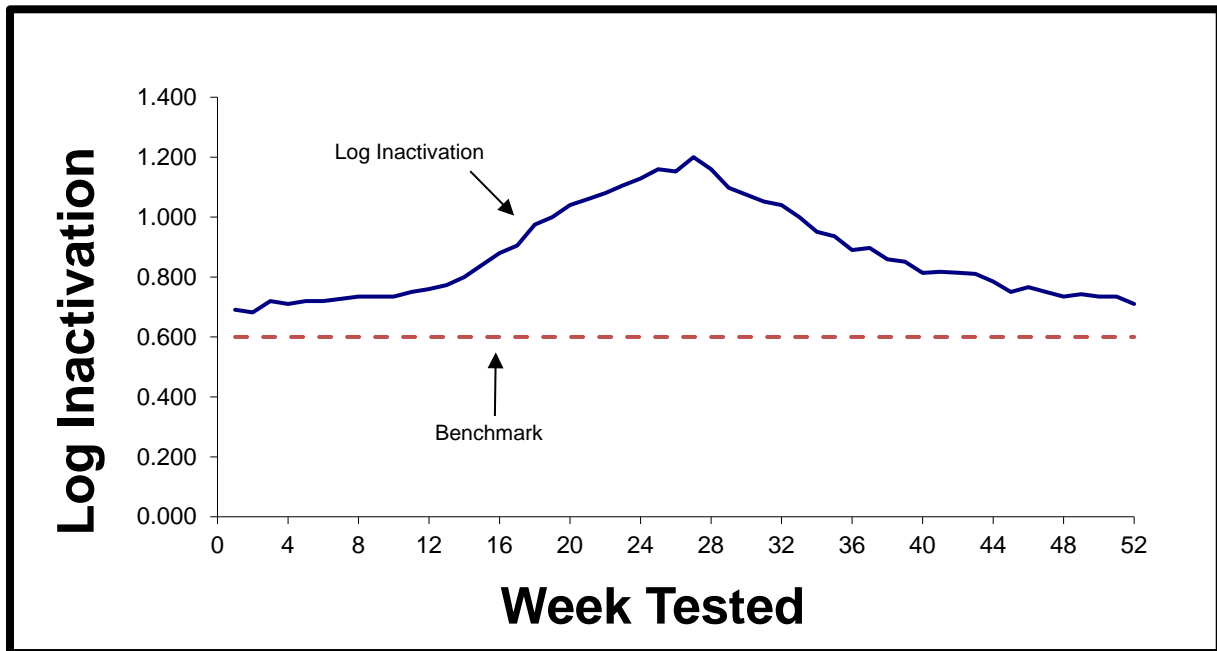




Disinfection Profiling and Benchmarking

Technical Guidance Manual



Office of Water (4606M)
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Disclaimer

This document provides guidance to states, tribes and the U.S. Environmental Protection Agency (EPA) exercising primary enforcement responsibility under the Safe Drinking Water Act (SDWA) and contains the EPA's current policy recommendations for complying with the disinfection profiling and benchmarking requirements of the suite of Surface Water Treatment Rules (SWTRs). Throughout this document, the terms "state" and "states" are used to refer to all types of primacy agencies including states, U.S. territories, American Indian tribes and the EPA.

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Acronyms

List of common abbreviations and acronyms used in this document:

AMWA	Association of Metropolitan Water Agencies
AWWA	American Water Works Association
APHA	American Public Health Association
BF	Baffling Factor
C	Concentration
CFR	Code of Federal Regulations
CSTR	Continuous Stirred Reactor Method
CT	Concentration x Time
CWS	Community Water System
DBP	Disinfection Byproduct
DBPRs	Disinfectants and Disinfection Byproducts Rules
DOM	Dissolved Organic Matter
DPD	N, N-diethyl-p-phenylenediamine
EPA	Environmental Protection Agency
ft	Feet
gal	Gallons
gpm	Gallons per Minute
GWUDI	Ground Water Under the Direct Influence of Surface Water
HAA5	Haloacetic Acids (Five Regulated)
HDT	Hydraulic detention time
IESWTR	Interim Enhanced Surface Water Treatment Rule
LRAA	Locational running annual average
LT1ESWTR	Long Term 1 Enhanced Surface Water Treatment Rule
LT2ESWTR	Long Term 2 Enhanced Surface Water Treatment Rule
MCL	Maximum Contaminant Level
mg/L	Milligrams per Liter
MRDL	Maximum Residual Disinfectant Level
NTNCWS	Non-transient Non-community Water System
PWS	Public Water System
Q	Peak Hourly Flow Rate
RED	Reduction equivalent dose
SCADA	Supervisory Control and Data Acquisition

SDWA	Safe Drinking Water Act
Stage 1 DBPR	Stage 1 Disinfectants and Disinfection Byproducts Rule
Stage 2 DBPR	Stage 2 Disinfectants and Disinfection Byproducts Rule
SWTR	Surface Water Treatment Rule
T	Contact Time
TDT	Theoretical Detention Time
TNCWS	Transient Non-community Water System
TOC	Total Organic Carbon
TTHM	Total Trihalomethanes
UV	Ultraviolet
UVT	UV transmittance
USEPA	United States Environmental Protection Agency
V	Volume
X log inactivation	Reduction to 1/10x of original concentration by disinfection
X log removal	Reduction to 1/10x of original concentration by physical removal
µm	Micron (10 ⁻⁶ meter)
UVDGM	Ultraviolet Disinfection Guidance Manual

Chapter 1 — Introduction

Under the Safe Drinking Water Act (SDWA), the Environmental Protection Agency (EPA) has developed interrelated regulations to control microbial pathogens, disinfectants, and disinfection byproducts (DBPs) in drinking water. These rules, collectively known as the microbial/disinfection byproducts (M/DBP) rules, primarily address two key public health concerns: acute threats from microbial contamination and chronic threats from disinfectant residuals and byproducts of disinfection. The EPA recognizes that a public water system (PWS) may encounter compliance issues when trying to simultaneously meet the goals of the following M/DBP rules:

- Surface Water Treatment Rule (SWTR);
- Interim Enhanced Surface Water Treatment Rule (IESWTR);
- Long Term 1 Enhanced Surface Water Treatment Rule (LT1ESWTR);
- Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR); and
- Stage 1 and Stage 2 Disinfectants and Disinfection Byproducts Rules (DBPRs).

Modifications to improve microbial treatment to comply with the SWTR, IESWTR, LT1ESWTR, and LT2ESWTR may adversely affect compliance with the Stage 1 DBPR and Stage 2 DBPR and vice versa. In addition to the challenges of simultaneously complying with this suite of M/DBP rules, a PWS must ensure that changes in treatment do not adversely affect compliance with other drinking water regulations and environmental regulations.

Simultaneous compliance with the M/DBP rules may present a significant challenge to PWSs and require them to reconsider their disinfection practices. But prior to making any significant modifications to their existing disinfection practices, PWSs should clearly understand the impact those changes could have on microbial protection. Disinfection profiling and benchmarking are procedures by which PWSs and state drinking water programs (referred to as “states” in this document), working together, can ensure that there will be no significant reduction in microbial protection as a result of modifying disinfection practices to maintain compliance with other regulations.

1.1 Purpose of Document

This guidance manual has been updated from the original technical guidance for disinfection profiling and benchmarking requirements pertaining to the IESWTR and LT1ESWTR, which apply to PWSs supplied by a surface water source or ground water source that is under the direct influence of surface water. It has been updated to help PWSs comply with the disinfection profiling and benchmarking requirements of the LT2ESWTR. This manual explains disinfection profiling and benchmarking, discusses when and why they are necessary, and provides guidance on how to collect data to calculate them. This manual also discusses how PWSs and states may use these data to make decisions about disinfection practices and provides an overview of different treatment practices that PWSs may consider adopting.

Additional copies of this document may be obtained by:

- Contacting the appropriate state office.
- Downloading from the EPA’s website at <https://www.epa.gov/dwreginfo/guidance-manuals-surface-water-treatment-rules>.
- Contacting the EPA by filling out an online form on the EPA Safe Drinking Water Information website at <https://www.epa.gov/ground-water-and-drinking-water/safe-drinking-water-information>.

1.2 Disinfection Profiling and Benchmarking

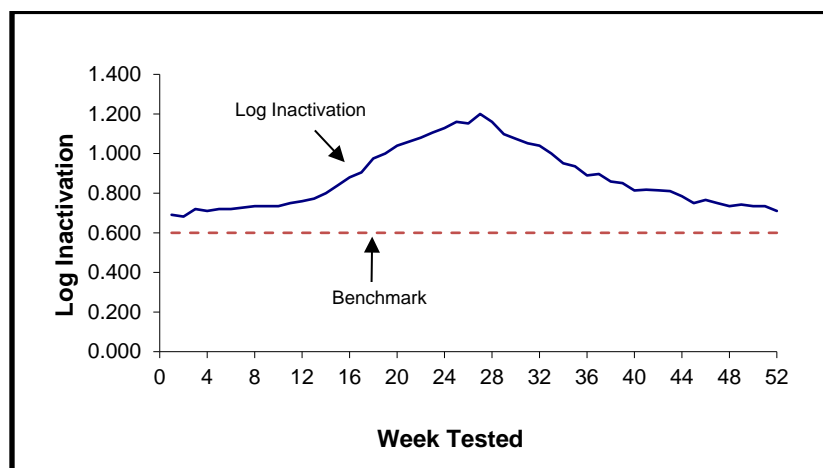
Disinfection is a critical element in controlling the transmission of disease from drinking water by inactivating disease-causing pathogens, such as bacteria, protozoa, and viruses that can affect human health.

The strength of a chemical disinfectant (e.g., chlorine, chlorine dioxide, ozone) for inactivating pathogens when in contact with water can be measured by its CT value.¹ Methods for determining CT based on operational data are described in Chapters 3 and 4. The CT values are used to evaluate the inactivation of pathogens by disinfection using a logarithmic scale, thus it is referred to as “log inactivation.” Log inactivation is simply the order of magnitude in which inactivation of unwanted organisms occurs and relates to the percentage of organisms inactivated. For example, a 2-log inactivation corresponds to a 99 percent inactivation and a 3-log inactivation corresponds to a 99.9 percent inactivation. Tables B-1 through B-8 summarize the required CT values to achieve inactivation of *Giardia* or viruses for the various chemical disinfectants including free chlorine, chlorine dioxide, ozone, and chloramines.

The strength of a physical disinfectant (e.g., UV light) for inactivating pathogens when in contact with water can be measured by its dosage rate. Table B-9 summarizes the UV dosage rates required to achieve various log inactivation credits for *Cryptosporidium*, *Giardia*, and viruses. Additional details on operational evaluations of the UV disinfection process are presented in Section 8.2.5.

A plot of log inactivation values provides a visual representation of the log inactivation that a treatment plant achieved by disinfection over time. A **disinfection profile** is this graphical representation of a system’s level of pathogen (e.g., *Giardia*, *Cryptosporidium*, or virus) inactivation during the course of a year. The disinfection profile is a tool that allows PWSs and states to assess the system’s performance under existing treatment processes. Figure 1-1 shows a sample disinfection profile for a system.

Figure 1-1. Sample Disinfection Profile



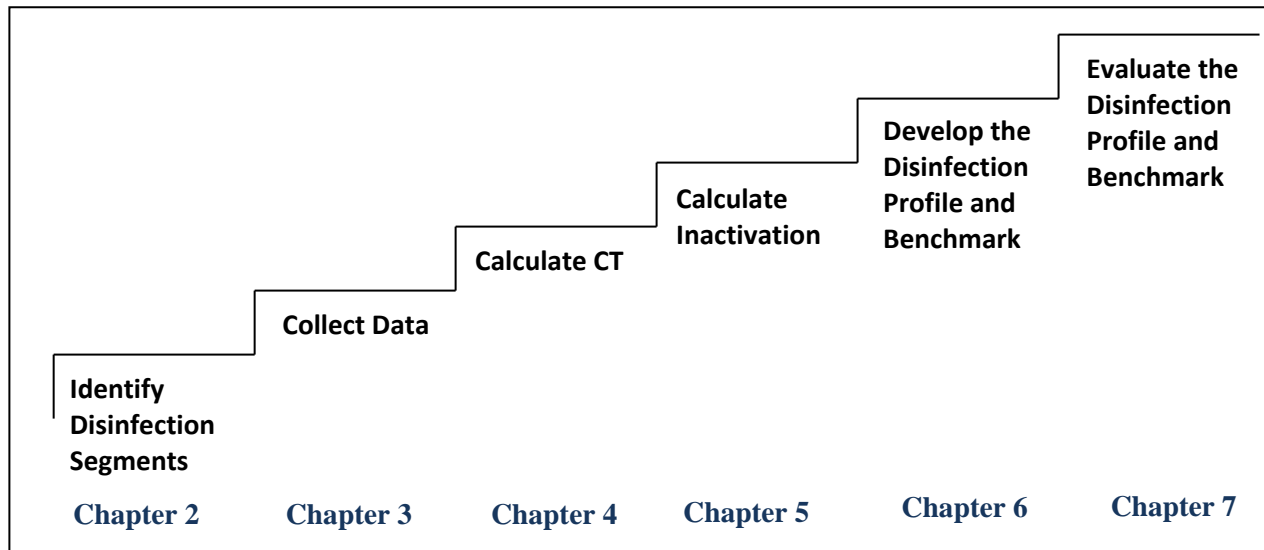
A **disinfection benchmark** is the lowest monthly average microbial inactivation achieved during the disinfection profiling time period. This value for each year of profiling data can be obtained from the same data used to plot the disinfection profile. Setting the disinfection benchmark is required only if a

¹ CT is defined as disinfectant residual **concentration (C)** multiplied by **contact time (T)**. A CT value is a measure of disinfection effectiveness for the time that microorganisms in the water are in contact with a disinfectant. See Chapter 4 for a discussion on CT values and how they are calculated.

PWS decides to make a significant change to its disinfection practices. The benchmark is used by the PWS and the state to ensure the minimum levels of inactivation of *Giardia* and viruses are maintained or to determine appropriate alternative benchmarks under different disinfection scenarios.

Remaining chapters in this manual describe in-depth procedures to develop a disinfection profile and benchmark. Figure 1-2 shows the steps PWSs should follow to develop a disinfection profile and benchmark, identifying the corresponding chapters that describe each step.

Figure 1-2. Steps in Developing a Disinfection Profile and Benchmark



1.3 Significant Change and Reporting Requirements

Compliance with DBP maximum contaminant levels (MCLs) or requirements to provide additional treatment for *Cryptosporidium* may require a PWS to modify its existing disinfection practices. The IESWTR, LT1ESWTR, and LT2ESWTR describe four types of significant changes to disinfection practices:

- Changes to the point of disinfection;
- Changes to the disinfectant(s) used in the treatment plant;
- Changes to the disinfection process; and or
- Any other modification identified by the state.

These modifications are discussed in more detail in Section 7.2. A PWS that is considering a significant change to its disinfection practice must develop a disinfection profile and calculate the disinfection benchmarks for *Giardia* and viruses. Prior to changing the disinfection practice, the system must notify the State and must include in this notice the following information:

- A completed disinfection profile and disinfection benchmark for *Giardia* and viruses.
- A description of the proposed change in disinfection practice.
- An analysis of how the proposed change will affect the current levels of disinfection.
- Any additional information requested by the state.

Disinfection profiling and benchmarking will help ensure that microbial protection is not compromised by any modifications to disinfection practices. The IESWTR, LT1ESWTR, and LT2ESWTR require PWSs to evaluate their disinfection practices and work with the state to ensure there are no unintended decreases in microbial protection when those PWSs change how they disinfect their water.

1.4 Using Disinfection Profiling and Benchmarking to Balance M/DBP Rules

Under the SWTR, every PWS must reliably and consistently provide the necessary treatment to achieve adequate *Giardia* and virus log removal and/or inactivation as listed in Table 1-1. Under the IESWTR and LT1ESWTR, these PWSs must also reliably and consistently provide *Cryptosporidium* removal. Under the LT2ESWTR, PWSs shown to have certain levels of *Cryptosporidium* in their source water are required to provide additional measures to ensure adequate *Cryptosporidium* removal and/or inactivation.

Log removal and/or inactivation relates to the percentage of microorganisms physically removed or inactivated by a given process. All surface water systems and ground water under the direct influence of surface water (GWUDI) systems are required to achieve at least 3-log (99.9%) removal and/or inactivation of *Giardia*, at least 4-log (99.99%) removal and/or inactivation of viruses and at least 2-log (99%) removal of *Cryptosporidium*. Removal is achieved through settling, filtration, or both and inactivation is achieved through disinfection.

Table 1-1. Minimum Removal and Inactivation Requirements for All Surface Water and GWUDI Filtered Systems

Microorganism	Required Log Removal and/or inactivation	Treatment
<i>Giardia</i>	3-log (99.9%)	Removal and/or Inactivation
Viruses	4-log (99.99%)	Removal and/or Inactivation
<i>Cryptosporidium</i> *	2-log (99%)	Removal
<p>* The IESWTR and LT1SWTR specify that the 2-log treatment requirement for <i>Cryptosporidium</i> can only be achieved through removal. If a PWS is required to meet additional log credits under LT2ESWTR, additional treatment credits beyond the 2-log requirement can be achieved with toolbox options, including inactivation. Refer to the <i>Long Term 2 Enhanced Surface Water Treatment Rule Toolbox Guidance Manual</i> (USEPA, April 2010) for more information regarding toolbox options.</p>		

States generally grant log removal credits based on treatment type, and the credits depend on the treatment processes. Conventional filtration, which includes a sedimentation step, is typically assigned the highest credit. Direct filtration relies primarily on filtration for removal. Credits for alternative filtration techniques vary based on the technology employed. Table 1-2 shows typical log removal credits and resulting inactivation values that must be achieved by various treatment technologies. For example, if a PWS uses conventional treatment, it may receive 2.5-log removal credit for *Giardia* and 2-log removal credit for viruses. Since the PWS must achieve at least 3-log removal and/or inactivation of *Giardia* and 4-log removal and/or inactivation of viruses, the resulting disinfection log inactivation requirements for

Giardia and viruses are 0.5-log and 2-log, respectively. For unfiltered systems (i.e., systems that have received filtration avoidance determinations), 3-log inactivation of *Giardia* and 4-log inactivation of viruses can only be achieved using disinfection. PWSs should check with their state for specific removal credits and inactivation requirements in case they differ from those listed in Table 1-2.

Table 1-2. Typical Removal Credits and Inactivation Requirements for Various Treatment Technologies

Process	Log Removal and/or Inactivation Required		Typical Log Removal Credits		Resulting Disinfection Log Inactivation Requirements	
	<i>Giardia</i>	Viruses	<i>Giardia</i>	Viruses	<i>Giardia</i>	Viruses
Conventional Treatment	3.0	4.0	2.5	2.0	0.5	2.0
Direct Filtration	3.0	4.0	2.0	1.0	1.0	3.0
Slow Sand Filtration	3.0	4.0	2.0	2.0	1.0	2.0
Diatomaceous Earth Filtration	3.0	4.0	2.0	1.0	1.0	3.0
Alternative (membranes, bag filters, cartridges)	3.0	4.0	*	*	*	*
Unfiltered	3.0	4.0	0	0	3.0	4.0

Source: USEPA. March 1991.

* PWSs must demonstrate to the state by pilot study or other means that the alternative filtration technology provides the minimum required log removal and inactivation shown in Table 1-1.

While minimum required levels of disinfection are regulated by the SWTR, the Stage 1 and Stage 2 DBPRs, herein referred to as “the DBPRs”, regulate the levels of DBPs allowed in distribution systems. The DBPs trihalomethanes and haloacetic acids are formed when organic matter in the water reacts with disinfectants such as chlorine. The MCLs of the regulated DBPs under the DBPRs are based on locational running annual averages (LRAAs) at or less than the following levels:

- Total Trihalomethanes (TTHM) at 0.080 milligrams per liter (mg/L); and
- Haloacetic Acids Five (HAA5) at 0.060 milligrams per liter (mg/L).

The DBPRs also set maximum residual disinfectant levels (MRDLs) for chlorine, chloramines, and chlorine oxide.

In order to meet the TTHM and HAA5 MCL requirements of the DBPRs, PWSs may need to consider changing their disinfection practices. PWSs with high levels of DBPs may need to modify disinfection practices to reduce the formation of DBPs. Some of these changes, such as the use of lower concentrations of disinfectant, will lessen microbial inactivation and may produce water of unsatisfactory microbial quality. Likewise, some PWSs may make significant changes to their disinfection practices to provide additional treatment for *Cryptosporidium* under the LT2ESWTR. The disinfection profiling and benchmarking requirements under IESWTR and LT1ESWTR were defined to protect public health by assessing the risk of exposure to microbial pathogens as PWSs take steps to comply with the DBPR requirements. The LT2ESWTR includes disinfection profile and benchmark requirements to ensure that any significant change in disinfection, whether for DBP control under the DBPRs, improved *Cryptosporidium* control under the LT2ESWTR, or both, does not significantly compromise existing

Giardia and virus protection. The LT2ESWTR requires that PWSs and states evaluate the effects of significant changes in disinfection practice on current microbial treatment levels. Disinfection profiling and benchmarking serve as tools for making such evaluations.

Under the IESWTR, LT1ESWTR, and LT2ESWTR, the disinfection benchmark is not intended to function as a regulatory standard. Rather, the objective of the disinfection profiling and benchmarking requirements is to facilitate interactions between the state and PWS to assess the impacts of proposed changes on microbial protection. Disinfection profiling and benchmarking can help decision-makers identify the strengths and weaknesses of existing systems and choose appropriate system modifications (see Chapter 7).

Final decisions regarding levels of disinfection for *Giardia* and viruses, beyond the minimum required by federal regulations, will continue to be left to the states in consultation with PWSs. To ensure that the level of treatment for both protozoan and viral pathogens is appropriate, states and PWSs should also consider site-specific factors such as source water contamination levels and the reliability of treatment processes.

1.5 Overview of Disinfection Profiling and Benchmarking Requirements

As stated in Section 1.1, this revised guidance is based on disinfection profiling and benchmarking requirements under the LT2ESWTR. Prior to LT2ESWTR, PWSs were required to develop a profile for *Giardia* (and viruses if chloramines, ozone, or chlorine dioxide were used as the primary disinfectant² or if required by the state) under the IESWTR or LT1ESWTR if they were a community water system (CWS) or a non-transient non-community water system (NTNCWS) that had a surface water or GWUDI source and had DBP levels in their distribution system exceeding the following conditions:

- The TTHM annual average, based on quarterly samples, was greater than 0.064 mg/L; or
- The HAA5 annual average, based on quarterly samples, was less than 0.048 mg/L.

The dates to complete a profile depended on a PWS's size and ranged from March 2000 to January 2004. Only PWSs that were required to develop a disinfection profile and then subsequently proposed to make significant changes to their disinfection practices were required to develop a benchmark and submit it along with other pertinent information to the state.

Under the LT2ESWTR, any PWS that has a surface water or GWUDI source and plans to make a significant change to its disinfection practices must develop a disinfection profile and calculate a disinfection benchmark for *Giardia* and viruses. The EPA believes that profiling for both target pathogens (*Giardia* and viruses) is appropriate because the types of treatment changes that PWSs will make to comply with the LT2ESWTR could lead to a significant change in the inactivation level for one pathogen but not the other (USEPA, August 2007). Disinfection benchmarking ensures that PWSs maintain protection against microbial pathogens as they implement the DBPRs and LT2ESWTR.

In general, viruses are more sensitive to chlorine than *Giardia* and *Cryptosporidium* but are more resistant to ultraviolet (UV) light disinfection. A PWS that adds UV light disinfection to meet *Cryptosporidium* treatment requirements will maintain a high level of inactivation for *Giardia* and *Cryptosporidium* but, if

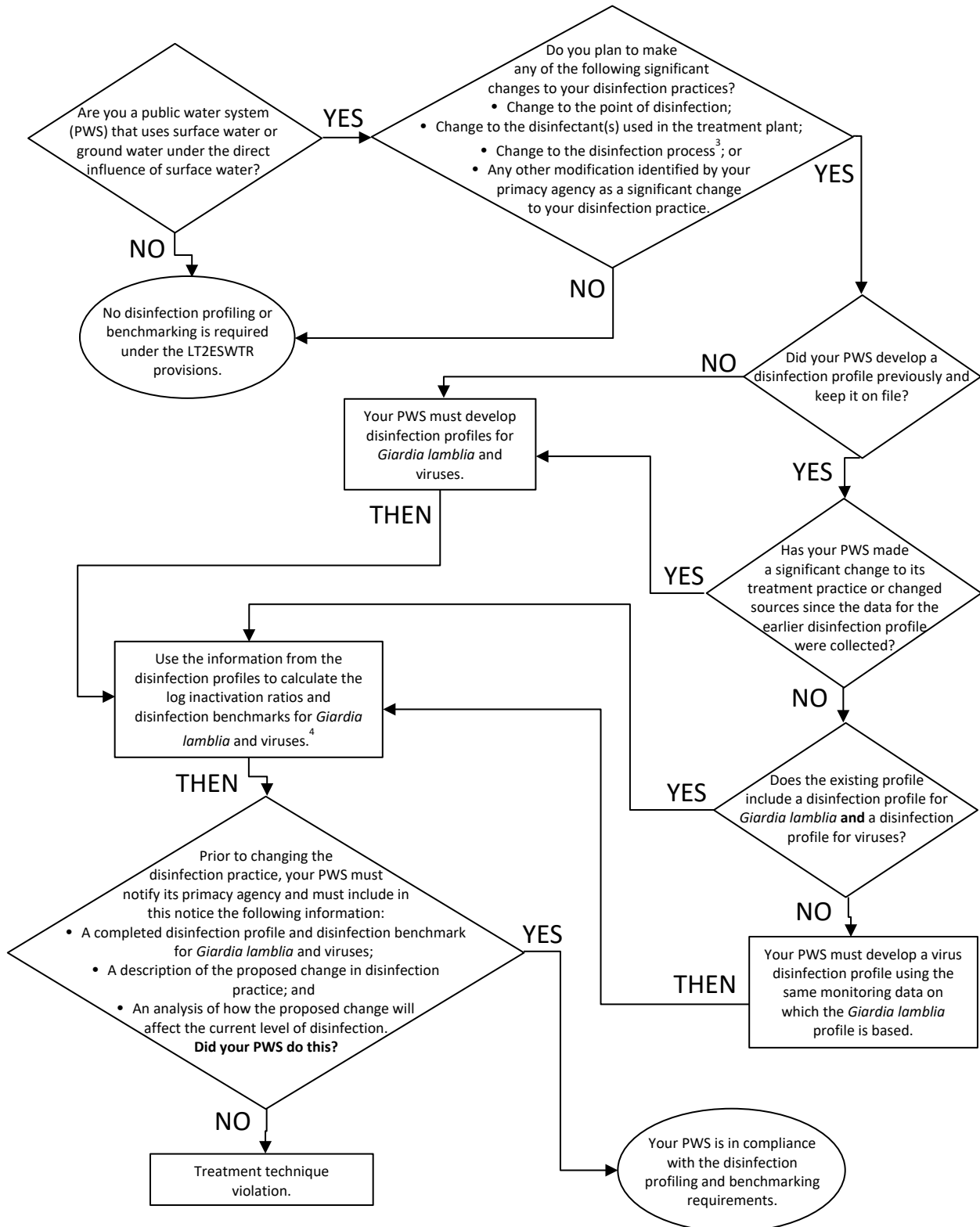
² Primary disinfectant is defined as the disinfectant used in a treatment system to achieve the necessary microbial inactivation. Secondary disinfectant is defined as the disinfectant used in a treatment system to maintain the disinfectant residual throughout the distribution system.

the addition of UV disinfection is coupled with a corresponding reduction in chlorination, the level of treatment for viruses may be significantly reduced.

PWSs are required to keep their disinfection profile and benchmark on file for review during sanitary surveys. Also, PWSs must notify the state as described in Section 1.3 before making significant changes to their disinfection practices.

The flowchart in Figure 1-3 provides information on the LT2ESWTR disinfection profiling and benchmarking requirements.

Figure 1-3. LT2ESWTR Disinfection Profile and Benchmark Decision Tree



³Some modifications to the disinfection process may include changing the contact basin geometry and baffling conditions, changing the pH during disinfection, decreasing the disinfectant dose during warmer temperatures, and increasing or decreasing flow through the plant.

⁴The total inactivation ratio for *Giardia* must be calculated using the procedures specified in 40 CFR 141.709(d)(1) through (3). The log of inactivation for viruses must use a protocol approved by the primacy agency.

1.6 Contents of this Guidance Document

This document is organized in the following chapters and appendices:

- Chapter 1 – Introduction

- Chapter 2 – Disinfection Segment

This chapter defines the term disinfection segment and describes ways in which a PWS can identify their disinfection segment(s).

- Chapter 3 – Data Collection

This chapter presents the data collection requirements for creating a disinfection profile.

- Chapter 4 – Calculating CT

This chapter presents methods and examples for calculating CT.

- Chapter 5 – Calculating Inactivation

This chapter presents information and examples for calculating *Giardia* and virus inactivation values to be used in the development of a disinfection profile.

- Chapter 6 – Developing the Disinfection Profile and Benchmark

This chapter provides information for developing a disinfection profile using calculated inactivation values. The chapter also presents information on when and how the disinfection benchmark must be calculated.

- Chapter 7 – Evaluating Disinfection Practice Modifications

This chapter discusses issues associated with making significant changes to treatment and how the disinfection profile and benchmark can be used to assess system modifications that may be considered for compliance.

- Chapter 8 – Treatment Considerations

This chapter gives an overview of different treatment methods and strategies PWSs can choose from when considering system modifications. This chapter also includes case studies on experiences with implementing different treatment methods.

- Appendix A – Glossary
- Appendix B – CT Tables
- Appendix C – Blank Worksheets
- Appendix D – Examples
- Appendix E – Tracer Studies
- Appendix F – Calculating the Volume of each Sub-unit
- Appendix G – Baffling Factors
- Appendix H – Conservative Estimate, Interpolation, and Regression Method Examples

1.7 References

USEPA. August 2007. *The Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) Implementation Guidance*. Washington, D.C.

USEPA. April 2010. *Long Term 2 Enhanced Surface Water Treatment Rule Toolbox Guidance Manual*. EPA 815-R-09-016. Washington, D.C.

Chapter 2 — Disinfection Segment

2.1 Introduction

The first step in developing a disinfection profile is to identify the disinfection segments within the treatment plant. A **disinfection segment** is a section of a treatment system beginning at one disinfectant injection or monitoring point and ending at the next disinfectant injection or monitoring point referred to as the ‘residual sampling point’. Each disinfectant injection point in a system must be associated with at least one sampling point. Each segment begins at the point of disinfection application and ends at the disinfectant residual sampling point. This sampling point is located just prior to the next disinfection application point or, for the last disinfection segment, at or before the entrance to the distribution system or the first customer. Data collection takes place at the residual sampling points (see Chapter 3 for types of data collected).

2.2 Identifying Disinfection Segments

The suggested starting point for analyzing a plant is to develop a summary of the unit processes, disinfectant injection points, and monitoring points. It may be helpful to use a sketch or plan drawing of the plant, such as those shown in Figures 2-1 through 2-6, when defining disinfection segments. The number of disinfection segments within a treatment train must equal or exceed the number of disinfectant application points in the system. For plants with multiple points of disinfectant application, such as ozone followed by chlorine, or chlorine applied at several points in the treatment train, the treatment train should be divided into multiple disinfection segments. If a PWS has multiple treatment plants, a disinfection profile applies only to the treatment plant where the data were collected to develop the disinfection profile; (i.e., a disinfection profile is specific to a treatment plant). A PWS with multiple treatment plants and a common distribution system that makes a disinfectant change at one of the treatment plants should consider whether that change will impact water quality in the distribution system and whether other treatment adjustments (e.g., corrosion control) may need to be made at other plants.

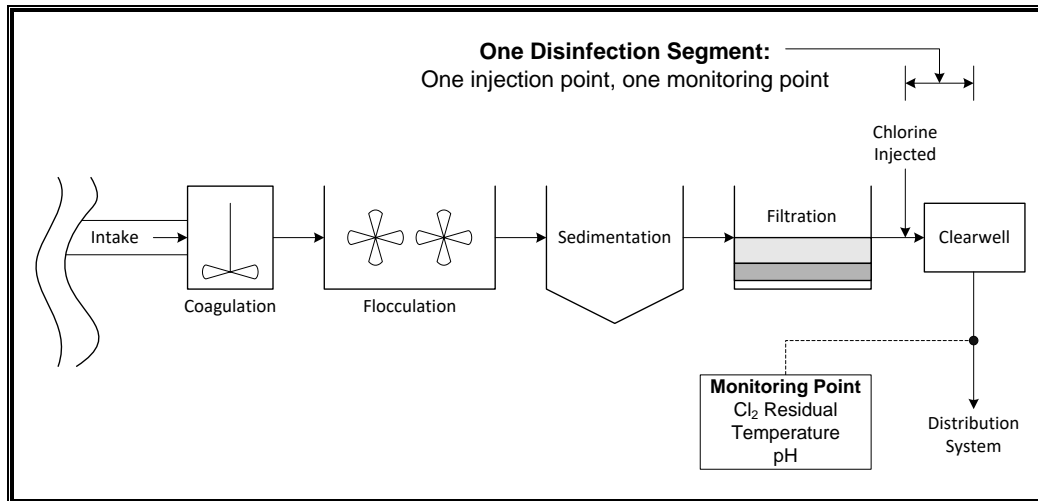
Disinfection segments may include one or more unit processes of the treatment train. PWSs may treat the entire plant as one disinfection segment or they may find it useful to divide the plant into multiple segments based on different mixing conditions or treatment units. For example, in a direct filtration plant where chlorine is applied at the rapid mixing stage and free chlorine residual is measured at the entrance to the distribution system, the whole plant is a single disinfection segment. The chlorine residual that is measured at the entry point to the distribution system, however, will be lower than the chlorine residual at points upstream in the treatment train due to chlorine demand and decay at various treatment stages. As a result, using only the entry point chlorine residual measurement to calculate inactivation will give a conservative CT value for the plant. Measuring free chlorine residual at the end of each treatment unit may provide a higher (and more representative) CT value (see Chapter 4 and Chapter 5 for a discussion on the relationship between CT and log inactivation).

Each treatment train will have its own disinfection profile based on its disinfection segment(s). Therefore, plants with multiple treatment trains may have multiple disinfection profiles. If the treatment trains are identical, and flow is split equally, the disinfection segments and corresponding profile for each train should be the same. If the treatment trains are very different, the PWS should identify all disinfection segments in each train and develop a disinfection profile for each train separately.

2.2.1 Single Disinfection Segment

Figure 2-1 shows a simple plant, with one injection point and one monitoring point, resulting in a single disinfection segment. The disinfection segment begins at the chlorine injection point prior to the clearwell and ends at the monitoring point after the clearwell.

Figure 2-1. Plant Schematic Showing a Conventional Filtration Plant with One Disinfection Segment



2.2.2 Multiple Disinfection Segments

Figure 2-2 is an example of a plant with two injection points and two monitoring points, resulting in two disinfection segments. Disinfection Segment 1 starts at the chlorine injection point prior to the coagulation basin and ends at the monitoring point after the filters. Disinfection Segment 2 starts at the chlorine injection point between the filters and the clearwell, and ends at the monitoring point after the clearwell and prior to the first customer.

Even for this simple plant, the analysis of how much disinfection takes place in the plant may be complicated. In this example, disinfection occurs in the coagulation basin, flocculation basin, sedimentation basin, filters, and clearwell, as well as in all the associated piping. PWSs may choose to break Disinfection Segment 1 into further segments adding chlorine residual monitoring points at the end of each of the treatment units.

Figure 2-2. Plant Schematic Showing a Conventional Filtration Plant with Two Disinfection Segments

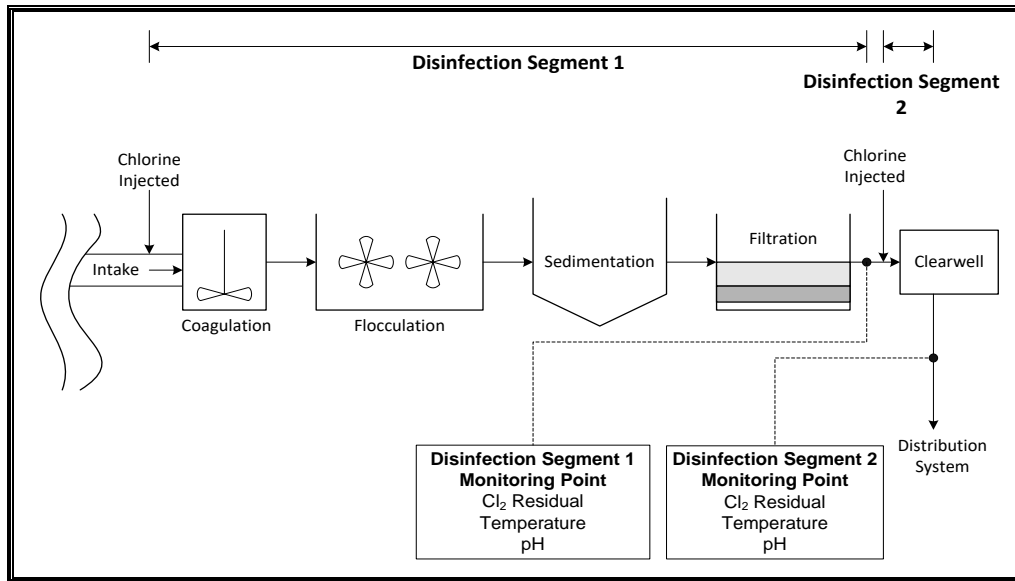


Figure 2-3 is an example of a plant with one injection point and multiple monitoring points. Although the PWS is required to have a minimum of one monitoring point, the chlorine is sampled in four locations to make use of the higher chlorine residual values at some segments in the plant; this results in a higher CT value for SWTR compliance, as opposed to monitoring at one location after the clearwell where the chlorine residual will be much lower than measurements prior to the clearwell. The first disinfection segment starts at the chlorine injection point before coagulation and ends at the first monitoring point after coagulation. The next three disinfection segments begin at one monitoring point and end at the following monitoring point. Therefore, even though there is only one injection point in this plant, there are four disinfection segments.

Figure 2-3. Plant Schematic Showing One Injection Point with Multiple Disinfection Segments

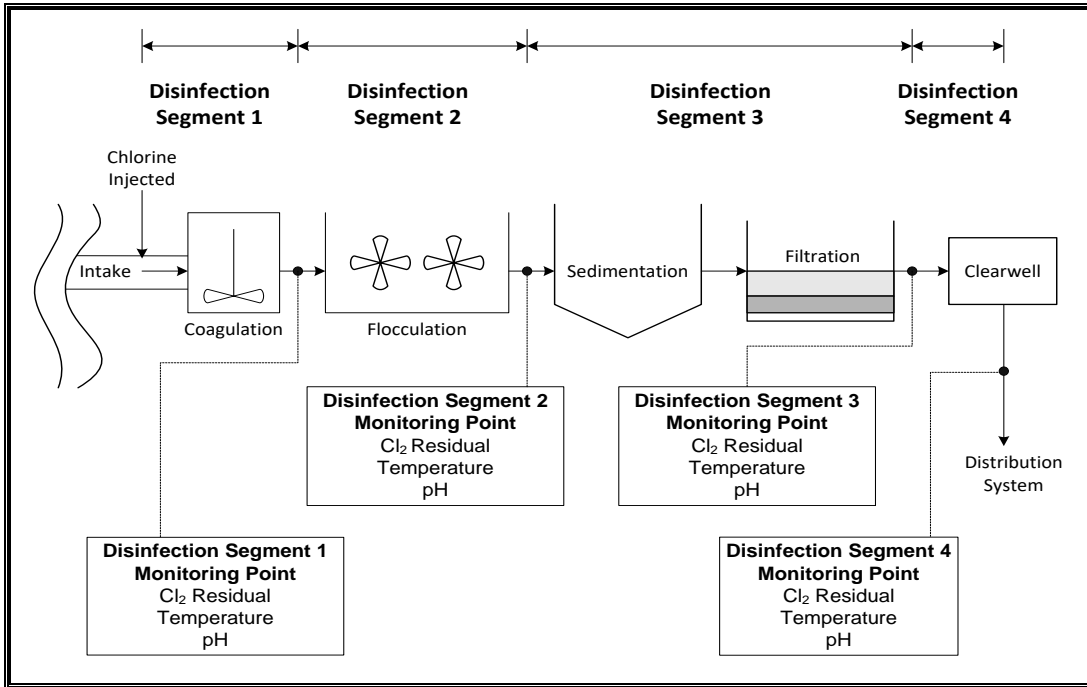
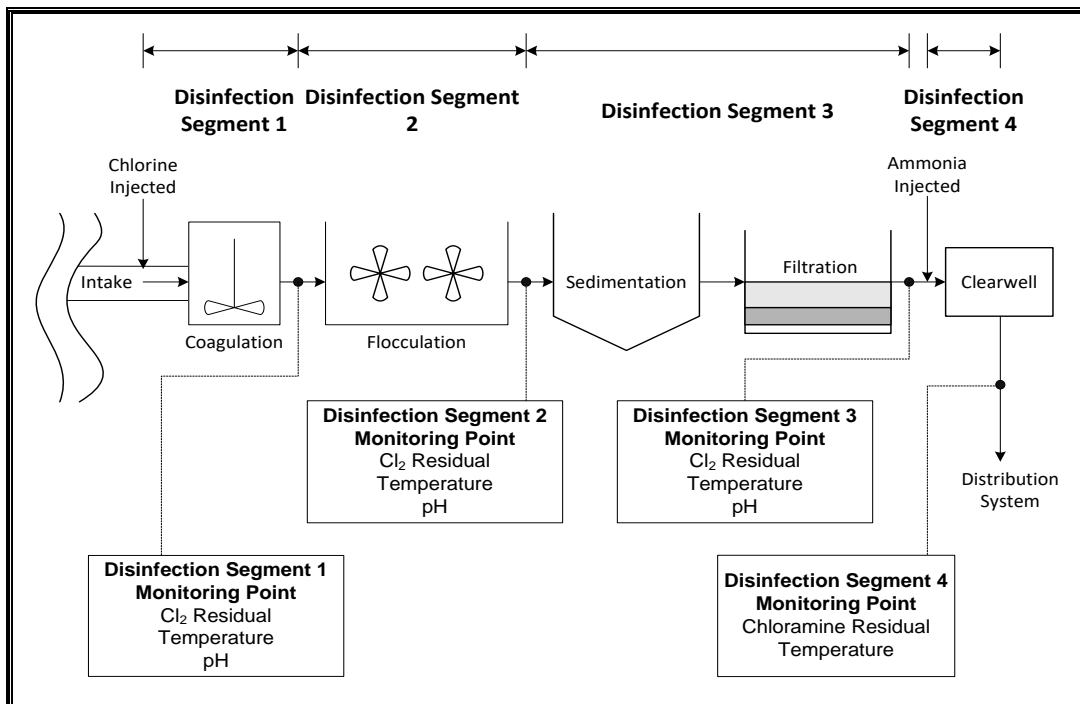


Figure 2-4 is another example of a more complicated plant schematic. Similar to Figure 2-3, this plant has four disinfection segments. The difference between these two plants is that the PWS in Figure 2-4 injects ammonia prior to the clearwell to form chloramines. The use of a different disinfectant results in a distinct disinfection segment.

Figure 2-4. Plant Schematic Showing Two Injection Points with Multiple Disinfection Segments



2.2.3 Disinfection Segments for Multiple Treatment Trains

For some system configurations, one profile would not accurately characterize the entire treatment process. In these cases, multiple profiles are suggested. Figure 2-5 shows a plant with multiple treatment trains and multiple disinfection segments. In this example, the treatment trains are identical in that all unit processes in both trains have the same dimensions, operating rates, and hydraulic capacities. Since the treatment trains are identical, and flow is split equally between the treatment trains, the disinfection profiles for Disinfection Segments 1a and 1b should be identical. Similarly, the disinfection profiles for Disinfection Segments 2a and 2b should be identical. However, PWSs should check with the state to determine if separate disinfection profiles are required for each treatment train.

Figure 2-5. Plant Schematic Showing Two Identical Treatment Trains and Each with Multiple Disinfection Segments

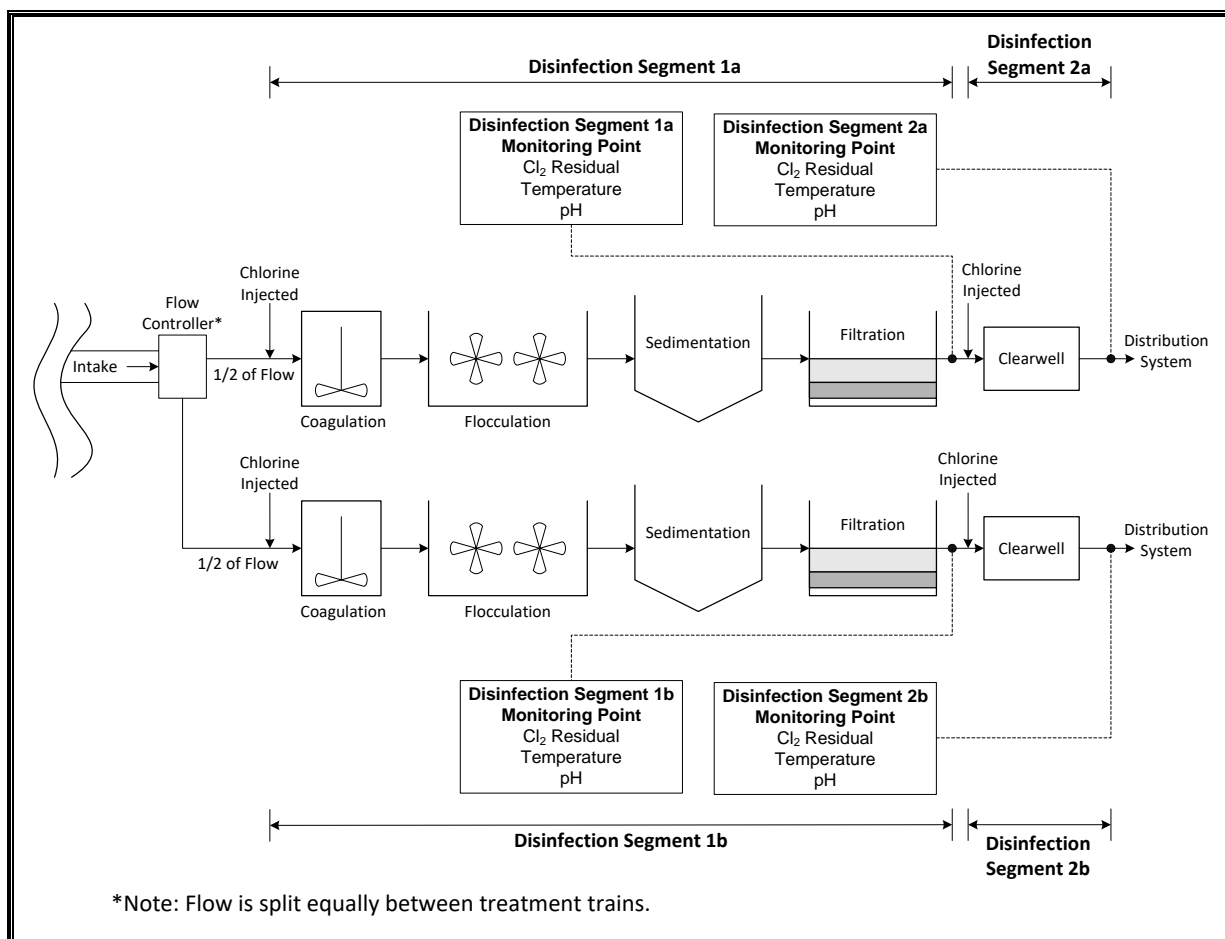
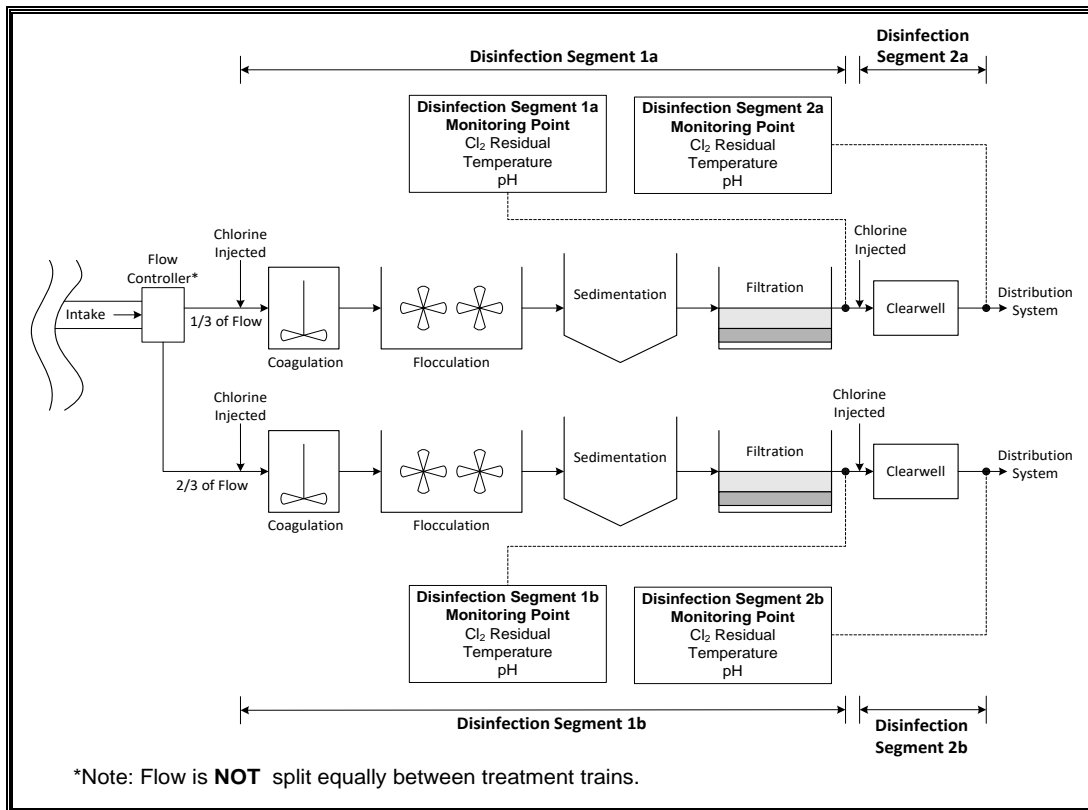
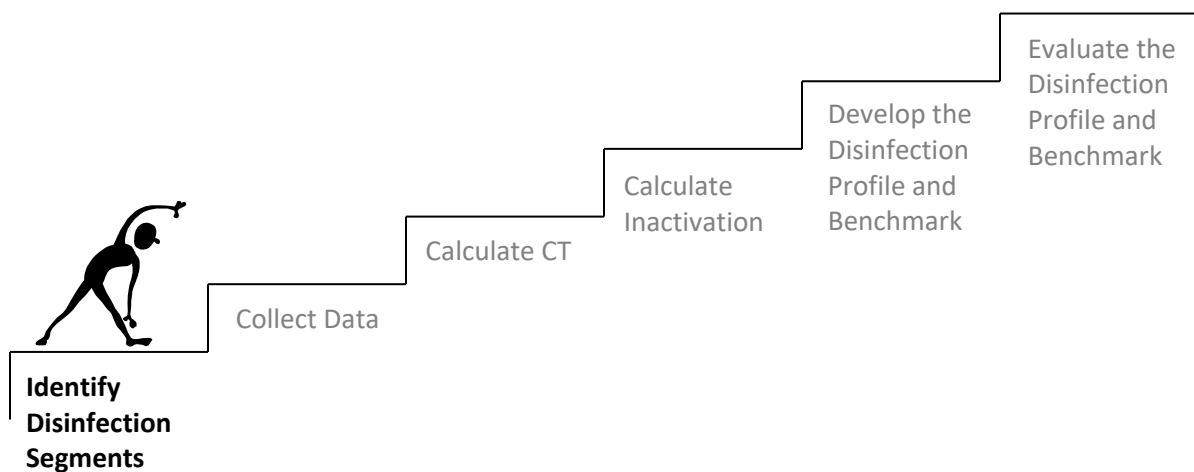


Figure 2-6 shows a plant with two treatment trains and multiple disinfection segments. In this example, although the treatment trains are identical the flow is not split equally between the treatment trains. The disinfection profiles for Disinfection Segments 1a and 1b may not be identical. Similarly, the disinfection profiles for Disinfection Segments 2a and 2b may not be identical. Therefore, this plant should develop a separate disinfection profile for each treatment train. Again, the PWS should check with the state on this issue.

Figure 2-6. Plant Schematic Showing Two Treatment Trains with Different Flows and Each with Multiple Disinfection Segments



2.3 Steps Completed



2.4 Next Step

Upon completing the activities in this chapter, the PWS will have completed the first of six steps in disinfection profiling: identifying disinfection segments. After all of the disinfection segments in the treatment system have been identified, data must be collected for each disinfection segment, as described in Chapter 3.

Chapter 3 — Data Collection

3.1 Introduction

Once a PWS has identified each disinfection segment, it must collect operational data during peak-hour flows for each segment for a minimum of 12 consecutive months. The data required to create a disinfection profile and benchmark are described in this section. PWSs required to comply with the disinfection profiling requirements of the IESWTR were required to collect daily measurements, while PWSs complying with the disinfection profiling requirements of the LT1ESWTR were required to collect weekly measurements of operational data. To develop a disinfection profile for the LT2ESWTR, a PWS must collect data at least once per week on the same day of the week for one year (52 measurements), during peak hourly flow for that day. PWSs may collect and use additional data to develop their disinfection profiles, as long as the data are evenly spaced over time.

3.2 Use of Grandfathered Data

PWSs can meet the disinfection profiling requirements under the LT2ESWTR by using previously collected data (i.e., grandfathered data). Use of grandfathered data is allowed if the PWS has not made a significant change in its disinfection practice or changed sources since the data were collected. This will permit most PWSs that prepared a disinfection profile under the IESWTR or the LT1ESWTR to avoid collecting any new operational data for developing a profile under the LT2ESWTR. PWSs that produced a disinfection profile for *Giardia* but not viruses under the IESWTR or LT1ESWTR must also develop the disinfection profile for viruses under the LT2ESWTR using the same monitoring data on which the original *Giardia* profile was based.

3.2.1 Data Needed for the Disinfection Profile

The basic data requirements for creating profiles based on *Giardia* and viruses are the same. Therefore, if a utility collects operating data sufficient to profile for *Giardia*, it can also develop a profile for viruses using the same data, as described in Chapter 5. Data can be measured manually or with on-line instrumentation as available. Data must be collected at least weekly for a period of twelve consecutive months. The following data must be gathered at peak hourly flow at the disinfectant residual sampling points for each disinfection segment in the treatment plant:

- **Peak Hourly Flow (Q).**
- **Residual Disinfectant Concentration (C).**
- **Water Temperature.**
- **pH** (if chlorine is used).

Data collected must be representative of the entire treatment plant. PWSs should consider adding or removing disinfection segments and residual sampling points to ensure that data sufficiently characterize system performance.

Peak Hourly Flow Rate (Q)

The time that the disinfectant is in contact with water in the disinfection segment, referred to as contact time (T) must be determined to calculate the CT value. Contact time is a function of flow. When the flow increases, the time the water spends in the plant and in contact with the disinfectant decreases. Using the peak hourly flow for analysis provides a conservative value for contact time. Therefore, all operational

data that affect the CT value are measured at peak hourly flow. Some PWSs may be able to use a single peak hourly flow for the entire plant. In other PWSs with multiple treatment trains, or where the peak hourly flow varies between disinfection segments, each treatment train or disinfection segment must be sampled during that segment's peak hourly flow. For example, the flow rate after the clearwell will be driven by the finished water pumps whereas the flowrate through the plant is driven by the raw water pumping rate or gravity flow.

Some options for determining peak hourly flow are:

- Flow meter records.
- Design flow rate.
- Maximum loading rates to the filters or other treatment process units.
- Raw water pumps records.
- Historical maximum flow.

When determining peak hourly flow, PWSs may want to take into consideration the location of their disinfection segment. For example, a PWS with a single disinfection segment with disinfection prior to the clearwell may consider using clearwell pumping rates versus raw water pump records to determine the peak hourly flow rate.

PWSs with supervisory control and data acquisition (SCADA) systems will be able to review records, identify the peak hourly flow and then obtain the residual disinfectant concentration, temperature, and pH (if chlorine is used) that were recorded during peak hourly flow. PWSs without SCADA should coordinate with the state to develop a procedure that allows the PWS to best identify peak hourly flow for data collection.

One possible approach for PWSs without SCADA is to determine when peak hourly flow occurred the day before data must be collected. The PWS can collect the residual disinfectant concentration, temperature, and pH (if chlorine is used) on the required day at the same time that peak hourly flow occurred on the previous day. Alternatively, PWSs may collect residual disinfectant concentration, temperature, and pH (if chlorine is used) data at three different times (such as before, during, and after) near the time when peak hourly flow occurred on the previous day. Then, based on pump records or other information, PWSs can determine when peak hourly flow actually occurred and use the data that were collected nearest to the time of peak hourly flow.

Residual Disinfectant Concentration (C)

The disinfectant residual concentration (C) is defined as the concentration of disinfectant measured in mg/L in a representative sample of water (40 CFR 141.2). This residual is measured at the residual sampling point in each disinfection segment. If, for example, a treatment plant has three disinfection segments, it will have three residual sampling points where data must be measured. The residual disinfectant concentration is monitored for each disinfection segment during peak hourly flow and is measured in milligrams per liter (mg/L). Monitoring the residual disinfectant at more than one location results in higher CT values because residual disinfectant concentration decreases with each subsequent treatment process. For more information on CT refer to Chapter 4.

The residual disinfectant concentration must be measured using methods listed in the current version of *Standard Methods for the Examination of Water and Wastewater* (APHA et al., 2017), as applicable. If approved by the state, residual disinfectant concentrations for free chlorine and combined chlorine may be measured using DPD (N, N-diethyl-p-phenylenediamine) colorimetric test kits (40 CFR 141.74). There are additional considerations for PWSs using ozone. While ozone residual values are measured using

Method 4500-03 B contained in the current version of *Standard Methods for the Examination of Water and Wastewater* (APHA et al., 2017), as applicable, average residual disinfectant concentrations (C) are also determined. Evaluating C for ozone is discussed further in Section 4.5.

Water Temperature

The effectiveness of all disinfectants, except for UV, is sensitive to water temperature. So, CT values vary with water temperature. Temperature should be measured at each monitoring point and at the same time as the residual disinfectant concentration, i.e., during peak hourly flow. The temperature should be recorded in degrees Celsius (°C) because the CT tables in Appendix B are based on temperature measured in °C (see Chapter 5 for an explanation of CT tables). Also, temperature must be measured using Method 2550 in the current version of *Standard Methods for the Examination of Water and Wastewater* (APHA et al., 2017), as applicable.

pH

If a PWS uses chlorine as a disinfectant, pH must be monitored because the disinfection effectiveness of chlorine is pH-sensitive and is more effective at lower pH values. The pH is sampled at each monitoring point and at the same time as the residual disinfectant concentration (during peak hourly flow). The CT tables in Appendix B for chlorine are based on the pH of the water. If using chloramines or chlorine dioxide as a disinfectant, keep in mind that while PWSs are not required to monitor for pH with these disinfectants, the CT tables list a pH range (pH between 6 and 9) for *Giardia* inactivation by chloramines and virus inactivation by chlorine dioxide.

PWSs must measure pH using the EPA Method 150.1 or 150.2, ASTM method D1293-95, or Method 4500-H⁺ in the current version of *Standard Methods for the Examination of Water and Wastewater* (APHA et al., 2017), as applicable.

3.3 Data Collection Worksheets

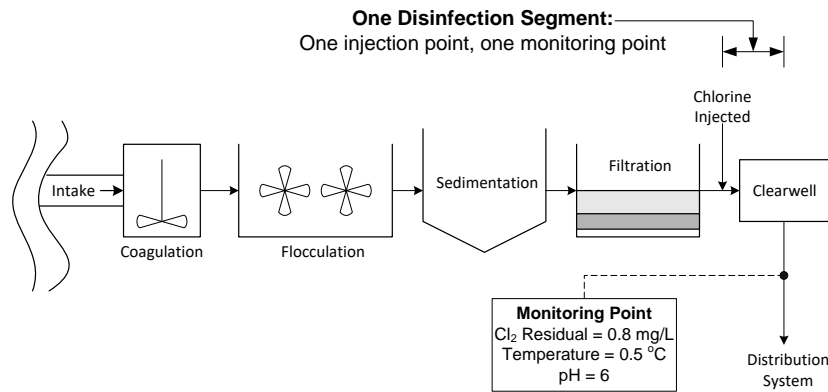
The worksheets in Appendix C are helpful for recording weekly disinfection profiling data. PWSs should verify that their state will accept the worksheets for recordkeeping and reporting purposes.

3.4 Data Collection Examples

Example 3-1 and 3-2 demonstrate the data collection requirements discussed in Section 3.3 for PWSs with single and multiple disinfection segments. The worksheets in Appendix C are used in these examples. For more examples, see Appendix D.

Example 3-1. Collecting Data for a Single Segment

The PWS is developing a disinfection profile for a single disinfection segment.



Step 1. Determine the peak hourly flow.

Clearwell pump records for this PWS show a peak hourly flow of 347 gallons per minute (gpm).

Step 2. Measure the chlorine residual, temperature, and pH (since chlorine is used) during peak hourly flow at the same monitoring point and at the same time.

During peak hourly flow, the PWS records the following measurements at the same monitoring point at the same time:

- Chlorine residual = 0.8 mg/L
- pH = 6
- Temperature = 0.5 °C

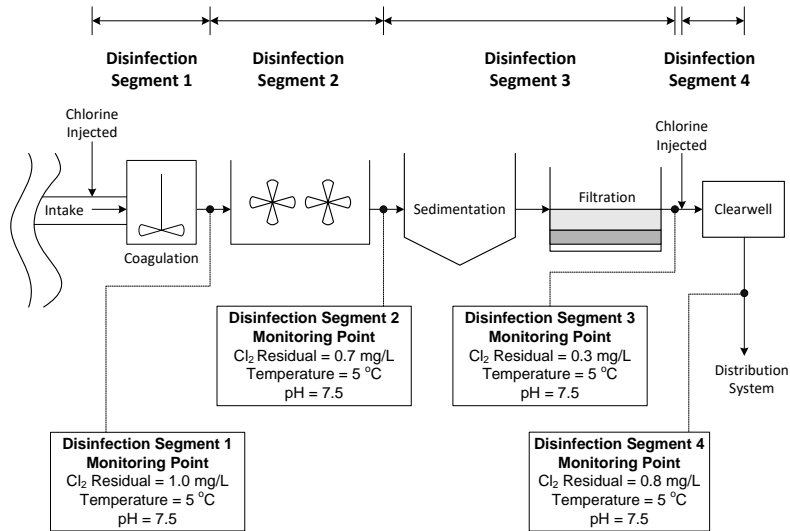
Step 3. Use Worksheet #1 in Appendix C (or another data collection method) to record water quality data for the disinfection profile.

WORKSHEET #1													
LOG INACTIVATION RATIO DETERMINATION FOR SURFACE WATER SYSTEMS OR GROUND WATER SYSTEMS UNDER THE DIRECT INFLUENCE OF SURFACE WATER													
Starting Month: <u>January</u>			Year: <u>2016</u>			PWSID: <u>AA1234567</u>			System/Water Source: <u>XYZ Water Plant</u>				
Disinfectant Type: <u>Free Chlorine</u>							Prepared by: <u>Joe Operator</u>						
Profile Type (check one): <input checked="" type="checkbox"/> <u>Giardia</u> <input type="checkbox"/> <u>Viruses</u>													
Disinfection Segment/Sequence of Application: <u>Clearwell/1st</u>													
Week #	3 Residual Disinf. Conc.	4 pH	5 Water Temp.	6 Peak Hourly Flow	7 Volume	8 TDT	9 Baffling Factor	10 Disinf. Contact Time	11 CT _{calc} = (C×T)	12 CT Req'd	13 Inactivation Ratio	14 Log Inactivation*	
1	0.8	6	0.5	347									
2													
3													
4													
5													
6													

*See worksheet #2 to determine total log inactivation if the system has multiple disinfection segments.

Example 3-2. Collecting Data for Multiple Disinfection Segments

The PWS is developing a disinfection profile for multiple disinfection segments.



Step 1. Determine the peak hourly flow for Disinfection Segments 1 through 4.

From the raw water pump records, the PWS determines the peak hourly flow to be 347 gpm for Disinfection Segments 1, 2, and 3.

From the clearwell pump records, the PWS determines the peak hourly flow to be 370 gpm for Disinfection Segment 4.

Step 2. Measure the chlorine residual, temperature, and pH (since chlorine is used) during peak hourly flow at the same monitoring point and at the same time.

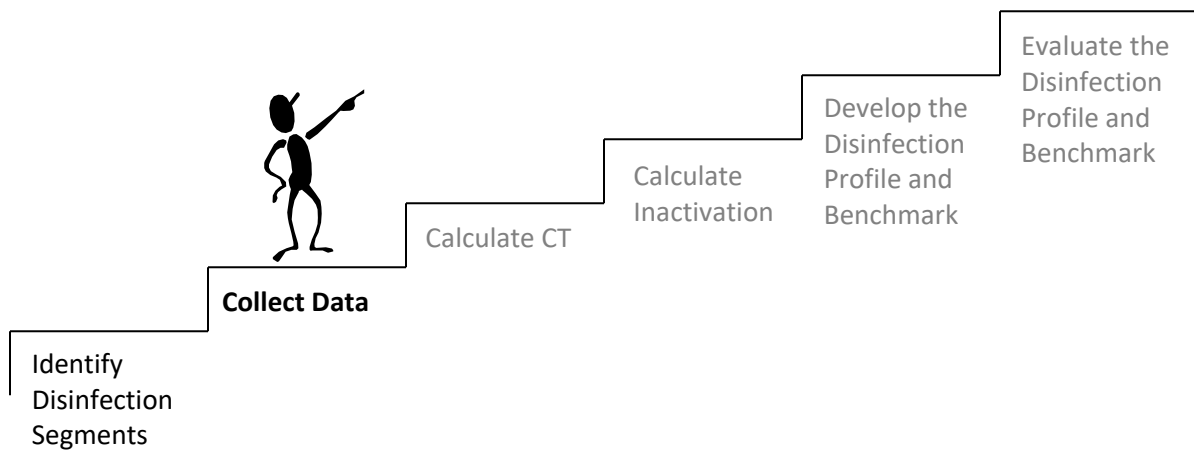
During peak hourly flow, the PWS records the following measurements at the same monitoring point at the same time:

Disinfection Segment	Chlorine Residual (mg/L)	Temperature (°C)	pH
1	1.0	5	7.5
2	0.7	5	7.5
3	0.3	5	7.5
4	0.8	5	7.5

Step 3. Use Worksheet #1 in Appendix C (or another data collection method) to record water quality data for the disinfection profile.

For PWSs with multiple segments, a separate copy of Worksheet #1 should be used for each disinfection segment. Example D-2 in Appendix D illustrates how to complete Worksheet #1 for multiple disinfection segments.

3.5 Steps Completed



3.6 Next Step

Upon completing the activities in this chapter, the PWS will have completed the second of six steps: collecting data. Now the CT value can be calculated. Chapter 4 explains how to calculate CT.

3.7 References

APHA, AWWA, WEF. 2017. *Standard Methods for the Examination of Water and Wastewater*, 23rd Edition. APHA, Washington, D.C.

Chapter 4 — Calculating CT

4.1 Introduction

The CT method is used to evaluate the amount of disinfection a treatment plant achieves and to determine compliance with the SWTR. If a PWS is required to complete a disinfection profile for the IESWTR, LT1ESWTR, or LT2ESWTR, it must collect operational data (or use grandfathered data) and calculate the CT value for each disinfection segment, known as CT_{calc} . The CT_{calc} value derived for each disinfection segment will be used to calculate the inactivation ratio for each disinfection segment. This section provides an overview of the procedure to determine C and T to calculate CT_{calc} values. For PWSs that use ozone as a disinfectant, refer to Section 4.5 for the applicable method for calculating CT.

The CT method cannot be used to evaluate UV disinfection. For PWSs that use UV light for disinfection, unlike chemical disinfectants, UV light does not leave a chemical residual that can be monitored to determine UV dose and inactivation credit. The UV dose depends on the UV intensity (measured by UV sensors), the flow rate, and the UV absorbance. The EPA's *Ultraviolet Disinfection Guidance Manual for the Final Long Term 2 Enhanced Surface Water Treatment Rule (UVDGM)* (USEPA, November 2006) provides guidance to PWSs using UV light for disinfection.

4.2 What is CT?

CT simply stands for the product of **concentration (C)** and **contact time (T)**. Conceptually, the CT value is a measure of disinfection effectiveness for the time that the water and disinfectant are in contact. It is evaluated as the product of disinfectant residual concentration and the contact time as shown in Equation 4-1. "C" is the disinfectant residual concentration measured in mg/L at peak hourly flow and "T" is the time, measured in minutes that the disinfectant is in contact with the water at peak hourly flow. The contact time (T) is measured from the point of disinfectant injection to a point where the residual is measured. From Equation 4-1, it can be seen that any design modifications that can increase T may allow the same inactivation (CT) with a decreased disinfectant residual. The CT_{calc} is the calculated CT value for a system based on its actual performance. Section 5.3 will discuss CT required, which is the required CT value that a PWS must achieve to be in compliance.

Equation 4-1

$$CT_{calc} \text{ (minutes-mg/L)} = C \times T$$

C = Residual disinfectant concentration measured during peak hourly flow in mg/L.

T = Time, measured in minutes, that the water is in contact with the disinfectant.

4.3 Determining "C"

"C" is the residual disinfectant concentration measured during peak hourly flow in mg/L. The residual disinfectant concentration must be measured for each disinfection segment. In addition, the residual disinfectant concentration must be measured at least once per week during peak hourly flow (if using grandfathered data collected for compliance with IESWTR profiling requirements, PWSs will have daily measurements during peak hourly flow). See Chapter 3 for information on the residual disinfectant concentration.

4.4 Determining “T”

Water does not flow through all treatment processes in a perfectly mixed condition. In some treatment units there can be substantial short circuiting. The disinfectant contact time (T), also referred to as T_{10} in the *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water* (USEPA, March 1991), is an estimate of the detention time within a basin or treatment unit during which 90 percent of the water passing through the unit is retained within the basin or treatment unit. T can be determined experimentally through a tracer study or it can be estimated based on a theoretical detention time (TDT) and baffling factor (BF). Appendix E provides a detailed discussion of tracer studies and how they can be used to determine disinfectant contact time. Estimation of T based on theoretical analysis is discussed here.

Once the peak hourly flow in each disinfection segment has been determined as described in Chapter 3, the following steps may be used to calculate T for a treatment system:

- For each basin, pipe, or unit process in each disinfection segment, calculate:
 - **Volume (V)** (see Section 4.4.1).
 - **Theoretical detention time (TDT)** (see Section 4.4.2).
 - **Baffling factor (BF)** (see Section 4.4.3).
 - **Contact time (T) for each basin, pipe, or unit process** based on TDT and BF (see Section 4.4.4).
- Sum the T values for each basin, pipe, or unit process to obtain the **total contact time (T)** for the disinfection segment.

4.4.1 Volume

The volume of water contained in each basin, pipe, or unit process in a disinfection segment is used to calculate T for that segment. Since some treatment units, such as clearwells, can have fluctuating levels that affect volume, PWSs should consult with the state regarding what volume should be used for the disinfection profile. Using internal volumes for units to account for wall thicknesses when possible can provide a more accurate estimate of the water volume. PWSs and states may want to consider the following options:

- Volumes can be based on the minimum volume that can occur in the treatment unit. This approach is the most conservative.
- Volumes can be based on the actual volume realized in the treatment unit during peak hourly flow if adequate information is available to identify the actual volume.
- Volumes can be based on the lowest volume realized in the treatment unit for that day.

Table 4-1 provides equations used to find the volume of the specific sub-units or segments. See Appendix F for detailed examples of sub-units and volume equations.

Table 4-1. Volume Equations for Shapes

Shape	Example of Unit with This Shape	Volume Equation
Cylindrical Pipes	Raw Water Pipe, Plant Piping, Finished Water Pipe	Length x Cross-sectional Area (πr^2)
Rectangular Basins	Rapid Mix, Flocculation and Sedimentation Basins, Clearwells	Length x Width x Minimum Water Depth
Cylindrical Basins	Rapid Mix, Flocculation and Sedimentation Basins, Clearwells	Minimum Water Depth x Cross-sectional Area (πr^2)
Rectangular Filters	Filtration	Surface Area of Filter x Depth of Water Above Filter Surface (Vol. of water in the media pores may also be used by calculating Length x Width x Media Depth x Percent Pore Space.)

4.4.2 Theoretical Detention Time

The theoretical detention time (TDT) is the theoretical time that the water is in a basin, pipe, or unit process assuming perfect plug flow. Perfect plug flow assumes no short-circuiting within the basin, pipe, or unit process and all the water follows a single flow path. The TDT is calculated by dividing the volume based on low water level by the peak hourly flow (Equation 4-2).

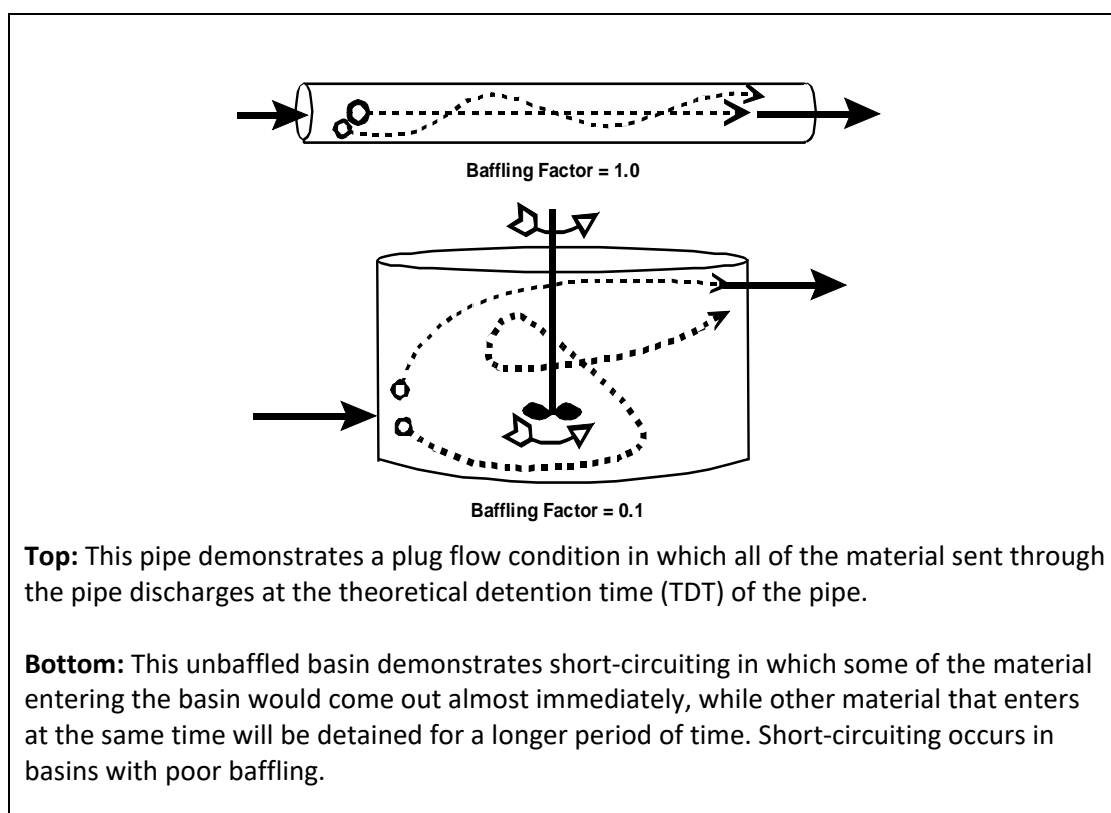
Equation 4-2

$TDT = V / Q$ <p>TDT = Theoretical Detention Time, in minutes V = Volume based on low water level, in gallons (gal) Q = Peak hourly flow, in gpm</p>
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4.4.3 Baffling Factor

The T in each basin, pipe, or unit process is a function of the physical configuration and baffling. The flow through a pipe is very different than the flow through an unbaffled basin (see Figure 4-1). The longest path a particle can take through a pipeline does not vary substantially from the shortest path. In the case of an unbaffled basin, however, some percentage of the flow may follow a path that goes directly from the inlet to the outlet. As a result, short-circuiting occurs and microorganisms in this path will only be in contact with the disinfectant for a relatively short time.

Figure 4-1. Baffling Characteristics of a Pipe and Clearwell



Baffling factors (BFs) help estimate the contact time of a basin, pipe, or unit process based on the volume of and flow rate through the basin, pipe, or unit process. Baffling factors recommended in Table 4.2 were developed based on tracer studies of basins with varying sizes and configurations. Table 4-2 and Appendix G provide a summary of theoretical baffling factors for various baffling conditions and basins.

Table 4-2. Baffling Factors

Baffling Condition	Baffling Factor	Baffling Description
Unbaffled (mixed flow)	0.1	None, agitated basin, very low length to width ratio, high inlet and outlet flow velocities.
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.

Source: USEPA. March 1991.

4.4.4 Calculate Contact Time

T in each basin, pipe, or unit process can be calculated once the TDT and BF are known (Equation 4-3). To evaluate total contact time in a disinfection segment, the T values for each basin, pipe and/or unit process within the segment have to be added together. Example 4-1 shows the procedure for determining T for a disinfection segment with only one clearwell. For examples with multiple units and segments, see Appendix D.

Equation 4-3

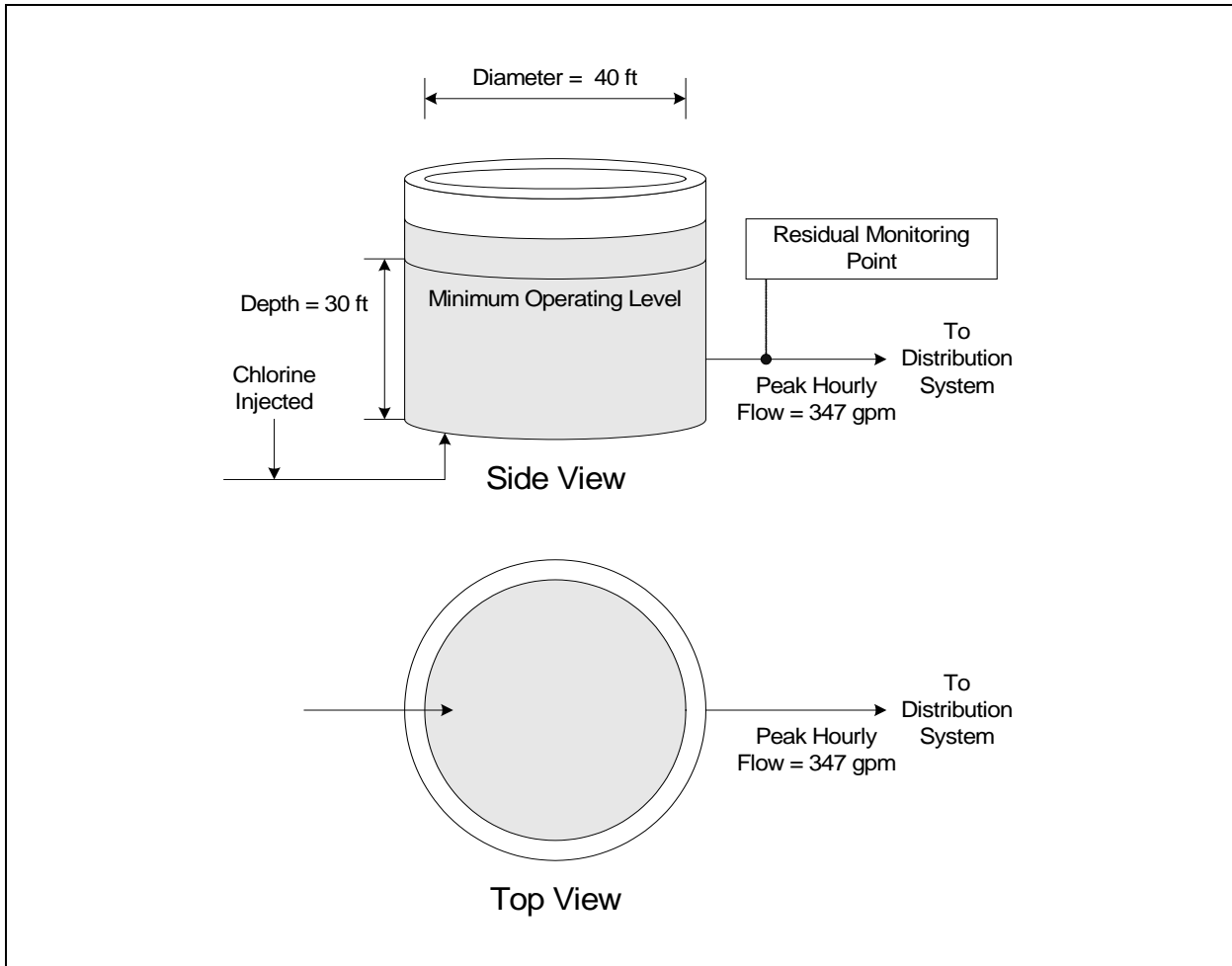
$$T = TDT \times BF$$

T = Time, measured in minutes, that the water is in contact with the disinfectant.

TDT = Theoretical detention time, in minutes

BF = Baffling factor

Example 4-1. Determining "T" for a clearwell with no baffling



Step 1. Measure the physical dimensions of the clearwell.

Measure the inner tank diameter to obtain the volume of water in the clearwell.

Diameter = 40 ft.

Measure the minimum operating depth in the clearwell to obtain a conservative estimate of the volume of water in the tank.

Minimum Water Depth = 30 ft.

Step 2. Calculate the volume of the clearwell based on low water level.

From Table 4-1 the equation for calculating the volume of a cylindrical basin is:

Volume (V) = minimum water depth x cross-sectional area (πr^2) where

$$\pi = 3.14$$

$$\text{Radius (r)} = \text{diameter} / 2 = 40 \text{ ft.} / 2 = 20 \text{ ft.}$$

$$V = 30 \text{ ft.} \times 3.14 \times (20 \text{ ft.})^2 = 37,680 \text{ ft}^3$$

$$V = 37,680 \text{ ft}^3 \times (7.48 \text{ gal} / \text{ft}^3)$$

$$V = 282,000 \text{ gallons}$$

The volume of the clearwell = 282,000 gallons

Note: More information on volume equations and calculations can be found in Appendix F.

Step 3. Calculate the theoretical detention time.

$$\text{TDT} = V / Q \text{ (Note: } Q = \text{peak hourly flow)} \quad \text{(See Equation 4-2)}$$

$$\text{TDT} = 282,000 \text{ gal} / 347 \text{ gpm}$$

$$\text{TDT} = 813 \text{ minutes}$$

The TDT in the clearwell is 813 minutes

Step 4. Determine the baffling factor for the clearwell.

From the diagram shown above, there is no baffling in the clearwell. From Table 4-2, the BF for an unbaffled basin is 0.1.

The BF for the clearwell = 0.1

Step 5. Calculate the contact time of the disinfectant in the clearwell.

Contact Time = TDT x BF (See Equation 4-3)
 T = 813 min x 0.1
 T = 81.3 minutes

The contact time (T) in the clearwell = 81.3 minutes

Step 6. Use Worksheet #1 in Appendix C (or another data collection method) to record data and calculate contact time.

WORKSHEET #1													
LOG INACTIVATION RATIO DETERMINATION FOR SURFACE WATER SYSTEMS OR GROUND WATER SYSTEMS UNDER THE DIRECT INFLUENCE OF SURFACE WATER													
Starting Month: <u>January</u>			Year: <u>2016</u>			PWSID: <u>AA1234567</u>			System/Water Source: <u>XYZ Water Plant</u>				
Disinfectant Type: <u>Free Chlorine</u>							Prepared by: <u>Joe Operator</u>						
Profile Type (check one): <input checked="" type="checkbox"/> <u>Giardia</u> <input type="checkbox"/> <u>Viruses</u>													
Disinfection Segment/Sequence of Application: <u>Clearwell/1st</u>													
Week #	3 Residual Disinf. Conc.	4 pH	5 Water Temp.	6 Peak Hourly Flow	7 Volume	8 TDT	9 Baffling Factor	10 Disinf. Contact Time	11 CT _{Calc} = (CxT)	12 CT Req'd	13 Inactivation Ratio	14 Log Inactivation*	
	C (mg/L)		(°C)	(gpm)	(gal)	(min.)		T (min.)	(min-mg/L)	(min-mg/L)	(Col 11 / Col 12)		
1	0.8	6	0.5	347	282,000	813	0.1	81.3					
2													
3													
4													
5													
6													

*See worksheet #2 to determine total log inactivation if the system has multiple disinfection segments.

4.5 Special Considerations for Ozone

Because of the unique characteristics of ozone, the procedures for determining C and T for disinfection with ozone differ from those recommended for PWSs using other chemical disinfectants (e.g., chlorine). The CT evaluation procedures presented above are not appropriate for ozone disinfection and would require excessive ozone dosages. Ozone is a powerful oxidant that reacts rapidly with organic and inorganic substances present in the water. Ozone quickly undergoes auto-decomposition and, therefore, its residual is much less stable than that of other chemical disinfectants and dissipates rapidly. In addition, for many ozone contactors, the residual in the contactor will vary in accordance with the formation method and rate of application. The residual will be non-uniform and is likely to be zero in a portion of the contactor. In addition to the non-uniformity of the ozone residual, monitoring the residual is difficult because of ozone's high reactivity and the closed design of the contactors.

There are separate methods for determining C and T for ozone disinfection. The recommended methods for determining C for ozone have not been modified from those presented in Appendix O of the *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources* (USEPA, March 1991). The C value can be determined for individual ozone contactor chambers based on the residual measured at several points throughout the chamber, or at the exit of the chamber. The EPA recommends the use of the average dissolved ozone concentration for C (USEPA, March 1991). The average concentration may be determined using one of the following methods:

1. Direct measurement of the concentration profile of dissolved ozone in each contact chamber (described in section O.3.2 of the *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources* (USEPA, March 1991)) and then using the direct measurements to calculate the average value.
2. Indirect prediction of the average concentration based on conservative correlations between dissolved ozone measurements at the contact chamber outlet and the average concentration within the ozone chamber (described in section O.3.3 of the *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources* (USEPA, March 1991)). Table 4-3 summarizes how to predict the average ozone concentration in an ozone contact chamber based on the concentration measured at the outlet of the chamber. Table 4-3 shows how the predictions of C vary based on the type of flow (e.g., uniformly mixed, plug flow, counter-current flow and co-current flow) in the chamber and whether the chamber is the first chamber where ozone is introduced in a multiple chamber ozone contactor or a subsequent chamber within the same ozone contactor. Table 4-3 shows that the outlet ozone concentration can often be used as the C value. However, in the first chamber of an ozone contactor with counter-current flow or co-current flow, the outlet ozone concentration must meet minimum values in order to get partial credit for inactivation of *Giardia* and viruses, as explained in the footnotes.

All ozone residuals must be measured using the Indigo Colorimetric Method (Method 4500-03 B), contained in the current version of *Standard Methods for the Examination of Water and Wastewater* (APHA et al., 2017), as applicable.

Table 4-3. Correlations to Predict C* Based on Ozone Residual Concentrations in the Outlet of a Chamber

Relative Order of Ozone Chamber	Classification of Ozone Chamber Based on Flow Configuration			
	Continuous Stirred Reactor Method (CSTR) with Turbine Agitator (Uniformly Mixed Flow)	Dissolution Chamber (Co-Current Flow)	Dissolution Chamber (Counter-Current Flow)	Reactive Flow Chamber with No Ozone Addition (Plug Flow)
First Chamber	C_{out}	$C_{out} > 0.1 \text{ mg/L}$ or $> 0.3 \text{ mg/L}^{\pm}$	$C_{out} > 0.1 \text{ mg/L}$ or $> 0.3 \text{ mg/L}^{\pm}$	Not Applicable
Subsequent Chambers	C_{out}	C_{out} or $(C_{out} + C_{in}) / 2$	$C_{out} / 2$	C_{out}

[±] For inactivation of *Giardia* and viruses, if permitted by the state, PWSs can receive 0.5 log *Giardia* inactivation credit for the first dissolution chamber providing that $C_{out} > 0.3 \text{ mg/L}$ and 1-log of virus inactivation credit providing that $C_{out} > 0.1 \text{ mg/L}$ and the volume of the first chamber is equal to the volume of subsequent chambers. For *Cryptosporidium*, the EPA recommends that no inactivation credit be granted in the first chamber due to the higher CT requirements for *Cryptosporidium* compared to *Giardia* and viruses (USEPA, March 1991).

C* - Characteristic concentration (mg/L), used for CT calculation.
 C_{out} - Ozone residual concentration at the outlet from the chamber.
 C_{in} - Ozone residual concentration at the inlet to the chamber, which can be C_{out} of the immediate upstream chamber.

The *Long Term 2 Enhanced Surface Water Treatment Rule Toolbox Guidance Manual* (USEPA, April 2010) discusses two initial and two corresponding extended methods for determining log removal with ozone. The extended methods are not discussed in this guidance manual. The first method is the T_{10} method, which uses a normal CT calculation and tables to determine inactivation. The T_{10} method is determined using tracer studies (see Appendix E) and is the time at which 90 percent of the water that enters the chamber will remain for at least T_{10} minutes. An example for calculating CT for ozone with the T_{10} method is in Appendix D.

For contactors that experience significant back mixing (T_{10} /hydraulic detention time (HDT) ≤ 0.5) or when no tracer data are available, EPA recommends using the Continuous Stirred Reactor (CSTR) method (USEPA, April 2010). This method uses the HDT of the ozone contactor, as described below, for estimating the contact time. The CSTR method should be applied to the individual chambers in the contactor. For the CSTR approach, log inactivation is calculated with Equation 4-4.

Equation 4-4

$$-\text{Log}(I/I_0) = \text{Log}(1 + 2.303 \times k_{10} \times C \times \text{HDT})$$

-Log (I/I₀) = the log inactivation
 k_{10} = log base 10 inactivation coefficient (L/mg-min)
 C = Concentration (mg/L)
 HDT = Hydraulic detention time (minutes)

The k_{10} values for the inactivation of *Cryptosporidium*, *Giardia*, and viruses with ozone can be expressed by the following equations (Temp = water temperature in °C):

Equation 4-5

Inactivation of *Cryptosporidium* with ozone:

$$k_{10} = 0.0397 \times (1.09757)^{\text{Temp}}$$

Equation 4-6

Inactivation of *Giardia* with ozone:

$$k_{10} = 1.0380 \times (1.0741)^{\text{Temp}}$$

Equation 4-7

Inactivation of virus with ozone:

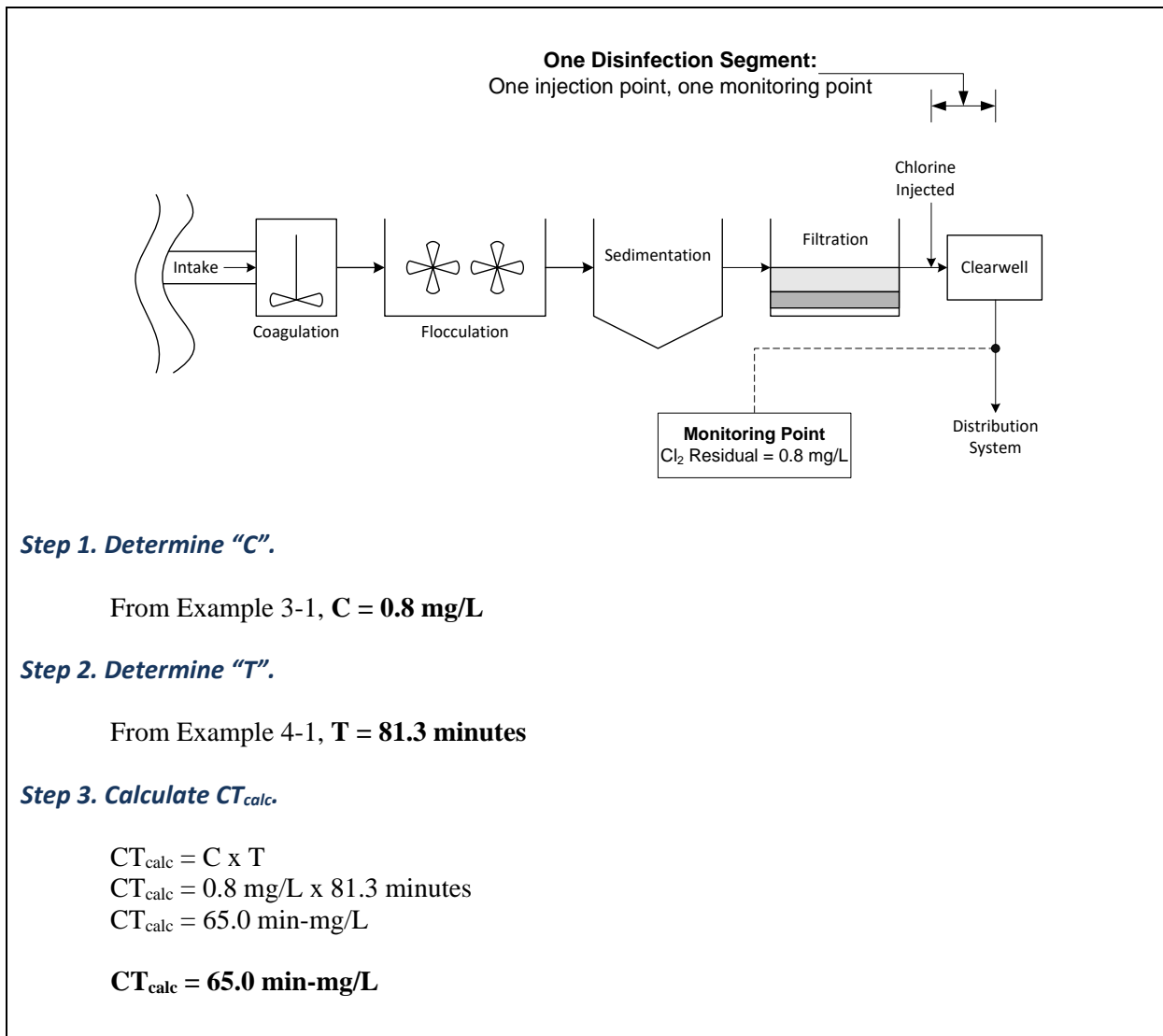
$$k_{10} = 2.1744 \times (1.0726)^{\text{Temp}}$$

The values of k_{10} for the inactivation of *Giardia* and viruses were derived from the k_{10} values for *Giardia* and virus inactivation listed in Appendix O of the SWTR Guidance Manual (USEPA, March 1991).

4.6 Calculate CT_{calc}

After the C and T for a segment have been determined, the disinfection effectiveness for the time that the water and disinfectant are in contact is calculated using Equation 4-1. Example 4-2 demonstrates how to determine CT_{calc} for one disinfection segment for the conventional filtration system also used in previous examples. If more than one disinfectant is used or if residual disinfectants are measured in more than one location, then CT_{calc} must be calculated for each disinfection segment. See the examples in Appendix D for more illustrations of calculating CT_{calc} under different operating conditions.

Example 4-2. Calculate CT_{calc}

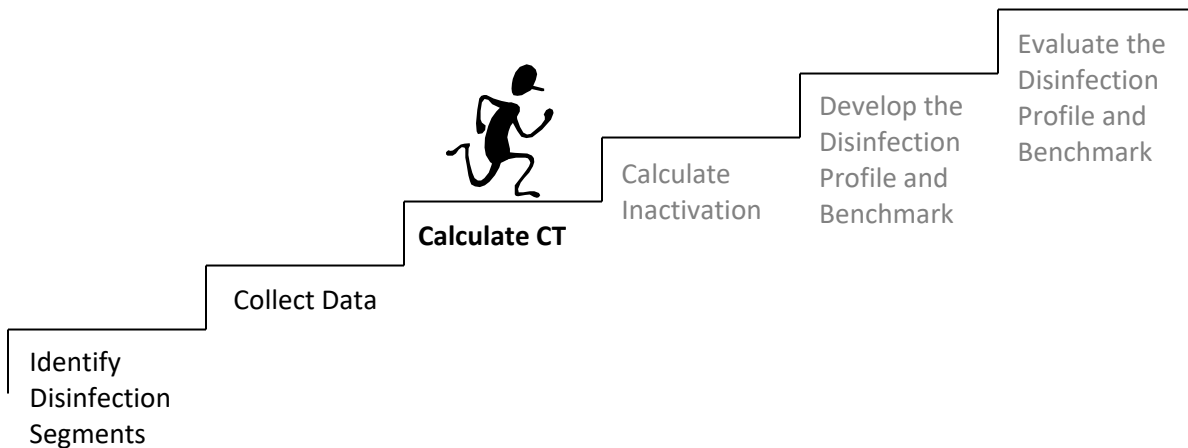


Step 4. Use Worksheet #1 in Appendix C (or another data collection method) to record data and calculate contact time.

WORKSHEET #1													
LOG INACTIVATION RATIO DETERMINATION FOR SURFACE WATER SYSTEMS OR GROUND WATER SYSTEMS UNDER THE DIRECT INFLUENCE OF SURFACE WATER													
Starting Month: <u>January</u>			Year: <u>2016</u>			PWSID: <u>AA1234567</u>			System/Water Source: <u>XYZ Water Plant</u>				
Disinfectant Type: <u>Free Chlorine</u>						Prepared by: <u>Joe Operator</u>							
Profile Type (check one): <input checked="" type="checkbox"/> <u>X</u> <u>Giardia</u> <input type="checkbox"/> <u>Viruses</u>													
Disinfection Segment/Sequence of Application: <u>Clearwell/1st</u>													
Week #	3	4	5	6	7	8	9	10	11	12	13	14	
	Residual Disinf. Conc.	pH	Water Temp.	Peak Hourly Flow	Volume	TDT	Baffling Factor	Disinf. Contact Time	CT _{Calc} = (CxT)	CT Req'd	Inactivation Ratio	Log Inactivation*	
	C (mg/L)		(°C)	(gpm)	(gal)	(min.)		T (min.)	(min-mg/L)	(min-mg/L)	(Col 11 / Col 12)		
1	0.8	6	0.5	347	282,000	813	0.1	81.3	65.0				
2													
3													
4													
5													
6													

*See worksheet #2 to determine total log inactivation if the system has multiple disinfection segments.

4.7 Steps Completed



4.8 Next Step

Upon completing the activities in this chapter, the PWS will have completed the third of six steps: calculating CT. In addition to CT_{calc}, CT required must also be determined to calculate log inactivation. Chapter 5 describes how to determine CT required and how to calculate log inactivation.

4.9 References

APHA, AWWA, WEF. 2017. *Standard Methods for the Examination of Water and Wastewater*, 23rd Edition. APHA, Washington, D.C.

USEPA. March 1991. *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water*. Washington, D.C.

USEPA. November 2006. *Ultraviolet Disinfection Guidance Manual for the Final Long Term 2 Enhanced Surface Water Treatment Rule*. EPA 815-R-06-006. Washington, D.C.

USEPA. April 2010. *Long Term 2 Enhanced Surface Water Treatment Rule Toolbox Guidance Manual*. EPA 815-R-09-016. Washington, D.C.

Chapter 5 — Calculating Inactivation

5.1 Introduction

Log inactivation is an expression of the magnitude of microorganisms inactivated during disinfection using a given process. The objective of this chapter is to demonstrate the calculations involved in determining the estimated log inactivation achieved through disinfection. This chapter describes the SWTR log inactivation method, procedures to determine minimum regulatory log inactivation for *Giardia* (3-log inactivation minus credit for removal) and viruses (4-log inactivation minus credit for removal), procedures to calculate estimated log inactivation for each disinfection segment of a plant, and the method to determine the overall estimated plant log inactivation. The chapter is structured to present concepts and guidelines followed by examples to demonstrate their applications.

A series of calculations are completed to determine logs of inactivation achieved through disinfection. First, CT_{calc} is determined (see Chapter 4). Then CT_{calc} is related to the required CT using CT tables. Individual CT tables specific to *Giardia* and viruses (see Appendix B) because the inactivation effectiveness of each disinfectant varies by microorganism. Estimated log inactivation values are calculated for each disinfection segment of the treatment train. Once the estimated log inactivation values for each segment have been calculated, they are summed to yield the total plant log inactivation.

5.2 CT Tables

The SWTR requires *Giardia* and virus inactivation for PWSs using surface water or GWUDI. Because of the difficulty in measuring actual microbial inactivation, the EPA has developed CT tables (see Appendix B) that can be used to estimate the inactivation achieved through different levels of chemical disinfection. These tables have been developed for approved disinfectants, including chlorine, ozone, chlorine dioxide, and chloramines. The CT tables are presented in the form of log inactivation for given operational conditions (temperature, pH, and residual concentration, as applicable) since the relationship between CT and log inactivation is relatively linear for most disinfectant and organism combinations. The CT tables for chlorine in Appendix B indicate the log inactivation of *Giardia* and viruses corresponding to the operating conditions of temperature, pH, and residual disinfectant concentration. The CT tables for *Giardia* inactivation by chloramines and virus inactivation by chlorine dioxide also list a range for pH values. PWSs are not required to monitor pH when using chloramines or chlorine dioxide for primary disinfection because unlike chlorine, the effectiveness of these disinfectants is not pH sensitive. However, PWSs should ensure that the pH falls within the pH range specified in the CT tables (pH between 6 and 9).

5.3 Determining CT Required

Based on system operating parameters and configurations, CT tables are used to determine the required CT value for a given level of inactivation. Required CT values are also represented as ‘ $CT_{log\ number}$ ’ where log number is the number of “nines” in the percentage removal and/or inactivation. For example, 3-log inactivation of *Giardia* corresponds to inactivation of 99.9% of the *Giardia* cysts and is represented as $CT_{99.9}$. Similarly, 4-log inactivation of viruses is represented as $CT_{99.99}$. The required CT must be evaluated for each disinfection segment based on the disinfectant used in that segment. The following guidelines can be used to obtain the required CT value from the CT tables for each disinfection segment:

- Find the appropriate table based on the disinfectant used and microorganism of concern (*Giardia* or viruses).
- Find the appropriate portion of the table and/or the appropriate column based on measured temperature and pH. PWSs should contact the state if the measured pH value is not included in the CT tables in Appendix B.
- Find the appropriate row based on the measured disinfectant residual (for chlorine only).
- Identify the required CT value based on the above information.

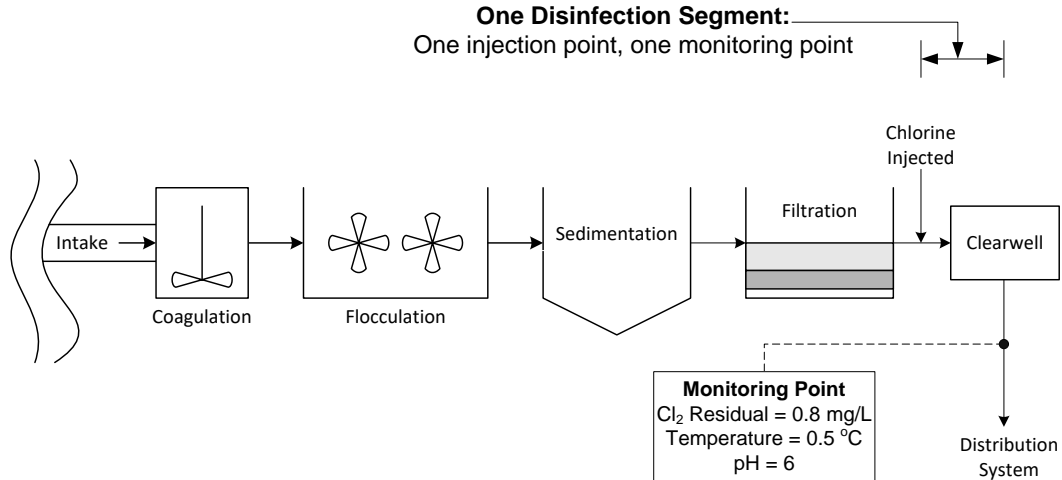
In some instances, the collected operational data for the disinfection profile will not coincide exactly with the values in the CT tables. For these situations, Appendix H demonstrates three possible methods of determining CT: conservative estimate, linear interpolation, and the regression method.

5.3.1 $CT_{99.9}$ for *Giardia*

All surface water systems or GWUDI systems are required to achieve 3-log (99.9%) removal and/or inactivation of *Giardia* through removal (sedimentation and filtration) and/or inactivation (disinfection) (40 CFR 141.70(a)(1)). Inactivation through disinfection can be achieved by one disinfectant or a combination of disinfectants. Example 5-1 illustrates how to determine the $CT_{99.9}$ value for *Giardia* for a PWS with one segment. See Example D-3 in Appendix D for PWSs with multiple segments.

Example 5-1. Determining CT_{99.9} Disinfection with Chlorine

The conventional filtration system discussed in Examples 3-1, 4-1, and 4-2 uses chlorine disinfectant only.



Step 1. Gather required data during peak hourly flow.

Water temperature = 0.5 °C
Chlorine residual = 0.8 mg/L
pH = 6.0

Step 2. Locate appropriate CT table.

The table for 3-log inactivation of *Giardia* by free chlorine is Table B-1 in Appendix B.

Step 3. Identify the appropriate portion of the table based on operating conditions and 3-log *Giardia* inactivation.

The first section of the table is for temperatures less than or equal to 0.5 °C. The first column in that section is for pH values less than or equal to 6.0. The disinfectant residual of 0.8 mg/L is found in the third row down on the chart. The relevant portion of Table B-1 is reprinted below.

Table 5-1. Excerpt from Table B-1

CT Values for 3-Log Inactivation of *Giardia* Cysts by Free Chlorine (0.5 °C portion of table for 0.4 to 1.2 mg/L free chlorine concentration)

Chlorine Concentration (mg/L)	Temperature ≤ 0.5 °C						
	pH						
	≤6.0	6.5	7.0	7.5	8.0	8.5	9.0
≤0.4	137	163	195	237	277	329	390
0.6	141	169	200	239	286	342	407
0.8	145	172	205	246	295	354	422
1.0	148	176	210	253	304	365	437
1.2	152	180	215	259	313	376	451

Step 4. Obtain $CT_{99.9}$ value.

From this chart, the value of CT for 3-log inactivation at 0.8 mg/L and pH of 6 is 145 min-mg/L.

$CT_{99.9}$ for *Giardia* = 145 min-mg/L

This value of $CT_{99.9}$ is the level of CT that the system would need to obtain to achieve 3-log *Giardia* inactivation with the conditions (pH, temperature, disinfectant residual) measured for a specific disinfection segment. Section 5.4 will demonstrate how the PWS will use a ratio of the CT_{calc} value, determined in Section 4.6, and this value of $CT_{99.9}$ to calculate their log inactivation ratio for the disinfection segment (see Section 5.4).

Note that if the residual concentration measured was 0.7 mg/L rather than 0.8 mg/L, the $CT_{99.9}$ could be calculated through interpolation between the values for 0.6 and 0.8 mg/L, or the more conservative of the two could be used (see Appendix H for more information regarding interpolation and conservative estimates).

Step 5. Use Worksheet #1 in Appendix C (or another data collection method) to determine CT_{99.9} and to record the value of CT_{99.9}.

The worksheet excerpt on the next page demonstrates how to record the data from this example and previous examples using Worksheet #1 in Appendix C.

WORKSHEET #1														
LOG INACTIVATION RATIO DETERMINATION FOR SURFACE WATER SYSTEMS OR GROUND WATER SYSTEMS UNDER THE DIRECT INFLUENCE OF SURFACE WATER														
Starting Month: <u>January</u>			Year: <u>2016</u>			PWSID: <u>AA1234567</u>			System/Water Source: <u>XYZ Water Plant</u>					
Disinfectant Type: <u>Free Chlorine</u>							Prepared by: <u>Joe Operator</u>							
Profile Type (check one): <input checked="" type="checkbox"/> <u>Giardia</u> <input type="checkbox"/> <u>Viruses</u>														
Disinfection Segment/Sequence of Application: <u>Clearwell/1st</u>														
Week #	3 Residual Disinf. Conc. C (mg/L)	4 pH	5 Water Temp. (°C)	6 Peak Hourly Flow (gpm)	7 Volume (gal)	8 TDT (min.)	9 Baffling Factor	10 Disinf. Contact Time T (min.)	11 CT _{calc} = (CxT) (min-mg/L)	12 CT Req'd (min-mg/L)	13 Inactivation Ratio (Col 11 / Col 12)	14 Log Inactivation*		
1	0.8	6	0.5	347	282,000	813	0.1	81.3	65.0	145				
2														
3														
4														
5														
6														
*See worksheet #2 to determine total log inactivation if the system has multiple disinfection segments.														

5.3.2 CT_{99.99} for Viruses

All surface water systems or GWUDI systems are required to achieve 4-log (99.99%) removal and/or inactivation of viruses through removal (sedimentation and filtration) and/or inactivation (disinfection) (40 CFR 141.70(a)(2)). The procedure for determining required CT for viruses is the same as the procedure used for *Giardia* in Section 5.3.1. The only difference is that PWSs must use the CT table provided for viruses for the given disinfectant and measured operational conditions.

5.4 Calculating Log Inactivation for One Disinfection Segment

Log inactivation can be calculated as a ratio of the CT_{calc} value achieved by the PWS to the CT value required for 3-log inactivation of *Giardia* or 4-log inactivation of viruses as shown in Equations 5-1 and 5-2. **However, PWSs should check with their state to determine if there is a specific state-required method for calculating virus inactivation.**

Use the following equation to calculate *Giardia* log inactivation for one disinfection segment:

Equation 5-1

$\text{Log Inactivation of } \textit{Giardia} = 3 \times (\text{CT}_{\text{calc}} / \text{CT}_{99.9})$
--

The following equation was used to calculate 4-log inactivation for the examples presented in this manual:

Equation 5-2

$\text{Log Inactivation of Viruses} = 4 \times (\text{CT}_{\text{calc}} / \text{CT}_{99.99})$

Example 5-2 shows how a PWS could calculate the *Giardia* log inactivation achieved in a system with one disinfection segment. See Appendix D for additional examples of calculating the log inactivation of *Giardia* and viruses.

Example 5-2. Determining Log Inactivation for *Giardia* for a PWS with One Disinfection Segment

The conventional filtration system discussed in Examples 3-1, 4-1, 4-2, and 5-1 uses chlorine disinfectant only. Determine the *Giardia* log inactivation achieved by the PWS.

Step 1. Determine CT_{calc} and $\text{CT}_{99.9}$ for the disinfection segment.

The following table summarizes the values previously calculated for CT_{calc} (see Example 4-2) and $\text{CT}_{99.9}$ (see Example 5-1):

Disinfection Segment	CT_{calc} min-mg/L	$\text{CT}_{99.9}$ for <i>Giardia</i> min-mg/L
1-Chlorine	65.0	145

Step 2. Calculate the inactivation ratio for the clearwell.

$$\begin{aligned} \text{Inactivation Ratio} &= \text{CT}_{\text{calc}} / \text{CT}_{99.9} \\ \text{Inactivation Ratio} &= 65.0 / 145 \\ \text{Inactivation Ratio} &= 0.448 \end{aligned}$$

Step 3. Calculate *Giardia* log inactivation for the clearwell.

$$\begin{aligned} \text{Giardia log inactivation} &= 3 \times (\text{CT}_{\text{calc}} / \text{CT}_{99.9}) \\ \text{Giardia log inactivation} &= 3 \times 0.448 \\ \text{Giardia log inactivation} &= 1.34 \end{aligned}$$

See Chapter 7 for more information on interpreting log inactivation values.

A calculation for virus inactivation must also be performed regardless of the disinfectant used (40 CFR 141.709(d)(4)).

Step 4. Use Worksheet #1 in Appendix C (or another data collection method) to record data and calculate log inactivation.

The worksheet excerpt below demonstrates how data may be recorded from this example and previous examples using Worksheet #1 in Appendix C.

WORKSHEET #1													
LOG INACTIVATION RATIO DETERMINATION FOR SURFACE WATER SYSTEMS OR GROUND WATER SYSTEMS UNDER THE DIRECT INFLUENCE OF SURFACE WATER													
Starting Month: <u>January</u>			Year: <u>2016</u>			PWSID: <u>AA1234567</u>			System/Water Source: <u>XYZ Water Plant</u>				
Disinfectant Type: <u>Free Chlorine</u>							Prepared by: <u>Joe Operator</u>						
Profile Type (check one): <input checked="" type="checkbox"/> <i>Giardia</i> <input type="checkbox"/> Viruses													
Disinfection Segment/Sequence of Application: <u>Clearwell/1st</u>													
Week #	3 Residual Disinf. Conc.	4 pH	5 Water Temp.	6 Peak Hourly Flow	7 Volume	8 TDT	9 Baffling Factor	10 Disinf. Contact Time	11 CT _{calc} = (CxT)	12 CT Req'd	13 Inactivation Ratio	14 Log Inactivation*	
	C (mg/L)		(°C)	(gpm)	(gal)	(min.)		T (min.)	(min-mg/L)	(min-mg/L)	(Col 11 / Col 12)		
1	0.8	6	0.5	347	282,000	813	0.1	81.3	65.0	145	0.448	1.34	
2													
3													
4													
5													
6													
*See worksheet #2 to determine total log inactivation if the system has multiple disinfection segments.													

5.5 Calculating Log Inactivation for Multiple Disinfection Segments

Log inactivation for a PWS with more than one disinfection segment is calculated as a sum of the ratios of the CT_{calc} value achieved by each disinfection segment to the CT value required for 3-log inactivation of *Giardia* or 4-log inactivation of viruses in each disinfection segment.

Equations 5-3 and 5-4 should be used to calculate *Giardia* and virus log inactivation, respectively, for a PWS with multiple disinfection segments. Similar to calculating virus log inactivation for a single disinfection segment, PWSs should check with their state to see if there is a specific state-required methodology.

Equation 5-3

$$\text{Log Inactivation of } \textit{Giardia} = 3 \times \sum (CT_{\text{calc}} / CT_{99.9})$$

Equation 5-4

$$\text{Log Inactivation of Viruses} = 4 \times \sum (CT_{\text{calc}} / CT_{99.99})$$

Example 5-3 shows how a PWS could use the worksheets in Appendix C to calculate the *Giardia* log inactivation achieved by a PWS with multiple disinfection segments. Example D-3 in Appendix D presents one method for determining virus log inactivation for a PWS with multiple segments.

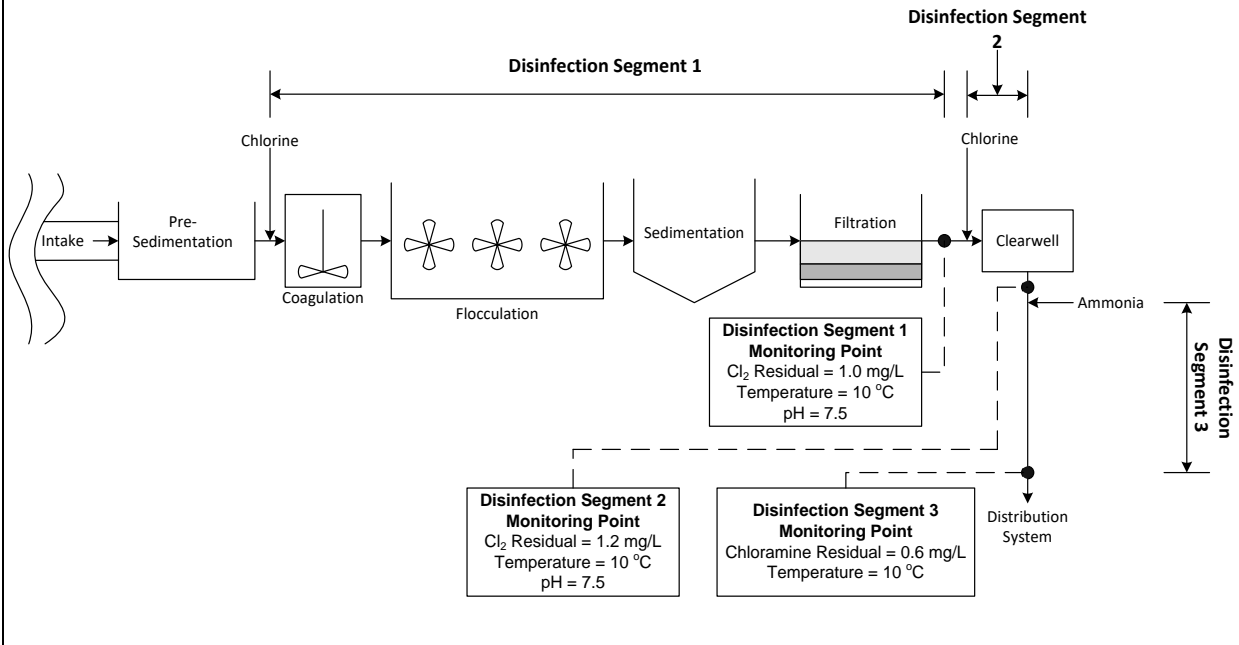
Example 5-3. Determining Total Log *Giardia* Inactivation for PWS with Multiple Disinfection Segments

The conventional filtration system discussed in Example D-2 in Appendix D uses chlorine as a pre-disinfectant and a primary disinfectant and uses chloramines as a secondary disinfectant.

The following table summarizes the calculations for each unit process in Example D-2.

Unit Process	Volume (gal)	Peak Hourly Flow (gpm)	TDT (min)	BF*	Contact Time (min)
Disinfection Segment 1					
Coagulation	24,000	5,000	4.8	0.1	0.48
Flocculation	80,000	5,000	16	0.1	1.6
Sedimentation	100,000	5,000	20	0.5	10
Filtration	45,000	5,000	9	0.7	6.3
Total:	249,000				18.4
Disinfection Segment 2:					
Clearwell	300,000	5,000	60	0.7	42
Disinfection Segment 3					
Pipe	31,000	5,000	6.2	1.0	6.2

* See Appendix G for baffling factors (BF).



Step 1. Use Worksheet #1 in Appendix C (or another data collection method) to record the data from Disinfection Segment 1 in Example D-2.

For this example, Worksheet #1 should be copied so the data from each disinfection segment can be entered.

WORKSHEET #1													
LOG INACTIVATION RATIO DETERMINATION FOR SURFACE WATER SYSTEMS OR GROUND WATER SYSTEMS UNDER THE DIRECT INFLUENCE OF SURFACE WATER													
Starting Month: <u>January</u>			Year: <u>2016</u>			PWSID: <u>AA7654321</u>			System/Water Source: <u>ABC Water Plant</u>				
Disinfectant Type: <u>Free Chlorine</u>							Prepared by: <u>Jon Operator</u>						
Profile Type (check one): <input checked="" type="checkbox"/> <u>X</u> <u>Giardia</u> <input type="checkbox"/> <u>Viruses</u>													
Disinfection Segment/Sequence of Application: <u>Coagulation, Flocculation, Sedimentation, Filtration/1st</u>													
Week #	3 Residual Disinf. Conc.	4 pH	5 Water Temp.	6 Peak Hourly Flow	7 Volume (gal)	8 TDT (min.)	9 Baffling Factor	10 Disinf. Contact Time	11 CT _{Calc} = (C×T) (min-mg/L)	12 CT Req'd (min-mg/L)	13 Inactivation Ratio (Col 11 / Col 12)	14 Log Inactivation*	
1	C (mg/L) 1.0	7.5	(°C) 10	(gpm) 5,000	(gal) 249,000	(min.) **	(min.) **	T (min.) 18.4	(min-mg/L) 18.4	(min-mg/L) 134	(Col 11 / Col 12) 0.137		
2													
3													
4													
5													
6													
*See worksheet #2 to determine total log inactivation if the system has multiple disinfection segments.													
**See the previous table showing details of each unit process for theoretical detention times and baffling factors.													

Step 2. Use Worksheet #1 in Appendix C (or another data collection method) to record the data from Disinfection Segment 2 in Example D-2.

WORKSHEET #1													
LOG INACTIVATION RATIO DETERMINATION FOR SURFACE WATER SYSTEMS OR GROUND WATER SYSTEMS UNDER THE DIRECT INFLUENCE OF SURFACE WATER													
Starting Month: <u>January</u>			Year: <u>2016</u>			PWSID: <u>AA7654321</u>			System/Water Source: <u>ABC Water Plant</u>				
Disinfectant Type: <u>Free Chlorine</u>							Prepared by: <u>Jon Operator</u>						
Profile Type (check one): <input checked="" type="checkbox"/> <u>X</u> <u>Giardia</u> <input type="checkbox"/> <u>Viruses</u>													
Disinfection Segment/Sequence of Application: <u>Clearwell/2nd</u>													
Week #	3 Residual Disinf. Conc.	4 pH	5 Water Temp.	6 Peak Hourly Flow	7 Volume (gal)	8 TDT (min.)	9 Baffling Factor	10 Disinf. Contact Time	11 CT _{Calc} = (C×T) (min-mg/L)	12 CT Req'd (min-mg/L)	13 Inactivation Ratio (Col 11 / Col 12)	14 Log Inactivation*	
1	C (mg/L) 1.2	7.5	(°C) 10	(gpm) 5,000	(gal) 300,000	(min.) 60	(min.) 0.7	T (min.) 42	(min-mg/L) 50	(min-mg/L) 137	(Col 11 / Col 12) 0.365		
2													
3													
4													
5													
6													
*See worksheet #2 to determine total log inactivation if the system has multiple disinfection segments.													

Step 3. Use Worksheet #1 in Appendix C (or another data collection method) to record the data from Disinfection Segment 3 in Example D-2.

WORKSHEET #1												
LOG INACTIVATION RATIO DETERMINATION FOR SURFACE WATER SYSTEMS OR GROUND WATER SYSTEMS UNDER THE DIRECT INFLUENCE OF SURFACE WATER												
Starting Month: <u>January</u>			Year: <u>2016</u>			PWSID: <u>AA7654321</u>			System/Water Source: <u>ABC Water Plant</u>			
Disinfectant Type: <u>Chloramine</u>						Prepared by: <u>Jon Operator</u>						
Profile Type (check one): <input checked="" type="checkbox"/> <u>X</u> <u>Giardia</u> <input type="checkbox"/> <u>Viruses</u>												
Disinfection Segment/Sequence of Application: <u>Transmission Pipe/3rd</u>												
Week #	3	4	5	6	7	8	9	10	11	12	13	14
	Residual Disinf. Conc. (mg/L)	pH	Water Temp. (°C)	Peak Hourly Flow (gpm)	Volume (gal)	TDT (min.)	Baffling Factor	Disinf. Contact Time (min.)	CT _{Calc} = (CxT) (min-mg/L)	CT Req'd (min-mg/L)	Inactivation Ratio (Col 11 / Col 12)	Log Inactivation*
1	0.6	N/A	10	5,000	31,000	6.2	1.0	6.2	3.7	1,850	0.002	
2												
3												
4												
5												
6												

*See worksheet #2 to determine total log inactivation if the system has multiple disinfection segments.

Step 4. Use Worksheet #2 in Appendix C (or another data collection method) determine total Giardia log inactivation

WORKSHEET #2							
TOTAL LOG INACTIVATION DETERMINATION FOR SURFACE WATER SYSTEMS OR GROUND WATER SYSTEMS UNDER THE DIRECT INFLUENCE OF SURFACE WATER							
Starting Month: <u>January</u>		Year: <u>2016</u>		PWSID: <u>AA7654321</u>			
System/Water Source: <u>ABC Water Plant</u>				Prepared by: <u>Jon Operator</u>			
Disinfectant Type: <u>Chlorine/Chloramine</u>							
Profile Type (check one): <input checked="" type="checkbox"/> <u>X</u> <u>Giardia</u> <input type="checkbox"/> <u>Viruses</u>							
Week #	Inactivation Ratio for each disinfection segment from Worksheet #1					Sum of Inactivation Ratios	Total Log Inactivation ¹
	Disinfection Segment 1	Disinfection Segment 2	Disinfection Segment 3	Disinfection Segment 4	Disinfection Segment 5		
1	0.137	0.365	0.002			0.504	1.51
2							
3							
4							
5							
6							

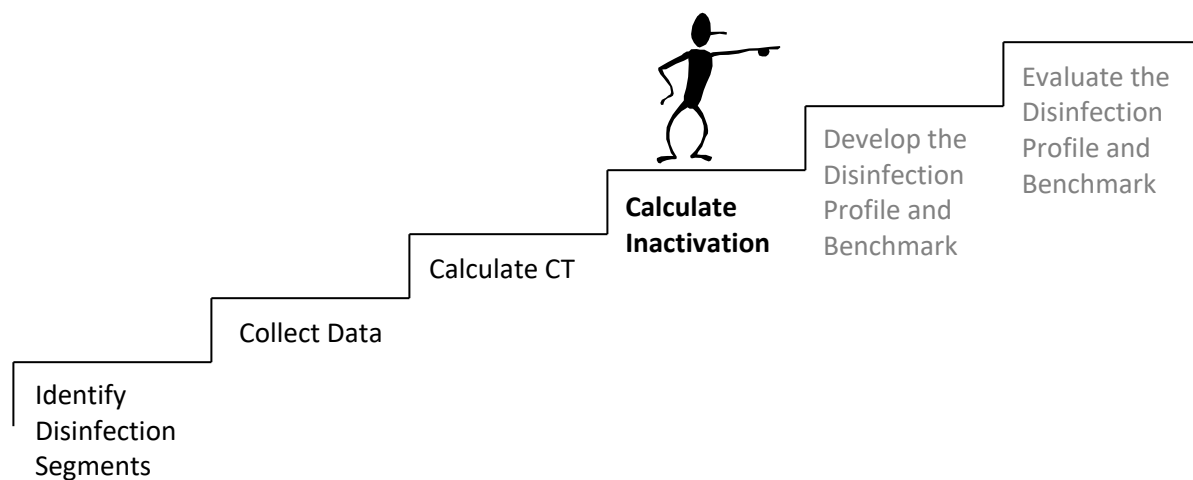
¹Giardia: Log Inactivation = 3 x Sum of Inactivation Ratios
 Viruses: Log Inactivation = 4 x Sum of Inactivation Ratios (or a method approved by the State)

Refer to Chapter 7 for more information on interpreting log inactivation values.

5.6 Available Spreadsheets

The EPA has also developed spreadsheets located at <https://www.epa.gov/dwreginfo/guidance-manuals-surface-water-treatment-rules> to help PWSs develop a disinfection profile and calculate a benchmark. One of the spreadsheets (the short form) is for PWSs with only one disinfection segment. The other spreadsheet (the long form) is for PWSs with more than one disinfection segment. They are designed to calculate the log inactivation provided by each disinfection segment or treatment stage of the PWS's treatment train based on various operating parameters (e.g., rate of flow, type of disinfectant, temperature, etc.). The spreadsheets will automatically calculate the log inactivation achieved by the facility, monthly average log inactivation, and the disinfection benchmark for both *Giardia* and viruses. The worksheets in Appendix C can also be used to manually record data and calculate contact time.

5.7 Steps Completed



5.8 Next Step

Upon completing the activities in this chapter, the PWS will have completed the fourth of six steps: calculating inactivation. Once a PWS has determined log inactivation values for at least once per week for a full year, then a disinfection profile and benchmark can be developed. Chapter 6 presents information on how to develop the disinfection profile and calculate a benchmark.

Chapter 6 — Developing the Disinfection Profile and Benchmark

6.1 Introduction

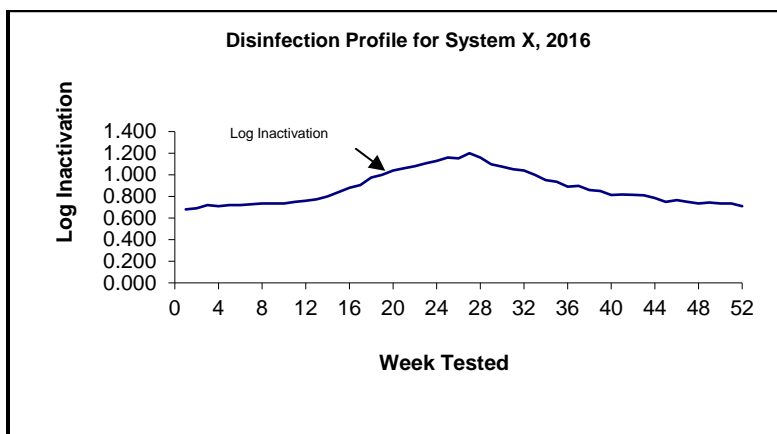
With the log inactivation values calculated in Chapter 5, a PWS can develop its disinfection profile and if needed, calculate a benchmark. A **disinfection profile** is a graphical representation of a PWS’s level of *Giardia* or virus inactivation measured over the course of a year (Figure 6-1 provides an example disinfection profile). The **disinfection benchmark** is the lowest monthly average log inactivation. For each year of disinfection profiling data collected, PWSs should determine the lowest average monthly level of both *Giardia* and virus inactivation. If a PWS is using monitoring data from more than one year, it repeats this calculation for each year for which data are available. The benchmark then becomes the average of the lowest monthly average values for each year.

PWSs must keep their disinfection profiles on file for review during sanitary surveys. A PWS is required to develop a disinfection profile and calculate a benchmark if the PWS plans to make a significant change to its disinfection practices (see Section 7.2 for a description of significant changes). The PWS must consult with the state for approval prior to making a significant change to its disinfection practices and cannot make changes during the year-long data collection period required to develop the profile. PWSs that meet the requirements for using grandfathered data can use the grandfathered data to develop a profile in lieu of collecting data (see Section 3.2). The disinfection profile and benchmark information will allow the state to assess appropriate modifications to disinfection practices, as necessary.

6.2 Constructing a Disinfection Profile

After log inactivation values have been calculated at least once each week for at least one year (using the method presented in Section 5.4), the PWS can produce a disinfection profile. A disinfection profile is simply a graph of log inactivation data as a function of time. The log inactivation values for *Giardia* and viruses may be plotted along the vertical axis of a graph with the corresponding weeks of the year plotted along the horizontal axis, as shown in Figure 6-1. After a disinfection profile is developed, it should be retained by the PWS in graphic form. Example 6-1 demonstrates how to create a disinfection profile.

Figure 6-1. Example of a Completed Disinfection Profile



Example 6-1. Disinfection Profile for *Giardia*

Create a disinfection profile for *Giardia* for the conventional filtration system that was discussed in Examples 3-1, 4-1, 4-2, 5-1, and 5-2.

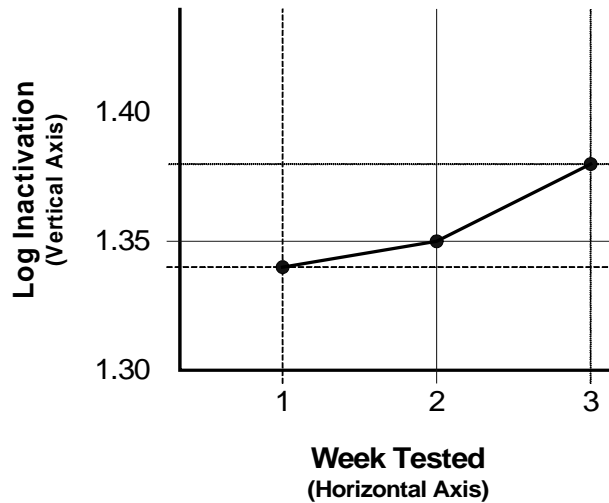
Step 1. Calculate the *Giardia* log inactivation once per week on the same day of the week for one year.

The table below shows the *Giardia* logs of inactivation that were calculated each week for one year using the methods presented in Section 5.4 and Example 5-2. This information can also be obtained from the first and last columns of Worksheet #1 in Appendix C for PWSs with one disinfection segment or Worksheet #2 in Appendix C for PWSs with multiple disinfection segments.

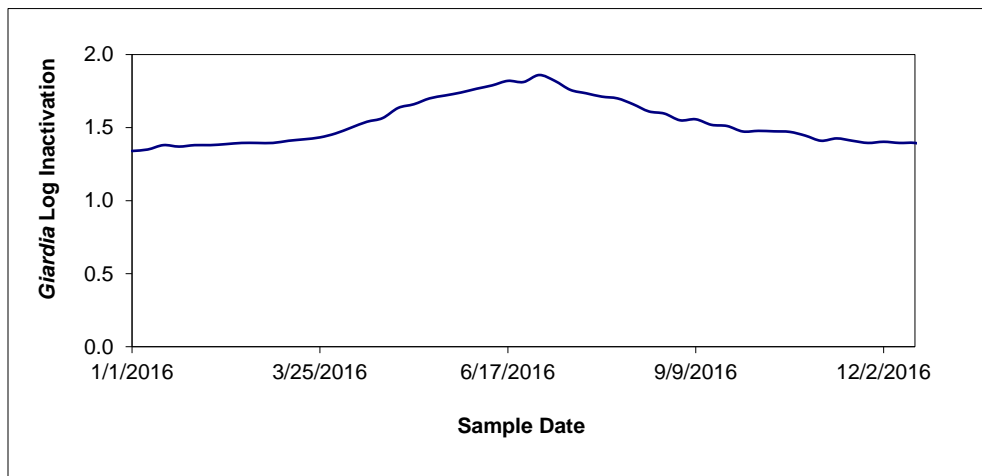
Month	Week	Log Inactivation	Month	Week	Log Inactivation
JAN	1	1.34	JULY	27	1.86
	2	1.35		28	1.82
	3	1.38		29	1.76
	4	1.37		30	1.74
	5	1.38		31	1.71
FEB	6	1.38	AUG	32	1.70
	7	1.39		33	1.66
	8	1.40		34	1.61
	9	1.40		35	1.60
MARCH	10	1.40	SEP	36	1.55
	11	1.41		37	1.56
	12	1.42		38	1.52
	13	1.43		39	1.51
APRIL	14	1.46		40	1.47
	15	1.50	OCT	41	1.48
	16	1.54		42	1.47
	17	1.57		43	1.47
	18	1.64		44	1.45
MAY	19	1.66	NOV	45	1.41
	20	1.70		46	1.43
	21	1.72		47	1.41
	22	1.74		48	1.40
JUNE	23	1.77	DEC	49	1.40
	24	1.79		50	1.40
	25	1.82		51	1.40
	26	1.81		52	1.37

Step 2. Plot the disinfection profile.

The logs of inactivation are plotted along the vertical axis with the corresponding weeks of the year plotted along the horizontal axis. For example, the log inactivation value for week 1 (1.34) is plotted on the vertical axis at a point corresponding to week 1 on the horizontal axis, as shown below. The log inactivation value for week 2 (1.35) is plotted on the horizontal axis at a point corresponding to week 2 on the horizontal axis. The log inactivation value for week 3 (1.38) is plotted on the horizontal axis at a point corresponding to week 3 on the horizontal axis. After the points are plotted, lines are drawn to connect the points in order by the week tested.



Continue to plot the points for each week until all 52 weeks have been plotted. The completed disinfection profile is shown below.



Once a disinfection profile has been completed, the PWS will have all of the data required to calculate a benchmark. The following sections discuss what a benchmark is and how it is calculated.

6.3 Calculating the Disinfection Benchmark

As explained in Chapter 1, benchmarking is used to characterize the minimum level of *Giardia* and virus logs of inactivation that were achieved under existing disinfection practices. A benchmark calculated under existing conditions can be compared to the benchmark calculated for anticipated conditions once proposed modifications are made. This comparison helps to ensure that changes to disinfection practices that result in lower inactivation levels are not made without appropriate state consultation and review. A disinfection benchmark is calculated using the following steps:

- Complete a disinfection profile that includes the calculation of log inactivation of *Giardia* and viruses for each week of the profile.
- Compute the average log inactivation for each calendar month of the profile by averaging the log inactivation values for each month (see Equation 6-1).

Equation 6-1

$$\text{Monthly Average Log Inactivation} = \frac{\text{Sum of Log Inactivation Values for the Month}}{\text{Number of Values per Month}}$$

Select the month with the lowest average log inactivation for the 12-month period. This value is the benchmark.

Example 6-2 demonstrates how to calculate the disinfection benchmark.

Example 6-2. Calculating a Disinfection Benchmark

Calculate the disinfection benchmark for *Giardia* for the conventional filtration system discussed in Examples 3-1, 4-1, 4-2, 5-1, 5-2, and 6-1.

Step 1. Calculate weekly *Giardia* log inactivation.

This step was completed in Example 6-1. The data are summarized below:

Month	Week	Log Inactivation	Month	Week	Log Inactivation
JAN	1	1.34	JULY	27	1.86
	2	1.35		28	1.82
	3	1.38		29	1.76
	4	1.37		30	1.74
	5	1.38		31	1.71
FEB	6	1.38	AUG	32	1.70
	7	1.39		33	1.66
	8	1.40		34	1.61

Month	Week	Log Inactivation	Month	Week	Log Inactivation
	9	1.40		35	1.60
MARCH	10	1.40	SEP	36	1.55
	11	1.41		37	1.56
	12	1.42		38	1.52
	13	1.43		39	1.51
APRIL	14	1.46		40	1.47
	15	1.50	OCT	41	1.48
	16	1.54		42	1.47
	17	1.57		43	1.47
	18	1.64		44	1.45
MAY	19	1.66	NOV	45	1.41
	20	1.70		46	1.43
	21	1.72		47	1.41
	22	1.74		48	1.40
JUNE	23	1.77	DEC	49	1.40
	24	1.79		50	1.40
	25	1.82		51	1.40
	26	1.81		52	1.37

Step 2. Calculate the monthly average log inactivation for each month.

Begin by averaging January's inactivation values:

<p>Average log inactivation for January = $\frac{\text{Sum of Log Inactivation Values}}{\text{Number of Values in Month}}$</p>

$$\begin{aligned}
 \text{Average log inactivation for January} &= \frac{1.34 + 1.35 + 1.38 + 1.37 + 1.38}{5 \text{ values}} \\
 &= (6.82) / (5) = \mathbf{1.36}
 \end{aligned}$$

Continue this process for each month. The following are the results for the example PWS:

January	1.36	July	1.78
February	1.39	August	1.64
March	1.41	September	1.52
April	1.54	October	1.47
May	1.71	November	1.41
June	1.80	December	1.39

Step 3. Identify the month with the lowest monthly average log inactivation. The log inactivation for this month is the disinfection benchmark.

The month with the lowest monthly average log inactivation is January, with a value of 1.36.

The benchmark is 1.36.

6.4 Seasonal Variations

When creating a profile and determining a benchmark, keep in mind that seasonal variations within a year and from year to year can be a factor for some PWSs. For example, Figures 6-2 through 6-4 present the disinfection profiles showing variations in weekly log inactivation of *Giardia* at a hypothetical PWS from 2014 through 2016. In general, as can be seen from Figures 6-2 and 6-3, seasonal variations in log inactivation of *Giardia* can be discerned from the disinfection profiles. However, as depicted in Figure 6-4, variations to the expected seasonal disinfection profile pattern may occur in a year with atypical weather conditions. Based on the three years of data, it appears that the lowest inactivation level (the benchmark) at this facility occurred in June 2015.

Figure 6-2. 2014 Data

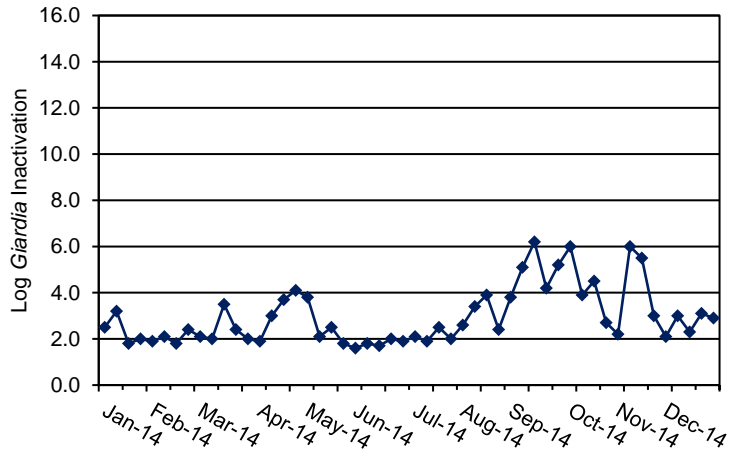


Figure 6-3. 2015 Data

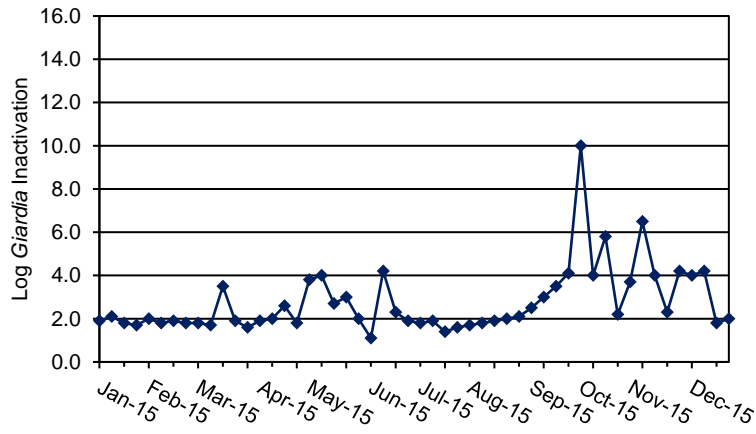
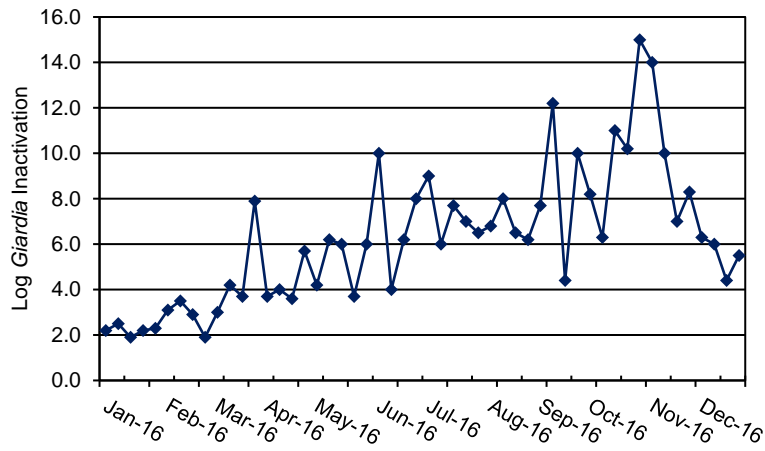


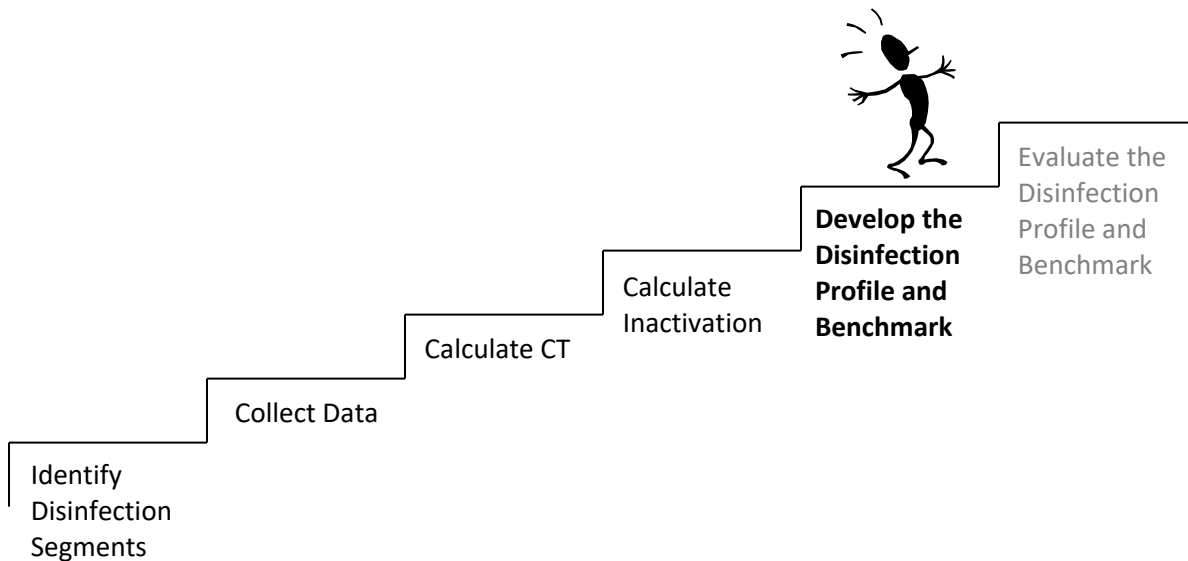
Figure 6-4. 2016 Data



6.5 The Complete Profile and Benchmark

PWSs should keep the completed disinfection profile and supporting data on file at the treatment plant or the PWS's offices in graphical form, as a spreadsheet, or in some other format approved by the state. In the event the PWS decides to modify its disinfection practice, the disinfection profile must be used to create a benchmark.

6.6 Steps Completed



6.7 Next Step

Upon completing the activities in this chapter, the PWS will have completed the fifth of six steps: developing a disinfection profile and benchmark. By calculating the benchmark, the PWS has identified its lowest monthly average inactivation value. This benchmark is used as a guide when evaluating disinfection practice modifications. Chapter 7 provides information on how to evaluate disinfection practice modifications.

Chapter 7 — Evaluating Disinfection Practice Modifications

7.1 Introduction

Compliance with the Stage 2 DBPR LRAA MCLs or requirements to provide additional treatment for *Cryptosporidium* may result in a PWS making significant modifications to their current disinfection practices. If a benchmark value is less than the required log inactivation, then the PWS can consider increasing the amount of disinfectant or the contact time. But increasing the amount of disinfectant could increase DBPs. If the benchmark is greater than the required inactivation in Table 1-2 (or as required by the state), the PWS can consider decreasing the amount of disinfectant added or altering other disinfection practices to continue to meet the required CT to decrease the formation of DBPs. Changes to disinfection practices that are considered significant are discussed in detail in this chapter. The purpose of disinfection profiling and benchmarking, and its usefulness to the state and the PWS are also discussed here.

The following terms may be helpful for understanding disinfection practices:

- **DBP Precursors** – DBP precursors are constituents naturally occurring in source water that react with a disinfectant to form DBPs. The primary DBP precursor is natural organic matter, which is monitored as total organic carbon (TOC). Organic matter reacts with the disinfectant to form TTHM, HAA5, and other DBPs. The Alternative Disinfectants and Oxidants Guidance Manual (USEPA, April 1999) provides more detailed information on DBP formation.
- **Pre-disinfection** – Pre-disinfection occurs when a disinfectant is added to the treatment train prior to the primary disinfectant injection location. The purpose of pre-disinfection is to obtain additional inactivation credits, to control microbiological growth in subsequent treatment processes, to improve coagulation, and/or to reduce tastes and odors.
- **Primary Disinfection** – The disinfectant used in a treatment system with the primary objective to achieve the necessary microbial inactivation.
- **Secondary Disinfection** – The disinfectant applied following primary disinfection in a treatment system with the primary objective to maintain the residual disinfectant throughout the distribution system.

7.2 Significant Changes to Disinfection Practices

As listed in Section 1.3, the IESWTR, LT1ESWTR, and LT2ESWTR describe four types of significant changes to disinfection practices. Those significant changes and related considerations are discussed in greater detail below.

7.2.1 Changes to the Point of Disinfection

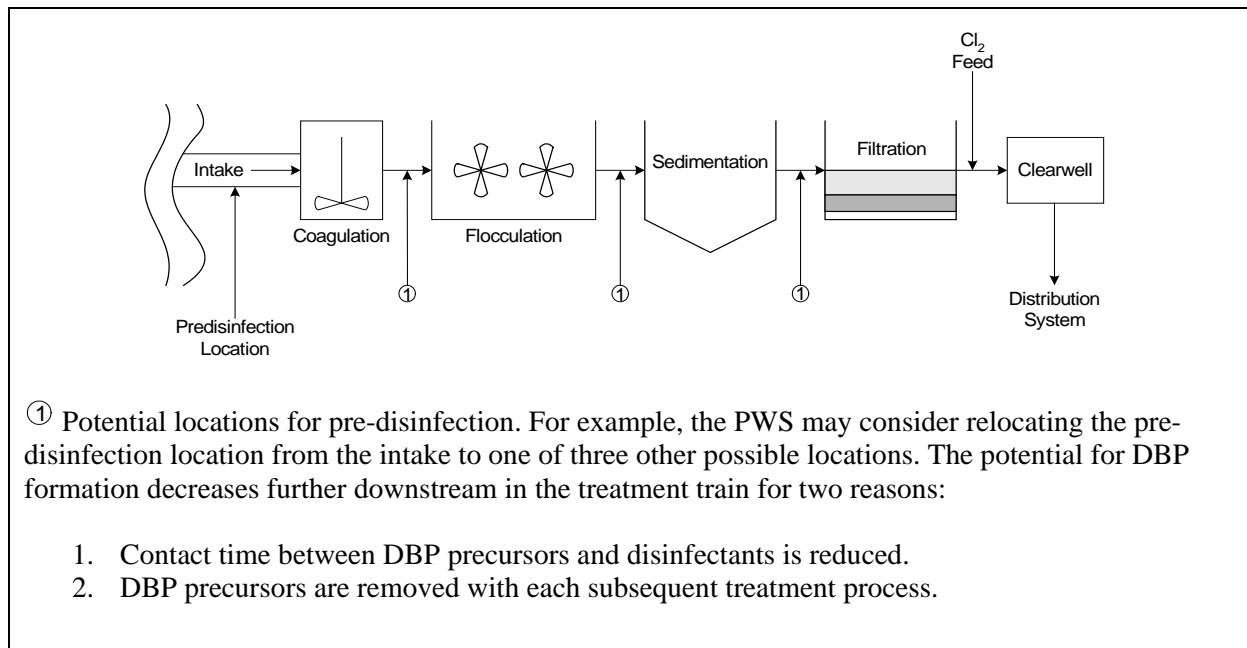
Any change in the location of the disinfectant application constitutes a significant change to disinfection practices. For instance, a PWS that uses pre-disinfection may consider moving the point of disinfectant application further downstream in the treatment train (see Figure 7-1). This modification can result in:

- A reduction of contact time (T) between DBP precursors and the disinfectant(s).

- A reduction in the production of DBPs (particularly if the new location is at a location downstream of treatment processes that have removed organic compounds that are precursors to DBP formation).
- A reduction of contact time (T) for inactivation.

A PWS that is considering moving the point of disinfectant application further downstream in the treatment process should ensure that it can maintain adequate disinfectant contact time and meet required log inactivation requirements for *Giardia* and viruses under the modified disinfecting conditions. Figure 7-1 shows an example of a PWS that considers relocating its pre-disinfection location.

Figure 7-1. Example of Moving the Point of Pre-disinfectant Application



7.2.2 Changes to Disinfectant Type

If a PWS is considering changing or adding a disinfectant, it is important to understand that each disinfectant has different levels of inactivation effectiveness for different types of pathogens. As a result, the CT requirements for the various disinfectants can be radically different. For instance, the CT required for chloramines to achieve 1-log inactivation of *Giardia* is about 18 times greater than the CT required for free chlorine. Therefore, if a PWS is considering changing from chlorine to chloramines, CT will have to be achieved either by raising the residual concentration in the disinfection zone or by increasing the contact time. A brief discussion of alternative disinfectants and oxidants that a PWS may consider is provided in Chapter 8.

Figure 7-2 is an example of a PWS that considers changing its disinfectant type. Figure 7-3 discusses a case where a change in both point of disinfection and disinfectant type are being considered.

Figure 7-2. Example of Changing Disinfectant Type

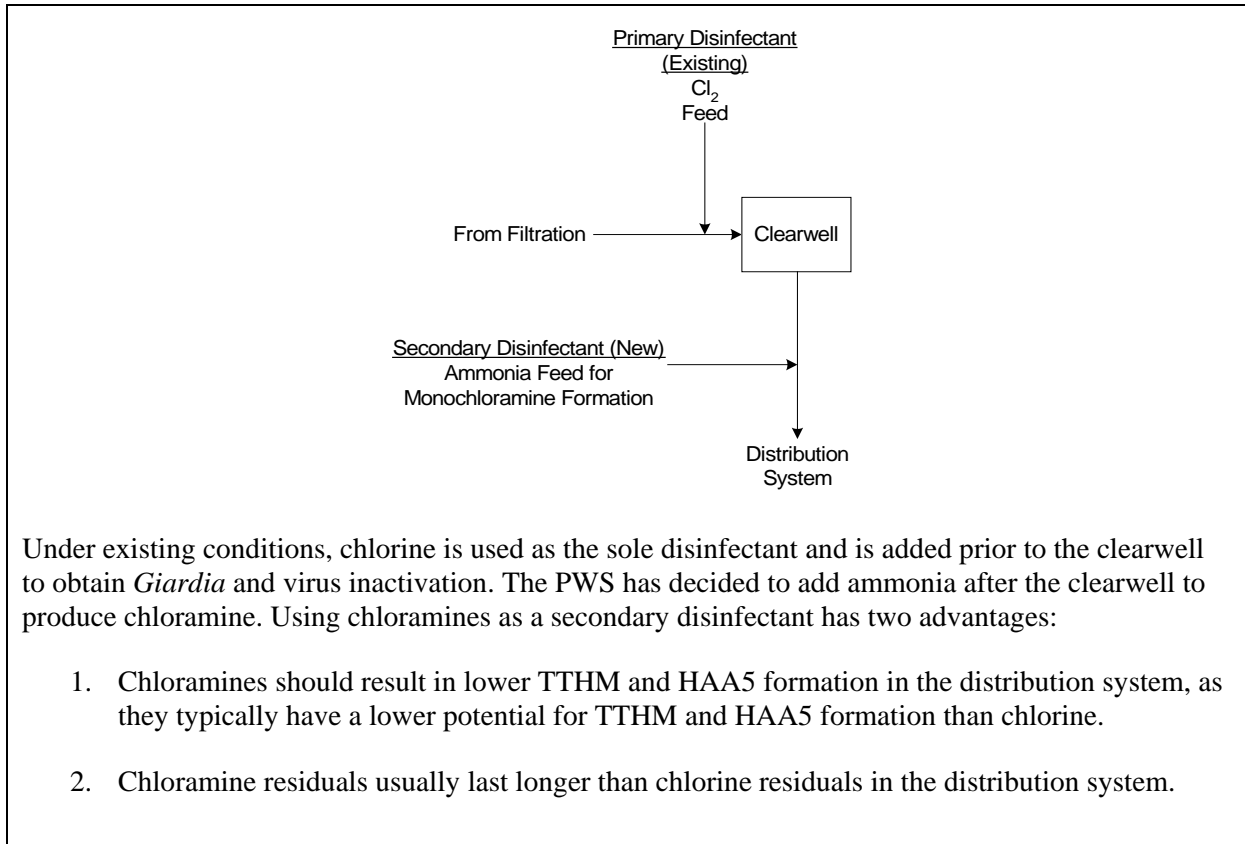
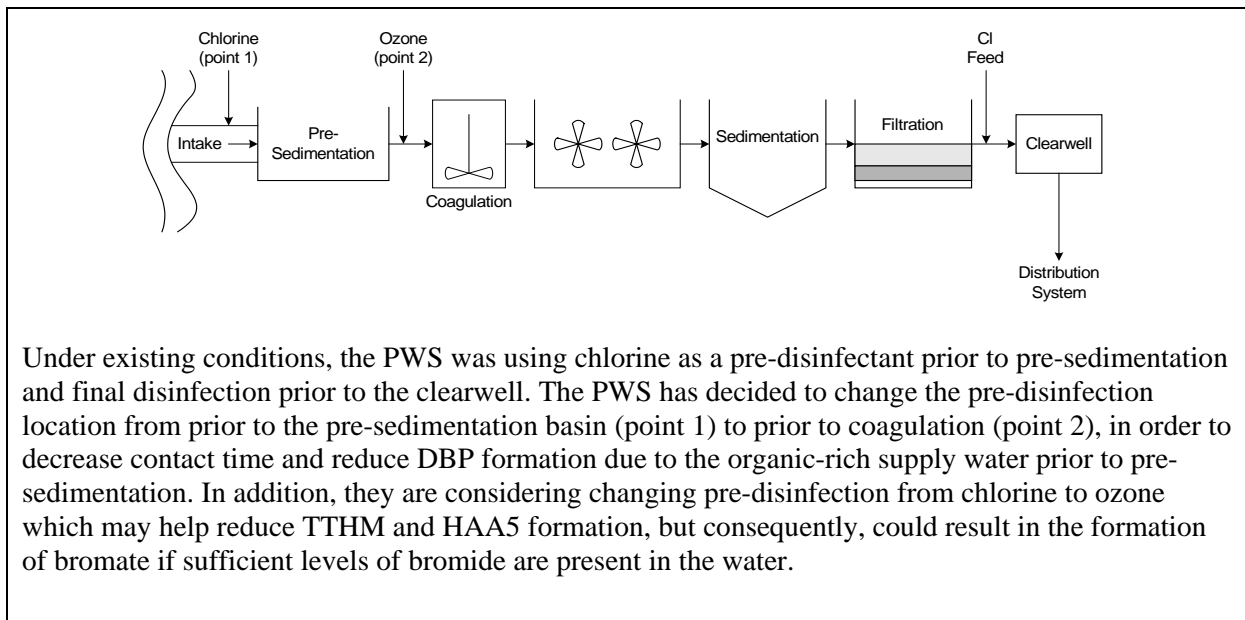


Figure 7-3. Changing Pre-disinfection Location and Type of Disinfectant



7.2.3 Changes to the Disinfection Process

Changes to the disinfection process itself also require PWSs to consult with the state before making the treatment change. Some modifications to the disinfection process include the following:

- Changing the contact basin geometry and baffling conditions.
- Changing the pH during disinfection.
- Decreasing the disinfectant dose during warmer temperatures.
- Increasing or decreasing flow through the plant.

Effects of Basin Geometry and Baffling Conditions

Changing the contact basin geometry or baffling conditions may result in more inactivation by increasing the contact time, the T value in the CT_{calc} value. The basin geometry changes the TDT while the baffling conditions change the BF in Equation 4-3 used to determine T (see Section 4.4.4). With this type of modification, additional inactivation can be achieved without increasing the disinfectant concentration.

pH Effects on Chlorine

Chlorine is very sensitive to pH. Decreases in pH provide increased chlorine inactivation of *Giardia* and viruses. Therefore, at lower pH values a lower chlorine dose or contact time can be applied to achieve a comparable level of inactivation of both *Giardia* and viruses. This in turn can reduce the potential for DBP formation. However, decreasing the pH is a process-sensitive issue and could result in other system changes, such as increased coagulant demand for proper floc formation, distribution system corrosion problems which, depending on a customer's plumbing or service connection type, could result in violations of the Lead and Copper Rule, or precipitation of certain inorganics. Extensive jar tests and pilot scale studies may be necessary before adjusting the pH.

Temperature Effects on Chlorine and DBP Formation

Chlorine is more effective at higher water temperatures, which results in faster chemical reactions and consequently, greater potential for DBP formation. Warmer surface waters frequently support more organic growth, supplying higher levels of DBP precursors. However, since chlorine is more reactive at higher temperatures, it is also more effective against microorganisms such as *Giardia* and viruses. Thus, when water temperatures are warmer the chlorine dose or contact time can be decreased and achieve the same amount of microbial inactivation as in cooler temperatures. However, warm temperatures also result in quicker chlorine decay so maintaining chlorine residual and microbial control in the distribution system could be adversely affected if the chlorine dose is decreased in the treatment plant. If a PWS decreases the chlorine dose or contact time during warmer months, the PWS should ensure that it is maintaining sufficient inactivation of both *Giardia* and viruses and also maintaining chlorine residual and microbial control in the distribution system.

7.2.4 Other Modifications

The modifications listed in Sections 7.2.1 through 7.2.3 are not an exhaustive list. States may determine that other types of changes are also significant. Therefore, a PWS should check with the state program office for assistance with determining whether a proposed change triggers the disinfection benchmarking procedure. Other modifications that may require state consultation and approval are enhanced coagulation, enhanced softening or oxidation. In addition, increased flow through the plant will have a direct impact on contact time. PWSs should work with the state to determine at what point increases in

plant flow constitute a change to disinfection practices. PWSs can refer to the *Alternative Disinfectants and Oxidants Guidance Manual* (USEPA, April 1999) and the *Enhanced Coagulation and Enhanced Precipitative Softening Guidance Manual* (USEPA, May 1999) for additional information. Copies of these guidance manuals can be obtained by downloading from the EPA's website at <https://www.epa.gov/dwreginfo/guidance-manuals-surface-water-treatment-rules>.

7.3 How the State Will Use the Benchmark

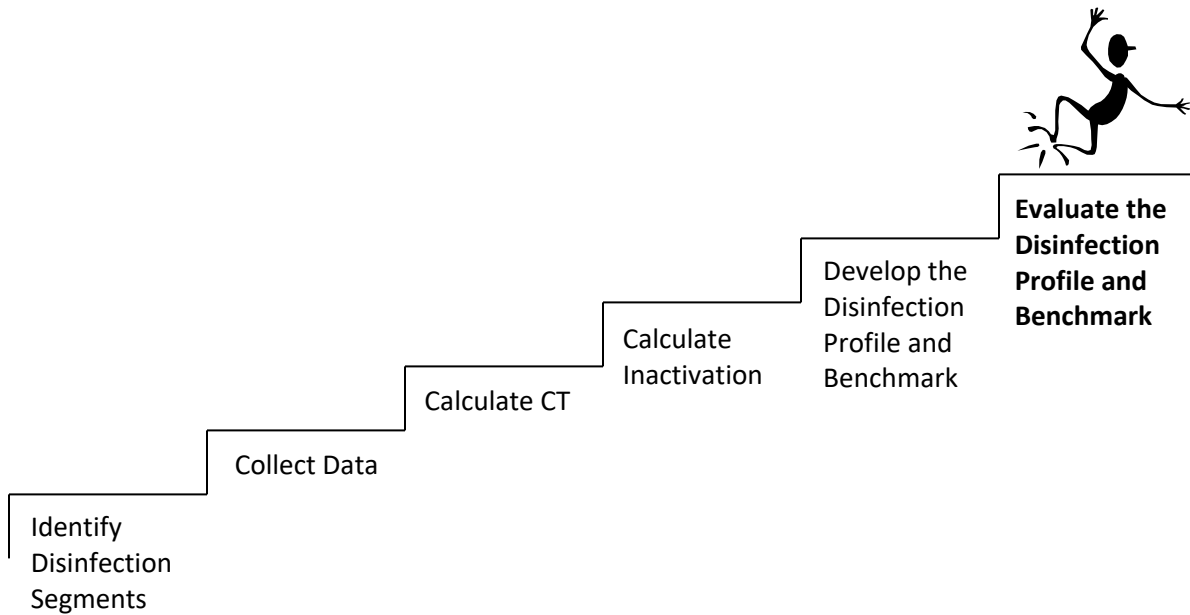
The state is expected to use the disinfection profile and benchmark to evaluate the microbial inactivation a PWS has achieved over time and compare this with the expected microbial inactivation the PWS will achieve after proposed disinfection practice modifications are made. The benchmark may be used by the state as a minimum level of inactivation of *Giardia* and viruses that must be maintained by PWSs when modifying their disinfection practices. The state may also use the disinfection profile and benchmark to determine an appropriate alternative benchmark under different disinfection scenarios.

PWSs with a benchmark that is less than the inactivation requirements in Table 1-2 or state-approved inactivation requirements (if they differ from Table 1-2) will need to modify disinfection practices in order to provide the necessary level of disinfection. An example would be a PWS with a conventional treatment plant that has calculated a benchmark of 0.3 for *Giardia* but is required to achieve 0.5-log *Giardia* inactivation through disinfection. This PWS would need to provide additional disinfection to achieve the required 0.5-log *Giardia* inactivation. At the same time, the PWS must ensure it maintains compliance with the DBPRs. The PWS must consult with the state and provide all necessary information prior to any significant modification, as described in Section 7.2.

PWSs may consider modifying disinfection practices if the benchmark is greater than the inactivation requirements in Table 1-2 or the inactivation required by the state. An example would be a PWS with a conventional treatment plant that has calculated a benchmark of 1.3 for *Giardia* but is only required to achieve a 0.5-log *Giardia* inactivation through disinfection. If this PWS uses chlorine and is having difficulty complying with TTHM and HAA5 MCLs, it may consider decreasing the number of chlorine injection points it utilizes. However, it must determine the CT needed to meet the 0.5-log *Giardia* inactivation as it tries to maintain compliance with the DBPRs. Again, the PWS must consult with the state prior to making any significant modifications and must provide all necessary information.

7.4 Steps Completed

Upon completing the activities in this chapter, the PWS will have completed all six steps in disinfection profiling and benchmarking.



7.5 References

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USEPA. May 1999. *Enhanced Coagulation and Enhanced Precipitative Softening Guidance Manual*. EPA 815-R-99-012. Washington, D.C.

Chapter 8 — Treatment Considerations

8.1 Introduction

As PWSs comply with the Stage 2 DBPR LRAA MCLs or requirements to provide additional treatment for *Cryptosporidium*, they may need to make significant modifications to their existing disinfection practices. This chapter summarizes different treatment options available to PWSs when considering such modifications. Some methods that PWSs may use to control DBPs, while meeting the inactivation levels required for *Giardia* and viruses, include the use of alternative disinfectants and oxidants, enhanced coagulation and softening, decreasing the contact time, or the use of alternative filtration techniques, such as membranes. PWSs may also opt to use chlorine dioxide, ozone, UV, or membrane filtration for *Cryptosporidium* treatment under the LT2ESWTR. As discussed in Chapter 7, the state must be consulted prior to any significant modifications to existing systems.

8.2 Alternative Disinfectants and Oxidants

This section discusses various alternative disinfectants and oxidants that may be considered for meeting both microbial inactivation and disinfection byproduct standards. A more complete discussion of this topic is provided in the *Alternative Disinfectants and Oxidants Guidance Manual* (USEPA, April 1999).

Retaining an adequate disinfectant residual at all points in the distribution system is important to inhibit bacteriological growth and using chlorine to achieve this has been a widely accepted practice, particularly in small PWSs. Chlorine is typically used in one of three forms: chlorine gas, sodium hypochlorite (typically liquid), and calcium hypochlorite (typically solid). Chlorine effectively inactivates a wide range of pathogens, including *Giardia* and viruses. Chlorine residuals are generally carried into the distribution system for further protection (see Example D1 in Appendix D).

However, the use of chlorine as a disinfectant, particularly as a pre-disinfectant, has typically been found to increase the formation of DBPs. The long detention time for water at the extremities of the distribution system also promotes DBP formation when chlorine is used. One option for resolving this problem is to use alternate primary disinfectants such as chlorine dioxide, ozone, or UV light. Other options are to add potassium permanganate as a pre-oxidant instead of chlorine or to use chloramines to maintain the distribution system residual. The type of oxidant used, its point of application and its concentration have significant effects on DBP formation. Consideration should also be given to the pH of the water, since lowering the pH decreases TTHM formation but increases formation of other chlorinated organic chemicals or forms of halomethanes (Dowbiggin and Thompson, 1990). In addition, higher water temperatures speed up the reaction between chlorine and organic material, thus increasing finished water TTHM and HAA5 levels (Singer, 1999).

8.2.1 Chloramines (NH₂Cl)

Chloramines are formed when chlorine and ammonia are added to the water, either simultaneously or sequentially. Chloramination is normally practiced at a ratio of approximately 1 part of ammonia to 4 parts of chlorine (on a mg/L basis) to ensure monochloramine formation (Kawamura, 2000). The ammonia can be applied before or after the chlorine. However, applying ammonia after the chlorine has been found to inactivate pathogens more effectively (AWWA, 1999). The CT tables presented in Appendix B of this guidance assume ammonia is added after chlorine to form chloramines. The CT tables illustrate that chloramines require significantly more contact time than chlorine to meet the required inactivation of *Giardia* and viruses.

Using chloramine as a secondary disinfectant has two advantages: 1) chloramine typically has a lower potential for TTHM and HAA5 formation than chlorine; and 2) chloramine residuals last longer than chlorine. Monochloramine is effective for controlling bacterial regrowth due to its ability to penetrate pipe biofilm (USEPA, April 1999). When chloramines are formed for secondary disinfection, ammonia is added to the treated water after the water treatment plant clearwell where primary disinfection is accomplished.

Potential water quality issues with monochloramine include corrosion, formation of DBPs, and nitrification. Monochloramine can impact kidney dialysis and should be removed from the dialysate water. Monochloramine should be removed from water used, for example, fish tanks due to detrimental effects. The use of monochloramine can cause pitting corrosion and a more uniform thinning of pipe surfaces (Kirmeyer et al., 2004). Kirmeyer et al. (2004) also reported that chloramine can attack rubber and plastic components in a water system, and that 43 percent of utilities surveyed experienced an increase in degradation of rubber materials. Although chloramination significantly reduces some DBPs associated with chlorine disinfection, such as THM and HAAs, its usage can contribute to the formation of other DBPs such as nitrosamines. Nitrification is a potential problem for utilities that utilize chloramines as a disinfectant and may occur when finished water contains excess ammonia and low chloramine residual (Kirmeyer et al., 2004). Areas of the distribution system with higher water age and warmer temperatures are more susceptible to nitrification.

8.2.2 Ozone (O₃)

One of the most widely studied alternatives to chlorine as a disinfectant is ozone. Ozone is used for both oxidation and disinfection. It must be generated at the point of application since it is an unstable molecule. Ozone is a powerful oxidant and is more effective than chlorine, chloramines, and chlorine dioxide for inactivation of viruses, *Cryptosporidium*, and *Giardia* (USEPA, April 1999). Its effectiveness is pH and temperature dependent. Ozone can only be used as a primary disinfectant, since it is unable to maintain a residual in the distribution system. Chlorine or chloramines should be applied as a secondary disinfectant to maintain a detectable residual in the distribution system. The following case study (Schneider and Tobiasson, 2000) discusses bench-scale studies using ozone as a pre-disinfectant prior to coagulation and its impact on the coagulation process using various coagulants.

Ozone is highly corrosive and toxic, and ozonation systems are relatively complex. The use of ozone poses some health and safety concerns that should be addressed by a utility considering its use. Instrumentation should be provided for ozone systems to protect both personnel and the equipment. While ozone does not form halogenated DBPs except in bromide-rich waters, it does form a variety of organic and inorganic byproducts, such as bromate. Bromate is regulated by the Stage 1 DBPR with an MCL of 0.010 mg/L.

8.2.3 Chlorine Dioxide (ClO₂)

Chlorine dioxide is a powerful oxidant and disinfectant that is effective at inactivating bacterial, viral, and protozoan pathogens (e.g., *Giardia* and *Cryptosporidium*). Chlorine dioxide is equal or superior to chlorine in its disinfecting ability. Chlorine dioxide is primarily used in the United States as a means of taste and odor control, oxidation of iron and manganese, and control of TTHMs and HAA5s by oxidizing precursors (Kawamura, 2000). It also has the ability to maintain a residual in the distribution system for an extended period of time (Kawamura, 2000).

Chlorine dioxide is usually generated on site from sodium chlorite solutions and one or more other chemical precursors (e.g., sodium hypochlorite, hydrochloric acid, sulfuric acid) or by an electrochemical oxidation process. Stock solutions produced on-site typically have a concentration of 500 mg/L. Chlorine dioxide gas cannot be compressed or stored commercially because it is explosive under pressure. Therefore, chlorine dioxide gas is never shipped (USEPA, December 1999).

Chlorine dioxide and chlorite, a disinfection byproduct of concern for PWSs using chlorine dioxide, are both regulated by the Stage 1 DBPR. The Stage 1 DBPR establishes an MRDL of 0.8 mg/L as ClO₂ that applies to all PWSs (CWS, NTNCWS, and transient non-community water systems (TNCWS)) using chlorine dioxide because chlorine dioxide can present an acute health risk at high enough levels. All PWSs that use chlorine dioxide must monitor for compliance with the MRDL daily at the entry point to the distribution system. The Stage 1 DBPR also establishes a chlorite MCL of 1.0 mg/L for systems that use chlorine dioxide for disinfection and oxidation. CWSs and NTNCWSs must collect daily samples at the entry point to the distribution system and monthly samples in the distribution system. Utilities using chlorine dioxide may have to use granular activated carbon or a chemical reducing agent, such as sulfur dioxide, to remove or reduce the chlorite residual.

8.2.4 Potassium Permanganate (KMnO₄)

Potassium permanganate is primarily used as a pre-oxidant to control algal growth; tastes and odors; and to remove iron, manganese, and color. It may also be used to control DBP formation by oxidizing organic precursors and reducing the demand for other disinfectants (USEPA, April 1999). A water treatment plant may choose to use potassium permanganate as a pre-oxidant, in lieu of chlorine, and then move the chlorination point further down the treatment train. This configuration may help control DBPs by delaying the introduction of chlorine until after the majority of precursors have been removed in the treatment process.

Case Study – Schneider and Tobiason (2000)

Jar-testing was used to study the effects of pre-ozonation on interactions among coagulants, particles, and natural organic matter. Synthetic water (deionized, distilled water with organic matter, particles and background ions added) and waters from Lake Gaillard in Branford, Connecticut; the Oradell reservoir in Oradell, New Jersey; and the Passaic River in Little Falls, New Jersey, were tested. Experiments were run with ozone only and with ozone followed by coagulation. The research found that when alum was used as a coagulant, pre-ozonation hindered the removal of turbidity and dissolved organic matter (DOM) at the conditions tested. Cationic polymers, however, allowed small increases in the removal of turbidity and DOM. It was found that varying the pre-ozone contact time from 4 to 28 minutes had little effect on settled water turbidity, TOC, and dissolved organic carbon for the conditions tested.

There are some disadvantages to using potassium permanganate. Potassium permanganate must be handled carefully when preparing the feed solution, since it can cause serious eye injury, irritate the skin and respiratory system, and can be fatal if swallowed. It also can turn the water a pink color.

8.2.5 Ultraviolet Radiation (UV)

UV disinfection is a well-established treatment technology for inactivating pathogens present in the environment. In the drinking water context, UV disinfection was initially most widely used in Europe, with hundreds of installations in place by 1985 (USEPA, November 2006). In North America, UV disinfection has been more widely employed in drinking water applications since 2000 to address health concerns associated with *Cryptosporidium*. As of the spring of 2008, there were at least 300 public water systems in the United States and Canada with UV installations treating flows >350 gallons per minute (Wright et al., 2012).

UV disinfection does not cause the formation of harmful disinfection byproducts and is highly effective for inactivating *Cryptosporidium* and *Giardia*. UV rays inactivate microorganisms by penetrating their cell walls to damage the DNA, interfering with reproduction. An additional advantage is that there are fewer safety concerns for using UV than for chemical disinfectants such as chlorine gas or chlorine dioxide. Further, UV disinfection does not change the pH or the corrosivity of the treated water (USEPA, April 2006).

The EPA's *Ultraviolet Disinfection Guidance Manual for the Final Long Term 2 Enhanced Surface Water Treatment Rule (UVDGM)* (USEPA, November 2006) provides guidance to PWSs using UV light for primary disinfection. The UV dose is expressed in millijoules per square centimeter (mJ/cm^2) or the equivalent, milliwatt-seconds per square centimeter ($\text{mW}\cdot\text{s}/\text{cm}^2$). The dose required to achieve a 2-log inactivation of *Cryptosporidium* and *Giardia* are $5.8 \text{ mJ}/\text{cm}^2$ and $5.2 \text{ mJ}/\text{cm}^2$, respectively. However, the dose required for virus inactivation is quite a bit higher, at $100 \text{ mJ}/\text{cm}^2$ for 2-log inactivation and $186 \text{ mJ}/\text{cm}^2$ for 4-log inactivation. Many PWSs use a combination of UV light for its ability to inactivate *Cryptosporidium* and *Giardia*, as well as chlorine that is highly effective for virus inactivation and then also carries a residual into the distribution system.

UV reactor validation is used to define the operational conditions under which the pathogens of concern are inactivated for a specific UV reactor manufacturer and model. Validation is a method of determining the operating conditions under which a UV reactor delivers a specified dose. This generally involves initial tests using a surrogate organism (e.g., bacteriophage MS2) rather than the target pathogen (e.g., *Cryptosporidium*) to establish the dose relationship between the two organisms. The conditions that are examined for full-scale testing to establish dose are flow rate, UV transmittance (UVT) (a measure of the fraction of incident light transmitted through a material) and lamp output. The EPA has developed guidance for validation of UV reactors (USEPA, November 2006) using one of two methods – the setpoint approach and the dose control method. In short, the setpoint approach establishes a measured UV intensity that corresponds to a specific dose and flow rate. The dose control method (also referred to as the calculated dose approach) provides a means of determining the required intensity that corresponds to a specific flow rate, UVT, and dose.

Despite the many advantages of UV light for primary disinfection, these systems also have some shortcomings.

- UV disinfection is less effective at inactivating some viruses, particularly adenovirus.
- Since UV is a physical disinfectant, not a chemical disinfectant, it does not leave a residual in the water and thus, a secondary disinfectant must be added to maintain a distribution system residual.
- Another disadvantage is that higher turbidity and organic material in the water may shield organisms and prevent them from being exposed to the UV light; therefore, it is recommended

that PWSs apply UV light as a disinfectant after filtration, where turbidity and organics in the water have been reduced.

- Another potential problem is that scale can form on the quartz sleeves that house the UV lamps, depending on the ions, hardness, alkalinity, and pH of the water. For example, a hardness level greater than 120 mg/L is a threshold of concern (Great Lakes, 2018). A build-up of scale causes a reduction in the amount of UV light that is transmitted to the water. However, regular cleaning of the sleeves can reduce the effects of scaling.
- Mercury can be released into the treated water when a UV lamp breaks (Wright et al., 2012). The amount of mercury that could potentially enter the water depends on the type of lamp and operation. Vapor phase mercury can dissolve into solution and be discharged downstream whereas liquid phase or amalgam mercury would tend to settle in the UV reactor. The author recommends developing a mercury mitigation plan (Wright et al., 2012).
- The use of UV light in a water treatment plant introduces several potential safety issues for operators including exposure of skin and eyes to UV light; electrical shock; burns from hot lamps or equipment; and exposure to mercury from a broken lamp. Safety measures must be developed and implemented to address each potential safety issue.
- Finally, the operation of the UV lamps may be temperature dependent. UV lamps are designed to operate within a specific temperature range to maximize UV light output (USEPA, November 2006). Without flowing water to cool the lamp, the lamp temperature can rise above the maximum operating temperature and break.

8.2.6 Comparison of Disinfectants

The EPA and the Association of Metropolitan Water Agencies (AMWA) funded a two-year study of 35 water treatment facilities to evaluate DBP production based on various combinations of primary and secondary disinfectants. Among four of the facilities, alternative disinfection strategies were investigated to evaluate the difference in DBP production from the PWSs' previous disinfection strategies (or base disinfection conditions). The results were analyzed in three reports (Metropolitan and Montgomery, 1989; Jacangelo et al., 1989; Malcolm Pirnie, Inc., 1992) that documented different aspects of the study. Table 8-1 summarizes the results of the study. This study illustrates that a change in primary disinfectant from chlorine to ozone or to chloramines may help reduce TTHM and HAA5.

Table 8-1. Study Results on Changing Primary and Secondary Disinfectants

Change in Disinfection Practice ¹ (Primary Disinfectant/Secondary Disinfectant)		DBP Concentration Change	
		TTHM	HAA5
Chlorine/Chlorine To Chlorine/Chloramines ²	Utility #7	Decrease	Decrease
Chlorine/Chlorine To Ozone/Chlorine	Utility #19	Decrease	Decrease
	Utility #36	No change	No change
Chlorine/Chloramines To	Utility #7	Decrease	Decrease

Ozone/Chloramines			
Chlorine/Chlorine To Chloramines/Chloramines	Utility #36	Decrease	Decrease
Ozone/Chlorine To Ozone/Chloramines	Utility #36	Decrease	Decrease
Chloramines/Chloramines To Ozone/Chloramines	Utility #25	Decrease	Decrease
	Utility #36	No change	No change
Chlorine/Chlorine To Ozone/Chloramines	Utility #7	Decrease	Decrease
	Utility #36	Decrease	Decrease
<p>1. Several studies were conducted to examine the effects of changing primary and secondary disinfectants on DBP levels. For instance, changing the secondary disinfectant from chlorine to chloramines resulted in a decrease in both TTHM and HAA5. Results are based on full-scale evaluations at Utilities #19 and #25 and on pilot scale evaluations at Utilities #7 and #36.</p> <p>2. Free chlorine contact time was 4 hours for Utility #7 during use of chlorine/chloramine strategy.</p> <p>Source: Malcolm Pirnie, Inc., 1992; Jacangelo et al., 1989.</p>			

8.3 Changes in Enhanced Coagulation and Softening

In conventional water treatment plants, precursors of DBPs may be removed through the coagulation process with aluminum or ferric salts and/or polymers. If a greater reduction in DBP levels is required, the treatment techniques of either enhanced coagulation or enhanced precipitative softening can be employed. With fewer precursors present, the formation of DBPs is thereby reduced. Enhanced coagulation also allows for more effective disinfection, since the chlorine demand is lower in water treated by enhanced coagulation. In addition, the lower pH resulting from enhanced coagulation allows chlorine to inactivate *Giardia* more effectively, since chlorine is more effective at lower pH values.

One way to implement enhanced coagulation is to change the type or dose of coagulant and/or polymer aid. However, before either enhanced coagulation or enhanced softening is implemented at a water treatment plant, the proposed changes should be evaluated through pilot testing or bench-scale studies similar to the case study by Bell-Ajy et al. (2000) described in the text box below. Jar testing is commonly used to simulate coagulant dose changes and their effectiveness. A water treatment plant operator should first determine the present status of the coagulation process by taking TOC samples from the raw water and the finished water. With these data, the operator can calculate the percent removal of TOC and determine a desired TOC removal.

Case Study - Bell-Ajy et al. (2000)

Research, including jar tests using raw water from 16 water utilities throughout the United States and two full-scale evaluations, was conducted to evaluate the optimal coagulation conditions for removal of TOC and DBPs. Jar test results showed that when optimized coagulation was implemented, treatment effectiveness seemed pH dependent. Jar tests using alum, ferric chloride, and polyaluminum chloride coagulants with sulfuric acid for pH reduction removed more TOC than those at higher pH levels. In the full-scale applications, enhanced coagulation effectively increased TOC removal and reduced trihalomethanes and trihalomethane formation potentials. With a lowering of pH during the coagulation process, turbidity and particle removals were improved. The researchers recommended that sludge generation, floc carryover and dewatering, along with the point of chlorine addition and alkalinity consumption, be considered in the treatment scheme before enhanced coagulation is implemented.

Changes to the coagulation and softening processes may have secondary effects on a water treatment plant. The pH of the water may be altered by the changes, thus affecting the disinfection process. Within the typical plant pH operating range of 5.5 to 9.5, decreasing pH improves the disinfection characteristics of chlorine and ozone but decreases the effectiveness of chlorine dioxide (USEPA, May 1999). If PWSs are considering decreasing the pH to improve plant performance, the decrease in pH may result in corrosion concerns in the distribution system and potential challenges complying with the Lead and Copper Rule.

Another secondary effect of enhanced coagulation or softening may be the production of a lighter, more fragile floc that can carry over onto the filters, thus shortening filter runs and increasing the amount of filter backwash water produced. Efficient sedimentation is extremely important prior to the filters to prevent filter overload.

More sludge may also result from enhanced coagulation and enhanced softening, because of increased coagulant and lime dosages and greater TOC removal. Inorganic contaminant levels for iron, manganese, aluminum, sulfate, chloride, and sodium in finished water may also increase with increased coagulant dosages (depending on type of coagulant used). A study by Carlson et al. (2000) presents secondary effects of enhanced coagulation and softening.

8.4 Increasing Contact Time

Increasing the CT value will provide additional disinfection credit for *Giardia* and virus inactivation. The CT value can be increased by constructing additional storage, increasing the disinfectant residual, changing the disinfectant, lowering the pH, increasing the minimum clearwell depth, lowering high service peak flows or improving clearwell hydraulics to allow for a greater detention time (Bishop, 1993). Increasing disinfectant concentrations to improve CT poses the problem of increasing the formation of DBPs, particularly when chlorine is used as the disinfectant.

As noted above, another way to gain additional disinfection credit without increasing the disinfectant dosage is to increase the detention time in the clearwell. Increased detention time serves to allow more contact time, thus providing more opportunity for the inactivation of microorganisms. As discussed in Chapter 4, the detention time used in the CT calculation is not equal to the theoretical detention time (basin volume divided by flow rate), but rather the amount of time in which 10 percent (no baffling) to 70 percent (superior baffling) of the fluid passes through a basin, process, or system in which a disinfectant residual is maintained. Certain basin shapes and designs allow good mixing, while others allow short-circuiting. The baffling factors listed in Table 4-2 account for various baffling conditions, inlet/outlet

designs, and basin configurations. A PWS desiring more contact time in order to increase its CT value may improve the hydraulics of its existing clearwell by increasing the detention time within the unit through baffling or inlet/outlet changes.

Possible clearwell changes are:

- Relocating the inlet and/or outlet to maximize the separation distance between them.
- Perforating the distribution and collection piping to disperse flow across the clearwell.
- Using overflow inlets to disperse existing horizontal inlet flows.
- Using baffles to disperse inlet flow.
- Perforating baffle walls to disperse flows into and out of basins.
- Using inlet or outlet weirs or launderers to distribute flow (Bishop et al., 1993).

8.5 Membranes

Another option for improving compliance with the microbial suite of rules is to install membrane filtration to improve removal of pathogens as well as DBP precursors. The four most common membrane technologies currently used in the water treatment industry are: reverse osmosis, nanofiltration, ultrafiltration, and microfiltration. Figure 8-1 presents the typical pore size range and removal capabilities for these membrane process classes. Membranes have a distribution of pore sizes, and this distribution will vary according to the membrane material and manufacturing process. When a pore size is stated, it can be presented as either nominal (i.e., the average pore size) or absolute (i.e., the maximum pore size) in terms of microns (μm). The removal capabilities of reverse osmosis and nanofiltration membranes are typically not stated in terms of pore size, but instead as a molecular weight cutoff representing the approximate size of the smallest molecule that can be removed by the membrane.

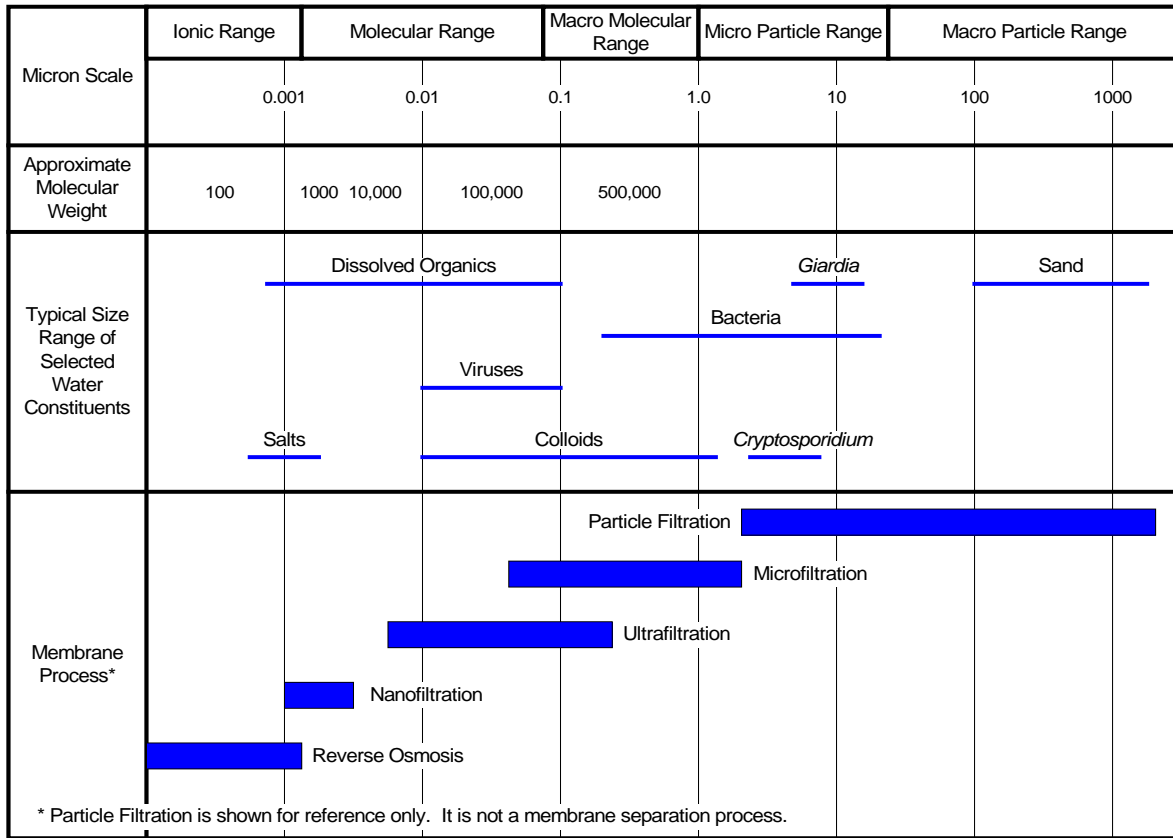
All of these membrane processes are effective at removing *Giardia*, *Cryptosporidium*, and most bacteria (provided there is not breakthrough). Removal efficiencies will depend on the type of membrane used. Reverse osmosis, nanofiltration, and ultrafiltration are capable of removing viruses. Reverse osmosis and nanofiltration are capable of removing inorganic and organic contaminants, including DBP precursors (AWWA, 1999).

Membranes can be effective in decreasing the amount of DBPs formed because:

- The removal of pathogens by membranes should reduce the amount of disinfectant required for inactivation and should, in turn, result in lower finished water DBP concentrations.
- The removal of DBP precursors should result in lower finished water DBP concentrations (when reverse osmosis or nanofiltration is used).

It is important to remember that these membrane processes are physical barriers only and must be followed by disinfection to ensure inactivation of pathogens not removed by the membrane barrier and maintain an adequate distribution system residual to control bacterial regrowth in downstream system plumbing. Some membranes are sensitive to disinfectants in the water and should not be downstream in the treatment process from the disinfectant point of application. Membranes can also be used to achieve other treatment objectives. More information on membranes can be obtained from the *Guidance Manual for Membrane Filtration, Nov 2005* (<https://www.epa.gov/dwreginfo/long-term-2-enhanced-surface-water-treatment-rule-documents>).

Figure 8-1. Particles Removed Through Membrane Technologies



Source: AWWA/ASCE, 1998.

8.6 References

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Appendix A — Glossary

baffle. A flat board or plate, deflector, guide or similar device constructed or placed in flowing water or slurry systems to cause more uniform flow velocities, to absorb energy, and to divert, guide, or agitate liquids (water, chemical solutions, slurry).

baffling factor (BF). The ratio of the actual contact time to the theoretical detention time.

clarifier. A large circular or rectangular tank or basin in which water is held for a period of time, during which the heavier suspended solids settle to the bottom by gravity. Clarifiers are also called settling basins and sedimentation basins.

clearwell. A reservoir for the storage of filtered water with sufficient capacity to prevent the need to vary the filtration rate in response to short-term changes in customer demand. Also used to provide chlorine contact time for disinfection.

coagulant. A chemical added to water that has suspended and colloidal solids to destabilize particles, allowing subsequent floc formation and removal by sedimentation, filtration, or both.

coagulation. As defined in 40 CFR 141.2, a process using coagulant chemicals and mixing by which colloidal and suspended materials are destabilized and agglomerated into flocs.

community water system (CWS). A public water system which serves at least 15 service connections used by year-round residents or regularly serves at least 25 year-round residents.

conventional filtration treatment. As defined in 40 CFR 141.2, a series of processes including coagulation, flocculation, sedimentation, and filtration resulting in substantial particulate removal.

Cryptosporidium. A disease-causing protozoan widely found in surface water sources. *Cryptosporidium* is spread by the fecal-oral route as a dormant oocyst from human and animal feces. In its dormant stage, *Cryptosporidium* is housed in a very small, hard-shelled oocyst form that is resistant to chlorine and chloramine disinfectants. When water containing these oocysts is ingested, the protozoan may cause a severe gastrointestinal disease called *cryptosporidiosis*.

CT or CT_{calc}. As defined in 40 CFR 141.2, the product of “residual disinfectant concentration” (C) in mg/l determined before or at the first customer, and the corresponding “disinfectant contact time” (T) in minutes, i.e., “C” x “T”. If a public water system applies disinfectants at more than one point prior to the first customer, it must determine the CT of each disinfectant sequence before or at the first customer to determine the total percent inactivation or “total inactivation ratio”. In determining the total inactivation ratio, the public water system must determine the residual disinfectant concentration of each disinfection sequence and corresponding contact time before any subsequent disinfection application point(s). “CT_{99.9}” is the CT value required for 99.9 percent (3-log) inactivation of *Giardia lamblia* cysts. CT_{99.9} for a variety of disinfectants and conditions appear in Tables 1.1- 1.6, 2.1, and 3.1 of §141.74(b)(3) in the *Code of Federal Regulations*. CT_{calc}/CT_{99.9} is the inactivation ratio. The sum of the inactivation ratios, or total inactivation ratio shown as $\Sigma [(CT_{calc}) / (CT_{99.9})]$ is calculated by adding together the inactivation ratio for each disinfection sequence. A total inactivation ratio equal to or greater than 1.0 is assumed to provide a 3-log inactivation of *Giardia lamblia* cysts.

diatomaceous earth filtration. As defined in 40 CFR 141.2, a process resulting in substantial particulate removal, that uses a process in which: (1) a “precoat” cake of diatomaceous earth filter media is deposited

on a support membrane (septum), and (2) while the water is filtered by passing through the cake on the septum, additional filter media, known as “body feed,” is continuously added to the feed water to maintain the permeability of the filter cake.

direct filtration. As defined in 40 CFR 141.2, a series of processes including coagulation and filtration, but excluding sedimentation, and resulting in substantial particulate removal.

disinfectant. As defined in 40 CFR 141.2, any oxidant, including but not limited to chlorine, chlorine dioxide, chloramines, and ozone added to water in any part of the treatment or distribution process, that is intended to kill or inactivate pathogenic microorganisms.

disinfectant contact time (T). As defined in 40 CFR 141.2, the time in minutes that it takes for water to move from the point of disinfectant application or the previous point of disinfectant residual measurement to a point before or at the point where residual disinfectant concentration (“C”) is measured. Where only one “C” is measured, “T” is the time in minutes that it takes for water to move from the point of disinfectant application to a point before or at where residual disinfectant concentration (“C”) is measured. Where more than one “C” is measured, “T” is (a) for the first measurement of “C”, the time in minutes that it takes for water to move from the first or only point of disinfectant application to a point before or at the point where the first “C” is measured and (b) for subsequent measurements of “C”, the time in minutes that it takes for water to move from the previous “C” measurement point to the “C” measurement point for which the particular “T” is being calculated. Disinfectant contact time in pipelines must be calculated based on “plug flow” by dividing the internal volume of the pipe by the maximum hourly flow rate through that pipe. Disinfectant contact time within mixing basins and storage reservoirs should be determined by tracer studies or an equivalent demonstration.

disinfection. As defined in 40 CFR 141.2, a process which inactivates pathogenic organisms in water by chemical oxidants or equivalent agents.

disinfection benchmark. The lowest monthly average microbial inactivation during the disinfection profile time period.

disinfection byproduct (DBP) precursors. Substances that can be converted into disinfection byproducts during disinfection. Typically, most of these precursors are constituents of natural organic matter. In addition, the bromide ion (Br⁻) is a precursor material.

disinfection byproducts (DBPs). Inorganic and organic compounds formed by the reaction of the disinfectant, natural organic matter, and the bromide ion during water disinfection processes. Regulated DBPs include trihalomethanes, haloacetic acids, bromate, and chlorite.

disinfection profile. As stated in 40 CFR 141.530, a graphical representation of your public water system’s level of *Giardia lamblia* or virus inactivation measured during the course of a year.

disinfection segment. A section of the system beginning at one disinfectant injection or monitoring point and ending at the next disinfectant injection or monitoring point.

effluent. Water or some other liquid that is raw, partially or completely treated that is flowing from a reservoir, basin, treatment process, or treatment plant.

enhanced coagulation. As defined in 40 CFR 141.2, the addition of sufficient coagulant for improved removal of disinfection byproduct precursors by conventional filtration treatment.

enhanced softening. As defined in 40 CFR 141.2, the improved removal of disinfection byproduct precursors by precipitative softening.

filtration. As defined in 40 CFR 141.2, a process for removing particulate matter from water by passage through porous media.

finished water. Water that has passed through a water treatment plant such that all the treatment processes are completed or “finished” and ready to be delivered to consumers. Also called product water.

flocculation. As defined in 40 CFR 141.2, a process to enhance agglomeration or collection of smaller floc particles into larger, more easily settleable particles through gentle stirring by hydraulic or mechanical means.

Giardia lamblia. Flagellated protozoan, which is shed during its cyst-stage with the feces of certain mammals. When water containing these cysts is ingested, the protozoan causes a severe gastrointestinal disease called giardiasis.

ground water under the direct influence of surface water (GWUDI). As defined in 40 CFR 141.2, any water beneath the surface of the ground with significant occurrence of insects or other macroorganisms, algae, or large-diameter pathogens such as *Giardia lamblia* or *Cryptosporidium*, or significant and relatively rapid shifts in water characteristics such as turbidity, temperature, conductivity, or pH which closely correlate to climatological or surface water conditions. Direct influence must be determined for individual sources in accordance with criteria established by the State. The State determination of direct influence may be based on site-specific measurements of water quality and/or documentation of well construction characteristics and geology with field evaluation.

haloacetic acids five (HAA5). As defined in 40 CFR 141.2, the sum of the concentrations in milligrams per liter of the haloacetic acid compounds (monochloroacetic acid, dichloroacetic acid, trichloroacetic acid, monobromoacetic acid, and dibromoacetic acid), rounded to two significant figures after addition.

influent water. Raw water plus recycle streams.

interpolation. A technique used to determine values that fall between the marked intervals on a scale.

log inactivation. The percentage of microorganisms inactivated through disinfection by a given process. One log inactivation means that 90% of the microorganisms are inactivated. Two log corresponds to 99%, three log is 99.9%, and four log corresponds to 99.99%.

log removal. A measure of the amount of microorganisms that are physically removed by a given process (e.g. filtration). One log removal means that 90% of the microorganisms are removed. Two log corresponds to 99%, three log is 99.9%, and four log corresponds to 99.99%.

maximum contaminant level (MCL). As defined in 40 CFR 141.2, the maximum permissible level of a contaminant in water which is delivered to any user of a public water system.

membrane filtration. A filtration process (e.g., reverse osmosis, nanofiltration, ultrafiltration, and microfiltration) using tubular or spiral-wound elements that exhibits the ability to mechanically separate water from other ions and solids by creating a pressure differential and flow across a membrane.

micrograms per liter (µg/L). One microgram of a substance dissolved in each liter of water. This unit is equal to parts per billion (ppb) since one liter of water is equal in weight to one billion micrograms.

micron. A unit of length equal to one micrometer (μm). One millionth of a meter or one thousandth of a millimeter. One micron equals 0.00004 of an inch.

milligrams per liter (mg/L). A measure of concentration of a dissolved substance. A concentration of one mg/L means that one milligram of a substance is dissolved in each liter of water. For practical purposes, this unit is equal to parts per million (ppm) since one liter of water is equal in weight to one million milligrams. Thus, a liter of water containing 10 milligrams of calcium has 10 parts of calcium per one million parts of water, or 10 parts per million (10 ppm).

noncommunity water system (NCWS). As defined in 40 CFR 141.2, a public water system that is not a community water system. A non-community water system is either a “transient non-community water system (TWS)” or a non-transient non-community water system (NTNCWS).”

nontransient noncommunity water system (NTNCWS). As defined in 40 CFR 141.2, a public water system that is not a community water system and that regularly serves at least 25 of the same persons over six months per year.

organics. Carbon-containing compounds that are derived from living organisms.

oxidant. Any oxidizing agent; a substance that readily oxidizes (removes electrons from) something chemically. Common drinking water oxidants are chlorine, chlorine dioxide, ozone, and potassium permanganate. Some oxidants also act as disinfectants.

oxidation. A process in which a molecule, atom, or ion loses electrons to an oxidant. The oxidized substance (which lost the electrons) increases in positive valence. Oxidation never occurs alone, but always as part of an oxidation-reduction (redox) reaction.

pathogens, or pathogenic organisms. Microorganisms that can cause disease (such as typhoid, cholera, or dysentery) in other organisms or in humans, animals, and plants. They may be bacteria, viruses, or protozoans and can be found in sewage, in runoff from animal farms, or rural areas populated with domestic and/or wild animals, and in water used for swimming.

pH. pH is an expression of the intensity of the basic or acid condition of a solution. Mathematically, pH is the negative logarithm (base 10) of the hydrogen ion concentration, $[\text{H}^+]$. $[\text{pH} = \log (1/\text{H}^+)]$. The pH may range from 0 to 14, where 0 is most acidic, 14 most basic, and 7 neutral. Natural waters usually have a pH between 6.5 and 8.5.

plug flow. The water travels through a basin, pipe, or unit process in such a fashion that the entire mass or volume is discharged at exactly the theoretical detention time of the unit.

pre-disinfection. The addition of a disinfectant to the treatment train prior to the primary disinfectant injection location. Generally, the purpose of pre-disinfection is to obtain additional inactivation credits, to control microbiological growth in subsequent treatment processes, to improve coagulation, or to reduce tastes and odors.

primary disinfection. The disinfectant used in a treatment system to achieve the necessary microbial inactivation.

public water system (PWS). As defined in 40 CFR 141.2, a system for the provision to the public of water for human consumption through pipes or, after August 5, 1998, other constructed conveyances, if such system has at least fifteen service connections or regularly serves an average of at least twenty-five

individuals daily at least 60 days out of the year. Such term includes: any collection, treatment, storage, and distribution facilities under control of the operator of such system and used primarily in connection with such system; and any collection or pretreatment storage facilities not under such control which are used primarily in connection with such system. Such term does not include any “special irrigation district.” A public water system is either a “community water system” or a “non-community water system”.

reservoir. Any natural or artificial holding area used to store, regulate, or control water.

residual disinfectant concentration (C). As defined in 40 CFR 141.2, the concentration of disinfectant measured in mg/L in a representative sample of water.

secondary disinfection. The disinfectant application in a treatment system to maintain the disinfection residual throughout the distribution system.

sedimentation. As defined in 40 CFR 141.2, a process for removal of solids before filtration by gravity or separation.

short-circuiting. A hydraulic condition in a basin or unit process that occurs when the actual flow time of water through the basin is less than the basin or unit process volume divided by the peak hourly flow.

state. As defined in 40 CFR 141.2, the agency of the State or tribal government which has jurisdiction over public water systems. During any period when a State or tribal government does not have primary enforcement responsibility pursuant to Section 1413 of the Safe Drinking Water Act, the term “state” means the Regional Administrator, U.S. Environmental Protection Agency.

surface water. As defined in 40 CFR 141.2, all water which is open to the atmosphere and subject to surface runoff.

theoretical detention time (TDT). The average length of time a drop of water or a suspended particle remains in a unit (tank, chamber, or pipe). Mathematically, it may be determined by dividing the volume of water in the tank by the flow rate through the tank.

total organic carbon (TOC). As defined in 40 CFR 141.2, total organic carbon in mg/L measured using heat, oxygen, ultraviolet irradiation, chemical oxidants, or combinations of these oxidants that convert organic carbon to carbon dioxide, rounded to two significant figures.

total trihalomethanes (TTHM). As defined in 40 CFR 141.2, the sum of the concentration in milligrams per liter of the trihalomethane compounds (trichloromethane [chloroform], dibromochloromethane, bromodichloromethane, and tribromomethane [bromoform]), rounded to two significant figures.

tracer. A foreign substance mixed with or attached to a given substance for subsequent determination of the location or distribution of the foreign substance.

tracer study. A study using a substance that can readily be identified in water (such as a dye) to determine the distribution and rate of flow in a basin, pipe, ground water, or stream channel.

transient noncommunity water system (TNCWS). As defined in 40 CFR 141.2, means a non-community water system that does not regularly serve at least 25 of the same persons over six months per year.

trihalomethane (THM). As defined in 40 CFR 141.2, one of the family of organic compounds, named as derivatives of methane, wherein three of the four hydrogen atoms in methane are each substituted by a halogen atom in the molecular structure.

virus. As defined in 40 CFR 141.2, a virus of fecal origin which is infectious to humans by waterborne transmission.

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Appendix B — CT Tables

Table B-1. CT Values* for 3-Log Inactivation of *Giardia* Cysts by Free Chlorine

Chlorine Concentration (mg/L)	Temperature <= 0.5°C							Temperature = 5°C							Temperature = 10°C						
	pH							pH							pH						
	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0
<=0.4	137	163	195	237	277	329	390	97	117	139	166	198	236	279	73	88	104	125	149	177	209
0.6	141	168	200	239	286	342	407	100	120	143	171	204	244	291	75	90	107	128	153	183	218
0.8	145	172	205	246	295	354	422	103	122	146	175	210	252	301	78	92	110	131	158	189	226
1.0	148	176	210	253	304	365	437	105	125	149	179	216	260	312	79	94	112	134	162	195	234
1.2	152	180	215	259	313	376	451	107	127	152	183	221	267	320	80	95	114	137	166	200	240
1.4	155	184	221	266	321	387	464	109	130	155	187	227	274	329	82	98	116	140	170	206	247
1.6	157	189	226	273	329	397	477	111	132	158	192	232	281	337	83	99	119	144	174	211	253
1.8	162	193	231	279	338	407	489	114	135	162	196	238	287	345	86	101	122	147	179	215	259
2.0	165	197	236	286	346	417	500	116	138	165	200	243	294	353	87	104	124	150	182	221	265
2.2	169	201	242	297	353	426	511	118	140	169	204	248	300	361	89	105	127	153	186	225	271
2.4	172	205	247	298	361	435	522	120	143	172	209	253	306	368	90	107	129	157	190	230	276
2.6	175	209	252	304	368	444	533	122	146	175	213	258	312	375	92	110	131	160	194	234	281
2.8	178	213	257	310	375	452	543	124	148	178	217	263	318	382	93	111	134	163	197	239	287
3.0	181	217	261	316	382	460	552	126	151	182	221	268	324	389	95	113	137	166	201	243	292
Chlorine Concentration (mg/L)	Temperature = 15°C							Temperature = 20°C							Temperature = 25°C						
	pH							pH							pH						
	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0
<=0.4	49	59	70	83	99	118	140	36	44	52	62	74	89	105	24	29	35	42	50	59	70
0.6	50	60	72	86	102	122	146	38	45	54	64	77	92	109	25	30	36	43	51	61	73
0.8	52	61	73	88	105	126	151	39	46	55	66	79	95	113	26	31	37	44	53	63	75
1.0	53	63	75	90	108	130	156	39	47	56	67	81	98	117	26	31	37	45	54	65	78
1.2	54	64	76	92	111	134	160	40	48	57	69	83	100	120	27	32	38	46	55	67	80
1.4	55	65	78	94	114	137	165	41	49	58	70	85	103	123	27	33	39	47	57	69	82
1.6	56	66	79	96	116	141	169	42	50	59	72	87	105	126	28	33	40	48	58	70	84
1.8	57	68	81	98	119	144	173	43	51	61	74	89	108	129	29	34	41	49	60	72	86
2.0	58	69	83	100	122	147	177	44	52	62	75	91	110	132	29	35	41	50	61	74	88
2.2	59	70	85	102	124	150	181	44	53	63	77	93	113	135	30	35	42	51	62	75	90
2.4	60	72	86	105	127	153	184	45	54	65	78	95	115	138	30	36	43	52	63	77	92
2.6	61	73	88	107	129	156	188	46	55	66	80	97	117	141	31	37	44	53	65	78	94
2.8	62	74	89	109	132	159	191	47	56	67	81	99	119	143	31	37	45	54	66	80	96
3.0	63	76	91	111	134	162	195	47	57	68	83	101	122	146	32	38	46	55	67	81	97

*Although units did not appear in the original tables, units are min-mg/L.

Table B-2. CT Values* for 4-Log Inactivation of Viruses by Free Chlorine

Temperature (°C)	pH	
	6-9	10
0.5	12	90
5	8	60
10	6	45
15	4	30
20	3	22
25	2	15

*Although units did not appear in the original tables, units are min-mg/L.

Table B-3. CT Values* for 3-Log Inactivation of *Giardia* Cysts by Chlorine Dioxide

Temperature (°C)					
<u>< = 1</u>	<u>5</u>	<u>10</u>	<u>15</u>	<u>20</u>	<u>25</u>
63	26	23	19	15	11

*Although units did not appear in the original tables, units are min-mg/L.

Table B-4. CT Values* for 4-Log Inactivation of Viruses by Chlorine Dioxide pH 6-9

Temperature (°C)					
<u>< = 1</u>	<u>5</u>	<u>10</u>	<u>15</u>	<u>20</u>	<u>25</u>
50.1	33.4	25.1	16.7	12.5	8.4

*Although units did not appear in the original tables, units are min-mg/L.

Table B-5. CT Values* for 3-Log Inactivation of *Giardia* Cysts by Ozone

Temperature (°C)					
<u>< = 1</u>	<u>5</u>	<u>10</u>	<u>15</u>	<u>20</u>	<u>25</u>
2.9	1.90	1.43	0.95	0.72	0.48

*Although units did not appear in the original tables, units are min-mg/L.

Table B-6. CT Values* for 4-Log Inactivation of Viruses by Ozone

Temperature (°C)					
<u>< = 1</u>	<u>5</u>	<u>10</u>	<u>15</u>	<u>20</u>	<u>25</u>
1.8	1.2	1.0	0.6	0.5	0.3

*Although units did not appear in the original tables, units are min-mg/L.

Table B-7. CT Values* for 3-Log Inactivation of *Giardia* Cysts by Chloramines^ pH 6-9

Temperature (°C)					
<u>< = 1</u>	<u>5</u>	<u>10</u>	<u>15</u>	<u>20</u>	<u>25</u>
3,800	2,200	1,850	1,500	1,100	750

*Although units did not appear in the original tables, units are min-mg/L.

^It is assumed that Chlorine is used as primary and Ammonia as secondary disinfectant to form Chloramines for disinfection (See Section 8.2.1).

Table B-8. CT Values* for 4-Log Inactivation of Viruses by Chloramines^

Temperature (°C)					
<u>< = 1</u>	<u>5</u>	<u>10</u>	<u>15</u>	<u>20</u>	<u>25</u>
2,883	1,988	1,491	994	746	497

*Although units did not appear in the original tables, units are min-mg/L.

^It is assumed that Chlorine is used as primary and Ammonia as secondary disinfectant to form Chloramines for disinfection (See Section 8.2.1).

Table B-9. UV Dose Table for *Cryptosporidium*, *Giardia*, and Virus Inactivation Credit (USEPA, April 2010)

Log credit	<i>Cryptosporidium</i> UV dose (mJ/cm ²)	<i>Giardia lamblia</i> UV dose (mJ/cm ²)	Virus UV dose (mJ/cm ²)
0.5	1.6	1.5	39
1.0	2.5	2.1	58
1.5	3.9	3.0	79
2.0	5.8	5.2	100
2.5	8.5	7.7	121
3.0	12	11	143
3.5	15	15	163
4.0	22	22	186

References

USEPA. July 2002. Code of Federal Regulations, Title 40, Chapter I, Section 141.2.

USEPA. April 2010. *Long Term 2 Enhanced Surface Water Treatment Rule Toolbox Guidance Manual*. EPA 815-R-09-016. Washington, D.C.

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Appendix C — Blank Worksheets

This appendix contains worksheets that can be used to record operational information on disinfection processes used for pathogen inactivation. A public water system (PWS) should confirm reporting requirements with its state prior to using these worksheets for compliance purposes. Examples using these worksheets are presented in Chapters 3 through 5 and Appendix D.

Worksheet #1 applies to PWSs with surface water or GWUDI sources of supply that use chemical disinfectants for pathogen inactivation. Worksheet #1 can be used to record weekly water quality and operational data needed to determine actual CT, required CT, and the pathogen inactivation credit.

Worksheet #2 applies to surface water and GWUDI systems using multiple segments of chemical disinfectants. Worksheet #2 can be used to add the inactivation ratios for each disinfection segment to calculate the total pathogen inactivation credit.

Worksheets #3, 4, 5, and 6 apply to PWSs using UV disinfection for pathogen inactivation. Systems using UV disinfection have different reporting requirements than systems using chemical disinfectants because pathogen inactivation is documented based on the UV dosage rate and not based on a CT value. The LT2ESWTR requires PWSs to report the following items to the state for UV disinfection:

- **Initial reporting** – Validation test results demonstrating operating conditions that achieve the UV dose required for compliance with the LT2ESWTR (See Worksheet #3).
- **Routine reporting** – Percentage of water entering the distribution system that was not treated by the UV reactors operating within validated conditions on a monthly basis (See Worksheets #4 and #5).
- **Additional UV calculation worksheet** – Worksheet #6 does not need to be submitted to the state. It is used to calculate the daily off-specification volume (i.e., the daily volume of water disinfected using UV components that are not equal to or better than installed UV components that have been properly validated). The daily off-specification volume is recorded on Worksheets #4 and #5. Note that Worksheets #4 and #5 refer to this worksheet as Figure 6.5 which is the figure number used in the UV Guidance Manual (USEPA, November 2006).

WORKSHEET #1
LOG INACTIVATION RATIO DETERMINATION FOR SURFACE WATER SYSTEMS OR
GROUND WATER SYSTEMS UNDER THE DIRECT INFLUENCE OF SURFACE WATER

Starting Month: _____ Year: _____ PWSID: _____ System/Water Source: _____

Disinfectant Type: _____ Prepared by: _____
 Profile Type (check one): *Giardia* Viruses

Disinfection Segment/Sequence of Application: _____

Week #	3	4	5	6	7	8	9	10	11	12	13	14
	Residual Disinf. Conc. (mg/L)	pH	Water Temp. (°C)	Peak Hourly Flow (gpm)	Volume (gal)	TDT (min.)	Baffling Factor	Disinf. Contact Time (min.)	CT _{Calc} = (C x T) (min-mg/L)	CT Req'd (min-mg/L)	Inactivation Ratio (Col 11 / Col 12)	Log Inactivation*
1												
2												
3												
4												
5												
6												
7												
8												
9												
10												
11												
12												
13												
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*See worksheet #2 to determine total log inactivation if the system has multiple disinfection segments.

Notes:

1. The PWS is only required to calculate log inactivation values once per week on the same day of the week. For instance, the PWS may choose to calculate log inactivation values on Wednesday of every week. If the PWS has more than one point of disinfectant application or uses more than one type of disinfectant, then the PWS can calculate log inactivation ratios on separate sheets and sum the log inactivation ratios to obtain the total inactivation achieved by the plant using Worksheet #2 in this Appendix.
2. Use a separate form for each disinfectant application point and related residual sample site. Enter the disinfectant and sequence position, e.g., "ozone/1st" or "chlorine dioxide/3rd".
3. Residual disinfectant concentration must be measured during peak hourly flow.
4. If the PWS uses chlorine, the pH of the disinfected water must be measured at the same location and time the chlorine residual disinfectant concentration is measured during peak hourly flow.
5. The water temperature must be measured at the same location and time the residual disinfectant concentration is measured during peak hourly flow. Temperature must be in degrees Celsius (°C).
6. Peak hourly flow for the day must be provided for the disinfection segment.
7. The volume is the operating volume in gallons realized by the pipe, basin, or treatment unit process during peak hourly flow.
8. Theoretical detention time in minutes equals the volume in gallons (in column 7) divided by the peak hourly flow in gpm (in column 6).
9. Enter the baffling factor for the PWS's pipe, basin(s) or treatment unit process as determined by a tracer study or assigned by the state.
10. Disinfectant contact time in minutes is determined by multiplying the theoretical detention time in minutes in column 8 by the baffling factor in column 9.
11. CT_{calc} is determined by multiplying the residual disinfectant concentration in mg/L in column 3 by the disinfectant contact time in minutes in column 10.
12. The $CT_{required}$ value should be determined based on the tables contained in Appendix B or tables in the USEPA *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water* (USEPA, March 1991). $CT_{required}$ for *Giardia* is $CT_{99.9}$ (or 3-log inactivation) and $CT_{required}$ for viruses is $CT_{99.99}$ (or 4-log inactivation).
13. Inactivation ratio equals CT_{calc} in column 11 divided by $CT_{required}$ in column 12.
14. Log Inactivation for *Giardia* = 3 x Inactivation ratio in column 13.
Log Inactivation for viruses = 4 x Inactivation ratio in column 13.

For multiple disinfection segments, Worksheet #2 should be used to sum inactivation ratios for each disinfection segment to calculate log inactivation.

WORKSHEET #2
TOTAL LOG INACTIVATION DETERMINATION FOR SURFACE WATER SYSTEMS OR
GROUND WATER SYSTEMS UNDER THE DIRECT INFLUENCE OF SURFACE WATER

Starting Month: _____ Year: _____ PWSID: _____

System/Water Source: _____ Prepared by: _____

Disinfectant Type: _____

Profile Type (check one): *Giardia* Viruses

Week #	Inactivation Ratio for each disinfection segment from Worksheet #1					Sum of Inactivation Ratios	Total Log Inactivation ¹
	Disinfection Segment 1	Disinfection Segment 2	Disinfection Segment 3	Disinfection Segment 4	Disinfection Segment 5		
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
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52							

¹ *Giardia*: Log Inactivation = 3 x Sum of Inactivation Ratios
 Viruses: Log Inactivation = 4 x Sum of Inactivation Ratios (or a method approved by the State)

Worksheet #3 Checklist for Key Elements of the UV Disinfection Validation Report

Yes	No	Check yes or no if your validation report contains the following elements:
		Detailed reactor documentation, including drawings and serial numbers, and procedures used to verify reactor properties.
		Validation test plan (either a summary of key elements, or the test plan can be attached to the validation report along with documentation of any deviations to the original test plan)
		Full-scale reactor testing results, with detailed results for each test condition evaluated. Data should include, but are not limited to: flow rate, measured UV intensity, UVT, lamp power, lamp status, and inlet and outlet concentrations of the challenge microorganism
		Collimated beam testing results, including detailed results for each collimated beam test used to create the UV dose-response equation: Volume and depth of microbial suspension UV Absorption of the microbial suspension Irradiance measurement before and after each irradiation Petri factor calculations and results Calculations for UV dose Derivation of the UV dose-response equation, including statistical methods and confidence intervals (i.e., calculation of UDR)
		QA/QC Check: Challenge microorganism QA/QC, including blanks, controls, and stability analyses
		QA/QC Check: Measurement uncertainty of the radiometer, date of most recent calibration, results of reference checks
		QA/QC Check: Measurement uncertainty of UV sensors and results of reference checks
		QA/QC Check: Measurement uncertainty of the flow meter, UV spectrophotometer, and any other measurement equipment used during full-scale testing
		Calculation of the validated dose, log inactivation credit, and validated operating conditions: Reduction equivalent dose (RED) for each test condition Calculation of the VF Setpoints if the reactor uses the UV Intensity Setpoint Approach Dose-monitoring equation if the reactor uses the Calculated Dose Approach Log inactivation credit for target pathogens (e.g., <i>Cryptosporidium</i> , <i>Giardia</i> , and viruses) Validated operating conditions (e.g., flow rate, lamp status, UVT)

Source: USEPA, November 2006

Worksheet #4 Example Daily Operating Log for Calculated Dose Approach

Reporting Period: _____
 System/Treatment Plant: _____
 PWSID: _____
 UV Reader: _____
 Process Train: _____
 Operator Signature: _____
 Date: _____

Maximum Validated Flow Rate: _____
 Minimum Validated UVT: _____
 Target Log Inactivation: _____
 Target Pathogen: _____
 Dose Required (D_{req}): _____
 Validation Factor (VF): _____

$$\text{Validated Dose} = \frac{\text{Calculated Dose}}{\text{VF} \times \text{CF}}$$

Calculated Dose = Dose that is calculated by validated PLC algorithm
 VF = Validation factor
 CF = UV intensity sensor correction factor.
 The CF is only applied if sensors do not meet recommended criteria
 (NOTE – a CF will not be needed in most cases)

Operational Data		Dose Requirements			Data at Daily Minimum Validated Dose				UV Dose Adequacy Determination	Total Off-Specification
Day	Run Time (hrs)	Total Production (MG)	Dose ¹ (mJ/cm ²)	Sensor Correction Factor ² [B]	Calculated Dose ³ (mJ/cm ²)	Daily Minimum Validated Dose ⁴ ((C)/(VF)(B)) (mJ/cm ²)	Flow Rate (MGD)	UVT (%)	Validated Dose > D _{req} (D) > (A)	Total Off-Specification Volume (MG)
1			[A]	[B]	[C]	[D]			(Y/N)	
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
12										
13										
14										
15										
16										
17										
18										
19										
20										
21										
22										
23										
24										
25										
26										
27										
28										
29										
30										
31										
Min										
Max										
Total										

¹ Dose is the dose required for the target log inactivation without a VF or Sensor CF applied and can be found in the UVCGM Table 1.4.
² Sensor CF will be 1 if no CF is used
³ Calculated dose is calculated using the dose algorithm in the PLC.
⁴ The Validated Dose is the dose based on the calculated dose that is normalized on the Validation Factor and Correction Factor
⁵ Off-specification worksheet (Figure 6.5) should be used to calculate daily off-specification volume. If UVT, flow rate, and/or Validated Dose off-specification occur simultaneously, the off-specification time should only be counted once

Source: USEPA, November 2006

Worksheet #5 Example Daily Operating Log for UV Intensity Setpoint Approach

Reporting Period: _____ System/Treatment Plant: _____ PWSID: _____ UV Reactor: _____ Process Train: _____ Operator Signature: _____ Date: _____		Maximum Validated Flow Rate: _____ Minimum Validated LVT: _____ Target Log Inactivation: _____ Target Pathogen: _____ Intensity Setpoint: _____								
Operational Data				Intensity Requirements			Daily Minimum Intensity		Total Flow Off-Specification	
Day	Run Time (hrs)	Min (mgd)	Ave (mgd)	Max (mgd)	Intensity Setpoint (W/m ²) [A]	Sensor Correction Factor ¹ [B]	Adjusted Intensity Setpoint (W/m ²) ([A] * [B]) [C]	Daily Minimum Intensity (W/m ²) [D]	Minimum Daily Intensity > Adjusted Intensity Setpoint (D) > [C] (Y/N)	Total Flow Off-Specification ³ (MG)
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
12										
13										
14										
15										
16										
17										
18										
19										
20										
21										
22										
23										
24										
25										
26										
27										
28										
29										
30										
31										
Min										
Max										
Total										

¹ Sensor CF will be 1 if no CF is used.
² LVT measurements are not required but could be useful in addressing operational issues.
³ Off-specification worksheet (Figure 6.5) should be used to calculate daily off-specification volume. If UV intensity or flowrate off-specification occur simultaneously, the off-specification time should only be counted once.

Source: USEPA, November 2006

Worksheet #6 Example Off-specification Calculation Worksheet

Reporting Period: _____

System/Treatment Plant: _____

PWSID: _____

Operator Signature: _____

Date: _____

Off-Specification Calculation Worksheet (Note - This sheet should only be used when an off-specification event occurs):

Date ¹	Reactor Number	Process Train Number	Off-Specification Event Description ²	Flow Rate ³ (MGD) [A]	Time (days) [B]	Off-Specification Volume (MG) (A)*[B]
Total Off-Specification Flow for the Day³						

¹ This worksheet should only be used for one date and one reactor.

² This worksheet assumes that the flowrate is constant during the off-specification event. Off-specification volume can also be obtained from a flow totalizer.

³ Off-Specification event can be caused by UV/T, flowrate, intensity, or validated dose being out of the validated range.

⁴ The total off-specification flow should be transferred to Figure 6.3 or 6.4 if any off-specification events occurred.

Source: USEPA, November 2006

References

USEPA. March 1991. *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water*. Washington, D.C.

USEPA. November 2006. *Ultraviolet Disinfection Guidance Manual for the Final Long Term 2 Enhanced Surface Water Treatment Rule*. EPA 815-R-06-006. Washington, D.C.

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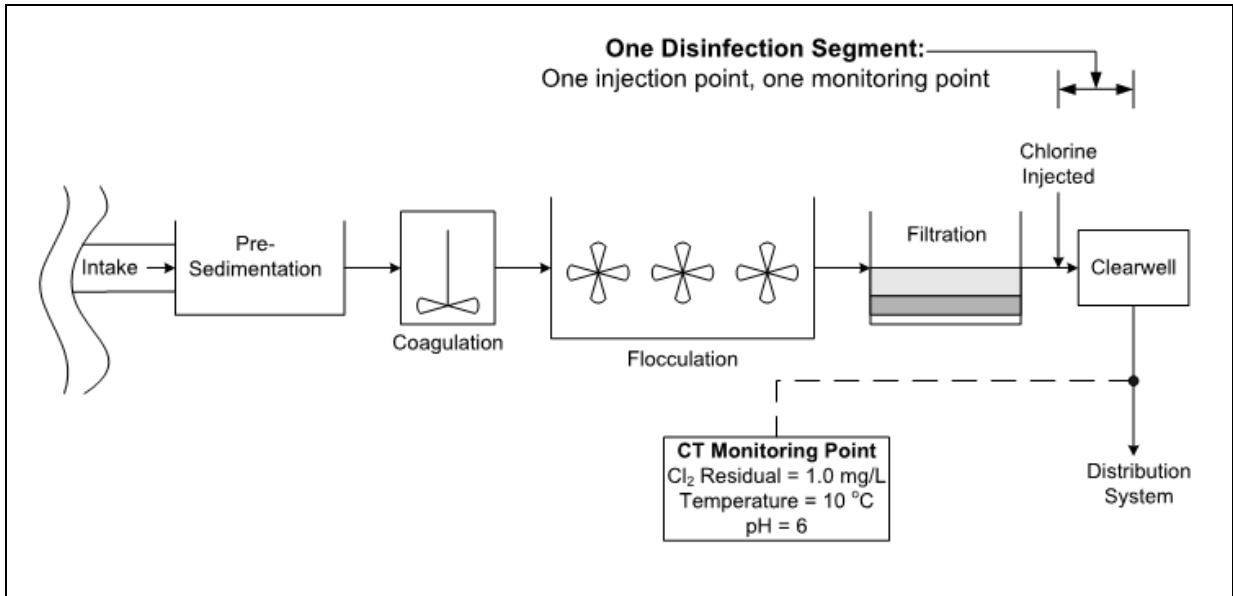
Appendix D — Examples

This appendix provides three examples of ways a PWS may comply with the regulations for a disinfection profile and a disinfection benchmark. This appendix does not establish any additional requirements for completing a disinfection profile or a disinfection benchmark beyond the regulations established in the LT2ESWTR, LT1ESWTR, and IESWTR.

The following examples are presented in this appendix:

- Example D-1: Calculate Log Inactivation for One Disinfection Segment and One Disinfectant (Chlorine)
- Example D-2: Calculate Log Inactivation for Three Disinfection Segments and Two Disinfectants (Chlorine as primary and Chloramines as secondary disinfectant)
- Example D-3: Develop a Disinfection Profile and Benchmark for a PWS with Multiple Disinfection Segments and Two Disinfectants (Ozone as primary and Chlorine as secondary disinfectant)

Example D-1. Calculate Log Inactivation for One Disinfection Segment and One Disinfectant



In this example, the direct filtration treatment system adds chlorine prior to the clearwell and is required to create a disinfection profile. The PWS plans on making a significant change to its disinfection practices in order to comply with LT2ESWTR and must determine the log inactivation for *Giardia* and viruses achieved through disinfection. This example walks through the steps taken to determine the log inactivation for *Giardia*.

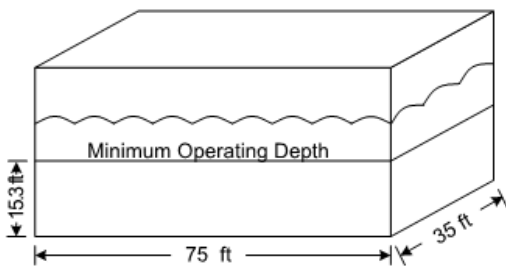
Step 1. Determine the peak hourly flow.

From the raw water pump records, the peak hourly flow (Q) is determined to be 5,000 gallons per minute (gpm).

Step 2. Measure the chlorine residual, temperature and pH (since chlorine is used) during peak hourly flow at the monitoring point and at the same time.

Temperature = 10 °C
 pH = 6
 Chlorine residual = $C_{\text{chlorine}} = 1.0 \text{ mg/L}$

Step 3. Measure the physical dimensions of the clearwell.



Measure the inner tank length and width to obtain the area of the clearwell.

Length = 75 ft

Width = 35 ft

Measure the minimum operating depth in the clearwell to obtain a conservative estimate of the volume of water in the tank.

Minimum Operating Depth = 15.3 ft

Step 4. Calculate the volume of the water in the clearwell based on low water level.

Volume (V) = minimum water depth x length x width

$$V = 15.3 \text{ ft} \times 75 \text{ ft} \times 35 \text{ ft} = 40,160 \text{ ft}^3$$

$$V = 40,160 \text{ ft}^3 \times (7.48 \text{ gal} / \text{ft}^3)$$

$$V = 300,000 \text{ gal}$$

Step 5. Calculate the Theoretical Detention Time (TDT) in the clearwell.

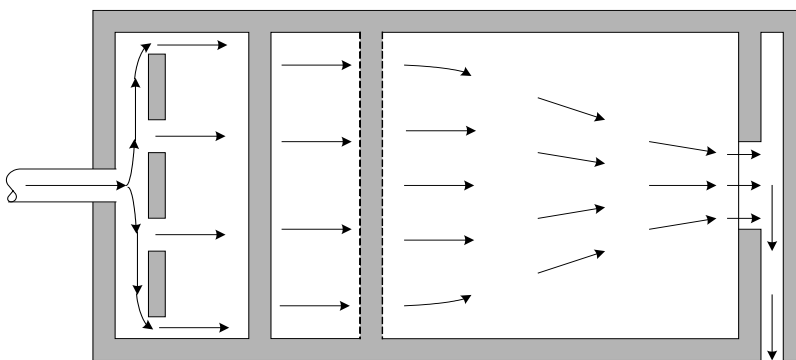
TDT = V / Q (Note: Q = peak hourly flow)

$$\text{TDT} = 300,000 \text{ gal} / 5,000 \text{ gpm}$$

$$\text{TDT} = 60 \text{ minutes}$$

Step 6. Determine the baffling factor (BF) for the clearwell.

Clearwell BF = 0.5 (from Table G-1 in Appendix G for average baffling condition as shown below.)



Step 7. Calculate the contact time of the disinfectant in the clearwell.

Contact Time (T) = TDT x BF

$$T = 60 \text{ min} \times 0.5$$

$$T = 30 \text{ minutes}$$

Step 8. Calculate the CT for the disinfection segment.

$$CT_{\text{calc}} = C_{\text{chlorine}} \times T$$

$$CT_{\text{calc}} = 1.0 \text{ mg/L} \times 30 \text{ min}$$

$$CT_{\text{calc}} = \mathbf{30 \text{ min-mg/L}}$$

Step 9. Determine the required $CT_{99.9}$ necessary to obtain 3-log *Giardia* inactivation.

The required CT value for 3-log *Giardia* inactivation ($CT_{99.9}$) may be obtained by using CT Table B-1 in Appendix B, CT Values for 3-Log Inactivation of *Giardia* Cysts by Free Chlorine. In this example, the required $CT_{99.9}$ is 79 min-mg/L for a pH of 6, temperature of 10°C, and C_{chlorine} of 1.0 mg/L. The relevant section of Table B-1 is reprinted below and the pertinent section of the table is highlighted.

Excerpt from Table B-1

CT Values for 3-Log Inactivation of *Giardia* Cysts by Free Chlorine (10°C portion of table, for concentrations from 0.4 to 1.2)

Chlorine Concentration (mg/L)	Temperature = 10°C						
	pH						
	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0
<=0.4	73	88	104	125	149	177	209
0.6	75	90	107	128	153	183	218
0.8	78	92	110	131	158	189	226
1.0	79	94	112	134	162	195	234
1.2	80	95	114	137	166	200	240

Step 10. Calculate the inactivation ratio for the clearwell.

$$\begin{aligned} \text{Inactivation ratio} &= CT_{\text{calc}} / CT_{99.9} \\ &= (30 \text{ min-mg/L}) / (79 \text{ min-mg/L}) \end{aligned}$$

$$\text{Inactivation ratio} = 0.380$$

Step 11. Calculate the *Giardia* log inactivation for the clearwell.

$$\text{Log inactivation} = 3 \times CT_{\text{calc}} / CT_{99.9}$$

$$\text{Log inactivation} = 3 \times 0.380$$

$$\text{Log inactivation} = \mathbf{1.14}$$

The *Giardia* log inactivation for this disinfection segment is 1.14.

Assuming the PWS received a 2.0 log *Giardia* removal credit from the state for direct filtration, it must achieve at least 1.0 log *Giardia* inactivation for a total 3.0 log *Giardia* removal and/or inactivation as required in the Surface Water Treatment Rule (40 CFR Section 141.70(a)(1)). The value of 1.14 log *Giardia* inactivation exceeds the required 1.0 log *Giardia* inactivation. A calculation for virus inactivation must also be performed as required under LT2ESWTR.

The worksheets in Appendix C can be used to record data and calculate log inactivation. The table below demonstrates how to record the data from this example using Worksheet #1 in Appendix C.

WORKSHEET #1
LOG INACTIVATION RATIO DETERMINATION FOR SURFACE WATER SYSTEMS OR
GROUND WATER SYSTEMS UNDER THE DIRECT INFLUENCE OF SURFACE WATER

Starting Month: January Year: 2016 PWSID: AA6543210 System/Water Source: LMN Water Plant

Disinfectant Type: Free Chlorine Prepared by: Jim Operator

Profile Type (check one): *Giardia* Viruses

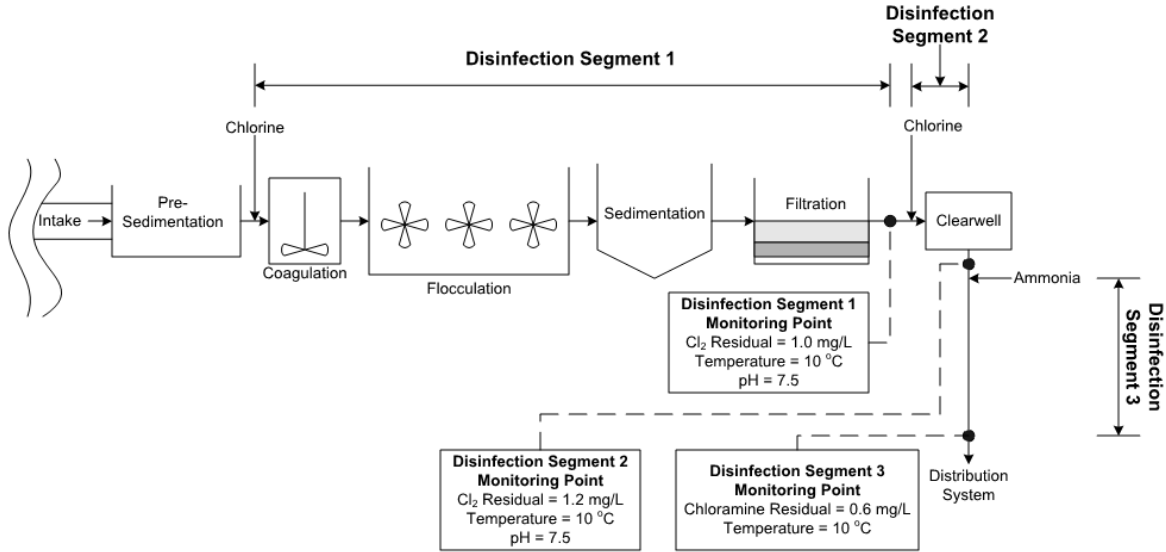
Disinfection Segment/Sequence of Application: Clearwell/1st

Week #	3	4	5	6	7	8	9	10	11	12	13	14
	Residual Disinf. Conc.	pH	Water Temp.	Peak Hourly Flow	Volume	TDT	Baffling Factor	Disinf. Contact Time	CT _{Calc} = (C×T)	CT Req'd	Inactivation Ratio	Log Inactivation*
	C (mg/L)		(°C)	(gpm)	(gal)	(min.)		T (min.)	(min-mg/L)	(min-mg/L)	(Col 11 / Col 12)	
1	1.0	6	10	5,000	300,000	60	0.5	30	30.0	79	0.38	1.14
2												
3												
4												
5												
6												

*See worksheet #2 to determine total log inactivation if the system has multiple disinfection segments.

Example D-2. Calculate Log Inactivation for Three Disinfection Segments and Two Disinfectants

In this example, chlorine is added to the conventional treatment system before coagulation as a pre-disinfectant and again prior to the clearwell as a primary disinfectant. Ammonia is added after the clearwell to create chloramines as the secondary disinfectant to maintain a residual throughout the distribution system. The PWS is considering changes to their disinfection practices. Therefore, under LT2ESWTR, the PWS is required to create a disinfection profile and benchmark and consult with the state. For the profile, the PWS is required to calculate the log inactivation for *Giardia* and viruses. This example walks through the steps taken to determine the log inactivation for *Giardia*.



Since there are three points where the disinfectant is added, the inactivation ratio must be calculated for each disinfection segment.

A. Determine the *Giardia* Inactivation Ratio for Disinfection Segment 1

Disinfection Segment 1 begins at the chlorine injection location just prior to coagulation and ends at the chlorine monitoring point just after the filters.

Step 1. Determine the peak hourly flow.

From the raw water pump records the peak hourly flow (Q) is determined to be 5,000 gpm.

Step 2. Measure the chlorine residual, temperature and pH (since chlorine is used) during peak hourly flow at the chlorine monitoring point and at the same time.

Temperature = 10°C

pH = 7.5

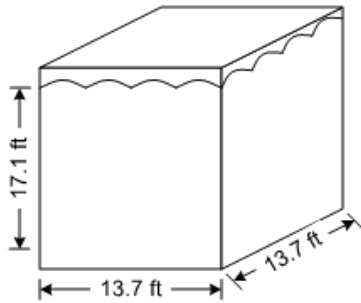
Chlorine residual = C_{chlorine} = 1.0 mg/L

Step 3. Measure the physical dimensions of the sub-units in Disinfection Segment 1.

Measure inner tank diameter or length and width to obtain the area of water in the tanks rather than the area of the tanks themselves.

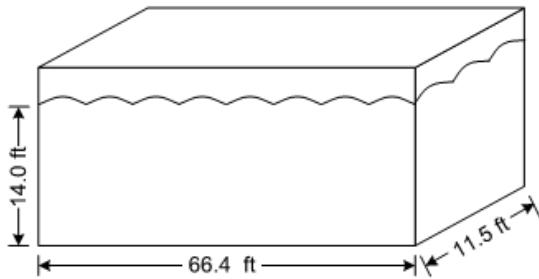
Measure the minimum operating depth in the tanks, where applicable, to obtain conservative estimates of the volume of water in the tanks.

Coagulation:



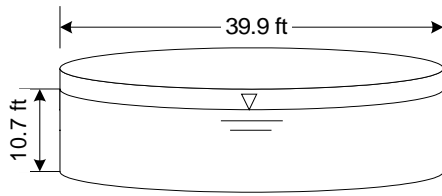
Length = 13.7 ft
Width = 13.7 ft
Depth = 17.1 ft

Flocculation:



Length = 66.4 ft
Width = 11.5 ft
Depth = 14.0 ft

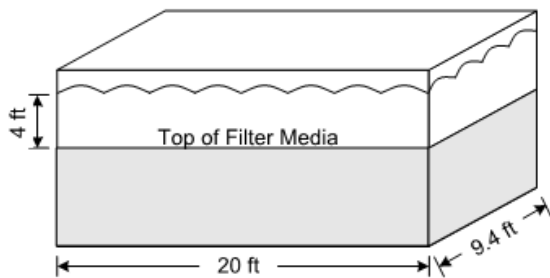
Sedimentation:



Diameter = 39.9 ft

Depth = 10.7 ft

Filtration:



Depth above filter media = 4 ft

Length = 20 ft

Width = 9.4 ft

Number of filters = 8

Step 4. Calculate the volume of the water in each sub-unit in Disinfection Segment 1.

Coagulation:

Volume (V) = Length x Width x Depth

$$V = 13.7 \text{ ft} \times 13.7 \text{ ft} \times 17.1 \text{ ft} = 3,210 \text{ ft}^3$$

$$V = 3,210 \text{ ft}^3 \times (7.48 \text{ gal} / \text{ft}^3)$$

$$V = \mathbf{24,000 \text{ gallons}}$$

Flocculation:

Volume (V) = Length x Width x Depth

$$V = 66.4 \text{ ft} \times 11.5 \text{ ft} \times 14.0 \text{ ft} = 10,690 \text{ ft}^3$$

$$V = 10,690 \text{ ft}^3 \times (7.48 \text{ gal} / \text{ft}^3)$$

$$V = \mathbf{80,000 \text{ gallons}}$$

Sedimentation:

$$\begin{aligned} \text{Volume (V)} &= \pi \times \text{Radius}^2 \times \text{Depth} \\ \pi &= 3.14 \text{ (constant)} \\ \text{Radius} &= \text{Diameter} / 2 = 39.9 / 2 = 19.95 \text{ ft} \\ V &= 3.14 \times (19.95 \text{ ft})^2 \times 10.7 \text{ ft} = 13,370 \text{ ft}^3 \\ V &= 13,370 \text{ ft}^3 \times (7.48 \text{ gal} / \text{ft}^3) \\ \mathbf{V} &= \mathbf{100,000 \text{ gallons}} \end{aligned}$$

Filtration:

$$\begin{aligned} \text{Volume (V)} &= \text{Length} \times \text{Width} \times \text{Depth of Water Above Media} \times \# \text{ of Filters} \\ V &= 20 \text{ ft} \times 9.4 \text{ ft} \times 4 \text{ ft} \times 8 \text{ filters} = 6,020 \text{ ft}^3 \\ V &= 6,020 \text{ ft}^3 \times (7.48 \text{ gal} / \text{ft}^3) \\ \mathbf{V} &= \mathbf{45,000 \text{ gallons}} \end{aligned}$$

Step 5. Calculate the Theoretical Detention Time (TDT) in the sub-units in Disinfection Segment 1.

$$TDT = V / Q$$

Coagulation:

$$\begin{aligned} TDT &= 24,000 \text{ gal} / 5,000 \text{ gpm} \\ TDT &= \mathbf{4.8 \text{ minutes}} \end{aligned}$$

Flocculation:

$$\begin{aligned} TDT &= 80,000 \text{ gal} / 5,000 \text{ gpm} \\ TDT &= \mathbf{16 \text{ minutes}} \end{aligned}$$

Sedimentation:

$$\begin{aligned} TDT &= 100,000 \text{ gal} / 5,000 \text{ gpm} \\ TDT &= \mathbf{20 \text{ minutes}} \end{aligned}$$

Filtration:

$$\begin{aligned} TDT &= 45,000 \text{ gal} / 5,000 \text{ gpm} \\ TDT &= \mathbf{9 \text{ minutes}} \end{aligned}$$

Step 6. Determine the baffling factors (BF) for the sub-units in Disinfection Segment 1.

The table below summarizes the baffling factors in this example for the sub-units in Disinfection Segment 1.

Unit Process	BF *
(1) Coagulation	0.1
(2) Flocculation	0.1
(3) Sedimentation	0.5
(4) Filtration	0.7

*See Appendix G for Baffling Factors

Step 7. Calculate the contact time (T) in the sub-units in Disinfection Segment 1.

$$T = \text{TDT} \times \text{BF}$$

Coagulation:

$$T = 4.8 \text{ min} \times 0.1$$
$$T = \mathbf{0.48 \text{ minutes}}$$

Flocculation:

$$T = 16 \text{ min} \times 0.1$$
$$T = \mathbf{1.6 \text{ minutes}}$$

Sedimentation:

$$T = 20 \text{ min} \times 0.5$$
$$T = \mathbf{10 \text{ minutes}}$$

Filtration:

$$T = 9 \text{ min} \times 0.7$$
$$T = \mathbf{6.3 \text{ minutes}}$$

Step 8. Calculate the total contact time in Disinfection Segment 1.

$$\text{Total Contact Time (T}_{\text{total}}) = \text{Sum of T in each sub-unit}$$
$$T_{\text{total}} = 0.48 \text{ min} + 1.6 \text{ min} + 10 \text{ min} + 6.3 \text{ min}$$
$$T_{\text{total}} = \mathbf{18.4 \text{ minutes}}$$

Step 9. Calculate the CT for Disinfection Segment 1 (CT_{calc})

$$CT_{\text{calc}} = C_{\text{chlorine}} \times T_{\text{total}}$$

$$CT_{\text{calc}} = 1.0 \text{ mg/L} \times 18.4 \text{ min}$$

$$CT_{\text{calc}} = 18.4 \text{ min-mg/L}$$

The CT_{calc} for Disinfection Segment 1 = 18.4 min-mg/L

Step 10. Determine the required CT_{99.9} necessary to obtain 3-log *Giardia* inactivation.

The required CT value for 3-log *Giardia* inactivation (CT_{99.9}) may be obtained by using CT Table B-1 in Appendix B, CT Values for 3-Log Inactivation of *Giardia* Cysts by Free Chlorine. The CT_{99.9} in this example is 134 min-mg/L for a pH of 7.5, temperature of 10°C, and C_{chlorine} of 1.0 mg/L. The relevant section of Table B-1 is reprinted below and the pertinent section of the table is highlighted.

Excerpt from Table B-1

CT Values for 3-Log Inactivation of *Giardia* Cysts by Free Chlorine (10°C portion of table, for concentrations from 0.6 to 1.4)

Chlorine Concentration (mg/L)	Temperature = 10°C						
	pH						
	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0
0.6	75	90	107	128	153	183	218
0.8	78	92	110	131	158	189	226
1.0	79	94	112	134	162	195	234
1.2	80	95	114	137	166	200	240
1.4	82	98	116	140	170	206	247

Step 11. Calculate the inactivation ratio for Disinfection Segment 1.

$$\text{Inactivation ratio} = CT_{\text{calc}} / CT_{99.9}$$

$$\text{Inactivation ratio} = (18.4 \text{ min-mg/L}) / (134 \text{ min-mg/L})$$

$$\text{Inactivation ratio} = 0.137$$

B. Determine the *Giardia* Inactivation Ratio for Disinfection Segment 2

Disinfection Segment 2 in this example begins at the chlorine injection location just prior to the clearwell and ends just after the clearwell.

Step 1. Determine the peak hourly flow.

The peak hourly flow (Q) for Disinfection Segment 2 is the same as the peak hourly flow in Disinfection Segment 1.

Peak hourly flow = 5,000 gpm.

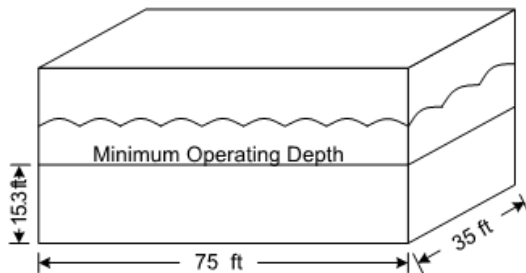
Step 2. Measure the chlorine residual, temperature, and pH (since chlorine is used) during peak hourly flow at the chlorine monitoring point and at the same time.

Temperature = 10°C

Chlorine residual = $C_{\text{chlorine}} = 1.2 \text{ mg/L}$

pH = 7.5

Step 3. Measure the physical dimensions of the clearwell.



Measure the inner tank length and width to obtain the volume of water in the clearwell rather than the volume of the tank itself.

Length = 75 ft

Width = 35 ft

Measure the minimum operating depth in the clearwell to obtain a conservative estimate of the volume of water in the tank.

Minimum Operating Depth = 15.3 ft

Step 4. Calculate the volume of the water in the clearwell based on low water level.

Volume (V) = minimum water depth x length x width

$$V = 15.3 \text{ ft} \times 75 \text{ ft} \times 35 \text{ ft} = 40,160 \text{ ft}^3$$

$$V = 40,160 \text{ ft}^3 \times (7.48 \text{ gal} / \text{ft}^3)$$

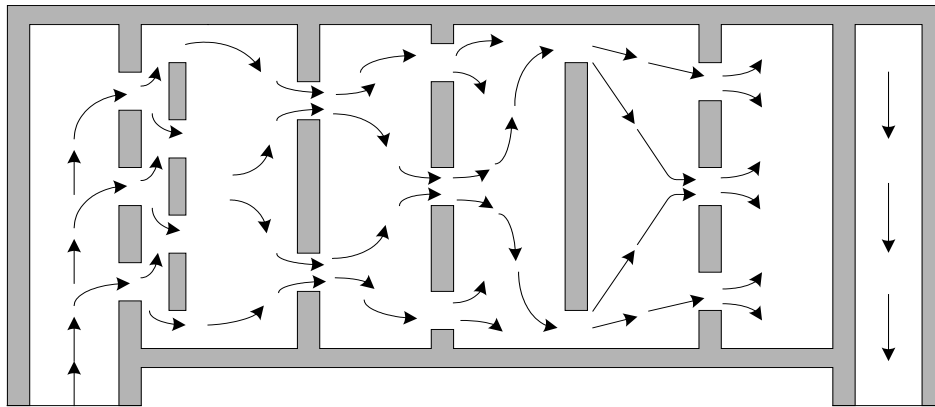
$$V = 300,000 \text{ gal}$$

Step 5. Calculate the Theoretical Detention Time in the clearwell.

$$\begin{aligned}\text{Theoretical Detention Time (TDT)} &= V / Q \\ \text{TDT} &= 300,000 \text{ gal} / 5,000 \text{ gpm} \\ \text{TDT} &= \mathbf{60 \text{ minutes}}\end{aligned}$$

Step 6. Determine the baffling factor for the clearwell.

Clearwell Baffling Factor (BF) = 0.7 (from Table G-1 for superior baffling condition as shown below.)



Step 7. Calculate the contact time of the disinfectant in the clearwell.

$$\begin{aligned}\text{Contact Time (T)} &= \text{TDT} \times \text{BF} \\ T &= 60 \text{ min} \times 0.7 \\ T &= \mathbf{42 \text{ minutes}}\end{aligned}$$

Step 8. Calculate the CT for the disinfection segment.

$$\begin{aligned}\text{CT}_{\text{calc}} &= C_{\text{chlorine}} \times T \\ \text{CT}_{\text{calc}} &= 1.2 \text{ mg/L} \times 42 \text{ min} \\ \text{CT}_{\text{calc}} &= \mathbf{50 \text{ min-mg/L}}\end{aligned}$$

Step 9. Determine the required $CT_{99.9}$ necessary to obtain 3-log *Giardia* inactivation.

The required CT value for 3-log *Giardia* inactivation ($CT_{99.9}$) may be obtained by using CT Table B-1 in Appendix B, CT Values for 3-Log Inactivation of *Giardia* Cysts by Free Chlorine. The $CT_{99.9}$ in this example is 137 min-mg/L for a pH of 7.5, temperature of 10°C, and C_{chlorine} of 1.2 mg/L. The relevant section of Table B-1 is reprinted below and the pertinent section of the table is highlighted.

Excerpt from Table B-1

CT Values for 3-Log Inactivation of *Giardia* Cysts by Free Chlorine (10°C portion of table, for concentrations from 0.8 to 1.6)

Chlorine Concentration (mg/L)	Temperature = 10°C						
	pH						
	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0
0.8	78	92	110	131	158	189	226
1.0	79	94	112	134	162	195	234
1.2	80	95	114	137	166	200	240
1.4	82	98	116	140	170	206	247
1.6	83	99	119	144	174	211	253

Step 10. Calculate the inactivation ratio for the clearwell.

Inactivation ratio = $CT_{\text{calc}} / CT_{99.9}$
Inactivation ratio = (50 min-mg/L) / (137 min-mg/L)
Inactivation ratio = 0.365

C. Determine the *Giardia* Inactivation Ratio for Disinfection Segment 3

Disinfection Segment 3 in this example begins at the chloramine injection location after the clearwell and ends at the monitoring point in the transmission pipe, which is prior to the first customer.

Step 1. Determine the peak hourly flow.

The peak hourly flow (Q) for Disinfection Segment 3 is the same as the peak hourly flow in Disinfection Segments 1 and 2.

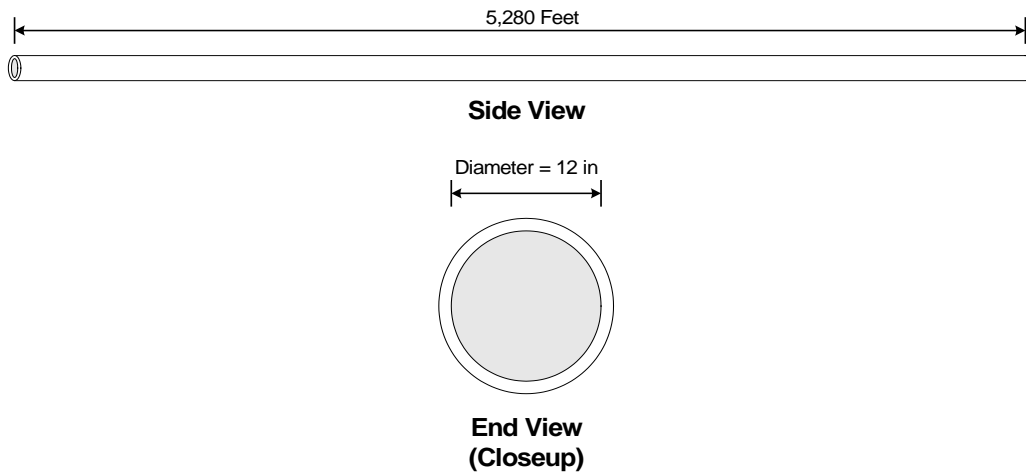
Peak hourly flow = 5,000 gpm

Step 2. Measure the chloramine residual and temperature during peak hourly flow at the chlorine monitoring point and at the same time.

Temperature = 10°C

Chloramine residual = $C_{\text{chloramine}}$ = 0.6 mg/L

Step 3. Measure the physical dimensions of the pipe.



Measure the length of the pipe and the inner pipe diameter to obtain the volume of water in the pipe rather than the volume of the pipe itself.

Diameter = 12 in x (1 ft / 12 in) = 1 ft

Length = 5,280 ft

Step 4. Calculate the volume of the water in the pipe.

Volume (V) = π x Radius² x Length

π = 3.14 (constant)

Radius = Diameter / 2 = 1.0 / 2 = 0.5 ft

$V = 3.14 \times (0.5 \text{ ft})^2 \times 5,280 \text{ ft} = 4,145 \text{ ft}^3$

$V = 4,145 \text{ ft}^3 \times (7.48 \text{ gal} / \text{ft}^3)$

$V = 31,000 \text{ gallons}$

Step 5. Calculate the Theoretical Detention Time in the pipe.

Theoretical Detention Time (TDT) = V / Q

TDT = 31,000 gal / 5,000 gpm

TDT = 6.2 minutes

Step 6. Determine the baffling factor for the pipe.

Baffling Factor (BF) = 1.0 (from Table G-1 in Appendix G for a pipe)

Step 7. Calculate the contact time of the disinfectant in the pipe.

$$\text{Contact Time (T)} = \text{TDT} \times \text{BF}$$

$$T = 6.2 \text{ min} \times 1.0$$

$$T = \mathbf{6.2 \text{ minutes}}$$

Step 8. Calculate the CT for the disinfection segment.

$$CT_{\text{calc}} = C_{\text{chloramine}} \times T$$

$$CT_{\text{calc}} = 0.6 \text{ mg/L} \times 6.2 \text{ min}$$

$$CT_{\text{calc}} = \mathbf{3.7 \text{ min-mg/L}}$$

Step 9. Determine the required $CT_{99.9}$ necessary to obtain 3-log *Giardia* inactivation.

The required CT value for 3-log *Giardia* inactivation ($CT_{99.9}$) may be obtained by using CT Table B-7 in Appendix B, CT Values for 3-Log Inactivation of *Giardia* Cysts by Chloramine pH 6-9. The $CT_{99.9}$ in this example is 1,850 min-mg/L for a temperature of 10°C. Table B-7 is reprinted below and the pertinent section of the table is highlighted.

Table B-7

CT Values for 3-Log Inactivation of *Giardia* Cysts by Chloramine pH 6-9

Temperature (°C)					
< = 1	5	10	15	20	25
3,800	2,200	1,850	1,500	1,100	750

Step 10. Calculate the inactivation ratio for the pipe.

$$\text{Inactivation ratio} = CT_{\text{calc}} / CT_{99.9}$$

$$\text{Inactivation ratio} = (3.7 \text{ min-mg/L}) / (1,850 \text{ min-mg/L})$$

$$\text{Inactivation ratio} = \mathbf{0.002}$$

D. Determine Total Giardia Log Inactivation for All Disinfection Segments.

Step 1. Determine the total Giardia inactivation ratio for all disinfection segments.

$$\text{Total Inactivation ratio} = \Sigma (CT_{\text{calc}} / CT_{99.9}) = 0.137 + 0.365 + 0.002 = 0.504$$

Step 2. Determine the total Giardia log inactivation for all disinfection segments.

$$\text{Total log inactivation} = 3 \times \Sigma (CT_{\text{calc}} / CT_{99.9})$$

$$\text{Total log inactivation} = 3 \times (0.504)$$

Total log inactivation = 1.51

The total *Giardia* log inactivation for all disinfection segments is 1.51.

Assuming the PWS received a 2.5 log *Giardia* removal credit from the state for conventional filtration, it must achieve at least 0.5 log *Giardia* inactivation for a total 3.0 log *Giardia* removal and/or inactivation as required in the Surface Water Treatment Rule (40 CFR Section 141.70(a)(1)). The value of 1.51 log *Giardia* inactivation exceeds the required 0.5 log *Giardia* inactivation.

E. Worksheets

The worksheets in Appendix C can be used to record data and calculate log inactivation.

The table below summarizes the calculations for each unit process in Disinfection Segment 1.

Unit Process	Volume (gal)	Peak Hourly Flow (gpm)	BF*	Contact Time (min)
Coagulation	24,000	5,000	0.1	0.48
Flocculation	80,000	5,000	0.1	1.6
Sedimentation	100,000	5,000	0.5	10
Filtration	45,000	5,000	0.7	6.3
Total:	249,000			18.4

* See Appendix G for baffling factors.

The worksheet excerpt below demonstrates how data may be recorded from Disinfection Segment 1 using Worksheet #1 in Appendix C. For this example, Worksheet #1 needs to be copied so the data from each disinfection segment can be entered.

WORKSHEET #1
LOG INACTIVATION RATIO DETERMINATION FOR SURFACE WATER SYSTEMS OR
GROUND WATER SYSTEMS UNDER THE DIRECT INFLUENCE OF SURFACE WATER

Starting Month: January Year: 2016 PWSID: AA7654321 System/Water Source: ABC Water Plant

Disinfectant Type: Free Chlorine Prepared by: Jon Operator
Profile Type (check one): Giardia Viruses

Disinfection Segment/Sequence of Application: Coagulation, Flocculation, Sedimentation, Filtration/1st

Week #	3 Residual Disinf. Conc. (mg/L)	4 pH	5 Water Temp. (°C)	6 Peak Hourly Flow (gpm)	7 Volume (gal)	8 TDT (min.)	9 Baffling Factor	10 Disinf. Contact Time (min.)	11 CT _{Calc} = (C×T) (min-mg/L)	12 CT Req'd (min-mg/L)	13 Inactivation Ratio (Col 11 / Col 12)	14 Log Inactivation*
1	1.0	7.5	10	5,000	249,000	**	**	18.4	18.4	134	0.137	
2												
3												
4												
5												
6												

*See worksheet #2 to determine total log inactivation if the system has multiple disinfection segments.

**See the previous table showing details of each unit process for theoretical detention times and baffling factors.

The worksheet excerpt below demonstrates how data may be recorded from Disinfection Segment 2 using Worksheet #1 in Appendix C.

WORKSHEET #1
LOG INACTIVATION RATIO DETERMINATION FOR SURFACE WATER SYSTEMS OR
GROUND WATER SYSTEMS UNDER THE DIRECT INFLUENCE OF SURFACE WATER

Starting Month: January Year: 2016 PWSID: AA7654321 System/Water Source: ABC Water Plant

Disinfectant Type: Free Chlorine Prepared by: Jon Operator
Profile Type (check one): Giardia Viruses

Disinfection Segment/Sequence of Application: Clearwell/2nd

Week #	3 Residual Disinf. Conc. (mg/L)	4 pH	5 Water Temp. (°C)	6 Peak Hourly Flow (gpm)	7 Volume (gal)	8 TDT (min.)	9 Baffling Factor	10 Disinf. Contact Time (min.)	11 CT _{Calc} = (C×T) (min-mg/L)	12 CT Req'd (min-mg/L)	13 Inactivation Ratio (Col 11 / Col 12)	14 Log Inactivation*
1	1.2	7.5	10	5,000	300,000	60	0.7	42	50	137	0.365	
2												
3												
4												
5												
6												

*See worksheet #2 to determine total log inactivation if the system has multiple disinfection segments.

The worksheet excerpt below demonstrates how data may be recorded from Disinfection Segment 3 using Worksheet #1 in Appendix C.

WORKSHEET #1
LOG INACTIVATION RATIO DETERMINATION FOR SURFACE WATER SYSTEMS OR
GROUND WATER SYSTEMS UNDER THE DIRECT INFLUENCE OF SURFACE WATER

Starting Month: January Year: 2016 PWSID: AA7654321 System/Water Source: ABC Water Plant

Disinfectant Type: Chloramine Prepared by: Jon Operator

Profile Type (check one): Giardia Viruses

Disinfection Segment/Sequence of Application: Transmission Pipe/3rd

Week #	3	4	5	6	7	8	9	10	11	12	13	14
	Residual Disinf. Conc. (mg/L)	pH	Water Temp. (°C)	Peak Hourly Flow (gpm)	Volume (gal)	TDT (min.)	Baffling Factor	Disinf. Contact Time (min.)	CT _{Calc} = (min-mg/L)	CT Req'd (min-mg/L)	Inactivation Ratio (Col 11 / Col 12)	Log Inactivation*
1	0.6	N/A	10	5,000	31,000	6.2	1.0	6.2	3.7	1,850	0.002	
2												
3												
4												
5												
6												

*See worksheet #2 to determine total log inactivation if the system has multiple disinfection segments.

The worksheet excerpt below demonstrates how to determine total *Giardia* log inactivation for all disinfection segments using Worksheet #2 in Appendix C.

WORKSHEET #2
TOTAL LOG INACTIVATION DETERMINATION FOR SURFACE WATER SYSTEMS OR
GROUND WATER SYSTEMS UNDER THE DIRECT INFLUENCE OF SURFACE WATER

Starting Month: January Year: 2016 PWSID: AA7654321

System/Water Source: ABC Water Plant Prepared by: Jon Operator

Disinfectant Type: Chlorine/Chloramine

Profile Type (check one): Giardia Viruses

Week #	Inactivation Ratio for each disinfection segment from Worksheet #1					Sum of Inactivation Ratios	Total Log Inactivation ¹
	Disinfection Segment 1	Disinfection Segment 2	Disinfection Segment 3	Disinfection Segment 4	Disinfection Segment 5		
1	0.137	0.365	0.002			0.504	1.51
2							
3							
4							
5							
6							

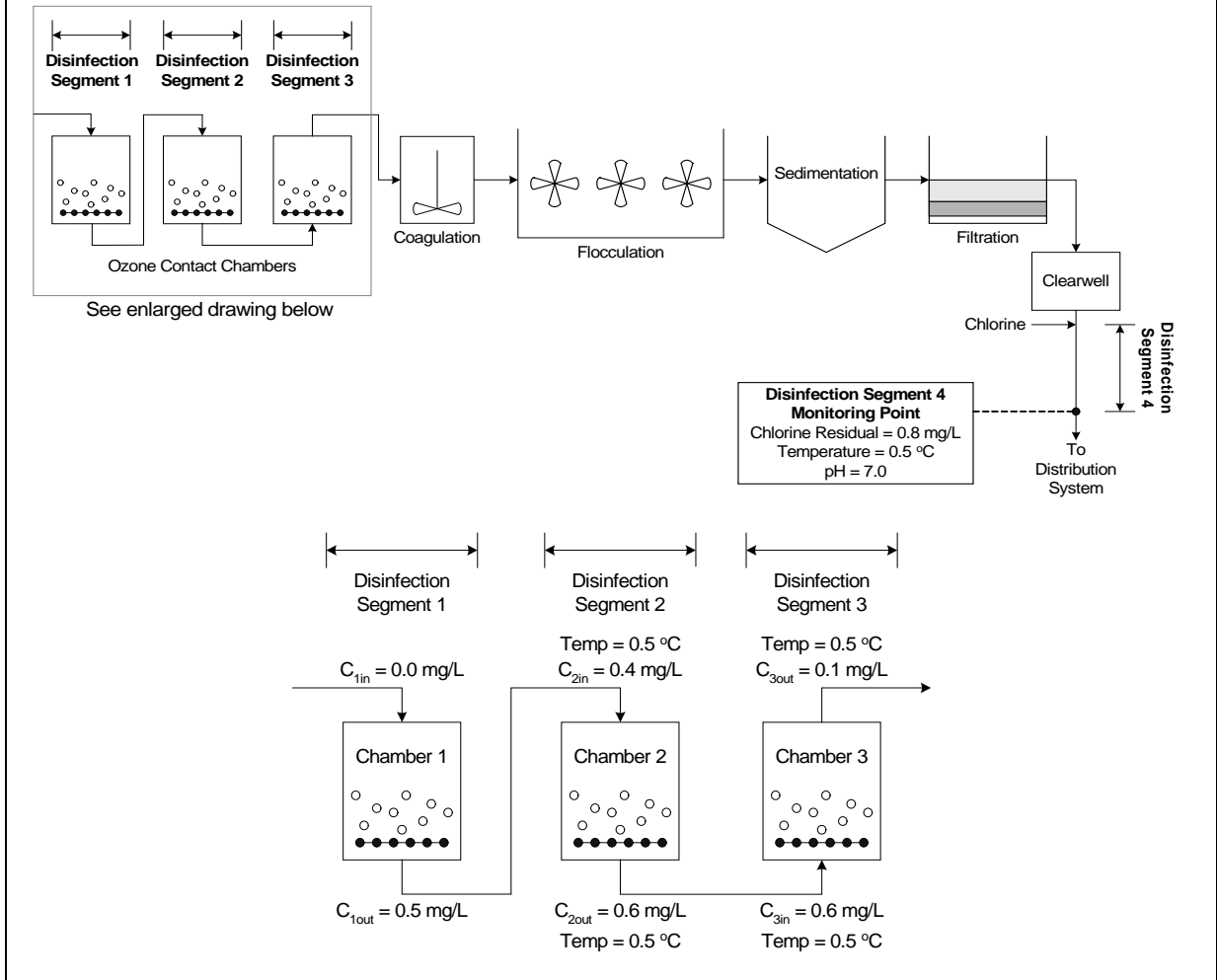
¹ *Giardia*: Log Inactivation = 3 x Sum of Inactivation Ratios

Viruses: Log Inactivation = 4 x Sum of Inactivation Ratios (or a method approved by the State)

Example D-3. Develop a Disinfection Profile and Benchmark for a PWS with Multiple Disinfection Segments

In this example, a conventional filtration treatment plant adds ozone in contact chambers at the head of the plant and injects chlorine after the clearwell for primary disinfection in the transmission pipe leaving the treatment plant (before the first customer). The ozone residual is measured at each ozone contact chamber and the chlorine residual is measured in the transmission pipe. Because ozone does not maintain a residual for any extended period of time, there is no disinfection segment for the coagulation, flocculation, sedimentation, filtration, and clearwell portions of the plant.

In the *Long Term 2 Enhanced Surface Water Treatment Rule Toolbox Guidance Manual*, April 2010, the EPA provides four methods for calculating CT in an ozone contactor: the T_{10} method, the Continuous Stirred Reactor Method (CSTR), the extended T_{10} method, and the extended CSTR method. Selecting the appropriate method(s) to use depends on the configuration of the ozone contactor, the availability of state-approved tracer testing results, and the amount of process evaluation and monitoring that a PWS wishes to undertake. Example D-3 demonstrates the T_{10} method. The T_{10} method is determined using tracer studies (see Appendix E) and is the time at which 90 percent of the water that enters the chamber will remain for at least T_{10} minutes. If no tracer study data are available for determining T_{10} , the EPA recommends using the CSTR method. The CSTR method uses the hydraulic detention time of the ozone contactor for estimating contact time. Examples for all four methods can be found in the *Long Term 2 Enhanced Surface Water Treatment Rule Toolbox Guidance Manual*, April 2010.



A. Determine the Giardia Log Inactivation for Disinfection Segment 1

Step 1. Measure the ozone residual at the inlet and outlet of Contact Chamber 1 during peak hourly flow.

For the first chamber, Chamber 1, which has a counter-current flow condition, temperature does not need to be measured as log inactivation credit is determined based on the outlet concentration.

$$C_{1in} = 0.0 \text{ mg/L}$$

$$C_{1out} = 0.5 \text{ mg/L}$$

Table D-1. Correlations to Predict C* Based on Ozone Residual Concentrations in the Outlet of a Chamber

Classification of Ozone Chamber Based on Flow Configuration				
Relative Order of Ozone Chamber	Continuous Stirred Reactor Method (CSTR) with Turbine Agitator (Uniformly Mixed Flow)	Dissolution Chamber (Co-Current Flow)	Dissolution Chamber (Counter-Current Flow)	Reactive Flow Chamber with No Ozone Addition (Plug Flow)
First Chamber	C_{out}	$C_{out} > 0.1 \text{ mg/L}$ or $> 0.3 \text{ mg/L}^{\pm}$	$C_{out} > 0.1 \text{ mg/L}$ or $> 0.3 \text{ mg/L}^{\pm}$	Not Applicable
Subsequent Chambers	C_{out}	C_{out} or $(C_{out} + C_{in}) / 2$	$C_{out} / 2$	C_{out}

[±] For inactivation of *Giardia* and viruses, if permitted by the state, PWSs can receive 0.5 log *Giardia* inactivation credit for the first dissolution chamber providing that $C_{out} > 0.3 \text{ mg/L}$ and 1-log of virus inactivation credit providing that $C_{out} > 0.1 \text{ mg/L}$ and the volume of the first chamber is equal to the volume of subsequent chambers. For *Cryptosporidium*, the EPA recommends that no inactivation credit be granted in the first chamber due to the higher CT requirements for *Cryptosporidium* compared to *Giardia* and viruses (USEPA, March 1991).

C* - Characteristic concentration (mg/L), used for CT calculation.

C_{out} - Ozone residual concentration at the outlet from the chamber.

C_{in} - Ozone residual concentration at the inlet to the chamber, which can be C_{out} of the immediate upstream chamber.

(Sources: *Long Term 2 Enhanced Surface Water Treatment Rule Toolbox Guidance Manual*, USEPA, April 2010 and *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources*, USEPA, March 1991)

Step 2. Determine the Giardia log inactivation in Contact Chamber 1.

In Contact Chamber 1, the flow is counter-current since the water flows in the opposite direction than the ozone (ozone is introduced in the bottom of the chamber and bubbles upward). According to Table D-1, the first chamber is given partial credit of **0.5 log *Giardia* inactivation** when the outlet ozone concentration is greater than 0.3 mg/L.

B. Determine the Giardia Log Inactivation for Disinfection Segment 2

Step 1. Measure the temperature and the ozone residual at the inlet and outlet of Contact Chamber 2 during peak hourly flow.

$$\text{Temperature} = 0.5^{\circ}\text{C}$$

$$C_{2in} = 0.4 \text{ mg/L}$$

$$C_{2out} = 0.6 \text{ mg/L}$$

Step 2. Determine C in Contact Chamber 2.

Table D-1. Correlations to Predict C* Based on Ozone Residual Concentrations in the Outlet of a Chamber

Classification of Ozone Chamber Based on Flow Configuration				
Relative Order of Ozone Chamber	Continuous Stirred Reactor Method (CSTR) with Turbine Agitator (Uniformly Mixed Flow)	Dissolution Chamber (Co-Current Flow)	Dissolution Chamber (Counter-Current Flow)	Reactive Flow Chamber with No Ozone Addition (Plug Flow)
First Chamber	C_{out}	$C_{out} > 0.1 \text{ mg/L}$ or $> 0.3 \text{ mg/L}^{\pm}$	$C_{out} > 0.1 \text{ mg/L}$ or $> 0.3 \text{ mg/L}^{\pm}$	Not Applicable
Subsequent Chambers	C_{out}	C_{out} or $(C_{out} + C_{in}) / 2$	$C_{out} / 2$	C_{out}

[±] For inactivation of *Giardia* and viruses, if permitted by the state, PWSs can receive 0.5 log *Giardia* inactivation credit for the first dissolution chamber providing that $C_{out} > 0.3 \text{ mg/L}$ and 1-log of virus inactivation credit providing that $C_{out} > 0.1 \text{ mg/L}$ and the volume of the first chamber is equal to the volume of subsequent chambers. For *Cryptosporidium*, the EPA recommends that no inactivation credit be granted in the first chamber due to the higher CT requirements for *Cryptosporidium* compared to *Giardia* and viruses (USEPA, March 1991).

C* - Characteristic concentration (mg/L), used for CT calculation.

C_{out} - Ozone residual concentration at the outlet from the chamber.

C_{in} - Ozone residual concentration at the inlet to the chamber, which can be C_{out} of the immediate upstream chamber.

(Sources: *Long Term 2 Enhanced Surface Water Treatment Rule Toolbox Guidance Manual*, USEPA, April 2010 and *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources*, USEPA, March 1991)

As in Contact Chamber 1, in Contact Chamber 2 the flow is counter-current since the water flows in the opposite direction that the ozone flows. According to Table D-1, $C = C_{out} / 2$ for subsequent contact chambers with counter-current flow.

$$C = C_{2out} / 2$$

$$C = 0.6 \text{ mg/L} / 2$$

$$C = \mathbf{0.3 \text{ mg/L}}$$

Step 3. Determine the contact time in Contact Chamber 2.

The contact time for all of the ozone contact chambers taken together was determined by a tracer study to be 15 minutes at peak hourly flow. The total contact time can be divided proportionally by volume between all three chambers if the chambers with final concentrations of zero (non-detectable) do not make up 50% or greater of the total volume of the chambers. Since the final concentration in all chambers is greater than zero and since the contact chambers all have equal volumes, the contact time can be divided equally between all three chambers:

$$T = T_{tot} / 3 \text{ chambers} = 15 \text{ min} / 3 \text{ chambers} = \mathbf{5 \text{ minutes per chamber}}$$

Step 4. Calculate CT_{calc} in Contact Chamber 2.

$$CT_{calc} = C \times T$$
$$CT_{calc} = 0.3 \text{ mg/L} \times 5 \text{ min}$$
$$CT_{calc} = \mathbf{1.5 \text{ min-mg/L}}$$

Step 5. Locate appropriate CT table.

The table for 3-log inactivation of *Giardia* by ozone is Table B-5 in Appendix B.

Step 6. Identify the appropriate portion of the table based on operating conditions.

Locate the column for 0.5°C ($\leq 1^\circ\text{C}$).

Table B-5
CT Values for 3-Log Inactivation of *Giardia* Cysts by Ozone

Temperature (°C)					
≤ 1	5	10	15	20	25
2.9	1.90	1.43	0.95	0.72	0.48

Step 7. Obtain $CT_{99.9}$ value.

From this chart it is determined that the value of CT for 3-log inactivation by ozone at 0.5°C is 2.9 min-mg/L.

$$CT_{99.9} = 2.9 \text{ min-mg/L}$$

Step 8. Calculate the *Giardia* inactivation ratio for Disinfection Segment 2.

$$\text{Inactivation ratio} = CT_{calc} / CT_{99.9}$$
$$\text{Inactivation ratio} = (1.5 \text{ min-mg/L} / 2.9 \text{ min-mg/L})$$
$$\mathbf{\text{Inactivation ratio} = 0.517}$$

Step 9. Calculate *Giardia* inactivation for Disinfection Segment 2.

$$\text{Giardia log inactivation} = 3 \times (CT_{calc} / CT_{99.9})$$
$$\text{Giardia log inactivation} = 3 \times 0.517$$
$$\mathbf{\text{Giardia log inactivation} = 1.55}$$

C. Determine the *Giardia* Log Inactivation for Disinfection Segment 3

Step 1. Measure the temperature and the ozone residual at the inlet and outlet of Contact Chamber 3 during peak hourly flow.

Temperature = 0.5°C

C_{3in} = 0.6 mg/L

C_{3out} = 0.1 mg/L

Step 2. Determine C in Contact Chamber 3.

Table D-1. Correlations to Predict C* Based on Ozone Residual Concentrations in the Outlet of a Chamber

Classification of Ozone Chamber Based on Flow Configuration				
Relative Order of Ozone Chamber	Continuous Stirred Reactor Method (CSTR) with Turbine Agitator (Uniformly Mixed Flow)	Dissolution Chamber (Co-Current Flow)	Dissolution Chamber (Counter-Current Flow)	Reactive Flow Chamber with No Ozone Addition (Plug Flow)
First Chamber	C _{out}	C _{out} > 0.1 mg/L or > 0.3 mg/L [±]	C _{out} > 0.1 mg/L or > 0.3 mg/L [±]	Not Applicable
Subsequent Chambers	C _{out}	C _{out} or (C _{out} + C _{in}) / 2	C _{out} / 2	C _{out}

[±] For inactivation of *Giardia* and viruses, if permitted by the state, PWSs can receive 0.5 log *Giardia* inactivation credit for the first dissolution chamber providing that C_{out} > 0.3 mg/L and 1-log of virus inactivation credit providing that C_{out} > 0.1 mg/L and the volume of the first chamber is equal to the volume of subsequent chambers. For *Cryptosporidium*, the EPA recommends that no inactivation credit be granted in the first chamber due to the higher CT requirements for *Cryptosporidium* compared to *Giardia* and viruses (USEPA, March 1991).

C* - Characteristic concentration (mg/L), used for CT calculation.

C_{out} - Ozone residual concentration at the outlet from the chamber.

C_{in} - Ozone residual concentration at the inlet to the chamber, which can be C_{out} of the immediate upstream chamber.

(Sources: *Long Term 2 Enhanced Surface Water Treatment Rule Toolbox Guidance Manual*, USEPA, April 2010 and *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources*, USEPA, March 1991)

In Contact Chamber 3, the flow is co-current since the water flows in the same direction that the ozone flows (see directional arrows in the diagram above). According to Table D-1, C = (C_{out} + C_{in}) / 2 for contact chambers with co-current flow.

$$C = (C_{3in} + C_{3out}) / 2$$

$$C = (0.6 \text{ mg/L} + 0.1 \text{ mg/L}) / 2$$

$$C = 0.35 \text{ mg/L}$$

Step 3. Determine the contact time in Contact Chamber 3.

It was determined in Part B, Step 3 of this example that the contact time in each chamber is 5 minutes.

$$T = 5 \text{ minutes}$$

Step 4. Calculate CT_{calc} in Contact Chamber 3.

$$CT_{calc} = C \times T$$

$$CT_{calc} = 0.35 \text{ mg/L} \times 5 \text{ min}$$

$$CT_{calc} = \mathbf{1.75 \text{ min-mg/L}}$$

Step 5. Locate appropriate CT table.

The table for 3-log inactivation of *Giardia* by ozone is Table B-5 in Appendix B.

Step 6. Identify the appropriate portion of the table based on operating conditions.

Locate the column for 0.5°C ($\leq 1^\circ\text{C}$).

Table B-5
CT Values for 3-Log Inactivation of *Giardia* Cysts by Ozone

Temperature (°C)					
≤ 1	5	10	15	20	25
2.9	1.90	1.43	0.95	0.72	0.48

Step 7. Obtain $CT_{99,9}$ value.

From this chart it is determined that the value of CT for 3-log inactivation by ozone at 0.5°C is 2.9 min-mg/L.

$$CT_{99,9} = 2.9 \text{ min-mg/L}$$

Step 8. Calculate the *Giardia* inactivation ratio for Disinfection Segment 3.

$$\text{Inactivation ratio} = CT_{calc} / CT_{99,9}$$

$$\text{Inactivation ratio} = (1.75 \text{ min-mg/L} / 2.9 \text{ min-mg/L})$$

$$\mathbf{\text{Inactivation ratio} = 0.603}$$

Step 9. Calculate *Giardia* inactivation for Disinfection Segment 3.

$$\text{Giardia log inactivation} = 3 \times (CT_{calc} / CT_{99,9})$$

$$\text{Giardia log inactivation} = 3 \times 0.603$$

$$\mathbf{\text{Giardia log inactivation} = 1.81}$$

D. Determine Giardia Log Inactivation for Disinfection Segment 4

Step 1. Determine the peak hourly flow.

From the raw water pump records the peak hourly flow (Q) is determined to be 5,000 gpm.

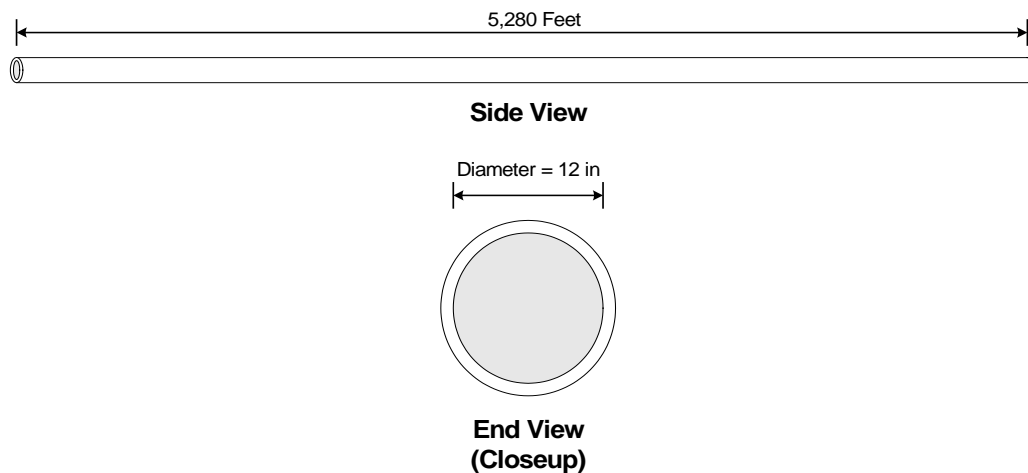
Step 2. Measure chlorine residual, temperature, and pH during peak hourly flow at the chlorine monitoring point located prior to the first customer in the distribution system.

Temperature = 0.5°C

pH = 7.0

Chlorine residual = C_{chlorine} = 0.8 mg/L

Step 3. Measure the physical dimensions of the pipe.



Measure the length of the pipe from the chlorine addition point to the chlorine monitoring point located prior to the first customer in the distribution system. Measure the inner pipe diameter to obtain the volume of water in the pipe rather than the volume of the pipe itself.

Diameter = 12 in x (1 ft / 12 in) = 1.0 ft

Length = 5,280 ft

Step 4. Calculate the volume of the water in the pipe.

Volume (V) = $\pi \times \text{Radius}^2 \times \text{Length}$

π = 3.14 (constant)

Radius = Diameter / 2 = 1.0 / 2 = 0.5 ft

$V = 3.14 \times (0.5 \text{ ft})^2 \times 5,280 \text{ ft} = 4,140 \text{ ft}^3$

$V = 4,140 \text{ ft}^3 \times (7.48 \text{ gal} / \text{ft}^3)$

$V = 31,000 \text{ gallons}$

Step 5. Calculate the Theoretical Detention Time in the pipe.

$$\begin{aligned} \text{Theoretical Detention Time (TDT)} &= V / Q \\ \text{TDT} &= 31,000 \text{ gal} / 5,000 \text{ gpm} \\ \text{TDT} &= 6.2 \text{ minutes} \end{aligned}$$

Step 6. Determine the baffling factor for the pipe.

$$\text{Baffling Factor (BF)} = 1.0 \text{ (from Table G-1 in Appendix G for a pipe)}$$

Step 7. Calculate the contact time of the disinfectant in the pipe.

$$\begin{aligned} \text{Contact Time (T)} &= \text{TDT} \times \text{BF} \\ T &= 6.2 \text{ min} \times 1.0 \\ T &= \mathbf{6.2 \text{ minutes}} \end{aligned}$$

Step 8. Calculate the CT for the disinfection segment.

$$\begin{aligned} \text{CT}_{\text{calc}} &= C_{\text{chlorine}} \times T \\ \text{CT}_{\text{calc}} &= 0.8 \text{ mg/L} \times 6.2 \text{ min} \\ \text{CT}_{\text{calc}} &= \mathbf{5.0 \text{ min-mg/L}} \end{aligned}$$

Step 9. Determine the required $CT_{99.9}$ necessary to obtain 3-log *Giardia* inactivation.

The required CT value for 3-log *Giardia* inactivation ($CT_{99.9}$) is obtained by using CT Table B-1 in Appendix B, CT Values for 3-Log Inactivation of *Giardia* Cysts by Free Chlorine. The $CT_{99.9}$ is 205 min-mg/L for a pH of 7.0, temperature of 0.5°C, and C_{chlorine} of 0.8 mg/L. The relevant section of Table B-1 is reprinted below and the pertinent section of the table is highlighted.

Excerpt from Table B-1

CT Values for 3-Log Inactivation of *Giardia* Cysts by Free Chlorine (0.5°C portion of table, for concentrations from 0.4 to 1.2 mg/L)

Chlorine Concentration (mg/L)	Temperature = 0.5°C						
	pH						
	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0
<=0.4	137	163	195	237	277	329	390
0.6	141	169	200	239	286	342	407
0.8	145	172	205	246	295	354	422
1.0	148	176	210	253	304	365	437
1.2	152	180	215	259	313	376	451

Step 10. Calculate the Giardia inactivation ratio for the pipe.

$$\begin{aligned}\text{Inactivation ratio} &= \text{CT}_{\text{calc}} / \text{CT}_{99.9} \\ \text{Inactivation ratio} &= (5.0 \text{ min-mg/L} / 205 \text{ min-mg/L}) \\ \text{Inactivation ratio} &= \mathbf{0.024}\end{aligned}$$

Step 11. Calculate the Giardia log inactivation for the pipe.

$$\begin{aligned}\text{Log inactivation} &= 3 \times \text{CT}_{\text{calc}} / \text{CT}_{99.9} \\ \text{Log inactivation} &= 3 \times 0.024 \\ \text{Log inactivation} &= \mathbf{0.07}\end{aligned}$$

The log inactivation of *Giardia* for Disinfection Segment 4 is 0.07.

E. Calculate the Total Giardia Inactivation for All Disinfection Segments

Step 1. Sum the Giardia log inactivation credits for all of the disinfection segments to determine the total Giardia log inactivation achieved.

From Disinfection Segment 1:
Giardia log inactivation = 0.50

From Disinfection Segment 2:
Giardia log inactivation = 1.55

From Disinfection Segment 3:
Giardia log inactivation = 1.81

From Disinfection Segment 4:
Giardia log inactivation = 0.07

$$\text{Total } \mathbf{Giardia \text{ log inactivation} = 0.50 + 1.55 + 1.81 + 0.07 = 3.93}$$

Assuming the PWS received a 2.5 log *Giardia* removal credit from the state for conventional filtration, it must achieve at least 0.5 log *Giardia* inactivation for a total 3.0 log *Giardia* removal and/or inactivation as required in the Surface Water Treatment Rule (40 CFR Section 141.70(a)(1)). The value of 3.93 log *Giardia* inactivation exceeds the required 0.5 log *Giardia* inactivation.

F. Determine Virus Log Inactivation for Disinfection Segment 1

Step 1. Determine the virus log inactivation in Contact Chamber 1.

Table D-1. Correlations to Predict C* Based on Ozone Residual Concentrations in the Outlet of a Chamber

Classification of Ozone Chamber Based on Flow Configuration				
Relative Order of Ozone Chamber	Continuous Stirred Reactor Method (CSTR) with Turbine Agitator (Uniformly Mixed Flow)	Dissolution Chamber (Co-Current Flow)	Dissolution Chamber (Counter-Current Flow)	Reactive Flow Chamber with No Ozone Addition (Plug Flow)
First Chamber	C_{out}	$C_{out} > 0.1 \text{ mg/L}$ or $> 0.3 \text{ mg/L}^{\pm}$	$C_{out} > 0.1 \text{ mg/L}$ or $> 0.3 \text{ mg/L}^{\pm}$	Not Applicable
Subsequent Chambers	C_{out}	C_{out} or $(C_{out} + C_{in}) / 2$	$C_{out} / 2$	C_{out}

[±] For inactivation of *Giardia* and viruses, if permitted by the state, PWSs can receive 0.5 log *Giardia* inactivation credit for the first dissolution chamber providing that $C_{out} > 0.3 \text{ mg/L}$ and 1-log of virus inactivation credit providing that $C_{out} > 0.1 \text{ mg/L}$ and the volume of the first chamber is equal to the volume of subsequent chambers. For *Cryptosporidium*, the EPA recommends that no inactivation credit be granted in the first chamber due to the higher CT requirements for *Cryptosporidium* compared to *Giardia* and viruses (USEPA, March 1991).

C* - Characteristic concentration (mg/L), used for CT calculation.

C_{out} - Ozone residual concentration at the outlet from the chamber.

C_{in} - Ozone residual concentration at the inlet to the chamber, which can be C_{out} of the immediate upstream chamber.

(Sources: *Long Term 2 Enhanced Surface Water Treatment Rule Toolbox Guidance Manual*, USEPA, April 2010 and *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources*, USEPA, March 1991)

In Contact Chamber 1, the flow is counter-current since the water flows in the opposite direction than the ozone (ozone is introduced in the bottom of the chamber and bubbles upward). According to Table D-1, the first chamber is given partial credit of **1 virus log inactivation** when the outlet ozone concentration is greater than 0.1 mg/L.

G. Determine Virus Log Inactivation for Disinfection Segment 2

Step 1. Determine the required $CT_{99.99}$ necessary to obtain 4-log virus inactivation for Contact Chamber 2.

The required CT value for 4-log virus inactivation ($CT_{99.99}$) is obtained by using CT Table B-6 in Appendix B, CT Values for 4-Log Inactivation of Viruses by Ozone. In this example the required $CT_{99.99}$ is 1.8 min-mg/L for a temperature of 0.5°C.

Table B-6

CT Values for 4-Log Inactivation of Viruses by Ozone

Temperature (°C)					
< = 1	5	10	15	20	25
1.8	1.2	1.0	0.6	0.5	0.3

Step 2. Calculate the virus inactivation ratio for Contact Chamber 2.

CT_{calc} has already been calculated for Disinfection Segment 2.

$$CT_{calc} = 1.5 \text{ min-mg/L}$$

$$\text{Inactivation ratio} = CT_{calc} / CT_{99.9}$$

$$\text{Inactivation ratio} = (1.5 \text{ min-mg/L} / 1.8 \text{ min-mg/L})$$

$$\text{Inactivation ratio} = \mathbf{0.833}$$

Step 3. Calculate the virus inactivation for Contact Chamber 2.

$$\text{Virus log inactivation} = 4 \times CT_{calc} / CT_{99.99}$$

$$\text{Virus log inactivation} = 4 \times 0.833$$

$$\text{Virus log inactivation} = \mathbf{3.3}$$

The log inactivation of viruses for Disinfection Segment 2 is 3.3.

H. Determine Virus Log Inactivation for Disinfection Segment 3

Step 1. Determine the required CT_{99.99} necessary to obtain 4-log virus inactivation for Contact Chamber 3.

The required CT value for 4-log virus inactivation (CT_{99.99}) is obtained by using CT Table B-6 in Appendix B, CT Values for 4-Log Inactivation of Viruses by Ozone. The required CT_{99.99} is 1.8 min-mg/L for a temperature of 0.5°C.

Table B-6

CT Values for 4-Log Inactivation of Viruses by Ozone

Temperature (°C)					
< = 1	5	10	15	20	25
1.8	1.2	1.0	0.6	0.5	0.3

Step 2. Calculate the virus inactivation ratio for Contact Chamber 3.

CT_{calc} has already been calculated for Disinfection Segment 3.

$$CT_{calc} = 1.75 \text{ min-mg/L}$$

$$\text{Inactivation ratio} = CT_{calc} / CT_{99.9}$$

$$\text{Inactivation ratio} = (1.75 \text{ min-mg/L} / 1.8 \text{ min-mg/L})$$

$$\text{Inactivation ratio} = \mathbf{0.972}$$

Step 3. Calculate the virus log inactivation for Disinfection Segment 4.

$$\text{Log inactivation} = 4 \times \text{CT}_{\text{calc}} / \text{CT}_{99.99}$$

$$\text{Log inactivation} = 4 \times 0.417$$

$$\text{Log inactivation} = 1.7$$

J. Calculate the Total Virus Inactivation for All Disinfection Segments

Step 1. Sum the virus log inactivations for all of the disinfection segments to determine the total virus log inactivation achieved.

From Disinfection Segment 1:
virus log inactivation = 1.0

From Disinfection Segment 2:
virus log inactivation = 3.3

From Disinfection Segment 3:
virus log inactivation = 3.9

From Disinfection Segment 4:
virus log inactivation = 1.7

$$\text{Total virus log inactivation} = 1.0 + 3.3 + 3.9 + 1.7 = 9.9$$

Assuming the PWS received a 2.0 log virus removal credit from the state for conventional filtration, it must achieve at least 2.0 log virus inactivation for a total 4.0 log virus removal and/or inactivation as required in the Surface Water Treatment Rule (40 CFR Section 141.70(a)(2)). The value of 9.9 log virus inactivation exceeds the required 2.0 log virus inactivation.

References

USEPA. March 1991. *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water*. Washington, D.C.

USEPA. April 2010. *Long Term 2 Enhanced Surface Water Treatment Rule Toolbox Guidance Manual*. Washington, D.C.

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Appendix E — Tracer Studies

E.1 Introduction

Information in this appendix is based on Appendix C in the *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources* (USEPA, 1991). For more information on tracer studies, readers are encouraged to consult Appendix C in the *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources* (USEPA, 1991) or *Tracer Studies in Water Treatment Facilities: A Protocol and Case Studies* (Teefy, 1996).

As indicated in Chapter 4, fluid passing through a pipe is assumed to have a detention time equal to the theoretical or mean residence time at a particular flow rate. However, in mixing basins, storage reservoirs, and other treatment plant process units, utilities may be required to determine the contact time for the calculation of CT through tracer studies or other methods approved by the state.

The contact time of mixing basins and storage reservoirs used in calculating CT should be the minimum detention time experienced by 90 percent of the water passing through the unit. This detention time was designated as T_{10} according to the convention adopted by Thirumurthi (1969). A profile of the flow through the basin over time can be generated by tracer studies. Information provided by these studies may be used for estimating the detention time, T_{10} , for the purpose of calculating CT. **(Note: T_{10} is referred to as “T” elsewhere in this document. However, for consistency with the *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources* (USEPA, 1991), T_{10} is used in this appendix.)**

This appendix presents a brief synopsis of tracer study methods, procedures, and data evaluation. More detailed information about conducting tracer studies is available in Appendix C of the *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources* (USEPA, 1991). It is important to obtain assistance from the state before conducting a tracer study to ensure state approval of the results.

E.2 Flow Evaluation

Although detention time is proportional to flow, it is not generally a linear function. Tracer studies may establish detention times for the range of flow rates experienced within each disinfectant segment. PWSs should note that a single flow rate might not characterize the flow through the entire PWS. With a series of reservoirs, clearwells, and storage tanks, flow will vary between each portion of the PWS.

Ideally, tracer tests should be performed for at least four flow rates that span the entire range of flow for the segment being tested. The flow rates should be separated by approximately equal intervals to span the range of operation, with one near average flow, two greater than average, and one less than average flow. The flows should also be selected so that the highest test flow rate is at least 91 percent of the highest flow rate expected to ever occur in that segment. Four data points should assure a good definition of the segment’s hydraulic profile.

The results of the tracer tests performed for different flow rates should be used to generate plots of T_{10} versus flow (Q) for each segment. A smooth line is drawn through the points on each graph to create a curve from which T_{10} may be read for the corresponding flow at peak hourly flow conditions. Refer to Appendix C, section C.1.7 of the *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources* (USEPA, 1991), for an illustration of this procedure.

The most accurate tracer test results are obtained when flow is constant through the segment during the course of the test. Therefore, the tracer study should be conducted at a constant flow whenever practical. For a treatment plant consisting of two or more equivalent process trains, a constant flow tracer test can be performed on a segment of the plant by holding the flow through one of the trains constant while operating the parallel train(s) to absorb any flow variations. Flow variations during tracer tests in treatment systems without parallel trains or with single clearwells and storage reservoirs are more difficult to avoid. In these instances, T_{10} should be recorded at the average flow rate over the course of the test.

E.3 Volume Evaluation

In addition to flow conditions, detention times determined by tracer studies depend on the water level and subsequent volume in treatment units. This is particularly pertinent to storage tanks, reservoirs, and clearwells, which, in addition to being contact basins for disinfection are also often used as equalization storage for distribution system demands and storage for backwashing. For these treatment units, the water levels in the reservoirs vary to meet the PWS demands. The actual detention time of these contact basins will also vary depending on whether they are emptying or filling.

For some process units, especially sedimentation basins that are operated at a near constant level (that is, flow in equals flow out), the detention time determined by tracer tests should be sufficient for calculating CT when the basin is operating at water levels greater than or equal to the level at which the test was performed. When conducting a tracer study to determine the detention time, a water level at or slightly below, but not above, the normal minimum operating level is recommended. For many plants, the water level in a clearwell or storage tank varies between high and low levels in response to distribution system demands. In such instances, in order to obtain a conservative estimate of the contact time, the tracer study should be conducted during a period when the tank level is falling (flow out greater than flow in).

E.4 Disinfection Segments

For PWSs that apply disinfectant(s) at more than one point or choose to profile the residual from one point of application, tracer studies should be conducted to determine T_{10} for each segment containing process unit(s). The T_{10} for a segment is used along with the residual disinfectant concentration prior to the next disinfectant application or monitoring point to determine the CT_{calc} for that segment. The inactivation ratio for the section is then determined. The total log inactivation achieved with all disinfection segments can then be determined by summing the inactivation ratios for all sections as explained in Chapter 5 of this document.

For PWSs that have two or more units of identical size and configuration, tracer studies could be conducted on one of the units but applied to both. The resulting graph of T_{10} versus flow can be used to determine T_{10} for all identical units.

PWSs with more than one segment in the treatment plant that are conducting a tracer study may determine T_{10} for each segment:

- By individual tracer studies through each segment.
- By one tracer study across the treatment system.

If possible, tracer studies should be conducted on each segment to determine the T_{10} for each segment. In order to minimize the time needed to conduct studies on each segment, the tracer studies should be started at the last segment of the treatment train prior to the first customer and completed with the first segment. Conducting the tracer studies in this order will prevent the interference of residual tracer material with subsequent studies.

For ozone contactors, flocculators, or any basin containing mixing, tracer studies should be conducted for the range of mixing used in the process. In ozone contactors, air or oxygen should be added in lieu of ozone to prevent degradation of the tracer. The flow rate of air or oxygen used for the contactor should be applied during the study to simulate actual operation. Tracer studies should then be conducted at several air/oxygen to water ratios to provide data for the complete range of ratios used at the plant. For flocculators, tracer studies should be conducted for various mixing intensities to provide data for the complete range of operations.

E.5 Tracer Study Methods

This section discusses the two most common methods of tracer addition employed in water treatment evaluations, the step-dose method, and the slug-dose method. Tracer study methods involve the application of chemical dosages and tracking the resulting effluent concentration as a function of time. The effluent concentration profile is evaluated to determine the detention time, T_{10} .

In preparation for beginning a tracer study, the raw water background concentration of the chosen tracer chemical should be established. The background concentration is important, not only to aid in the selection of the tracer dosage, but also to facilitate proper evaluation of the data.

The background tracer concentration should be determined by monitoring for the tracer chemical prior to beginning the test. The sampling point(s) for the pre-tracer study monitoring should be the same as the points to be used for residual monitoring to determine CT values. PWSs should use the following monitoring procedure:

- Prior to the start of the test, regardless of whether the chosen tracer material is a treatment chemical, the tracer concentration in the water is monitored at the sampling point where the disinfectant residual will be measured for CT calculations.
- If a background tracer concentration is detected, monitor it until a constant concentration, at or below the raw water background level, is achieved. This measured concentration is the baseline tracer concentration.

Following the determination of the tracer dosage, feed and monitoring point(s), and a baseline tracer concentration, tracer testing can begin.

Equal sampling intervals, as could be obtained from automatic sampling, are not required for either tracer study method. However, using equal sample intervals for the slug-dose method can simplify the analysis

of the data. During testing, the time and tracer residual of each measurement should also be recorded on a data sheet. In addition, the water level, flow, and temperature should be recorded during the test.

E.5.1 Step-Dose Method

The step-dose method entails introduction of a tracer chemical at a constant dosage until the concentration at the desired end point reaches a steady-state level. At time zero, the tracer chemical feed is started and left at a constant rate for the duration of the test. Over the course of the test, the tracer residual should be monitored at the required sampling point(s) at a frequency determined by the overall detention time and site-specific considerations. As a general guideline, sampling at intervals of 2 to 5 minutes should provide data for a well-defined plot of tracer concentration versus time. If on-site analysis is available, less frequent residual monitoring may be possible until a change in residual concentration is first detected. Regular sampling is continued until the residual concentration reaches a steady-state value.

One graphical method of evaluating step-dose test data involves plotting a graph of dimensionless concentration (tracer concentration (C) / applied tracer concentration (C_o)) versus time and reading the value for T₁₀ directly from the graph at the appropriate dimensionless concentration. Alternatively, the data from step-dose tracer studies may be evaluated numerically by developing a semi-logarithmic plot of the dimensionless data. The semi-logarithmic plot allows a straight line to be drawn through the data. The resulting equation of the line is used to calculate the T₁₀ value, assuming that the correlation coefficient indicates a good statistical fit (0.9 or above). Drawing a smooth curve through the data discredits scattered data points from step-dose tracer tests.

Step-dose tracer studies are frequently employed in drinking water applications for the following reasons:

- The resulting normalized concentration versus time profile is directly used to determine T₁₀, the detention time required for calculating CT; and,
- Very often, the necessary feed equipment is available to provide a constant rate of application of the tracer chemical.

One other advantage of the step-dose method is that the data may be verified by comparing the concentration versus elapsed time profile for samples collected at the start of dosing with the profile obtained when the tracer feed is discontinued.

E.5.2 Slug-Dose Method

In the slug-dose method, a large instantaneous dose of tracer is added to the incoming water and samples are taken at the exit of the unit over time as the tracer passes through the unit. At time zero for the slug-dose method, the dose of tracer is added to the influent of the unit. The same sampling locations and frequencies described for step-dose method tests also apply to slug-dose method tracer studies. One exception for this method is that the tracer concentration profile will not equilibrate to a steady-state concentration. Because of this, the tracer should be monitored frequently enough to ensure acquisition of data needed to identify the peak tracer concentration.

Slug-dose method tests should be checked by performing a material balance to ensure that all tracer that was fed is recovered. In other words, mass applied equals mass discharged.

Data from slug-dose tracer tests may be analyzed by converting it to the mathematically equivalent of step-dose data and using the techniques discussed above for the step-dose method to determine T_{10} . A graph of dimensionless concentration versus time should be drawn which represents the results of a slug-dose tracer test. The key to converting between the data forms is obtaining the total area under the slug-dose data curve. This area is found by integrating the curve graphically or numerically. The conversion to step-dose data is then completed in several mathematical steps involving the total area.

Slug-dose concentration profiles can have many shapes, depending on the hydraulics of the basin. Therefore, slug-dose data points should not be discredited by drawing a smooth curve through the data prior to its conversion to step-dose data.

A disadvantage of the slug-dose method is that very concentrated solutions are needed for the dose in order to adequately define the concentration versus time profile. Intensive mixing is therefore necessary to minimize potential density-current effects and to obtain a uniform distribution of the instantaneous tracer dose across the basin. This is inherently difficult under water flow conditions often existing at inlets to basins. Other disadvantages of using the slug-dose method include:

- The concentration and volume of the instantaneous tracer dose needs to be carefully computed to provide an adequate tracer profile at the effluent of the basin;
- The resulting concentration versus time profile should not be used to directly determine T_{10} without further manipulation; and,
- A mass balance on the treatment segment should be used to determine whether the tracer was completely recovered.

One advantage of this method is that it may be applied where chemical feed equipment is not available at the desired point of addition, or where the equipment available does not have the capacity to provide the necessary concentration of the chosen tracer chemical. Although, in general, the step-dose procedure offers the greatest simplicity, both methods are theoretically equivalent for determining T_{10} . Either method or another method may be used for conducting drinking water tracer studies, and the choice of method may be determined by site-specific constraints or the PWS's experience.

E.6 Tracer Selection

An important step in any tracer study is the selection of a chemical to be used as the tracer. Ideally, the selected tracer chemical should be readily available, conservative (that is, not consumed or removed during treatment), easily monitored, and acceptable for use in potable water supplies. Chloride and fluoride are nontoxic and approved for potable water use and are typically the most common tracer chemicals employed in drinking water plants. Rhodamine WT can be used as a fluorescent tracer in water flow studies in accordance with the following guidelines:

- Raw water concentrations should be limited to a maximum concentration of 10 mg/L;
- Drinking water concentrations should not exceed 0.1 $\mu\text{g/L}$;
- Studies that result in human exposure to the dye should be brief and infrequent; and,
- Concentrations as low as 2 $\mu\text{g/L}$ can be used in tracer studies because of the low detection level in the range of 0.1 to 0.2 $\mu\text{g/L}$.

The use of Rhodamine B as a tracer in water flow studies is not recommended by the EPA.

The choice of a tracer chemical can be made based, in part, on the selected dosing method and on the availability of chemical feeding equipment. For example, the high density of concentrated salt solutions and their potential for inducing density currents usually precludes chloride and fluoride as the selected chemical for slug-dose tracer tests.

Fluoride can be a convenient tracer chemical for step-dose tracer tests of clearwells because it is frequently applied for finished water treatment. However, when fluoride is used in tracer tests on clarifiers, allowances should be made for fluoride that is absorbed on floc and settles out of water (Hudson, 1975). Additional considerations when using fluoride in tracer studies include:

- It is difficult to detect at low levels.
- Many states impose a finished water limitation of 1 mg/L.
- The federal secondary and primary drinking water standards (i.e., the Secondary Maximum Contaminant Level (SMCL) and MCL) for fluoride are 2 and 4 mg/L, respectively).

For safety reasons, particularly for people on dialysis, fluoride is not recommended for use as a tracer in PWSs that normally do not fluoridate their water. The use of fluoride is only recommended in cases where the feed equipment is already in place. The PWS may wish to turn off the fluoride feed in the plant for 12 or more hours prior to beginning the fluoride feed for the tracer study. Flushing out fluoride residuals prior to conducting the tracer study is recommended to reduce background levels and avoid spiked levels of fluoride that might exceed the EPA's MCL or SMCL for fluoride in drinking water. In instances where only one of two or more parallel units is tested, flow from the other units would dilute the tracer concentration prior to leaving the plant and entering the distribution system. Therefore, the impact of drinking water standards on the use of fluoride and other tracer chemicals can be alleviated in some cases.

E.7 References

Hudson, H.E., Jr. 1975. Residence Times in Pretreatment. *Journal AWWA*, 67(1): 45-52.

Teefy, Susan. 1996. *Tracer Studies in Water Treatment Facilities: A Protocol and Case Studies*. American Water Works Association Research Foundation. Denver, CO.

Thirumurthi, D. 1969. "A Breakthrough in the Tracer Studies of Sedimentation Tanks." *J. WPCF*. R405-R418.

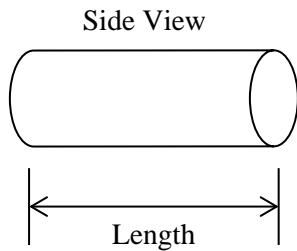
USEPA. March 1991. *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems using Surface Water Sources*. Washington, D.C.

Appendix F — Calculating the Volume of Each Sub-Unit

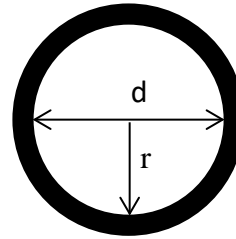
Note: If dimensions are in feet and the volume is calculated in cubic feet, then the volume should be converted to gallons by using the conversion: $1 \text{ ft}^3 = 7.48 \text{ gal}$.

Water Pipe (raw or treated):

Fluid Volume = Length x Cross-Sectional Area (Assumes full-pipe flow)



Cross-Section View

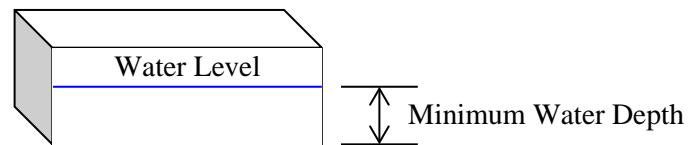
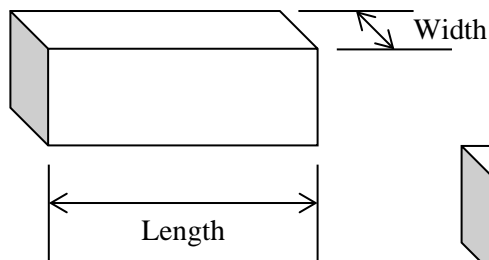


Rectangular Basin:

Fluid Volume = Length x Width x
Minimum Water Depth

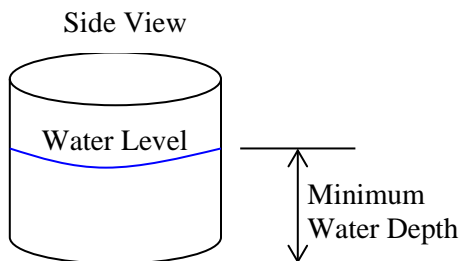
Cross-Sectional Area = $3.1416 \times r^2$

$r = \text{inner radius} = d / 2$

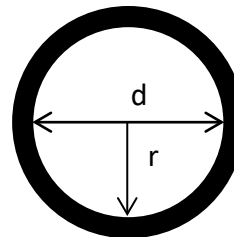


Cylindrical Basin:

Fluid Volume = Minimum Water Depth x Cross-Sectional Area



Top View

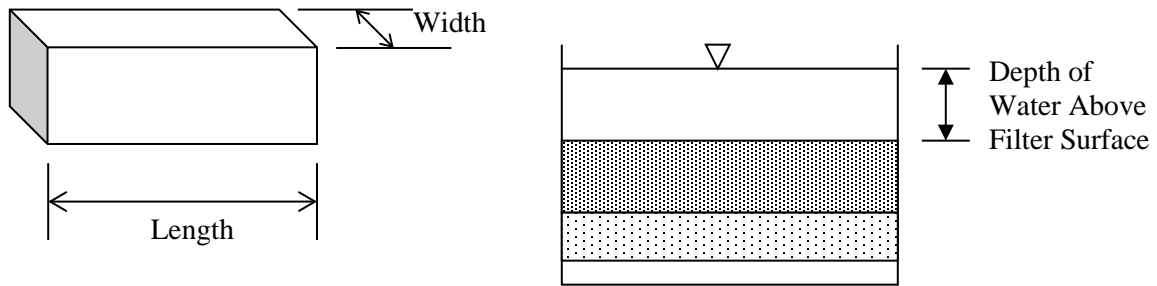


Cross-Sectional Area = $3.1416 \times r^2$

$r = \text{inner radius} = d / 2$

Filters:

Fluid Volume = Volume of Water Above Filter Surface
= Length x Width x Depth of Water Above Filter Surface



Note: Some states may give credit for volume in media. Check with the state for the appropriate method to use for calculating volume in media.

Appendix G — Baffling Factors

G.1 Introduction

Information in this appendix is based on Appendix C in the *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources* (USEPA, 1991). References to the main body of the report, section headers, and some terminology have been modified to better relate to the content of this Disinfection Profiling and Benchmarking Technical Guidance Manual. **(Note: T_{10} is referred to as “T” elsewhere in this document. However, for consistency with the *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources* (USEPA, 1991), T_{10} is used in this appendix and when discussing ozone.)**

In some situations, conducting tracer studies for determining the disinfectant contact time, T_{10} , may be impractical or prohibitively expensive. The limitations may include a lack of funds, personnel, or equipment necessary to conduct the study. States may allow the use of “rule of thumb” fractions representing the ratio of T_{10} to T , and the theoretical detention time (TDT), to determine the detention time, T_{10} , to be used for calculating CT values. This method for determining T_{10} involves multiplying the TDT by the rule of thumb fraction, T_{10}/T , which is representative of the particular basin configuration for which T_{10} is desired. These fractions provide rough estimates of the actual T_{10} and PWSs should coordinate with their state when selecting a baffling factor.

Tracer studies conducted by Marske and Boyle (1973) and Hudson (1975) on chlorine contact chambers and flocculators/settling basins, respectively, were used as a basis in determining representative T_{10}/T values for various basin configurations. Marske and Boyle (1973) performed tracer studies on 15 distinctly different types of full-scale chlorine contact chambers to evaluate design characteristics that affect the actual detention time. Hudson (1975) conducted 16 tracer tests on several flocculation and settling basins at six water treatment plants to identify the effect of flocculator baffling and settling basin inlet and outlet design characteristics on the actual detention time.

G.2 Impact of Design Characteristics

The significant design characteristics for assigning a baffling factor include length-to-width ratio, the degree of baffling within the basins and the effect of inlet baffling and outlet weir configuration. These physical characteristics of the contact basins affect their hydraulic efficiencies in terms of dead space, plug flow and mixed flow proportions. The dead space zone of a basin is basin volume through which no flow occurs. The remaining volume where flow occurs is comprised of plug flow and mixed flow zones. The plug flow zone is the portion of the remaining volume in which no mixing occurs in the direction of flow. The mixed flow zone is characterized by complete mixing in the flow direction and is the complement to the plug flow zone. All of these zones were identified in the studies for each contact basin. Comparisons were then made between the basin configurations and the observed flow conditions and design characteristics.

The ratio T_{10}/T was calculated from the data presented in the studies and compared to its associated hydraulic flow characteristics. Both studies resulted in T_{10}/T values that ranged from 0.3 to 0.7. The results of the studies indicate how basin baffling conditions can influence the T_{10}/T ratio, particularly baffling at the inlet and outlet to the basin. As the basin baffling conditions improved, higher T_{10}/T values were observed, with the outlet conditions generally having a greater impact than the inlet conditions.

As discovered from the results of the tracer studies performed by Marske and Boyle (1973) and Hudson (1975), the effectiveness of baffling in achieving a high T_{10}/T fraction is more related to the geometry and baffling of the basin than the function of the basin. For this reason, T_{10}/T values may be defined for five levels of baffling conditions rather than for particular types of contact basins. General guidelines were developed relating the T_{10}/T values from these studies to the respective baffling characteristics. These guidelines can be used to determine the T_{10} values for specific basins.

G.3 Baffling Classifications

The purpose of baffling is to maximize utilization of basin volume, increase the plug flow zone in the basin and minimize short circuiting. Some form of baffling at the inlet and outlet of the basins is used to evenly distribute flow across the basin. Additional baffling may be provided within the interior of the basin (intra-basin) in circumstances requiring a greater degree of flow distribution. Ideal baffling design reduces the inlet and outlet flow velocities, distributes the water as uniformly as practical over the cross section of the basin, minimizes mixing with the water already in the basin and prevents entering water from short circuiting to the basin outlet as the result of wind or density current effects. Five general classifications of baffling conditions – un baffled, poor, average, superior, and perfect (plug flow) - were developed to categorize the results of the tracer studies for use in determining T_{10} from the TDT of a specific basin. The T_{10}/T fractions associated with each degree of baffling are summarized in Table G-1. Factors representing the ratio between T_{10} and the TDT for plug flow in pipelines and flow in a completely mixed chamber have been included in Table G-1 for comparative purposes. However, in practice the theoretical T_{10}/T values of 1.0 for plug flow and 0.1 for mixed flow are seldom achieved because of the effect of dead space. Conversely, the T_{10}/T values shown for the intermediate baffling conditions already incorporate the effect of the dead space zone, as well as the plug flow zone, because they were derived empirically rather than from theory.

Table G-1. Baffling Classifications

Baffling Condition	T_{10}/T	Baffling Description
Un baffled (mixed flow)	0.1	None, agitated basin, very low length to width ratio, high inlet and outlet flow velocities.
Poor	0.3	Single or multiple un baffled 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.

Source: USEPA. March 1991.

As indicated in Table G-1, poor baffling conditions consist of an un baffled inlet and outlet with no intra-basin baffling. Average baffling conditions consist of intra-basin baffling and either a baffled inlet or outlet. Superior baffling conditions consist of at least a baffled inlet and outlet, and intra-basin baffling to redistribute the flow throughout the basin’s cross-section.

The three basic types of basin inlet baffling configurations are a target-baffled pipe inlet, an overflow weir entrance, and a baffled submerged orifice or port inlet. Typical intra-basin baffling structures include diffuser (perforated) walls; launders; cross, longitudinal, or maze baffling to cause horizontal and/or vertical serpentine flow; and longitudinal divider walls, which prevent mixing by increasing the length-to-width ratio of the basin(s). Commonly used baffled outlet structures include free-discharging weirs, such as sharp-crested and multiple V-notch, and submerged ports or weirs. Weirs that do not span the width of the contact basin, such as Cipolletti weirs, should not be considered baffling as their use may substantially increase weir overflow rates and the dead space zone of the basin.

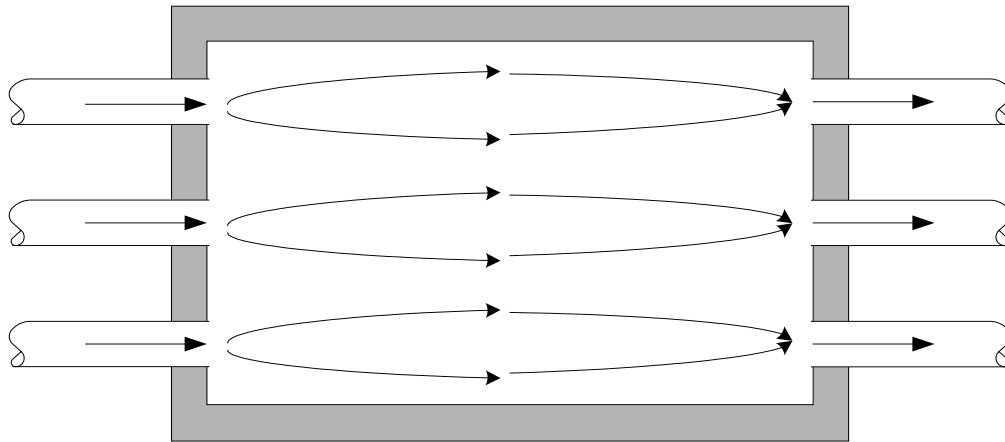
G.4 Examples of Baffling

Examples of baffling conditions for rectangular and circular basins are explained and illustrated in this section. Typical uses of various forms of baffled and unbaffled inlet and outlet structures are also illustrated.

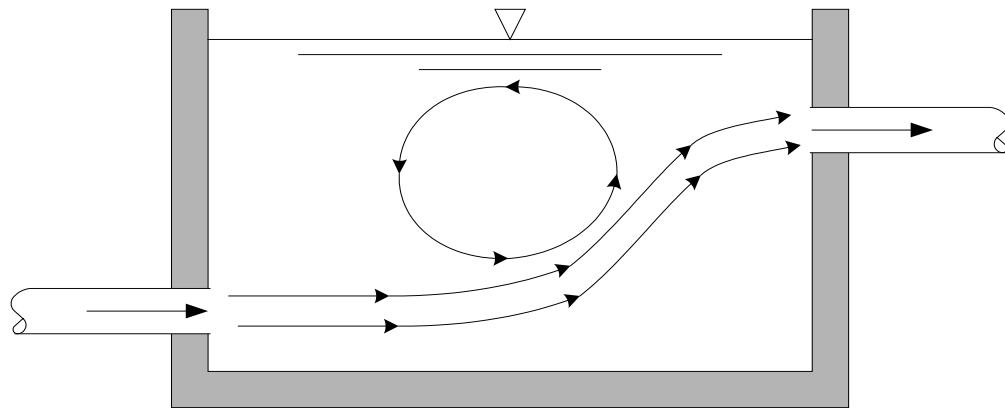
The plan and section views of a rectangular basin with poor baffling conditions, which can be attributed to unbaffled inlet and outlet pipes, are illustrated in Figure G-1. The flow pattern shown in the plan view indicates straight-through flow with dead space occurring in the regions between the individual pipe inlets and outlets. The section view reveals additional dead space from a vertical perspective in the upper inlet and lower outlet corners of the contact basin. Vertical mixing occurs as bottom density currents induce a counter-clockwise flow in the upper water layers.

The inlet flow distribution is markedly improved by the addition of an inlet diffuser wall and intra-basin baffling as shown in Figure G-2. However, only average baffling conditions are achieved for the basin because of the inadequate outlet structure - a Cipolletti weir. The width of the weir is short in comparison with the width of the basin. Consequently, dead space exists in the corners of the basin, as shown by the plan view. In addition, the small weir width causes a high weir overflow rate, which results in short circuiting in the center of the basin.

Figure G-1. Poor Baffling Conditions- Rectangular Contact Basin

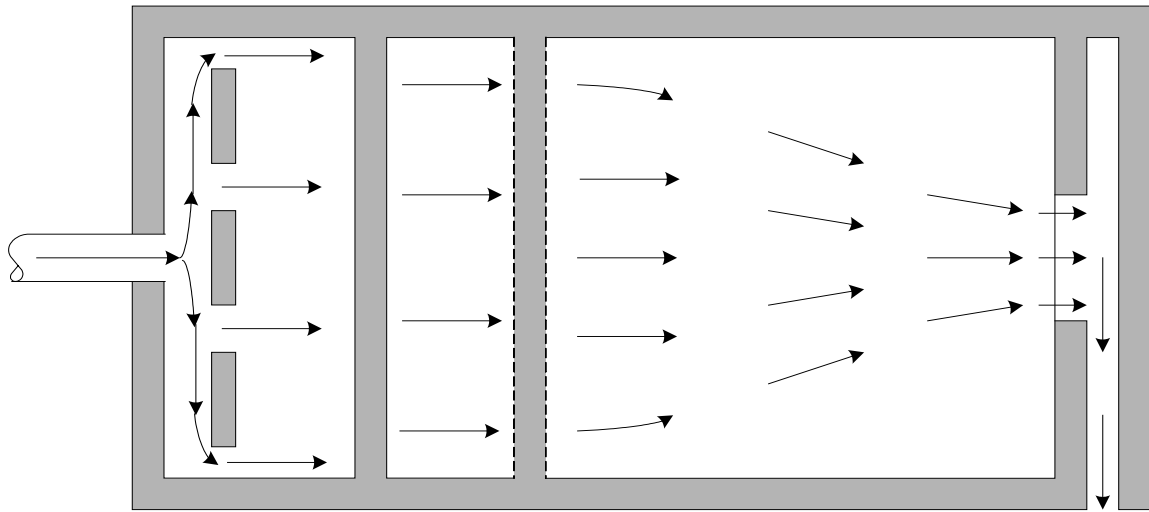


Plan View

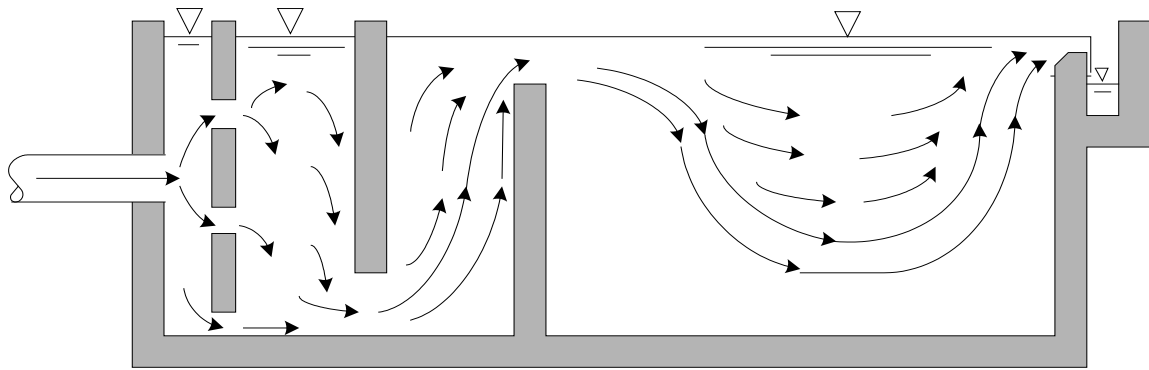


Section View

Figure G-2. Average Baffling Conditions- Rectangular Contact Basin



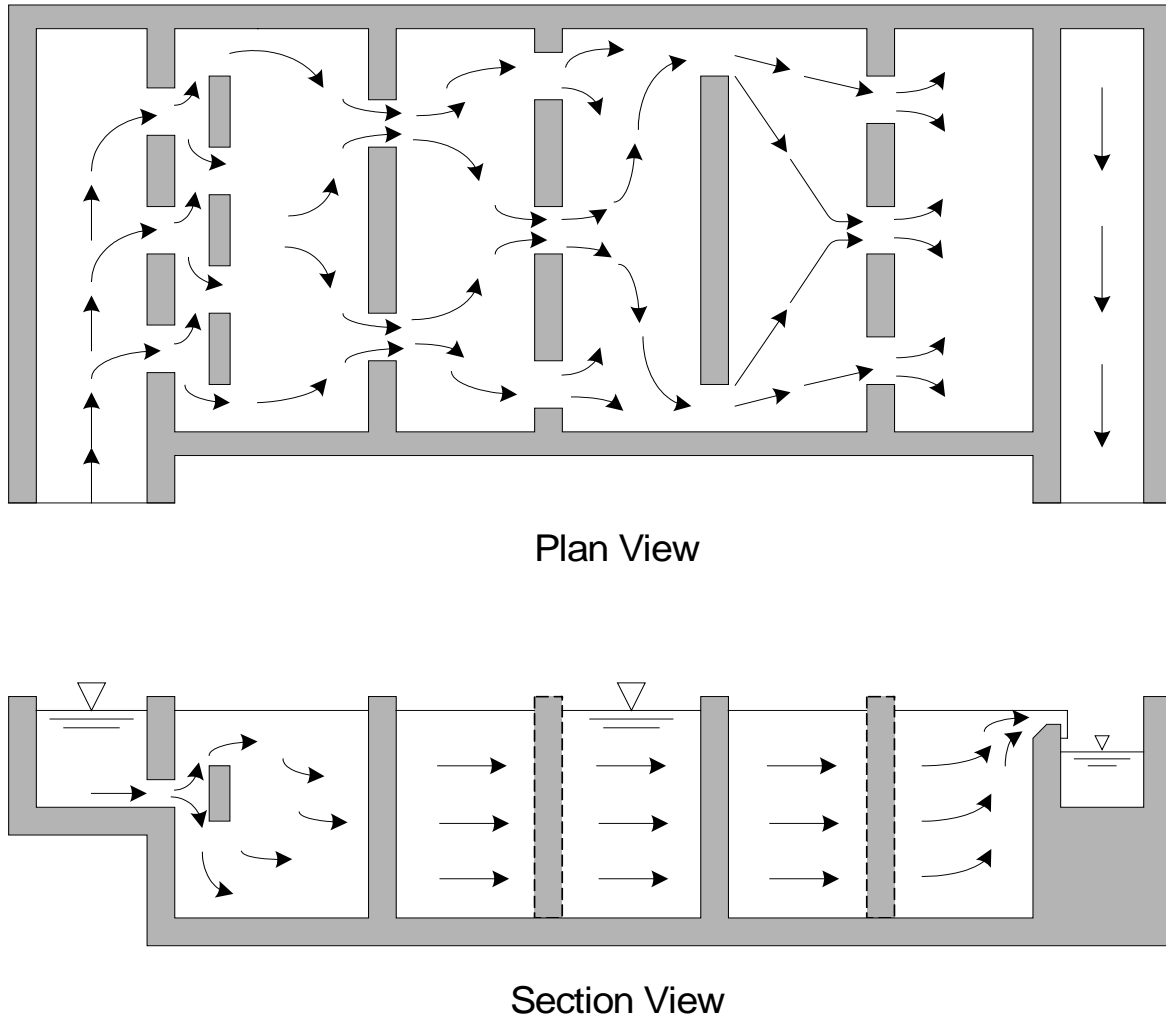
Plan View



Section View

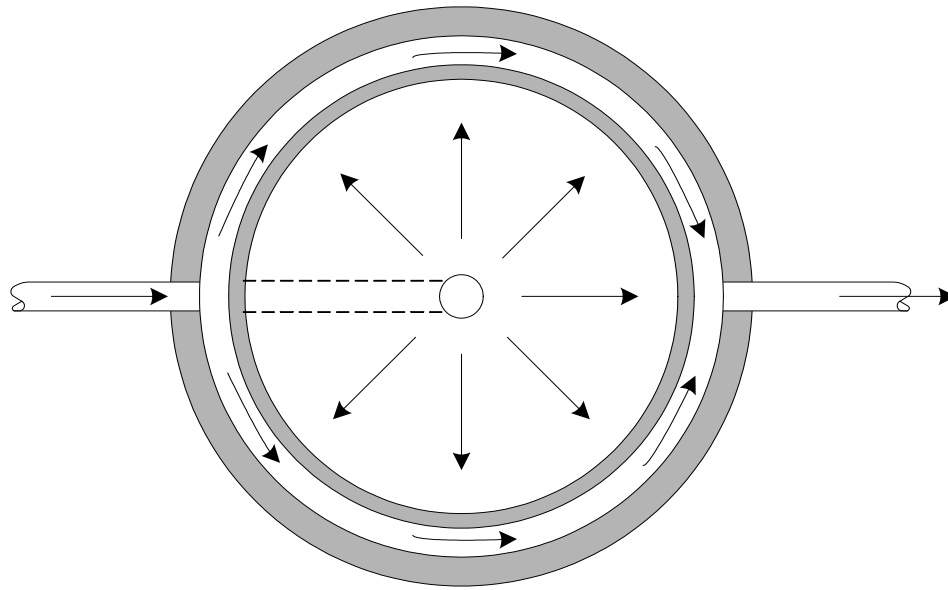
Superior baffling conditions are demonstrated by the flow pattern and physical characteristics of the basin shown in Figure G-3. The inlet to the basin consists of submerged, target-baffled ports. This inlet design serves to reduce the velocity of the incoming water and distribute it uniformly throughout the basin's cross-section. The outlet structure is a sharp-crested weir that extends for the entire width of the contact basin. This type of outlet structure will reduce short circuiting and decrease the dead space fraction of the basin, although the overflow weir does create some dead space at the lower corners of the effluent end.

Figure G-3. Superior Baffling Conditions- Rectangular Contact Basin

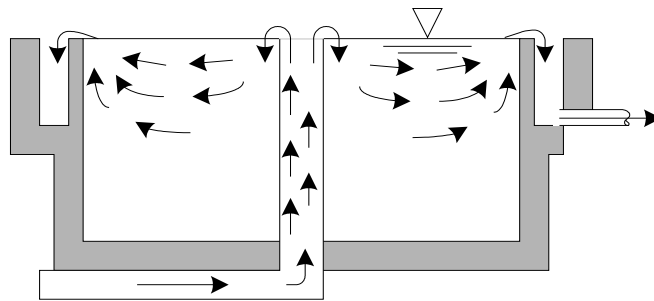


The plan and section of a circular basin with poor baffling conditions, which can be attributed to flow short circuiting from the center feed well directly to the effluent trough are shown in Figure G-4. Short circuiting occurs in spite of the outlet weir configuration because the center feed inlet is not baffled. The inlet flow distribution is improved somewhat in Figure G-5 by the addition of an annular ring baffle at the inlet which causes the inlet flow to be distributed throughout a greater portion of the basin's available volume. However, the baffling conditions in this contact basin are only average because the inlet center feed arrangement does not entirely prevent short circuiting through the upper levels of the basin.

Figure G-4. Poor Baffling Conditions- Circular Contact Basin

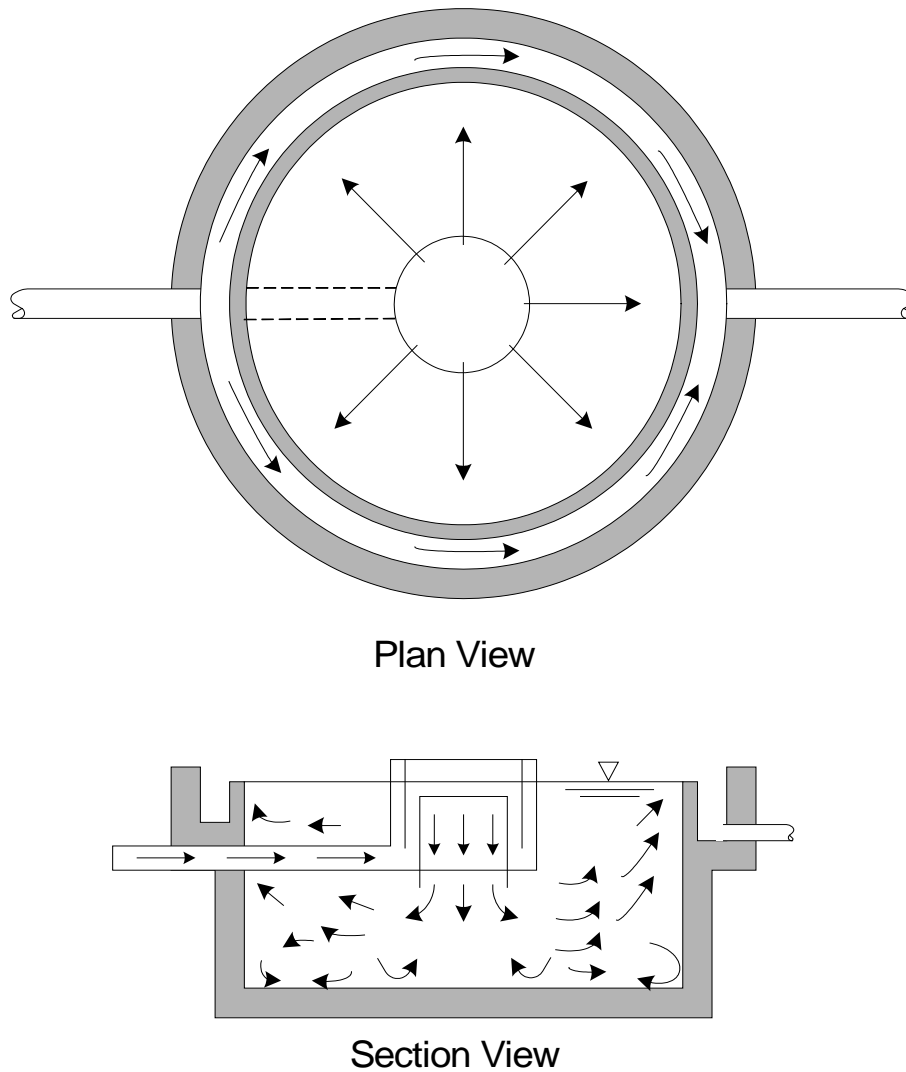


Plan View



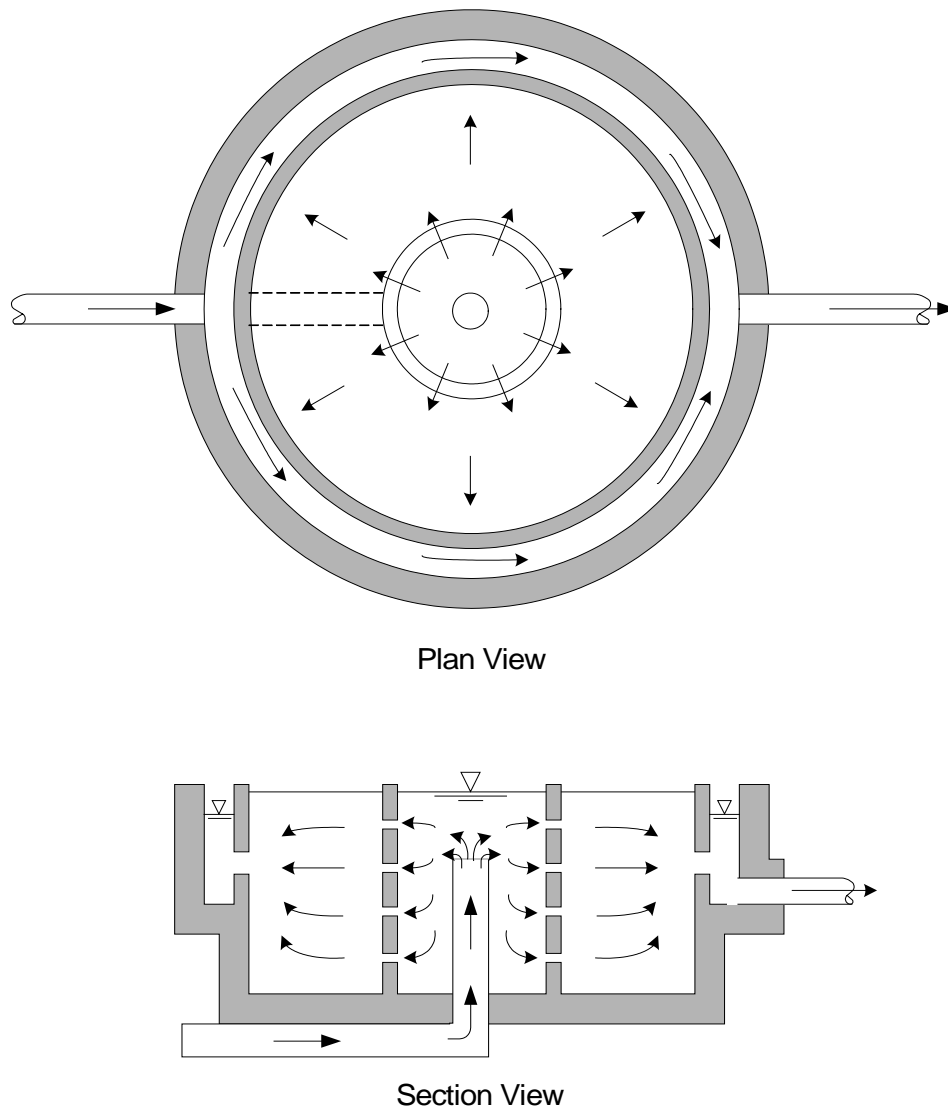
Section View

Figure G-5. Average Baffling Conditions- Circular Contact Basin



Superior baffling conditions are attained in the basin configuration shown on Figure G-6 through the addition of a perforated inlet baffle and submerged orifice outlet ports. As indicated by the flow pattern, more of the basin's volume is utilized due to uniform flow distribution created by the perforated baffle. Short circuiting is also minimized because only a small portion of flow passes directly through the perforated baffle wall from the inlet to the outlet ports.

Figure G-6. Superior Baffling Conditions- Circular Contact Basin



G.5 Additional Considerations

Flocculation basins and ozone contactors represent water treatment processes with slightly different characteristics from those presented in Figures G-1 through G-6 because of the additional effects of mechanical agitation and mixing from ozone addition, respectively. Studies by Hudson (1975) indicated that a single-compartment flocculator had a T_{10}/T value less than 0.3, corresponding to a dead space zone of about 20 percent and a very high mixed flow zone of greater than 90 percent. In this study, two four-compartment flocculators, one with and the other without mechanical agitation, exhibited T_{10}/T values in the range of 0.5 to 0.7. This observation indicates that not only will compartmentation result in higher T_{10}/T values through better flow distribution, but also that the effects of agitation intensity on T_{10}/T are reduced where sufficient baffling exists. Therefore, regardless of the extent of agitation, baffled flocculation basins with two or more compartments should be considered to possess average baffling conditions ($T_{10}/T = 0.5$), whereas unbaffled, single-compartment flocculation basins are characteristic of poor baffling conditions ($T_{10}/T = 0.3$).

Similarly, multiple stage ozone contactors are baffled contact basins which show characteristics of average baffling conditions. Single stage ozone contactors should be considered as being poorly baffled. However, circular turbine ozone contactors may exhibit flow distribution characteristics that approach those of completely mixed basins, with a T_{10}/T of 0.1, as a result of the intense mixing.

In many cases, settling basins are integrated with flocculators. Data from Hudson (1975) indicates that poor baffling conditions at the flocculator/settling basin interface can result in backmixing from the settling basin to the flocculator. Therefore, settling basins that have integrated flocculators without effective inlet baffling should be considered as poorly baffled, with a T_{10}/T of 0.3, regardless of the outlet conditions, unless intra-basin baffling is employed to redistribute flow. If intra-basin and outlet baffling is utilized, then the baffling conditions should be considered average with a T_{10}/T of 0.5.

Filters are special treatment units because their design and function is dependent on flow distribution that is completely uniform. Except for a small portion of flow that short circuits the filter media by channeling along the walls of the filter, filter media baffling provides a high percentage of flow uniformity and can be considered superior baffling conditions for the purpose of determining T_{10} . As such, the T value can be obtained by subtracting the volume of the filter media, support gravel, and underdrains from the total volume and calculating the TDT by dividing this volume by the flow through the filter (check with the state on what volume may be allowed in a filter). The TDT may then be multiplied by using a factor of 0.7, corresponding to superior baffling conditions, to determine the T_{10} value.

G.6 Conclusions

The recommended T_{10}/T values and examples are presented as a guideline for use by the state in determining T_{10} . Conditions that are combinations or variations of the above examples may exist and warrant the use of intermediate T_{10}/T values such as 0.4 or 0.6. As more data on tracer studies become available, specifically correlations between other physical characteristics of basins and the flow distribution efficiency parameters, further refinements to the T_{10}/T fractions, and definitions of baffling conditions may be appropriate.

G.7 References

Hudson, H.E., Jr. 1975. Residence Times in Pretreatment. *Journal AWWA*, 67(1): 45-52.

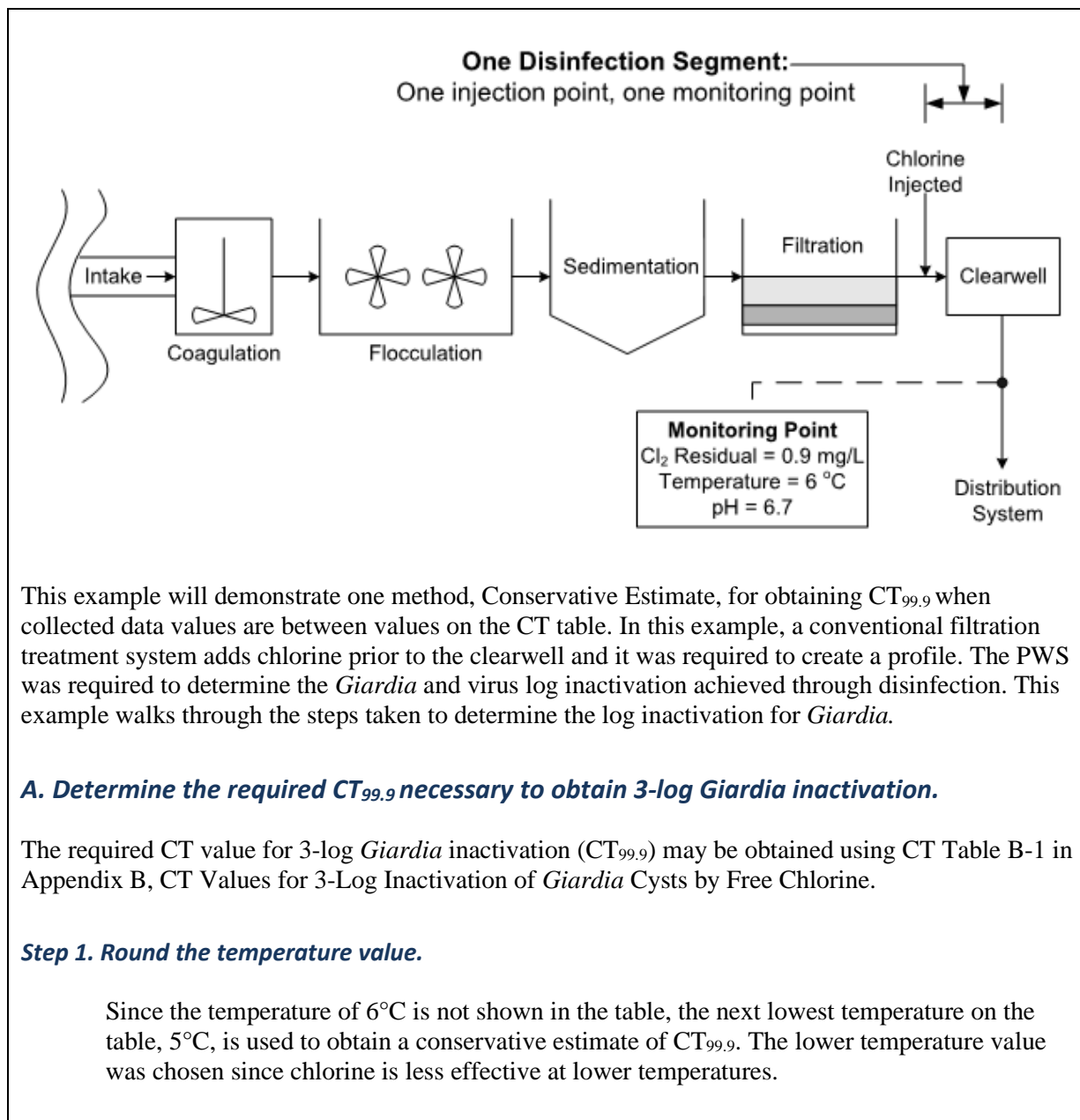
Marske, D.M. and J.D. Boyle. 1973. Chlorine Contact Chamber Design – A Field Evaluation. *Water and Sewage Works*, January, pp. 70-77.

USEPA. March 1991. *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems using Surface Water Sources*. Washington, D.C.

Appendix H — Conservative Estimate, Interpolation and Regression Method Examples

In some instances, the collected data for the disinfection profile will not coincide exactly with the values in the CT tables. The following examples present three methods on how to obtain $CT_{99.9}$ values. PWSs that plan to use any of these methods should check with their state to determine if the desired method is acceptable.

Example H-1. Conservative Estimate Example for Obtaining $CT_{99.9}$



Step 2. Round the pH value.

Since the pH of 6.7 is not shown in the table, the next highest pH, 7.0, is used to obtain a conservative estimate of CT_{99.9}. The higher pH value was chosen since chlorine is less effective at a higher pH.

Step 3. Round the residual chlorine concentration value.

Since the residual chlorine concentration of 0.9 mg/L is not shown on the table, the next highest residual chlorine concentration, 1.0 mg/L, is used to obtain a conservative estimate of CT_{99.9}. A higher residual chlorine concentration is used to obtain a higher required CT_{99.9} value, which will result in a lower calculated log inactivation ratio value.

Step 4. Determine CT_{99.9}.

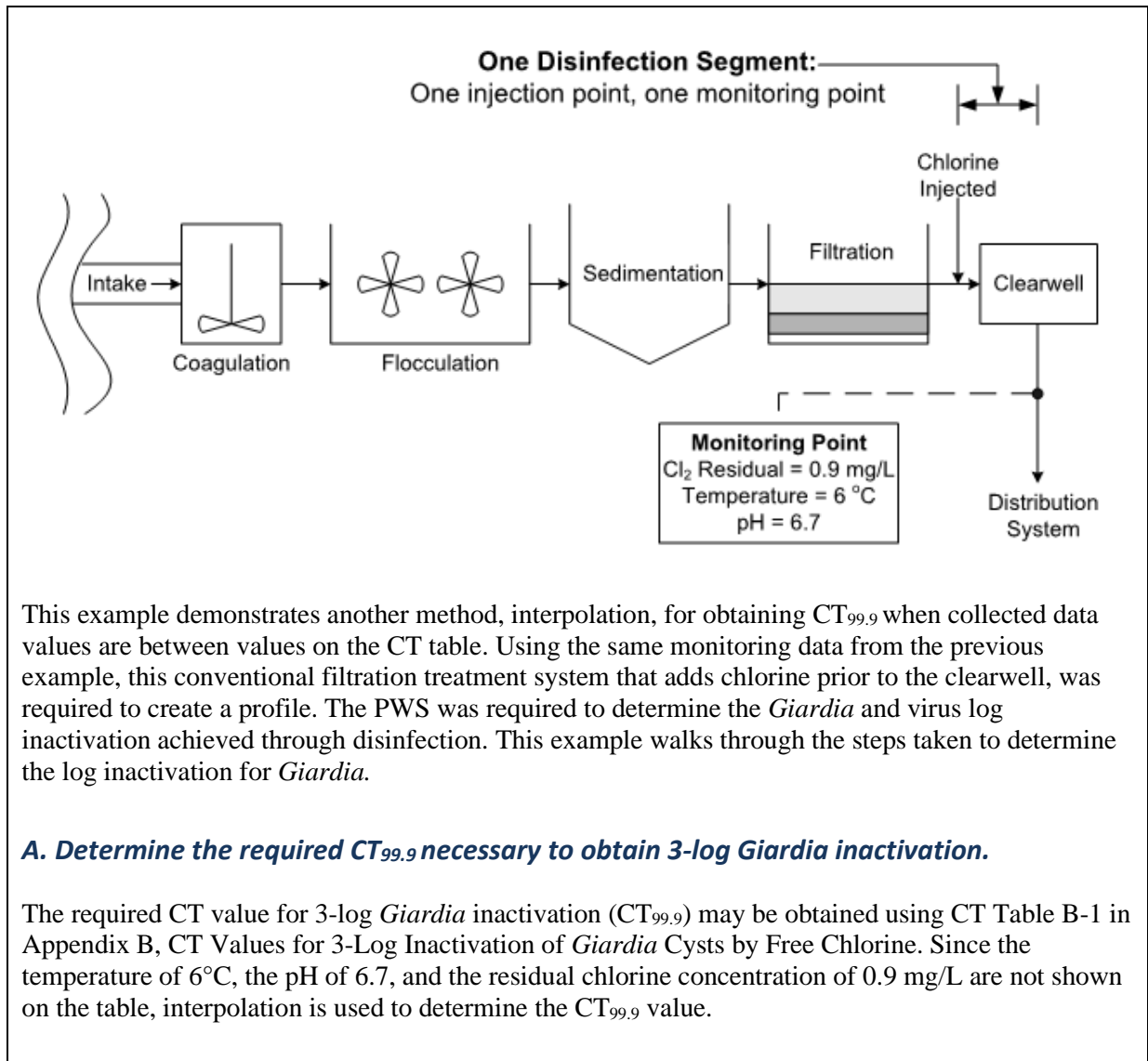
In this example, the CT_{99.9} is 149 min-mg/L for a pH of 7.0, temperature of 5°C and C_{chlorine} of 1.0 mg/L. The relevant section of Table B-1 is reprinted below and the pertinent section of the table is highlighted.

Excerpt from Table B-1

CT values for 3-Log Inactivation of *Giardia* Cysts by Free Chlorine (5°C portion of table for 0.4 to 1.2 mg/L)

Chlorine Concentration (mg/L)	Temperature 5°C						
	pH						
	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0
<=0.4	97	117	139	166	198	236	279
0.6	100	120	143	171	204	244	291
0.8	103	122	146	175	210	252	301
1.0	105	125	149	179	216	260	312
1.2	107	127	152	183	221	267	320

Example H-2. Interpolation Example for Obtaining $CT_{99.9}$



This example demonstrates another method, interpolation, for obtaining $CT_{99.9}$ when collected data values are between values on the CT table. Using the same monitoring data from the previous example, this conventional filtration treatment system that adds chlorine prior to the clearwell, was required to create a profile. The PWS was required to determine the *Giardia* and virus log inactivation achieved through disinfection. This example walks through the steps taken to determine the log inactivation for *Giardia*.

A. Determine the required $CT_{99.9}$ necessary to obtain 3-log *Giardia* inactivation.

The required CT value for 3-log *Giardia* inactivation ($CT_{99.9}$) may be obtained using CT Table B-1 in Appendix B, CT Values for 3-Log Inactivation of *Giardia* Cysts by Free Chlorine. Since the temperature of 6°C, the pH of 6.7, and the residual chlorine concentration of 0.9 mg/L are not shown on the table, interpolation is used to determine the $CT_{99.9}$ value.

Step 1. Interpolate for $CT_{99.9}$ at pH of 6.7 at the next lowest temperature of 5°C and the next lowest residual chlorine concentration of 0.8 mg/L.

Excerpt from Table B-1

CT Values for 3-Log Inactivation of *Giardia* Cysts by Free Chlorine (5°C portion of table for 0.4 to 1.2 mg/L)

Chlorine Concentration (mg/L)	Temperature 5°C						
	pH						
	<=6.0	6.5	7.0	7.5	8.0	8.5	9.0
<=0.4	97	117	139	166	198	236	279
0.6	100	120	143	171	204	244	291
0.8	103	122	146	175	210	252	301
1.0	105	125	149	179	216	260	312
1.2	107	127	152	183	221	267	320

$$\frac{(CT_{99.9} \text{ at pH } 7.0) - (CT_{99.9} \text{ at pH } 6.5)}{\text{pH } 7.0 - \text{pH } 6.5} = \frac{(CT_{99.9} \text{ at pH } 6.7) - (CT_{99.9} \text{ at pH } 6.5)}{\text{pH } 6.7 - \text{pH } 6.5}$$

$$\frac{146 \text{ min-mg/L} - 122 \text{ min-mg/L}}{7.0 - 6.5} = \frac{(CT_{99.9} \text{ at pH } 6.7) - 122 \text{ min-mg/L}}{6.7 - 6.5}$$

$$\frac{24 \text{ min-mg/L}}{0.5} = \frac{(CT_{99.9} \text{ at pH } 6.7) - 122 \text{ min-mg/L}}{0.2}$$

$$\frac{24 \text{ min-mg/L} \times 0.2}{0.5} = (CT_{99.9} \text{ at pH } 6.7) - 122 \text{ min-mg/L}$$

$$9.6 \text{ min-mg/L} = (CT_{99.9} \text{ at pH } 6.7) - 122 \text{ min-mg/L}$$

$$CT_{99.9} \text{ at pH } 6.7 = 9.6 \text{ min-mg/L} + 122 \text{ min-mg/L}$$

$$CT_{99.9} \text{ at pH } 6.7 = 131.6 \text{ min-mg/L}$$

Step 2. Interpolate for $CT_{99.9}$ at pH of 6.7 at the next highest temperature of 10°C and the next lowest residual chlorine concentration of 0.8 mg/L.

Excerpt from Table B-1

CT Values for 3-Log Inactivation of *Giardia* Cysts by Free Chlorine (10°C portion of table for 0.4 to 1.2 mg/L)

Chlorine Concentration (mg/L)	Temperature 10°C						
	pH						
	≤ 6.0	6.5	7.0	7.5	8.0	8.5	9.0
≤ 0.4	73	88	104	125	149	177	209
0.6	75	90	107	128	153	183	218
0.8	78	92	110	131	158	189	226
1.0	79	94	112	134	162	195	234
1.2	80	95	114	137	166	200	240

$$\frac{(CT_{99.9} \text{ at pH } 7.0) - (CT_{99.9} \text{ at pH } 6.5)}{\text{pH } 7.0 - \text{pH } 6.5} = \frac{(CT_{99.9} \text{ at pH } 6.7) - (CT_{99.9} \text{ at pH } 6.5)}{\text{pH } 6.7 - \text{pH } 6.5}$$

$$\frac{110 \text{ min-mg/L} - 92 \text{ min-mg/L}}{7.0 - 6.5} = \frac{(CT_{99.9} \text{ at pH } 6.7) - 92 \text{ min-mg/L}}{6.7 - 6.5}$$

$$\frac{18 \text{ min-mg/L}}{0.5} = \frac{(CT_{99.9} \text{ at pH } 6.7) - 92 \text{ min-mg/L}}{0.2}$$

$$\frac{18 \text{ min-mg/L} \times 0.2}{0.5} = (CT_{99.9} \text{ at pH } 6.7) - 92 \text{ min-mg/L}$$

$$7.2 \text{ min-mg/L} = (CT_{99.9} \text{ at pH } 6.7) - 92 \text{ min-mg/L}$$

$$CT_{99.9} \text{ at pH } 6.7 = 7.2 \text{ min-mg/L} + 92 \text{ min-mg/L}$$

$$CT_{99.9} \text{ at pH } 6.7 = 99.2 \text{ min-mg/L}$$

Step 3. Interpolate for $CT_{99.9}$ at pH of 6.7, temperature of 6°C, and the next lowest residual chlorine concentration of 0.8 mg/L.

The table below summarizes the $CT_{99.9}$ values determined at a pH of 6.7, residual chlorine concentration of 0.8 mg/L and temperatures of 5°C and 10°C.

pH = 6.7		
Chlorine Concentration	Temperature	
	5°C	10°C
0.8 mg/L	131.6 min-mg/L	99.2 min-mg/L

$$\frac{(CT_{99.9} \text{ at } 10^{\circ}\text{C}) - (CT_{99.9} \text{ at } 5^{\circ}\text{C})}{10^{\circ}\text{C} - 5^{\circ}\text{C}} = \frac{(CT_{99.9} \text{ at } 6^{\circ}\text{C}) - (CT_{99.9} \text{ at } 5^{\circ}\text{C})}{6^{\circ}\text{C} - 5^{\circ}\text{C}}$$

$$\frac{99.2 \text{ min-mg/L} - 131.6 \text{ min-mg/L}}{10^{\circ}\text{C} - 5^{\circ}\text{C}} = \frac{(CT_{99.9} \text{ at } 6^{\circ}\text{C}) - 131.6 \text{ min-mg/L}}{6^{\circ}\text{C} - 5^{\circ}\text{C}}$$

$$\frac{-32.4 \text{ min-mg/L}}{5^{\circ}\text{C}} = \frac{(CT_{99.9} \text{ at } 6^{\circ}\text{C}) - 131.6 \text{ min-mg/L}}{1^{\circ}\text{C}}$$

$$\frac{-32.4 \text{ min-mg/L} \times 1^{\circ}\text{C}}{5^{\circ}\text{C}} = (CT_{99.9} \text{ at } 6^{\circ}\text{C}) - 131.6 \text{ min-mg/L}$$

$$-6.48 \text{ min-mg/L} = (CT_{99.9} \text{ at } 6^{\circ}\text{C}) - 131.6 \text{ min-mg/L}$$

$$CT_{99.9} \text{ at } 6^{\circ}\text{C} = -6.48 \text{ min-mg/L} + 131.6 \text{ min-mg/L}$$

$$CT_{99.9} \text{ at } 6^{\circ}\text{C} = 125.1 \text{ min-mg/L}$$

$CT_{99.9}$ at a pH of 6.7, temperature of 6°C, and residual chlorine concentration of 0.8 mg/L is 125.1 min-mg/L.

Step 4. Repeat steps 1 through 3 at the same pH and temperatures, but with a residual chlorine concentration of 1.0 mg/L.

The results are summarized in the table, below.

pH	Temperature (°C)	Residual Chlorine Conc. (mg/L)	CT _{99.9} (min-mg/L)
6.7	5	1.0	134.6
6.7	10	1.0	101.2
6.7	6	1.0	127.9

CT_{99.9} at a pH of 6.7, temperature of 6°C, and residual chlorine concentration of 1.0 mg/L is 127.9 min-mg/L.

Step 5. Interpolate for CT_{99.9} at pH of 6.7, temperature of 6°C, and residual chlorine concentration of 0.9 mg/L.

The table below summarizes the CT_{99.9} values determined at a pH of 6.7, temperature of 6°C, and residual chlorine concentrations of 0.8 mg/L and 1.0 mg/L.

pH = 6.7		
Temperature	Chlorine Residual Conc.	
	0.8 mg/L	1.0 mg/L
6°C	125.1 min-mg/L	127.9 min-mg/L

$$\frac{(CT_{99.9} \text{ at } 1.0 \text{ mg/L}) - (CT_{99.9} \text{ at } 0.8 \text{ mg/L})}{1.0 \text{ mg/L} - 0.8 \text{ mg/L}} = \frac{(CT_{99.9} \text{ at } 0.9 \text{ mg/L}) - (CT_{99.9} \text{ at } 0.8 \text{ mg/L})}{0.9 \text{ mg/L} - 0.8 \text{ mg/L}}$$

$$\frac{127.9 \text{ min-mg/L} - 125.1 \text{ min-mg/L}}{1.0 \text{ mg/L} - 0.8 \text{ mg/L}} = \frac{(CT_{99.9} \text{ at } 0.9 \text{ mg/L}) - 125.1 \text{ min-mg/L}}{0.9 \text{ mg/L} - 0.8 \text{ mg/L}}$$

$$\frac{2.8 \text{ min-mg/L}}{0.2 \text{ mg/L}} = \frac{(CT_{99.9} \text{ at } 0.9 \text{ mg/L}) - 125.1 \text{ min-mg/L}}{0.1 \text{ mg/L}}$$

$$\frac{2.8 \text{ min-mg/L} \times 0.1 \text{ mg/L}}{0.2 \text{ mg/L}} = (\text{CT}_{99.9} \text{ at } 0.9 \text{ mg/L}) - 125.1 \text{ min-mg/L}$$

$$1.4 \text{ min-mg/L} = (\text{CT}_{99.9} \text{ at } 0.9 \text{ mg/L}) - 125.1 \text{ min-mg/L}$$

$$\text{CT}_{99.9} \text{ at } 0.9 \text{ mg/L} = 1.4 \text{ min-mg/L} + 125.1 \text{ min-mg/L}$$

$$\text{CT}_{99.9} \text{ at } 0.9 \text{ mg/L} = 126.5 \text{ min-mg/L}$$

$\text{CT}_{99.9}$ at a temperature of 6°C, pH of 6.7, and residual chlorine concentration of 0.9 mg/L is 126.5 min-mg/L.

Note that this $\text{CT}_{99.9}$ value of 126.5 min-mg/L is substantially lower than the value of 149 min-mg/L obtained through the conservative estimate in Example H-1. Making use of this interpolation approach will allow the PWS to demonstrate compliance at a lower level of disinfection dose.

Example H-3. Regression Example for Obtaining $CT_{99.9}$ when Free Chlorine is Used as the Disinfectant

The regression method is useful for calculating $CT_{99.9}$ when using free chlorine as a disinfectant for a long historical data set of pH, temperature, and residual disinfectant concentrations. Instead of having to look up CT values weekly, the regression method allows the operator to simply use a formula that is a function of pH, temperature, and residual disinfectant concentration.

An empirical model was developed by Smith et al. (1995), that directly predicts CT values that are equal to or greater than the original CT values in the SWTR over the entire range of variables covered in the *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources* (USEPA, March 1991). The equations below can be used to directly compute CT values for chlorine inactivation:

$$CT_{99.9} = (0.353 \times I)(12.006 + e^{(2.46 - 0.073 \times \text{temp} + 0.125 \times C + 0.389 \times \text{pH})}) \quad [\text{for temperatures } < 12.5^\circ\text{C}]$$

$$CT_{99.9} = (0.361 \times I)(-2.261 + e^{(2.69 - 0.065 \times \text{temp} + 0.111 \times C + 0.361 \times \text{pH})}) \quad [\text{for temperatures } \geq 12.5^\circ\text{C}]$$

Where:

I = 3 (the number of log inactivation credits required)

temp = temperature in degrees Celsius

C = residual chlorine concentration in mg/L

pH = the pH value

The following example walks through the steps taken to determine the log inactivation credits for *Giardia* using the regression method when free chlorine is the disinfectant.

A. Determine the required $CT_{99.9}$ necessary to obtain 3-log *Giardia* inactivation.

The regression method is used to determine the $CT_{99.9}$ value.

Step 1. Determine whether the temperature is above, below, or equal to 12.5°C.

Once again, using the same monitoring data from the previous examples, the temperature is 6°C. Therefore, the first equation listed above will be used to determine the required CT value for 3-log *Giardia* inactivation ($CT_{99.9}$).

Step 2. Determine $CT_{99.9}$.

With a pH of 6.7 and residual chlorine concentration of 0.9 mg/L during peak hourly flow, calculate the $CT_{99.9}$ using the regression method as follows:

$$CT_{99.9} = (0.353 \times I)(12.006 + e^{(2.46 - 0.073 \times \text{temp} + 0.125 \times C + 0.389 \times \text{pH})})$$

$$CT_{99.9} = (0.353 \times 3)(12.006 + e^{(2.46 - 0.073 \times 6 + 0.125 \times 0.9 + 0.389 \times 6.7)})$$

$$CT_{99.9} = 134 \text{ min-mg/L}$$

This value is between the values obtained from the other two methods (conservative method: 149 min-mg/L; linear interpolation: 126.5 min-mg/L).

References

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