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Disinfection Profiling and Benchmarking Guidance Manual

DISCLAIMER

This manual describes the practice of disinfection profiling and benchmarking as required under the U.S. Environmental Protection Agency's (EPA) Interim Enhanced Surface Water Treatment Rule (IESWTR) promulgated December 16, 1998. Disinfection profiling and benchmarking are procedures to ensure that microbial inactivation is not significantly reduced due to implementation of the Stage 1 Disinfectant and Disinfection Byproduct Rule (DBPR) also promulgated on December 16, 1998.

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ACRONYMS

AOC	Assimilable organic carbon
ASDWA	Association of State Drinking Water Administrators
AWWA	American Water Works Association
AWWARF	AWWA Research Foundation
BAC	Biologically active carbon
BAF	Biologically active filtration
BAT	Best Available Technology
BDOC	Biodegradable organic carbon
BMP	Best Management Practice
C/C_o	Dimensionless concentration
CFR	Code of Federal Regulations
CFU	Coliform forming units
CSO	Combined Sewer Overflow
CT	Disinfectant residual concentration (C, in mg/L), multiplied by contact time (T, in min); a measure of disinfection effectiveness.
CWS	Community Water System
D/DBP	Disinfectants and disinfection byproducts
DBPR	Disinfectants and Disinfection Byproducts Rule
DBP	Disinfection byproduct
DBPFP	Disinfection byproduct formation potential
DOC	Dissolved organic carbon
DSE	Distribution system equivalent
EPA	United States Environmental Protection Agency
IESWTR	Interim Enhanced Surface Water Treatment Rule
GAC	Granular activated carbon
gpm	Gallons per minute
GWR	Ground Water Rule
GWSS	Ground Water Supply Survey
GWUDI	Ground water under the direct influence
HAA5	Five haloacetic acids
ICR	Information Collection Rule
IESWTR	Interim Enhanced Surface Water Treatment Rule
IOA	International Ozone Association
M-DBP	Microbial/disinfection byproducts
MCL	Maximum Contaminant Level

MCLG	Maximum Contaminant Level Goal
MDL	Method Detection Limit
mg/L	Milligrams per liter
mgd	Million Gallons per Day
MRDL	Maximum Residual Disinfectant Level (as mg/L)
MRDLG	Maximum Residual Disinfectant Level Goal
MRL	Minimum Reporting Level
NIPDWR	National Interim Primary Drinking Water Regulation
NOM	Natural Organic Matter
N_o	Influent concentration
NPS	Non-point source
N_t	Distribution system concentraion
NTU	Nepthelometric turbidity units
POE	Point-of-Entry Technologies
POU	Point-of-Use Technologies
ppb	Parts per billion
ppm	Parts per million
PWS	Public water system
Q	Peak hourly flow rate
RSC	Relative Source Contribution
SDWA	Safe Drinking Water Act
SM	Standard Methods
SSO	Sanitary Sewer Overflow
SWTR	Surface Water Treatment Rule
T_{10}	Contact time
TDT	Theoretical detention time
THM	Trihalomethane
THMFP	Trihalomethane formation potential
TOC	Total organic carbon
TNRCC	Texas Natural Resource Conservation Commission
TTHM	Total trihalomethane
USEPA	United States Environmental Protection Agency
UV	Ultraviolet
V	Volume
WHPA	Wellhead protection area
WIDB	Water Industry Data Base

EXECUTIVE SUMMARY

The objective of this guidance manual is to help Public Water Systems (PWSs) in implementing the practice of disinfection profiling and benchmarking as required under the Interim Enhanced Surface Water Treatment Rule (IESWTR) promulgated December 16, 1998. The IESWTR applies to surface water or Ground Water Under Direct Influence (GWUDI) of surface water systems serving 10,000 people or more.

This guidance manual describes the applicability of the profiling and benchmarking provisions to PWSs and details the procedures for generating a disinfection profile and calculating the disinfection benchmark. Finally, this guidance manual provides guidance to PWSs on determining "significant changes" to disinfection practices, communicating with the State, and the use of the disinfection benchmark in modifying disinfection practices.

The IESWTR defines a disinfection profile as a compilation of daily *Giardia* and/or virus log inactivation over a period of a year or more. Disinfection benchmarking is a baseline or benchmark of historical microbial inactivation practices developed from disinfection profiling data.

Applicability

Systems are required to develop a disinfection profile for *Giardia* if their distribution system DBP running annual average for either TTHM or HAA5 concentrations in the distribution system is greater than or equal to 0.064 mg/L or 0.048 mg/L, respectively. Systems need one year of TTHM and HAA5 same time period data for disinfection profile determination.

Systems that are required to profile and intend to "significantly" modify their disinfection practice are required under the IESWTR to develop disinfection benchmarking for *Giardia*. Significant changes to disinfection practices are defined under IESWTR as:

- Moving the point of disinfection
- Changing the type of disinfectant
- Changing the disinfection process
- Making any other change designated as significant by the State.

Systems planing to modify their disinfection practices by adding or switching disinfectants to ozone or chloramines are required to develop a disinfection profile and benchmark for viruses. Moreover, EPA strongly recommends that systems switching to chlorine dioxide also develop a virus profile.

Creating a Disinfection Profile

Systems required to develop a disinfection profile must:

- Conduct daily monitoring for a minimum period of one year by no later than March 2001.
- And may also use 1 or 2 years of acceptable grandfathered data, in addition to the 1-year of new operational data.
- Or may use grandfathered data to develop a 3-year disinfection profile. Systems must coordinate with the State to confirm acceptability of grandfathered data no later than March 2001, but must conduct the required monitoring until the State approves the system's request to use grandfathered data.

Use of CT Values for Disinfection Profiling

The Surface Water Treatment Rule (SWTR) requires physical removal and/or inactivation of 3-logs (99.9 percent) of *Giardia* and 4-logs (99.99 percent) of viruses. For disinfection profiling and benchmarking, the CT (see p. v for definition) approach will be used to compute the log inactivation of *Giardia* or viruses achieved during water treatment.

To use the SWTR CT tables, disinfectant type, temperature, and pH (for chlorine only) data are needed. Using this operating information, the CT value corresponding to inactivation of 3-logs of *Giardia* ($CT_{3\text{-log}, \textit{Giardia}}$) and/or 4-logs of viruses ($CT_{4\text{-log, virus}}$) can be read from the SWTR CT tables. Once the CT required to achieve 3-log inactivation of *Giardia* and/or 4-log inactivation of viruses is determined, the actual plant CT needs to be calculated. By determining contact time (T_{10}) for each treatment unit within a disinfection segment (based on baffling factors or tracer studies) T_{10} is multiplied by residual disinfectant concentration for the disinfection segment.

The plant log inactivation for *Giardia* and/or viruses is the sum of log inactivation for each segment. From the daily estimated plant log inactivation data, a disinfection profile can be created.

Determining the Benchmark

From the daily plant log inactivation records, systems need to compute the average log inactivation for each calendar month. The lowest monthly average log inactivation values for each 12-month period are then averaged to determine the benchmark. If one year of data is available, the lowest monthly average log inactivation is the disinfection benchmark.

Systems considering modifications to the disinfection practices can use the benchmark to assess modification impacts. This assessment is done by calculating the "modification benchmark" and comparing it to the current benchmark.

If the modification to disinfection practice results in a lower inactivation, an alternative disinfection benchmark may improve a system's ability to meet the DBPR MCLs without significantly compromising existing microbial protection.

Systems, under State guidance, may choose to develop an alternative benchmark that is lower than the existing benchmark. For example, a system may choose to develop an alternative benchmark when the system cannot simultaneously meet the disinfection benchmark and the Stage 1 DBPR MCLs. The system may also choose this course of action because of very high levels of microbial inactivation and/or high quality source water that has low pathogen occurrence levels.

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1. Introduction

This manual is one in a series of guidance manuals published by EPA to assist both States and Public Water Systems (PWSs) in complying with the Interim Enhanced Surface Water Treatment Rule (IESWTR) and Stage 1 Disinfectant and Disinfection Byproduct Rule (DBPR) drinking water regulations. Other EPA guidance manuals include:

- Alternative Disinfectants and Oxidants Guidance Manual (1999)
- Microbial and Disinfection Byproduct Simultaneous Compliance Guidance Manual (1999)
- Uncovered Finished Water Reservoirs Guidance Manual (1999)
- Unfiltered Systems Guidance Manual (1999)
- Guidance Manual for Compliance with the Interim Enhanced Surface Water Treatment Rule: Turbidity Provisions (1999)
- Guidance Manual for Conducting Sanitary Surveys of Public Water Systems; Surface Water and Ground Water Under the Direct Influence (GWUDI) of Surface Water (1999)
- Guidance Manual for Enhanced Coagulation and Enhanced Precipitative Softening (1999).

This guidance manual describes the practice of disinfection profiling and benchmarking as required under the U.S. Environmental Protection Agency's (EPA) IESWTR promulgated December 16, 1998. This guidance manual will assist PWSs and States with the implementation of the disinfection profiling and benchmarking provisions of the IESWTR. As described in the IESWTR, these provisions are intended to ensure that microbial inactivation is not unduly compromised as public water systems strive to meet the Stage 1 DBPR.

This guidance manual is organized into several chapters and appendices which are intended to accomplish the following:

- Defines disinfection profiling and benchmarking, State involvement, and provides a list of primary resources of information used to develop this guidance (Chapter 1).
- Describes the applicability of the profiling and benchmarking provisions to public water systems (Chapter 2).
- Provides a description of the procedures for generating a disinfection profile and provides an example profile (Chapter 3).
- Provides a description of the procedures for calculating the disinfection benchmark and provides an example of a benchmark calculation (Chapter 4).
- Discusses the use of the benchmark in modifying disinfection practices, communicating with the State, and assessing "significant changes" to

disinfection practices (Chapter 5).

- Discusses how a system may use an alternative benchmark in consultation with the State to remain in compliance with the Stage 1 DBPR MCLs while still not compromising microbial protection (Chapter 6).
- Provides an overview of the development of profiling and benchmarking regulations (Appendix A).
- Explains the significance of the log inactivation concept (Appendix B).
- Provides the CT values for inactivations achieved by various disinfectants (Appendix C).
- Presents discussions on the determination of contact time (Appendix D).
- Provides an example of the Regression Method in determining $CT_{3\text{-log},\mathit{Giardia}}$ (Appendix E).

1.1 Disinfection Profiling and Benchmarking

The IESWTR requires water systems to develop a disinfection profile if they exceed certain disinfection byproduct (DBP) levels in their distribution system. Water systems will have to develop a profile if their average total trihalomethane (TTHM) or five haloacetic acids (HAA5) concentrations in the distribution system exceed specified concentrations. Thus ***applicable PWSs must develop a disinfection profile*** if either of the following conditions exist:

- The TTHM annual average, based on quarterly samples, is $\geq$ 0.064 mg/L; or
- The HAA5 annual average, based on quarterly samples, is $\geq$ 0.048 mg/L.

The Microbial and Disinfection Byproduct (M-DBP) Advisory Committee recommended a value of 80 percent of the maximum contaminant levels (MCLs) because available data indicated that DBP levels varied from year to year due to many factors (i.e., changes in source water quality, changes in water demand, etc.). The Advisory Committee targeted these systems as likely candidates to modify their disinfection practices to comply with the Stage 1 DBPR. Systems have until March 2000 to complete DBP monitoring if data are not already available. Precursor removal strategies could be used in lieu of or in conjunction with changes to existing disinfection practices for Stage 1 DBPR compliance.

Only systems required to develop a profile and proposing to make significant changes to disinfection practices are required to develop a benchmark and submit it and other pertinent information to the State as part of the consultation process. ***Note that profiling and benchmarking based on virus inactivation is required only for systems proposing to add or switch to ozone or chloramines. Virus profiling and benchmarking is strongly recommended for systems proposing to add or switch to chlorine dioxide.***

1.2 Purpose of Disinfection Profiling and Benchmarking

Under the IESWTR, disinfection profiling and benchmarking are used to determine the existing levels of disinfection. As water systems comply with the Stage 1 DBPR, they may make significant modifications to their existing disinfection practices. It is essential that water systems understand the impact on microbial protection while making significant changes in their disinfection practices. Disinfection profiling and benchmarking are procedures by which systems and States, working together, can ensure that there will be no significant reduction in microbial protection as the result of modifying disinfection practices to meet DBP MCLs under the Stage 1 DBPR (USEPA, 1997a).

1.2.1 Disinfection Profiling: Definition and Purpose

The IESWTR defines a disinfection profile as a compilation of daily *Giardia* and/or virus log inactivations over a period of a year or more (USEPA, 1997a). Inactivation of pathogens is typically reported in orders of magnitude inactivation of organisms on a logarithmic scale. As an illustration, a 2-log inactivation corresponds to a 99 percent inactivation and a 3-log inactivation corresponds to a 99.9 percent inactivation (see Appendix B for further discussion). As required under the IESWTR, a disinfection profile must be developed for a period between one to three years, depending on the availability and quality of existing data (see Section 2.3).

The daily log inactivation values are calculated based on daily measurements of operational data (i.e., disinfectant residual concentration, contact time, temperature, and pH). A plot of daily log inactivation values versus time provides a visual representation of the log inactivation that the treatment plant achieved over time. From this plot, changes in log inactivation due to temperature, flow, disinfectant residual concentrations, or other changes can be seen.

The procedures and calculations for disinfection profiling are discussed in detail in Chapter 3 of this manual.

1.2.2 Disinfection Benchmarking: Definition and Purpose

Disinfection benchmarking is a baseline or benchmark of historical microbial inactivation practices developed from disinfection profiling data. The benchmark is determined from interpretation and analysis of the disinfection profile. This benchmark value identifies the lowest log inactivation that a system has achieved over a period of time. As used under the IESWTR, the benchmark sets the target disinfection level for alternative disinfection schemes. A minimum of 3-log *Giardia lamblia* and 4-log virus removal and/or inactivation performance must be achieved at all times to comply with the existing Surface Water Treatment Rule (SWTR) promulgated in 1989. Inactivation levels below the benchmark may be implemented after State consultation. States should evaluate inactivation levels below the benchmark by taking source water, watershed, and treatment factors into consideration.

The objective of the disinfection benchmark is to facilitate interactions between the States and PWSs for the purpose of assessing the impact on microbial risk of proposed significant changes to existing disinfection practices. The disinfection benchmark provides a criterion for the designs of alternative disinfection strategies. A system that is required to prepare a disinfection profile will not be allowed to make a significant change to disinfection practices without first consulting with the State.

1.3 State Review

Under the IESWTR, States will perform the review of disinfection profiles and benchmarks for water systems. The State will review disinfection profiles as part of periodic sanitary surveys. If a system is required to develop a disinfection profile and subsequently decides to make a significant change in disinfection practice, the system must consult with the State before implementing such a change. Significant changes are defined under IESWTR as (USEPA, 1998a):

1. Moving the point of disinfection
2. Changing the type of disinfectant
3. Changing the disinfection process
4. Making any other change designated as significant by the State.

Supporting materials for obtaining approval from the State must include a description of the proposed change, the disinfection profile, and an analysis of how the proposed change will affect existing levels of microbial protection.

1.4 Primary Information Sources

This document was developed using several primary reference documents previously developed by EPA. Material from the following publications were used substantially throughout this document:

- AWWA. 1991. *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources*. Washington, D.C. (Also published by USEPA, 1991)
- USEPA. 1997a. "National Primary Drinking Water Regulations; Interim Enhanced Surface Water Treatment Rule; Notice of Data Availability; Proposed Rule." 62 *FR* 59485. November 3.
- USEPA. 1998a. "National Primary Drinking Water Regulations; Interim Enhanced Surface Water Treatment Rule; Final Rule." 63 *FR* 69477. December 16.

Because each of the above documents was previously published by the EPA and provides substantial reference material throughout this document, specific citations are not provided when a publication is paraphrased in this document.

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2. APPLICABILITY OF DISINFECTION PROFILING AND BENCHMARKING

Disinfection profiling and disinfection benchmarking are two separate provisions under the IESWTR and are triggered by separate criteria, although the benchmarking process requires profiling. This chapter illustrates the applicability of the disinfection profiling and benchmarking provisions under the IESWTR to public water systems and how a water system can make this determination.

2.1 Systems Subject to the IESWTR

The IESWTR applies only to water systems using surface water or ground water under the direct influence (GWUDI) of surface water, that serve 10,000 or more people. Systems that serve fewer than 10,000 people are not regulated under the IESWTR and, therefore, the disinfection profile and benchmark provisions do not apply to these systems at this time, although the Long-Term 1 Enhanced Surface Water Treatment Rule (LT1ESWTR), expected to be promulgated in November 2000, will likely require profiling and benchmarking for these systems. If a system's source water is not defined as surface water or GWUDI as defined under the IESWTR, the profile and benchmark provisions are not applicable.

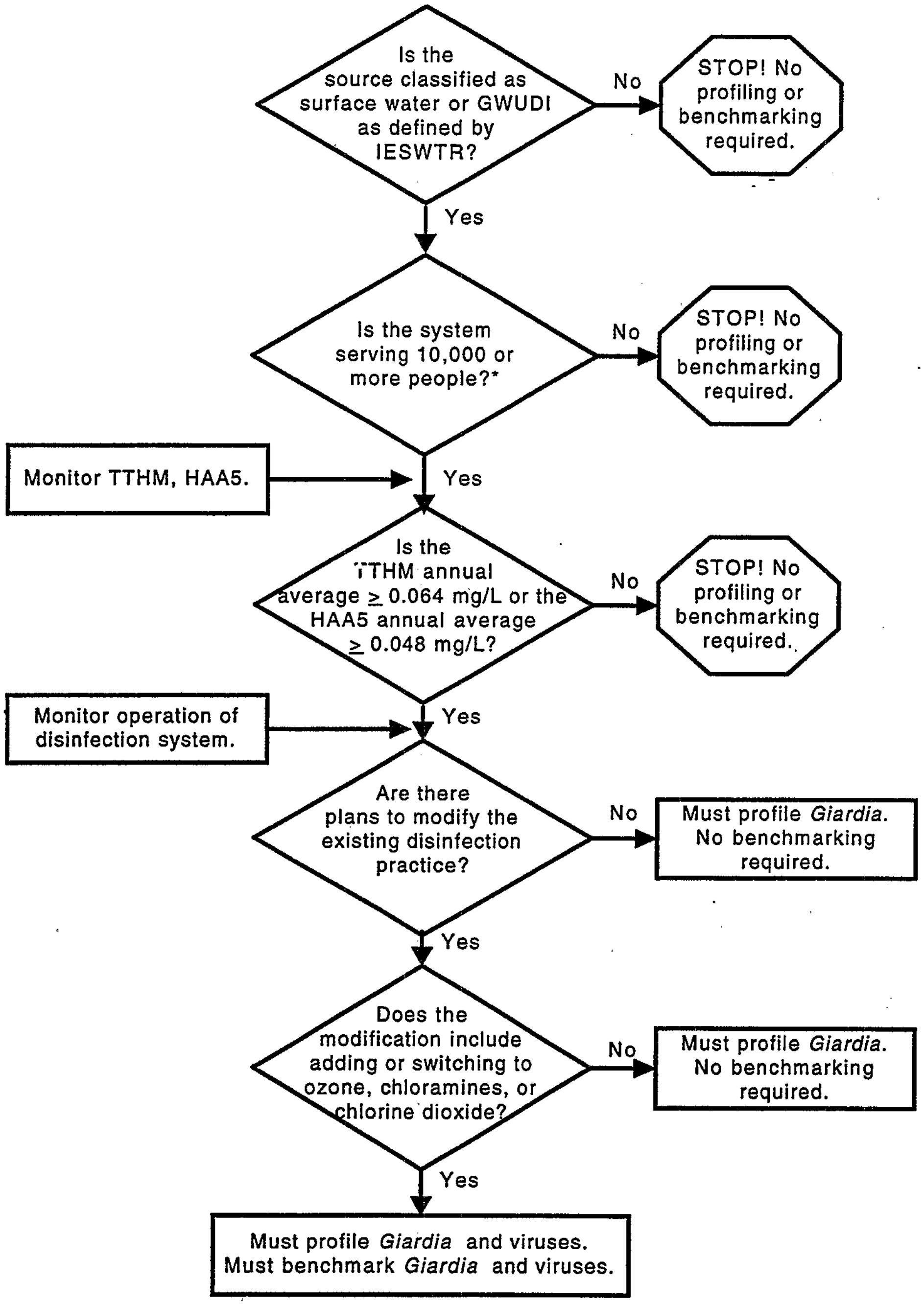
2.2 Profiling and Benchmarking Applicability

The IESWTR specifies that disinfection profiles and benchmarks may be based upon the inactivation of *Giardia* and, in some cases, viruses. Disinfection profile and/or benchmark development must, at a minimum, be based upon the inactivation of *Giardia*. However, under certain circumstances, as explained in Section 2.3 (and highlighted in Figure 2-1), some systems will be required to develop an additional profile and benchmark based on virus inactivation. The process for determining the applicability of disinfection profiling and benchmarking to public water systems is described in the following sections and illustrated in a corresponding decision tree (Figure 2-1).

2.3 Systems Required to Profile *Giardia*

Systems are required to develop a disinfection profile for *Giardia* if their distribution system DBP concentrations exceed certain criteria. Specifically, if the running annual average for either TTHM or HAA5 concentrations in the distribution system are greater than or equal to 0.064 mg/L or 0.048 mg/L, respectively, water systems must develop a profile for *Giardia*. The 12-month profile must be generated by March 2001.

Systems with existing DBP concentrations approaching or exceeding these MCLs are more likely to modify disinfection practices; therefore, these systems are required to develop a disinfection profile. Systems with very low DBP concentrations are not likely


Is the source classified as surface water or GWUDI as defined by IESWTR?
No
STOP! No profiling or benchmarking required.
Yes
Is the system serving 10,000 or more people?*
No
STOP! No profiling or benchmarking required.
Monitor TTHM, HAA5.
Yes
Is the TTHM annual average ≥ 0.064 mg/L or the HAA5 annual average ≥ 0.048 mg/L?
No
STOP! No profiling or benchmarking required.
Monitor operation of disinfection system.
Yes
Are there plans to modify the existing disinfection practice?
No
Must profile Giardia. No benchmarking required.
Yes
Does the modification include adding or switching to ozone, chloramines, or chlorine dioxide?
No
Must profile Giardia. No benchmarking required.
Yes
Must profile Giardia and viruses. Must benchmark Giardia and viruses.

* Systems serving fewer than 10,000 people will have to comply at a later date.

Figure 2-1. Profile and Benchmark Decision Tree

to modify their disinfection practices to control DBPs under the Stage 1 DBPR and are, therefore, not required to develop a profile. However, these systems may modify disinfection practices for other reasons and may find profile data useful for design purposes.

2.3.1 *Giardia* Profile

As depicted in Figure 2-1, systems meeting the size and source water applicability requirements must develop a disinfection profile for *Giardia* if either of the following conditions exist:

- The TTHM annual average concentration in the distribution system, for the most recent one-year period, is greater than or equal to 0.064 mg/L; or
- The HAA5 annual average concentration in the distribution system, for the most recent one-year period, is greater than or equal to 0.048 mg/L.

The TTHM and HAA5 data used to determine whether disinfection profiling is required must meet the specifications described in Section 2.3.2. As shown in Figure 2-1, systems that do not meet either of these criteria would not have to conduct a disinfection profile or benchmark.

The Advisory Committee selected the TTHM and HAA5 criteria listed above for determining the applicability of disinfection profiling for *Giardia* based upon the prediction that water systems not achieving DBP concentrations at least 20 percent below MCLs would likely change disinfection practices to control DBPs (i.e., apply a 20 percent margin of safety) to ensure continuing compliance.

2.3.2 TTHM and HAA5 Data Requirements

As described above, TTHM and HAA5 data are used to make the profiling determination for *Giardia*. The IESWTR specifies the TTHM and HAA5 data that are to be used for the disinfection profile determination. In all cases, the following criteria apply:

- One year of TTHM and HAA5 data is used to make a profiling determination.
- The TTHM and HAA5 data must be from the same time period.

Since the Information Collection Rule (ICR) requires the collection of TTHM and HAA5 data consistent with the profiling applicability determination, the discussion of data requirements for ICR and non-ICR systems is presented separately.

ICR Systems

Systems participating in the ICR have the required quarterly TTHM and HAA5 data and are assigned to use these data to determine applicability of benchmarking unless the State determines otherwise. Therefore, the requirements listed above apply to ICR systems' TTHM and HAA5 data. ICR TTHM and HAA5 values are computed as the annual average of quarterly averages of the Distribution System Equivalent (DSE) sample, two average residence time samples and one maximum residence time sample.

Non-ICR Systems

All water systems affected by the IESWTR are currently conducting quarterly monitoring of TTHMs under the current TTHM regulation. However, only some non-ICR systems have conducted the necessary HAA5 quarterly monitoring. For those water systems with existing HAA5 data, the State will decide the applicability of using that non-ICR data in the profiling determination based on the following criteria:

- **Applicable HAA5 Data**: These systems have HAA5 data that meet the provisions of 40 *Code of Federal Regulations* (*CFR*) §141.72 (a)(2)(ii) (Disinfection profiling and benchmarking), which stipulates that systems using "grandfathered" data must use TTHM data collected at the same time under the provisions of §141.12 (Maximum contaminant levels for total trihalomethanes) and §141.30 (Total trihalomethanes sampling, analytical and other requirements). The state must be confident that the sample collection, handling, and analyses were adequate to provide accurate results. If a system has made a modification to its treatment train since the HAA5 samples were collected, and this modification would likely have an impact on HAA5 formation, the state must carefully consider whether the data are still applicable to the modified system.
- **No HAA5 Data or Data Not Applicable**: These systems either do not have HAA5 data or have data that are judged by the State to not be adequate for the disinfection profile applicability determination (i.e., data may not be applicable if sample location, handling, and analytical method requirements currently applied to TTHM monitoring as outlined in 40 *CFR* §141.12 and §141.30 are not met). Systems without adequate HAA5 data must perform HAA5 quarterly monitoring that meets the requirements specified in 40 *CFR* §141.12 and §141.30. The monitoring must be for four quarters; must completed no later than March 2000; and must be collected during the same time period as TTHM data.

State Approval of a More Representative Data Set

The State has the authority to approve a more representative data set to determine profiling applicability if the system makes such a request or if the State determines that a more representative data set exists. This may occur under a variety of situations, including, but not limited to:

- A change in treatment or disinfection practice(s)
- A change in source water or source water blending.

2.4 Systems Required to Benchmark *Giardia*

Systems required to profile that intend to significantly modify their disinfection practice are required under the IESWTR to develop disinfection benchmarking for *Giardia*. A more detailed description of what constitutes a significant modification is presented in Chapter 5.

2.5 Systems Required to Profile and Benchmark Viruses

Under the IESWTR, some systems are required to create a disinfection profile and benchmark for viruses in addition to *Giardia*. A system must create a disinfection profile and benchmark for viruses if all of the following are true:

1. The system is a surface water system or GWUDI serving 10,000 people or more.
2. The TTHM annual average $\geq$ 0.064 mg/L or HAA5 annual average $\geq$ 0.048 mg/L.
3. The system plans to modify their disinfection practices by adding or switching disinfectants to ozone or chloramines. EPA strongly recommends that systems switching to chlorine dioxide also develop a virus profile.

For systems adding or switching disinfectants to ozone, chloramines, or chlorine dioxide, meeting a benchmark based on *Giardia* does not ensure that the inactivation of viruses will be maintained. Chlorine is much more effective at inactivating viruses than it is at inactivating *Giardia*. Alternative disinfectants such as ozone, chloramines, and chlorine dioxide are relatively less effective at inactivating viruses as they are inactivating *Giardia*. For this reason, systems switching to alternative disinfectants must profile and benchmark viruses inactivation.

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3. CREATING A PROFILE: DATA REQUIREMENTS AND CALCULATIONS

Disinfection profiling is the characterization of a water system's practices (log inactivation) over a period of time. Appendix B presents a discussion on the development of log inactivation methods under the SWTR and an example on how to calculate log inactivations. The disinfection profile is a graphical representation of the magnitude of daily *Giardia* or virus inactivations which is developed, in part, based on daily measurements of the following operational parameters:

- Disinfectant residual concentrations
- Peak hourly flow rate
- Temperature
- pH (chlorine only).

For purposes of complying with the requirements of the IESWTR, a profile can be prepared from historical treatment plant operating data, if adequate data are available, or the profile may have to be prepared using data acquired in a new monitoring program.

As noted in Chapter 2, depending on the disinfectant employed, the IESWTR requires profiles for either *Giardia* or *Giardia* and virus. The basic data requirements for creating a profile based on *Giardia* or virus are the same. Therefore, if a utility collects operating data sufficient to profile for *Giardia*, it can also develop a profile for viruses with only slight modifications to the calculations described in this chapter.

3.1 Data for Profiling

The IESWTR provides direction on operational data needed for calculating the disinfection profile. If approved by the State, existing historical (i.e., grandfathered) operational data may be used for this purpose. If a system does not have three years of approved grandfathered data, then it must conduct additional monitoring of operational data to meet the requirements of the IEWSTR. The system may develop a profile using a combination of both grandfathered data (where less than three years of approved data are available) and new data. This section provides guidance on the use of grandfathered data, the need for conducting additional monitoring, the required quality of the existing data, and the State's role in approving the use of available operational data.

Water systems should not use existing data if these data do not accurately represent the system's current level of disinfection. For example, existing data should not be used for systems that have recently made significant modification to their disinfection practices. A significant modification includes changes in disinfectants or changes in plant hydraulics or piping schemes that affect disinfection contact time. These treatment train modifications may substantially impact the level of inactivation provided as indicated by the CT and render existing data unrepresentative of the system's current inactivation performance. CT, in mg-min/L, is the product of C (the residual disinfectant concentration in mg/L) and T, (the time that water is in contact with the disinfectant in minutes).

3.1.1 Operational Data Required for Profiling

The IESWTR requires systems with less than three years of applicable data to conduct daily monitoring for profiling. As required in the IESWTR, the following data must be gathered daily at peak hourly flow at each disinfectant residual sampling point in the treatment plant:

- Disinfectant residual concentration in the treatment plant
- Peak hourly flow rate
- Temperature
- pH (if the system uses chlorine).

For systems with more than one point of disinfectant application, the same data must be collected at least daily at each of the disinfectant residual sampling points (i.e., segments). Section 3.2.2 provides a detailed description of acceptable water quality data analysis methods. Section 3.3.1 and Appendix D contain detailed descriptions of segments.

The time that the disinfectant is in contact with water in the disinfection segment must be determined on a daily basis to complete the CT calculations. This contact time, measured as T_{10}, is determined based on the peak hourly flow rate occurring during the 24-hour period and the detention time that is equaled or exceeded by 90 percent of the water passing through the basin. This procedure is detailed in Appendix D. States may allow systems to use non-peak flow measurements, but EPA is convinced that such measurements will result in a higher inactivation and may result in a higher benchmark.

3.1.2 Data Quantity

The IESWTR requires systems to create a disinfection profile that covers a minimum of 12 consecutive months. The profile may span a maximum of 36 consecutive months. All systems will therefore need one- to three- years of data to calculate daily log inactivations. Existing data may be used if the State determines that the quality of the data is sufficient. Under the IESWTR, systems without three years of existing acceptable operational data are required to monitor for one additional year.

Systems required to develop disinfection profiles under this rule must exercise one of the following three options:

- Option 1 - Systems must conduct daily monitoring as described below. This monitoring must be completed no later than March 2001 and must cover a period of one year. The data collected from this monitoring must be used to develop a one-year disinfection profile.

- Option 2 -Systems that conduct monitoring under this rule, as described under Option 1, may also use one or two years of acceptable grandfathered data, in addition to the one-year of new operational data, in developing the disinfection profile.
- Option 3 -Systems that have three years of acceptable existing operational data are not required to conduct monitoring to develop the disinfection profile under this rule. Instead, they may use grandfathered data to develop a three-year disinfection profile. Systems must coordinate with the State to confirm acceptability of grandfathered data no later than March 2000, but must conduct the required monitoring until the State approves the system's request to use grandfathered data.

3.1.3 Data Quality

As noted above and in the IESWTR, existing data may be used by systems to calculate disinfection profiles if the data are approved by the State. For existing data to be acceptable to the State, the data must be "substantially equivalent" to the quality of CT data prescribed in the existing SWTR and in this guidance manual.

Substantially equivalent data are data that meet the sampling location, handling, and analytical method requirements described in this guidance manual and the *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources* (AWWA, 1991). The data should accurately characterize disinfection throughout the treatment plant. Detailed descriptions of acceptable methods for collecting the required data are provided in Sections 3.2 and 3.3 of this guidance manual. For systems that have recent recorded their daily log inactivation calculations, the State should verify the accuracy of these calculations as part of its data review and acceptance process.

3.2 Procedure to Determine Log Inactivation

This section provides an overview of the procedure to calculate CT values to determine log inactivation as designed under the SWTR and for disinfection profiling.

3.2.1 Use of CT Values for Disinfection Profiling

The CT method is used to evaluate the amount of disinfection a treatment plant achieves and to determine compliance with the SWTR. The SWTR requires physical removal and/or inactivation of 3-logs of *Giardia* and 4-logs of viruses. For disinfection profiling and benchmarking, the CT approach will be used to compute the log inactivation of *Giardia* or viruses achieved during water treatment.

The CT values corresponding to 3-log *Giardia* and 4-log viral inactivations are the basis for determining the estimated log inactivation achieved by the plant on any given day. Operational information required to use the SWTR CT tables include: disinfectant type, temperature, pH (for chlorine only), and residual disinfectant concentration. Using this operating information, the CT value corresponding to inactivations of 3-logs of *Giardia* ($CT_{3\text{-log}, \textit{Giardia}}$) and 4-logs of viruses ($CT_{4\text{-log, virus}}$) can be read from the SWTR CT tables. These CT values are used to determine the estimated log inactivation achieved by applying a disinfectant to water.

The SWTR CT tables are provided in Appendix C for reference. These tables contain CT values corresponding to specified log inactivations of *Giardia* or viruses.

3.2.2 Steps to Calculate Log Inactivation

To construct a disinfection profile, actual treatment plant inactivations need to be determined using the SWTR CT tables. Data must be representative of the entire treatment plant, from the initial point of disinfectant/oxidant addition to the entrance to the distribution system; and is not limited to the segments used for compliance with the inactivation requirements of the SWTR.

Estimated log inactivations are calculated for each disinfection segment of the treatment train. Once the log inactivations for each segment are calculated, they are summed to yield the total plant log inactivations. The following steps, which are described in greater detail in subsequent sections of this chapter and are shown in Figure 3-1, provide the general procedure for calculating the estimated log inactivations to generate disinfection profiles:

- Systems measure the following operational data each day at each disinfectant residual sampling point (Section 3.3):
  - Disinfectant residual concentration (C, in mg/L)
  - Water temperature (°C)
  - Water pH (for systems using chlorine).
- Systems determine the peak hourly flow rate for each day from flow monitoring records. The systems calculate contact time (T_{10}) for each disinfection segment based on baffling factors or tracer studies ***(Section 3.4).***
- Systems calculate CT_{actual} for each disinfection segment under actual operating conditions (i.e., C x T_{10}) ***(Section 3.4).***
- Systems determine the CT required for 3-log *Giardia* inactivation ($CT_{3\text{-log}, \textit{Giardia}}$) and/or 4-log virus inactivation ($CT_{4\text{-log, virus}}$) from the SWTR CT Tables ***(Section 3.4 and Appendix C).*** These required CT values are dependent on the disinfectant type, residual concentration, temperature, and pH.
- Systems calculate the estimated log inactivation for *Giardia* and/or viruses for each disinfection segment ***(Section 3.4)*** using:
  - Segment log inactivation of *Giardia* = $3.0 * CT_{actual} / CT_{3\text{-log}, \textit{Giardia}}$
  - Segment log inactivation of viruses = $4.0 * CT_{actual} / CT_{4\text{-log, viruses}}$

- Systems sum the segment log inactivations to determine the plant log inactivations due to chemical disinfection (the segment log inactivation are additive) ***(Section 3.4)*** using:
  - Plant log inactivation of *Giardia* = $\sum$ (segment log inactivation of *Giardia*)
  - Plant log inactivation of viruses = $\sum$ (segment log inactivation of viruses)

Figure 3-1 provides a schematic of the disinfection profiling methodology based on the log inactivation method.

3.2.3 Determining Disinfectant Residual Concentrations, pH, and Temperature

The disinfectant residual concentration is defined as the concentration of disinfectant used to protect the distribution system from recontamination. This residual is measured, along with temperature and pH, at a location referred to as the "residual sampling point." If a treatment plant has three disinfection segments it will therefore, have three residual sampling points that must be measured. Disinfection segments are further defined in Section 3.3.1.

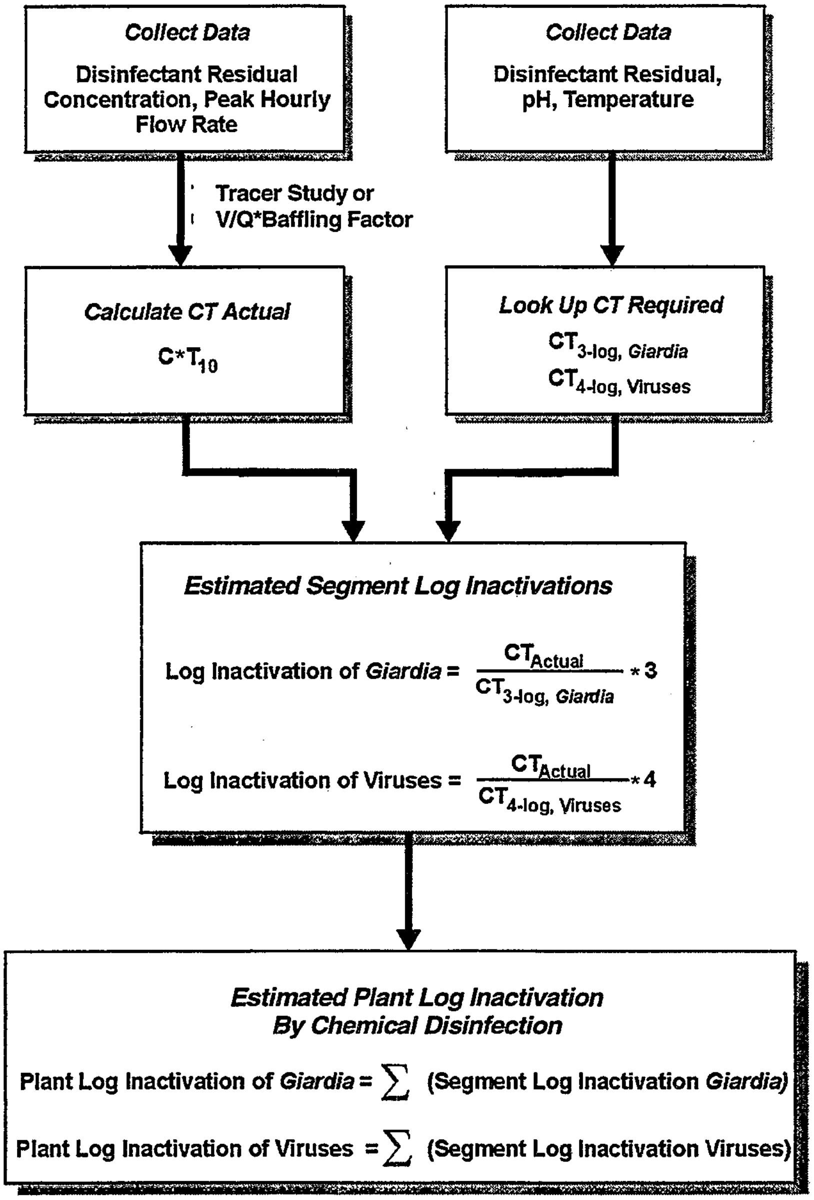
Collect Data
Disinfectant Residual Concentration, Peak Hourly Flow Rate
Collect Data
Disinfectant Residual, pH, Temperature
Tracer Study or V/Q*Baffling Factor
Calculate CT Actual
$C*T_{10}$
Look Up CT Required
$CT_{3\text{-log},\ Giardia}$
$CT_{4\text{-log},\ Viruses}$
Estimated Segment Log Inactivations
Log Inactivation of Giardia = $\frac{CT_{Actual}}{CT_{3\text{-log},\ Giardia}} * 3$
Log Inactivation of Viruses = $\frac{CT_{Actual}}{CT_{4\text{-log},\ Viruses}} * 4$
Estimated Plant Log Inactivation By Chemical Disinfection
Plant Log Inactivation of Giardia = $\sum$ (Segment Log Inactivation Giardia)
Plant Log Inactivation of Viruses = $\sum$ (Segment Log Inactivation Viruses)

Figure 3-1. Disinfection Profiling Methodology

Table 3-1. Acceptable Laboratory Methods for Analyses

Parameter	Acceptable Method(s)[1]	Examples of Commercial Test Kits/Equipment[2]
Temperature[3]	Thermometric (SM 2550)	Any good, mercury-filled thermometer but thermocouples are acceptable
pH[3]	Electrometic (SM 4500-H+) Electrometic (EPA A50.1&2)	Hach EC series & One series LaMotte DHA 3000 Orion A series & 300 series
Free Chlorine	Amperometric, Titration (SM 4500-Cl D)	Hach Amperometric Titrator Fischer-Porter 17T200 Capital Controls 1870E (on-line monitor) Great Lakes 95CL (on-line monitor)
	DPD Ferrous, Titration (SM 4500-Cl F)	LaMotte 6806/DT
	DPD, Colorimetric (SM 4500-Cl G)	Hach DR100, DR700 & DR/2000 Hach Pocket Colorimeter LaMotte DC-1100Cl LaMotte SMART Colorimeter Hach CL17 (on-line monitor)
	Syringaldizine (FACTS) (SM 4500-Cl H)	
Chloramine	Amperometric, Titration (SM 4500-Cl D)	Hach Amperometric Titrator Fischer-Porter 17T200 Capital Controls 1870E (on-line monitor) Great Lakes 95CL (on-line monitor)
	DPD Ferrous, Titration (SM 4500-Cl F)	LaMotte 6806/DT
	DPD, Colorimetric (SM 4500-Cl G)	Hach DR100, DR700 & DR/2000 Hach Pocket Colorimeter LaMotte DC-1100Cl LaMotte SMART Colorimeter Hach CL17 (on-line monitor)
Chlorine Dioxide	Amperometric, Titration (SM 4500-ClO_2 E)	Hach Amperometric Titrator Fischer-Porter 17T200
	Amperometric, Titration (SM 4500-ClO_2 D)	(Note: Platinum-Platinum electrodes are required.)
	DPD-Glycine (SM 4500-ClO_2 D)	LaMotte DC1100-CLO
Ozone	Indigo Method (SM 4500-O_3 B)	Hach DR/2000 & DR/4000 (Note: Spectrophotometric procedure is required.)

[1] SM – *Standard Methods* (1995); EPA – EPA Methods, 1995.

[2] This is not a complete list of all commercially available test kits nor an endorsement of any specific product.

[3] Samples must be analyzed prior to changes in character (e.g., sample allowed to warm prior to taking temperature)

3.2.4 Determining Contact Time, T_{10}

The contact time or detention time, T_{10}, is the value estimated using the theoretical detention time (TDT) and baffling factors or from data collected from a tracer study.

As discussed in Section 3.3.1, the treatment train may be divided into several disinfection segments, corresponding to the number of disinfectant application points. The disinfection segments may include several unit processes of the treatment train. The total T_{10} for the disinfection segment is the sum of each T_{10} for each unit process within the segment. The T_{10} can also be calculated for the whole plant or an entire segment instead of for individual segments, as long as there are no additional points of disinfectant addition.

The segment T_{10} is multiplied by the disinfectant residual at the end of the segment to yield the segment CT_{actual}. Section 3.4 provides an example of segmenting the treatment train and the corresponding CT calculations.

There are two methods to determine the contact time for a treatment process. The first method calculates contact time by utilizing the hydraulic characteristics of the treatment basin and baffling factors. These baffling factors are shown in Appendix D or may be available from the State. The second method involves conducting a tracer study for each disinfection segment. Baffling factors are used to determine T_{10} from theoretical detention times in systems when it is impractical to conduct tracer studies. These two methods and their use are discussed in detail in Sections 3.2.4.1 and 3.2.4.2.

Tracer Studies versus Baffling Factors

Tracer studies are more accurate than baffling factors as they provide a real measure of the contact time by measuring the time it takes for the tracer to flow through each segment in the treatment train. Tracer studies provide a better understanding of how well the disinfectant is mixing with the water for the hydraulic conditions of a specific water treatment plant. The disadvantage of the tracer study is that it is costly to conduct. The baffling factor method is a useful alternative for determining the contact time. It is less labor intensive, inexpensive, and easy to perform. The disadvantage, however, is that the baffling factors may not accurately represent the actual contact time of the system.

A conservative approach to calculating the contact time with baffling factors is to select the lowest baffling condition that is applicable. Baffling conditions include: very poor, poor, average, superior, or perfect. If it is not clear whether the baffling condition for a basin is average or superior, then the conservative approach is to use the average condition for the T_{10} calculations.

Contact Time for Unit Process

The unit processes that comprise each disinfection segment may include sedimentation, filtration, and pipeline flow, among others. Each of these reactors has special hydraulic characteristics affecting the contact time. In pipelines, the contact time can be assumed equivalent to the theoretical detention time and is calculated by dividing the internal volume of the pipeline by the peak hourly flow rate through the pipeline. Pipeline flow is assumed to be plug flow with no dead zones or unutilized volume in the reactor. Therefore, each unit of water is assumed to spend the same time in the pipeline, referred to as the TDT. For reactors of other shapes (e.g., a rectangular sedimentation basin) the time spent by the water in the reactor may vary over a range. For example, some water may move faster by short-circuiting while other water may spend more time in the reactor trapped in "dead zones" resulting in little flow. This variation in the time that water could spend in a particular unit process leads to a distribution of potential residence times from which T_{10} can be determined.

Contact Time for Pipe Flow

The contact time calculation for pipe flow is simply the theoretical detention time, which is the volume (V, in gallons) divided by the peak hourly flow rate (Q, in gallons per minute (gpm)),

$$T_{10} = \text{Contact Time} = V/Q \text{ (applicable to pipe flow only)}$$

Pipe flow does not require a tracer study to calculate contact time. The baffling factor for pipe flow is 1.0.

The following example of pipe flow assumes the pipeline to be 2,800 feet long and to have a cross-sectional area of 18 square feet (calculated from its inside diameter). The peak hourly flow rate in the pipeline is 10,651 gpm. The volume of water contained within the full pipeline is the length multiplied by the cross-sectional area. The resulting volume is:

$$\text{Volume, } V = 2800 \text{ feet} * 18 \text{ feet}^2 = 50{,}400 \text{ ft}^3$$

Converting the volume to gallons,

$$V = 50{,}400 \text{ ft}^3 * 7.48 \text{ gallons/1 ft}^3 = 376{,}992 \text{ gallons}$$

Calculating the contact time,

$$T_{10} = V/Q = 376{,}992 \text{ gallons} / 10{,}651 \text{ gpm}$$
$$T_{10} = 35.4 \text{ minutes}$$

Contact Time in Mixing Basins and Storage Reservoirs

In mixing basins and storage reservoirs, the theoretical detention time generally does not represent the actual disinfectant contact time because of short-circuiting. Thus, determining contact time is more complicated with basins.

The time used to compute CT_{actual} in treatment basins depends on the reservoir shape, inlets, outlets, and baffling. Most clearwells and some other treatment basins were not designed to provide optimal hydraulic characteristics for contact with a disinfectant. Utilities are required to determine the contact time in mixing basins, storage reservoirs, and other treatment plant unit processes for the calculation of CT_{actual} through tracer studies or other methods approved by the State. For the purpose of determining compliance with the disinfection requirements of the SWTR, the contact time of mixing basins and storage reservoirs used in calculating CT_{actual} should be the detention time in which 90 percent of the water passing through the unit is retained within the basin, (i.e., T_{10}). Information provided by tracer studies is used for estimating the detention time T_{10} for the purpose of calculating CT_{actual}. If tracer studies are not practical, the TDT and baffling factor approach can be used. In Appendix D, complete descriptions of both the TDT and baffling factor method and the tracer test method to evaluate T_{10} are provided. A plant with multiple treatment trains and different operating characteristics should have the critical train identified.

3.2.4.1 Determining Contact Time Using Baffling Factors

The TDT is computed by dividing the volume of a unit process by the peak hourly flow rate (TDT=V/Q). Baffling factors (T_{10}/T) selected for a specific unit process are multiplied by the theoretical detention time to yield an estimate of the contact time, T_{10}, as follows:

$$T_{10} = \text{Contact Time} = V/Q * T_{10}/T$$

Table 3-2 describes baffling classifications and baffling factors (T_{10}/T ratios). The baffling factor is a function of design of the basin. A baffling factor of 1.0 represents plug flow characteristics. In plug flow, the TDT is equivalent to the contact time, T_{10}. Design modifications that can increase T_{10} may allow the same inactivation (CT) with a decreased disinfectant residual.

Table 3-2. Baffling Classifications and Factors

Baffling Condition	**T_{10}/T**	**Baffling Description**
Unbaffled (mixed flow)	0.1	None, agitated basin, very low length to width ratio, high inlet and outlet flow velocities
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: AWWA, 1991.

Using the following example information, the TDT can be calculated:

- Volume of a contact basin = 500,000 gallons
- Peak hourly rate = 10,000 gpm
- Contact basin = unbaffled.

The TDT is then calculated as follows:

$$TDT = V/Q = 500{,}000 \text{ gallons}/10{,}000 \text{ gpm} = 50 \text{ minutes}$$

However, because the contact basin is unbaffled, the T_{10}/T is 0.1 and the resulting actual contact time used for determining log inactivation is:

$$T_{10} \text{ (contact time)} = 50 \text{ minutes} * 0.1 = 5 \text{ minutes}$$

The CT value for this unit process at 1.2 mg/L residual chlorine is:

$$CT = 5 \text{ minutes} * 1.2 \text{ mg/L} = 6 \text{ mg-min/L.}$$

By improving contact conditions through inlet and outlet and some intra-basin perforated baffles, the T_{10}/T may improve to 0.7 and, therefore, the new contact time is:

$$T_{10} \text{ (contact time)} = 50 \text{ minutes} * 0.7 = 35 \text{ minutes.}$$

The new CT value at 1 mg/L of chlorine is:

$$CT = 35 \text{ minutes} * 1.2 \text{ mg/L} = 42 \text{ mg-min/L}$$

At a pH value of 6.0 and a water temperature of 15°C, the CT value needed to achieve a 2-log inactivation of *Giardia* by free chlorine (Table C-4, Appendix C) is 35 mg-min/L. At a pH value of 6.0 and a water temperature of 15°C the CT value needed to achieve 2.5-log inactivation of *Giardia* by free chlorine (Table C-4, Appendix C) is 44 mg-min/L.

To determine the estimated *Giardia* log inactivation for the CT value of 42 mg-min/L, linear interpolation may be used as follows:

$$\text{Estimated Log removal} = (42 \text{ mg-min/L} * 2.5 \text{ logs}) / 44 \text{ mg-min/L} = 2.4$$

or

$$\text{Estimated Log removal} = (42 \text{ mg-min/L} * 2 \text{ logs}) / 35 \text{ mg-min/L} = 2.4$$

In order to determine the contact time using baffling factors, the following steps ought to be taken:

- Determine peak hourly flow rate, Q, based on operation records;
- Determine the volume of each unit process;
- Calculate the TDT, where TDT = V/Q;
- Determine the baffling factor based on the unit processes baffling conditions, T_{10}/T;
- Calculate the contact time, where $T_{10} = TDT * T_{10}/T$; and
- Determine the segment T_{10} by summing each T_{10} of the unit processes in the segment.

3.2.4.2 Determining Contact Time Using a Tracer Study

A tracer study uses a chemical tracer to determine the detention time of water flowing through a unit process, segment, or system. Typical chemical tracers include chloride ions, fluoride ions, and a fluorescent dye Rhodamine WT. Ideally, the selected tracer chemical should be readily available, easily monitored, and acceptable for use in potable water supplies. The tracer should also be conservative (i.e., the tracer is not consumed or removed during treatment). Fluoride ions can generally be used in lower concentrations than chloride because they are typically present in lower concentrations in the water. Rhodamine is a fluorescent tracer that, if selected, must be used following certain guidelines found in Appendix D. Selection of a particular chemical tracer may depend on the unit processes and the salt concentrations present in the water. Specific instructions on chemical tracers and under what conditions are they most effective are found in Appendix D. If a tracer study is needed in order to find T_{10}, a water system should consult the latest tracer study guidance from the State.

The tracer chemical should be added at the same points in the treatment train as the disinfectant to be used in the CT calculations, since it will be used to determine T_{10} for the disinfection segment. Two common methods of tracer addition are the step-dose method and the slug-dose method. In the step-dose method, the tracer chemical is injected at a constant dosage and the endpoint concentration is monitored. To determine a 90 percent recovery for the tracer, endpoint sampling should continue until the tracer concentration reaches a steady-state level. With the slug-dose method, a large dose of tracer chemical is instantaneously injected. An effective way to achieve instantaneous addition is to use a gravity-fed tube to release the single dose. The tracer concentration is monitored at the endpoint, until the entire dose has passed through the system. Unlike the step-dose method, a mass balance is required to determine whether the entire tracer dose was recovered. Additional mathematical manipulation is required to determine T_{10} from the concentration versus time profile.

The test procedure for determining the contact time with a tracer study is generally as follows:

- The system determines the flow rate or rates to be used in the study.
- The system selects the tracer chemical and determines the raw water background concentration of the tracer chemical. The background level is needed to both determine the quantity of chemical to feed and to evaluate the data properly.
- The system determines the tracer addition locations, plans the sample collection logistics and frequency, and determines the appropriate tracer dosage. Sampling frequencies depend on the size of the basin—the larger the basin the easier it is to obtain an adequate profile with less frequent sampling is needed. Small basins need more frequent sampling. However, to obtain an adequate profile, large systems may be more difficult to handle than small basins because sampling events are longer in duration thus presenting logistical problems in staffing for sample collection and sample analysis.
- The system conducts the tracer test using either the step-dose or slug-dose methods.
- The system compiles and analyzes the data.
- The system calculates T_{10}.

Additional discussions on tracer studies and determining contact times are provided in Appendix D. Additional references for information on tracer studies and details concerning how to conduct one are as follows:

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3.3 Monitoring Procedures

This section describes the various monitoring procedures for disinfection profiling as required under the IESWTR. It addresses the following topics: defining disinfection segments within a treatment train based on the number of disinfection application points and determining disinfectant residual concentrations.

3.3.1 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 systems 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. Each segment begins at the point of disinfection application and ends at the disinfection 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. As stated before, disinfection segments may include several unit processes of the treatment train.

For instance, if the treatment train includes two applications of chlorine, then the treatment train is divided into two disinfection segments. The first segment begins at the first point of disinfectant application and ends at the residual disinfectant sampling point, just prior to the second disinfectant application point. The second disinfection segment begins at the second point of disinfectant application and ends at the second disinfectant residual sampling point. For any system, the last disinfection segment must end at or before the entrance to the distribution system or before the first customer. Disinfection segments always start at the application point of a disinfectant and end at the residual sampling point.

Systems may find it useful to divide a single disinfection segment 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 network, the whole plant is a single disinfection segment. The T_{10}/T value multiplied by the free chlorine concentration will give a conservative CT value for the plant (due to free chlorine volatilization at various treatment stages). Therefore, by measuring the free chlorine residual at the end of each treatment unit will provide a different CT value and hence a less conservative estimate of log inactivation.

Section 3.6.1 provides a detailed example of how to define disinfection segments and then use these segments to compute CT and log inactivation values.

3.4 Calculating Estimated Log Inactivation

The objective of this section is to demonstrate, in greater detail, the calculations involved in determining the estimated log inactivations. The section describes the SWTR log inactivation method, procedures to determine minimum regulatory log inactivations for *Giardia* (3-log removal) and viruses (4-log removal), procedures to calculate estimated log inactivations for one disinfection segment of a plant, and the method to determine the overall estimated plant log inactivation.

3.4.1 SWTR Log Inactivation CT Method

The SWTR requires *Giardia* and virus inactivations for drinking water systems. Because of the difficulty in measuring actual microbial inactivations, EPA developed CT tables (see Appendix C) that can be used to estimate the inactivations achieved through chemical disinfection. These tables were developed for approved disinfectants, including chlorine, ozone, chlorine dioxide, and chloramines.

The tables indicate the log inactivation of *Giardia* and viruses corresponding to the operating conditions of temperature, pH, residual disinfectant concentration, and contact time. These tables are presented in the form of log inactivation versus operational conditions since the relationship between CT and log inactivation of *Giardia* is relatively linear for most disinfectant and organism combinations. Log inactivation is an expression of the magnitude of microorganisms that are inactivated during the disinfection process. Table 3-3 presents log inactivations and their corresponding percent inactivations.

Table 3-3. Log Inactivations and Percent Inactivations

Log Inactivation	Percent Inactivation
0.0	0.000
0.5	68.38
1.0	90.00
2.0	99.00
3.0	99.90
4.0	99.99
5.0	99.999
6.0	99.9999
7.0	99.99999

Appendix B provides a detailed explanation for the development of the log inactivation method under the SWTR.

3.4.2 Determining $CT_{3\text{-log, Giardia}}$ and $CT_{4\text{-log, virus}}$

To calculate the estimated log inactivation of a plant, Equation 3-1 and Equation 3-2 must be used to calculate the log inactivations of each disinfection segment. The estimated log inactivations for each segment are then summed to calculate the estimated log inactivations of the plant.

$$\text{Estimated Log Inactivation of Giardia} = 3.0 * \frac{CT_{\text{actua}}}{CT_{\text{3-log, Giardia}}} \quad \textbf{Equation 3-1}$$

$$\text{Estimated Log Inactivation of Viruses} = 4.0 * \frac{CT}{CT_{\text{4-log, Virus}}} \quad \textbf{Equation 3-2}$$

Equations 3-1 and 3-2 are derived in Section 3.4.3. To use Equation 3-1 and Equation 3-2 in order to calculate the estimated log inactivations of a segment the operator must know the CT_{actual} and the required $CT_{3\text{-log, }\mathit{Giardia}}$ or required $CT_{4\text{-log, virus}}$. CT_{actual} is determined based on daily sampling of the residual disinfectant concentration, C, and calculating the contact time, T_{10}. The sampling, and calculation of contact time, must be performed for each of the disinfectant segments using the procedures described in Section 3.2. This section describes how to determine the required $CT_{3\text{-log, }\mathit{Giardia}}$ and the required $CT_{4\text{-log, virus}}$ for each of the disinfection segments.

Since plants rarely operate at a pH, temperature and residual disinfection concentration that exactly matches the CT tables in the *Guidance Manual for*

Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources (AWWA, 1991), the operator may determine a CT value that lies in between the values. These tables are presented in Appendix C of this guidance manual.

In addition to linear interpolation (see example in Section 3.2.4.1), two methods are presented in this manual for determining the CT values, the "Approximation Method" and the "Regression Method." The PWS should be consistent when choosing a method to calculate CT.

The Regression Method is an efficient way to calculate $CT_{3\text{-log},\ \textit{Giardia}}$ using a computer spreadsheet when free chlorine is the disinfectant being used. This method uses empirical regression equations (Smith et al., 1995) to estimate the CT required to inactivate 3-log *Giardia* with chlorine. An example of the Regression Method is found in Appendix E.

The Approximation Method can be used for $CT_{3\text{-log},\ \textit{Giardia}}$ or $CT_{4\text{-log},\ \text{virus}}$ for all disinfectants. With this method, conservative values of pH, temperature, and residual disinfectant concentration are used to select a CT value from the table. The Approximation Method is more conservative than linear interpolation and the Regression Method as it approximates the value of the required $CT_{3\text{-log},\ \textit{Giardia}}$ and the required $CT_{4\text{-log},\ \text{virus}}$. Systems with a pH greater than 9.0 should follow applicable State guidance. The explanation of this method is adapted from a publication by the Texas Natural Resource Conservation Commission (TNRCC, 1998) and is also discussed in the *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources* (AWWA, 1991).

Since it requires no mathematical calculations and reduces errors, the Approximation Method is usually recommended because it is easier to use. However, this method is conservative and slightly underestimates the actual effectiveness of the disinfection process. Also, linear interpolation for all disinfectants is acceptable.

Procedure ($CT_{3\text{-log},\ \text{Giardia}}$):

- Go to Table 3-4 for *Giardia* inactivation using free chlorine.
- Find the CT for the temperature that is equal to (or slightly below) the actual temperature of the water. For example, if the temperature is 19°C, use the 15°C table.
- Go to the section of the table for the pH which is equal to (or slightly above) the actual pH of the water. For example, if the pH is 7.2, use the pH=7.5 section.
- Look at the far left side of the table and find the chlorine concentration that is equal to (or slightly above) the actual free chlorine

concentration. For example, if the chlorine concentration is 1.1 mg/L, use the 1.2 mg/L row. If the chlorine concentration is above 3mg/L, use the values corresponding to 3mg/L.

- The value shown at the intersection of the concentration row and the temperature/pH column is the value of the required-$CT_{3\text{-log},\ \mathit{Giardia}}$. For example, at pH 7.5, 15°C, and 1.2 mg/L of chlorine, the required $CT_{3\text{-log},\ \mathit{Giardia}}$ is 92 mg-min/L.

Example:

Find the value of $CT_{3\text{-log},\ \mathit{Giardia}}$ for a water temperature of 10.8°C, a pH of 8.2, and a residual of 2.5 mg/L for a plant that is using free chlorine as the disinfectant. Use the next lower temperature, 10°C.

Using Table 3-4, look under the pH=8.5 across the 2.6 mg/L row to find that the $CT_{3\text{-log},\ \mathit{Giardia}}$ is 234 mg-min/L.

Important Note:

The procedure to calculate the required $CT_{3\text{-log},\ \mathit{Giardia}}$ when using free chlorine for water with a pH greater than 9.0 requires the use of the pH 9.0 table or applicable State guidance. No *Giardia* disinfection credit is allowed for free chlorine if the pH in the disinfection segment is above 11.5.

Procedure ($CT_{4\text{-log},\ virus}$):

- Go to Table 3-5 for viral inactivation using free chlorine.
- Go to the column for the temperature that is equal to (or slightly below) the actual temperature of the water. For example, if the temperature of the water is 10.5°C, use the temperature = 10°C column.
- The value shown in the 10°C temperature column is the value of $CT_{4\text{-log},\ virus}$.

Table 3-4. Required CT Values (mg-min/L) for 3-log Inactivation of *Giardia* Cysts by Free Chlorine, pH 6.0-9.0

Chlorine Concentration (mg/L)	Temperature<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	19	23	277	329	390	97	11	13	166	198	236	279	73	88	104	12	149	177	209
0.6	141	169	20	23	286	342	407	100	12	14	171	204	244	291	75	90	107	12	153	183	218
0.8	145	172	20	24	295	354	422	103	12	14	175	210	252	301	78	92	110	13	158	189	226
1	148	176	21	25	304	365	437	105	12	14	179	216	260	312	79	94	112	13	162	195	234
1.2	152	180	21	25	313	376	451	107	12	15	183	221	267	320	80	95	114	13	166	200	240
1.4	155	184	22	26	321	387	464	109	13	15	187	227	274	329	82	98	116	14	170	206	247
1.6	157	189	22	27	329	397	477	111	13	15	192	232	281	337	83	99	119	14	174	211	253
1.8	162	193	23	27	338	407	489	114	13	16	196	238	287	345	86	10	122	14	179	215	259
2	165	197	23	28	346	417	500	116	13	16	200	243	294	353	87	10	124	15	182	221	265
2.2	169	201	24	29	353	426	511	118	14	16	204	248	300	361	89	10	127	15	186	225	271
2.4	172	205	24	29	361	435	522	120	14	17	209	253	306	368	90	10	129	15	190	230	276
2.6	175	209	25	30	368	444	533	122	14	17	213	258	312	375	92	11	131	16	194	234	281
2.8	178	213	25	31	375	452	543	124	14	17	217	263	318	382	93	11	134	16	197	239	287
3	181	217	26	31	382	460	552	126	15	18	221	268	324	389	95	11	137	16	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.	8.0	8.5	9.0	<=6.	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	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	58	69	83	10	122	147	177	44	52	62	75	91	110	132	29	35	41	50	61	74	89
2.2	59	70	85	10	124	150	181	44	53	63	77	93	113	135	30	35	42	51	62	75	90
2.4	60	72	86	10	127	153	184	45	54	65	78	95	115	139	30	36	43	52	63	77	92
2.6	61	73	88	10	129	156	188	46	55	66	80	97	117	141	31	37	44	53	65	78	94
2.8	62	74	89	10	132	159	191	47	56	67	81	99	119	143	31	37	45	54	66	80	96
3	63	76	91	11	134	162	195	47	57	68	83	101	122	146	32	38	46	55	67	81	97

For CT values for the inactivation of *Giardia* and viruses using chlorine dioxide, ozone, or chloramines, use the Tables in Appendix C.

Example:

Find the value of the required $CT_{4\text{-log, virus}}$ for a water temperature of 10.8°C and a pH of 9.0 for a plant that is using free chlorine as the disinfectant.

Using Table 3-5 for free chlorine and using 10°C, the required $CT_{4\text{-log, virus}}$ is 6 mg-min/L.

Table 3-5. Required CT Values (mg-min/L) for 4-Log Inactivation of Viruses by Free Chlorine, pH 6.0-9.0

Temperature (°C)	CT Value (mg-min/L)	Temperature (°C)	CT Value (mg-min/L)
0.5	12	13	4.8
1	11.6	14	4.4
2	10.7	15	4
3	9.8	16	3.8
4	8.9	17	3.6
5	8	18	3.4
6	7.6	19	3.2
7	7.2	20	3
8	6.8	21	2.8
9	6.4	22	2.6
10	6	23	2.4
11	5.6	24	2.2
12	5.2	25	2

3.4.3 Log Inactivation Calculations

This section provides the procedures for calculating log inactivations for generating disinfection profiles. This section provides an example of calculating estimated log inactivations using the Approximation Method to determine $CT_{3\text{-log, }\mathit{Giardia}}$ and $CT_{4\text{-log, virus}}$ when using free chlorine at pH less than or equal to 9.0. At pH greater than 9.0, systems must use the pH 9.0 table or State-approved protocol. The procedure is as follows:

Estimated log inactivation is calculated by assuming the relationship between CT and log inactivation is linear and can be represented mathematically by the following equation:

$$\frac{\text{Estimated Log Inactivation}}{\text{3 -Log Inactivation}} = \frac{CT_{\text{actual}}}{CT_{99.9\ (\text{or 3-log, } Giardia)}}$$

Rearranging the equation:

$$\text{Estimated Log Inactivation} = 3.0 * \frac{CT_{\text{actual}}}{CT_{\text{required}}}$$

Assuming a base condition of 3-log inactivation for *Giardia* and 4-log inactivation for viruses, the general equations are as follows:

$$\text{Estimated Log Inactivation of Giardia} = 3.0 * \frac{CT_{\text{actual}}}{CT_{\text{3-log, Giardia}}}$$

Equation 3-1

$$\text{Estimated Log Inactivation of Viruses} = 4.0 * \frac{CT_{\text{actual}}}{CT_{\text{4-log, Virus}}}$$

Equation 3-2

These general equations are actually extrapolations of the SWTR based on the 3-log and 4-log inactivation values. However, they can be used by any surface water treatment plant, whether practicing filtration or not. The equations remain valid for systems with lower required inactivations (i.e., filtration plants) because of the linear relationship between CT and log inactivation.

3.4.4 Summing the Estimated Log Inactivations of each Segment to Determine the Log Inactivation of the Plant

Once the $CT_{\text{3-log, } Giardia}$ and $CT_{\text{4-log, virus}}$ have been determined for a segment in a treatment plant, this information can be used in Equation 3-1 or Equation 3-2 along with the CT_{actual} to calculate the daily log inactivation of *Giardia* or viruses for a given segment. The daily log inactivation of the plant is then calculated by summing the log inactivations of the individual segments into a daily log inactivation for the plant as follows:

$$\text{Total plant log inactivation} = \Sigma(\text{segment log inactivation})$$

3.5 The Completed Profile

The disinfection profile consists of the daily log *Giardia* (or virus) inactivation levels plotted against time. The log inactivation calculation methodology was used for a specific system as an example for developing the IESWTR. Figures 3-2 through 3-4 present the disinfection profiles showing variations in daily log inactivations of *Giardia* at a sample facility from 1994 through 1996. In general, as can be seen from Figures 3-2 and 3-3, seasonal variations in log removal of *Giardia* can be discerned from the disinfection profiles. However, as depicted in Figure 3-4, 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 at this facility occurred at the end of June 1995.

Systems should keep the completed profile and supporting data on file at the treatment plant or at its offices in graphical form, as a spreadsheet, or in some other format approved by the State. A system is not required to submit the profile and supporting data to the State unless it is requested or if the system intends to make a significant modification to its disinfection practice. It is important to retain the profile and supporting data in the event the system decides to modify its disinfection practice and must therefore, create a benchmark.

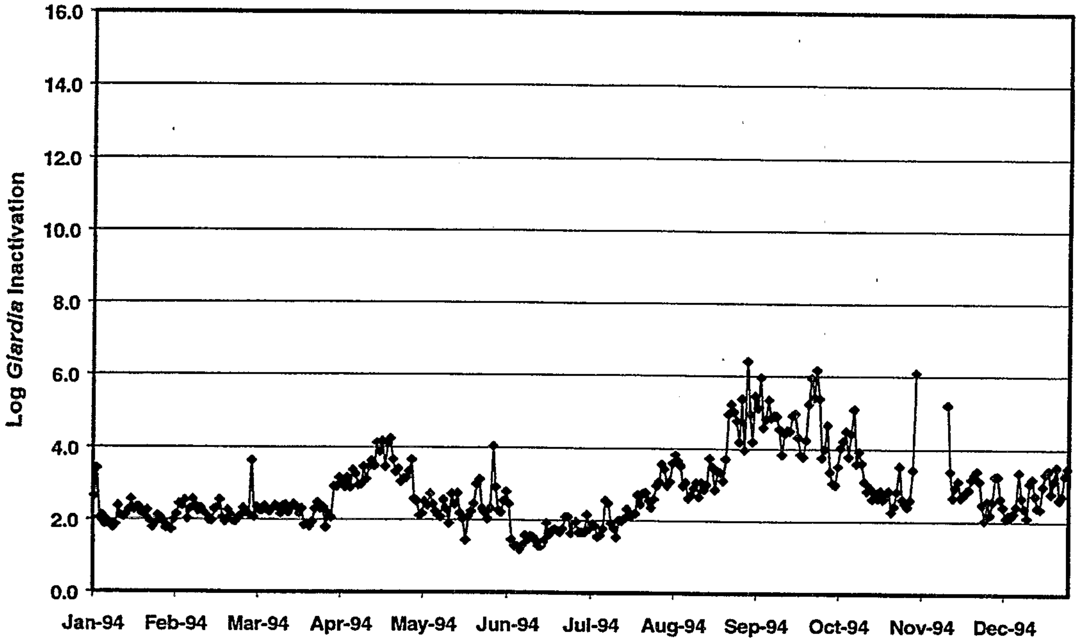


Figure 3-2. 1994 Profiling Data

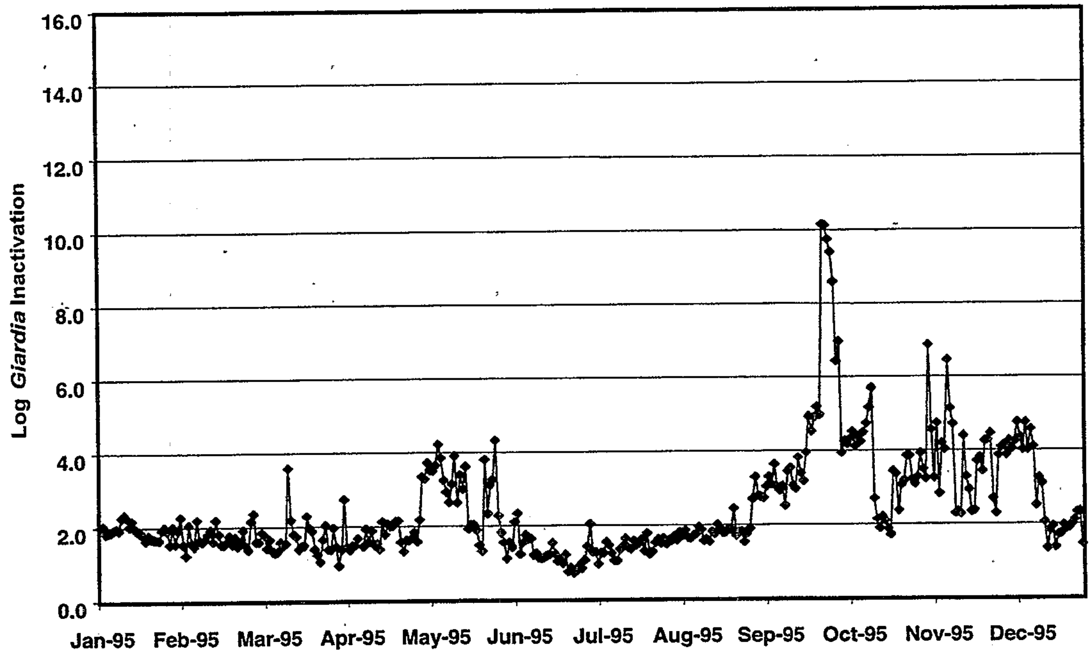


Figure 3-3. 1995 Profiling Data

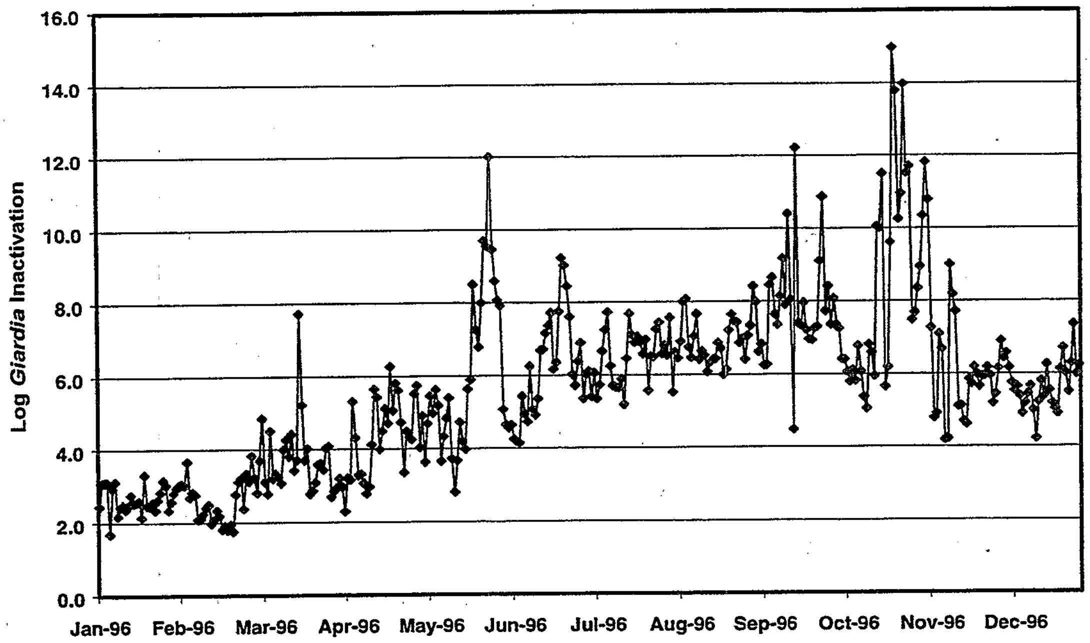


Figure 3-4. 1996 Profiling Data

3.6 Examples of Estimating Log Inactivation of Giardia and Viruses for Conventional Filtration Plants

These examples are intended to enhance the discussion of CT calculations provided earlier. These examples illustrate the necessary information and computations needed to perform a complete CT analysis and to determine log inactivation of *Giardia* and viruses for a single day. Where applicable, a reference is given to the location within the text where a more complete description of the topic can be found. Chapter 4 continues these examples by developing a disinfection benchmark. Chapter 5 also demonstrates the utility of a disinfection benchmark in designing alternative disinfection strategies to control DBPs while meeting existing levels of disinfection.

The data required for estimating log inactivation are:

- pH (chlorine only)
- Water temperature, in °C
- Disinfectant residual, in mg/L
- Peak hourly rate for the day, in gpm
- Volume of water in each segment of treatment plant, in gallons
- Baffling conditions.

The last two data elements, the volume of water in each segment and the baffling conditions, are set by the treatment plant configuration. pH and water temperature measurements should be measured at the same time the disinfectant residual sample is being taken. Measurements of these parameters should be conducted during or about the peak hour demand time.

As stated earlier, when calculating estimated log inactivation the following rules are set as guidance to develop a conservative (when compared to direct linear interpolation of CT values) log inactivation estimate:

1. Temperature – if the water temperature falls in between what is listed in the tables the system should use the CT value corresponding to the next lower temperature.

2. pH – if the water pH falls in between what is listed in the tables, systems should use the CT value corresponding to the next higher pH value. For pH values greater than 9.0, systems should use pH 9.0 or apply State guidance.

3. Disinfectant residual – if the disinfectant residual value is in between what is listed in the tables, the system should use the next higher value to calculate the $CT_{3\text{-log},\ Giardia}$. If the disinfectant residual is greater than 3 mg/L, the system must use 3 mg/L for calculating estimated CT and to determine the $CT_{3\text{-log},\ Giardia}$ value and for calculation of CT_{actual}.

3.6.1 Example of Developing a Disinfection Profile for a 40 mgd Plant

This example considers disinfection at a 40 mgd conventional filtration plant. The plant is five years old and is expected to reach capacity in 25 years. A process diagram for the plant is shown in Figure 3-5. The plant process train is divided into three disinfection segments. Chlorine is dosed at two locations: to the raw water and immediately prior to filtration. Ammonia is applied just prior to the clearwell to form chloramines. The three disinfection segments are shown at the top of the diagram. Each segment begins at the point of disinfectant application, and ends at the disinfectant residual sampling point. The diagram indicates information needed to calculate the theoretical detention time using the peak hourly flow rate and T_{10} for each unit process determined by the baffling factor approach discussed earlier and in Appendix D.

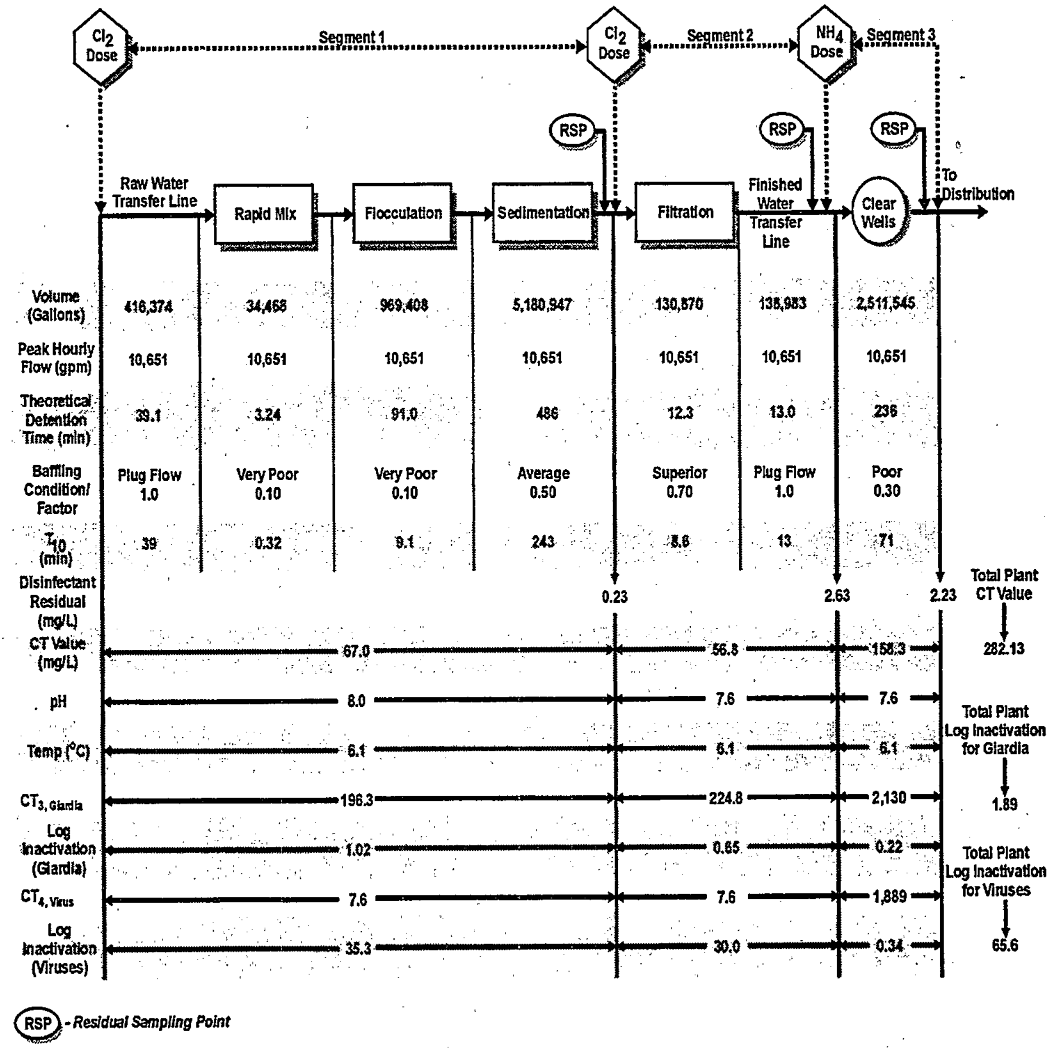

Cl_2 Dose
Segment 1
Cl_2 Dose
Segment 2
NH_4 Dose
Segment 3
RSP
RSP
RSP
Raw Water Transfer Line
Rapid Mix
Flocculation
Sedimentation
Filtration
Finished Water Transfer Line
Clear Wells
To Distribution
Volume (Gallons)
416,374
34,468
969,408
5,180,947
130,870
138,983
2,511,545
Peak Hourly Flow (gpm)
10,651
10,651
10,651
10,651
10,651
10,651
10,651
Theoretical Detention Time (min)
39.1
3.24
91.0
486
12.3
13.0
236
Baffling Condition/ Factor
Plug Flow 1.0
Very Poor 0.10
Very Poor 0.10
Average 0.50
Superior 0.70
Plug Flow 1.0
Poor 0.30
T_{10} (min)
39
0.32
9.1
243
8.6
13
71
Disinfectant Residual (mg/L)
0.23
2.63
2.23
CT Value (mg/L)
67.0
56.8
158.3
Total Plant CT Value
282.13
pH
8.0
7.6
7.6
Temp (°C)
6.1
6.1
6.1
Total Plant Log Inactivation for Giardia
1.89
$CT_{3, Giardia}$
196.3
224.8
2,130
Log Inactivation (Giardia)
1.02
0.65
0.22
Total Plant Log Inactivation for Viruses
65.6
$CT_{4, Virus}$
7.6
7.6
1,889
Log Inactivation (Viruses)
35.3
30.0
0.34
RSP - Residual Sampling Point

Figure 3-5. 40 mgd Conventional Filtration Process Diagram

The plant actually consists of four identical, parallel 10 mgd process trains, so there are four rapid mix basins, four flocculation basins, etc., all of equivalent size. Because each of the four trains are identical, the approach to calculating the TDT for a process (e.g., rapid mix) is to sum the volumes of the reactors (four times the volume of a single reactor) and divide by the total plant peak hourly flow rate. Table 3-6 summarizes the design conditions for each unit process.

Table 3-6. Unit Process Design Conditions Summary

	Raw Water Line	**Rapid Mix**	**Flocculation**	**Sedimentation**	**Filtration**	**Finished Water Transfer Line**	**Clearwells**
Design Flow (mgd)	40	40	40	40	40	40	**40**
Theoretical Detention Time (min)	15.0	1.24	34.9	372	4.71	5.00	**90.4**
Hydraulic Loading Rate	*n/a*	*n/a*	*n/a*	0.362 *gpm/ft²*	4.8 *gpm/ft²*	*n/a*	***n/a***

Note: See Figure 3-5 for reactor volumes.
n/a – not applicable

The design parameters listed in Table 3-6 are higher than current plant peak water demand. Moreover, treatment plant peak hourly flow rate varies by day of the week, by season, by special events, and by type of economic activities and cycles which may require heavy uses of water during specific times of the day.

The calculations detailed in Section 3.6.1.1 use the data presented in Figure 3-5. These calculations illustrate the procedure for computing the log inactivations of *Giardia* and viruses. The first step involves collecting the appropriate data required for computing log inactivation. Since chlorine is used in this plant, pH and temperature are measured at the same times and locations as the chlorine residual (i.e., the residual sampling points). Temperature measured at the head of the plant is acceptable because it is generally lower than the temperature of the finished water. For this plant, the peak hourly flow rate during the day of interest was determined to be 10,651 gallons per minute (15.3 mgd). This flow is determined by examining the flow record to find the greatest volume of water passing through the system during any one hour during the day. The peak hourly rate, during the day of interest, is about 38 percent of plant capacity. This low percentage level is expected to occur on a low-demand day and in a five-year-old plant that is expected to reach capacity in 25 years.

For each unit process within a disinfection segment, the volume, theoretical detention time, baffling condition, and T_{10} must be determined if tracer study data are not available. Volume calculations for each unit process are presented later Section 3.6.1.1, and are discussed in Appendix D. The volume of the unit occupied by water, not the total unit volume, is used to compute TDT. For example, for filters, the volume of media must be subtracted to get the volume of the filter process occupied by water. Additionally, for clearwells or tanks with variable storage volume, the minimum storage volume during the day is used. The different types of equations used to calculate the volumes are shown in Table 3-7.

Table 3-7. Volume Equations

Volume of Filtration	= Volume of Filters – Volume of Media = (# of filters) x (Length) x (Width) x (Total depth) – (# of filters) x (Length) x (Width) x (Depth of media) x (Porosity)
Volume of Raw Water Pipe	= (Length) x (Cross-sectional Area)
Volume of Rapid Mix Basins	= (# of basins) x (Length) x (Width) x (Depth of water)
Volume of Water in Clearwells	= (# of tanks) x (Minimum water depth) x (Cross-sectional Area)

The theoretical detention time is the unit process volume divided by the peak hourly flow rate. This theoretical detention time must be multiplied by a baffling factor to yield T_{10} (i.e., contact time), if tracer study data are not available. Baffling classifications, T_{10} definition, and determination are discussed in detail in Appendix D.

3.6.1.1 Contact Time Computations for 40 mgd Plant

The following pages illustrate detailed calculations to determine contact time for each unit process, as shown in Figure 3-5.

Unit Process: RAW WATER PIPE

VOLUME OF RAW WATER PIPE = *(Length) x (Cross-sectional Area)*

= $(2{,}835\ ft) \times \pi \times (2.5\ ft)^2$

= $55{,}665\ ft^3$

Convert cubic feet to gallons = $55{,}665\ ft^3 \times \frac{7.48\,gallons}{1\,ft^3} = 416{,}374\ gallons$

FLOW RATE = Peak hourly flow occurring during the 24-hour period

= 10,651 gpm

THEORETICAL DETENTION TIME (TDT)= $\frac{\text{Volume of Unit Process}}{\text{Flow Rate}}$

TDT RAW WATER PIPE = $\frac{416{,}374\ \text{gallons}}{10{,}651\ \text{gpm}}$

= *39.1 minutes*

BAFFLING CONDITION = Perfect flow (Refer to Appendix D for determining baffling factors).

T_{10}/T = 1.0

Unit T_{10} RAW WATER PIPE = $TDT \times T_{10}/T$

= (39.1 minutes) x (1.0)

= 39 minutes

Unit Process: RAPID MIX BASIN

VOLUME OF RAPID MIX BASINS = *(# of basins) x (Length) x (Width) x (Depth of Water)*

= *(4) x(12 ft) x (12 ft) x (8 ft)*

= $4{,}608\ ft^3$

Convert cubic feet to gallons = $4{,}608\ ft^3 \times \frac{7.48\,gallons}{1\,ft^3} = 34{,}468$ gallons

FLOW RATE = Peak hourly flow occurring during the 24-hour period

= 10,651 gpm

THEORETICAL DETENTION TIME (TDT) = $\frac{\text{Volume of Unit Process}}{\text{Flow Rate}}$

TDT RAPID MIX BASINS = $\frac{34{,}468 \text{ gallons}}{10{,}651 \text{ gpm}}$

= *3.24 minutes*

BAFFLING CONDITION = Unbaffled basin (Refer to Appendix D for determining baffling factors).

T_{10}/T = 0.10

Unit T_{10} RAPID MIX BASINS = $TDT \times T_{10}/T$

= *(3.24 minutes) x (0.10)*

= *0.32 minutes*

Unit Process: FLOCCULATION

VOLUME OF FLOCCULATION BASINS = *(# of basins) x (Length) x (Width) x (Depth of Water)*

= *(4) x (60 ft) x (30 ft) x (18 ft)*

= $129{,}600\ ft^3$

Convert cubic feet to gallons = $129{,}600\ ft^3 \times \frac{7.48 gallons}{1ft^3} = 969{,}408\ gallons$

FLOW RATE = Peak hourly flow occurring during the 24-hour period

= 10,651 gpm

THEORETICAL DETENTION TIME (TDT) = $\frac{\text{Volume of Unit Process}}{\text{Flow Rate}}$

TDT FLOCCULATION BASIN = $\frac{\text{969,408 gallons}}{\text{10,651 gpm}}$

= *91.0 minutes*

BAFFLING CONDITION = Unbaffled basin (Refer to Appendix D for determining baffling factors).

T_{10}/T = 0.10

Unit T_{10} FLOCCULATION BASIN = $TDT \times T_{10}/T$

= *(91.0 minutes) x (0.10)*

= *9.1 minutes*

Unit Process: SEDIMENTATION

VOLUME OF SEDIMENTATION BASINS = *(# of basins) x (Length) x (Width) x (Depth of Water)*

= *4 x 234 ft x 74 ft x 10 ft*

= $692{,}640\ ft^3$

Convert cubic feet to gallons = $692{,}640\ ft^3 \times \frac{7.48 gallons}{1ft^3} = 5{,}180{,}947\ gallons$

FLOW RATE = Peak hourly flow occurring during the 24-hour period

= 10,651 gpm

THEORETICAL DETENTION TIME (TDT) = $\frac{\text{Volume of Unit Process}}{\text{Flow Rate}}$

TDT SEDIMENTATION BASIN = $\frac{\text{5,180,947 gallons}}{\text{10,651 gpm}}$

= *486 minutes*

BAFFLING CONDITION = Average baffling conditions (Refer to Appendix D for determining baffling factors).

T_{10}/T = 0.50

Unit T_{10} SEDIMENTATION BASINS = $TDT \times T_{10}/T$

= *(486 minutes) x (0.50)*

= *243 minutes*

Unit Process: FILTRATION

VOLUME OF FILTRATION = Volume of Filters – Volume of Media

= *(# of filters) x (Length) x (Width) x (Total Depth)* –*

(# of filters) x (Length) x (Width) x (Depth of Media) x (Porosity)

= *(9) x (36 ft) x (18 ft) x (4 ft) – (9) x (36 ft) x (18 ft) x (2 ft) x (0.5)*

= $23{,}328\ ft^3 - 5{,}832\ ft^3 = 17{,}496\ ft^3$

*Total depth is the depth of media plus the minimum depth of water above the media. For this example, the plant operates with 2 feet of media and a minimum of 2 feet of water above the media.

Convert cubic feet to gallons = $17{,}496\ ft^3 \times \frac{7.48\,gallons}{1ft^3} = 130{,}870\ gallons$

FLOW RATE = Peak hourly flow occurring during the 24-hour period

= 10,651 gpm

THEORETICAL DETENTION TIME (TDT) = $\frac{\text{Volume of Unit Process}}{\text{Flow Rate}}$

TDT FILTRATION BASIN = $\frac{\text{130,870 gallons}}{\text{10,651 gpm}}$

= *12.3 minutes*

BAFFLING CONDITION = Superior baffling conditions (Refer to Appendix D for determining baffling factors).

T_{10}/T = 0.70

Unit T_{10} FILTRATION = $TDT \times T_{10}/T$

= *(12.3 minutes) x (0.70)*

= *8.6 minutes*

Unit Process: FINISHED WATER PIPE

VOLUME OF FINISHED WATER PIPE = *(Length) x (Cross-Sectional Area)*

= $946.3 \text{ ft} \times \pi \times (2.5 \text{ f})\text{t}^2$

= $18{,}581 \text{ ft}^3$

Convert cubic feet to gallons = $18{,}581 \text{ ft}^3 \times \frac{7.48 \text{gallons}}{1 \text{ft}^3} = 138{,}983 \text{ gallons}$

FLOW RATE = Peak hourly flow occurring during the 24-hour period

= *10,651 gpm*

THEORETICAL DETENTION TIME (TDT) = $\frac{\text{Volume of Unit Process}}{\text{Flow Rate}}$

TDT FINISHED WATER PIPE = $\frac{138{,}983 \text{ gallons}}{10{,}651 \text{ gpm}}$

= *13.0 minutes*

BAFFLING CONDITION = Plug flow baffling conditions (Refer to Appendix D for determining baffling factors).

T_{10}/T = 1.0

Unit T_{10} FINISHED WATER LINE = $TDT \times T_{10}/T$

= *(13.0 minutes) x (1.0)*

= *13 minutes*

Unit Process: CLEARWELLS

VOLUME OF WATER IN CLEARWELLS* = *(# of tanks) x (Minimum water depth) x (Cross-sectional Area)*

= $(2) \times (20\ ft) \times (8{,}394.2\ ft)$

= $335{,}768\ ft^3$

Convert cubic feet to gallons = $335{,}768\ ft^3 \times \frac{7.48\ gallons}{1\ ft^3} = 2{,}511{,}545\ gallons$

*Volume of clearwells should reflect a constant minimum storage level that is maintained during peak hour flows. See Chapter 3 and Appendix D for more discussion.

FLOW RATE = Peak hourly flow occurring during the 24-hour period

= 10,651 gpm

THEORETICAL DETENTION TIME (TDT) = $\frac{\text{Volume of Unit Process}}{\text{Flow Rate}}$

TDT CLEARWELLS = $\frac{2{,}511{,}545\ \text{gallons}}{10{,}651\ \text{gpm}}$

= *236 minutes*

BAFFLING CONDITION = Poor baffling conditions (Refer to Appendix D for determining baffling factors).

T_{10}/T = 0.30

Unit T_{10} CLEARWELLS = $TDT \times T_{10}/T$

= *(236 minutes) x (0.30)*

= *71 minutes*

3.6.1.2 Log Inactivation Computations for 40 mgd Plant

Following the diagram in Figure 3-5, the next step is to compute the estimated log inactivation of *Giardia* and viruses for each disinfection segment. ***Note that profiling and benchmarking based on virus inactivation is required only for systems proposing to add or switch to ozone or chloramines. Profiling and benchmarking for virus inactivation is strongly recommended for systems proposing to add or switch to chlorine dioxide.*** This step requires the temperature, pH (only for chlorine), and residual disinfectant concentration for each segment, as well as the T_{10} values computed in Section 3.6.1.1. The segment T_{10} is the sum of the T_{10} for each unit process in the segment. To compute CT_{actual}, multiply the segment T_{10} by the residual disinfectant concentration.

Look up the CT required to inactivate 3-log *Giardia* ($CT_{3\text{-log}, \textit{Giardia}}$) and 4-log viruses ($CT_{4\text{-log, virus}}$) in the CT tables (Tables 3-4 and 3-5 or Appendix C). If the temperature, pH, or residual concentration values fall between those values listed in Tables 3-4 and 3-5 use the guidelines stated earlier in Section 3.6. Once CT_{actual} and the CT required for 3-log *Giardia* and 4-log virus inactivation are calculated, the estimated log inactivation for the segment can then be computed:

$$\text{Estimated Segment log inactivation of } \textit{Giardia} = 3.0 * CT_{actual} / CT_{3\text{-log}, \textit{Giardia}}$$

$$\text{Estimated Segment log inactivation of Viruses} = 4.0 * CT_{actual} / CT_{4\text{-log, virus}}$$

Determine log inactivation for each disinfection segment for the 40 mgd plant example:

SEGMENT 1

The concentration of chlorine measured at the end of Segment 1 was 0.23 mg/L.

$$\begin{aligned} CT_{actual} &= \text{(residual disinfection concentration) x (sum of } T_{10}\text{'s for each unit process)} \\ &= \text{(0.23 mg/L of chlorine) x (39 + 0.32 + 9.1 + 243 minutes)} \\ &= 67.03 \text{ mg-min/L} \end{aligned}$$

Determine the $CT_{3\text{-log}, \textit{Giardia}}$ (i.e., 3-log inactivation of *Giardia*) from Table 3-4 or the CT tables in Appendix C using the appropriate temperature, pH, and residual chlorine concentration. Assuming:

Temperature = 6.1°C
pH = 8.0
Cl_2 = 0.23 mg/L

Using Table 3-4 for 5°C, pH 8.0, and concentration = 0.4 mg/L to select the appropriate CT value.

$$CT_{3\text{-log}, \textit{Giardia}} = 198 \text{ mg-min/L}$$

Determine the $CT_{4\text{-log, virus}}$ (i.e., 4-log inactivation of viruses) from Table 3-5 or the CT tables in Appendix C.

Temperature = 6.1°C

pH = 8.0

Cl_2 = 0.23mg/L

Since the temperature of 6.1°C is not covered in the CT table, use the next lower temperature, 6°C.

$$CT_{4\text{-log, virus}} = 7.6 \text{ mg-min/L}$$

Determine estimated log inactivation of *Giardia* and viruses for Segment 1:

$$\text{Estimated Log inactivation of } \textit{Giardia} = 3.0 \text{ x } (CT_{\text{actual}} / CT_{3\text{-log, } \textit{Giardia}})$$

$$= 3.0 \text{ x } (67.03 / 198)$$

$$= 1.02$$

$$\text{Estimated Log inactivation of viruses} = 4.0 \text{ x } (CT_{\text{actual}} / CT_{4\text{-log, virus}})$$

$$= 4.0 \text{ x } (67.03 / 7.6)$$

$$= 35.3$$

SEGMENT 2

The concentration of chlorine measured at the end of Segment 2 was 2.63 mg/L.

CT_{actual} = (residual disinfection concentration) x (sum of T_{10}'s for each unit process)

= (2.63 mg/L of chlorine) x (8.6 minutes + 13.0 minutes)

= 56.8 mg-min/L

Determine $CT_{3\text{-log, } \textit{Giardia}}$ (i.e., 3-log inactivation of *Giardia*) from Table 3-4 using temperature, pH, and residual chlorine concentration. Assuming:

Temperature = 6.1°C

pH = 7.6

Cl_2 = 2.63 mg/L

$$CT_{3\text{-log, } \textit{Giardia}} = 263 \text{ mg-min/L}$$

Determine required $CT_{4\text{-log, virus}}$ (i.e., 4-log inactivation of viruses) from Table 3-5 or the CT tables in Appendix C using the following temperature and pH.

Temperature = 6.1°C

pH = 7.6

Since the temperature of 6.1°C is not covered in Table 3-5, use the next lower temperature.

$$CT_{4\text{-log, virus}} = 7.6 \text{ mg-min/L}$$

Determine log inactivation of *Giardia* and viruses for Segment 2:

$$\text{Estimated Log inactivation of } Giardia = 3.0 \times (CT_{actual} / CT_{3\text{-log, } Giardia})$$

$$= 3.0 \times (56.8 / 263)$$

$$= 0.65$$

$$\text{Estimated Log inactivation of viruses} = 4.0 \times (CT_{actual} / CT_{4\text{-log, virus}})$$

$$= 4.0 \times (56.8 / 7.6)$$

$$= 30.0$$

SEGMENT 3

The concentration of chloramine measured at the end of Segment 3 was 2.23 mg/L.

CT_{actual} = (residual disinfection concentration) x (sum of T_{10}'s for each unit process)

= (2.23 mg/L of chloramine) x (71 minutes)

= 158.3 mg-min/L

Determine $CT_{3\text{-log, } Giardia}$ (i.e., 3-log inactivation of *Giardia*) from the chloramine tables in Appendix C. Assuming:

Temperature = 6.1 °C

Since the temperature of 6.1°C is not covered in the Appendix C CT tables for chloramine, use the next lower temperature.

$$CT_{3\text{-log, } Giardia} = 2{,}130 \text{ mg-min/L}$$

Determine $CT_{4\text{-log, virus}}$ (i.e., 4-log inactivation of viruses) from the CT tables in Appendix C using temperature. Assuming:

Temperature = 6.1 °C

Since the temperature of 6.1 °C is not covered in the CT tables, use the next lower temperature.

$$CT_{4\text{-log, virus}} = 1{,}889 \text{ mg-min/L}$$

Determine estimated log inactivation of *Giardia* and viruses for Segment 3:

$$\text{Estimated Log inactivation of } Giardia = 3.0 * (CT_{actual} / CT_{3\text{-log, } Giardia})$$

$$= 3.0 * (158.3 / 2{,}130)$$

$$= 0.22$$

$$\text{Estimated Log inactivation of viruses} = 4.0 * (CT_{actual} / CT_{4\text{-log, virus}})$$

$$= 4.0 * (158.3 / 1{,}889)$$

$$= 0.34$$

3.6.1.3 Estimated Plant Log Inactivation for 40 mgd Plant

The final step is to calculate the estimated log inactivation by chemical disinfection for the entire plant. The estimated plant log inactivation is simply the sum of the segment log inactivation for the particular organism (*Giardia* or viruses).

Estimated Log inactivation for the entire plant by disinfection chemical = Sum of estimated log inactivations of each disinfection segment

= Estimated Log inactivation Segment 1 + Estimated Log inactivation Segment 2 + Estimated Log inactivation Segment 3

Estimated Log inactivation of *Giardia* for the entire plant = 1.02 + 0.65 + 0.22

= 1.89

Estimated Log inactivation of viruses for the entire plant = 35.3 + 30.0 + 0.34

= 65.64

EPA guidance suggests that conventional filtration treatment receive a 2.5-log credit for *Giardia* removal through sedimentation and filtration. Therefore, to comply with the SWTR, the plant must achieve at least 0.5-logs inactivation (to achieve at least 3.0-logs of combined removal and inactivation). This plant is in compliance with the SWTR.

3.6.2 Example of Developing a Disinfection Profile for a 5 mgd Plant for One Month

This disinfection profile example was developed for a direct filtration treatment plant in Missouri with a design capacity of 5 mgd. The treatment plant consists of an intake structure with a pumping station, two units for rapid mixing, two flocculation units, and three sand filters of equal treatment capacity. Each sand filter is sized for situatuins when one is out of service, the other two are capable of carrying design flow. The treatment plant has a clearwell that is used as a contact basin and is used for storage. The volume of the clear well is equivalent to one-day average production (2.5 million gallons); the dead storage volume is 1.25 million gallons (storage volume used to calculate contact time).

Table 3-8 presents the output data of a spreadsheet designed to develop a disinfection profile for systems using various chemical disinfectants. Because chlorine is applied at the rapid mixing stage and the free chlorine residual is measured only at the clearwell, the same value is used for various treatment units.

The data presented in Table 3-8 for pH, temperature and chlorine residual values are actual readings from the treatment plant. The plant is expected to run at design capacity in 15 years. Currently it serves a population of about 12,000 and runs a maximum peak hourly rate of 2000 gpm or 2.6 mgd.

The input data needed to calculate daily log inactivation and develop disinfection profile are: the type of disinfectant, date, daily pH, temperature, peak hourly rate, volume of each treatment process and disinfectant free residual at each sampling point. Table 3-9 presents the input and output data used for 9/01/96. Using a spreadsheet, Table 3-9 is developed as an example of automated calculations of estimated log inactivation for *Giardia* and viruses using the Approximation Method for the month of September 1996.

Details on how to calculate volume of water in each process unit were provided previously in a step-by-step detailed example of a 40-mgd treatment plant in Section 3.6.1.

Table 3-8. Actual Readings From a SW Treatment Plant in Missouri

	SEGMENT 1				
Date	**09/01/96**				
Disinfectants	**Cl_2**				
Process Name	**Rapid Mix**	**Flocculation**	**Sedimentation**	**Filtration**	**Clear Well**
Volume (gal)	**3,500**	**130,000**	**0**	**80,000**	**1,250,000**
Baffling Condition (T_{10}/T)	**0.1**	**0.3**	**0.1**	**0.3**	**0.1**
Peak Hourly Flow (gpm)	1,820	1,820	1,820	1,820	1,820
Theoretical Detention Time (min)	1.92	71.43	0.00	43.96	686.81
T_{10} (min)	0.19	21.43	0.00	13.19	68.68
Free Disinfectant Concentration (mg/L)[1]	0.95	0.95	0.95	0.95	0.95
Plant CT Value (mg-min/L)	0.18	20.36	0.00	12.53	65.25
pH	7.59	7.59	7.59	7.59	7.59
Temperature (°C)	23.9	23.9	23.9	23.9	23.9
$CT_{3\text{-log,Giardia}}$	81	81	81	81	81
$CT_{4\text{-log,viruses}}$	2.4	2.4	2.4	2.4	2.4
Estimated Plant Giardia Log Inactivation	0.01	0.75	0.00	0.46	2.42
Estimated Plant Viruses Log Inactivation	0.30	33.93	0.00	20.88	108.75

Segment 1 Totals		
	T_{10}	103.49
	CT	98.31
	$CT_{3\text{-log,Giardia}}$	81
	$CT_{4\text{-log,viruses}}$	2.4
	Giardia Log Inactivation	**3.64**
	Virus Log Inactivation	**163.86**

[1] Plant only measures residual at discharge from clearwell, therefore, this residual is assumed to be the residual throughout the plant.

Table 3-9. Input and Output Data Used to Calculate Log Inactivations

		SEGMENT 1							
Date	**Peak Hourly Flow Rate (gpm)**	**pH**	**Temperature**	**Disinfectant Residual (mg/L)**	**Segment CT Actual**	**3-log *Giardia* CT**	**4-log Viruses CT**	**Estimated Segment *Giardia* Inactivation**[1]	**Estimated Segment Virus Inactivation**[2]
09/01/96	1,820	7.59	23.9	0.95	98.31	81	2.4	3.64	163.86
09/02/96	1,880	7.85	22.8	1.17	117.22	83	2.6	4.24	180.34
09/03/96	1,855	7.87	21.5	1.02	103.57	83	2.8	3.74	147.95
09/04/96	1,840	7.81	21	1.23	125.91	85	2.8	4.44	179.87
09/05/96	1,840	7.86	21	1.03	105.44	83	2.8	3.81	150.62
09/06/96	1,830	7.94	20.3	1.04	107.04	83	3.0	3.87	142.72
09/07/96	1,810	8.11	19.4	1.1	114.47	134	3.2	2.56	143.08
09/08/96	1,820	7.89	18.9	1.03	106.59	111	3.4	2.88	125.40
09/09/96	1,875	7.67	19.6	1.29	129.58	114	3.2	3.41	161.98
09/10/96	1,834	7.64	19.7	1.24	127.32	114	3.2	3.35	159.15
09/11/96	1,867	6.75	19.8	1.03	103.93	76	3.2	4.10	129.91
09/12/96	1,811	6.65	18.9	1.0	103.98	76	3.4	4.10	122.33
09/13/96	1,847	6.73	18.5	1.03	105.04	76	3.4	4.15	123.58
09/14/96	1,869	6.85	19	1.01	101.77	76	3.2	4.02	127.21
09/15/96	1,839	6.72	20.3	1.1	112.64	57	3.0	5.93	150.19
09/16/96	1,846	6.92	21.1	1.16	118.33	57	2.8	6.23	169.04
09/17/96	1,828	6.71	19.4	1.08	111.26	76	3.2	4.39	139.07
09/18/96	1,823	6.96	18	0.61	63.02	73	3.4	2.59	74.14
09/19/96	1,820	6.89	16.4	1.29	133.47	78	3.8	5.13	140.50
09/20/96	1,845	7.00	15.6	1.17	119.47	92	4.0	3.90	119.47
09/21/96	1,860	700	15.7	1.03	104.31	92	40	3.40	104.31
09/22/96	1,852	7.06	15.8	0.96	97.65	90	4.0	3.26	97.65
09/23/96	1,855	6.62	15.5	1.18	119.84	76	4.0	4.73	119.84
09/24/96	1,843	7.43	15.1	1.12	114.49	92	4.0	3.73	114.49
09/25/96	1,859	7.27	14.9	1.3	131.72	140	4.4	2.82	119.74
09/26/96	1,835	7.38	14.1	1.12	114.97	137	4.4	2.52	104.52
09/27/96	1,845	7.41	13.3	1.05	107.19	137	4.8	2.35	89.32
09/28/96	1,860	7.28	13	1.31	132.69	140	4.8	2.84	110.57
09/29/96	1,855	7.43	13.3	1.58	160.47	144	4.8	3.34	133.73
09/30/96	1,824	7.42	14	1.45	149.73	144	4.4	3.12	136.11

[1] $3.0 \times \frac{CT_{actual}}{CT_{3\text{-log}, \textit{Giardia}}}$

[2] $4.0 \times \frac{CT_{actual}}{CT_{4\text{-log, viruses}}}$

3.6.3 Determination of Disinfection Profile and Benchmark

Listed below are tasks needed to develop the disinfection profile and set the benchmark:

- Repeat the above calculations for 1, 2, or 3 years of available or collected data.
- Arrange total plant estimated log inactivation in chronological order, beginning with the earliest data.
- Develop a graphical plot of estimated log inactivation versus time (i.e., disinfection profile). Inactivation should be on the y-axis and time (days) should be on the x-axis.
- Calculate the average (arithmetic mean) estimated disinfection log inactivation for each calendar month.
- Determine the calendar month in a year with the lowest average log inactivation. The lowest average month becomes the "critical period" for that year.

Table 3-10 lists the critical periods for this plant in each year and the corresponding log inactivation.

Table 3-10. Critical Periods for Existing Disinfection Practice

Year	Month of Critical Period for *Giardia* Inactivation	Log Inactivation of *Giardia*	Month of Critical Period for Viral Inactivation	Log Inactivation of Viruses
1994	February	2.0	February	63.3
1995	February	1.5	February	50.7
1996	January	1.6	February	50.8

The benchmark is the lowest monthly average log inactivation and is calculated as the average of the three critical periods. For the plant illustrated in Table 3-10, the benchmarks for *Giardia* and viruses are calculated as follows:

$$\begin{aligned}\text{Benchmark}_{Giardia} &= \text{Average Log Inactivation of Critical Periods}\\ &= (2 + 1.5 + 1.6)/3\\ &= 1.7\\ \text{Benchmark}_{\text{viruses}} &= \text{Average Log Inactivation of Critical Periods}\\ &= (63.3 + 50.7 + 50.8)/3\\ &= 54.9\end{aligned}$$

The disinfection profiles and benchmarks based on *Giardia* and viruses are illustrated in Figures 3-6 and 3-7.

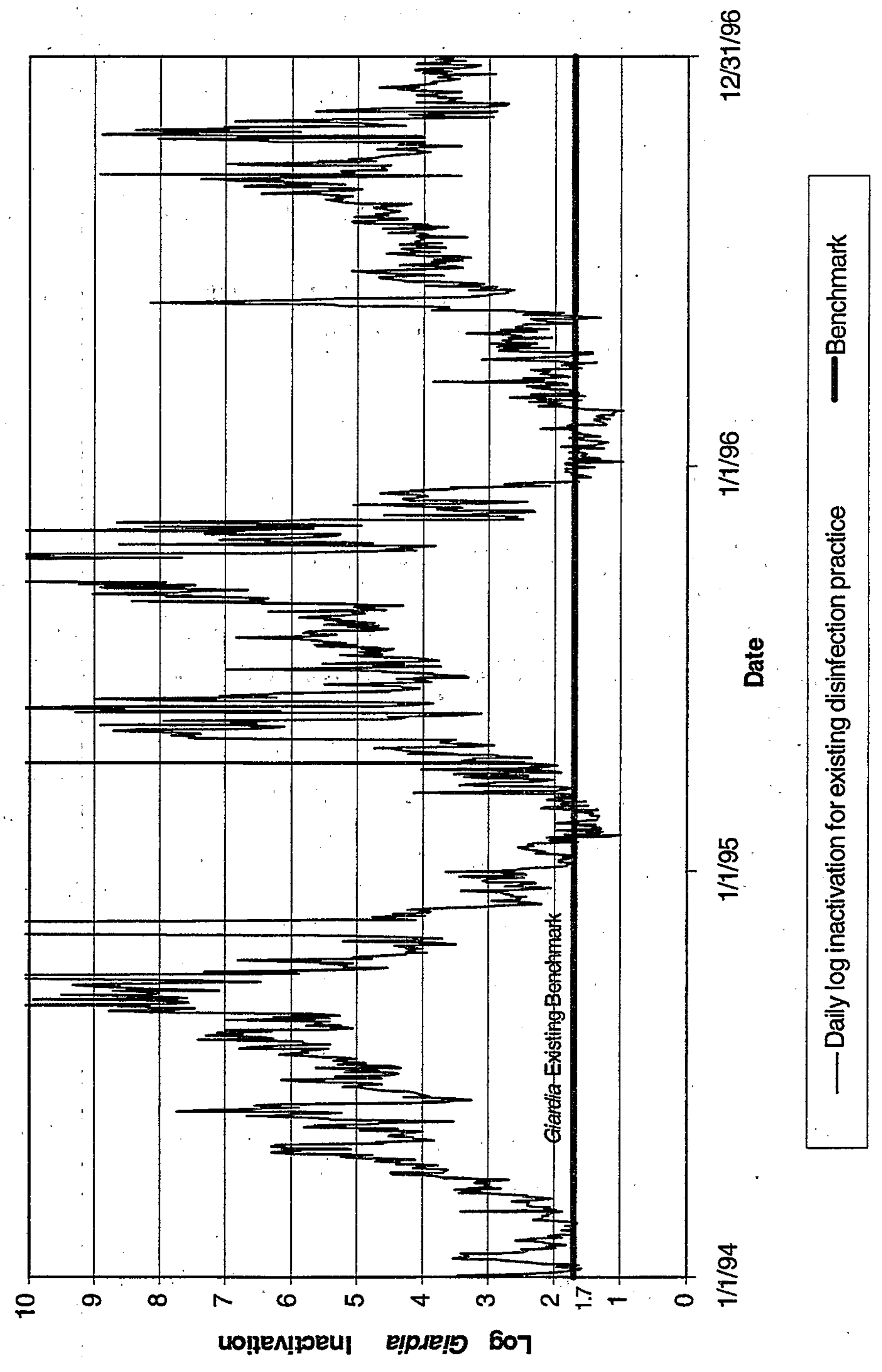


Figure 3-6. Log *Giardia* Inactivation for Existing Disinfection Practice

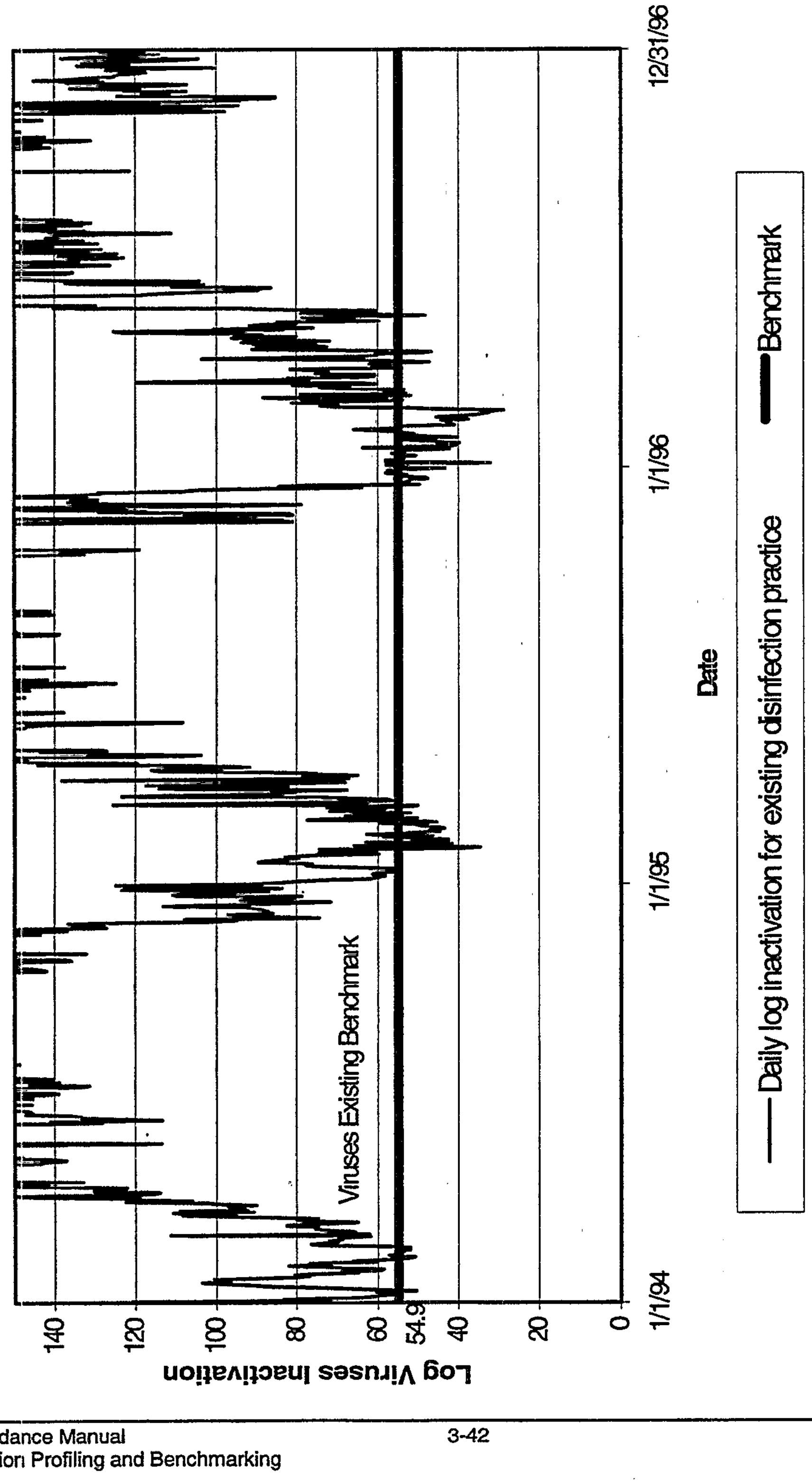


Figure 3-7. Log Virus Inactivation for Existing Disinfection Practice

3.6.4 Modification of Disinfection Practice

In this example for a 40 mgd plant, the utility has determined that DBP concentrations exceed profiling applicability triggers and has developed a profile. It then intends to modify its disinfection practice to control DBPs. The plant is considering two options for control:

Option 1

- Replace pre-oxidation using chlorine with potassium permanganate preoxidation. Although no disinfection credit is available for using potassium permanganate, the utility staff believes that it would effectively control tastes and odors. The point of chlorination is moved downstream of sedimentation to assist in the control of DBPs.
- Apply the chlorine dose after sedimentation to increase the chlorine residual by 20 percent to offset the loss in disinfection contact time.
- Add ammonia prior to the clearwell as in the original disinfection scheme.

A process diagram of Option 1 proposed modifications is shown in Figure 3-8.

Option 2

- Replace pre-oxidation using chlorine with potassium permanganate preoxidation.
- Add an ozone contactor just prior to rapid mix to compensate for the loss in disinfection credit associated with eliminating prechlorination. The ozone contactor would have a theoretical detention time of 1.3 minutes under the design flow of 40 mgd. The utility plans to operate under conditions providing the ozone residuals presented in Table 3-11. Table 3-11 illustrates CT calculations and log inactivation calculations under specific assumptions. Also, biologically active filtration to control AOC produced by ozonation will be used to control distribution system regrowth. Refer to the *Alternative Disinfectants and Oxidants Guidance Manual* (USEPA, 1999a) for more information.
- Move the point of chlorination just downstream of filtration to assist with the control of DBPs and virus inactivation.
- Add ammonia prior to the clearwell as in the original disinfection scheme.

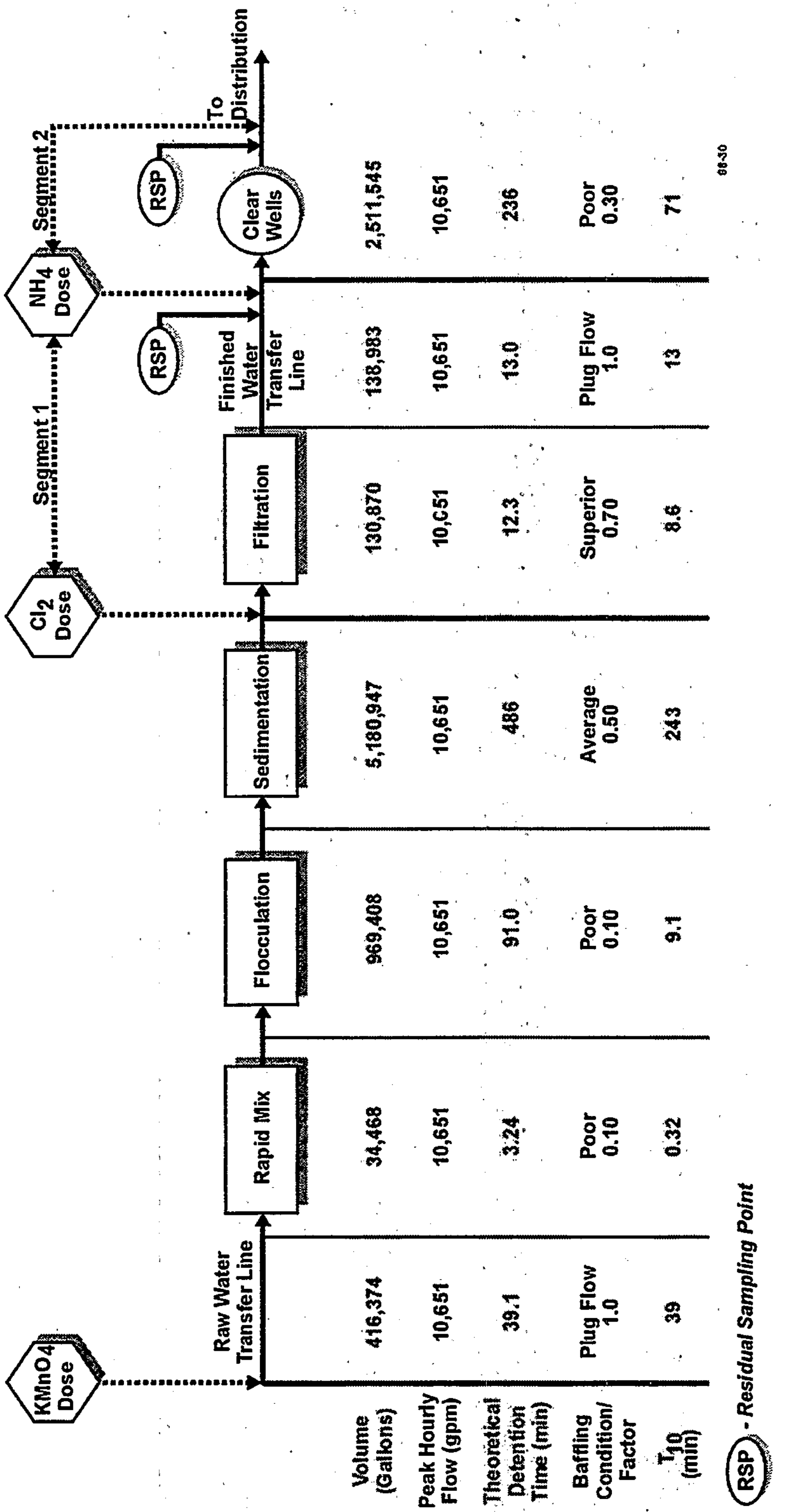
A process diagram of Option 2 proposed modifications is shown in Figure 3-9.

Table 3-11. Example Log Inactivation Calculations for Multi-Stage Ozone Contactor

Ozone Contact Chamber	Flow Direction	Volume (gallons)	Theoretical Detention Time (min)	Residual Ozone Concentration (mg/L)	C used in CT (mg/L)	T/T10	T10 (min)	CT actual (mg*min/L)	CT 3-log, Giardia (mg*min/L), Temp = 6 °C	CT 4-log, virus (mg*min/L) Temp = 6 °C	Actual *Giardia* Log Inactivation	Actual Virus Log Inactivation
1a	Down	6193.5	0.58	0.8		0.6	0.35	N/A*			0.5*	1.0*
1b	Up	6193.5	0.58	0.65	0.65	0.6	0.35	0.23	1.81	1.16	0.38	0.78
2a	Down	6193.5	0.58	0.55	0.275	0.6	0.35	0.10	1.81	1.16	0.16	0.33
2b	Up	6193.5	0.58	0.55	0.55	0.6	0.35	0.19	1.81	1.16	0.32	0.66
3a	Down	6193.5	0.58	0.45	0.225	0.6	0.35	0.08	1.81	1.16	0.13	0.27
3b	Up	6193.5	0.58	0.4	0.4	0.6	0.35	0.14	1.81	1.16	0.23	0.48
Totals							2.1	0.73			1.71	3.53

Notes: The peak hourly flow rate was determined to be 10,651 gallons per minute. The C used in CT computations for downflow chambers where gas is applied is 1/2 of the measured ozone residual concentration.

* CT credit is not available in the downflow chamber of the first stage of an ozone contactor. If the ozone residual at the outlet of the first contactor is greater than 0.3 mg/L, then the Giardia and virus log inactivation credits are 0.5 and 1.0, respectively. If the ozone residual at the outlet is less than 0.3 but greater than 0.1 mg/L, then the Giardia and virus log inactivation credits are 0 and 1.0, respectively.


KMnO4 Dose
Cl2 Dose
NH4 Dose
Segment 1
Segment 2
Raw Water Transfer Line
Rapid Mix
Flocculation
Sedimentation
Filtration
Finished Water Transfer Line
RSP
RSP
Clear Wells
To Distribution
RSP - Residual Sampling Point
98-30

	Raw Water Transfer Line	Rapid Mix	Flocculation	Sedimentation	Filtration	Finished Water Transfer Line	Clear Wells
Volume (Gallons)	416,374	34,468	969,408	5,180,947	130,870	138,983	2,511,545
Peak Hourly Flow (gpm)	10,651	10,651	10,651	10,651	10,651	10,651	10,651
Theoretical Detention Time (min)	39.1	3.24	91.0	486	12.3	13.0	236
Baffling Condition/ Factor	Plug Flow 1.0	Poor 0.10	Poor 0.10	Average 0.50	Superior 0.70	Plug Flow 1.0	Poor 0.30
T_{10} (min)	39	0.32	9.1	243	8.6	13	71

Figure C-3. Option 1 Process Diagram

Figure 3-8. Option 1 Process Diagram

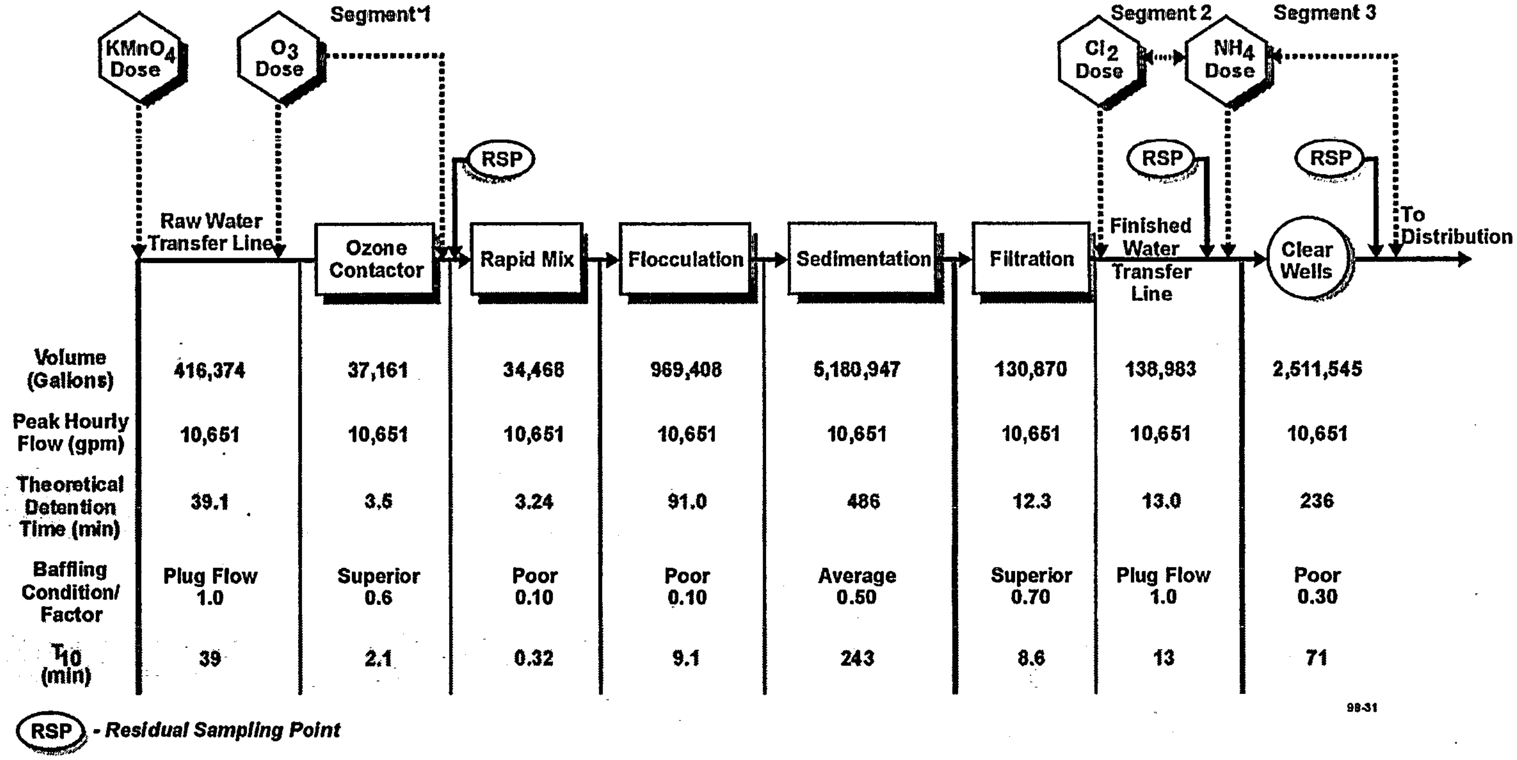

Segment 1
Segment 2
Segment 3
$KMnO_4$ Dose
O_3 Dose
Cl_2 Dose
NH_4 Dose
RSP
RSP
RSP
Raw Water Transfer Line
Ozone Contactor
Rapid Mix
Flocculation
Sedimentation
Filtration
Finished Water Transfer Line
Clear Wells
To Distribution
Volume (Gallons)
416,374
37,161
34,468
969,408
5,180,947
130,870
138,983
2,511,545
Peak Hourly Flow (gpm)
10,651
10,651
10,651
10,651
10,651
10,651
10,651
10,651
Theoretical Detention Time (min)
39.1
3.5
3.24
91.0
486
12.3
13.0
236
Baffling Condition/ Factor
Plug Flow 1.0
Superior 0.6
Poor 0.10
Poor 0.10
Average 0.50
Superior 0.70
Plug Flow 1.0
Poor 0.30
T_{10} (min)
39
2.1
0.32
9.1
243
8.6
13
71
98-31
RSP - *Residual Sampling Point*

Figure C-4. Option 2 Process Diagram

Figure 3-9. Option 2 Process Diagram

A disinfection profile and alternative disinfection benchmark were developed for the first disinfection option (i.e., using potassium permanganate for pre-oxidation and using a chlorination point downstream for post-sedimentation). The proposed modification to disinfection does not include adding or switching to ozone, chloramines, or chlorine dioxide. Therefore, developing a profile and benchmark based on virus inactivation is not required. Table 3-12 lists the critical periods for each year and the corresponding log inactivation values.

Table 3-12. Critical Periods for Disinfection Option 1

Year	Month of Critical Period for *Giardia* Inactivation	Log Inactivation Of *Giardia*
1994	February	0.7
1995	February	0.5
1996	January	0.5

$$\text{Modification Benchmark}_{Giardia} = \text{Average Log Inactivation of Critical Periods}$$

$$= (0.7 + 0.5 + 0.5)/3$$

$$= 0.6$$

The daily log inactivations and modification benchmark for *Giardia* are illustrated in Figure 3-10. Note that the modification $\text{Benchmark}_{Giardia}$ for Option 1 is 0.6-log inactivation, which is lower than the existing $\text{Benchmark}_{Giardia}$ of 1.7-log inactivation. The system realizes that a higher free chlorine residual will improve the alternative benchmark level by about 0.2-log inactivation (say from 0.6 mg/L to 1.2 mg/L of free chlorine at 5°C and a pH of 8). These results indicate that Option 1 would not provide an equivalent degree of protection against *Giardia* as compared to the existing disinfection scheme.

A system is not prohibited from making a change that will result in a lower benchmark. Either the chlorine dose or contact time could be increased for this option to meet the current disinfection benchmark. A long-term option could involve increasing contact time by improving baffling conditions in the contact basin. The system may consult with the State on how to change its disinfection practice that will result in a lower inactivation level and at the same time protect public health as detailed in Chapter 5 (Using the Benchmark) and 6 (Alternative Disinfection Benchmark) of this guidance manual.

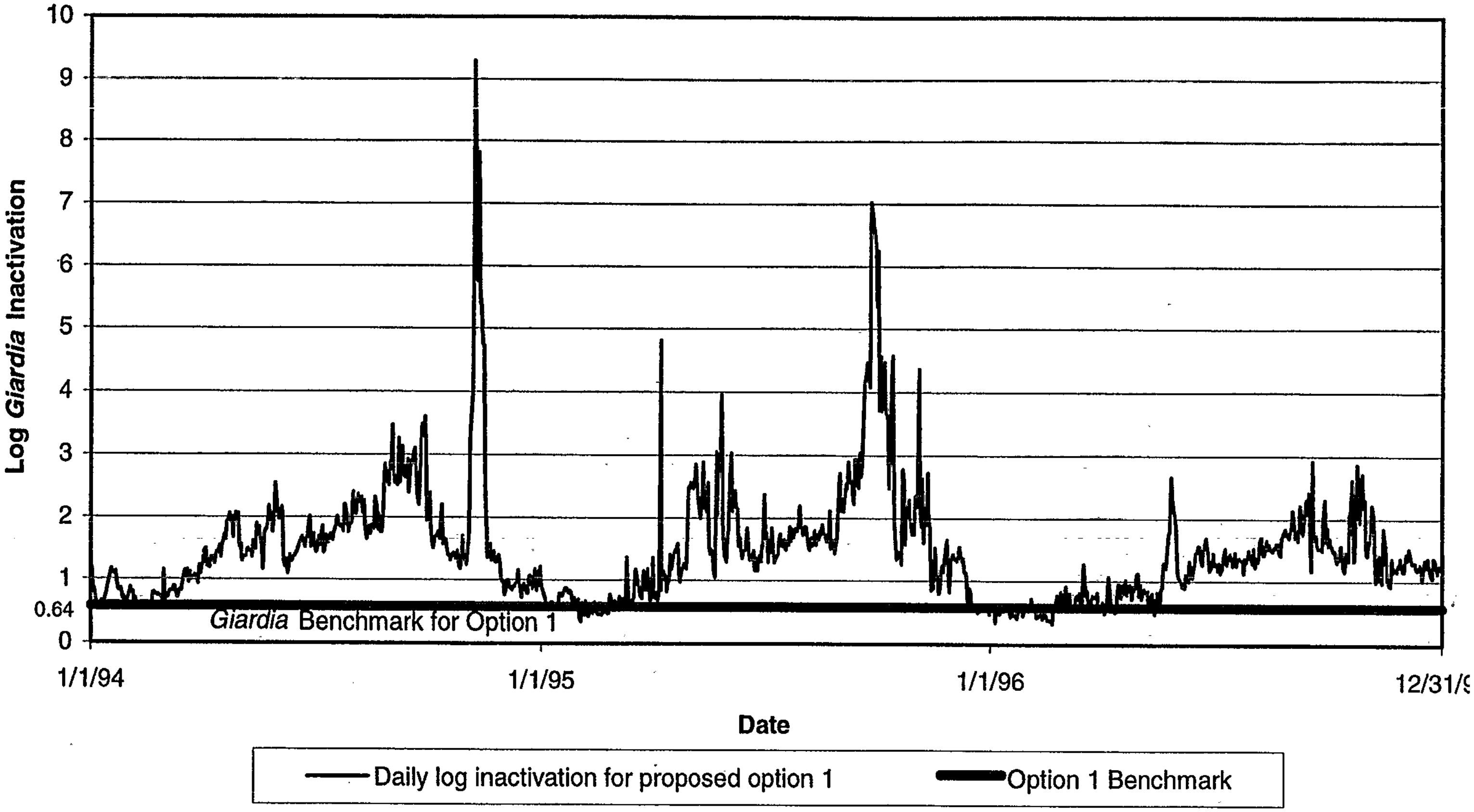


Figure 3-10. Log *Giardia* Inactivation for Disinfection Option 1

A disinfection profile and benchmark were also developed for the second disinfection option using the same methods as Option 1. Because Option 2 would add ozone to the disinfection system, profiling and benchmarking based on virus inactivation is also required. Table 3-13 lists the critical periods for each year and the corresponding log inactivation values

Table 3-13. Critical Periods for Disinfection Option 2

Year	Month of Critical Period for *Giardia* Inactivation	Log Inactivation of *Giardia*	Month of Critical Period for Virus Inactivation	Log Inactivation of Viruses
1994	February	2.6	February	19.3
1995	February	2.1	February	15.4
1996	January	2.1	February	15.5

$$\text{Modification Benchmark}_{\textit{Giardia}} = \text{Average Log Inactivation of Critical Periods}$$

$$= (2.6 + 2.1 + 2.1)/3$$

$$= 2.3$$

$$\text{Modification Benchmark}_{\text{viruses}} = \text{Average Log Inactivation of Critical Periods}$$

$$= (19.3 + 15.4 + 15.5)/3$$

$$= 16.7$$

The daily log inactivations and benchmarks of *Giardia* and viruses are illustrated in Figures 3-11 and 3-12. Note that the Modification Benchmark$_{\textit{Giardia}}$ for Option 2 achieves 2.3-log inactivation, which is higher than the existing Benchmark$_{\textit{Giardia}}$ of 1.7-log inactivation. This indicates that Option 2 would provide equivalent or better microbial protection against *Giardia* when compared with the existing disinfection strategy.

However, the Modification Benchmark$_{\text{viruses}}$ for Option 2 achieves a log inactivation of 16.7, which is lower than the existing Benchmark$_{\text{viruses}}$ of 54.9-log inactivation. Consequently, Option 2 would not provide an equivalent degree of microbial protection against viruses when compared with the existing disinfection strategy, although 16.7-log inactivation of viruses would provide excellent protection against these pathogens. This indicates that the proposed disinfection strategy works against *Giardia*, but the utility would need to consult with the State prior to implementing an alternative benchmark for virus inactivation. See Chapter 6 for more information.

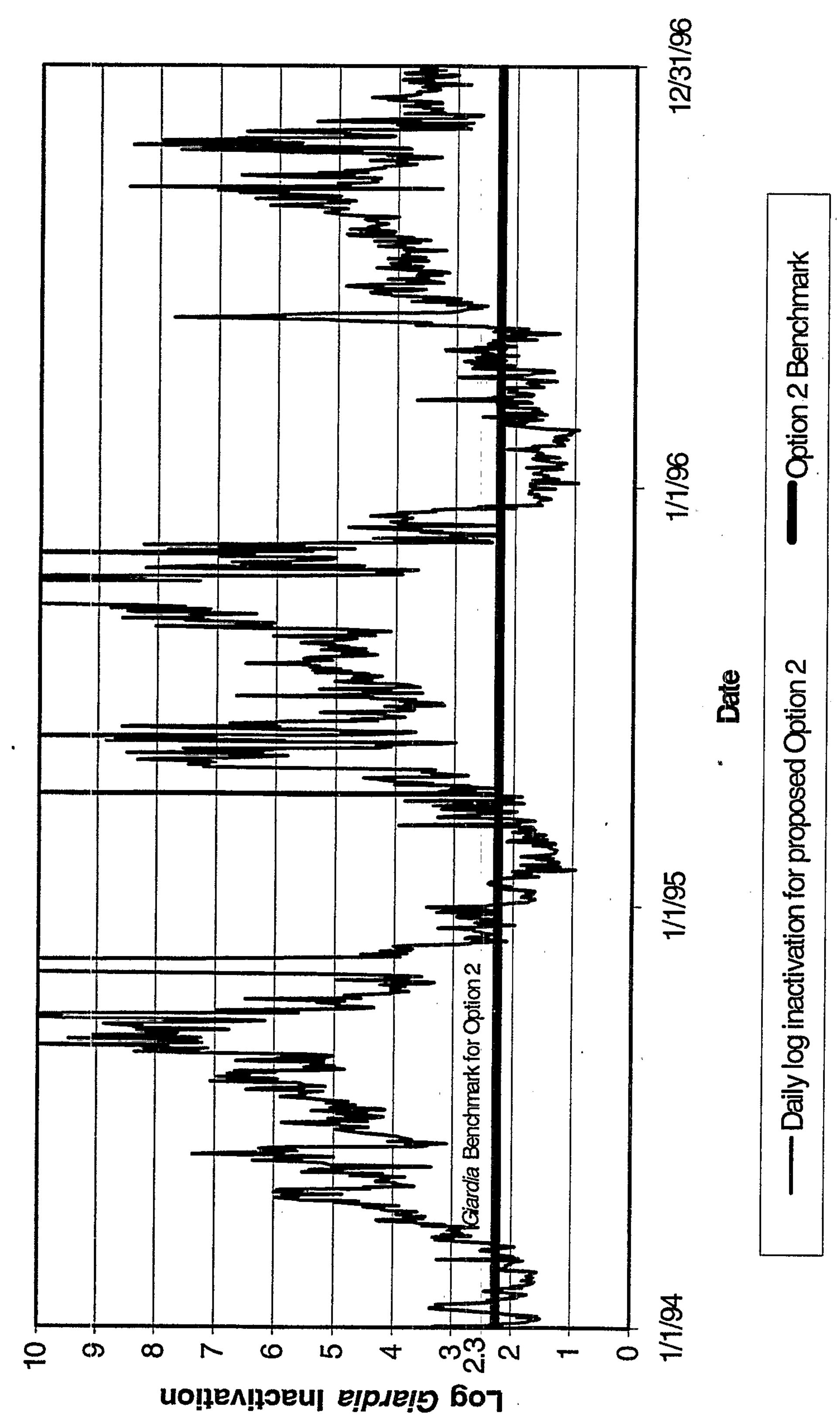


Figure 3-11. Log *Giardia* Inactivation for Disinfection Option 2

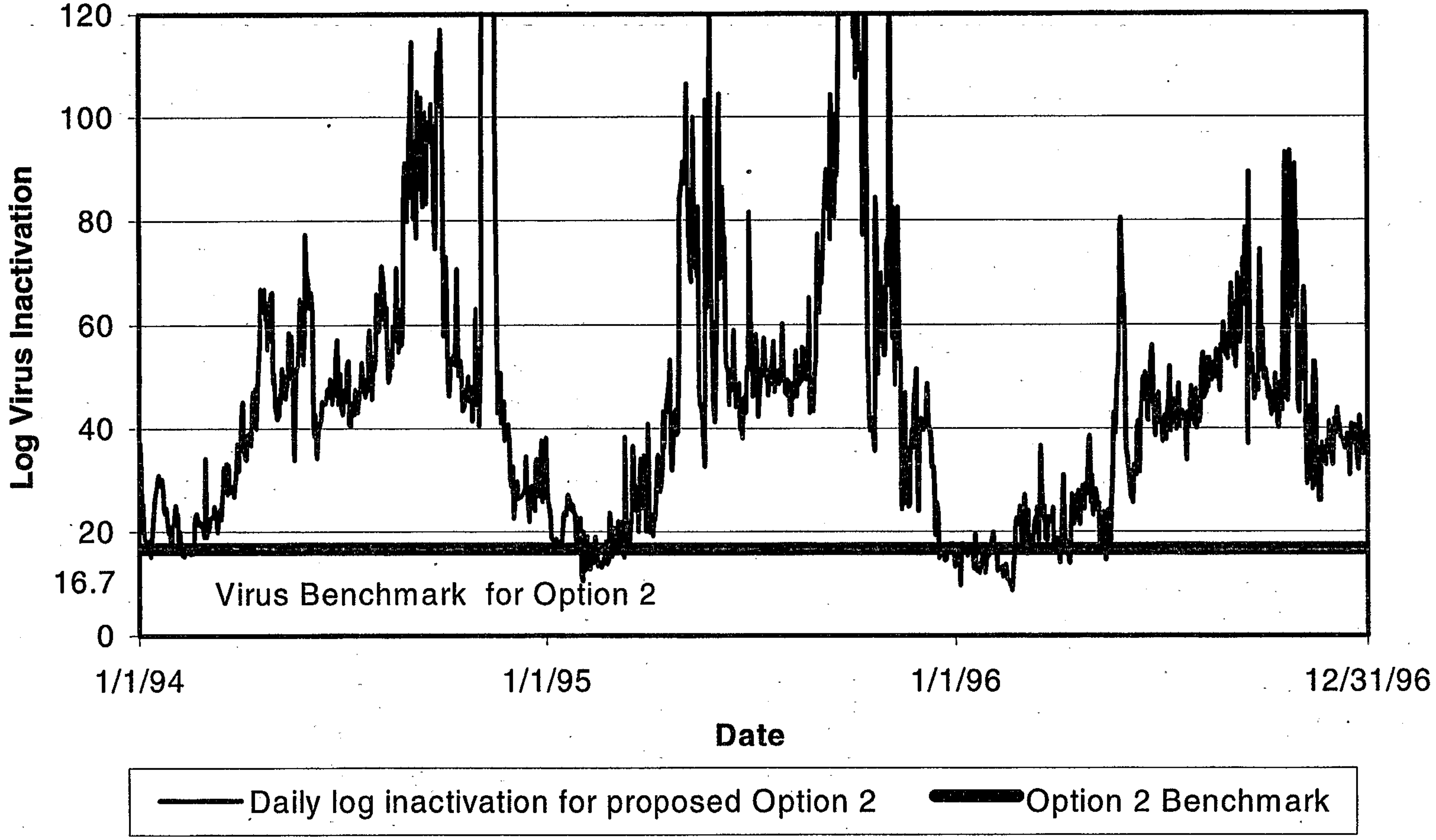


Figure 3-12. Log Virus Inactivation for Disinfection Option

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4. CALCULATING THE BENCHMARK

The IESWTR requires systems to use disinfection benchmarking to determine whether there may be a significant reduction in microbial inactivation as a result of modifying disinfection practices to meet the Stage 1 DBPR MCLs for TTHMs and HAA5. This determination will allow for an informed consultation with the State to assess appropriate modifications to disinfection practices, as necessary. As explained in Chapter 1, benchmarking is used to characterize the minimum level of *Giardia* and, in some cases, virus log inactivations that are provided under current disinfection practices to ensure that changes to disinfection practices do not result in inactivation levels lower than the calculated benchmark without appropriate State consultation and review. The disinfection benchmark quantifies a lower bound of the existing disinfection practices so that alternative disinfection strategies can be compared to current minimum levels of disinfection. This chapter describes the procedure to calculate a disinfection benchmark.

4.1 Applicability

Water systems required to develop a disinfection profile are required to develop a benchmark based on *Giardia* inactivation if they are planning to "significantly modify" their disinfection practices.

Systems that are planning to add or switch primary disinfectants to include ozone, chloramines, or chloride dioxide must also calculate a profile and benchmark based on virus inactivation in addition to *Giardia*. Virus inactivation must be determined for these systems to address the possibility of reduced protection against viruses when using an alternative disinfectant.

4.2 Benchmark Calculations

The calculation of disinfection profiling, including the estimated log inactivation of *Giardia* and viruses, is described in Chapter 3 of this guidance manual. Once the disinfection profile is calculated, the methodology for determining the benchmark is the same for viruses as it is for *Giardia*.

As described in the IESWTR, a disinfection benchmark is calculated using the following steps:

- Complete a disinfection profile that includes the calculation of log inactivation of *Giardia* and/or viruses for each day of the profile.
- Compute the average log inactivation for each calendar month of the profile by averaging the daily log inactivation values.

- For each 12-month period the profile covers (i.e., 0-12 months, 12-24 months, and 24-36 months), select the month with the lowest average log inactivation for each 12-month period. This month is the "lowest average month" for the 12-month period ($LowestAverageMonth_i$, where i designates the first, second, or third year and is known as the "critical period").
  - If data from only one year are available, the critical period for that year becomes the benchmark.
  - If data from multiple years are available, systems must calculate their benchmarks as the average of the lowest monthly averages for each year. Using three years of data as an example, the benchmark would be calculated as follows:

$$Benchmark = \frac{(LowestAverageMonth_1 + LowestAverageMonth_2 + LowestAverageMonth_3)}{3}$$

The following example demonstrates how a benchmark is calculated using three years of log inactivation data.

Disinfection Benchmark Example Calculation:

Step 1. Calculate the monthly average log inactivations for each month of disinfection profiling data. In this example, three years of data are available. Table 4-1 presents the daily log inactivation values of a hypothetical system for the month of January 1998.

The monthly average log inactivation is calculated by summing the daily values and dividing by the number of days in the month as follows:

$$Monthly\ Average\ Log\ Inactivation = \frac{\sum Daily\ Log\ Inactivation\ Values}{Days\ per\ Month}$$

For this example, the monthly average log inactivation for January 1998 is 3.94, calculated as follows:

$$\frac{\sum Daily\ Log\ Inactivation\ Values}{Days\ per\ Month} = \frac{120.10}{31} = 3.94$$

Monthly average log inactivations are then calculated in a similar manner for the other 35 months in the three-year period.

Table 4-1. Daily Log Inactivation for Hypothetical Plant for January 1998

Date	Log Inactivation	Date	Log Inactivation
1/1/98	3.26	1/17/98	3.62
1/2/98	3.17	1/18/98	4.31
1/3/98	3.36	1/19/98	4.73
1/4/98	4.82	1/20/98	4.19
1/5/98	3.65	1/21/98	3.23
1/6/98	3.22	1/22/98	4.22
1/7/98	4.03	1/23/98	3.34
1/8/98	4.97	1/24/98	3.63
1/9/98	4.77	1/25/98	4.35
1/10/98	4.31	1/26/98	3.24
1/11/98	4.57	1/27/98	3.04
1/12/98	3.89	1/28/98	3.07
1/13/98	4.11	1/29/98	3.68
1/14/98	4.30	1/30/98	4.54
1/15/98	3.10	1/31/98	4.48
1/16/98	4.89		

Step 2. Next, the minimum monthly average log inactivation values for **each year** (each 12-month period) should be identified. Table 4-2 provides the average monthly log inactivations for the hypothetical system in this example. The minimum values for each year (i.e., January 1996, January 1997, and February 1998) are highlighted.

This example is typical in that lowest monthly average log inactivation values often occur during the winter due to the reduced effectiveness of disinfection at lower temperatures. Note that the three minimum monthly values for each year are **not** the minimum three values for the entire three-year record (i.e., although the average log inactivation of 3.09 for February 1997 is less than the average log inactivation 3.23 for January 1996, the January 1996 value is used). That is, the minimum monthly average for each of the three years is used to calculate the benchmark, not the three lowest values.

Table 4-2. Monthly Average Log Inactivation Values for Hypothetical Plant

January-96	***3.23***	***January-97***	***3.04***	January-98	3.94
February-96	3.42	February-97	3.09	***February-98***	***3.07***
March-96	3.62	March-97	3.68	March-98	4.31
April-96	4.31	April-97	4.54	April-98	4.27
May-96	4.73	May-97	4.48	May-98	3.45
June-96	4.19	June-97	3.26	June-98	4.11
July-96	4.56	July-97	3.17	July-98	4.30
August-96	4.22	August-97	3.36	August-98	3.62
September-96	3.34	September-97	4.82	September-98	4.77
October-96	3.63	October-97	3.65	October-98	3.68
November-96	4.35	November-97	3.22	November-98	4.54
December-96	3.65	December-97	4.03	December-98	3.52

Step 3. Finally, the benchmark is calculated as an average of the minimum monthly average values for each of the three years. For this example, the benchmark is calculated as follows:

$$\frac{\sum LowestAverageMonths_i}{Number\ of\ years} = \frac{(3.23+3.04+3.07)}{3} = 3.11$$

If the plant has only two years of log inactivation data (i.e., 1997 and 1998), the average of the minimum values for 1997 and 1998 are used and the benchmark is equal to 3.06 (i.e., [3.04+3.07]/2). Likewise, if the plant has only one year of acceptable data (i.e., 1998), the single lowest average month is used and the benchmark is 3.07.

Several detailed examples are provided in Chapter 5 to further illustrate the calculation of benchmarks when modifications to disinfection practices are being considered.

4.3 The Completed Benchmark

As required in the IESWTR, water systems must work with their states when calculating benchmarks. Once the benchmarking calculations are completed, water systems must submit the calculations and supporting data to the State for consultation prior to changing disinfection practices. The State will use the benchmark to evaluate the microbial inactivation the system has achieved over time and compare this with the modified disinfection system. The use of the benchmark is discussed further in Chapter 5.

5. Using the Benchmark

The IESWTR establishes the disinfection benchmark as the lower bound on disinfection effectiveness of an existing water system. The benchmark may be used by the State as a minimum level of inactivation of *Giardia* and viruses that must be maintained by water systems when modifying their disinfection practices. The State would then require that all proposed modifications to existing disinfection practices be designed to meet current disinfection benchmarks. The State may also use the profile and benchmark to determine an appropriate alternative benchmark (see Chapter 6). Disinfection benchmarks provide a reference point for States to evaluate whether systems will compromise microbial protection when complying with the Stage 1 DBPR provisions to control disinfection byproducts.

This chapter provides a definition of significant modifications to disinfection practices, and describes State involvement in the process. Chapter 6 includes a discussion on how a State may set alternative disinfection benchmarks for systems that cannot maintain their current *Giardia* or virus benchmark.

5.1 Definition: Modifying Disinfection Practices

This section describes example modifications to disinfection practice that may trigger the benchmarking process required under the IESWTR. Although this section summarizes several DBP control alternatives as illustrative examples, it is not meant to provide a comprehensive discussion of this subject. A more complete discussion of certain DBP control alternatives is provided in the *Alternative Disinfectants and Oxidants Guidance Manual* (USEPA, 1999a).

A public water system may consider modifying their disinfection practices to comply with provisions of the Stage 1 DBPR. Significant modifications to disinfection practices trigger disinfection benchmarking requirements under the IESWTR. As described in the IESWTR, significant modifications to disinfection practices are defined as the following:

- Moving the point of disinfectant application
- Changing the disinfectant(s) used in the treatment plant
- Changing disinfection practices
- Any other modification identified by the State as significant.

A brief description of each of these four types of modifications is presented below.

5.1.1 Moving the Point of Disinfectant Application

Water systems using pre-disinfection might consider moving the point of disinfectant application further into the plant treatment train to reduce the contact time between DBP precursors and the disinfectant(s). The TTHM formation potential may be reduced by as much as 50 percent through conventional coagulation and settling (Singer and Chang, 1989; Summers et al., 1997).

Conventional water treatment plants that apply chlorine to raw water generally have adequate contact time for disinfection. Many water systems have eliminated or changed their pre-disinfection practices to control DBPs. Pre-disinfection practices involve using chemical or physical processes to remove precursors from the source water. Moving the point of disinfection after clarification with enhanced coagulation allows for greater removal of DBP precursors before disinfectant is added and also reduces the disinfectant demand of the water. When moving the point of disinfection further into the treatment process, a system must consider whether adequate contact time is available to achieve sufficient disinfection and how this modification will affect the benchmark. Systems may find that seasonal use of this modification is helpful in reducing summer DBP levels, which are typically the highest.

5.1.2 Changing the Disinfectant(s) Used In the Treatment Plant

Water systems may consider changing the disinfectant used in their treatment plant to comply with the Stage 1 DBPR MCLs. Several studies have evaluated the implications of changing the disinfection practices in water treatment plants. EPA and the Association of Metropolitan Water Agencies (AMWA) funded a two-year study of 35 water treatment facilities to evaluate DBP production. Among four of the facilities, alternative disinfection strategies were investigated to evaluate the difference in DBP production from the plants' 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 5-1 presents the 10 potential strategies often considered for primary and secondary disinfection. Table 5-2 lists the changes in DBP production observed in the four plants after eight of these new strategies were implemented.

As shown in Table 5-2, employing different and more carefully selected primary and secondary disinfectants reduced the amount of DBPs produced. In general, the results followed the characteristics of the DBPs associated with the primary disinfectant used (i.e., halogenated DBPs with chlorine compounds). Organic oxidation products form when strong oxidants such as ozone are used. However, by carefully selecting the primary and secondary disinfectants, and avoiding long contact times and high dosages of halogens, the total DBP formation declined. It is important to note that the study did not evaluate bromate formation.

Table 5-1. Strategies for Primary and Secondary Disinfectants

Base Disinfection Condition	Modified Disinfection Practice
Chlorine/Chlorine	Chlorine/Chloramine
Chlorine/Chlorine	Chloramine/Chloramine
Chlorine/Chlorine	Chlorine dioxide/Chloramine
Chlorine/Chlorine	Ozone/Chlorine
Chlorine/Chlorine	Ozone/Chloramine
Chlorine/Chlorine	Chlorine dioxide/Chlorine
Chlorine/Chloramine	Ozone/Chloramine
Chlorine/Chloramine	Chlorine dioxide/Chloramine
Ozone/Chlorine	Ozone/Chloramine
Chloramine/Chloramine	Ozone/Chloramine

Note: Disinfectants are listed as primary disinfectant/secondary disinfectant

Since systems can initially determine what is considered a significant change in disinfection practice (including those specifically identified by the State), they may also consider changing the disinfectant and point of disinfectant application. For example, a system shifting from chlorine/chlorine to chlorine dioxide/chloramine may want to consider shifting the ammonia application point after the point of chlorine application to allow for some chlorine contact time for virus inactivation.

5.1.3 Changes to Disinfection Practices

Other significant changes to disinfection practices also require water systems to consult with the State before making the treatment change. Types of modifications considered significant include, but are not limited to, the following:

- Changes in the contact basin geometry and baffling conditions
- Increases in the pH during disinfection by greater than 1 unit (for chlorine only)
- Changes in the raw water source.

The IESWTR requires that water systems provide information to the State supporting the rationale for the potential treatment change. Types of supporting materials include a description of the proposed change, the disinfection profile, and an analysis of how the proposed change will affect the current disinfection benchmark.

Table 5-2. Impacts of Disinfection Practice on DBP Formation

Disinfection Byproduct	Change in Disinfection Practice (Primary Disinfectant/Secondary Disinfectant)				
	Chlorine/Chlorine To Chlorine/Chloramines	Chlorine/Chlorine To Ozone/Chlorine		Chlorine/Chloramines to Ozone/Chloramines	Chlorine/Chlorine to Chloramines/Chloramines
	Utility #7	Utility #19	Utility #36	Utility #7	Utility #36
Total Trihalomethanes	Decrease	Decrease	No change	Decrease	Decrease
Total Haloacetic Acids	Decrease	Decrease	No change	Decrease	Decrease
Total Haloacetonitriles	Decrease	Decrease	No change	Decrease	Decrease
Total Haloketones	Decrease	No change	Increase	Increase	Decrease
Total Aldehydes	Not analyzed	Not analyzed	Increase	Not analyzed	Decrease
Chloropicrin	No change	Increase	Increase	Decrease	No change
Chloral Hydrate	Decrease	Increase	Increase	Decrease	Decrease
Cyanogen Chloride	No change	Not analyzed	No change	No change	Increase

Disinfection Byproduct	Change in Disinfection Practice (Primary Disinfectant/Secondary Disinfectant)				
	Ozone/Chlorine To Ozone/Chloramines	Chloramines/Chloramines To Ozone/Chloramines		Chlorine/Chlorine To Ozone/Chloramines	
	Utility #36	Utility #25	Utility #36	Utility #7	Utility #36
Total Trihalomethanes	Decrease	Decrease	No change	Decrease	Decrease
Total Haloacetic Acids	Decrease	Decrease	No change	Decrease	Decrease
Total Haloacetonitriles	Decrease	No change	No change	Decrease	Decrease
Total Haloketones	Decrease	No change	Increase	Decrease	Decrease
Total Aldehydes	Decrease	Increase	Increase	Not analyzed	Increase
Chloropicrin	Increase	Increase	Increase	Decrease	Increase
Chloral Hydrate	Decrease	Decrease	Increase	Decrease	Decrease
Cyanogen Chloride	Increase	Increase	Increase	No change	Increase

Notes: Results based on full-scale evaluation at Utilities #19 and #25 and on pilot scale evaluations at Utilities #7 and #36.
Free chlorine contact time was 4 hours for Utility #7 during use of chlorine/chloramine strategy.

Systems must demonstrate efficacy of chloramines as a primary disinfectant if they are to be used as such. Source: Malcolm Pirnie, Inc., 1992; Jacangelo et al., 1989.

Source: Malcolm Pirnie, Inc., 1992; Jacangelo et al., 1989.

5.1.4 Other Modifications Identified by the State

The State may ultimately determine what changes in water system operations constitute a change in disinfection practices. If the State concludes that a change in disinfection practice is a significant modification, the water system must develop and submit a disinfection benchmark.

The modifications listed in Sections 5.1.1 through 5.1.3 are not an exhaustive list and may be amended at the State's discretion. Therefore, a water system should check with the State program office for assistance in determining whether the proposed change triggers the disinfection benchmarking procedure. Water systems can refer to *Alternative Disinfectants and Oxidants Guidance Manual* for additional information and references on disinfectant capabilities and the potential implications of modifying disinfection practices (USEPA, 1999a).

5.2 Communicating with the State

The IESWTR requires public water systems to consult with the State in order to assess the impact that disinfection modifications may have on their current log inactivation levels. Using the disinfection benchmarking method, the State may determine if the change in disinfection practice is acceptable (e.g., meets the current disinfection benchmark). However, there is no federal requirement for State approval of disinfection modifications.

As required under the IESWTR, the system must submit profiling information to the State. Profiling information includes:

- Detailed plans (schematic) and operating strategy of the proposed modifications to disinfection practices.
- The disinfection profile and supporting calculations and data for both the existing practice and the proposed change.
- The current disinfection benchmark value and supporting calculations.
- Detailed calculations that assess the potential impact of the intended changes in disinfection practice (i.e., with regard to anticipating changes in log inactivation to achieve modifications on current log inactivation (discussed in Section 5.3)).

Note that systems adding or switching to ozone or chloramines must provide the above information for both *Giardia* and viruses. EPA strongly recommends that systems also calculate a virus profile and benchmark if they are switching to chlorine dioxide.

5.3 Calculations to Identify Modification Impact

To assess the impact of modifications on current log inactivation, systems need to perform several additional benchmarking calculations. Specifically, water systems should calculate "modification benchmarks," based on the current operating conditions before the process change is made. These modification benchmarks should be compared to the original benchmark to evaluate the expected inactivation level of the modified disinfection practice.

The steps to calculate these modification benchmarks are as follows:

- Identify the lowest average months from the original profile (i.e., the one to three months that were averaged to calculate the original benchmark).
- Using the temperature, pH, and contact times (unless the modification significantly changes these values) from the original profile calculations, systems calculate the daily log inactivation for *Giardia* (and/or viruses) for each day of the month under the proposed modification (i.e., for conditions after the modification is complete). The water system will need to assume reasonable values for the disinfectant residuals. It may also need to calculate or estimate contact times, or identify new points of disinfectant residual sampling to reflect the modification.
- Calculate the average log *Giardia* and/or virus inactivation for the months identified in the first bullet.
- Calculate the average of the monthly values. This value is the modification benchmark.
- Compare the original benchmark to the modification benchmark. If the modification benchmark is greater than the original benchmark, the modification will likely be acceptable after consultation with the State. Modification benchmarks lower than the original benchmark should be evaluated by the State to determine whether the resulting level of disinfection is still considered adequate based on source water quality and watershed conditions (discussed further in Chapter 6).

The system and State should discuss the reasons for any modification and whether better options exist, and assess the modification's impact on log inactivation. The State and the system should jointly assess the impact that the proposed modification will have on log inactivation levels of *Giardia* and/or viruses.

A detailed example of calculating the impact of changes in disinfection practices, including the comparison of original and modification benchmarks, is provided in Section 5.5.

5.4 Alternative Benchmark

As addressed in the IESWTR, situations will exist when a system may need to develop an alternative benchmark to comply with the Stage 1 DBPR provisions. These situations are detailed in Chapter 6.

The disinfection benchmark can also be met by a combination of inactivation with a chemical disinfectant and an improvement in the physical removal of pathogens after consultation with the State. Consider an unfiltered system with a disinfection benchmark of 4-logs for *Giardia*. If this system were to implement conventional filtration and receive 2.5-log *Giardia* removal credit, the chemical disinfection required to meet the existing disinfection benchmark could be reduced to 1.5-log *Giardia* inactivation. Likewise, a utility that makes a process enhancement to improve pathogen removal could receive credit toward achieving its existing disinfection benchmark. Consider a conventional filtration plant that upgrades its process to include ultrafiltration using membranes. Because ultrafiltration has been demonstrated to achieve greater than 6-logs of *Giardia* removal, the existing *Giardia* disinfection benchmark could be reduced by an amount deemed acceptable by the State (AWWARF, 1997). The remainder of the existing disinfection benchmark could be accomplished with chemical disinfection.

5.5 Illustrative Examples

This section considers simple examples of disinfection byproduct control. These examples are applicable to conventional filtration plants that are considering additional control of DBPs to comply with the Stage 1 DBPR. The examples include process changes that may accomplish the goals of controlling DBP levels and disinfection benchmarking. This section does not discuss major process changes, such as alternative primary disinfectants, since they require extensive engineering evaluation. As discussed previously, the system should only implement significant changes to a disinfection practice after careful consideration and consultation with the State. In most circumstances, the system should seek the assistance of a qualified professional engineer to develop and implement a process change. The *Microbial and Disinfection Byproducts Simultaneous Compliance Guidance Manual* (USEPA, 1999b) presents case studies and scenarios involving solutions to some of the potential conflicting compliance issues.

5.5.1 DBP Control using Enhanced Coagulation

5.5.1.1 Base Conditions (Plant A)

This section considers the base condition to be a conventional filtration plant (Plant A) that practices prechlorination. Table 5-3 lists the important raw water characteristics, while Table 5-4 describes the important unit processes of Plant A.

Table 5-3. Raw Water Quality (Plant A)

Parameter	Value
PH	7.5-8.0
TOC (mg/L)	3.8-5.0
UV-254 (1/cm)	0.1-0.15
Bromide (mg/L)	0.15-0.2
Temperature (°C)	6-20
Alkalinity (mg/L as $CaCO_3$)	50-60
SUVA (L/mg-m)	~ 2.5 – 3.7

Table 5-4. Base Condition Unit Processes (Plant A)

Process	Characteristics
Influent	Raw Water Characteristics above
Chlorine	Dose 4 mg/L
Alum	Dose 20 mg/L
Rapid Mix	5 minutes detention, 0.1 baffling factor
Flocculation	20 minutes detention, 0.3 baffling factor
Settling	90 minutes detention, 0.3 baffling factor
Filtration	15 minutes detention, 0.5 baffling factor
Clearwell	60 minutes detention, 0.1 baffling factor
Distribution	3 days maximum detention time

The disinfection benchmark for *Giardia* for this conventional filtration plant is 0.75-logs. This system applies chlorine to the raw water for disinfection to achieve at least a 0.2 mg/L distribution system residual. Since chlorine and alum are both acids, the pH is reduced from about 7.5 in the influent to 7.1 in the finished water. Total organic carbon is removed in the coagulation/settling process from 5.0 mg/L in the raw water to 3.7 mg/L in the finished water (which is inadequate to meet Stage 1 DBPR requirements for enhanced coagulation). This results in a concurrent decline in SUVA.

The TTHM and HAA5 concentrations experienced by this system with its three-day detention time in the distribution system are listed in Table 5-5. The running annual average (RAA) TTHM and HAA5 values are 87 and 58 µg/L, respectively. Because the TTHM value exceeds the Stage 1 MCL, this system must implement a strategy for TTHM control. Also, since the HAA5 concentration is close to the MCL, the system should implement a HAA5 control strategy.

Table 5-5. System DBP Concentrations (Plant A)

Parameter	Summer	Winter	RAA
TTHM (µg/L)	145	29	87
HAA5 (µg/L)	71	44	58

Note: Running annual average is based on quarterly sampling (not shown).

The plant examines making four modifications to its disinfection practices to control DBPs. These modifications include:

1. Practicing enhanced coagulation as required by the Stage 1 DBPR
2. Installing chloramination to provide residual disinfection
3. Moving the point of chlorine application after settling (possibly a seasonal change)
4. Improving hydraulic characteristics of clearwell.

The system operator assesses whether practicing enhanced coagulation is likely to achieve the desired TTHM and HAA5 reductions. Based on UV absorbance, TOC concentrations, and DBP levels, the plant's management decides to employ enhanced coagulation as a first step to control DBP levels.

5.5.1.2 Enhanced Coagulation for DBP Control (Plant A)

Enhanced coagulation improves the removal of organic carbon in the coagulation and settling processes. Because the system is not exempt from enhanced coagulation requirements, it must achieve TOC removal requirements as stated in Table 5-6. Because waters with greater alkalinity and lower TOC concentrations are more difficult to coagulate, performance requirements in these categories are lower than for other categories.

Table 5-6. Proposed Required Removal of TOC by Enhanced Coagulation/Enhanced Softening for Surface Water Systems Using Conventional Treatment

Source Water TOC (mg/L)	Source Water Alkalinity (mg/L as $CaCO_3$)		
	0-60	>60-120	>120[1]
>2.0-4.0	35.0%	25.0%	15.0%
>4.0-8.0	45.0%	35.0%	25.0%
>8.0	50.0%	40.0%	30.0%

Enhanced coagulation alternative compliance criteria applicable to waters with raw-water SUVA ≤ 2.0 L/mg-m.

[1] Systems practicing precipitative softening must meet the TOC removal requirements in this column.

The system in question has a raw water alkalinity of 50-60 mg/L as $CaCO_3$ and a raw water TOC of 4.5-5.0 mg/L. Based on Table 5-6, these conditions require the utility to remove 45 percent or more TOC through the coagulation and settling process as an annual average (refer to the *Guidance Manual for Enhanced Coagulation and Enhanced Precipitative Softening* for additional information (USEPA, 1999g)). The utility currently adds 20 mg/L of alum. This alum dose reduces the TOC from 5.0 to 3.7 mg/L through settling. This is equivalent to 26 percent removal ([5.0-3.7]/5.0*100%). Through jar testing, the plant operators determine that it needs to add 40 mg/L alum to achieve 45 percent removal of TOC (i.e.; to achieve 2.7 mg/L TOC in its settled water). Practicing enhanced coagulation in settled water is expected to result in the following DBP concentrations in the distribution system (Table 5-7).

Table 5-7. System DBP Concentrations with Enhanced Coagulation, Settled Water Chlorination (Plant A)

Parameter	Summer		Winter		RAA	
	Before EC	After EC	Before EC	After EC	Before EC	After EC
TTHM (µg/L)	145	99	29	20	87	60
HAA5 (µg/L)	71	54	44	33	58	44

Note: Running Annual Average (RAA) is based on quarterly sampling (not shown).
EC = Enhanced Coagulation

In addition to controlling DBPs, enhanced coagulation allows for more effective disinfection. This occurs by two mechanisms:

- A greater residual is provided for the same chlorine dose since the chlorine demand is lower in water treated by enhanced coagulation.
- Chlorine is more effective at inactivating *Giardia* at the lower pH resulting from enhanced coagulation.

The disinfectant residual achieved by a given dose is a function of contact time and disinfectant demand of the water, among other factors. Because TOC exerts a disinfectant demand, the disinfectant residual will be greater when practicing enhanced coagulation (for the same chlorine dose).

The addition of alum to water decreases the pH of the water. For instance, the pH of the settled water under the original 20 mg/L alum dose was 7.1, whereas the pH of the settled water under the 40 mg/L alum dose is 6.6. This drop in pH with enhanced coagulation may adversely impact corrosion in the distribution system and should be mitigated appropriately. The drop in pH actually improves disinfection, because chlorine is more effective at inactivating *Giardia* at lower pH. Acids, such as hydrochloric acid, are used in treatment plants to lower pH levels to enhance coagulation and improve filter performance. Table 5-8 indicates the improved disinfection occurring due to enhanced coagulation and disinfection of settled water. The system also maintains a disinfection level above its current benchmark. The system also may reduce its chlorine dose to maintain its pre-enhanced coagulation chlorine residual levels of 0.8mg/L and to conserve financial reserves.

Table 5-8. Impact of Enhanced Coagulation on Disinfection (Plant A)

Coagulation Practice	Chlorine Residual in Finished Water (mg/L)	Contact Time (minutes)	CT (mg-min/L)	pH at Residual Sampling Point	Log Inactivation of *Giardia* at 5°C
Existing (20 mg/L Alum)	0.8	47	37.6	7.1	0.75
Enhanced (40 mg/L Alum)	1.2	47	56.6	6.6	1.3

5.5.2 Treatment Changes for DBP Control When Enhanced Coagulation is Insufficient

5.5.2.1 Base Conditions (Plant B)

The base condition considered for this example, Plant B, is a conventional filtration plant that practices prechlorination. Table 5-9 lists the important raw water characteristics for this plant, while Table 5-10 describes the important unit processes of Plant B.

Table 5-9. Raw Water Quality (Plant B)

Parameter	Value
pH	7.6-7.9
TOC (mg/L)	4.0-5.0
UV-254 (1/cm)	0.15-0.2
Bromide (mg/L)	0.15-0.2
Temperature (°C)	5.0-24
Alkalinity (mg/L as CaCO3)	50-60

Table 5-10. Base Condition Unit Processes (Plant B)

Process	Characteristics
Influent	Raw Water Characteristics above
Chlorine	Dose 4 mg/L
Alum	Dose 20 mg/L
Rapid Mix	5 minutes detention, 0.1 baffling factor
Flocculation	20 minutes detention, 0.3 baffling factor
Settling	80 minutes detention, 0.3 baffling factor
Filtration	15 minutes detention, 0.5 baffling factor
Clearwell	60 minutes detention, 0.1 baffling factor
Distribution	3 days maximum detention time

The disinfection benchmark for *Giardia* for this conventional filtration plant is 1.0 log. This system applies chlorine to the raw water for disinfection and maintains a detectable residual throughout the distribution system. The effects of both chlorine and alum on pH is evident in the decrease in pH levels from about 7.6 in the influent to 6.9 in the finished water. TOC is removed in the coagulation/settling process from 5.0 mg/L in the raw water to 3.7 mg/L in the finished water. This results in a concurrent decline in UV absorbance.

The TTHM and HAA5 concentrations experienced by this system with its 3-day detention time in the distribution system are listed in Table 5-11. The running annual average (RAA) TTHM and HAA5 values are 99 and 65 μg/L. Because the TTHM value exceeds the Stage 1 MCL, this system must implement a strategy for DBP control.

Table 5-11. System DBP Concentrations (Plant B)

Parameter	Summer	Winter	RAA
TTHM (μg/L)	165	39	99
HAA5 (μg/L)	85	55	65

Note: Running annual average is based on quarterly sampling (not shown).

The plant examines making four modifications to its disinfection practices to control DBPs. These modifications include:

1. Practicing enhanced coagulation as required by the Stage 1 DBPR
2. Installing chloramination to provide residual disinfection
3. Moving the point of chlorine application after settling (possibly a seasonal change)
4. Improving hydraulic characteristics of the clearwell.

5.5.2.2 Enhanced Coagulation for DBP Control (Plant B)

Because the system is not exempt from enhanced coagulation requirements, it must achieve the TOC removal requirements stated in Table 5-6.

The system in question has a raw water alkalinity of 50-60 mg/L as $CaCO_3$ and a raw water TOC of 4.5-5.0 mg/L. Based on Table 5-6, these conditions require the utility to remove 45 percent or more TOC through the coagulation and settling process as an annual average. The utility currently adds 20 mg/L of alum. This alum dose reduces the TOC from 5.0 to 3.7 mg/L through settling. This is equivalent to 26 percent removal ([5.0-3.7]/5.0*100%). Through jar testing, the plant operators determine that they need to add 40 mg/L alum to achieve 45 percent removal of TOC (i.e., to achieve 2.7 mg/L TOC in its settled water). Practicing enhanced coagulation results in the following DBP concentrations in the distribution system (Table 5-12).

Table 5-12. System DBP Concentrations with Enhanced Coagulation (Plant B)

Parameter	Summer		Winter		RAA	
	Before EC	After EC	Before EC	After EC	Before EC	After EC
TTHM (µg/L)	165	99	39	25	99	73
HAA5 (µg/L)	85	65	55	38	65	57

Note: Running annual average is based on quarterly sampling (not shown).

In addition to reducing DBPs, enhanced coagulation allows for more effective disinfection and some TOC removal. Because TOC exerts a disinfectant demand, the disinfectant residual will be greater (for the same chlorine dose).

The addition of alum to water decreases the pH of the water. For instance, when the pH of the settled water under the original 20 mg/L alum dose was 7.1, the pH of the settled water under the 40 mg/L dose was 6.5. This drop in pH with enhanced coagulation may adversely impact corrosion in the distribution system and should be mitigated appropriately. The drop in pH actually improves disinfection, however, since chlorine is more effective at inactivating *Giardia* at lower pH. Table 5-13 indicates the improved coagulation occurring due to enhanced coagulation. The system also maintains a disinfection level above its current benchmark.

Table 5-13. Impact of Enhanced Coagulation on Disinfection (Plant B)

Coagulation Practice	Chlorine Residual in Finished Water (mg/L)	Contact Time (minutes)	CT (mg-min/L)	pH at Residual Sampling Point	Log Inactivation of Giardia at 5°C
Existing (10 mg/L Alum)	1.4	44	61.6	7.1	1
Enhanced (40 mg/L Alum)	1.8	44	79.2	6.5	1.7

While improving its level of *Giardia* inactivation, the system fails to reach the desired reductions in TTHM and HAA5 levels (see Section 2.5). The system considers switching to chloramines for a secondary disinfectant in order to reduce DBP levels.

5.5.2.3 Chloramines

Chloramines can be used as a secondary disinfectant to control DBP formation in the distribution system. This system is considering the application of free chlorine to its raw water, with application of ammonia to the suction line of the high service pumps. This allows disinfection using free chlorine, while quenching the free chlorine residual with ammonia to limit formation of regulated DBPs in the distribution system. The use of chloramines for residual disinfection is dicussed extensively in the *Alternative Disinfectants and Oxidants Guidance Manual* (USEPA, 1999a).

The use of chloramines by this system will not affect its primary disinfection because ammonia is applied following the clearwell. Therefore, the disinfection level listed in Table 5-13 for enhanced coagulation (1.7-log *Giardia* inactivation) is still applicable for this system using chloramines for residual disinfection.

Chloramines will effectively control DBP formation in the distribution system. For systems that exceed DBP MCLs within the plant, rather than the distribution system, ammonia would need to be applied prior to the clearwell for effective DBP control. For this system, application of ammonia at the suction line of the high service pumps (after clearwell) allows disinfection levels to be maintained while further controlling DBPs. For this system, use of chloramines combined with enhanced coagulation and settled water chlorination results in TTHM and HAA5 concentrations of 66 µg/L and 51 µg/L running annual average, respectively.

5.5.2.4 Moving the Point of Chlorine Application after Settling

The purpose of this modification is to reduce the concentration of DBP precursors prior to the addition of chlorine. TOC is removed during the coagulation/settling process. For this system, the TOC level declines from about 5.0 to 3.7 mg/L after settling, with the addition of 20 mg/L of alum. Moving the point of chlorination, therefore, results in the chlorination of water with significantly lower TOC. Because TOC is a surrogate measure for natural organic material (a principal DBP precursor), and the TOC level has been reduced, this should reduce the formation of DBPs.

Moving the point of chlorine application from raw water to settled water results in DBP formation shown in Table 5-14. The chlorine dose is not changed from the baseline condition which is 4.0 mg/L. This modification results in a decrease in TTHM concentration of about 20 percent and HAA5 concentration of about 30 percent.

Table 5-14. System DBP Concentrations After Enhanced Coagulation and Moving the Point of Chlorination

Parameter	Summer		Winter		RAA	
	Only EC	After moving POC	Only EC	After moving POC	Only EC	After moving POC
TTHM (µg/L)	99	80	25	20	73	55
HAA5 (µg/L)	65	46	38	27	57	35

Note: Running annual average is based on quarterly sampling (not shown).
POC = Point of Chlorination
EC = Enhanced Coagulation

Under baseline conditions, the system added chlorine to the raw water and used the detention time available in the rapid mix, flocculation, and sedimentation basins. This contact time is about 31 minutes at peak hourly flow (i.e., 70 percent of total contact time available). Once the system moves chlorine application to settled water, it loses the benefit of this contact time.

The achieved chlorine residual is a function of chlorine dose and decay. Chlorine decay depends on the chlorine demand of the water and contact time, among other factors. Organic carbon exerts chlorine demand. Because settled water contains less TOC and because chlorine is in contact with water for a shorter duration, the chlorine residual in the finished water is greater when chlorine is applied to settled water (Table 5-15). For application of chlorine to settled water, the chlorine residual is greater but the contact time is shorter. This results in an overall decrease in disinfection level (i.e., the CT) by about 50 percent.

Table 5-15. Impact of Moving Chlorine Application Point on Disinfection

Chorine Application Point	Contact Time (minutes)	Chlorine Residual in Finished Water (mg/L)	CT (mg-min/L)	Log Inactivation of Giardia at 5°C and pH 6.5
Raw Water	44	1.8	79.2	1.7
Settled Water	13.5	2.8	37.8	0.8

Moving the point of chlorine application from raw to settled water does assist in controlling DBP formation but is less than the disinfection benchmark. However, if the chlorine application point is moved seasonally, this may not be an issue. This is discussed further in the next section.

5.5.2.5 Seasonal Chlorine Application Points

The plant operators consider changing the point of disinfectant application only during summer when DBP formation is highest, and the CTs required for pathogen inactivation are at their lowest. A seasonal change in the point of chlorine application can assist in controlling DBPs and meeting disinfection benchmarking goals.

The disinfection benchmark characterizes the minimum disinfection achieved based on historic plant operating data. Because the effectiveness of disinfection is significantly reduced at lower temperatures, the benchmark is typically determined during the winter months (i.e., December, January, and February). Therefore, the existing disinfection level in these months should be maintained. However, disinfection is more effective in summer, and therefore does not require as high a CT as in winter. This may allow a utility to move the point of chlorine application downstream in the treatment train when less contact time is needed.

Disinfection byproduct formation is typically greatest in summer, since the rate of DBP formation is greater at higher temperatures and in the presence of DBP precursors (e.g., when algae may be at their highest concentrations.) These contrasting issues of needing to maintain disinfection levels in winter and needing to control DBPs primarily during summer lead to the concept of seasonal DBP application points. That is, apply chlorine early in the process train in winter to maximize contact time and apply chlorine later in the process train in summer to control DBPs.

The plant operators decide to use the existing raw water chlorination point from December through February, and move the point of chlorination to settled water from March through November. The winter chlorination point and dose will be the same as historic practices, so the existing benchmark will be maintained. The impact of seasonal chlorine application points on DBP concentrations is summarized in Table 5-16. The seasonal chlorine application points evaluated at this utility satisfy the existing disinfection benchmark (1.0) by maintaining critical winter disinfection.

Table 5-16. System DBP Concentrations After Enhanced Coagulation and Moving of Chlorine Application Points

Parameter	Summer	Winter	RAA
TTHM (µg/L)	80	25	57
HAA5 (µg/L)	46	38	42

Note: Running annual average is based on quarterly sampling (not shown).
RAA = Running Annual Average

Table 5-17 shows the impact of moving the disinfection point during the summer season on *Giardia* inactivation. By moving the point of chlorine application to settled water during warmer periods, the DBP concentrations were controlled below the Stage 1 MCLs. This was accomplished using the same chlorine dose. A utility considering this alternative must ensure that the minimum disinfection requirements of the SWTR are met at all times and that an adequate disinfectant residual is provided for distribution.

Table 5-17. Impact Of Moving Chlorine Application During The Summer Season

Chorine Application Point	Contact Time (minutes)	Chlorine Residual in Finished Water (mg/L)	CT (mg-min/L)	Log Inactivation of *Giardia* at 20°C and pH 6.5	Log Inactivation of *Giardia* at 5°C and pH 6.5
Raw Water (Winter)	44	1.8	79.2	--	1.7
Settled Water (Summer)	13.5	2.8	37.8	2.0	--

5.5.2.6 Clearwell Baffling

Moving the point of chlorination to settled water combined with practicing enhanced coagulation will allow plants to comfortably meet Stage 1 DBP MCLs. Enhanced coagulation also improves disinfection, but it cannot make up for the reduced contact time associated with moving chlorine application from raw to settled water. Compare the Log inactivation values for raw water (1.0) with enhanced coagulation (1.7) presented on Table 5-18. For this system, moving the point of chlorination combined with enhanced coagulation results in a 50 percent decrease in disinfection level. Although seasonal chlorination point strategy could meet disinfection benchmarking goals by maintaining existing winter disinfection, another method to meet benchmarking goals would be to improve the hydraulics of the clearwell using baffles.

Baffling and disinfection contact time are discussed extensively in Appendix D. The clearwell for the system being discussed is not baffled and has been estimated to have a baffling factor (T_{10}/T) of 0.1. This is the worst classification of baffling for disinfection contact time and the system only receives credit for 10 percent of the theoretical detention time (60 minutes). Therefore, opportunity exists to substantially improve disinfection by improving the hydraulic characteristics of the clearwell for disinfection contact time.

Table 5-18. Cumulative Impact of Settled Water Chlorination, Enhanced Coagulation and Clearwell Baffling on Disinfection (Plant B)

Modification	Disinfection Contact Time (minutes)	Disinfectant Residual (mg/L)	CT (mg-min/L)	Finished Water pH	Log Inactivation of Giardia
1. Original Raw Water Chlorination at 5°C	44	1.4	61.6	7.1	1.0 (benchmark)
2. Enhanced Coagulation at 5°C	44	1.8	79.2	6.5	1.7
3. Seasonal Settled Water Chlorination at 20°C	13.5	2.8	37.8	6.5	2.0
4. Regular Settled Water Chlorination at 5°C	13.5	2.8	37.8	6.9	0.64
5. Enhanced Coagulation, Settled Water Chlorination at 5°C	13.5	2.8	37.8	6.5	0.8
6. Enhanced Coagulation, Settled Water Chlorination, Clearwell Baffling at 5°C	37.5	2.8	105	6.5	2.7

The system has developed a design to baffle the clearwell and improve its baffling factor from 0.1 to 0.5 (average conditions). The baffling design includes inlet and outlet baffles, with some intra-basin baffles. Using the theoretical detention time of 60 minutes, a baffling factor of 0.1 yields 6 minutes of contact time (T_{10}) while a factor of 0.5 yields 30 minutes of contact time. Please review other sections of this manual for calculations using baffling factors and guidance on baffling the clearwell or other basins. Table 5-18 compares the cumulative impact on disinfection of the modifications presented above: moving point of chlorination (regular or during summer season only), enhanced coagulation, and clearwell baffling.

Table 5-18 indicates that enhanced coagulation, seasonal settled water chlorination, and clearwell baffling together provide greater disinfection than the original practice of chlorinating raw water, using a chlorine dose of 4 mg/L for both situations. Baffling the clearwell is not expected to significantly impact DBP formation. Therefore, RAA TTHM and HAA5 concentrations are expected to be 57 µg/L and 46 µg/L, respectively. The greater disinfection provided through baffling modification, enhanced coagulation and settled water chlorination, would allow the utility to reduce its chlorine dose to less than 3 mg/L and still meet or exceed its disinfection benchmark, further controlling DBP concentrations.

5.5.3 Summary of Treatment Modification Strategies Impact on Disinfection and DBP Control

The system described as Plant B had running annual average DBP concentrations greater than the Stage 1 DBPR MCLs. The system considered four strategies for DBP control. These strategies and their impacts on disinfection and byproduct formation are summarized in Table 5-19. This experience demonstrates how a single change did not allow simultaneous compliance. Rather, several carefully selected components were integrated for DBP control while maintaining the historical disinfection benchmark.

Table 5-19. Summary Impacts of DBP Control Strategies Original Practice – Raw Water Chlorination

Strategy	Disinfection	Byproduct Control
Settled Water Chlorination	-	+
Enhanced Coagulation	+	+
Clearwell Baffling	+	0
Chloramines for residual disinfection	0	+

Note: + for improvement, - for degradation, 0 for no impact

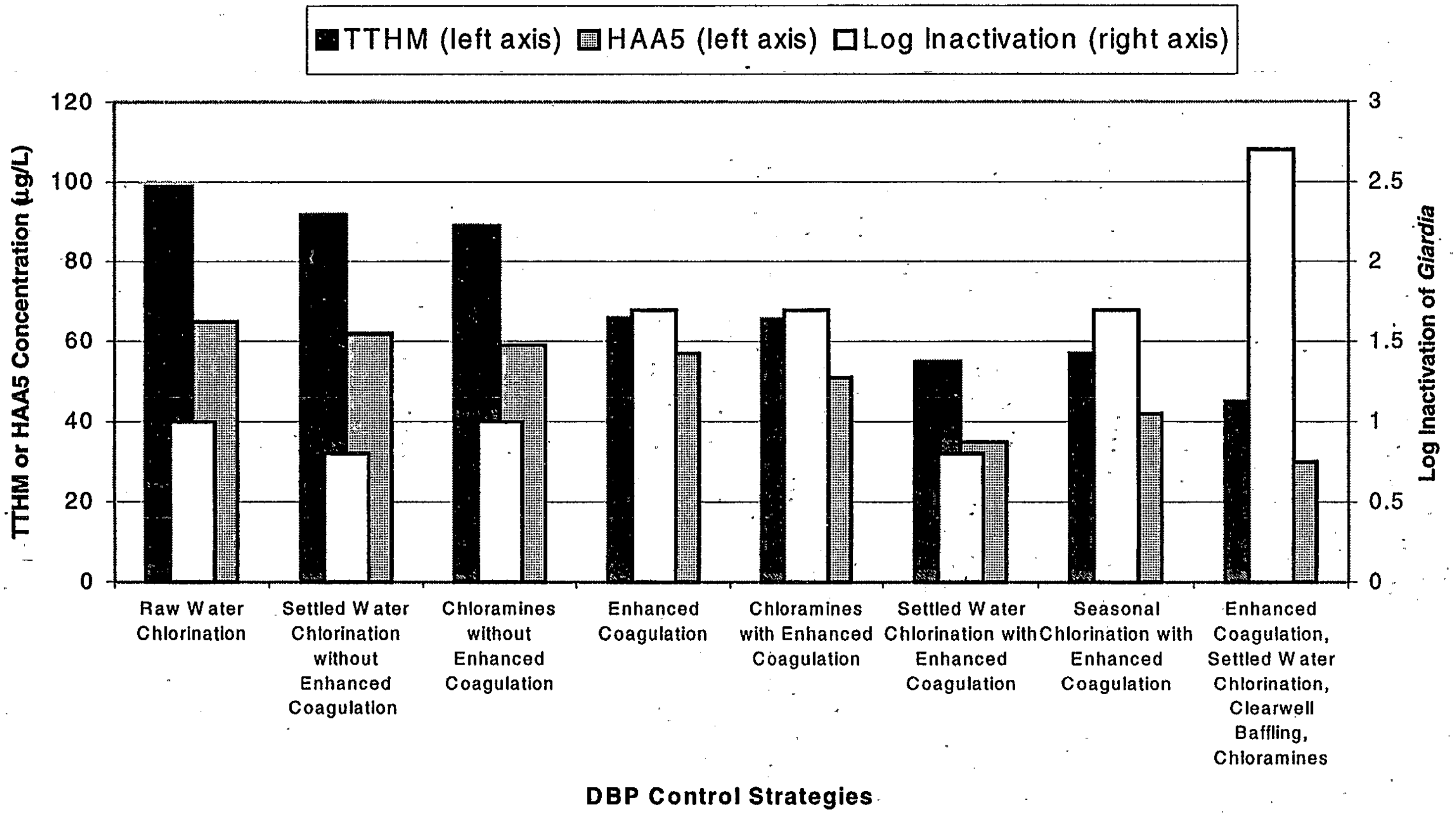
Table 5-20 and Figure 5-1 summarizes the experience of "Plant B" in selecting a DBP control strategy that maintains historical critical period disinfection levels. No single component solved these problems. Instead, several carefully selected components were required to meet DBP MCLs while maintaining historical critical period disinfection. Moving the point of chlorination to settled water combined with enhanced coagulation allowed the utility to meet Stage 1 DBP MCLs, but sacrificed disinfection due to the shorter chlorine contact time. Historical disinfection levels were achieved by also baffling the clearwell to recover some of the lost disinfection contact time. Another alternative for meeting the disinfection benchmark would be to maintain seasonal chlorine application points. This strategy would chlorinate raw water during critical period disinfection months used to calculate the benchmark (i.e.; winter conditions). During warmer conditions, chlorine would be applied to settled water to control DBPs. Seasonal chlorine application points combined with enhanced coagulation would have also met the Stage 1 DBP MCLs and disinfection benchmarking goals for the system under consideration.

Table 5-20. Impact of DBP Control Strategies on Disinfection and Byproduct Formation

Treatment Type	TTHM Concentration[1] (μg/L)	HAA5 Concentration[1] (μg/L)	Critical Log Inactivation of *Giardia*[2]
Raw Water Chlorination	99	65	1.0
Settled Water Chlorination without Enhanced Coagulation	92	62	0.8
Chloramines without Enhanced Coagulation	89	59	1.0
Enhanced Coagulation	73	57	1.7
Chloramines with Enhanced Coagulation	66	51	1.7
Settled Water Chlorination with Enhanced Coagulation	55	35	0.8
Seasonal Chlorination with Enhanced Coagulation	57	42	1.7
Enhanced Coagulation, Settled Water Chlorination, Clearwell Baffling, Chloramines	45	30	2.7

[1] as running annual average

[2] at 5°C and pH 6.5



Note: Settled water chlorination refers to year-round chlorination.

Figure 5-1. Impact of DBP Control Strategies on Disinfection and Byproduct Formation

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6. Alternative Disinfection Benchmark

Some systems may not be able to meet Stage 1 DBPR MCLs while maintaining their existing disinfection practices and benchmark. Under these conditions, the system must consult with the State to discuss appropriate compliance strategies, including an alternative disinfection benchmark. The alternative disinfection benchmark would be lower than the calculated disinfection benchmark, allowing the utility greater flexibility to achieve compliance with DBPR MCLs while still not significantly compromising microbial protection. However, the alternative disinfection benchmark must not be lower than the disinfection requirements of the SWTR.

Each State will formulate its own plan for evaluating inactivation data and setting alternative disinfection benchmarks. The plan should foster cooperation between the State and water systems. The goal of an alternative disinfection benchmark is to improve a system's ability to meet the DBPR MCLs without significantly compromising existing microbial protection. The system and State should consider source water quality, existing physical barriers to pathogens, and the risk of waterborne disease to set an alternative disinfection benchmark. The information and examples presented here are intended as guidance. Each State should develop its own plan for evaluating and setting alternative disinfection benchmarks.

The following examples describe characteristics of systems that may choose to develop an alternative benchmark:

- Systems that cannot simultaneously meet the disinfection benchmark and the Stage 1 DBPR MCLs and which have:
  - very high levels of microbial inactivation and/or
  - high quality source water that has low pathogen occurrence levels.

These examples are not meant to be exhaustive. If a system has circumstances similar to the above examples, it may want to consult the State to set an alternative disinfection benchmark to gain greater flexibility for complying with the provisions of the Stage 1 DBPR.

Systems with Very High Levels of Microbial Inactivation

Some water systems have very high existing levels of inactivation. These high values may be the result of the following:

- The disinfectant dose is controlled by the need to maintain a residual in the distribution system rather than by the need to provide the primary disinfection required by the SWTR. The dose required to provide a distribution system residual often determines in-plant disinfection practices.

- To simplify compliance with the SWTR, a system may operate with a "minimum specified residual" under worst case operating conditions. Because the worst case conditions may not occur simultaneously (i.e., lowest temperature and greatest peak hourly flow rate), the utility may be achieving much greater disinfection levels than required by the SWTR.
- The disinfectant in use may be much more effective against a particular pathogen. For example, chlorine is much more effective at inactivating viruses than it is *Giardia*. For this reason, systems that inactivate *Giardia* with chlorine may be achieving very high logs inactivation of viruses (e.g., greater than 10 logs) as indicated by extrapolation using the CT concept. A system may want to apply for an alternative disinfection benchmark for viruses, if it is considering switching to another disinfectant or improving its physical removal processes.
- The treatment plant is operating well below design flow and, therefore, disinfection contact time is extremely long.

In the above examples, the benchmark inactivation for *Giardia* and/or viruses may be so high that the log inactivation levels would be well in excess of treatment needed. Therefore, there may be an opportunity to reduce the level of calculated inactivation without significantly increasing the risk of waterborne disease.

Systems Exceeding the Stage 1 DBP MCLs

It may be very difficult for some systems to maintain current levels of *Giardia* or virus inactivation and simultaneously comply with Stage 1 DBPR MCLs (0.080 mg/L and 0.060 mg/L for TTHM and HAA, respectively). These systems may want to set an alternative benchmark to obtain greater flexibility for DBPR compliance.

Consider a system that has been using free chlorine for primary disinfection and maintenance of a distribution system residual. The system is interested in switching to chloramines for residual disinfection in order to limit free chlorine contact time and control DBP formation. Chloramines are less effective for inactivating both *Giardia* and viruses. Therefore, if ammonia is added prior to the historical point of chlorine residual measurement, the level of primary disinfection would be diminished from historical practices (i.e., the system would fall below its existing disinfection benchmark). In this example the system could either increase the free chlorine residual to meet the existing benchmark or apply to the State for an alternative disinfection benchmark. Another option, presented earlier, is the seasonal use of chloramines, which may not require an alternative benchmark.

Systems with High Quality Source Water

Water systems with very stable and high quality source water (usually in well-protected watersheds) may have a lower risk of microbial occurrence. Disinfection of high quality water with low pathogen occurrence, beyond the requirements of the SWTR, may not be warranted provided that filtration is well operated and watershed control is practiced.

The SWTR requires all plants to provide at least 4-log inactivation and/or removal of viruses and 3-log inactivation and/or removal of *Giardia*. Because SWTR allows states to give credit for filtration, the log inactivation required by chemical disinfection can be significantly lower. The EPA recommends that the State allow more credits for *Giardia* and virus removal by filtration if the following applies (AWWA, 1991):

1. It is determined that the system is not currently at significant risk of microbiological contamination at the existing level of disinfection.
2. Less stringent interim disinfection conditions are necessary for the system to modify its disinfection process to optimally achieve compliance with the SWTR as well as forthcoming DBP regulations.

Table 6-1 presents the different log removal credits allocated for different types of filtration.

Table 6-1. Log Removal Credits for Filtration

Filtration	Giardia Log Removal	Virus Log Removal	Conditions for Credit Allocation
Conventional	2.5	2.0	Meets the following: A)Total treatment train achieves 1) at least 99% turbidity removal or filtered water turbidities are less than 0.5 NTU or 2) 99.9% particle removal in size ranges of 5 to 15 um is demonstrated; and B)The level of HPC bacteria in the filtered water entering the distribution system is consistently less than 10/mL.
Direct Filtration	2.0	1.0	Same conditions as above.
Slow-Sand Filtration	2.0	2.0	Same conditions as above.
Diatomaceous Earth Filtration	2.0	1.0	Same conditions as above.

Source: AWWA, 1991.

Figure 6-1 illustrates the potential range for alternative disinfection benchmarks. The daily log inactivation of *Giardia* or viruses over a period of time constitutes the disinfection profile. The disinfection benchmark, shown as a solid horizontal line on the profile, is the average of the lowest month of each year. Therefore, the benchmark is typically determined by the disinfection practiced in winter months (January and February in the profile shown). The level of inactivation required by the SWTR (assuming States grant a removal credit of 2.5-logs for conventional treatment and 2-logs for direct filtration) is shown as horizontal dashed lines on the figure for conventional and direct filtration. This log inactivation removal is determined by subtracting the physical removal credit for filtration from the total log inactivation/removal required by the SWTR. The bold arrows denote the range for alternative disinfection benchmarks. Alternative disinfection benchmarks are lower than existing disinfection benchmarks, but always must be equal to or greater than requirements of the SWTR.

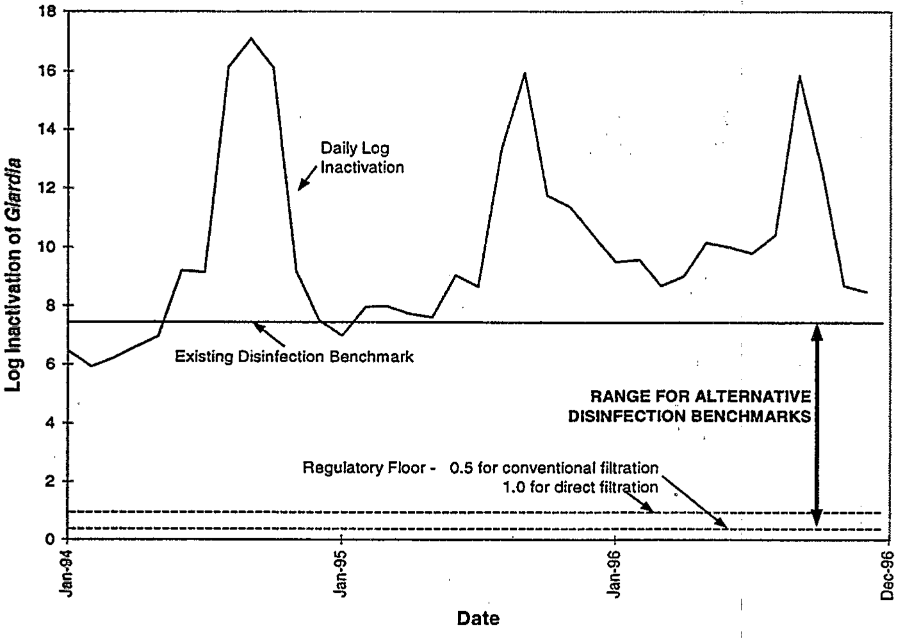

Figure 6-1. Range for Alternative Disinfection Benchmarks

6.1 Methodology

Options for developing the alternative disinfection benchmark are described below. These options are guidance only. The State may choose to adopt a methodology for setting alternative benchmarks based on this guidance or develop other methodologies. However, under no circumstances may the State set an alternative disinfection benchmark lower than disinfection level required by the SWTR.

The goal of the SWTR is to ensure that the annual risk of *Giardia lamblia* infection for an individual is less than 10^{-4} cases/person/year. The SWTR used an exponential risk assessment model (Rose, 1988) to calculate the logs of treatment necessary to keep the annual risk of infection below 10^{-4} cases/person/year for different concentrations of *Giardia lamblia* cysts in source water. EPA developed two options, or methodologies, for setting an alternative benchmark from this risk paradigm.

Cryptosporidium was not used as a reference for establishing alternative disinfection benchmarks because most systems currently employ disinfection which is assumed to provide little or no inactivation of this pathogen. Therefore, any change in disinfection practice is not addressed with respect to *Cryptosporidium.* These options are provided as guidance or recommendations only. Systems and States may use or modify these options or develop their own options.

Option 1 – No Monitoring

This option allows a utility to set an alternative disinfection benchmark without characterizing the quality of its source water. The lack of monitoring data requires the assumption that high levels of disinfection be provided. This option may be attractive to systems that have average source water quality, have high existing disinfection benchmarks, and do not need flexibility to meet the DBPR MCLs.

The goal of the SWTR is to limit infections by *Giardia* to one per year per 10,000 people (10^{-4} cases/person/year). This is assumed to be the maximum acceptable risk of infection. For source water having an average of 1 *Giardia* cyst per 100 L (very good quality water) and receiving 3-logs of treatment for *Giardia*, the risk of infection is about 10^{-4} cases/person/year. If one assumes a maximum *Giardia* concentration for source water of 100,000 per 100 L, then an 8-log removal/inactivation would be needed to maintain a 10^{-4} cases/person/year risk for *Giardia*. The 100,000 cysts per 100L concentration is approximately one order of magnitude higher than the highest *Giardia* cyst concentration known to be measured in source waters of drinking water supplies (LeChevallier et al., 1991b). The value of 8-logs is calculated by assuming that a finished water cyst concentration of 10^{-3} per 100L would be needed to achieve about a 10^{-4} risk of infection (cases/person/year) (Regli et al., 1991).

Table 6-2 applies to systems that need to set an alternative disinfection benchmark without the benefit of monitoring data. All systems that choose this option should achieve an 8-log treatment (combination of physical removal and chemical inactivation) for *Giardia* to meet the minimum acceptable risk. Assuming a 2.5-log physical removal by conventional filtration, 5.5-logs *Giardia* inactivation is the minimum alternative disinfection benchmark.

Table 6-2 also indicates minimum alternative disinfection benchmarks for viruses. These were derived assuming a maximum virus concentration in source waters of 10,000 per 100L and assuming that a viral concentration of 10^{-7} L would be needed to achieve a 10^{-4} risk level (Regli et al., 1991).

Credits for the physical removal of pathogens by filtration should be subtracted from the total treatment requirements to derive the level of treatment needed by chemical disinfection. The removal of pathogens is dependent on the organism of interest and the filtration process. Guidance for removal credits for filtration are provided in the Filtration Credit (logs) columns of Table 6-2, reprinted from the *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources* (AWWA, 1991).

Table 6-2. Alternative Disinfection Benchmarks for Systems Not Monitoring

Filtration Process	*Giardia*			Virus		
	Total Treatment Required (logs)*	Filtration Credit (logs)	Alternative Disinfection Benchmark (logs)	Total Treatment Required (logs)*	Filtration Credit (logs)	Alternative Disinfection Benchmark (logs)
Conventional	8.0	2.5	5.5	9.0	2.0	7.0
Direct	8.0	2.0	6.0	9.0	1.0	8.0
Slow Sand	8.0	2.0	6.0	9.0	2.0	7.0
Diatomaceous Earth	8.0	2.0	6.0	9.0	1.0	8.0

* Assuming source water *Giardia* concentration of 100,000/100 L and viral concentration of 10,000/100L.
Source: AWWA, 1991.

Option 2 – Source Water Characterization

For this option, a system monitors its source water quality for one year. The alternative benchmark is developed based on the quality of the source water. Source water is characterized by monitoring either *E. coli* or fecal coliform. Unfiltered systems already monitor for fecal coliforms as a requirement to avoid filtration and therefore could continue to monitor for fecal coliform to help set an alternative benchmark. Guidelines for source water characterization are presented later in this section. At the end of the sampling duration, the system determines the 90th percentile value for *E. coli* or fecal coliform concentration, and uses these measurements for the alternative disinfection benchmark.

Until better analytical methods are developed and tested for protozoa, EPA believes that *E. coli* or fecal coliforms are the best available indicator at this time since these parameters can be practically measured and indicate the potential for pathogen contamination in the source water. EPA also believes that guidelines for prescribing minimum level of total treatment, for purposes of establishing alternative disinfection benchmarks, can be reasonably prescribed based on *E. coli* or fecal coliform levels in the source water.

The SWTR specifies that unfiltered systems must have a running six month 90th percentile source water fecal coliform levels of less than 20/100 mL as one of the criteria for avoiding filtration. Similarly, such systems must also provide at least 3-log inactivation of *Giardia* through disinfection each day that water is delivered to customers. If the system fails to achieve 3-log inactivation any two or more days per month, the system is in violation of a treatment technique requirement for that month. If the violation occurs during a second month in any 12 consecutive months the system serves water to the public, then the system must install filtration unless the State decides that one of the violations was unusual and unpredictable. Filtration is triggered, regardless of the cause, after a third violation.

EPA believes that this minimum level of inactivation, as prescribed under the SWTR, is an appropriate alternative benchmark for unfiltered systems having an excess of 3-logs of inactivation for *Giardia* or 4-logs of inactivation for viruses.

EPA recommends a minimum alternative benchmark of 1-log inactivation of *Giardia* for systems using conventional treatment and 1.5-log inactivation of *Giardia* for systems using direct, slow sand, or diatomaceous earth filtration for filtered systems that want to lower their disinfection level below the benchmark. This is recommended if the source water 90th percentile for either *E. coli* or fecal coliforms is less than 20/100 mL based on one year of water with at least five samples taken each week. Similarly, EPA recommends a minimum alternative benchmark of 2.5-log virus inactivation for systems using conventional treatment or slow sand filtration and 3.5-log virus inactivation for systems using direct or diatomaceous earth filtration.

EPA believes that plant operations to meet the minimum alternative benchmark as described above and the new turbidity performance criteria in the IESWTR should prevent significant increases in microbial risk for systems choosing to change their disinfection practices while complying with the Stage 1 DBPR.

Systems with higher source water *E. coli* or fecal coliform concentrations should provide alternative benchmarks as indicated in Tables 6-2 and 6-3 and Figures 6-2 and 6-3. EPA developed the recommended proportions, presented in the above mentioned tables and figures, by first assuming the worst case source water concentrations (i.e., the 90th percentile) *E. coli* or fecal coliform concentrations of 20,000/100 mL would correspond to worst case *Giardia* concentrations of 100,000 per 100 L, and treat at such contamination levels, including 5.5-log *Giardia* inactivation for systems using conventional treatment, and 6-log *Giardia* inactivation for systems using direct, slow sand, or diatomaceous earth filtration. These inactivation levels would be needed to achieve the SWTR's 10^{-4} annual risk of infection goal, assuming the minimum *Giardia* physical removal credits recommended for filtration under the SWTR. EPA then assumed that proportional levels of disinfection treatment between the two sample points should provide a reasonable barrier of protection against microbial risk if systems wish to change their disinfection practices to comply with the Stage 1 DBPR.

Table 6-3 presents the recommended alternative disinfection benchmarks as a function of source water quality and the physical removal process employed. The values in the table have been interpolated between the two endpoints of poor and good water quality, and include the credits mentioned above for sedimentation and filtration. Once the system has determined its 90th percentile value of indicator organism in source water, it may use Table 6-3 to select the recommended minimum alternative disinfection benchmark.

A graphical representation of Table 6-3 is presented in Figures 6-2 and 6-3. These figures display the 90th percentile indicator concentrations on the y-axis, with recommended alternative disinfection benchmarks on the x-axis. The two lines on each figure represent the different filtration processes.

Table 6-3. Impact of Source Water Quality and Filtration Process on Alternative Disinfection Benchmark

	Giardia Alternative Disinfection Benchmark (log inactivation)		Virus Alternative Disinfection Benchmark (log inactivation)	
90th Percentile Indicator Concentration* (cfu/100ml)	**Conventional**	**Direct, Slow Sand, or Diatomaceous Earth**	**Conventional or Slow Sand**	**Direct or Diatomaceous Earth**
< 20	1.0	1.5	2.5	3.5
30	1.3	1.8	2.8	3.8
40	1.5	2.0	3.0	4.0
50	1.6	2.1	3.1	4.1
60	1.7	2.2	3.2	4.2
70	1.8	2.3	3.3	4.3
80	1.9	2.4	3.4	4.4
90	2.0	2.5	3.5	4.5
100	2.0	2.5	3.5	4.5
200	2.5	3.0	4.0	5.0
300	2.8	3.3	4.3	5.3
400	3.0	3.5	4.5	5.5
500	3.1	3.6	4.6	5.6
600	3.2	3.7	4.7	5.7
700	3.3	3.8	4.8	5.8
800	3.4	3.9	4.9	5.9
900	3.5	4.0	5.0	6.0
1,000	3.5	4.0	5.0	6.0
2,000	4.0	4.5	5.5	6.5
3,000	4.3	4.8	5.8	6.8
4,000	4.5	5.0	6.0	7.0
5,000	4.6	5.1	6.1	7.1
6,000	4.7	5.2	6.2	7.2
7,000	4.8	5.3	6.3	7.3
8,000	4.9	5.4	6.4	7.4
9,000	5.0	5.5	6.5	7.5
10,000	5.0	5.5	6.5	7.5
≥20,000	5.5	6.0	7.0	8.0

* Indicator concentration refers to either *E. coli* or fecal coliform.

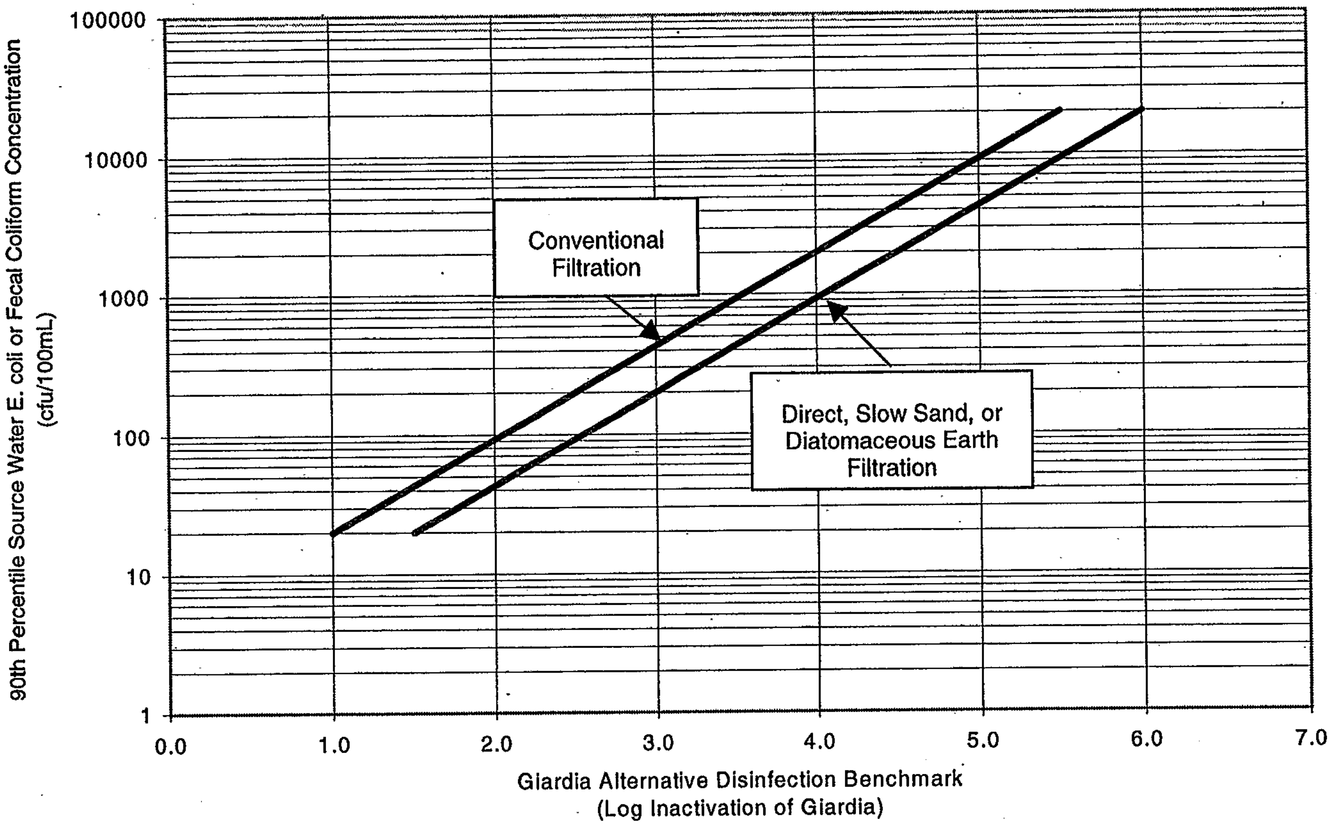

Figure 6-2. Impact of Source Water Quality and Filtration Process on *Giardia* Alternative Disinfection Benchmark

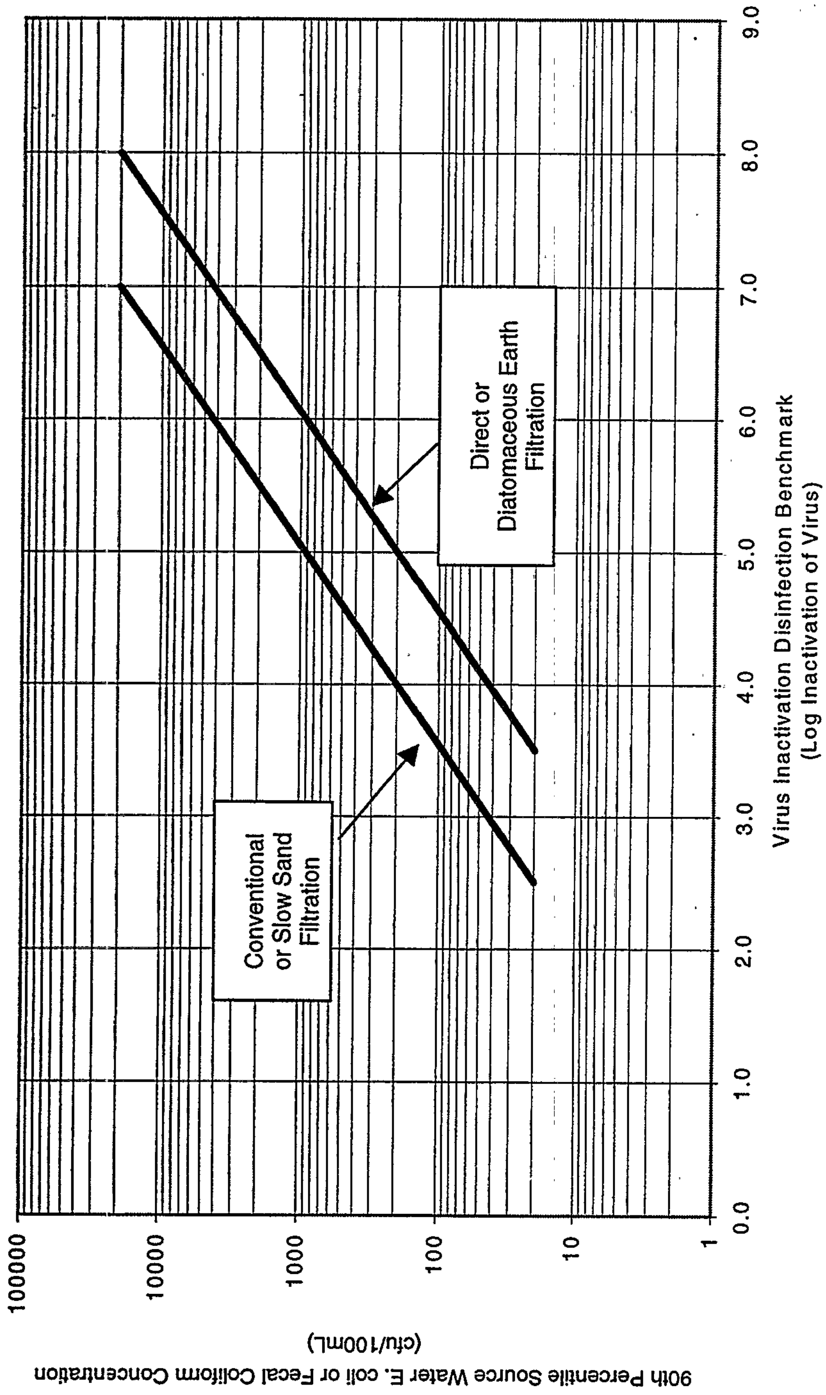

Figure 6-3. Impact of Source Water Quality and Filtration Process on Virus Alternative Disinfection Benchmark

Adjustment Factors

It may be appropriate for the State and system to consider adjusting the alternative disinfection benchmark based on qualitative factors. These factors would allow the State and system to increase or decrease the alternative disinfection benchmark based on information not considered in the methodology.

Examples of conditions that might be used by the State and system to increase the alternative disinfection benchmark:

- Upstream sewage discharge, combined sewer overflow (CSO), sanitary sewer overflow (SSO), contaminated stormwater, feedlots upstream
- Operational issues (e.g., variability of finished water quality)
- Variable source water quality
- Previous waterborne disease outbreaks
- Noncompliance with Total Coliform Rule.

Examples of conditions that might be used by the State and system to decrease the alternative benchmark:

- Excellent filter effluent quality (less than 0.1 NTU), especially with average raw water turbidities greater than 10 NTU
- Two-stages of physical treatment (e.g., conventional treatment and nanofiltration)
- Exceptionally low fecal coliform or *E. coli* levels (i.e., substantially less than the 20/100 mL cutoff) if the system is at the minimum indicated alternative disinfection benchmark
- Occasional use of ozone or other oxidants for taste and odor, iron, and manganese control
- Large credits for long contact times with water transported through transmission lines prior to treatment plant.

6.2 Schedule Guidance

The date for complying with Stage 1 DBPR and IESWTR is December 2001 (3 years after promulgation) for subpart H systems serving at least 10,000 people. Therefore, EPA recommends that a one-year source water monitoring program to support the development of an alternative disinfection benchmark begin in, or before, the last quarter of 2000. Waiting until the last quarter of 2000 would not be prudent, since it would not allow time to develop the alternative disinfection benchmark and implement and select a strategy to meet DBPR MCLs and the alternative benchmark. A system may want to proceed with TTHM, HAA5 monitoring and source water monitoring simultaneously rather than sequentially to provide the greatest flexibility for complying with all applicable rules. Table 6-4 shows a schedule that may allow systems to use Option 2 to develop an alternative disinfection benchmark and still provide time for a utility to implement a DBP control strategy that will meet the alternative disinfection benchmark by the compliance deadline.

Table 6-4. Example Schedule for Compliance with M-DBP Rules

<table>
<tr><th></th><th colspan="4">1999</th><th colspan="4">2000</th><th colspan="4">2001</th><th colspan="4">2002</th></tr>
<tr><td>DBPR and IESWTR Compliance Task</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td>Source Water Characterization</td><td></td><td colspan="4">↔</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Profile/benchmark/State consultation</td><td></td><td></td><td></td><td></td><td></td><td colspan="4">↔</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Apply State-approved Alternative Disinfection Benchmark</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="7">↔</td></tr>
<tr><td>Implement Improvements/ changes (if needed)</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="7">↔</td></tr>
</table>

6.3 Source Water Characterization

Source water characterization used to develop an alternative disinfection benchmark includes sample collection, sample analysis, data evaluation and reporting. The objective is to characterize the source water, prior to any treatment, in terms of either fecal coliform or *E. coli* concentrations. Elevated concentrations of fecal coliform and *E. coli* in surface water indicate a greater probability of contamination by pathogens. Understanding the quality of the source water allows the State and water system to select an appropriate level for the alternative disinfection benchmark.

Sample Collection. Water systems collect five water samples per week, on different days, for one year. The one-year monitoring period will assess seasonal differences in source water character. If five samples per week are collected and analyzed over a 52-week calendar year, the water system will have 260 data values at the end of the year.

Source water samples should be collected at a location prior to treatment. At this location, the water should not be subject to surface runoff. It is not appropriate for systems to collect samples downstream from the addition of a disinfectant or oxidant. In addition, it is not appropriate for systems to collect samples downstream of coagulation/sedimentation or filtration.

The samples should be collected by the grab method using sterile whirlpack bags, sterile plastic, or sterile glass containers. The volume required is less than 100 ml (120 ml bottles are standard bacteriological sampling bottles), but the laboratory should be contacted for verification. No chemical preservative is required, but the sample should be stored in an iced cooler. Sample temperature should be between 1 and 4.4°C during transportation and samples should be stored in the dark. The sample must not be held more than 6 hours prior to laboratory analysis (Standard Methods, 1995).

Sample Analysis. The fecal coliform and *E. coli* samples should be analyzed using one of four analytical methods identified in EPA National Primary Drinking Water Regulations, 40 *CFR* 141.21(f)(6)(i-iv). The methods include:

1. An extension of Method 9221E described in Standard Methods (1995)
2. An extension of Method 9221B using nutrient agar
3. Minimal medium ONPG-MUG Test documented by Edberg, et al. (1988).
4. The Colisure Test by Milipore Corporation, Technical Services Department, 80 Ashby Road, Bedford, MA 01730.

Data Evaluation. In any week, the system should obtain five values for indicator organism concentrations corresponding to five different days of that week. If a system misses the collection of a value, the system should record the letter "M" for missing data, for the day of the week that the data value was not collected. Therefore, in any week, the utility will obtain five values, some of which will be the letter "M" if data are missing. Systems are encouraged to collect all 260 values and not to have missing values. Values that are missed are assumed to have poor water quality and count against the system when developing the alternative disinfection benchmark.

In general, data on concentrations of microbiological organisms in water from streams, lakes, and reservoirs often exhibit a large number of samples with very low concentrations and a few samples with high concentrations. Thus, the average or mean concentration is not a very good measure on the expected concentrations because of the few large values. For this reason, a distribution frequency (percent of samples above or below a specified value) is more meaningful. For setting the alternative disinfection benchmark, EPA recommends the 90th percentile value.

To determine the 90th percentile value the data should be sorted from the largest value to the smallest value recorded (regardless of the date of collection). All of the "M," or missing values, should be placed at the top of the list. The result of this action should be a list of the top 26 data values of the 260 total values with missing values at the top of the list followed by the largest numerical values that decrease to the smallest value at the bottom of the list. The 90th percentile value is found by locating the 26th number of the list. It is this 90th percentile value that characterizes the quality of the source water for developing the alternative disinfection benchmark.

As part of the consultation with the State, the system may want to explain why samples were missed (e.g., sample container lost or samples not analyzed in a timely manner). The system may then be able to develop a different 90th percentile by dropping missed samples from the calculation.

Use of Historical Database. Some systems may already monitor their source water for fecal coliform and *E. coli*. The resulting historical database may be sufficient for the State and system to develop an alternative disinfection benchmark. The historical database is considered sufficient for making this determination if:

- The raw water sampling location is upstream from the point of any treatment
- At least five samples per week are collected on different days
- The sampling period covers at least one year
- Methods of analysis are consistent with those presented herein.

6.4 Watershed Control Program

A watershed control program is a surveillance and monitoring program that is conducted to protect the quality of a surface water source. An aggressive and detailed watershed control program is desirable to effectively limit or eliminate potential contamination by microbial pathogens. A watershed program may impact parameters such as turbidity, certain organic compounds, viruses, total and fecal coliforms, *Giardia*, *Cryptosporidium*, and areas of wildlife habitation. However, the program is expected to have little or no impact on parameters such as naturally occurring inorganic chemicals. Limiting human activity in the watershed may reduce the likelihood of animals becoming infected with pathogens and thereby reduce the transmission of pathogens by wildlife. Preventing animal activity near the source water intake prior to disinfection may also reduce pathogen occurrence at the intake.

The effect of a watershed program is difficult to quantify since many variables that influence water quality are beyond the control or knowledge of the water supplier. As a result, the benefit of a watershed control program or specific control measures must in many cases be based on accumulated cause and effect data and on the general knowledge of the impact of control measures rather than on actual quantification. The effectiveness of a program to limit or eliminate potential contamination by microbial pathogens will be determined based on: the comprehensiveness of the watershed review; the ability of the water system to effectively carry out and monitor the management decisions regarding control of detrimental activities occurring in the watershed; and the potential for the water system to maximize land ownership and/or control of land use within the watershed. Under the SWTR, a watershed control program should include as a minimum:

- A description of the watershed including its hydrology and land ownership
- Identification, monitoring and control of watershed characteristics and activities in the watershed which may have an adverse effect on the source water quality
- A program to gain ownership or control of the land within the watershed through written agreements with landowners, for the purpose of controlling activities which will adversely affect the microbiological quality of the water
- An annual report which identifies special concerns in the watershed and how they are being handled, identifies activities in the watershed, projects adverse activities expected to occur in the future and how the utility expects to address them.

Appendix J of the *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources* (AWWA, 1991) contains a more detailed guide to a comprehensive watershed program.

In preparing a watershed control program, surface water systems should draw upon the State watershed assessments and non-point source (NPS) pollution management programs required by §319 of the Clean Water Act. Information on these programs is available from State water quality agencies or EPA's regional offices. Assessments identify NPS pollutants in water and assess the water quality. Utilities should use the assessments when evaluating pollutants in their watershed. Surface water quality assessments can also be obtained from the lists of waters prepared under §304(1) of the Clean Water Act, and State biennially prepared §305(b) reports.

State NPS management programs identify best management practices (BMPs) to be employed in reducing NPS pollution. These management programs can be incorporated in the watershed program to protect against degradation of the source water quality.

For systems using ground water sources under the influence of surface water, the control measures delineated in the Wellhead Protection (WHP) program encompass the requirements of the watershed control program, and can be used to fulfill the requirements of the watershed control program. Guidance on the content of Wellhead Protection Programs and the delineation of wellhead protection areas is given in *Guidance for Applicants for State Wellhead Protection Program Assistance Funds Under the Safe Drinking Water Act* (USEPA, 1987a) and *Guidelines for Delineation of Wellhead Protection Areas* (USEPA, 1987b), available at www.epa.gov/OGWDW000/whpnp.html.

As a minimum, the WHP program must:

- Specify the duties of State agencies, local governmental entities and public water supply systems with respect to the development and implementation of Programs.
- Determine the wellhead protection area (WHPA) for each wellhead as defined in subsection 1428(e) based on all reasonably available hydrogeologic information, ground water flow, recharge and discharge and other information the State deems necessary to adequately determine the WHPA.
- Identify within each WHPA all potential anthropogenic sources of contaminants which may have any adverse effect on the health of persons.
- Describe a program that contains, as appropriate, technical assistance, financial assistance, implementation of control measures, education, training and demonstration projects to protect the water supply within WHPAs from such contaminants.
- Present contingency plans for locating and providing alternate drinking water supplies for each public water system in the event of well or wellfield contamination by such contaminants.
- Consider all potential sources of such contaminants within the expected wellhead area of a new water well which serves a public water supply system.
- Provide for public participation.

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APPENDIX A. HISTORY

This section describes the historical development of disinfection profiling and benchmarking procedures and is important in understanding the purpose and intent of these procedures under the IESWTR.

Regulatory Background

The Safe Drinking Water Act (SDWA) Amendments of 1996 mandate that EPA develop interrelated regulations to control microbial pathogens and disinfectants/disinfection byproducts (D/DBPs) in drinking water. These rules are collectively known as the microbial/disinfection byproducts (M-DBP) rules and are intended to address complex risk trade-offs between the desire to inactivate pathogens found in water and the need to reduce chemical compounds formed as byproducts during disinfection.

To address the complex risk trade-offs between chronic DBP health risks and acute pathogenic health risks, EPA promulgated the ICR in May 1996 as a means to obtain data from large systems (i.e., surface water systems serving more than 100,000 people and groundwater systems serving more than 50,000 people). Information requested in the ICR addresses source water quality, byproduct formation, and drinking water treatment plant design and operations. Since promulgation and implementation of the ICR was delayed, information from the ICR was unavailable for two rulings, therefore the profiling and benchmarking procedures were developed.

EPA is promulgating the M-DBP cluster of rules in two phases. The rules in the first phase, the Stage 1 DBPR and the IESWTR, were promulgated December 16, 1998. The Stage 1 DBPR applies to all community water systems and nontransient noncommunity water systems that treat their water with a chemical disinfectant for either primary or residual treatment and addresses the formation of DBPs during water treatment. The IESWTR applies to all public water systems that use surface water or GWUDI, and serve greater than 10,000 people. The IESWTR amends the Surface Water Treatment Rule (SWTR) and includes new and more stringent requirements for controlling waterborne pathogens including *Giardia*, viruses, and *Cryptosporidium.*

A Long-Term 1 ESWTR will be promulgated in December 2000 and will address treatment requirements for surface water systems serving fewer than 10,000 people. EPA had hoped to use ICR data for the IESWTR and Stage 1 DBPR, but delays in promulgation eliminated this potential data source.

The second phase, the Stage 2 DBPR and the Long-Term 2 ESWTR, will be promulgated in 2002 and will revisit the regulations for the formation of byproducts during disinfection for all systems and the inactivation and removal of pathogens for surface water systems, respectively. The key dates for these regulatory activities are provided in Table A-1.

Table A-1. Key Dates for Regulatory Activities

Date	Regulatory Action
December 2000	Promulgate Long-Term 1 Enhanced Surface Water Treatment Rule
May 2002	Promulgate Stage 2 Disinfectants and Disinfection Byproduct Rule
May 2002	Promulgate Long-Term 2 Enhanced Surface Water Treatment Rule

Convening of the Federal Advisory Committee

In May 1996, EPA initiated a series of public meetings to exchange information on issues related to M-DBP regulations. In 1997, the EPA established the M-DBP Advisory Committee under the Federal Advisory Committee Act (FACA) to facilitate stakeholder participation and to help meet the deadlines for the IESWTR and Stage 1 DBPR established by Congress in the 1996 SDWA Amendments. The purpose of this Advisory Committee was to collect, share, and analyze new information and data, as well as to build consensus on the regulatory implications of this new information.

The Advisory Committee was concerned that water systems would reduce disinfection (e.g., logs of *Giardia* inactivation) to meet Stage 1 DBPR requirements for DBPs. At the time the SWTR was issued, EPA had limited data concerning *Giardia* and *Cryptosporidium* occurrence in source waters and treatment efficiencies. The 3-log removal/inactivation of *Giardia* and 4-log removal/inactivation of enteric viruses required by the SWTR were developed to provide protection from most pathogens in source waters. However, additional data have become available since promulgation of the SWTR concerning source water occurrence and treatment efficiencies for *Giardia*, as well as for *Cryptosporidium* (LeChevallier et al., 1991a; 1991b).

The Advisory Committee was concerned that if water systems currently provide four or more logs of removal/inactivation for *Giardia*, such systems might reduce existing levels of disinfection to meet the DBP requirements of the Stage 1 DBPR. This change in disinfection practices could result in systems only marginally meeting the 3-log removal/inactivation requirement for *Giardia* specified in the current SWTR. Depending upon source water *Giardia* concentrations, such treatment changes could lead to significant increases in microbial risk (Regli et al., 1993; Grubbs et al., 1992; USEPA, 1994b).

The M-DBP Advisory Committee's recommendations to the EPA included tighter turbidity performance criteria and individual filter monitoring requirements as part of the IESWTR. The revised turbidity performance criteria would contribute to a key IESWTR objective, that is to establish a microbial backstop to prevent significant increases in microbial risk when systems implement the DBP standards under the Stage 1 DBPR. The Advisory Committee also agreed that another major component of a microbial backstop would be provisions for disinfection profiling and benchmarking.

Profiling and Benchmarking Procedures

The M-DBP Advisory Committee made recommendations to EPA on disinfection profiling and benchmarking procedures to assure that pathogen control is maintained while the Stage 1 DBPR provisions are implemented. In developing the profiling and benchmarking procedures, the Advisory Committee evaluated the following issues; what information systems should be gathered to evaluate current disinfection practices, how the profiling and benchmark procedures should operate, and how systems and States should work together to assure that microbial control is maintained.

Based on data provided by systems and reviewed by the Advisory Committee, the microbial inactivation baseline, expressed as logs of *Giardia* inactivation, demonstrated high variability. Inactivation varied by several logs on a day-to-day basis at any particular treatment plant and by 10 or more ten logs over a year due to changes in water temperature, flow rate (and consequently contact time), seasonal changes in residual disinfectant, pH, and disinfectant demand (and consequently disinfectant residual). There were also differences between years at individual plants.

To address these variations, the Advisory Committee recommended a disinfection profiling approach for a system to characterize their existing disinfection practices. In essence, this approach allows a plant to chart or plot its daily levels of *Giardia* inactivation on a graph that, when viewed on a seasonal or annual basis, represents a "profile" of the plant's inactivation performance. The system can use the profile to develop a baseline or "benchmark" of inactivation against which to measure possible changes in disinfection practices.

This approach makes it possible for a plant to change its disinfection practices to meet the Stage 1 DBPR maximum contaminant levels (MCLs), without a significant increase in microbial risk. The benchmarking approach and guidance in this manual provide tools for plants to understand potential impacts of modifying disinfection practices.

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APPENDIX B. LOG INACTIVATION METHODS

Development of the Log Inactivation Method under the SWTR

The disinfection profile is based on microbial inactivation. As part of the SWTR, EPA developed a method to calculate microbial inactivation for evaluating the effectiveness of disinfection in a water system. Chemical disinfection does not remove microorganisms from water but inactivates them so they can no longer infect consumers. Under the method developed for the SWTR, the actual plant disinfection conditions are converted to a theoretical level of inactivation of specific microorganisms.

The conversion from plant conditions to microbial inactivation is accomplished based on "CT tables" developed for the SWTR, where C is the residual disinfectant concentration (mg/L) and T is the time (in minutes) that water is in contact with the disinfectant. These tables relate CT values to levels of inactivation under various operating conditions. Different tables exist for different disinfectants. As the CT value is increased, a greater percentage of microorganisms are inactivated by chemical disinfection. The CT, and therefor the level of inactivation, can be increased by applying greater doses of the disinfectant or by increasing the time that the water is in contact with the disinfectant.

The level of inactivation is generally referred to in terms of "log inactivation" since inactivation is measured on a logarithmic scale (i.e., orders of magnitude reduction). For example, a 2-log inactivation and/or removal of *Giardia* corresponds to inactivating 99 percent of the *Giardia* cysts through the disinfection process while a 3-log inactivation and/or removal corresponds to a 99.9 percent inactivation.

Log inactivation is a measure of the percent of microorganisms that are inactivated during the disinfection process and is defined as:

$$\text{Log Inactivation} = \text{Log}\left(\frac{N_o}{N_T}\right)$$

Where,

N_o = initial (influent) concentration of viable microorganisms
N_T = concentration of surviving microorganisms
Log = logarithm to base 10

Log inactivation is related to the percent inactivation, defined as:

$$\text{Percent Inactivation} = \left(1 - \frac{N_T}{N_o}\right) * 100$$

Therefore, the relationship between log inactivation and percent inactivation is as follows:

$$\text{Percent Inactivation} = \left(1 - \frac{1}{10^{\text{Log Inactivation}}}\right) * 100$$

or,

$$\text{Log Inactivation} = \text{Log}\left(\frac{100}{100 - \text{Percent Inactivation}}\right)$$

The following two examples illustrate the relationship between influent and effluent concentrations, percent inactivation, and log inactivation.

Example 1

A utility has an influent concentration (N_o) of active Giardia *of 10,000 cysts/100L and a concentration of surviving microorganisms at the first point in the distribution system (N_T) of 10 cysts/100L. What is the log inactivation of this treatment process?*

$$\text{Log Inactivation} = \text{Log}\left(\frac{N_o}{N_T}\right)$$

$$\text{Log Inactivation} = \text{Log}\left(\frac{10{,}000}{10}\right)$$

$$\text{Log Inactivation} = \text{Log } 1{,}000$$

$$\text{Log Inactivation} = 3$$

Example 2

Given that the utility has a 3-Log Inactivation of Giardia, *what is the percent inactivation of* Giardia*?*

$$\text{Percent Inactivation} = \left(1 - \frac{1}{10^{\text{Log Inactivation}}}\right) * 100$$

$$\text{Percent Inactivation} = \left(1 - \frac{1}{10^{3}}\right) * 100$$

$$\text{Percent Inactivation} = \left(1 - \frac{1}{1{,}000}\right) * 100$$

$$\text{Percent Inactivation} = (1 - .001) * 100$$

$$\text{Percent Inactivation} = 99.9$$

As the two examples show, a 3-log inactivation equals 99.9 percent inactivation. Table B-1 presents similar calculations for different log inactivations and corresponding percent inactivations.

Table B-1. Log Inactivation and Percent Inactivation

Log Inactivation	*Percent Inactivation*
0.0	0.00
0.5	68.38
1.0	90.00
2.0	99.00
3.0	99.90
4.0	99.99
5.0	99.999
6.0	99.9999
7.0	99.99999

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APPENDIX C. CT VALUES FOR INACTIVATIONS ACHIEVED BY VARIOUS DISINFECTANTS

This appendix provides a reprint of the CT tables for determining inactivations achieved by various disinfectants. These tables were originally provided in EPA's *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Sources* (AWWA, 1991).

Table C-1. CT Values for Inactivation of *Giardia* Cysts by Free Chlorine at 0.5°C or Lower

CHLORINE CONCENTRATION	pH<=6 Log Inactivation						pH=6.5 Log Inactivation						pH=7.0 Log Inactivation						pH=7.5 Log Inactivation					
(mg/L)	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0
<=0.4	23	46	69	91	114	137	27	54	82	109	136	163	33	65	98	130	163	195	40	79	119	158	198	237
0.6	24	47	71	94	118	141	28	56	84	112	140	169	33	67	100	133	167	200	40	80	120	159	199	239
0.8	24	48	73	97	121	145	29	57	86	115	143	172	34	68	103	137	171	205	41	82	123	164	205	246
1	25	49	74	99	123	148	29	59	88	117	147	176	35	70	105	140	175	210	42	84	127	169	211	253
1.2	25	51	76	101	127	152	30	60	90	120	150	180	36	72	108	143	179	215	43	86	130	173	216	259
1.4	26	52	78	103	129	155	31	61	92	123	153	184	37	74	111	147	184	221	44	89	133	177	222	266
1.6	26	52	79	105	131	157	32	63	95	126	155	189	38	75	113	151	188	226	46	91	137	182	228	273
1.8	27	54	81	108	135	162	32	64	97	129	161	193	39	77	116	154	193	231	47	93	140	186	233	279
2	28	55	83	110	138	165	33	66	99	131	164	197	39	79	118	157	197	236	48	95	143	191	238	286
2.2	28	56	85	113	141	169	34	67	101	134	169	201	40	81	121	161	202	242	50	99	149	198	248	297
2.4	29	57	86	115	143	172	34	68	103	137	171	205	41	82	124	165	206	247	50	99	149	199	248	298
2.6	29	58	88	117	146	175	35	70	105	139	174	209	42	84	126	168	210	252	51	101	152	203	253	304
2.8	30	59	89	119	148	178	36	71	107	142	178	213	43	86	129	171	214	257	52	103	155	207	258	310
3	30	60	91	121	151	181	36	72	109	145	181	217	44	87	131	174	218	261	53	105	158	211	263	316

CHLORINE CONCENTRATION	pH=8.0 Log Inactivation						pH=8.5 Log Inactivation						pH=9.0 Log Inactivation					
(mg/L)	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0
<=0.4	46	92	139	185	231	277	55	110	165	219	274	329	65	130	195	260	325	390
0.6	48	95	143	191	238	286	57	114	171	228	285	342	68	136	204	271	339	407
0.8	49	98	148	197	246	295	59	113	177	236	295	354	70	141	211	281	352	422
1	51	101	152	203	253	304	61	122	183	243	304	365	73	146	219	291	364	437
1.2	52	104	157	209	261	313	63	125	188	251	313	376	75	150	226	301	376	451
1.4	54	107	161	214	268	321	65	129	194	258	323	387	77	155	232	309	387	464
1.6	55	110	165	219	274	329	66	132	199	265	331	397	80	159	239	318	398	477
1.8	56	113	169	225	282	338	68	136	204	271	339	407	82	163	245	326	408	489
2	55	115	173	231	288	346	70	139	209	278	348	417	83	167	250	333	417	500
2.2	59	118	177	235	294	353	71	142	213	284	355	426	85	170	256	341	426	511
2.4	60	120	181	241	301	361	73	145	218	290	363	435	87	174	261	348	435	522
2.6	61	123	184	245	307	368	74	148	222	296	370	444	89	178	267	355	444	533
2.8	63	125	188	250	313	375	75	151	226	301	377	452	91	181	272	362	453	543
3	64	127	191	255	318	382	77	153	230	307	383	460	92	184	276	369	460	552

Source: AWWA, 1991.

Table C-2. CT Values for Inactivation of Giardia Cysts by Free Chlorine at 5°C

CHLORINE CONCENTRATION (mg/L)	pH<=6 Log Inactivation						pH=6.5 Log Inactivation						pH=7.0 Log Inactivation						pH=7.5 Log Inactivation					
	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0
<=0.4	16	32	49	65	81	97	20	39	59	78	98	117	23	46	70	93	116	139	28	55	83	111	138	166
0.6	17	33	50	67	83	100	20	40	60	80	100	120	24	49	72	95	119	143	29	57	86	114	143	171
0.8	17	34	52	69	86	103	20	41	61	81	102	122	24	49	73	97	122	146	29	58	88	117	146	175
1	18	35	53	70	88	105	21	42	63	83	104	125	25	50	75	99	124	149	30	60	90	119	149	179
1.2	18	36	54	71	89	107	21	42	64	85	106	127	25	51	76	101	127	152	31	61	92	122	153	183
1.4	18	36	55	73	91	109	22	43	65	97	108	130	26	52	78	103	129	155	31	62	94	125	156	187
1.6	19	37	56	74	93	111	22	44	66	88	110	132	26	53	79	105	132	158	32	64	96	128	160	192
1.8	19	38	57	76	95	114	23	45	69	90	113	135	27	54	81	108	135	162	33	65	98	131	163	196
2	19	39	58	77	97	116	23	46	69	92	115	138	28	55	83	110	138	165	33	67	100	133	167	200
2.2	20	39	59	79	98	118	23	47	70	93	117	140	28	56	85	113	141	169	34	68	102	136	170	204
2.4	20	40	60	80	100	120	24	48	72	95	119	143	29	57	86	115	143	172	35	70	105	139	174	209
2.6	20	41	61	81	102	122	24	49	73	97	122	146	29	58	88	117	146	175	36	71	107	142	178	213
2.8	21	41	62	83	103	124	25	49	74	99	123	148	30	59	89	119	148	178	36	72	109	145	181	217
3	21	42	63	84	105	126	25	50	76	101	126	151	30	61	91	121	152	182	37	74	111	147	184	221

CHLORINE CONCENTRATION (mg/L)	pH=8.0 Log Inactivation						pH=8.5 Log Inactivation						pH=9.0 Log Inactivation					
	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0
<=0.4	33	66	99	132	165	198	39	79	118	157	197	236	47	93	140	186	233	279
0.6	34	68	102	136	170	204	41	81	122	163	203	244	49	97	146	194	243	291
0.8	35	70	105	140	175	210	42	84	126	168	210	252	50	100	151	201	251	301
1	36	72	108	144	180	216	43	87	130	173	217	260	52	104	156	208	260	312
1.2	37	74	111	147	184	221	45	89	134	178	223	267	53	107	160	213	267	320
1.4	38	76	114	151	189	227	46	91	137	183	228	274	55	110	165	219	274	329
1.6	39	77	116	155	193	232	47	94	141	197	234	281	56	112	169	225	281	337
1.8	40	79	119	159	198	238	48	96	144	191	239	287	58	115	173	230	288	345
2	41	81	122	162	203	243	49	98	147	196	245	294	59	118	177	235	294	353
2.2	41	83	124	165	207	248	50	100	150	200	250	300	60	120	181	241	301	361
2.4	42	84	127	169	211	253	51	102	153	204	255	306	61	123	184	245	307	368
2.6	43	86	129	172	215	258	52	104	156	208	260	312	63	125	189	250	313	375
2.8	44	88	132	175	219	263	53	106	159	212	265	318	64	127	191	255	318	382
3	45	89	134	179	223	268	54	108	162	216	270	324	65	130	195	259	324	389

Source: AWWA, 1991.

Table C-3. CT Values for Inactivation of Giardia Cysts by Free Chlorine at 10°C

CHLORINE CONCENTRATION (mg/L)	pH<=6 Log Inactivation						pH=6.5 Log Inactivation						pH=7.0 Log Inactivation						pH=7.5 Log Inactivation					
	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0
<=0.4	12	24	37	49	61	73	15	29	44	59	73	88	17	35	52	69	87	104	21	42	63	83	104	125
0.6	13	25	38	50	63	75	15	30	45	60	75	90	18	36	54	71	89	107	21	43	64	85	107	128
0.8	13	26	39	52	65	78	15	31	46	61	77	92	18	37	55	73	92	110	22	44	66	87	109	131
1	13	26	40	53	66	79	16	31	47	63	78	94	19	37	56	75	93	112	22	45	67	89	112	134
1.2	13	27	40	53	67	80	16	32	48	63	79	95	19	38	57	76	95	114	23	46	69	91	114	137
1.4	14	27	41	55	68	82	16	33	49	65	82	98	19	39	58	77	97	116	23	47	70	93	117	140
1.6	14	28	42	55	69	83	17	33	50	66	83	99	20	40	60	79	99	119	24	48	72	96	120	144
1.8	14	29	43	57	72	86	17	34	51	67	84	101	20	41	61	81	102	122	25	49	74	98	123	147
2	15	29	44	58	73	87	17	35	52	69	87	104	21	41	62	83	103	124	25	50	75	100	125	150
2.2	15	30	45	59	74	89	18	35	53	70	88	105	21	42	64	85	106	127	26	51	77	102	128	153
2.4	15	30	45	60	75	90	18	36	54	71	89	107	22	43	65	86	108	129	26	52	79	105	131	157
2.6	15	31	46	61	77	92	18	37	55	73	92	110	22	44	66	87	109	131	27	53	80	107	133	160
2.8	16	31	47	62	78	93	19	37	56	74	93	111	22	45	67	89	112	134	27	54	82	109	136	163
3	16	32	48	63	79	95	19	38	57	75	94	113	23	46	69	91	114	137	28	55	83	111	138	166

CHLORINE CONCENTRATION (mg/L)	pH=8.0 Log Inactivation						pH=8.5 Log Inactivation						pH=9.0 Log Inactivation					
	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0
<=0.4	25	50	75	99	124	149	30	59	89	118	148	177	35	70	105	139	174	209
0.6	26	51	77	102	128	153	31	61	92	122	153	183	36	73	109	145	182	218
0.8	26	53	79	105	132	158	32	63	95	126	158	189	38	75	113	151	188	226
1	27	54	81	108	135	162	33	65	98	130	163	195	39	78	117	156	195	234
1.2	28	55	83	111	138	166	33	67	100	133	167	200	40	80	120	160	200	240
1.4	28	57	85	113	142	170	34	69	103	137	172	206	41	82	124	165	206	247
1.6	29	58	87	116	145	174	35	70	106	141	176	211	42	84	127	169	211	253
1.8	30	60	90	119	149	179	36	72	108	143	179	215	43	86	130	173	216	259
2	30	61	91	121	152	182	37	74	111	147	184	221	44	88	133	177	221	265
2.2	31	62	93	124	155	186	38	75	113	150	188	225	45	90	136	181	226	271
2.4	32	63	95	127	158	190	38	77	115	153	192	230	46	92	138	184	230	276
2.6	32	65	97	129	162	194	39	78	117	156	195	234	47	94	141	187	234	281
2.8	33	66	99	131	164	197	40	80	120	159	199	239	48	96	144	191	239	287
3	34	67	101	134	168	201	41	81	122	162	203	243	49	97	146	195	243	292

Source: AWWA, 1991.

Table C-4. CT Values for Inactivation of Giardia Cysts by Free Chlorine at 15°C

CHLORINE CONCENTRATION (mg/L)	pH<=6						pH=6.5						pH=7.0						pH=7.5					
	Log Inactivation						Log Inactivation						Log Inactivation						Log Inactivation					
	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0
<=0.4	8	16	25	33	41	49	10	20	30	39	49	59	12	23	35	47	58	70	14	28	42	55	69	83
0.6	8	17	25	33	42	50	10	20	30	40	50	60	12	24	36	48	60	72	14	29	43	57	72	86
0.8	9	17	26	35	43	52	10	20	31	41	51	61	12	24	37	49	61	73	15	29	44	59	73	88
1	9	18	27	35	44	53	11	21	32	42	53	63	13	25	38	50	63	75	15	30	45	60	75	90
1.2	9	18	27	36	45	54	11	21	32	43	53	64	13	25	38	51	63	76	15	31	46	61	77	92
1.4	9	18	28	37	46	55	11	22	33	43	54	65	13	26	39	52	65	78	16	31	47	63	78	94
1.6	9	19	28	37	47	56	11	22	33	44	55	66	13	26	40	53	66	79	16	32	48	64	80	96
1.8	10	19	29	38	48	57	11	23	34	45	57	68	14	27	41	54	68	81	16	33	49	65	82	98
2	10	19	29	39	48	58	12	23	35	46	58	69	14	28	42	55	69	83	17	33	50	67	83	100
2.2	10	20	30	39	49	59	12	23	35	47	58	70	14	28	43	57	71	85	17	34	51	68	85	102
2.4	10	20	30	40	50	60	12	24	36	48	60	72	14	29	43	57	72	86	18	35	53	70	88	105
2.6	10	20	31	41	51	61	12	24	37	49	61	73	15	29	44	59	73	88	18	36	54	71	89	107
2.8	10	21	31	41	52	62	12	25	37	49	62	74	15	30	45	59	74	89	18	36	55	73	91	109
3	11	21	32	42	53	63	13	25	38	51	63	76	15	30	46	61	76	91	19	37	56	74	93	111

CHLORINE CONCENTRATION (mg/L)	pH=8.0						pH=8.5						pH=9.0					
	Log Inactivation						Log Inactivation						Log Inactivation					
	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0
<=0.4	17	33	50	66	83	99	20	39	59	79	98	118	23	47	70	93	117	140
0.6	17	34	51	68	85	102	20	41	61	81	102	122	24	49	73	97	122	146
0.8	18	35	53	70	88	105	21	42	63	84	105	126	25	50	76	101	126	151
1	18	36	54	72	90	108	22	43	65	87	108	130	26	52	78	104	130	156
1.2	19	37	56	74	93	111	22	45	67	89	112	134	27	53	80	107	133	160
1.4	19	38	57	76	95	114	23	46	69	91	114	137	28	55	83	110	138	165
1.6	19	39	58	77	97	116	24	47	71	94	118	141	28	56	85	113	141	169
1.8	20	40	60	79	99	119	24	48	72	96	120	144	29	59	87	115	144	173
2	20	41	61	81	102	122	25	49	74	98	123	147	30	59	89	118	148	177
2.2	21	41	62	83	103	124	25	50	75	100	125	150	30	60	91	121	151	181
2.4	21	42	64	85	106	127	26	51	77	102	128	153	31	61	92	123	153	184
2.6	22	43	65	86	108	129	26	52	78	104	130	156	31	63	94	125	157	188
2.8	22	44	66	88	110	132	27	53	80	106	133	159	32	64	96	127	159	191
3	22	45	67	89	112	134	27	54	81	109	135	162	33	65	98	130	163	195

Source: AWWA, 1991.

Table C-5. CT Values for Inactivation of Giardia Cysts by Free Chlorine at 20°C

CHLORINE CONCENTRATION (mg/L)	pH<=6 Log Inactivation 0.5	1.0	1.5	2.0	2.5	3.0	pH=6.5 Log Inactivation 0.5	1.0	1.5	2.0	2.5	3.0	pH=7.0 Log Inactivation 0.5	1.0	1.5	2.0	2.5	3.0	pH=7.5 Log Inactivation 0.5	1.0	1.5	2.0	2.5	3.0
<=0.4	6	12	18	24	30	36	7	15	22	29	37	44	9	17	26	35	43	52	10	21	31	41	52	62
0.6	6	13	19	25	32	38	8	15	23	30	38	45	9	18	27	36	45	54	11	21	32	43	53	64
0.8	7	13	20	26	33	39	8	15	23	31	38	46	9	18	28	37	46	55	11	22	33	44	55	66
1	7	13	20	26	33	39	8	16	24	31	39	47	9	19	28	37	47	56	11	22	34	45	56	67
1.2	7	13	20	27	33	40	8	16	24	32	40	48	10	19	29	38	48	57	12	23	35	46	58	69
1.4	7	14	21	27	34	41	8	16	25	33	41	49	10	19	29	39	48	58	12	23	35	47	58	70
1.6	7	14	21	28	35	42	8	17	25	33	42	50	10	20	30	39	49	59	12	24	36	48	60	72
1.8	7	14	22	29	36	43	9	17	26	34	43	51	10	20	31	41	51	61	12	25	37	49	62	74
2	7	15	22	29	37	44	9	17	26	35	43	52	10	21	31	41	52	62	13	25	38	50	63	75
2.2	7	15	22	29	37	44	9	18	27	35	44	53	11	21	32	42	53	63	13	26	39	51	64	77
2.4	8	15	23	30	38	45	9	18	27	36	45	54	11	22	33	43	54	65	13	26	39	52	65	78
2.6	8	15	23	31	38	46	9	18	28	37	46	55	11	22	33	44	55	66	13	27	40	53	67	80
2.8	8	16	24	31	39	47	9	19	28	37	47	56	11	22	34	45	56	67	14	27	41	54	68	81
3	9	16	24	31	39	47	10	19	29	38	48	57	11	23	34	45	57	68	14	28	42	55	69	83

CHLORINE CONCENTRATION (mg/L)	pH=8.0 Log Inactivation 0.5	1.0	1.5	2.0	2.5	3.0	pH=8.5 Log Inactivation 0.5	1.0	1.5	2.0	2.5	3.0	pH=9.0 Log Inactivation 0.5	1.0	1.5	2.0	2.5	3.0
<=0.4	12	25	37	49	62	74	15	30	45	59	74	89	19	35	53	70	88	105
0.6	13	26	39	51	64	77	15	31	46	61	77	92	18	36	55	73	91	109
0.8	13	26	40	53	66	79	16	32	48	63	79	95	19	38	57	75	94	113
1	14	27	41	54	68	81	16	33	49	65	82	98	20	39	59	78	98	117
1.2	14	28	42	55	69	83	17	33	50	67	83	100	20	40	60	80	100	120
1.4	14	28	43	57	71	85	17	34	52	69	86	103	21	41	62	82	103	123
1.6	15	29	44	58	73	87	18	35	53	70	88	105	21	42	63	84	105	126
1.8	15	30	45	59	74	89	18	36	54	72	90	108	22	43	65	86	108	129
2	15	30	46	61	76	91	18	37	55	73	92	110	22	44	66	88	110	132
2.2	16	31	47	62	78	93	19	38	57	75	94	113	23	45	68	90	113	135
2.4	16	32	48	63	79	95	19	38	58	77	96	115	23	46	69	92	115	139
2.6	16	32	49	65	81	97	20	39	59	78	98	117	24	47	71	94	117	141
2.8	17	33	50	66	83	99	20	40	60	79	99	119	24	48	72	95	119	143
3	17	34	51	67	84	101	20	41	61	81	102	122	24	49	73	97	122	146

Source: AWWA, 1991.

Table C-6. CT Values for Inactivation of Giardia Cysts by Free Chlorine at 25°C

CHLORINE CONCENTRATION (mg/L)	pH<=6 Log Inactivation						pH=6.5 Log Inactivation						pH=7.0 Log Inactivation						pH=7.5 Log Inactivation					
	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0
<=0.4	4	8	12	16	20	24	5	10	15	19	24	29	6	12	18	23	29	35	7	14	21	28	35	42
0.6	4	8	13	17	21	25	5	10	15	20	25	30	6	12	18	24	30	36	7	14	22	29	36	43
0.8	4	9	13	17	22	26	5	10	16	21	26	31	6	12	19	25	31	37	7	15	22	29	37	44
1	4	9	13	17	22	26	5	10	16	21	26	31	6	12	19	25	31	37	8	15	23	30	38	45
1.2	5	9	14	18	23	27	5	11	16	21	27	32	6	13	19	25	32	38	8	15	23	31	38	46
1.4	5	9	14	18	23	27	6	11	17	22	28	33	7	13	20	26	33	39	8	16	24	31	39	47
1.6	5	9	14	19	23	28	6	11	17	22	28	33	7	13	20	27	33	40	8	16	24	32	40	48
1.8	5	10	15	19	24	29	6	11	17	23	28	34	7	14	21	27	34	41	8	16	25	33	41	49
2	5	10	15	19	24	29	6	12	13	23	29	35	7	14	21	27	34	41	8	17	25	33	42	50
2.2	5	10	15	20	25	30	6	12	18	23	29	35	7	14	21	28	35	42	9	17	26	34	43	51
2.4	5	10	15	20	25	30	6	12	19	24	30	36	7	14	22	29	36	43	9	17	26	35	43	52
2.6	5	10	16	21	26	31	6	12	19	25	31	37	7	15	22	29	37	44	9	18	27	35	44	53
2.8	5	10	16	21	26	31	6	12	19	25	31	37	8	15	23	30	38	45	9	18	27	36	45	54
3	5	11	16	21	27	32	6	13	19	25	32	38	8	15	23	31	38	46	9	18	28	37	46	55

CHLORINE CONCENTRATION (mg/L)	pH=8.0 Log Inactivation						pH=8.5 Log Inactivation						pH=9.0 Log Inactivation					
	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0	0.5	1.0	1.5	2.0	2.5	3.0
<=0.4	8	17	25	33	42	50	10	20	30	39	49	59	12	23	35	47	58	70
0.6	9	17	26	34	43	51	10	20	31	41	51	61	12	24	37	49	61	73
0.8	9	18	27	35	44	53	11	21	32	42	53	63	13	25	38	50	63	75
1	9	19	27	36	45	54	11	22	33	43	54	65	13	26	39	52	65	78
1.2	9	18	28	37	46	55	11	22	34	45	56	67	13	27	40	53	67	80
1.4	10	19	29	38	48	57	12	23	35	46	58	69	14	27	41	55	68	82
1.6	10	19	29	39	48	58	12	23	35	47	58	70	14	28	42	56	70	84
1.8	10	20	30	40	50	60	12	24	36	48	60	72	14	29	43	57	72	86
2	10	20	31	41	51	61	12	25	37	49	62	74	15	29	44	59	73	89
2.2	10	21	31	41	52	62	13	25	38	50	63	75	15	30	45	60	75	90
2.4	11	21	32	42	53	63	13	26	39	51	64	77	15	31	46	61	77	92
2.6	11	22	33	43	54	65	13	26	39	52	65	78	16	31	47	63	78	94
2.8	11	22	33	44	55	66	13	27	40	53	67	80	16	32	48	64	80	96
3	11	22	34	45	56	67	14	27	41	54	68	81	16	32	49	65	81	97

Source: AWWA, 1991.

Table C-7. CT Values for Inactivation of Viruses by Free Chlorine, pH 6.0-9.0

	Temperature (°C)																									
Inactivation (log)	**0.5**	**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**
2	6.0	5.8	5.3	4.9	4.4	4.0	3.8	3.6	3.4	3.2	3.0	2.8	2.6	2.4	2.2	2.0	1.8	1.6	1.4	1.2	1.0	1.0	1.0	1.0	1.0	1.0
3	9.0	8.7	8.0	7.3	6.7	6.0	5.6	5.2	4.8	4.4	4.0	3.8	3.6	3.4	3.2	3.0	2.8	2.6	2.4	2.2	2.0	1.8	1.6	1.4	1.2	1.0
4	12.0	11.6	10.7	9.8	8.9	8.0	7.6	7.2	6.8	6.4	6.0	5.6	5.2	4.8	4.4	4.0	3.8	3.6	3.4	3.2	3.0	2.8	2.6	2.4	2.2	2.0

Source: AWWA, 1991. Modified by linear interpolation between 5°C increments.

Table C-8. CT Values for Inactivation of Giardia Cysts by Chlorine Dioxide, pH 6.0-9.0

Inactivation (log)	Temperature (°C)																								
	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
0.5	10.0	8.6	7.2	5.7	4.3	4.2	4.2	4.1	4.1	4.0	3.8	3.7	3.5	3.4	3.2	3.1	2.9	2.8	2.6	2.5	2.4	2.3	2.2	2.1	2.0
1	21.0	17.9	14.9	11.8	8.7	8.5	8.3	8.1	7.9	7.7	7.4	7.1	6.9	6.6	6.3	6.0	5.8	5.5	5.3	5.0	4.7	4.5	4.2	4.0	3.7
1.5	32.0	27.3	22.5	17.8	13.0	12.8	12.6	12.4	12.2	12.0	11.6	11.2	10.8	10.4	10.0	9.5	9.0	8.5	8.0	7.5	7.1	6.7	6.3	5.9	5.5
2	42.0	35.8	29.5	23.3	17.0	16.6	16.2	15.8	15.4	15.0	14.6	14.2	13.8	13.4	13.0	12.4	11.8	11.2	10.6	10.0	9.5	8.9	8.4	7.8	7.3
2.5	52.0	44.5	37.0	29.5	22.0	21.4	20.8	20.2	19.6	19.0	18.4	17.8	17.2	16.6	16.0	15.4	14.8	14.2	13.6	13.0	12.2	11.4	10.6	9.8	9.0
3	63.0	53.8	44.5	35.3	26.0	25.4	24.8	24.2	23.6	23.0	22.2	21.4	20.6	19.8	19.0	18.2	17.4	16.6	15.8	15.0	14.2	13.4	12.6	11.8	11.0

Source: AWWA, 1991. Modified by linear interpolation between 5°C increments.

Table C-9. CT Values for Inactivation of Viruses by Chlorine Dioxide, pH 6.0-9.0

Inactivation (log)	Temperature (°C)																								
	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
2	8.4	7.7	7.0	6.3	5.6	5.3	5.0	4.8	4.5	4.2	3.9	3.6	3.4	3.1	2.8	2.7	2.5	2.4	2.2	2.1	2.0	1.8	1.7	1.5	1.4
3	25.6	23.5	21.4	19.2	17.1	16.2	15.4	14.5	13.7	12.8	12.0	11.1	10.3	9.4	8.6	8.2	7.7	7.3	6.8	6.4	6.0	5.6	5.1	4.7	4.3
4	50.1	45.9	41.8	37.6	33.4	31.7	30.1	28.4	26.8	25.1	23.4	21.7	20.1	18.4	16.7	15.9	15.0	14.2	13.3	12.5	11.7	10.9	10.0	9.2	8.4

Source: AWWA, 1991. Modified by linear interpolation between 5°C increments.

Table C-10. CT Values for Inactivation of Giardia Cysts by Chloramine, pH 6.0-9.0

	Temperature (°C)																								
Inactivation (log)	**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**
0.5	635	568	500	433	365	354	343	332	321	310	298	286	274	262	250	237	224	211	198	185	173	161	149	137	125
1	1,270	1,136	1,003	869	735	711	687	663	639	615	592	569	546	523	500	474	448	422	396	370	346	322	298	274	250
1.5	1,900	1,700	1,500	1,300	1,100	1,066	1,032	998	964	930	894	858	822	786	750	710	670	630	590	550	515	480	445	410	375
2	2,535	2,269	2,003	1,736	1,470	1,422	1,374	1,326	1,278	1,230	1,184	1,138	1,092	1,046	1,000	947	894	841	788	735	688	641	594	547	500
2.5	3,170	2,835	2,500	2,165	1,830	1,772	1,714	1,656	1,598	1,540	1,482	1,424	1,366	1,308	1,250	1,183	1,116	1,049	982	915	857	799	741	683	625
3	3,800	3,400	3,000	2,600	2,200	2,130	2,060	1,990	1,920	1,850	1,780	1,710	1,640	1,570	1,500	1,420	1,340	1,260	1,180	1,100	1,030	960	890	820	750

Source: AWWA, 1991. Modified by linear interpolation between 5°C increments.

Table C-11. CT Values for Inactivation of Viruses by Chloramine

	Temperature (°C)																								
Inactivation (log)	**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**
2	1,243	1,147	1,050	954	857	814	771	729	686	643	600	557	514	471	428	407	385	364	342	321	300	278	257	235	214
3	2,063	1,903	1,743	1,583	1,423	1,352	1,281	1,209	1,138	1,067	996	925	854	783	712	676	641	605	570	534	498	463	427	392	356
4	2,883	2,659	2,436	2,212	1,988	1,889	1,789	1,690	1,590	1,491	1,392	1,292	1,193	1,093	994	944	895	845	796	746	696	646	597	547	497

Source: AWWA, 1991. Modified by linear interpolation between 5°C increments.

Table C-12. CT Values for Inactivation of Giardia Cysts by Ozone

	Temperature (°C)																								
Inactivation (log)	**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**
0.5	0.48	0.44	0.40	0.36	0.32	0.30	0.28	0.27	0.25	0.23	0.22	0.20	0.19	0.17	0.16	0.15	0.14	0.14	0.13	0.12	0.11	0.10	0.10	0.09	0.08
1.0	0.97	0.89	0.80	0.72	0.63	0.60	0.57	0.54	0.51	0.48	0.45	0.42	0.38	0.35	0.32	0.30	0.29	0.27	0.26	0.24	0.22	0.21	0.19	0.18	0.16
1.5	1.50	1.36	1.23	1.09	0.95	0.90	0.86	0.81	0.77	0.72	0.67	0.62	0.58	0.53	0.48	0.46	0.43	0.41	0.38	0.36	0.34	0.31	0.29	0.26	0.24
2.0	1.90	1.75	1.60	1.45	1.30	1.23	1.16	1.09	1.02	0.95	0.89	0.82	0.76	0.69	0.63	0.60	0.57	0.54	0.51	0.48	0.45	0.42	0.38	0.35	0.32
2.5	2.40	2.20	2.00	1.80	1.60	1.52	1.44	1.36	1.28	1.20	1.12	1.04	0.95	0.87	0.79	0.75	0.71	0.68	0.64	0.60	0.56	0.52	0.48	0.44	0.40
3.0	2.90	2.65	2.40	2.15	1.90	1.81	1.71	1.62	1.52	1.43	1.33	1.24	1.14	1.05	0.95	0.90	0.86	0.81	0.77	0.72	0.67	0.62	0.58	0.53	0.48

Source: AWWA, 1991. Modified by linear interpolation between 5°C increments.

Table C-13. CT Values for Inactivation of Viruses by Ozone

	Temperature (°C)																								
Inactivation (log)	**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**
2	0.90	0.83	0.75	0.68	0.60	0.58	0.56	0.54	0.52	0.50	0.46	0.42	0.38	0.34	0.30	0.29	0.28	0.27	0.26	0.25	0.23	0.21	0.19	0.17	0.15
3	1.40	1.28	1.15	1.03	0.90	0.88	0.86	0.84	0.82	0.80	0.74	0.68	0.62	0.56	0.50	0.48	0.46	0.44	0.42	0.40	0.37	0.34	0.31	0.28	0.25
4	1.80	1.65	1.50	1.35	1.20	1.16	1.12	1.08	1.04	1.00	0.92	0.84	0.76	0.68	0.60	0.58	0.56	0.54	0.52	0.50	0.46	0.42	0.38	0.34	0.30

Source: AWWA, 1991. Modified by linear interpolation between 5°C increments

APPENDIX D. DETERMINATION OF DISINFECTANT CONTACT TIME

This appendix originally appeared as Appendix C in the *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources* (AWWA, 1991). References to the main body of the report, section headers, and some terminology have been modified to relate better to the content of this *Disinfection Profiling and Benchmarking Guidance Manual.*

As indicated in Chapter 3, 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 will be required to determine the contact time for the calculation of CT through tracer studies or other methods approved by the Primacy Agency.

For the purpose of determining compliance with the disinfection requirements of the SWTR, 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 is used for estimating the detention time, T_{10}, for the purpose of calculating CT.

This appendix is divided into three sections. The first section presents a brief synopsis of tracer study methods, procedures, and data evaluation. In addition, examples are presented for conducting hypothetical tracer studies to determine the T_{10} contact time in a clearwell. The second section presents a method of determining T_{10} from theoretical detention times in systems where it is impractical to conduct tracer studies. The third section provides examples on how to incorporate baffling classification and factors into CT calculations and provides detailed practical examples on the use of tracer studies and baffling conditions to calculate T_{10}/T.

D.1 Tracer Studies

D.1.1 Flow conditions

Although detention time is proportional to flow, it is not generally a linear function. Therefore, tracer studies are needed to establish detention times for the range of flow rates experienced within each disinfectant segment.

As discussed in Section 3.4.2, a single flow rate may not characterize the flow through the entire system. With a series of reservoirs, clearwells, and storage tanks, flow will vary between each portion of the system.

In filter plants, the plant flow is relatively uniform from the intake through the filters. An increase or reduction in the intake pumping capacity will impart a proportional change in flow through each process unit prior to and including the filters. Therefore, at a constant intake pumping rate flow variations between disinfectant segments within a treatment plant, excluding clearwells, are likely to be small, and the design capacity of the plant, or plant flow, can be considered the nominal flow rate through each individual process unit within the plant. Clearwells may operate at a different flow rate than the rest of the plant, depending on the pumping capacity.

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 will 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} vs. Q for each segment in the system. 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 Q at peak hourly flow conditions. This procedure is presented in Section D.1.8.

It may not be practical for all systems to conduct studies at four flow rates. The number of tracer tests that are practical to conduct is dependent on site-specific restrictions and resources available to the system. Systems with limited resources can conduct a minimum of one tracer test for each disinfectant segment at a flow rate of not less than 91 percent of the highest flow rate experienced at that segment. If only one tracer test is performed, the detention time determined by the test may be used to provide a conservative estimate in CT calculations for that segment for all flow rates less than or equal to the tracer test flow rate. T_{10} is inversely proportional to flow rate, therefore, the T_{10} at a flow rate other than that which the tracer study was conducted (T_{10S}) can be approximated by multiplying the T_{10} from the tracer study (T_{10T}) by the ratio of the tracer study flow rate to the desired flow rate, (i.e., $T_{10S} = T_{10T} \cdot Q_T/Q_D$).

Where:

T_{10S} = T_{10} at system flow rate

T_{10T} = T_{10} at tracer flow rate

Q_T = tracer study flow rate

Q_D = system flow rate

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 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.

D.1.2 Other Tracer Study Considerations

In addition to flow conditions, detention times determined by tracer studies are dependent on the water level in the contact basin. 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. In such instances, the water levels in the reservoirs vary to meet the system 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 which are operated at a near constant level (that is, flow in equals flow out), the detention time determined by tracer tests is valid for calculating CT when the basin is operating at water levels greater than or equal to the level at which the test was performed. If the water level during testing is higher than the normal operating level, the resulting concentration profile will predict an erroneously high detention time. Conversely, extremely low water levels during testing may lead to an overly conservative detention time. Therefore, 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). This procedure will provide a detention time for the contact basin, which is also valid when the water level is rising (flow out less than flow in) from a level that is at or above the level when the T_{10} was determined by the tracer study. Whether the water level is constant or variable, the tracer study for each segment should be repeated for several different flows, as described in the previous segment.

For clearwells that are operated with extreme variations in water level, maintaining a CT to comply with inactivation requirements may be impractical. Under such operating conditions, a reliable detention time is not provided for disinfection. However, the system may install a weir to ensure a minimum water level and provide a reliable detention time.

Systems comprised of storage reservoirs that experience seasonal variations in water levels might perform tracer studies during the various seasonal conditions. For these systems, tracer tests should be conducted at several flow rates and representative water levels that occur for each seasonal condition. The results of these tests can be used to develop hydraulic profiles of the reservoir for each water level. These profiles can be plotted on the same axis of T_{10} vs. Q and may be used for calculating CT for different water levels and flow rates.

Detention time may also be influenced by differences in water temperature within the system. For plants with potential for thermal stratification, additional tracer studies are suggested under the various seasonal conditions that are likely to occur. The contact times determined by the tracer studies under the various seasonal conditions should remain valid as long as no physical changes are made to the mixing basin(s) or storage reservoir(s).

The portion of the system with a measurable contact time between two points of disinfection or residual monitoring is referred to as a segment. For systems 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 may or may not include a length of pipe and is used along with the residual disinfectant concentration prior to the next disinfectant application or monitoring point to determine the CTcalc for that segment. The inactivation ratio for the segment is then determined. The total inactivation and log inactivation achieved in the system can then be determined by summing the inactivation ratios for all segments as explained in Section 3.5.

For systems that have two or more units of identical size and configuration, tracer studies only need to be conducted on one of the units. The resulting graph of T_{10} vs. flow can be used to determine T_{10} for all identical units.

Systems with more than one segment in the treatment plant may determine T_{10} for each segment:

- By individual tracer studies through each segment, or
- By one tracer study across the 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 of the system. Conducting the tracer studies in this order will prevent the interference of residual tracer material with subsequent studies.

However, it may not always be practical for systems to conduct tracer studies for each segment because of time and manpower constraints. In these cases, one tracer study may be used to determine the T_{10} values for all of the segments at one flow rate. This procedure involves the following steps:

- Add tracer at the beginning of the furthest upstream disinfection segment.
- Measure the tracer concentration at the end of each disinfection segment.

- Determine the T_{10} to each monitoring point, as outlined in the data evaluation examples presented in Section D.1.7.
- Subtract T_{10} values of each of the upstream segments from the overall T_{10} value to determine the T_{10} of each downstream segment.

This approach is valid for a series of two or more consecutive segments as long as all process units within the segments experience the same flow condition. This approach is illustrated by Hudson (1975) in which step-dose tracer tests were employed to evaluate the baffling characteristics of flocculators and settling basins at six water treatment plants. At one plant, tracer chemical was added to the rapid mix, which represented the beginning of the furthest upstream disinfection segment in the system. Samples were collected from the flocculator and settling basin outlets, and analyzed to determine the residence-time characteristics for each segment. Tracer measurements at the flocculator outlet indicated an approximate T_{10} of 5 minutes through the rapid mix, interbasin piping, and flocculator. Based on tracer concentration monitoring at the settling basin outlet, an approximate T_{10} of 70 minutes was determined for the combined segments, including the rapid mix, interbasin piping, flocculator, and settling basin. The flocculator T_{10} of 5 minutes was subtracted from the combined segments' T_{10} of 70 minutes, to determine the T_{10} for the settling basin alone (65 minutes).

This approach may also be applied in cases where disinfectant application and/or residual monitoring is discontinued at any point between two or more segments with known T_{10} values. These T_{10} values may be summed to obtain an equivalent T_{10} for the combined segments.

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.

D.1.3 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 to a system, and tracking the resulting effluent concentration as a function of time. The effluent concentration profile is evaluated to determine the detention time, T_{10}.

While both tracer test methods can use the same tracer materials and involve measuring the concentration of tracer with time, each has distinct advantages and disadvantages with respect to tracer addition procedures and analysis of results.

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. Step-dose tracer studies are frequently employed in drinking water applications for the following reasons:

- The resulting normalized concentration vs. time profile-is directly used to determine T_{10}, 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.

Alternatively, with 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. A disadvantage of this technique is that very concentrated solutions are needed for the dose in order to adequately define the concentration versus time profile. Intensive mixing is therefore required 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 must be carefully computed to provide an adequate tracer profile at the effluent of the basin;
- The resulting concentration vs. time profile cannot be used to directly determine T_{10} without further manipulation; and
- A mass balance on the treatment segment is required 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 is acceptable for conducting drinking water tracer studies, and the choice of the method may be determined by site-specific constraints or the system's experience.

D.1.4 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. Historically, many chemicals have been used in tracer studies that do not satisfy all of these criteria, including potassium permanganate, alum, chlorine, and sodium carbonate. However, chloride and fluoride are the most common tracer chemicals employed in drinking water plants that are nontoxic and approved for potable water use. 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 ug/L;
- Studies that result in human exposure to the dye must be brief and infrequent; and
- Concentrations as low as 2 mg/L can be used in tracer studies because of the low detection level in the range of 0.1 to 0.2 ug/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 also 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, and
- The federal secondary and primary drinking water standards (i.e., the MCLs) 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 systems 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 system 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 from the system prior to conducting the tracer study, is recommended to reduce background levels and avoid spiked levels of fluoride that might exceed 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.

D.1.5 Tracer Addition

The tracer chemical should be added at the same point(s) in the treatment train as the disinfectant to be used in the CT calculations.

D.1.5.1 Step-dose Method

The duration of tracer addition is dependent on the volume of the basin, and hence, it's theoretical detention time. In order to approach a steady-state concentration in the water exiting the basin, tracer addition and sampling should usually be continued for a period of two to three times the theoretical detention time (Hudson, 1981). It is not necessary to reach a steady-state concentration in the exiting water to determine T_{10}; however, it is necessary to determine tracer recovery. It is recommended that the tracer recovery be determined to identify hydraulic characteristics or density problems. Generally, a 90 percent recovery is considered to provide reliable results for the evaluation of T_{10}.

In all cases, the tracer chemical should be dosed in sufficient concentration to easily monitor a residual at the basin outlet throughout the test. The required tracer chemical concentration is generally dependent upon the nature of the chosen tracer chemical including its background concentration, and the mixing characteristics of the basin to be tested. Recommended chloride doses on the order of 20 mg/L (Hudson, 1975) should be used for step-method tracer studies where the background chloride level is less than 10 mg/L. Also, fluoride concentrations as low as 1.0 to 1.5 mg/L are practical when the raw water fluoride level is not significant (Hudson, 1975). However, tracer studies conducted on systems suffering from serious short-circuiting of flow may require substantially larger step-doses. This would be necessary to detect the tracer chemical and to adequately define the effluent tracer concentration profile.

D.1.5.2 Slug-dose Method

The duration of tracer measurements using the slug-dose method is also dependent on the volume of the basin, and hence, it's theoretical detention time. In general, samples should be collected for at least twice the basin's theoretical detention time, or until tracer concentrations are detected near background levels. In order to get reliable results for T_{10} values using the slug-dose method it is recommended that the total mass of tracer recovered be approximately 90 percent of the mass applied. This guideline requires sampling until the tracer concentration recedes to the background level. The total mass recovered during testing will not be known until completion of the testing and analysis of the data collected. The sampling period needed is very site specific. Therefore, it may be helpful to conduct a first run tracer test as a screen to identify the appropriate sampling period for gathering data to determine T_{10}.

Tracer addition for slug-dose method tests should be instantaneous and provide uniformly mixed distribution of the chemical. Tracer addition is considered instantaneous if the dosing time does not exceed 2 percent of the basin's theoretical detention time (Marske and Boyle, 1973). One recommended procedure for achieving instantaneous tracer dosing is to apply the chemical by gravity flow through a funnel and hose apparatus. This method is also beneficial because it provides a means of standardization, which is necessary to obtain reproducible results.

The mass of tracer chemical to be added is determined by the desired theoretical concentration and basin size. The mass of tracer added in slug-dose tracer tests should be the minimum mass needed to obtain detectable residual measurements to generate a concentration profile. As a guideline, the theoretical concentration for the slug-dose method should be comparable to the constant dose applied in step-dose tracer tests, (i.e., 10 to 20 mg/L and 1 to 2 mg/L for chloride and fluoride, respectively). The maximum mass of tracer chemical needed is calculated by multiplying the theoretical concentration by the total basin volume. This is appropriate for systems with high dispersion and/or mixing. This quantity is diluted as required to apply an instantaneous dose, and minimize density effects. It should be noted that the mass applied is not likely to get completely mixed throughout the total volume of the basin. Therefore, the detected concentration might exceed theoretical concentrations based on the total volume of the basin. For these cases, the mass of chemical to be added can be determined by multiplying the theoretical concentration by only a portion of the basin volume. An example of this is shown in Section D.1.7.2 for a slug-dose tracer study. In cases where the tracer concentration in the effluent must be maintained below a specified level, it may be necessary to conduct a preliminary test run with a minimum tracer dose to identify the appropriate dose for determining T_{10} without exceeding this level.

D.1.6 Test Procedure

In preparation for beginning a tracer study, the raw water background concentration of the chosen tracer chemical must be established. The background concentration is essential, not only for aiding 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. The monitoring procedure is outlined in the following steps:

If the tracer chemical is normally added for treatment, discontinue its addition to the water in sufficient time to permit the tracer concentration to recede to its background level before the test is begun.

- 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.

D.1.6.1 Step-dose Method

At time zero, the tracer chemical feed will be 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 vs. time. If on-site analysis is available, less frequent residual monitoring may be possible until a change in residual concentration is first detected. As a guideline, in systems with a theoretical detention time greater than 4 hours, sampling may be conducted every 10 minutes for the first 30 minutes, or until a tracer concentration above the baseline level is first detected. In general, shorter sampling intervals enable better characterization of concentration changes; therefore, sampling should be conducted at 2 to 5-minute intervals from the time that a concentration change is first observed until the residual concentration reaches a steady-state value. A reasonable sampling interval should be chosen based on the overall detention time of the unit being tested.

If verification of the test is desired, the tracer feed should be discontinued, and the receding tracer concentration at the effluent should be monitored at the same frequency until tracer concentrations corresponding to the background level are detected. The time at which tracer feed is stopped is time zero for the receding tracer test and must be noted. The receding tracer test will provide a replicate set of measurements that can be compared with data derived from the rising tracer concentration versus time curve. For systems which currently feed the tracer chemical, the receding curve may be generated from the time the feed is turned off to determine the background concentration level.

D.1.6.2 Slug-dose Method

At time zero for the slug-dose method, a large instantaneous dose of tracer will be 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 with 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 of the tracer fed is recovered, or, mass applied equals mass discharged.

D.1.7 Data Evaluation

Data from tracer studies should be summarized in tables of time and residual concentration. These data are then analyzed to determine the detention time, T_{10}, to be used in calculating CT. Tracer test data from either the step-dose or slug-dose method can be evaluated graphically, numerically, or by a combination of these techniques.

D.1.7.1 Step-dose Method

The graphical method of evaluating step-dose test data involves plotting a graph of dimensionless concentration (C/Co) versus time and reading the value for T_{10} 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 T_{10} 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.

An illustration of the T_{10} determination will be presented in an example of the data evaluation required for a clearwell tracer study.

D.1.7.2 Slug-dose Method

Data from slug-dose tracer tests is analyzed by converting it to the mathematically equivalent step-dose data and using techniques discussed in Section D.1.7.1 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 graphically or numerically integrating the curve. The conversion to step-dose data is then completed in several mathematical steps involving the total area.

A graphical technique for converting the slug-dose data involves physically measuring the area using a planimeter. The planimeter is an instrument used to measure the area of a plane closed curve by tracing its boundary. Calibration of this instrument to the scale of the graph is required to obtain meaningful readings.

The rectangle rule is a simple numerical integration method that approximates the total area under the curve as the sum of the areas of individual rectangles. These rectangles have heights and widths equal to the residual concentration and sampling interval (time) for each data point on the curve, respectively. Once the data has been converted, T_{10} may be determined in the same manner as data from step-dose tracer tests.

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. The steps and specific details involved with evaluating data from both tracer study methods are illustrated in the following examples.

Example for Determining T_{10} in a Clearwell

Two tracer studies employing the step-dose and slug-dose methods of tracer addition were conducted for a clearwell with a theoretical detention time, T, of 30 minutes at an average flow of 2.5 MGD. Because fluoride is added at the inlet to the clearwell as a water treatment chemical, necessary feed equipment was in place for dosing a constant concentration of fluoride throughout the step-dose tracer test. Based on this convenience, fluoride was chosen as the tracer chemical for the step-dose method test. Fluoride was also selected as the tracer chemical for the slug-dose method test. Prior to the start of testing, a fluoride baseline concentration of 0.2 mg/L was established for the water exiting the clearwell.

Step-dose Method Test

For the step-dose test a constant fluoride dosage of 2.0 mg/L was added to the clearwell inlet. Fluoride levels in the clearwell effluent were monitored and recorded every 3 minutes. The raw tracer study data, along with the results of further analyses are shown in Table D-1.

The steps in evaluating the raw data shown in the first column of Table D-1 are as follows. First, the baseline fluoride concentration, 0.2 mg/L, is subtracted from the measured concentration to give the fluoride concentration resulting from the tracer study addition alone. For example, at elapsed time = 39 minutes, the tracer fluoride concentration, C, is obtained as follows:

$$\begin{aligned} C &= C_{measured} - C_{baseline} \\ &= 1.85 \text{ mg/L} - 0.2 \text{ mg/L} \\ &= 1.65 \text{ mg/L} \end{aligned}$$

This calculation was repeated at each time interval to obtain the data shown in the third column of Table D-1. As indicated, the fluoride concentration rises from 0 mg/L at t = 0 minutes to the applied fluoride dosage of 2 mg/L, at t = 63 minutes.

The next step is to develop dimensionless concentrations by dividing the tracer concentrations in the second column of Table D-1 by the applied fluoride dosage, Co = 2 mg/L. For time = 39 minutes, C/Co is calculated as follows:

$$C/Co = (1.65 \text{ mg/L})/(2.0 \text{ mg/L})$$

$$= 0.82$$

The resulting dimensionless data, presented in the fourth column of Table D-1, is the basis for completing the determination of T_{10} by either the graphical or numerical method.

TABLE D-1. CLEARWELL DATA - STEP-DOSE TRACER TEST(1,2,3)

	Fluoride Concentration		
t (minutes)	**Measured (mg/L)**	**Tracer (mg/L)**	**Dimensionless (C/Co)**
0	0.20	0	0
3	0.20	0	0
6	0.20	0	0
9	0.20	0	0
12	0.29	0.09	0.045
15	0.67	0.47	0.24
18	0.94	0.74	0.37
21	1.04	0.84	0.42
24	1.44	1.24	0.62
27	1.55	1.35	0.68
30	1.52	1.32	0.66
33	1.73	1.53	0.76
36	1.93	1.73	0.86
39	1.85	1.65	0.82
42	1.92	1.72	0.86
45	2.02	1.82	0.91
48	1.97	1.77	0.88
51	1.84	1.64	0.82
54	2.06	1.86	0.93
57	2.05	1.85	0.92
60	2.10	1.90	0.95
63	2.14	1.94	0.96

1. Baseline conc. = 0.2 mg/L, fluoride dose = 2.0 mg/L
2. Measured conc. = Tracer conc. + Baseline conc.
3. Tracer conc. = Measured conc. - Baseline conc.

In order to determine T_{10} by the graphical method, a plot of C/Co vs. time should be generated using the data in Table D-1. A smooth curve should be drawn through the data as shown on Figure D-1.

T_{10} is read directly from the graph at a dimensionless concentration (C/Co) corresponding to the time for which 10 percent of the tracer has passed at the effluent end of the contact basin (T_{10}). For step-dose method tracer studies, this dimensionless concentration is C/Co = 0.10 (Levenspiel, 1972).

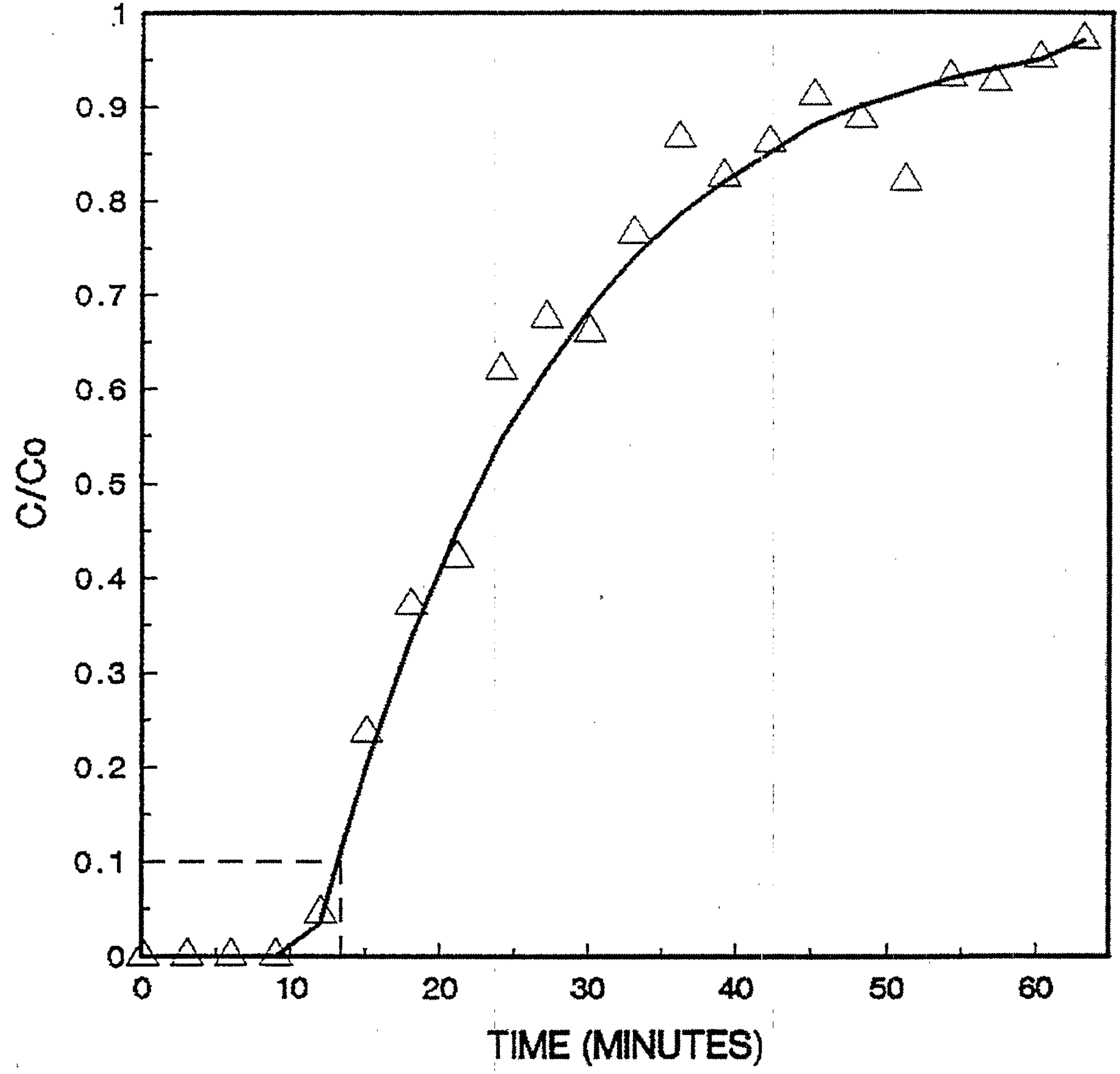


Figure D-1. C/Co vs. Time — Graphical Analysis for T_{10}

T_{10} should be read directly from Figure D-1 at C/Co = 0.1 by first drawing a horizontal line (C/Co = 0.1) from the Y-axis (t = 0) to its intersection with the smooth curve drawn through the data. At this point of intersection, the time read from the X-axis is T_{10} and may be found by extending a vertical line downward to the X-axis. These steps were performed as illustrated on Figure D-1, resulting in a value for T_{10} of approximately 13 minutes.

For the numerical method of data analysis, several additional steps are required to obtain T_{10} from the data in the fourth column of Table D-1. The forms of data necessary for determining T_{10} through a numerical solution are $\log_{10}$ (1-C/Co) and t/T, the elapsed time divided by the theoretical residence time. These are obtained by performing the required mathematical operations on the data in the fourth column of Table D-1. For example, recalling that the theoretical detention time, T, is 30 minutes, the values for $\log_{10}$ (1-C/Co) and t/T are computed as follows for the data at t = 39 minutes:

$$\begin{aligned}\log_{10}(1\text{-}C/Co) &= \log_{10}(1-0.82)\\ &= \log_{10}(0.18)\\ &= -0.757\end{aligned}$$

$$t/T = 39\ \text{min}/30\ \text{min} = 1.3$$

This calculation was repeated at each time interval to obtain the data shown in Table D-2. These data should be linearly regressed as $\log_{10}$ (1-C/Co) versus t/T to obtain the fitted straight-line parameters to the following equation:

$$\text{(1)}\qquad \mathbf{\log_{10}(1\text{-}C/Co) = m(t/T) + b}$$

In equation 1, m and b are the slope and intercept, respectively, for a plot of $\log_{10}$ (1-C/Co) vs. t/T. This equation can be used to calculate T_{10}, assuming that the correlation coefficient for the fitted data indicates a good statistical fit (0.9 or above).

A linear regression analysis was performed on the data in Table D-2, resulting in the following straight-line parameters:

slope = m = -0.774
intercept = b = 0.251
correlation coefficient = 0.93

Table D-2. Data For Numerical Determination Of T_{10}

t / T	Log_{10} (1-C/Co)
0	0
0.1	0
0.2	0
0.3	0
0.4	-0.020
0.5	-0.116
0.6	-0.201
0.7	-0.237
0.8	-0.420
0.9	-0.488
1.0	-0.468
1.1	-0.629
1.2	-0.870
1.3	-0.757
1.4	-0.854
1.5	-1.046
1.6	-0.939
1.7	-0.745
1.8	-1.155
1.9	-1.125
2.0	-1.301
2.1	-1.532

Although these numbers were obtained numerically, a plot of $\log_{10}$ (1-C/Co) versus t/T is shown for illustrative purposes on Figure D-2 for the data in Table D-2. In this analysis, data for time = 0 through 9 minutes were excluded because fluoride concentrations above the baseline level were not observed in the clearwell effluent until t = 12 minutes.

Equation 1 is then rearranged in the following form to facilitate a solution for T_{10}:

$$\text{(2)} \qquad T_{10}/T = (\log_{10}(1 - 0.1) - b)/m$$

In equation 2, as with graphical method, T_{10} is determined at the time for which C/Co = 0.1. Therefore, in equation 2, C/Co has been replaced by 0.1 and t (time) by T_{10}. To obtain a solution for T_{10}, the values of the slope, intercept, and theoretical detention time are substituted as follows:

$$T_{10}/30 \text{ min.} = (\log_{10}(1 - 0.1) - 0.251)/(-0.774)$$
$$T_{10} = 12 \text{ minutes}$$

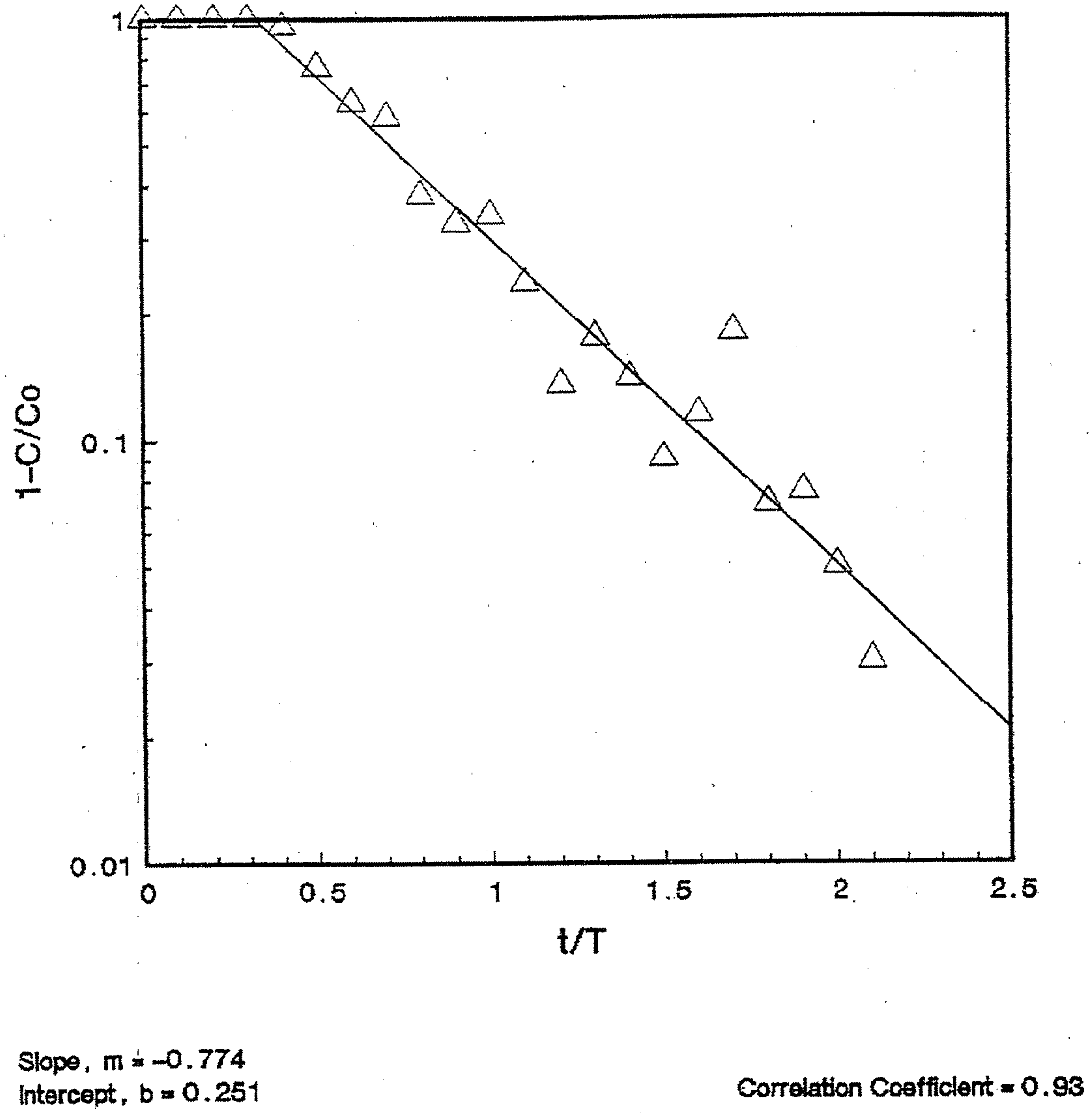


Figure D-2. 1-C/Co vs. t/T — Numerical Analysis for T_{10}

In summary both the graphical and numerical methods of data reduction resulted in comparable, but not identical values for T_{10}. With the numerical method, T_{10} was determined as the solution to an equation based on the straight-line parameters to a linear regression analysis of the tracer study data instead of an "eyeball' estimate from a data plot.

Slug-dose Method Test

A slug-dose tracer test was also performed on the clearwell at a flow rate of 2.5 mgd. A theoretical clearwell fluoride concentration of 2.2 mg/L was selected. The fluoride dosing volume and concentration were determined from the following considerations:

Dosing Volume

- The fluoride injection apparatus consisted of a funnel and a length of copper tubing. This apparatus provided a constant volumetric feeding rate of 7.5 liters per minute (L/min) under gravity flow conditions.
- At a flow rate of 2.5 mgd, the clearwell has a theoretical detention time of 30 minutes. Since the duration of tracer injection should be less than 2 percent of the clearwell's theoretical detention time for an instantaneous dose, the maximum duration of fluoride injection was:

  Max. dosing time = 30 minutes x .02 = 0.6 minutes

- At a dosing rate of 7.5 L/min, the maximum fluoride dosing volume is calculated to be:

  Max. dosing volume = 7.5 L/min. x 0.6 minutes = 4.5 L

For this tracer test, a dosing volume of 4 liters was selected, providing an instantaneous fluoride dose in 1.8 percent of the theoretical detention time.

Fluoride Concentration

- The theoretical detention time of the clearwell, 30 minutes, was calculated by dividing the clearwell volume, 52,100 gallons or 197,200 liters, by the average flow rate through the clearwell, 2.5 mgd.
- Assuming the tracer is completely dispersed throughout the total volume of the clearwell, the mass of fluoride required to achieve a theoretical concentration of 2.2 mg/L is calculated as follows:

$$\text{Fluoride mass (initial)} = 2.2\ \text{mg/L} \times 197{,}200\ \text{L} \times \frac{1g}{1000mg} = 434\text{g}$$

- The concentration of the instantaneous fluoride dose is determined by dividing this mass by the dosing volume, 4 liters:

$$\text{Fluoride concentration} = \frac{434g}{4L} = 109\ \text{g/L}$$

Fluoride levels in the exit to the clearwell were monitored and recorded every 3 minutes. The raw slug-dose tracer test data are shown in Table D-3.

The first step in evaluating the data for different times is to subtract the baseline fluoride concentration, 0.2 mg/L, from the measured concentration at each sampling interval (Table D-3). This is the same as the first step used to evaluate step-dose method data and gives the fluoride concentrations resulting from the tracer addition alone, shown in the third column of Table D-3. As indicated, the fluoride concentration rises from 0 mg/L at t = 0 minutes to the peak concentration of 3.6 mg/L at t = 18 minutes. The exiting fluoride concentration gradually recedes to near zero at t = 63 minutes. It should be noted that a maximum fluoride concentration of 2.2 mg/L is based on assuming complete mixing of the tracer added throughout the total clearwell volume. However, as shown in Table D-3, the fluoride concentrations in the clearwell effluent exceeded 2.2 mg/L for about 6 minutes between 14 and 20 minutes. These higher peak concentrations are caused by the dispersion of tracer throughout only a portion of the total clearwell volume. If a lower tracer concentration is needed in the effluent because of local or federal regulations, the mass to be added should be decreased accordingly.

The dimensionless concentrations in the fourth column of Table D-3 were obtained by dividing the tracer concentrations in the third column by the clearwell's theoretical concentration, Co = 2.2 mg/L. These dimensionless concentrations were then plotted as a function of time, as is shown by the slug-dose data on Figure D-3. These data points were connected by straight lines, resulting in a somewhat jagged curve.

The next step in evaluating slug-dose data is to determine the total area under the slug-dose data curve on Figure D-3. Two methods exist for finding this area - graphical and numerical. The graphical method is based on a physical measurement of the area using a planimeter. This involves calibration of the instrument to define the units' conversion and tracing the outline of the curve to determine the area. The results of performing this procedure may vary depending on instrument accuracy and measurement technique. Therefore, only an illustration of the numerical technique for finding the area under the slug-dose curve will be presented for this example.

The area obtained by either the graphical or numerical method would be similar. Furthermore, once the area is found, the remaining steps involved with converting the data to the step-dose response are the same.

Table D-3. Clearwell Data — Slug-Dose Tracer Test(1,2,3)

	Fluoride Concentration		
T (Minutes)	**Measured (mg/L)**	**Tracer (mg/L)**	**Dimensionless (C/Co)**
0	0.2	0	0
3	0.2	0	0
6	0.2	0	0
9	0.2	0	0
12	1.2	1	0.45
15	3.6	3.4	1.55
18	3.8	3.6	1.64
21	2.0	1.8	0.82
24	2.1	1.9	0.86
27	1.4	1.2	0.55
30	1.3	1.1	0.50
33	1.5	1.3	0.59
36	1.0	0.8	0.36
39	0.6	0.4	0.18
42	1.0	0.8	0.36
45	0.6	0.4	0.18
48	0.8	0.6	0.27
51	0.6	0.4	0.18
54	0.4	0.2	0.09
57	0.5	0.3	0.14
60	0.6	0.4	0.18
63	0.4	0.2	0.09

1. Measured conc. = Tracer conc. + Baseline conc.
2. Baseline conc. = 0.2 mg/L, fluoride slug dose conc. = 109 g/L, theoretical conc. = 2.2 mg/L.
3. Tracer conc. = Measured conc. – Baseline conc.

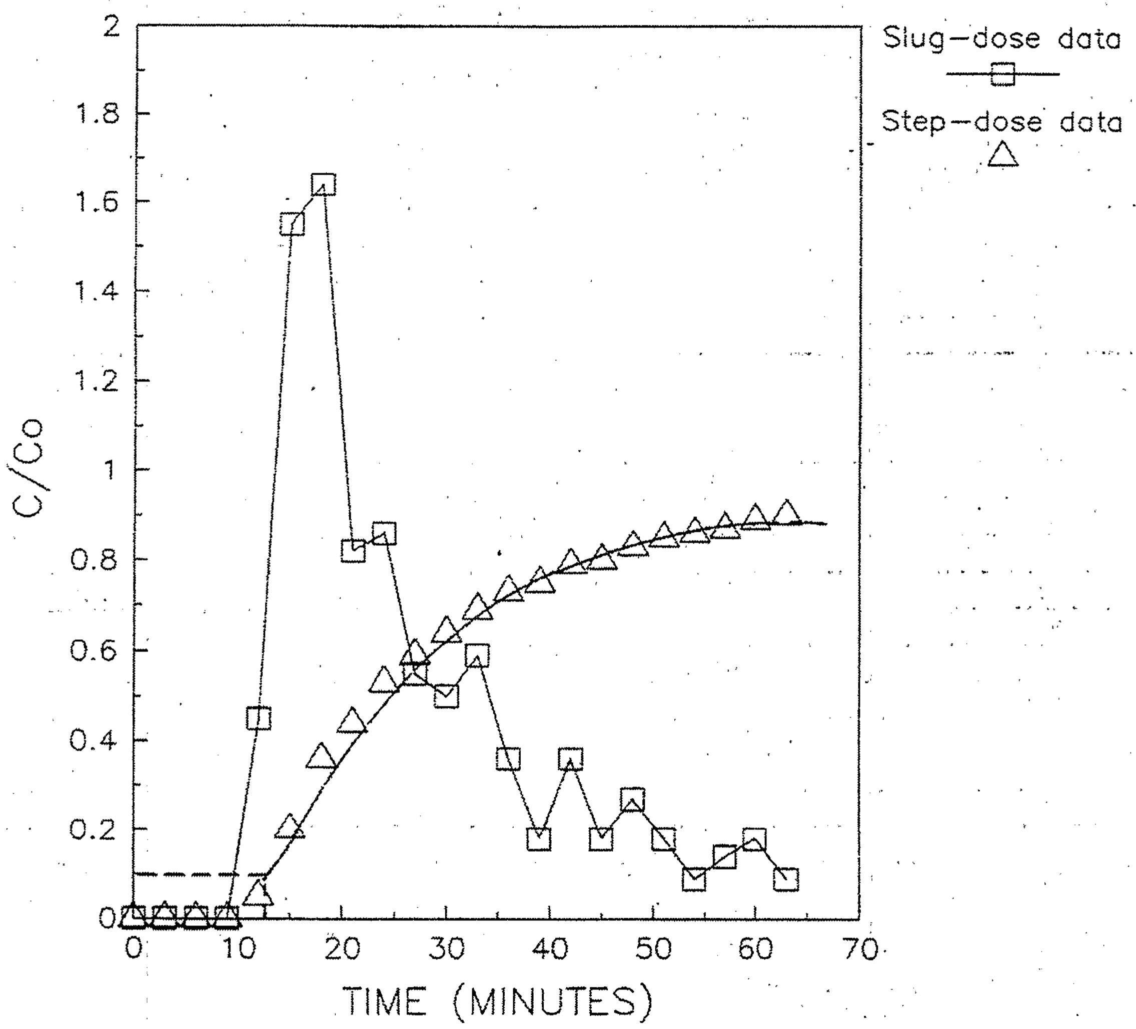


Figure D-3. C/Co vs. Time — Conversion of Slug- to Step-Dose Data

Table D-4 summarizes the results of determining the total area using a numerical integration technique called the rectangle rule. The first and second columns in Table D-4 are the sampling time and fluoride concentration resulting from tracer addition alone, respectively. The steps in applying these data are as follows. First, the sampling time interval, 3 minutes, is multiplied by the fluoride concentration at the end of the 3-minute interval to give the incremental area, in units of milligram minutes per liter. For example, at elapsed time, t = 39 minutes, the incremental area is obtained as follows:

Incremental area = sampling time interval x fluoride conc.
= 39-36) minutes x 0.4 mg/L
= 0.2 mg-min/L

This calculation was repeated at each time interval to obtain the data shown in the third column of Table D-4.

If the data had been obtained at unequal sampling intervals, then the incremental area for each interval would be obtained by multiplying the fluoride concentration at the end of each interval by the time duration of the interval. This convention also requires that the incremental area be zero at the first sampling point, regardless of the fluoride concentration at that time.

As is shown in Table D-4, all incremental areas were summed to obtain 59.4 mg-min/L, the total area under the slug-dose tracer test curve. This number represents the total mass of fluoride that was detected during the course of the tracer test divided by the average flow rate through the clearwell.

To complete the conversion of slug-dose data to its equivalent step-dose response requires two additional steps. The first involves summing, consecutively, the incremental areas in the third column of Table D-4 to obtain the cumulative area at the end of each sampling interval. For example₁ the cumulative area at time, t = 27 minutes is found as follows:

Cumulative area = 0 + 0 + 0 + 0 + 3 + 10.2 + 10.8 + 5.4 + 5.7 + 3.6
= 38.7 mg-min/L

The cumulative areas for each interval are recorded in the fourth column of Table D-4.

Table D-4. Evaluation of Slug-Dose Data

T (Minutes)	Fluoride (mg/L)	Incremental Area (mg-min/L)	Cumulative Area (mg-min/L)	Equivalent Step-Dose Data
0	0	0	0	0
3	0	0	0	0
6	0	0	0	0
9	0	0	0	0
12	1	3	3	0.05
15	3.4	10.2	13.2	0.22
18	3.6	10.8	24.0	0.40
21	1.8	5.4	29.4	0.49
24	1.9	5.7	35.1	0.59
27	1.2	3.6	38.7	0.65
30	1.1	3.3	42.0	0.71
33	1.3	3.9	45.9	0.77
36	0.8	2.4	48.3	0.81
39	0.4	1.2	49.5	0.83
42	0.8	2.4	51.9	0.87
45	0.4	1.2	53.1	0.89
48	0.6	1.8	54.9	0.92
51	0.4	1.2	56.1	0.94
54	0.2	0.6	56.7	0.95
57	0.3	0.9	57.6	0.97
60	0.4	1.2	58.8	0.99
63	0.2	0.6	59.4	1.00
Total Area = 59.4				

The final step in converting slug-dose data involves dividing the cumulative area at each interval by the total mass applied. Total area based on applied mass is calculated as follows:

$$\text{Total area mass applied/average flow} = 434\text{ g} \times 1000\frac{mg}{g} / 6{,}570\frac{L}{\text{min}}$$

$$= 66.1\frac{mg\text{ - }min}{L}$$

For time = 39 minutes, the resulting step-dose data point is calculated as follows:

C/Co = 49.5 mg-min/L / 59.4 mg-min/L
= 0.83

The result of performing this operation at each sampling interval is the equivalent step-dose data. These data points are shown in the fifth column of Table D-4 and are also plotted on Figure D-3 to facilitate a graphical determination of T_{10}. A smooth curve was fitted to the step-dose data as shown on the figure.

T_{10} can be determined by the methods illustrated previously in this example for evaluating step-dose tracer test data. The graphical method illustrated on Figure D-3 results in a reading of $T_{10} = 15$ minutes.

D.1.7.3 Additional Considerations

In addition to determining T_{10} for use in CT calculations, slug-dose tracer tests provide a more general measure of the basin's hydraulics in terms of the fraction of tracer recovery. This number is representative of short-circuiting and dead space in the unit resulting from poor baffling conditions and density currents induced by the tracer chemical. A low tracer recovery is generally indicative of inadequate hydraulics. However, inadequate sampling in which peaks in tracer passage are not measured will also result in an under estimate of tracer recovery. The tracer recovery is calculated by dividing the mass of fluoride detected by the mass of fluoride dosed.

The dosed fluoride mass was calculated previously and was 434 grams. The mass of detected fluoride can be calculated by multiplying the total area under the slug-dose curve by the average flow, in appropriate units, at the time of the test. The average flow in the clearwell during the test was 2.5 mgd or 6,570 L/min. Therefore, the mass of fluoride tracer that was detected is calculated as follows:

$$\begin{aligned}\text{Detected fluoride mass} &= \text{total area x average flow}\\ &= 59.4\ \frac{mg\text{ - }min}{L} \times \frac{1\ g}{1000\ mg} \times 6{,}570\ \frac{L}{min}\\ &= 390\ \text{g}\end{aligned}$$

Tracer recovery is then calculated as follows:

$$\begin{aligned}\text{Fluoride recovery} &= \text{detected mass/dosed mass x 100}\\ &= 390\ \text{g} / 434\ \text{g x } 100\\ &= 90\ \%\end{aligned}$$

This is a typical tracer recovery percentage for a slug-dose test, based on the experiences of Hudson (1975) and Thirumurthi (1969).

D.1.8 Flow Dependency of T_{10}

For systems conducting tracer studies at four or more flows, the T_{10} detention time should be determined by the above procedures for each of the desired flows. The detention times should then be plotted versus flow. For the example presented in the previous section, tracer studies were conducted at additional flows of 1.1, 4.2, and 5.6 MGD. The T_{10} values at the various flows were:

Flow	T_{10}
1.1	25
2.5	13
4.2	7
5.6	4

T_{10} data for these tracer studies were plotted as a function of the flow, Q, as shown in Figure D-4.

If only one tracer test is performed, the flow rate for the tracer study should be not less than 91 percent of the highest flow rate experienced for the segment. The hydraulic profile to be used for calculating CT would then be generated by drawing a line through points obtained by multiplying the T_{10} at the tested flow rate by the ratio of the tracer study flow rate to each of several different flows in the desired flow range.

For the example presented in the previous section, the clearwell experiences a maximum flow at peak hourly conditions of 6.0 mgd. The highest tested flow rate was 5.6 mgd, or 93 percent of the maximum flow. Therefore, the detention time, T_{10} = 4 minutes, determined by the tracer test at a flow rate of 5.6 mgd may be used to provide a conservative estimate of T_{10} for all flow rates less than or equal to the maximum flow rate, 6.0 mgd. The line drawn through points found by multiplying T_{10} = 4 minutes by the ratio of 5.6 mgd to each of several flows less than 5.6 mgd is also shown in Figure D-4 for comparative purposes with the hydraulic profile obtained from performing four tracer studies at different flow rates.

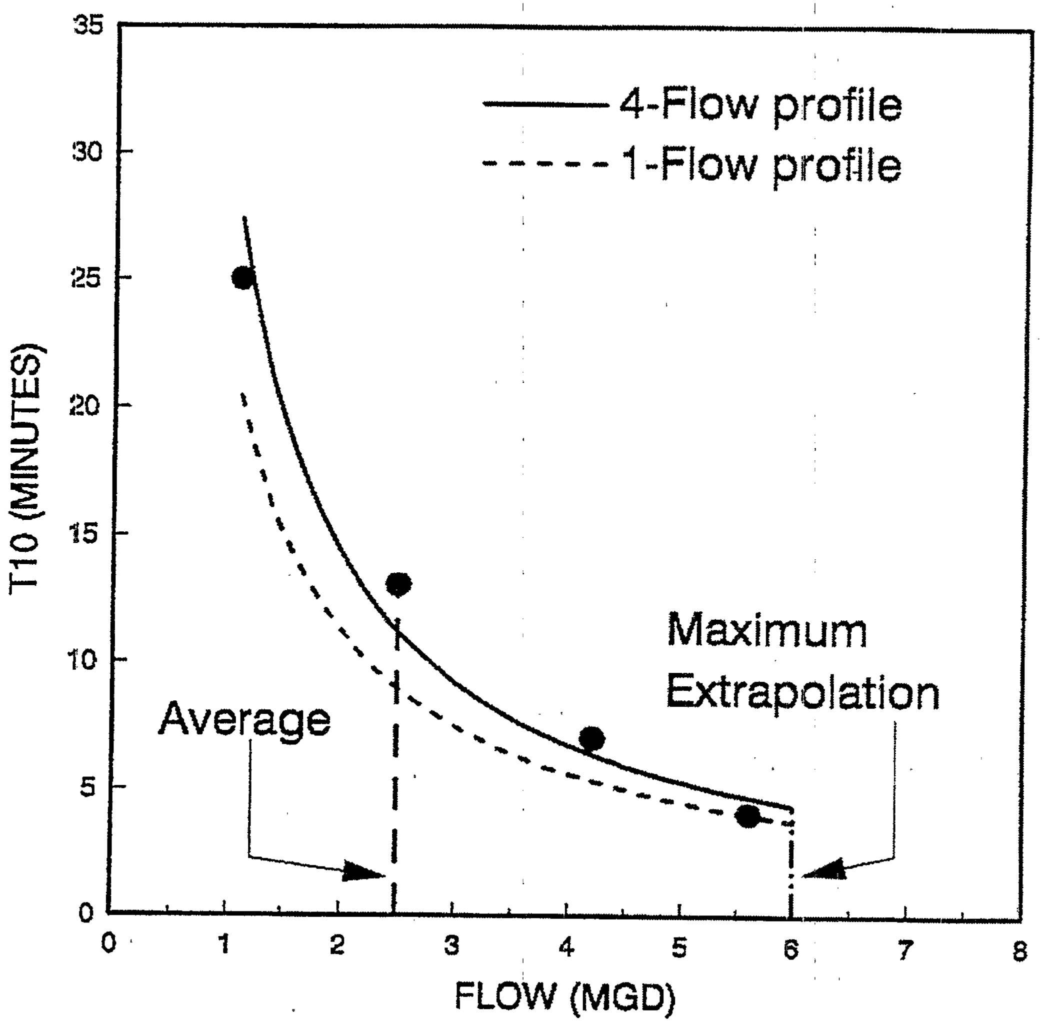


Figure D-4. Detention Time vs. Flow

D.2 Determination of T_{10} without Conducting a Tracer Study

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, manpower or equipment necessary to conduct the study. For these cases, the Primacy Agency may allow the use of "rule of thumb" fractions representing the ratio of T_{10} to T, and the theoretical detention time, to determine the detention time, T_{10}, to be used for calculating CT values. This method for finding T_{10} involves multiplying the theoretical detention time by the rule of thumb fraction, T_{10}/T, that is representative of the particular basin configuration for which T_{10} is desired. These fractions provide rough estimates of the actual T_{10} and are recommended to be used only on a limited basis.

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.

D.2.1 Impact of Design Characteristics

The significant design characteristics 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.

D.2.2 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. Three general classifications of baffling conditions - poor, average, and superior - were developed to categorize the results of the tracer studies for use in determining T_{10} from the theoretical detention time of a specific basin. The T_{10}/T fractions associated with each degree of baffling are summarized in Table D-5. Factors representing the ratio between T_{10} and the theoretical detention time for plug flow in pipelines and flow in a completely mixed chamber have been included in Table D-5 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 D-5. Baffling Classifications

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

As indicated in Table D-5, poor baffling conditions consist of an unbaffled 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.

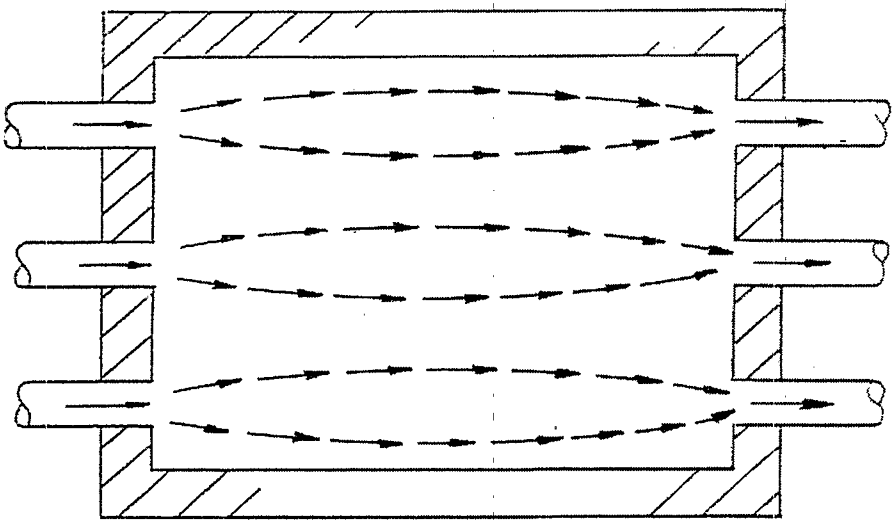
The three basic types of basin inlet baffling configurations are: a target-baffled pipe inlet, an overflow weir entrance, and a baffled submerged orifice or port inlet. Typical intra-basin baffling structures include: diffuser (perforated) walls; launders; cross, longitudinal, or maze baffling to cause 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 Cipolleti weirs, should not be considered baffling as their use may substantially increase weir overflow rates and the dead space zone of the basin.

D.2.3 Examples of Baffling

Examples of these levels of baffling conditions for rectangular and circular basins are explained and illustrated in the following section. Typical uses of various forms of baffled and unbaffled inlet and outlet structures are also illustrated.

The plan and section of a rectangular basin with poor baffling conditions, which can be attributed to the unbaffled inlet and outlet pipes, is illustrated on Figure D-5. 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 also 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 on Figure D-6. However, only average baffling conditions are achieved for the basin as a whole because of the inadequate outlet structure - a Cipolleti weir. The width of the weir is short in comparison with the width of the basin.



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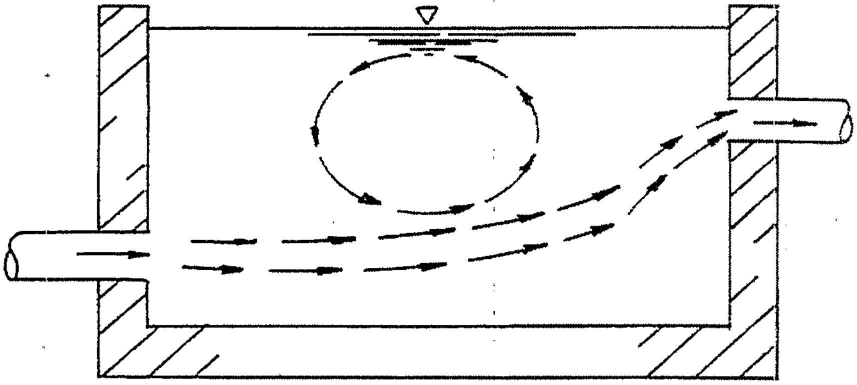
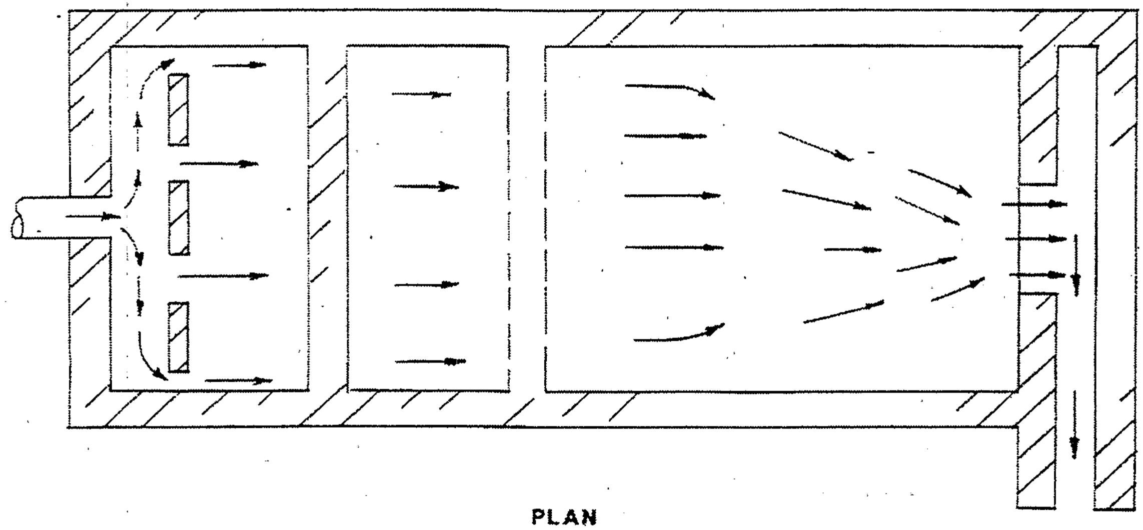


SECTION

Figure D-5. Poor Baffling Conditions — Rectangular Contact Basin



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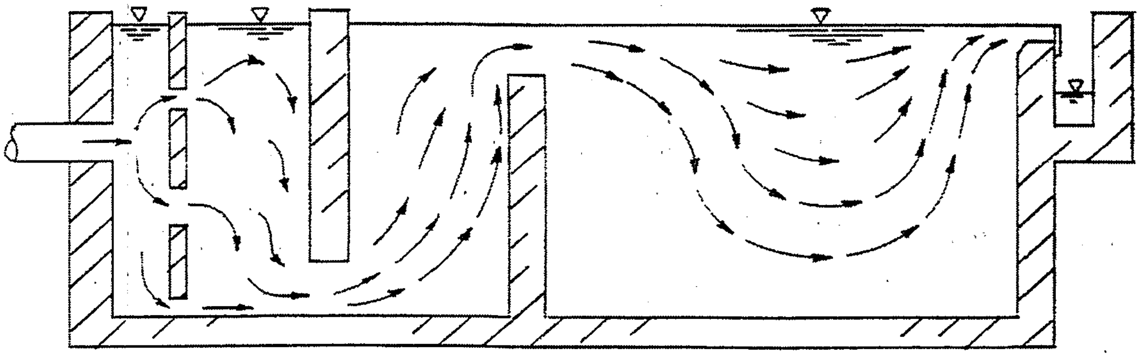

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Figure D-6. Average Baffling Conditions — Rectangular Contact Basin

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.

Superior baffling conditions are exemplified by the flow pattern and physical characteristics of the basin shown on Figure D-7. 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. These inlet and outlet structures are in some cases by themselves sufficient to attain superior baffling conditions; however, maze-type intra-basin baffling was included as an example of how this type of baffling aids in flow redistribution within a 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 is shown on Figure D-8. 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 on Figure D-9 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.

Superior baffling conditions are attained in the basin configuration shown on Figure D-10 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.

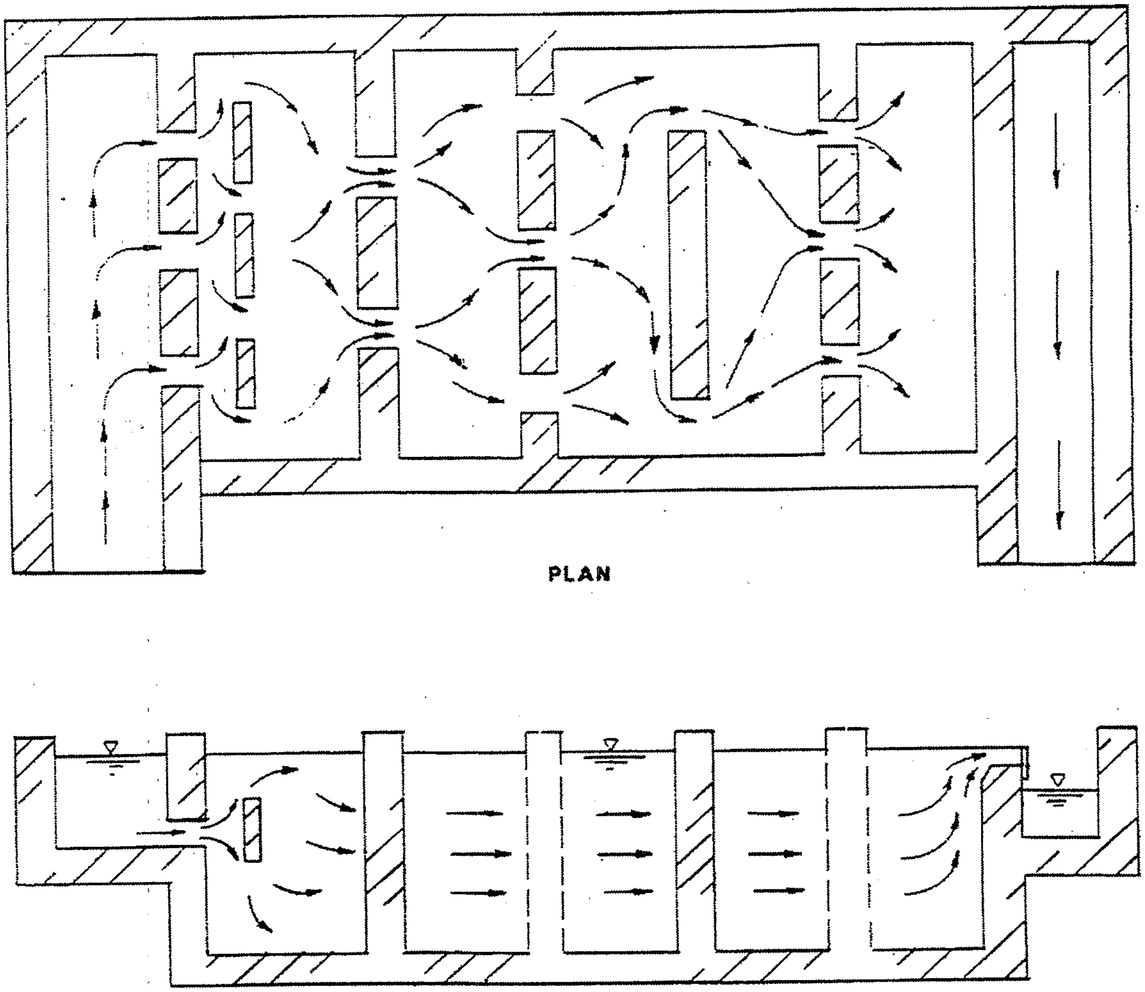
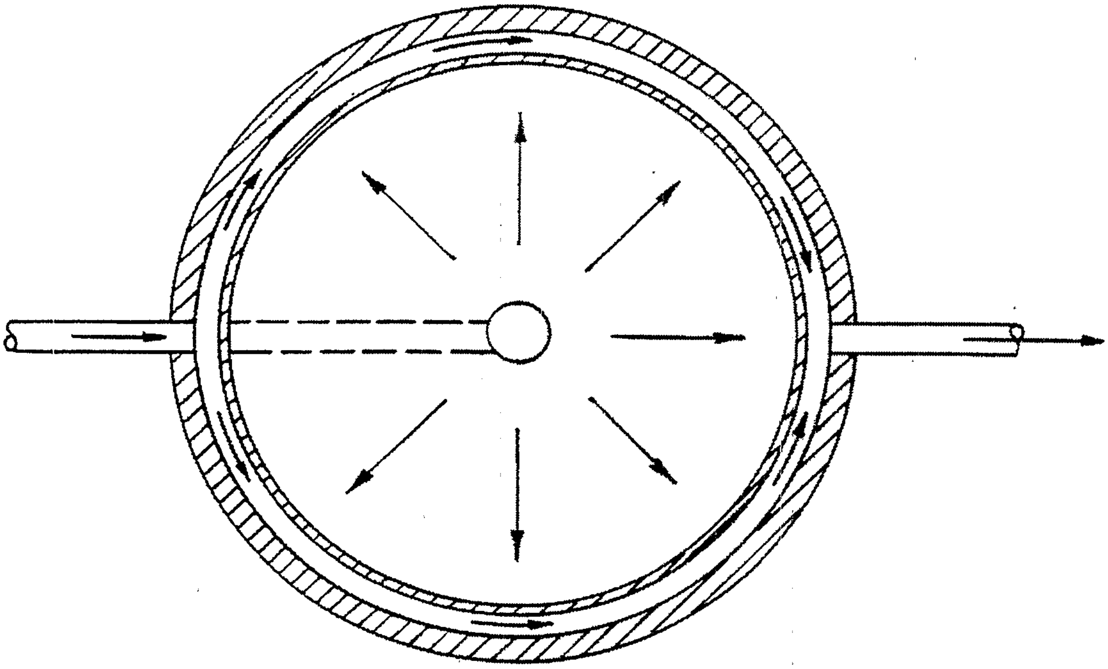


Figure D-7. Superior Baffling Conditions — Rectangular Contact Basin



PLAN

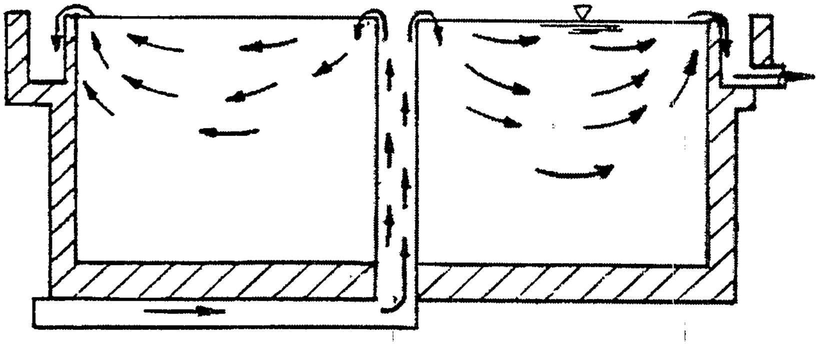


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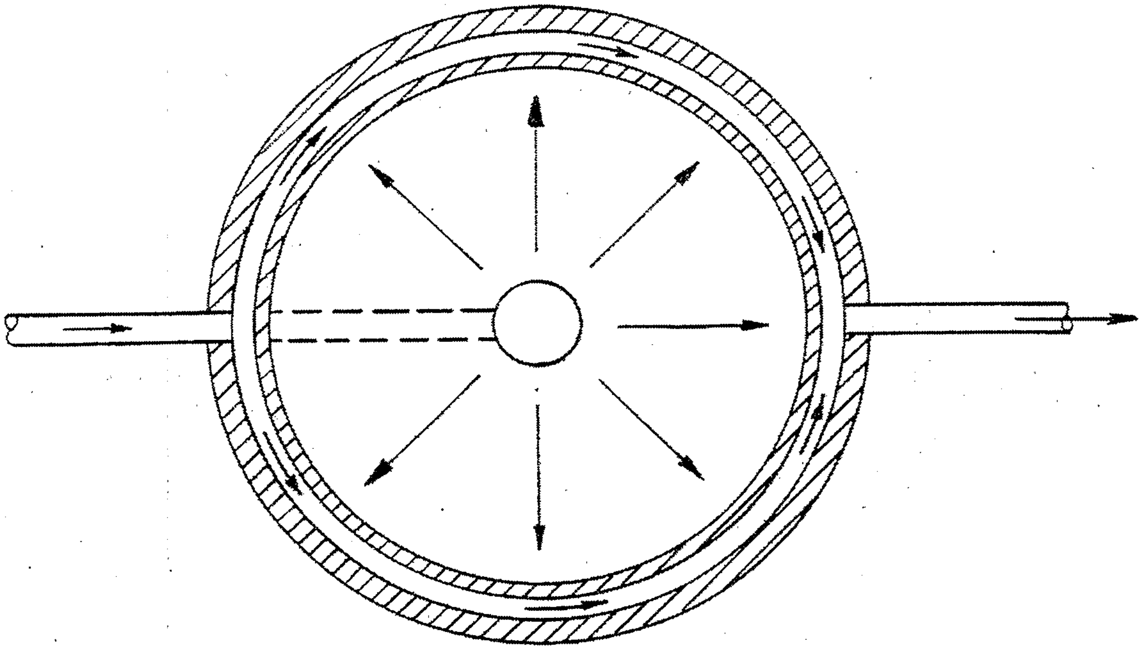
Figure D-8. Poor Baffling Conditions — Circular Contact Basin



PLAN

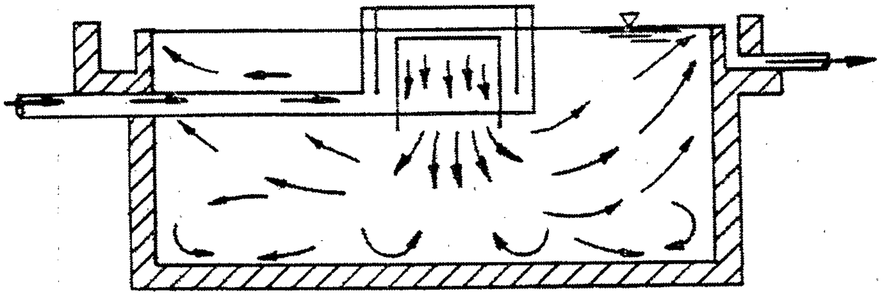


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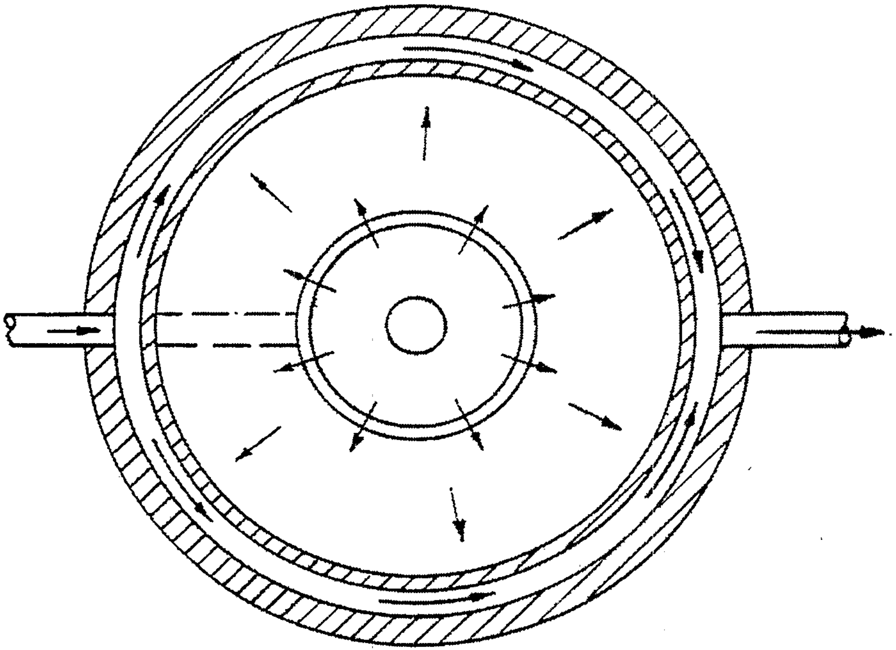
Figure D-9. Average Baffling Conditions — Circular Contact Basin



PLAN

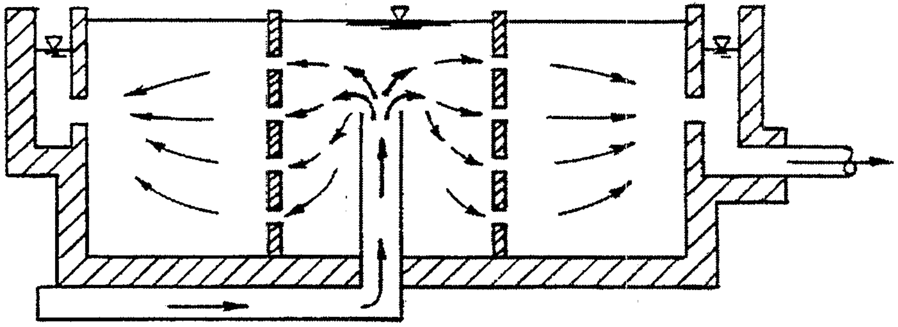


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Figure D-10. Superior Baffling Conditions — Circular Contact Basin

D.2.4 Additional Considerations

Flocculation basins and ozone contactors represent water treatment processes with slightly different characteristics from those presented in Figures D-5 through D-10 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_0 value can be obtained by subtracting the volume of the filter media, support gravel, and underdrains from the total volume and calculating the theoretical detention time by dividing this volume by the flow through the filter. The theoretical detention time is then multiplied by a factor of 0.7, corresponding to superior baffling conditions, to determine the T_{10} value.

D.2.5 Conclusions

The recommended T_{10}/T values and examples are presented as a guideline for use by the Primacy Agency in determining T_{10} values in site specific conditions and when tracer studies cannot be performed because of practical considerations. Selection of T_{10}/T

values in the absence of tracer studies was restricted to a qualitative assessment based on currently available data for the relationship between basin baffling conditions and their associated T_{10}/T values. Conditions which 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.

D.3 Use of Baffling Conditions and Tracer Studies to Determine Contact Time

This section provides further discussion and practical examples for using baffling factors and tracer studies to determine the contact time.

Use of Baffling Conditions to Determine Contact Time

To determine a contact time using baffling factors, data about the treatment system are needed. These data include volumes of the unit processes, the peak hourly flow rate, and the baffling factors of each unit process based on the baffling condition. The volume of the unit process is the volume of water in that portion of the treatment system. This volume does not include equipment such as filter media that take up a portion of the basin volume. Thus, the volume of a filtration process used in determining contact time will be the volume of filtration basin beneath the minimum water level minus the volume occupied by the filter media and underdrain. The peak hourly flow rate is the maximum quantity of water passing through the process during a one-hour period within the 24-hour duration. The peak hourly flow rate should be determined from the system operation records.

For example, suppose a unit process within a disinfection segment is composed of a flocculation basin with unbaffled conditions. Thus, from Table 3-2 the T_{10}/T value is 0.1. In this example the volume of the basin is 969,500 gallons and the peak hourly flow rate is 10,651 gpm. The TDT can be calculated as follows:

$$\text{TDT} = V/Q = 969{,}500 \text{ gallons} / 10{,}651 \text{ gpm} = 91.0 \text{ minutes}$$

If the theoretical detention time for the unit process is 91.0 minutes, then the resulting contact time is 9.1 minutes. That is,

$$T_{10} \text{ (contact time)} = 91.0 \text{ minutes} * 0.1 = 9.1 \text{ minutes}$$

If the disinfection segment consists of several unit processes, then the theoretical detention time should be calculated for each unit process. The T_{10} should be determined

from the TDT and baffling factor for each unit process in the segment. The segment T_{10} is the sum of the T_{10}s from each unit process.
The following list is a summary of the steps required to determine the contact time with baffling factors:

- Determine peak hourly flow rate, Q, based on operation records;
- Determine the volume of each unit process;
- Calculate the Theoretical Detention Time, where TDT = V/Q;
- Determine the Baffling Factor based on the unit processes baffling conditions;
- Calculate the Contact Time, where $T_{10} = TDT * T_{10}/T$; and
- Determine the segment T_{10} by summing the T_{10}s of the unit processes in the segment.

Determining Contact Time Using a Tracer Study

A tracer study uses a chemical tracer to determine the detention time of water flowing through a unit process, segment, or system as stated earlier in Chapter 3. Typical chemical tracers include chloride ions, fluoride ions, and Rhodamine WT. Ideally, the selected tracer chemical should be readily available, conservative, easily monitored, and acceptable for use in potable water supplies. By conservative it is meant that the tracer is not consumed or removed during treatment. Fluoride ions can generally be used in lower concentrations than chloride because they are typically present in lower concentrations in the water. Rhodamine is a fluorescent tracer that if selected must be used following guidelines presented earlier in this appendix. Selection of a particular chemical tracer may depend on the unit processes and the salt concentrations present in the water. If a tracer study is needed in order to find T_{10}, a water system should consult the latest tracer study guidance from the state.

The tracer chemical should be added at the same points in the treatment train as the disinfectant to be used in the CT calculations, since it will be used to determine T_{10} for the disinfection segment. Two common methods of tracer addition are the step-dose method and the slug-dose method. In the step-dose method, the tracer chemical is injected at a constant dosage and the endpoint concentration is monitored. To determine a 90 percent recovery for the tracer, endpoint sampling should continue until the tracer concentration reaches a steady-state level. With the slug-dose method, a large dose of tracer chemical is injected, instantaneously. An effective way to achieve instantaneous addition is to use a gravity-fed tube to release the single dose. The tracer concentration is monitored at the endpoint, until the entire dose has passed through the system. Unlike the step-dose method, a mass balance is required to determine whether the entire tracer dose was recovered. Additional mathematical manipulation is required to determine T_{10} from the concentration versus time profile.

Data from tracer studies should be summarized in tables of time and residual concentration. These data are then analyzed to determine the detention time, T_{10}, to be used in calculating CT. Tracer test data from either the step or slug-dose method can be evaluated graphically, numerically, or by a combination of these techniques. The graphical method of evaluating step-dose test data involves plotting a graph of dimensionless concentration (C/C_0) versus time and reading the value for T_{10} directly from the graph at the appropriate dimensionless concentration. C_0 is the dosage concentration injected into the system and C is the tracer concentration at any time during the test. Alternatively, the data from step-dose tracer studies may be evaluated numerically by developing a semi-logarithmic plot of the dimensionless data (see Section D.1). 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 T_{10} value, assuming there is a good statistical fit. That is, the data points are not too scattered and the line drawn is a reasonable approximation of the data points. The slug-dose method, however, requires data to be analyzed by converting it to the mathematically equivalent step-dose data and using techniques discussed above for step-dose data evaluation. This procedure is more complicated and the details to evaluate the slug-dose data are found in Section D.1.7.2.

Several other considerations when conducting a tracer study are the temperature, flow rates, and water levels in the basins. Detention time may be influenced by differences in water temperature within the system. For plants with potential for thermal stratification, additional tracer studies are suggested under the various seasonal conditions that are likely to occur. The contact times determined by the tracer studies under the various seasonal conditions should remain valid as long as no physical changes are made to the mixing basin(s) or storage reservoir(s).

Detention time is proportional to flow. However, it is not always a linear relationship. Therefore, it is best to conduct tracer studies over a range of flow rates typical of the disinfectant segment. Flow rates may vary throughout the treatment system as the water travels through the unit processes. The goal of the tracer tests is to determine an accurate portrayal of the contact time within each unit process. Thus, it is important to select the flows carefully. Ideally, tracer tests should be performed for at least four flow rates that span the entire range of flow for the section being tested. The flow rates should be separated by approximately equal intervals to span the range of operation. The four flow rates should be one near the 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 section.

It may not be practical for all systems to conduct studies at four flow rates. The number of tracer tests that are practical to conduct is dependent on site-specific restrictions and resources available to the system. Systems with limited resources can conduct a minimum of one tracer test for each disinfectant segment at a flow rate of not less than 91 percent of the highest flow rate experienced at that section. If only one tracer test is performed, the detention time determined by the test may be used to provide a conservative estimate in CT calculations for that section for flow rates less than or equal to the tracer test flow rate. See Section D.1.1 for calculating a T_{10} at a different flow rate than the tracer test flow rate.

Tracer studies should be conducted during periods when the water level is maintained in accordance with normal plant operation. For basins that have constant water level, the recommended procedure is to maintain the basin's water level at or slightly below, but not above, the normal level. For basins that are operated at extreme water levels, particularly clearwells, disinfectant contact time should not be used to compute the total CT value because reliable detention time is not provided for disinfection. The recommended water levels during the tracer study for several unit processes are summarized in Table D-6.

Table D-6. Recommended Water Levels during a Tracer Study

Unit Process	**Recommended Water Levels**
Sedimentation Basins – Operating at a Near Constant Level	Water levels at or slightly below, but not above, the normal minimum operating level.
Clearwell and Storage Tanks	Conduct study during a period when tank level is falling.
Clearwells Operated with Extreme Variation in Water Level	Does not provide a reliable detention time. However, the system may install a weir to ensure a minimum water level and provide a reliable detention time.
Storage Reservoirs – Experiencing Seasonal Variations	Perform studies during various seasonal conditions by using representative water levels for each seasonal condition.

As stated earlier in Chapter 3, the tracer must be added at the same locations in the plant where the disinfectant is added. The duration of tracer addition should be sufficient to approach steady-state conditions which is usually two to three times the theoretical detention time. Tracer dosage should be in sufficient concentration to easily monitor the concentration in the effluent. If there is low background tracer concentration, the dosage can be fairly low (i.e., in the range of 1 to 2 mg/L for fluoride ions). However, for basins with serious short-circuiting, substantially larger dosages are necessary to detect the tracer and to define the effluent tracer profile adequately. The test procedure for determining the Contact Time with a tracer study is generally as follows:

- The system determines the flow rate or rates to be used in the study.
- The system selects the tracer chemical and determine the raw water background concentration of the tracer chemical. The background level is needed to both determine the quantity of chemical to feed and to evaluate the data properly.
- The system determines the tracer addition locations, plan the sample collection logistics and frequency, and determine the appropriate tracer dosage. Sampling frequencies depend on the size of the basin—the larger the basin the easier it is to obtain an adequate profile with less frequent sampling. Small basins need more frequent sampling.
- The system conducts the tracer test using either the step-dose or slug-dose methods.
- The system compiles and analyzes the data.
- The system calculates T_{10}.

Additional references for information on tracer studies and details concerning how to conduct one are listed below:

- Hudson, H.E., Jr. 1975. "Residence Times in Pretreatment." *J. AWWA*. January:45-52.
- Hudson, H.E., Jr. 1981. *Water Clarification Processes: Practical Design and Evaluation*. Van Nostrand Reinhold Company, New York.
- Levenspiel, O. 1972. *Chemical Reaction Engineering*, second edition. John Wiley and Sons, New York.
- Marske, D.M. and J.D. Boyle. 1973. "Chlorine Contact Chamber Design – A Field Evaluation." *Water and Sewage Works*. January:70-77.
- Missouri Department of Natural Resources, Public Drinking Water Program. 1991. *Guidance Manual for Surface Water System Treatment Requirements.*
- Teefy S.M. and P.C. Singer. 1990. "Performance and Analysis of Tracer Tests to Determine Compliance of a Disinfection Scheme with the SWTR." *J. AWWA*. 82(12):88-98.
- Thirumurthi, D. 1969. "A Breakthrough in the Tracer Studies of Sedimentation Tanks." *J. WPCF*. R405-R418. November.
- TNRCC. 1995. *Public Water Supply Technical Guidance Manual*, Chapt. 27, Texas Natural Resources Conservation Commission, Austin, TX.

APPENDIX E. USING THE REGRESSION METHOD

E.1 Using the Regression Method to Find $CT_{3\text{-log, }Giardia}$ When Using Chlorine

Plants may choose to use the Regression Method to determine the value of $CT_{3\text{-log, Giardia}}$. when using free chlorine. This method is useful to calculate the $CT_{3\text{-log, Giardia}}$ for a long historical data set of pH, temperature and residual disinfection concentrations. Unlike the Approximation Method, the operator is not required to manually look up values in a table for each day of the historical record. (Recall that systems that are required to create a disinfection profile must do so fcr one to three years of daily data.) Instead of having to look up CT values for each day in the record, the Regression Method allows the operator to simply use a formula that is a function of pH, temperature and residual disinfection concentration. Using this formula in a spreadsheet should greatly reduce the time required to calculate the disinfection profile. The following section presents the equations and demonstrates its utility in calculating $CT_{3\text{-log,, Giardia}}$.

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 SWTR Guidance Manual. The equations below can be used to directly compute CT values for chlorine inactivation:

$$CT = (0.353*I)(12.006+e^{(2.46-0.073*temp+0.125*C+0.389*pH)}) \qquad \textbf{Equation 3-3}$$

(for temperature < 12.5 °C)

$$CT = (0.361*I)(-2.261+e^{(2.69-0.065*temp+0.111*C+0.361*pH)}) \qquad \textbf{Equation 3-4}$$

(for temperature ≥ 12.5 °C)

Where:

I = 3, the number of logs inactivation required
Temp= temperature in degrees Celsius
C = residual chlorine concentration in mg/L
pH = the negative log concentration of hydrogen ion
e = 2.7183, the base for the natural logarithm

The SWTR did not include log inactivation credit for waters with pH greater than 9.0. As such, if the plant operates at a pH level higher than 9.0, the Approximation Method described above should be used to calculate the $CT_{3\text{-log, Giardia}}$. Systems should apply State requirements, however, in the absence of state regulations, the utility should default to using CT values calculated for a pH less than 9.0.

Procedure:

- Determine whether the temperature is above or below 12.5 °C to select between Equations 3-3 and 3-4 to directly compute the CT values for *Giardia* inactivation. using chlorine (If using a spreadsheet an "IF" statement can be used to select the correct equation based on the temperature.)
- Use daily temperature (°C,) residual disinfectant concentration (mg/L), pH, and I = 3 in the appropriate equation to calculate the $CT_{3\text{-log, Giardia}}$

Example:

Find the value of $CT_{3\text{-log, Giardia}}$ for a water temperature of 11°C, a pH of 8.2, and a residual of 2.5 mg/L for a plant that is using free chlorine as the disinfectant.

Using Equation 3-3 since temperature is less than 12.5 °C, then:

$$CT = (0.353I)(12.006+e^{(2.46-0.073\text{temp}+0.125C+0.389\text{pH})})$$

$$CT = (1.059)(12.006+e^{(2.46-0.073*11+0.125*2.5+0.389*8.2)})$$

$$CT = (1.059)(12.006+e^{(2.46-.803+.3125+3.189)})$$

$$CT = (1.059)(12.006+e^{(5.1585)})$$

$$CT = (1.059)(12.006+173.90)$$

$$CT = 196.87$$

The $CT_{3\text{-log, Giardia}}$ of 197 as calculated by the Regression Method more closely approximates the actual $CT_{3\text{-log, Giardia}}$ than the values calculated using the Approximation Method that estimates the $CT_{3\text{-log, Giardia}}$ at 234 (see Section 3.5).

E.2 Calculation of Estimated Log Inactivation Using the Regression Method

Required CT values for 3-log inactivation of *Giardia* using chlorine can be determined using CT tables as provided in Appendix C, or can be calculated using disinfectant-specific equations, such as the chlorine equations developed by Smith et al (1995). These equations predict required CT values for 3-log inactivation that are greater than or equal to the original values in the SWTR over the entire range of independent variables covered in the *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources* (AWWA, 1991). Using these equations, CT values for inactivation of *Giardia* using chlorine can be computed.

- For Temperature < 12.5 °C:
  $CT = (0.353\,I)(12.006+e^{(2.46-0.073\text{ temp}+0.125\text{ C}+0.389\text{ pH})})$
- For Temperature ≥ 12.5 °C:
  $CT = (0.361\,I)(-2.261+e^{(2.69-0.065\text{ temp}+0.111\text{ C}+0.361\text{ pH})})$

Where:

I = 3, log removal of *Giardia*

e = 2.7183, the base of the natural logarithm

C = chlorine residual concentration (mg/L)

Temp = temperature in °C

Once the CT required for inactivation of 3-log *Giardia* and 4-log viruses is determined, the actual log inactivation for that segment can be estimated as:

$$\text{Estimated Segment Log Inactivation of } \textit{Giardia} = 3.0 * CT_{\text{actual}} / CT_{\text{3-log, Giardia}}$$

$$\text{Estimated Segment Log Inactivation of viruses} = 4.0 * CT_{\text{actual}} / CT_{\text{4-log, virus}}$$

The total plant estimated log inactivation due to chemical disinfection is:

$$\text{Total Plant Estimated Inactivation due to chemical disinfection} = \Sigma \text{ segment inactivation}$$

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