UV dose can be delivered. The EPA UVDGM framework allows for flexibility in the UV dose, with the target dose depending on the amount of pathogen inactivation credit being sought (see Table 5). Challenge testing must evaluate the operating conditions of flow rate, UV transmittance, and lamp status. In addition, the testing must account for lamp fouling and aging, measurement uncertainty of on-line sensors, and the UV dose distribution in the reactor (CDPH 2013). At a minimum, validation must involve testing at the high and low flow rates, as well as two intermediate flow rates. At each flow rate, three tests must be conducted with three paired influent and effluent samples per test.

The DVGW and NSF frameworks require that validation testing verify a UV dose of 40 mJ/cm^2 under all validated operating conditions, with an alarm system indicating when the system is not providing the required dose.

Table 5. UV dose requirements (mJ/cm^2) for pathogen inactivation per USEPA (2006).

Target Pathogens	Log Inactivation							
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
Cryptosporidium	1.6	2.5	3.9	5.8	8.5	12	15	22
Giardia	1.5	2.1	3.0	5.2	7.7	11	15	22
Virus	39	58	79	100	121	143	163	186

[1] 40 CFR 141.720(d)(1)

As part of validation testing, an alarm setpoint method must be selected. The two options are:

- UV intensity setpoint method: specifies UV intensity setpoint (or multiple setpoints for different flow rate ranges) corresponding to the validated dose; if the system drops below the setpoint(s), an alarm is triggered
- Calculated dose method: a dose-monitoring equation is used to verify the dose in real time as a function of UV transmittance, flow, and UV intensity. If the calculated dose drops below the required level, an alarm is triggered

The amount of pathogen credit a UV reactor can receive depends on the validation testing. Under the EPA framework, a reactor is validated for a specific level of pathogen inactivation; a validated reactor should receive that inactivation credit if it is operated within the validated range of conditions. For both the DVGW and NSF validated reactors, DNWS will likely need two reactors validated for 40 mJ/cm^2 in series to obtain virus credit. For both reactor types, two reactors in series should receive 3.5-log virus credit and 6-log credit for both *Cryptosporidium* and *Giardia*.

Field Verification

UV reactors validated in accordance with each of the three frameworks discussed above do not need to perform field verification with pathogen challenge tests.

Ongoing Monitoring of Treatment Performance

Several parameters must be measured continuously to verify UV treatment performance. These parameters are flow rate, influent UV transmittance, influent turbidity, and UV intensity. These parameters must all fall within the validated range of conditions for the reactor to receive pathogen inactivation credit. In addition, monitoring must be provided for critical system information such as lamp status, lamp age, and number of on/off cycles for all systems.

In order to apply the UV dose table provided by EPA (see Table 5), the water entering the UV reactor must have undergone filtration that achieved an effluent turbidity less than or equal to 0.3 NTU 95% of the time and never greater than 1 NTU[5]. For all validation frameworks, the influent water quality to the UV reactor *must* fall within the validated range of conditions.

[5] This requirement does not apply to drinking water systems whose source water quality complies with the requirements to avoid filtration.

4.4.2 UV – Non-Potable Reuse – California

Validation

Validation of UV reactors for use in non-potable reuse systems in California must follow the NWRI guidelines. Reactors are validated for a specific UV dose, depending on the type of filtration pretreatment used (see Table 6). Validation involves challenge testing with MS2 (a commonly used viral pathogen indicator) over a range of operating conditions. A minimum of four flow rates must be tested: minimum, maximum, and two intermediate flows. At each flow rate, three tests must be conducted, with each test consisting of three replicates of paired influent and effluent MS2 samples. The MS2 removal data, along with operating data that were collected such as UV transmittance, flow rate, and UV intensity, are used to develop a predictive dose model. This model can be used to define the range of acceptable operating conditions at which the required dose can be achieved.

Table 6. UV pretreatment and dose requirements for non-potable reuse applications (NWRI 2012).

Filtration Pretreatment	Water Quality Requirements	UV Dose[a] (mJ/cm^2)
Granular Media Filtration	24-hour avg turbidity $\leq$ 2 NTU Turbidity $\leq$ 5 NTU 95% of the time Turbidity never > 10 NTU $UVT_{254} \geq$ 55%	$\geq$100
Membrane Filtration	Turbidity $\leq$ 0.2 NTU 95% of the time Turbidity never > 0.5 NTU $UVT_{254} \geq$ 65%	$\geq$80
Reverse Osmosis	Turbidity $\leq$ 0.2 NTU 95% of the time Turbidity never > 0.5 NTU $UVT_{254} \geq$ 90%	$\geq$50

[a] For maximum daily flow

Field Verification

The NWRI guidelines for UV treatment recommend spot-check commissioning tests for pathogen inactivation performance. These are similar to the validation challenge tests, in which pathogens or appropriate surrogates are spiked into the system and paired influent and effluent samples are used to quantify inactivation. The guidelines recommend that eight spot-check tests be done at a variety of operating conditions to verify that the intent of the design is met. Seven out of the eight tests should meet or exceed the level of performance that would be expected based on the system design.

Ongoing Monitoring of Treatment Performance

Several parameters are frequently measured for the UV system to ensure it is operating within the range of validated conditions. These parameters are flow rate, UV intensity, influent UV

transmittance and turbidity, and operational UV dose. In addition, monitoring must be provided for critical system information such as lamp status, lamp age, and number of on/off cycles.

In addition, non-potable applications in California are required to conduct daily total coliform (TC) monitoring that must comply with the following:

- 7-day median TC $\leq$ 2.2 MPN/100 mL
- TC > 23 MPN/100 mL in no more than 1 sample per month
- TC never > 240 MPN/100 mL

As discussed previously, we recommend an adaptive total coliform monitoring approach that will allow for a reduction in sampling frequency over time.

For non-potable applications, filtration pretreatment is required for UV systems. The requirements for both UV influent water quality and UV dose are dependent on the type of pretreatment used. The requirements for both are summarized in Table 6. These water quality requirements were developed based on the operating experience of existing plants; water with quality outside this range can be treated by a UV system if it has been tested during validation.

4.4.3 UV – Bacteria Crediting

UV dose tables do not exist for bacteria as they do for viruses and protozoa. The available data suggest that virus inactivation is a conservative indication of bacteria inactivation (LeChevallier and Au 2004), whereas protozoa inactivation may not be (Tchobanoglous et al. 2004). Therefore, we recommend awarding the same credit for bacteria as is achieved for virus.

4.4.4 UV Frameworks Comparison and Overview

An overview of the available pathogen crediting frameworks for UV systems is provided in Figure 8. On-site reuse systems are likely to rely on previously validated UV reactors rather than undergo the validation process, which may be prohibitively expensive. One challenge with this is that most of the reactors that have been validated at the relevant flow rates for DNWS are intended for use in drinking water applications. Using these reactors in the non-potable reuse context poses several issues. For example, the water quality of drinking water is very different from that of a graywater or blackwater. UV reactor validation results in a specific range of operating conditions, including a lower bound on influent UV transmittance. These conditions may be difficult for the alternative source waters to meet. We recommend that systems seeking virus inactivation credit through the use of previously validated reactors provide a validated UV dose of at least 80 mJ/cm^2. This can be done with two DVGW or NSF reactors in series. Such a setup should receive 3.5-log enteric virus credit and 6-log protozoa credit. If a UV reactor (or equivalent combination of reactors in series) has been validated to a dose of 150 mJ/cm^2 or greater, it may be eligible for 6-log enteric virus credit.

Systems using UV reactors validated under the NWRI guidelines can receive credit, depending on dose, of up to 5-log enteric virus inactivation. This framework does not explicitly grant protozoa credit because of the lack of a regulatory driver to do so. However, based on the doses provided, these reactors should receive 6-log protozoa inactivation credit for UV doses of 50, 80, or 100 mJ/cm^2.

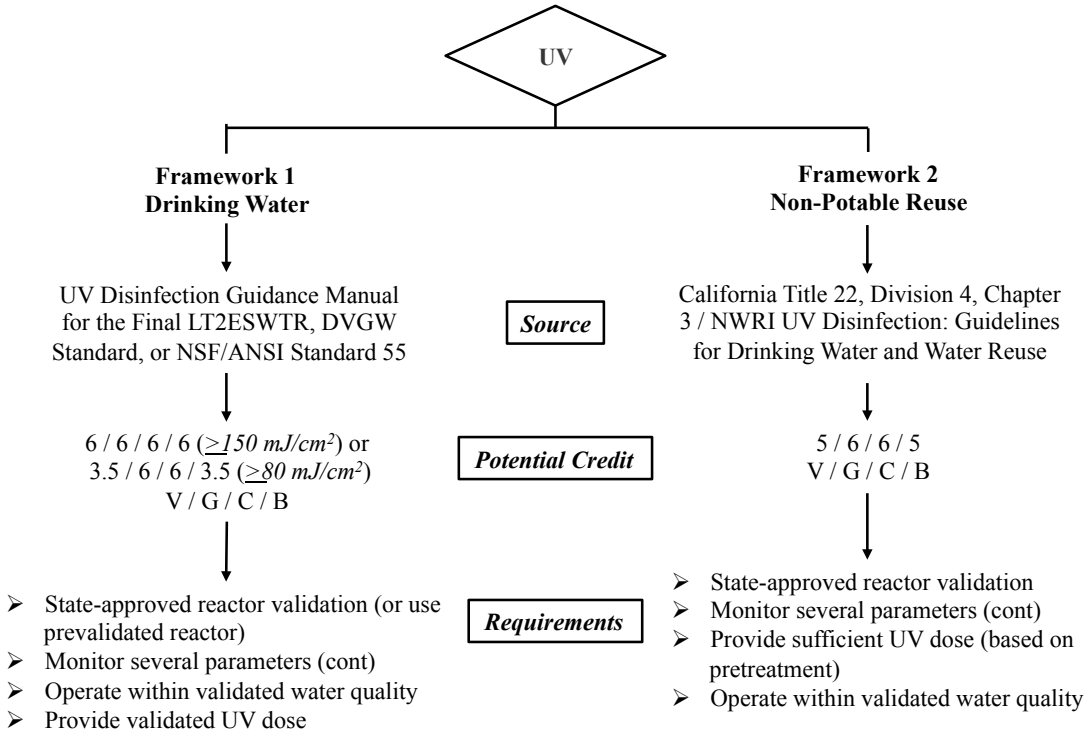


Figure 8. Summary of UV pathogen crediting frameworks, including the framework source, potential pathogen credits, and requirements.

4.5 Chlorine

Chlorine is a powerful disinfectant that is commonly used in drinking water, non-potable reuse, and potable reuse treatment. The mechanism of pathogen inactivation is the oxidation and destruction of biological material. In addition to its use as a primary disinfectant, chlorine is also commonly used as a secondary disinfectant to maintain a residual in the distribution system. The presence of a disinfectant residual in the distribution system is critical to maintaining microbial stability and preventing regrowth.

4.5.1 Free Chlorine – Drinking Water & Potable Reuse – California

Validation

In order to achieve pathogen credit through the use of the CT tables, a free chlorine contactor must have a defined T_{10}. The most common and generally preferred way to characterize the T_{10} is through the use of a tracer study. As previously described in Section 3.2, tracer studies are used to develop flow profiles through reactors. Detailed information for conducting a tracer study can be found in Appendix D of the EPA Disinfection Benchmarking and Profiling Guidance Manual (USEPA 1999).

Conducting a tracer study can be prohibitively expensive or impractical in certain situations; therefore, the EPA allows the Primacy Agency to use 'rule of thumb' baffling factors to determine T_{10} in the absence of tracer data. The baffling factor is the ratio of T_{10} to the average

hydraulic residence time. Higher baffling factors indicate a higher "plug flow" nature of the reactor, which is desirable for disinfection. Low baffling factors indicate that some of the water is exiting quickly, thereby spending less time in contact with the disinfectant.

The classifications of reactors by baffling factors provided by the EPA is presented in Table 7. The descriptions provided in this table are relatively unspecific, and because it is uncommon to use the approach of assuming a conservative baffling factor, there is limited information about the appropriate value to use for different reactor configurations. The available information suggests that for a simple cylindrical tank, the baffling factor is approximately 0.1 regardless of the inlet/outlet configuration and the presence of diffuser walls or pipes[6] (Crozes et al. 1999). This aligns with the assumption presented in Table 7 for an unbaffled basin. The use of diffuser piping only increased the baffling factor to 0.14, and the use of diffuser walls increased it to 0.2. Based on this information, it is recommended that a cylindrical chlorine contact tank should assume a baffling factor of 0.1. Alternative configurations, such as pipeline contactors, could also be used. The benefit of such systems is their potential to demonstrate significantly higher baffling factors.

Table 7. Baffling classifications for reactor configurations.

Baffling Condition	T_{10}/T	Baffling Description
Unbaffled (mixed flow)	0.1	None, agitated basin, very low length to width ratio, high inlet and outlet flow velocities. Can be approximately achieved in flash mix tank
Poor	0.3	Single or multiple unbaffled inlets and outlets, no intra-basin baffles
Average	0.5	Baffled inlet or outlet with some intra-basin baffles
Superior	0.7	Perforated inlet baffle, serpentine or perforated intra-basin baffles, outlet weir or perforated launders
Perfect (plug flow)	1.0	Very high length to width ratio (pipeline flow), perforated inlet, outlet, and intra-basin baffles

Field Verification

Neither EPA nor California provides any specific pathogen-related requirements to be completed upon system startup. Field verification of performance is achieved through the use of the ongoing monitoring techniques outlined below.

Ongoing Monitoring of Treatment Performance

In order to calculate CT, free chlorine systems need to continuously measure free chlorine residual at the point corresponding to the T_{10} determined as described above. While ORP, which is very sensitive to chlorine residuals, can be a useful tool for the control of such systems, monitoring ORP alone is not sufficient to ensure free chlorine disinfection, as ORP cannot be directly related to free chlorine concentration to calculate CT. Additional parameters that are required are flow rate and pH. In order to ensure that a free chlorine residual is being provided, a control system must be used that can modulate the chlorine dose to maintain the desired free

[6] Design elements commonly used to improve baffling.

chlorine residual. The use of such a control system will enable systems to use the EPA CT tables for free chlorine disinfection.

For drinking water, no pretreatment is required for free chlorine disinfection. The treatment requirement is to provide the CT corresponding to the desired pathogen inactivation credit.

4.5.2 Chlorine Disinfection – Non-Potable Reuse – California

Validation

The requirement for chlorine disinfection in non-potable reuse is to provide a 450 mg-min/L CT, with a 90-minute modal contact time (T_{Modal}). The modal contact time is typically demonstrated using a tracer study. The California recycled water regulations do not lay out a framework for obtaining chlorine credit in non-potable contexts without conducting a tracer study. However, correspondence with the Division of Drinking Water indicates that it may be possible to use conservative assumptions to obtain approval for a 90-minute modal contact time with no tracer study.

Field Verification

California does not provide any specific pathogen-related requirements to be completed upon system startup. Field verification of performance is achieved through the use of the ongoing monitoring techniques outlined below.

Ongoing Monitoring of Treatment Performance

Several parameters must be continuously measured, namely chlorine residual at the same point at which the modal contact time was demonstrated and flow rate through the reactor. In addition, non-potable applications in California are required to conduct daily total coliform (TC) monitoring that must comply with the following:

- 7-day median TC $\leq$ 2.2 MPN/100 mL
- TC > 23 MPN/100 mL in no more than 1 sample per month
- TC never > 240 MPN/100 mL

As discussed previously, we recommend an adaptive total coliform monitoring approach that will allow for a reduction in sampling frequency over time.

Filtration pretreatment is required prior to chlorine disinfection for non-potable reuse. The requirements for filtrate water quality depend on the filtration technology; these requirements are summarized in Table 8. The required treatment is a CT of 450 mg-min/L with a 90-minute modal contact time.

Table 8. Water quality requirements for filtration pretreatment to chlorine disinfection for non-potable reuse in California (CDPH 2014).

Filtration Pretreatment	Water Quality Requirements
Granular Media Filtration	24-hour avg turbidity ≤ 2 NTU Turbidity ≤ 5 NTU 95% of the time Turbidity never > 10 NTU
Membrane Filtration	Turbidity ≤ 0.2 NTU 95% of the time Turbidity never > 0.5 NTU

4.5.3 Chlorine – Bacteria Crediting

Given the uncertainties in the water qualities of potential DNWS source waters, we recommend granting bacteria inactivation credit based on the CT framework only when preceded by membrane filtration. Multiple studies have shown that turbidity has a significant impact on bacterial inactivation with free chlorine in recycled waters, and virus inactivation is often not a conservative indicator of bacterial inactivation (Huitric et al. 2014, Maguin et al. 2009, Pecson et al. *submitted*). After consultation with the NWRI DNWS panel, we recommend granting bacteria inactivation credit for free chlorine disinfection that is equivalent to the virus credit received if it is preceded by either a (1) membrane filter or (2) MBR that meets the turbidity requirements (see Sections 4.1 and 4.2). More work is needed to develop a bacteria CT crediting approach for free chlorine for treatment trains without membrane filtration. For non-membrane based trains, we recommend using effluent coliform monitoring to achieve compliance with the bacterial LRTs.

4.5.4 Chlorine – Additional Considerations

Recently, several California utilities have sought regulatory approval for the use of *free* chlorine disinfection in recycled water contexts. This is an important distinction because the regulations currently do not differentiate between free and combined chlorine; a CT of 450 mg-min/L is required regardless of chlorine speciation. Nevertheless, free chlorine is known to be a more powerful oxidant than chloramines, achieving equivalent levels of pathogen inactivation at significantly lower CT values. Recent studies have shown 5-log virus inactivation with free chlorine CTs ranging from 3 to 22 mg-min/L, i.e., at CTs 20- to 100-fold less than the default requirements (Adelman et al. 2016, Huitric et al. 2014, Maguin et al. 2009, Pecson 2016, Pecson et al. *submitted*). A significant obstacle for the implementation of a *free* chlorine strategy is the presence of ammonia in the feed water. Ammonia reacts with free chlorine to form the less potent chloramine species. One strategy for dealing with ammonia is breakpoint chlorination, where sufficient free chlorine is added to oxidize all the ammonia. Once the free chlorine completes the ammonia breakpoint reaction, any additional chlorine added will remain in its free chlorine form. The downside of the breakpoint approach is that it requires high doses of chlorine to oxidize any ammonia present (often 8-10 mg/L of chlorine to breakpoint 1 mg/L of ammonia). In order to obtain free chlorine disinfection credit, there must be a measurable free chlorine residual exiting the reactor.

Generally, systems with significant ammonia levels cannot be relied upon for disinfection of viruses or protozoa. For systems using free chlorine disinfection that may have small amounts of ammonia present (<< 2 mg/L), a chlorine dosing control system should be used to ensure that ammonia is oxidized through breakpoint chlorination and that a free chlorine residual is present. A control system allows chlorine to be dosed in proportion to the influent ammonia concentration, so that enough is added to breakpoint the ammonia and then to achieve the necessary free chlorine residual. This strategy requires that the free chlorine residual measurement be used to modulate the chlorine dose; if the residual is too low, the system doses more chlorine, and vice versa (Pecson 2016, Pecson et al. *submitted*).

4.5.5 Chlorine Frameworks Comparison and Overview

A summary of the pathogen crediting frameworks for free chlorine disinfection is provided in Figure 9. Given the impacts of wastewater-derived particulates on disinfection efficiency, we recommend the use of the non-potable framework for crediting. Systems can use either the default disinfection requirements (e.g., 450 mg-min/L CT with 90-minute modal contact time) or seek approval for a free chlorine approach. It is recommended that any that projects seeking free chlorine disinfection credit provide pre-treatment with MBR to both (1) reduce influent ammonia concentrations to negligible levels and (2) ensure a low-turbidity feedwater to the chlorine process, and (3) provide a chlorine dosing control system to ensure continuous free chlorine residual.

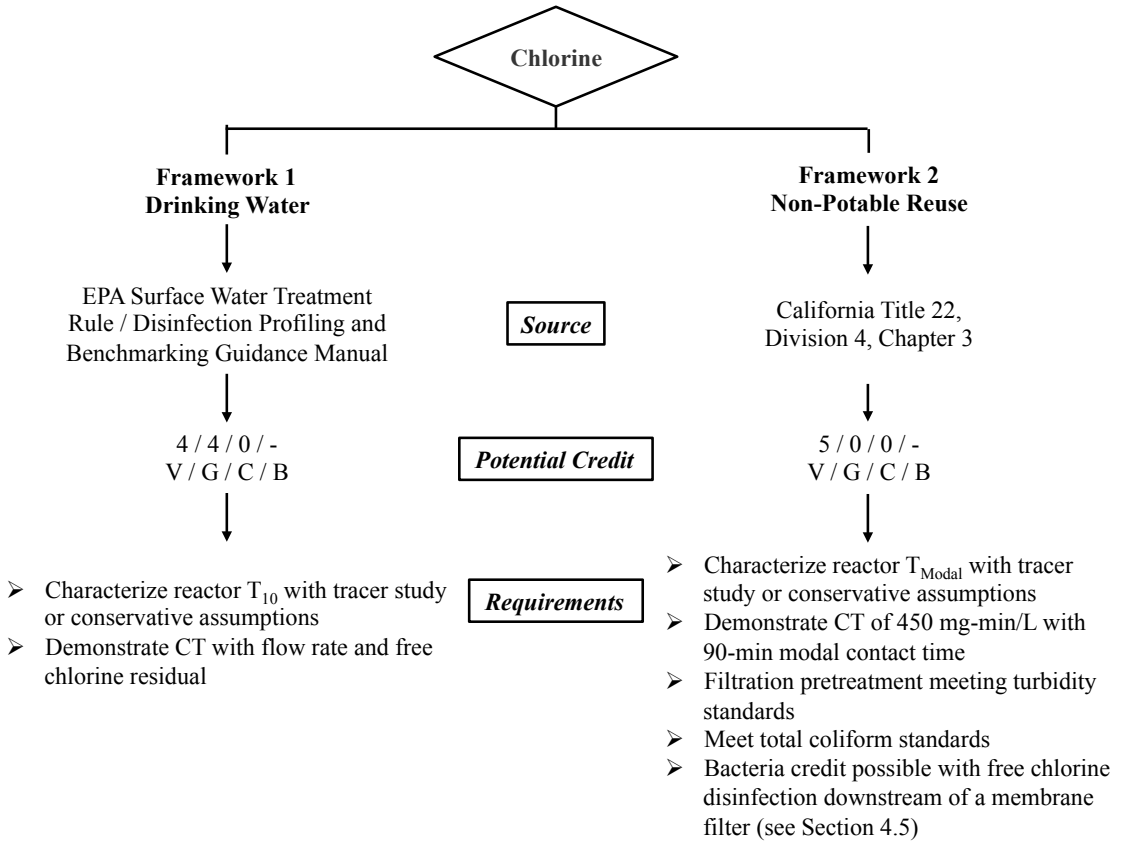


Figure 9. Summary of free chlorine pathogen crediting frameworks, including the framework source, potential pathogen credits, and requirements.

4.6 Ozone

Ozone is commonly used in drinking water both for disinfection and to control taste and odor issues. In addition to being effective at inactivating viruses, *Giardia*, and *Cryptosporidium*, it can also oxidize and break down organic matter. Because ozone reacts quickly in water, an ozone residual cannot be maintained on the timescale needed for use in a distribution system.

4.6.1 Ozone – Drinking Water – California

Validation

Ozone disinfection is carried out in ozone contactors, with credit granted based on the CT framework. The EPA provides CT tables for virus, *Giardia*, and *Cryptosporidium* (USEPA 1991). Several methods of varying complexity are available for calculating ozone CT. The appropriate method for a given application depends on the availability of tracer study data, the type and configuration of reactor used, and the degree of monitoring that a system is able to undertake. In general, using a tracer study allows reactors to obtain higher CT credit because in the absence of tracer data, conservative assumptions must be made regarding flow characteristics and short circuiting. If a tracer study is conducted, the approach is the same as that used for free

chlorine reactor characterization, as outlined in Appendix D of the EPA Disinfection Benchmarking and Profiling Guidance Manual (USEPA 1999).

The simplest method for calculating ozone CT is the T_{10} method. This method requires tracer data, as the EPA does not recommend using rule of thumb estimations of baffling factor for ozone contactors (USEPA 2010). Ozone contactors generally consist of a series of chambers; these could be physically distinct chambers or simply segments of a long reactor. In the T_{10} method, there are two types of chambers: chambers where ozone is added, and reactive chambers. Calculating ozone CT involves summing the CT achieved in each chamber where credit is granted. The first chamber where ozone is added, called the 'first dissolution chamber,' is not granted any inactivation credit for *Cryptosporidium* but can be awarded partial credit for *Giardia* and virus inactivation depending on reactor design and ozone residual concentration at the outlet of the first chamber. Following the first dissolution chamber, the ozone residual, reactor T_{10} (obtained from a tracer study), and water temperature are used to calculate the CT of each chamber. A simplified example of calculating ozone CT in a reactor with a dissolution chamber and one reactive chamber is shown in Figure 10. The example shown only includes a single ozone residual meter at the end of the contactor; however, typically multiple meters will be used along the length of a reactor to obtain higher CT credit. In the example shown in Figure 10, an ozone residual meter could be used at the end of the dissolution chamber to obtain partial credit for virus and *Giardia*; with a residual >0.3 mg/L, the system could obtain 0.5-log *Giardia* credit and 1-log virus credit. CT values calculated from the reactive chambers are translated to LRVs via the following equations[7]:

$$\text{Virus LRV} = 2.1744 * 1.0726^{\text{Temp}} * \text{CT}$$
$$\textit{Giardia}\ \text{LRV} = 1.038 * 1.0741^{\text{Temp}} * \text{CT}$$
$$\textit{Cryptospiridium}\ \text{LRV} = 0.0397 * 1.09757^{\text{Temp}} * \text{CT}$$

More complex CT calculation methods are available for systems with three or more reactive chambers; details on these methods, as well as methods that do not require tracer data, can be found in Chapter 11 and Appendix B of the LT2ESWTR Toolbox Guidance Manual (USEPA 2010).

[7] Equations correspond to EPA CT tables

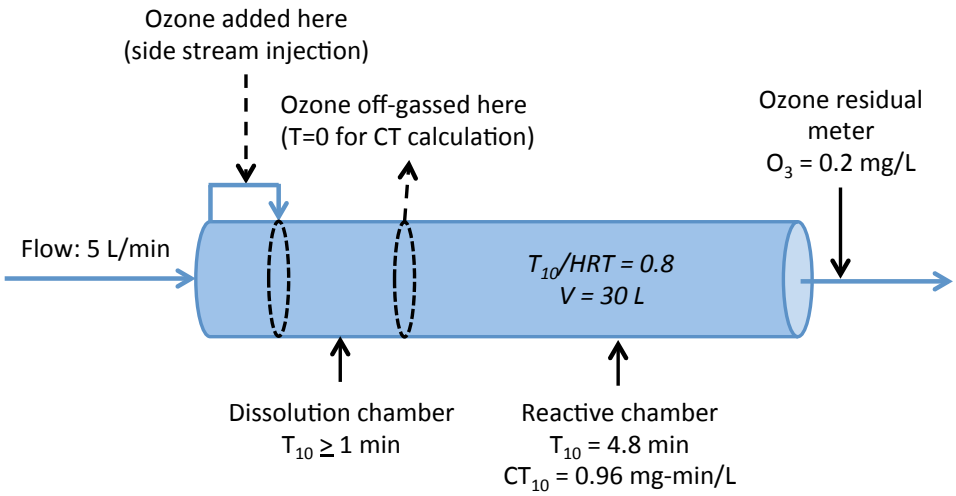


Figure 10. Example of how ozone reactor CT is calculated using T_{10} method.

Field Verification

Neither the EPA nor California provides any specific pathogen-related requirements to be completed upon system startup. Field verification of performance is achieved through the use of the ongoing monitoring techniques outlined below.

Ongoing Monitoring of Treatment Performance

The LT2ESWTR requires daily CT monitoring during peak hourly flow; given the uncertainty in when peak hourly flow will occur, the EPA recommends hourly CT monitoring to ensure the peak is captured. A more typical approach than hourly monitoring is continuous online monitoring of the parameters used to calculate CT, i.e. flow rate, ozone residual, and water temperature.

4.6.2 Ozone – Bacteria Crediting

As with chlorine, there are currently no CT tables linking ozone dose to bacterial inactivation. Therefore, we do not recommend granting bacteria inactivation credit based on the CT framework. Despite the absence of a surrogate crediting framework, ozone is known to be effective at inactivating bacteria. Until a validated CT framework is developed, we recommend using effluent coliform monitoring to demonstrate ozone performance. Additional research in this area is recommended to develop a bacterial removal framework for ozone.

4.6.3 Ozone – Framework Overview

An overview of the ozone pathogen crediting framework is provided in Figure 11.

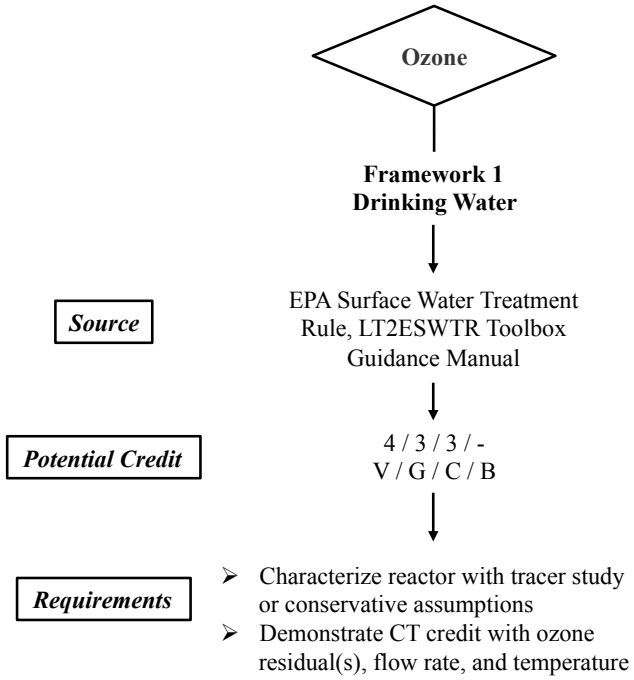


Figure 11. Summary of ozone pathogen crediting framework, including the framework source, potential pathogen credits, and requirements.

5 Recommendations Summary

Recommendations contained throughout this document are summarized in Table 9.

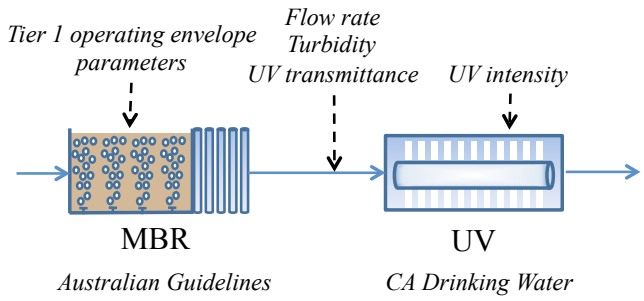
Table 9. Summary of recommendations contained in this document.

General	• Use LRTs corresponding to risk goal of 10^{-4} infection ppy • Use proposed bacteria crediting frameworks where appropriate to meet bacterial LRTs • If a treatment train does not achieve the bacterial LRT using crediting frameworks, use adaptive total coliform monitoring scheme that allows for a reduction in sampling frequency over time if systems consistently demonstrate compliance with the effluent standard • Use an effluent total coliform standard of < 2.2 MPN/100 mL where monitoring is required • Consider effluent bacteria monitoring on a monthly or quarterly basis as additional verification that treatment performance is maintained over time • Further evaluation of appropriate surrogates for bacterial crediting is recommended
MF/UF	• Allow systems to use either the drinking water or non-potable reuse framework, depending on whether they are seeking credit for protozoa removal • Do not award bacteria removal credit under the existing surrogate framework at this time
MBR	• Pending DDW approval of and/or an independent assessment of the Australian guidelines, use Tier 1 default pathogen credits for MBRs operating within the Tier 1 operating envelope • For MBRs not able to operate within Tier 1 envelope, use California non-potable reuse framework without pathogen credits
RO	• Allow pathogen removal credit with continuous monitoring of either electrical conductivity or total organic carbon • Award bacteria removal credit at the same level as that awarded for viruses and protozoa
UV	• Validated reactors can be used if water quality is within validated ranges • EPA, DVGW, NSF, and NWRI validation frameworks should all be accepted • Drinking water reactors can be credited with 3.5-log virus and 6-log protozoa credit with a dose of 80 mJ/cm2; these systems would not need to undergo spot checking • Non-potable reuse reactors can be credited with 5-log virus and 6-log protozoa with the UV dose corresponding to the pretreatment; these systems require spot check bioassays • Assign bacterial log removal credit at a level equivalent to virus
Chlorine	• Use an assumed baffling factor of 0.1 for a cylindrical tank in the absence of tracer data • Use the non-potable framework for crediting, allowing either the default disinfection requirements (450 mg-min/L CT with 90-minute modal contact time) or case-to-case approval of a free chlorine approach • Projects seeking free chlorine disinfection credit should provide pre-treatment with MBR to (1) reduce influent ammonia concentrations to negligible levels and (2) ensure a low-turbidity feedwater to the chlorine process, and (3) provide a chlorine dosing control system to ensure continuous free chlorine residual • Require free chlorine monitoring rather than ORP if CT credit is being sought; this is established practice because ORP cannot be directly related to free chlorine concentration • Award bacteria credit equivalent to virus credit only for free chlorine disinfection preceded by membrane filtration
Ozone	• Use the drinking water framework for disinfection with ozone • Do not award bacteria credit under the existing surrogate framework at this time

6 Example Treatment Trains

6.1 Graywater

An example treatment train for DNWS treating graywater for indoor use is presented in Figure 12. The treatment train includes an MBR and UV, with the MBR meeting the Australian guidelines for receiving pathogen credits. In addition, the MBR effluent quality (i.e. turbidity and UVT) must fall within the validated range for the UV reactor. The UV system provides a dose greater than or equal to 150 mJ/cm^2 under all validated operating conditions, as demonstrated through online monitoring of several parameters (see Figure 12). This treatment train exceeds the virus, protozoa, and bacteria LRTs required from the DNWS report.



Pathogen Credits			Total	Required
V	1.5	6	**7.5**	**6**
G	2	6	**8**	**4.5**
C	2	6	**8**	**4.5**
B	4	6	**10**	**3.5**

Validation & Field Verification Requirements	
Field verification of operation within Tier 1 envelope	Validation for dose of 150 mJ/cm^2 per EPA, NSF, or DVGW

Treatment Requirements	
Effluent turbidity ≤ 0.2 NTU Operation within Tier 1 envelope	Influent UVT ≥ minimum validated value for UV reactor UV dose ≥150 mJ/cm^2

Figure 12. Example treatment train for decentralized non-potable system treating graywater. Log reduction targets are based on achieving risk of 10^{-4} infections per person per year.

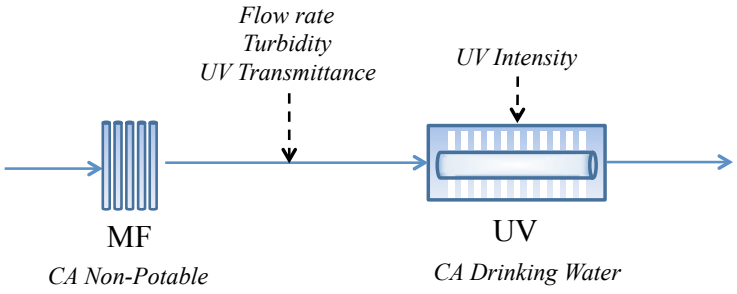
6.2 Stormwater & Foundation Drainage

An example treatment train for stormwater (10^{-3} dilution) and foundation drainage[8] is provided in Figure 13, along with the validation, field verification, monitoring, and treatment requirements. The treatment train includes MF and UV, with MF being credited according to the

[8] Due to lack of pathogen data for foundation drainage, the NWRI report specifies using the stormwater LRTs for this source.

California non-potable reuse regulations and UV according to the drinking water regulations. The use of MF instead of MBR in this train may be acceptable assuming that stormwater has significantly lower organic loads than graywater. This assumption would need to be confirmed in each case using site-specific water quality data.

An example train for stormwater (10^{-1} dilution) is provided in Figure 14; the train consists of MF, UV, and free chlorine. The MF is not credited with pathogen reduction, in accordance with California non-potable reuse requirements. In addition to meeting the non-potable effluent turbidity standards, the MF effluent must fall within the validated water quality range of the UV reactor. The UV reactor must provide a dose of at least 80 mJ/cm^2. The chlorine system must provide a CT of no less than 10 mg-min/L, with a verified **free** chlorine residual. A free chlorine dosing control system is required to ensure that free chlorine residual is maintained even in the presence of ammonia in the feedwater. This treatment train exceeds the virus, protozoa, and bacteria LRTs required from the DNWS report. As with the 10^{-3} stormwater treatment train, the water quality of the source water should be evaluated to verify that sufficient organics control can be obtained without the use of MBR, i.e., with MF alone.

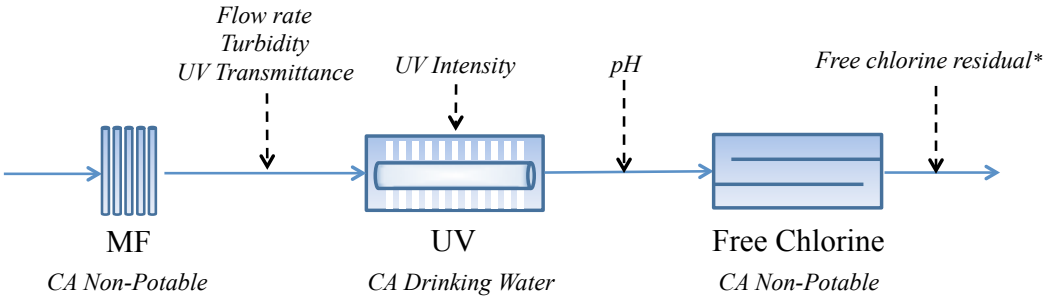


	Pathogen Credits		Total	Required
V	0	3.5	**3.5**	**3.5**
G	0	6	**6**	**3.5**
C	0	6	**6**	**3.5**
B	0	3.5	**3.5**	**3**

Validation & Field Verification Requirements	
None	Validation for dose of 80 mJ/cm^2 per EPA, NSF, or DVGW

Treatment Requirements	
Effluent turbidity: - 95% ≤ 0.2 NTU - Never > 0.5 NTU	Influent UVT ≥ minimum validated value for UV reactor UV dose ≥ 80 mJ/cm^2

Figure 13. Example treatment train for decentralized non-potable system treating stormwater (10^{-3} dilution of wastewater). Log reduction targets are based on achieving risk of 10^{-4} infections per person per year.



	Pathogen Credits			Total	Required
V	0	3.5	5	**8.5**	**5.5**
G	0	6	0	**6**	**5.5**
C	0	6	0	**6**	**5.5**
B	0	3.5	5	**8.5**	**5**

Validation & Field Verification Requirements		
None	Validation for dose of 80 mJ/cm^2 per EPA, NSF, or DVGW	Tracer study or assumed baffling factor of 0.1

Treatment Requirements		
Effluent turbidity: - 95% ≤ 0.2 NTU - Never > 0.5 NTU	Influent UVT ≥ minimum validated value for UV reactor UV dose ≥ 80 mJ/cm^2	CT no less than 10 mg-min/L** with verified free chlorine residual

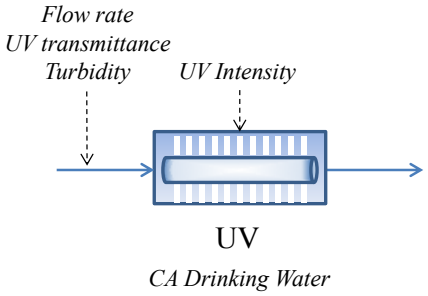
** System must have chlorine dosing control system to ensure free chlorine residual in the presence of ammonia in feedwater*
*** See Maguin et al. (2009), Huitric et al. (2014), Pecson (2016)*

Figure 14. Example treatment train for decentralized non-potable system treating stormwater (10^{-1} dilution of wastewater). Log reduction targets are based on achieving risk of 10^{-4} infections per person per year.

6.3 Roof Runoff

The NWRI report specifies only bacterial LRTs for roof runoff; there are no LRTs for virus or protozoa. The example treatment train in Figure 15 uses UV with a dose of 80 mJ/cm^2 to achieve the bacterial LRTs. This treatment train may need to be preceded by a filtration step to remove solids; this determination should be made based on the quality of a particular source water.

Because we do not recommend granting credit for bacteria inactivation through the free chlorine CT surrogate framework in the absence of membrane filtration, a treatment train using free chlorine to treat roof runoff would have to use effluent monitoring for total coliform. The only requirement for this train would be that it meets the effluent total coliform the standards.



		Total	Required
V	N/A	**N/A**	**N/A**
G	N/A	**N/A**	**N/A**
C	N/A	**N/A**	**N/A**
B	3.5	**3.5**	**3.5**

Validation & Field Verification Requirements

Validation for dose of 80 mJ/cm^2 per EPA, NSF, or DVGW

Treatment Requirements

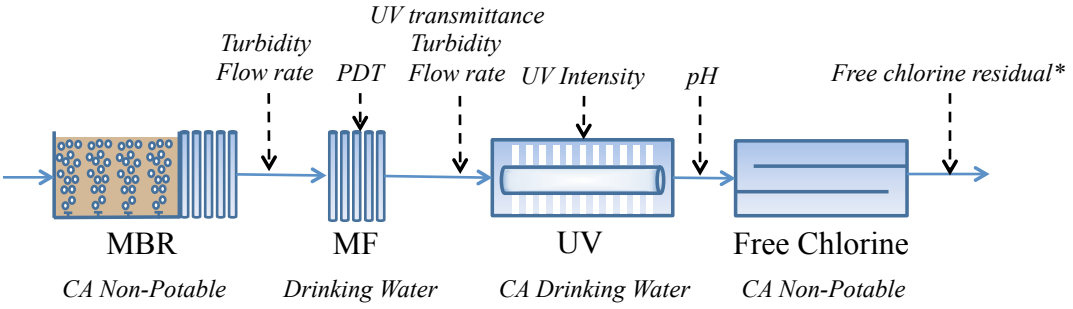
Influent turbidity:
- 95% $\leq$ 0.3 NTU; never > 1 NTU
Influent UVT $\geq$ minimum validated value for UV reactor
UV dose $\geq$ 80 mJ/cm^2

Figure 15. Example treatment train for decentralized non-potable system treating roof runoff.

6.4 Blackwater

Two example treatment trains for DNWS treating blackwater for indoor use are shown in Figure 16 and Figure 17. The key difference between these trains is whether or not the MBR receives pathogen credit. Train A includes an MBR, MF, UV, and free chlorine. In this train, the only requirement for the MBR is that it meets the California non-potable effluent turbidity standards. The MF can receive protozoa credit with a daily pressure decay test and effluent turbidity meeting the drinking water standards. In addition, the MF effluent quality must be within the validated range of the UV reactor. The MBR is not replaced by the MF because the biological treatment is necessary to reduce the concentration of organics. The MF is included to obtain the additional necessary protozoa removal credit. The chlorine system must provide a CT of no less than 10 mg-min/L, with a verified **free** chlorine residual. A free chlorine dosing control system is required to ensure that free chlorine residual is maintained even in the presence of ammonia in the feedwater.

Blackwater train B consists of an MBR, UV, and free chlorine. In this train, the MBR receives pathogen credit per the Australian guidelines. The MBR must operate within the Tier 1 operating envelope, with an effluent turbidity $\leq$ 0.2 NTU. The MBR effluent must be within the validated range of water quality of the UV reactor. The UV reactor (or multiple reactors in series) must provide a UV dose of 80 mJ/cm^2 to receive 3.5-log virus and bacteria credit and 6-log protozoa credit. The remaining virus credits are obtained through free chlorine disinfection per the same requirements as for blackwater train A.



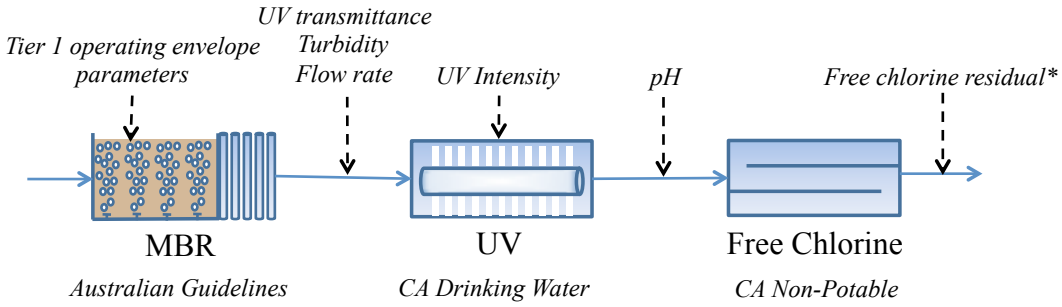
	Pathogen Credits				Total	Required
V	0	0	3.5	5	**8.5**	**8.5**
G	0	4	6	0	**10**	**7**
C	0	4	6	0	**10**	**7**
B	0	0	3.5	5	**8.5**	**6**

Validation & Field Verification Requirements			
None	None	Validation for dose of 80 mJ/cm^2 per EPA, NSF, or DVGW	Tracer study or assumed baffling factor of 0.1

Treatment Requirements			
Effluent turbidity: - 95% ≤ 0.2 NTU - Never > 0.5 NTU	PDT ≤ control limit Effluent turbidity ≤ 0.15 NTU	Influent UVT ≥ min validated value for UV reactor UV dose ≥ 80 mJ/cm^2	CT no less than 10 mg-min/L** with verified free chlorine residual

** System must have chlorine dosing control system to ensure free chlorine residual in the presence of ammonia in feedwater*
*** See Maguin et al. (2009), Huitric et al. (2014), Pecson (2016)*

Figure 16. Example treatment train A for decentralized non-potable system treating blackwater. Log reduction targets are based on achieving risk of 10^{-4} infections per person per year.



	Pathogen Credits			Total	Required
V	1.5	3.5	5	**10**	**8.5**
G	2	6	0	**8**	**7**
C	2	6	0	**8**	**7**
B	4	3.5	5	**12.5**	**6**

Validation & Field Verification Requirements

Field verification of operation within Tier 1 envelope	Validation for dose of 80 mJ/ cm^2 per EPA, NSF, or DVGW	Tracer study or assumed baffling factor of 0.1

Treatment Requirements

Effluent turbidity $\leq$ 0.2 NTU Operation within Tier 1 envelope	Influent UVT $\geq$ minimum validated value for UV reactor UV dose $\geq$ 80 mJ/cm^2	CT no less than 10 mg-min/ L** with verified free chlorine residual

** System must have chlorine dosing control system to ensure free chlorine residual in the presence of ammonia in feedwater*
*** See Maguin et al. (2009), Huitric et al. (2014), Pecson (2016)*

Figure 17. Example treatment train B for decentralized non-potable system treating blackwater. Log reduction targets are based on achieving risk of 10^{-4} infections per person per year.

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