

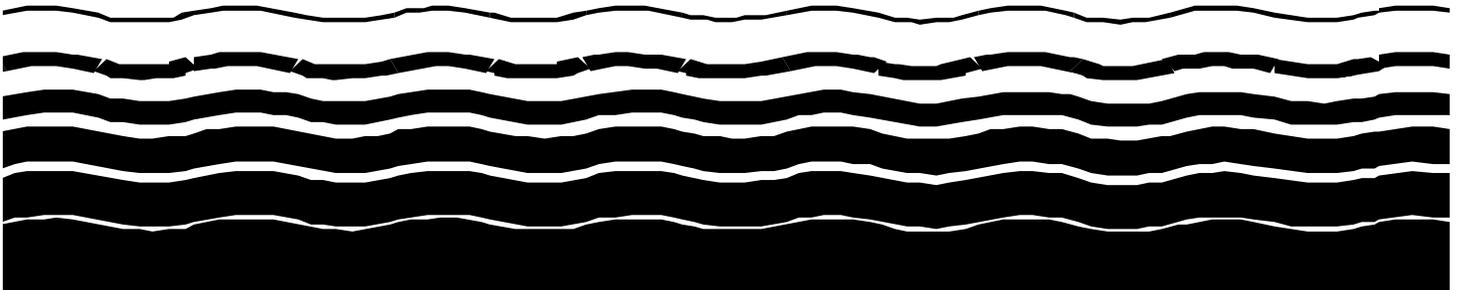


United States
Environmental Protection
Agency

Office of Water
(4607)

EPA 815-R-99-015
August 1999

Microbial and Disinfection Byproduct Rules Simultaneous Compliance Guidance Manual



DISCLAIMER

This manual describes many of the potential conflicts that may arise as systems comply with the rules currently being developed by the U.S. Environmental Protection Agency (EPA), known collectively as the Microbial and Disinfection Byproduct (M-DBP) cluster of rules.

This document was issued in support of EPA regulations and policy initiatives involving development and implementation of the Information Collection Rule, Disinfectants and Disinfection Byproduct Rule, Enhanced Surface Water Treatment Rule, and Ground Water Rule. This document also discusses simultaneous compliance issues involving the Lead and Copper Rule and the Total Coliform Rule.

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ACKNOWLEDGMENTS

The guidance manual has been reviewed in accordance with the EPA's technical and administrative review policies and approved for publication. The EPA gratefully acknowledges the assistance of the members of the Microbial and Disinfection Byproducts Federal Advisory Committee and Technical Work Group for their comments and suggestions to improve this document. EPA also wishes to thank the representatives of drinking water utilities, researchers, and the American Water Works Association for their review and comment, as well as the following individuals:

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ACRONYMS

AIDS	Acquired immune deficiency syndrome
AOB	Ammonia-oxidizing bacteria
AOC	Assimilable organic carbon
AWWA	American Water Works Association
AWWARF	AWWA Research Foundation
BAT	Best available technology
BDOC	Biodegradable dissolved organic carbon
Cl ₂	Chlorine
ClO ₂	Chlorine dioxide
CMA	Chlorine Manufacturers Association
CPE	Comprehensive Performance Evaluation
CT	Residual disinfectant concentration (in mg/L) multiplied by the contact time (in min); a measure of disinfection effectiveness
DBAA	Dibromoacetic Acid
DBPs	Disinfection byproducts
DBPR	Disinfectants and Disinfection Byproducts Rule
D/DBPs	Disinfectants/disinfection byproducts
DNA	Deoxyribonucleic acid
DOC	Dissolved organic carbon
EBCT	Empty bed contact time
EPA	U.S. Environmental Protection Agency
ESWTR	Enhanced Surface Water Treatment Rule
FPA	Flavor profile analysis
GAC	Granular activated carbon
GWR	Ground Water Rule
HAAs	Haloacetic acids
HAA5	Five Haloacetic acids (the sum of mono-, di-, and trichloroacetic acids and mono- and dibromoacetic acids)
HOCl	Hypochlorous Acid
HPC	Heterotrophic plate count
ICR	Information Collection Rule
IESWTR	Interim Enhanced Surface Water Treatment Rule
LCR	Lead and Copper Rule
LOX	Liquefied oxygen
LT1ESWTR	Long-Term 1 ESWTR
LT2ESWTR	Long-Term 2 ESWTR
MCC	Motor control center
MCLs	Maximum contaminant levels
MCLGs	Maximum contaminant level goals
M-DBP	Microbial and disinfection byproducts

mg/L	Milligrams per liter
MIB	2- methylisoborneol
mm	millimeters
mpy	mils per year
MRDLs	Maximum residual disinfectant levels
MRDLGs	Maximum residual disinfectant level goals
MWCO	Molecular weight cutoff
MWD	Metropolitan Water District of Southern California
NF	Nanofiltration
nm	Nanometer
NODA	Notice of Data Availability
NOM	Natural organic matter
NTU	Nephelometric turbidity units
PAC	Powdered activated carbon
PODR	Point of diminishing return
POE	Point-of-entry
POU	Point-of-use
PWS	Public Water System
RNA	Ribonucleic acid
SCCRWA	South Central Connecticut Regional Water Authority
SDS	Simulated distribution system
SDWA	Safe Drinking Water Act
SUVA	Specific ultraviolet absorbance (UV_{254}/DOC in L/mg-m)
SWTR	Surface Water Treatment Rule
TCAA	Trichloroacetic Acid
TCR	Total Coliform Rule
THM	Trihalomethane
THMFP	Trihalomethane formation potential
TOC	Total organic carbon
TOX	Total organic halides
TTHMs	Total trihalomethanes
UF	Ultrafiltration
UV	Ultraviolet
VFDs	Variable frequency drives
µm	Micrometer

1. INTRODUCTION

The Safe Drinking Water Act (SDWA) Amendments of 1996 require the U.S. Environmental Protection Agency (EPA) to develop several new drinking water regulations. A group of these regulations, known as the Microbial and Disinfection Byproduct (M-DBP) Rules, addresses two key public health concerns: acute threats from microbial contamination and chronic threats from disinfectant residuals and byproducts of disinfection.

EPA recognizes that some Public Water Systems (PWSs) may encounter technological conflicts when trying to meet the goals of the different regulations. Because each of these rules has equivalent stature in the law and requires simultaneous compliance, the goal of one rule cannot be undermined in favor of the goal of another. Simultaneous compliance issues may present a significant challenge to PWSs.

This guidance manual describes many of the potential conflicts that may arise as systems comply with these rules, and provides possible solutions and approaches to resolve these conflicts. The remainder of this chapter provides a brief overview of the major M-DBP Rules, an explanation of how conflicts between some of these regulations can occur, an overview of the use of disinfectants in water treatment, and a discussion of the goals and contents of this manual.

1.1 Regulatory Context

The application of chemical disinfection and filtration to drinking water in the United States has successfully controlled the transmission of disease-causing organisms (pathogens) through drinking water supply systems. Waterborne diseases, such as typhoid and cholera, have been virtually eliminated as a result. For example, in Niagara Falls, New York, between 1911 and 1915, the number of typhoid-related deaths dropped from 185 out of 100,000 people to nearly zero after introduction of filtration and disinfection to the city's water supply (White, 1992). Nevertheless, the United States is still vulnerable to waterborne disease outbreaks, as demonstrated by the 1993 Milwaukee *Cryptosporidium* outbreak.

While disinfection (or the inactivation of infectious organisms) will continue to be a critical element of drinking water treatment, recent research confirms that disinfection can create health risks from disinfectant residuals and disinfection byproducts (DBPs). As such, pursuant to the 1996 SDWA Amendments, EPA is developing interrelated regulations (i.e., the M-DBP cluster of rules) to control health risks from microbial pathogens and disinfectants/disinfection byproducts (D/DBPs). The following four sets of rules address, or will address, disinfection practices for the control of pathogens and DBPs:

- **Information Collection Rule (ICR).** On May 14, 1996, EPA promulgated a final ICR that requires PWSs to submit data to EPA on source water quality, byproduct formation, and drinking water treatment plant design and operations (61 *FR* 24353). This information will be used to support development of the remaining M-DBP Rules.
- **Disinfectants and Disinfection Byproducts Rule (DBPR).** This rule, being promulgated in two phases, will limit the amount of disinfectant residual and DBPs allowed in the distribution system. EPA promulgated the Stage 1 DBPR on December 16, 1998 (63 *FR* 69390). This rule is applicable to all community water systems (CWSs) and non-transient non-community water systems (NTNCWSs) that add a disinfectant, and transient non-community water systems (TNCWSs) that use chlorine dioxide. EPA expects to propose the Stage 2 DBPR in the fall of 2000, with promulgation scheduled for May 2002.
- **Enhanced Surface Water Treatment Rule (ESWTR).** This rule, being promulgated in two phases, will amend the existing Surface Water Treatment Rule (SWTR) and will include new requirements for improved particle removal in drinking water treatment plants. EPA promulgated the Interim ESWTR (IESWTR) on December 16, 1998, which generally applies only to systems serving at least 10,000 people (63 *FR* 69477). The Long-Term 1 ESWTR will address systems serving fewer than 10,000 people. The Long-Term 2 ESWTR will incorporate ICR data and may include site-specific treatment requirement. These rules are scheduled to be promulgated in November 2000 and May 2002, respectively.
- **Ground Water Rule (GWR).** This rule, which is still in the proposal development phase, will address microbial contamination in drinking water systems using ground water as their source. This rule will apply to the approximately 180,000 PWSs using ground water not under the direct influence of surface water and will specify the appropriate use of disinfection and encourage the use of best management practices (BMPs) to assure public health protection. EPA expects the GWR to be promulgated in November 2000.

Table 1-1 lists the dates for M-DBP regulatory activities.

Table 1-1. Key Dates for M-DBP Regulatory Activities

Date	Regulatory Action
November 2000	Promulgate Ground Water Rule (GWR)
November 2000	Promulgate Long-Term 1 Enhanced Surface Water Treatment Rule (LT1ESWTR)
May 2002	Promulgate Long-Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR)
May 2002	Promulgate Stage 2 Disinfection Byproducts Rule (Stage 2 DBPR)

Although a PWS may be in compliance with current SDWA regulations, it may encounter compliance issues as it begins to implement the M-DBP Rules. Simplistically, the regulations

may conflict because PWSs will have to increase/upgrade disinfection to reduce the risk of microbial contamination in finished water, while at the same time minimize the formation of DBPs. For example, enhanced coagulation lowers pH which increases the formation of haloacetic acids (HAAs), while enhanced softening raises pH which promotes trihalomethane (THM) formation. A PWS can raise the pH of water through the treatment process, which favors DBP precursor removal through removal of organic carbon, but may also reduce the disinfection effectiveness of free chlorine. Similarly, rules designed to ensure chemical stability can compete with rules designed to protect against byproduct risk. For example, removal of organic carbon under the DBPR may reduce the chemical stability of the treated water as required by the Lead and Copper Rule (LCR).

These two examples highlight potential conflicts that could occur as PWSs attempt to comply with all applicable regulations. A possible solution to the problems in these two examples might involve pH adjustments to the water prior to leaving the plant. Implementation of this solution means the PWS must recognize the competing demands in complying with the new rules and take action to eliminate the potential for noncompliance among these and other SDWA rules.

Since the DBPR and IESWTR are the most likely to cause conflicts, either with each other, or with other drinking water regulations, this guidance manual focuses on these two regulatory packages.

1.1.1 DBPR

The Stage 1 DBPR regulates the public health risks associated with DBPs and disinfectant chemicals in drinking water. The rule lowers the only pre-existing Maximum Contaminant Level (MCL); establishes new MCLs, Maximum Contaminant Level Goals (MCLGs), Maximum Residual Disinfectant Levels (MRDLs), and Maximum Residual Disinfectant Level Goals (MRDLGs); and extends MCLs to all system sizes. The rule also requires enhanced coagulation or enhanced precipitative softening for certain systems. Table 1-2 shows the MRDLGs and MRDLs for chlorine, chloramines, and chlorine dioxide. Table 1-3 summarizes MCLGs and MCLs for the various primary drinking water contaminants related to disinfection. In some cases, a treatment technique is prescribed in lieu of an MCL where it is not economically or technically feasible to determine compliance with a numeric standard. Under the Stage 2 DBPR, EPA will reevaluate MCLs for total trihalomethanes (TTHMs), five haloacetic acids (HAA5), and other DBPs.

Table 1-2. National Primary Drinking Water Standards for Disinfectants

Disinfectant	MRDLG (mg/L)	MRDL (mg/L)
Chlorine+	4 (as Cl ₂)	4.0 (as Cl ₂)
Chloramines++	4 (as Cl ₂)	4.0 (as Cl ₂)
Chlorine Dioxide	0.8 (as ClO ₂)	0.8 (as ClO ₂)

+ Measured as free chlorine.

++ Measured as total chlorine.

Table 1-3. Standards Related to Disinfectants and Disinfection Byproducts

Compound	MCLG (mg/L)	MCL (mg/L)	Potential Health Effects
Total Coliform Rule (TCR) and SWTR Standards			
<i>Giardia lamblia</i>	Zero	TT	Gastroenteric Disease
<i>Legionella</i>	Zero	TT	Legionnaire's Disease
Heterotrophic Plate Count	N/A	TT	Indicates Water Quality and Effectiveness of Treatment
Total Coliform	Zero	< 5% positive ⁺	Indicates Gastroenteric Pathogens
Turbidity	N/A	TT	Interferes with Disinfection
Viruses	Zero	TT	Gastroenteric Disease
DBPR Standards for DBPs			
Chloroform	Zero	See TTHMs	Cancer, Liver, Kidney, and Reproductive Effects
Dibromochloromethane	0.06	See TTHMs	Nervous System, Liver, Kidney, Reproductive Effects
Bromodichloromethane	Zero	See TTHMs	Cancer, Liver, Kidney, and Reproductive Effects
Bromoform	Zero	See TTHMs	Cancer, Nervous System, Liver and Kidney Effects
TTHMs	N/A	0.10 (I) 0.080 (S1)	Cancer and Other Effects
Dichloroacetic Acid	Zero	See HAA5	Cancer, Reproductive, Developmental Effects
Trichloroacetic Acid	Zero	See HAA5	Liver, Kidney, Spleen, Developmental Effects
HAA5	N/A	0.060 (S1)	Cancer and Other Effects
Bromate	Zero	0.010 (S1)	Cancer
Chlorite	0.8	1.0 (S1)	Developmental and Reproductive Effects

Source: AWWA Internet, 1997.

I = 1979 Interim, only applies to public water systems serving 10,000 people or more.

S1 = Stage 1 DBPR

TT = Treatment technique requirement

+ = No more than one positive if < 40 samples/month

1.1.2 IESWTR

The SWTR of 1989 established the goals of microbial integrity and focused specifically on reducing risks from *Giardia* cysts and viruses in surface water and ground water under the direct influence of surface water. The IESWTR does not change these goals. To meet these goals, the SWTR established treatment removal efficiencies for *Giardia* cysts and viruses in filtered and unfiltered surface water systems (AWWA, 1991). Table 1-4 summarizes these log removal/inactivation requirements. EPA also provided guidance for systems with poorer quality source water to evaluate the need for additional treatment.

Table 1-4. Log Removal/Inactivation through Filtration and Disinfection Required Under the 1989 SWTR

Process	Log Removal Requirements	
	<i>Giardia</i> Cysts	Viruses
Total log removal/inactivation required	3.0	4.0
• Conventional sedimentation/filtration credit ¹	2.5	2.0
• Disinfection inactivation required	0.5	2.0
• Direct filtration credit ¹	2.0	1.0
• Disinfection inactivation required	1.0	3.0
• Slow sand filtration credit ¹	2.0	2.0
• Disinfection inactivation required	1.0	2.0
• Diatomaceous earth credit ¹	2.0	1.0
• Disinfection inactivation required	1.0	3.0
• No filtration	0.0	0.0
• Disinfection inactivation required	3.0	4.0

Source: AWWA, 1991.

¹ Credits for guidance only. The State may allow a different credit.

The IESWTR adds requirements for control of *Cryptosporidium* and sets an MCLG of zero for this pathogen. The IESWTR applies to public water systems that use surface water or ground water under the direct influence of surface water (GWUDI) and serve at least 10,000 people. In addition, States are required to conduct sanitary surveys for all surface water and GWUDI systems, including those that serve fewer than 10,000 people (63 FR 69477). Five treatment alternatives for *Cryptosporidium* were proposed by EPA in its 1994 proposed IESWTR. One alternative required a 2-log removal of *Cryptosporidium* oocysts by filtration with pretreatment. In the 1997 IESWTR Notice of Data Availability (NODA), EPA recognized the limited data available and solicited comments. Most commentors opposed greater log removal requirements for *Cryptosporidium* due to a lack of understanding of dose-response relationships, treatment effectiveness, site-specific occurrence data, and analysis justifying higher treatment costs (USEPA, 1997b).

The IESWTR requires that all surface water systems required to filter, using conventional filtration treatment or direct filtration, achieve a turbidity performance criterion of 0.3 Nephelometric Turbidity Units (NTUs), 95 percent of the time within any one-month period, based on four-hour sampling intervals in the system's combined filter effluent water. In addition, the turbidity level of a system's combined filtered effluent at each plant must at no time exceed 1 NTU, based on samples taken every four hours. Requirements for technologies such as diatomaceous earth filtration and slow sand filtration remain the same (i.e., as regulated by the SWTR).

1.2 Use of Disinfectants

As noted previously, disinfection is a critical element in the elimination of pathogens from drinking water. Disinfection inactivates disease-causing pathogens, such as bacteria, protozoa, and viruses, that can affect humans by causing illnesses such as diarrhea and fever or, in the most extreme cases, death. Infection and disease can occur following even one-time exposure to a pathogen in drinking water.

Although disinfection has reduced the risk of people contracting an illness through public drinking water systems, one of the side effects of disinfection is the formation of DBPs. DBPs are formed when disinfectants react with organic and inorganic compounds in the water. The adverse effects of DBPs are generally associated with chronic (i.e., long-term) exposure. However, some DBPs pose potential acute, or short-term risks, to consumers.

Chlorine is, by far, the most commonly used disinfectant in the United States and is used as a post-treatment disinfectant in 68 percent of all surface water treatment plants (USEPA, 1997b). Chlorine however, reacts with natural organic matter (NOM) and bromide to form halogenated compounds such as THMs, HAAs, and halo ketones.

In addition to chlorine, other disinfectants and disinfection techniques, such as chloramines, chlorine dioxide, and ozone, are also used in the United States. These different disinfectants have various levels of effectiveness in eliminating disease-causing pathogens. For example, while chlorine is more effective than chlorine dioxide at inactivating viruses, the opposite is true for the inactivation of *Giardia* cysts. Ozone is better than both chlorine and chlorine dioxide at inactivating viruses and *Giardia* cysts, while chloramines are less effective than chlorine and chlorine dioxide at inactivating both organisms (AWWA, 1991).

Various disinfectants react with NOM to form different DBPs. While chlorine predominantly produces halogenated organics, ozone produces aldehydes, ketones, and inorganic byproducts. Chlorine dioxide produces chlorate and chlorite, while ozone produces bromate when used in the presence of bromide. The type and amount of DBPs formed during treatment not only depends on the type and dose of disinfectant used, but also on water quality, treatment

sequences, and environmental factors such as temperature, pH, and contact time (Bellar et al., 1974; Rook, 1974; McGuire et al., 1990).

Disinfectants and DBPs of current interest in drinking water treatment, based on limited occurrence and health effects data, include the following:

- Halogenated organic byproducts
 - THMs
 - HAAs
- Inorganic byproducts
 - Bromate
 - Chlorite
- Disinfection residuals
 - Chlorine
 - Chloramines
 - Chlorine dioxide

In addition to inactivating pathogens in the source water, disinfectants are also used as oxidants in drinking water treatment to:

- Control nuisance Asiatic clams and zebra mussels
- Oxidize iron and manganese
- Maintain a residual to prevent biological regrowth in the distribution system
- Remove taste and odors
- Improve coagulation and filtration efficiency
- Prevent algal growth in sedimentation basins and filters
- Act as indicators of distribution system integrity.

These additional uses for disinfectants can compound the problem of DBP formation since different types of DBPs are lowered or increased with different types of disinfectants/oxidants. In addition, DBP control in the distribution system might necessitate further action at or beyond the treatment plant limits.

Given the range of disinfectants available, each having unique inactivation efficiencies and producing a variety of DBPs, PWSs will have to evaluate the risk-risk tradeoffs associated with each of these alternative disinfectants. The rules will force the PWSs to figure out the appropriate technology/engineering solutions in order to meet all of their requirements. It is expected that alternative disinfectants will play an increasingly important role in the efforts of utilities to meet treatment standards. PWSs will have to make complicated technological and economic decisions to comply with the different drinking water regulations.

1.3 Goal of Manual

The goal of this manual is to provide information that PWSs can use to address operational problems which may result from their efforts to implement the Stage 1 DBPR and the IESWTR. Co-implementation of these new rules can lead to conflicts, potentially resulting in noncompliance with either of these regulations or with pre-existing regulations, such as the LCR and the TCR. This manual identifies many of the known conflicts that may occur between these rules and provides recommendations for resolving them. In conjunction with promulgation of the IESWTR and Stage 1 DBPR, EPA recently published several additional guidance manuals that may also assist PWSs in resolving these potential conflicts. These references include the following:

- Disinfection Profiling and Benchmarking Guidance Manual (1999)
- Alternative Disinfectants and Oxidants 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)
- Conducting Sanitary Surveys of Public Water Systems; Surface Water Systems and Ground Water Under the Direct Influence (GWUDI) of Surface Water Systems Guidance Manual (1999)
- Guidance Manual for Enhanced Coagulation and Enhanced Precipitative Softening (1999).

1.4 Organization of Manual

This manual is organized to provide a tool for PWSs, States, and others to consult when evaluating simultaneous compliance issues and alternatives. Several case studies are presented throughout this document to better illustrate how the guidance can be put into practice. The remaining chapters of this manual are organized as follows:

- **Chapter 2** provides general background information on pathogen inactivation and the role of disinfectants in DBP formation. This chapter also describes the Stage 1 DBPR and the IESWTR and some of the known compliance issues.
- **Chapter 3** describes the difficulties a PWS may have in simultaneously meeting regulatory requirements of the Stage 1 DBPR and IESWTR and addresses specific simultaneous compliance issues.
- **Chapter 4** describes the difficulties a PWS may have in simultaneously meeting regulatory requirements of the M-DBPR and LCR and addresses specific simultaneous compliance issues.

- **Chapter 5** describes the difficulties a PWS may have in simultaneously meeting regulatory requirements of the M-DBPR and TCR and addresses specific simultaneous compliance issues.
- **Chapter 6** identifies operational issues associated with implementation of treatment plant modifications and enhancements to achieve simultaneous compliance.
- **Chapter 7** lists the references used in the development of this report.

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2. BACKGROUND AND SPECIFIC REGULATORY REQUIREMENTS

Rook's discovery of trihalomethanes in drinking water in 1972 both fostered and underlined the perception that many drinking water supplies are contaminated and that the nation's drinking water supply is at risk for future contamination (Rook, 1974). At the time, the identification of these potential carcinogens was one of the most important factors leading to the enactment of the original 1974 SDWA. Since then, regulatory agencies have been charged with developing health risk assessments as a means of guiding risk management.

This chapter discusses the inactivation of pathogens and the role of disinfectants in DBP formation. This discussion provides a brief overview of waterborne disease-causing pathogens, methods of inactivating these pathogens using disinfectants, DBP formation potential and control strategies. In addition, a summary of compliance issues related to the regulatory requirements of the Stage 1 DBPR and the IESWTR is included.

2.1 Inactivation of Pathogens

Although the epidemiological relationship between water and disease was suggested as early as the mid-1850s, it was not accepted that water could be a carrier of disease-producing organisms until the establishment of Pasteur's germ theory of disease in the mid-1880s. Cholera was one of the first diseases to be recognized as capable of being waterborne. During the mid-1880s, London experienced the "Broad Street Well" cholera epidemic and Dr. John Snow conducted his now famous epidemiological study (Culp/Wesner/Culp, 1986). He concluded that the source of the contamination was a soldier who had contracted the infection while stationed in India. Solutions for eliminating the threat of waterborne disease evolved years later with the introduction of filtration and disinfection. Since then, filtration and disinfection have dramatically reduced the transmission of waterborne diseases in the United States. However, while the threat of waterborne disease has been drastically reduced since the early 1900s, it has not been entirely eliminated.

2.1.1 Recent Waterborne Outbreaks

Within the past 25 years, pathogens such as *E. coli*, *Giardia lamblia*, *Cryptosporidium parvum*, and *Legionella pneumophila* have been involved in numerous documented waterborne disease outbreaks. Enteropathogenic *E. coli* and *Giardia lamblia* were first identified as etiological agents responsible for waterborne outbreaks in the 1960s. In 1975, a large waterborne disease outbreak at Crater Lake National Park in Oregon was attributed to *E. coli* bacteria (Craun, 1981). Between 1972 and 1981, 50 waterborne outbreaks of giardiasis

occurred nationwide involving about 20,000 reported cases (Craun and Jakubowski, 1986). The biggest documented outbreak in the United States occurred in 1993 in Milwaukee, where an estimated 403,000 people became ill and 4,400 people were hospitalized because of exposure from *Cryptosporidium*. This was also the first recorded infection in humans as a result of exposure to *Cryptosporidium* in water.

White (1992) considered the two most significant causes of illnesses attributed to public drinking water supplies to be source water contamination and deficiencies in treatment. About 46 percent of the outbreaks in public water systems have been related to these two particular problems, with 92 percent of individual illnesses caused by these two problems. The 1993 *Cryptosporidium* outbreak was associated with a deterioration of raw water quality and a simultaneous decrease in the effectiveness of the coagulation-filtration process, which led to an increase in the turbidity of the treated water and inadequate removal of *Cryptosporidium* oocysts (Kramer et al., 1996; MacKenzie et al., 1994).

Levy et al. (1998), using 1995 through 1996 Centers for Disease Control (CDC) data, concluded that only three of the ten reported outbreaks during this time period, associated with community water systems, were caused by problems at water treatment plants. The other seven outbreaks resulted from problems in the water distribution systems and cross-connection/plumbing of individual facilities such as restaurants.

Outbreaks are also possible in drinking water systems with no apparent treatment deficiencies or breakdowns, such as that which occurred in Las Vegas, Nevada from January to May 1994 (Roefler et al., 1996). In this instance, the CDC found the "... first documented epidemiologically confirmed waterborne outbreak from a water system with no treatment deficiencies or breakdowns" (Roefler et al., 1996).

2.1.2 Pathogens of Primary Concern

Source waters, especially surface waters, support microbiological communities that include pathogens. Because these microorganisms can be responsible for public health problems, the microbiological characteristics of the water source are one of the most important parameters in ensuring effective water treatment. In addition to public health, microbiological characteristics can also affect the physical and chemical quality of the water and treatment plant operations. Table 2-1 shows the attributes of three pathogen groups of primary concern in water treatment: bacteria, viruses, and protozoa.

Table 2-1. Attributes of Waterborne Pathogens of Primary Concern

Organism	Size (µm)	Mobility	Point(s) Of Origin	Resistance to Disinfection	Removal by Sedimentation, Coagulation, and Filtration
Bacteria	0.1–10	Motile, Nonmotile	Humans and animals, water, and contaminated food	Type specific – bacterial spores typically have the highest resistance, whereas vegetative bacteria have the lowest resistance	2- to 3-log removal
Viruses	0.01–0.1	Nonmotile	Humans and animals, polluted water, and contaminated food	More resistant than vegetative bacteria	1- to 3-log removal
Protozoa	4–20	Motile, Nonmotile	Humans and animals, sewage, decaying vegetation, and water	More resistant than viruses or vegetative bacteria	2- to 3-log removal

Source: Culp/Wesner/Culp, 1986.

2.1.2.1 Bacteria

Bacteria are single-celled organisms ranging in size from 0.1 to 10 micrometers (µm). Their shape, components, size, and manner of growth are used to characterize these organisms. Most bacteria can be grouped by shape using four general categories: spheroid, rod, curved rod or spiral, and filamentous. Cholera, a disease prevalent in Europe during the eighteenth and nineteenth centuries is transmitted by the bacterium, *Vibrio cholerae*. Outbreaks of cholera in the mid 1800's prompted Dr. John Snow to study the disease's transmission through a common water supply. *Salmonella typhosa* and *shigella spp.* are also well known types of bacteria known to affect PWSs. Outbreaks of these bacterial diseases are especially rampant in parts of the world with poor sanitary practices.

2.1.2.2 Viruses

Viruses are composed of a strand of genetic material, either deoxyribonucleic acid (DNA) or ribonucleic acid (RNA), and a protective protein coat. All viruses are obligate parasites, unable to carry out any form of metabolism, and are completely dependent upon host cells for replication. Viruses typically range from 0.01 to 0.1 µm in size, are very species-specific with respect to infection, and typically attack only one type of host. Viruses such as Hepatitis B virus, poliovirus, and picornavirus are transmitted through food, personal contact, exchange of body fluids, or potable water. Some viruses, such as the retroviruses (including the human immunodeficient virus (HIV) group) appear to be too fragile for water transmission to warrant significant danger to public health (Riggs, 1989).

2.1.2.3 Protozoa

Protozoa are single-celled eucaryotic microorganisms without cell walls that utilize bacteria and other organisms for food. Most protozoa are free-living in nature and can be encountered in water; however, several species are parasitic and live on or in host organisms. Host organisms vary from primitive organisms, such as algae, to highly complex organisms, such as humans. *Giardia lamblia* and *Cryptosporidium* are two protozoa that present greater challenges to treatment because of their resistance to disinfection.

Giardia lamblia

Giardia lamblia is a flagellated protozoan that is responsible for giardiasis, a disease that can cause symptoms such as fatigue, cramping, and intermittent diarrhea. The life cycle of *Giardia* includes a cyst stage. During the cyst stage, the organism remains dormant and is extremely resilient, allowing it to survive extreme environmental conditions. A *Giardia* cyst's life cycle continues with the formation of an environmentally resistant outer shell (cyst) and the process in which the vegetative form of the parasite emerges from the cyst, known as excystation. *Giardia* is spread from person to person when a person touches the stool, or an object which has been contaminated by the stool, of an infected person and then ingests the cyst. Infection is often spread by not properly washing hands after bowel movements, after changing diapers, or before preparing foods (CDC, 1998). In addition to humans, wild and domestic animals have been implicated as hosts.

Currently, there is no simple and reliable method for assaying *Giardia* cysts in water samples. Microscopic methods for detection and enumeration are tedious and require examiner skill and patience. Although *Giardia* cysts are considered relatively resistant to chlorine, especially at higher pH levels and low temperatures, there are systems that are effectively using chlorine and chlorine dioxide for disinfection of *Giardia* cysts. Ozone and removal by filtration also appear to be an effective disinfectant for inactivating *Giardia*. *Giardia* cysts are relatively large (i.e., between 7 and 15 μm) and can be filtered effectively using diatomaceous earth, granular media, or membranes.

Cryptosporidium

Cryptosporidium is a protozoan similar to *Giardia*. It forms oocysts (i.e., the fertilized egg form of the *Cryptosporidium*) as part of its life cycle that are resistant to disinfection. The oocysts are smaller than *Giardia* cysts, typically ranging from about 4 to 6 μm in diameter. These oocysts can survive under adverse conditions. Once ingested by a warm-blooded animal, they will undergo excystation and continue their life cycle. The primary symptom of cryptosporidiosis is acute diarrhea. Other symptoms include vomiting, abdominal pain, and low-grade fever. Animals, person-to-person contact, and contaminated drinking water have been identified as sources of infection.

Due to the increase in outbreaks of cryptosporidiosis, a tremendous amount of research has focused on *Cryptosporidium* within the last 10 years. Medical interest has increased due to its potentially life-threatening impact on individuals with acquired immune deficiency syndrome (AIDS), other immunocompromised populations, such as people undergoing chemotherapy for cancer, pregnant women, and the very old or very young.

2.1.3 Mechanisms of Pathogen Inactivation

In water treatment, disinfection is one of the primary methods used to inactivate pathogens. Three primary mechanisms are responsible for pathogenic inactivation by disinfection:

- Destruction or impairment of cellular structural organization
- Interference with energy-yielding metabolism
- Interference with biosynthesis and growth.

The first mechanism of pathogen inactivation is to adversely affect the structure of the cell. The destruction or impairment of the structural integrity of cells is achieved by attacking major cell constituents, such as destroying the cell wall or impairing the functions of semi-permeable membranes. The second mechanism of inactivation is to interfere with the metabolism or cellular activity of a pathogen. Metabolic interference can occur through oxidizing enzyme functional groups, thus rendering the enzymes non-functional. The third mechanism is to interfere with biosynthesis and growth. This can be achieved by preventing synthesis of normal proteins, nucleic acids, coenzymes, or the cell wall.

Disinfectants can cause combinations of inactivation mechanisms depending on the type of disinfectant and microorganism. Montgomery (1985) believed that the primary factors controlling disinfection efficiency, and hence pathogen inactivation, are: (1) the ability of the disinfectant to oxidize or rupture the cell wall, and (2) the ability of the disinfectant to diffuse into the cell and interfere with cellular activity.

2.1.4 Effect of Parameters on Inactivation

Disinfection effectiveness depends on many factors including the type and amount of disinfectant used, the organisms being treated, physiological condition of the organisms, time the disinfectant is in contact with the water, and other water quality characteristics (such as the quantity of dissolved organics in the water). The type of disinfectant used greatly affects the efficiency of inactivation. The stronger the disinfectant, the more quickly the disinfection process occurs. Increasing the disinfectant dose, or disinfectant residual, will increase the rate of pathogen inactivation but may also increase the formation of harmful DBPs. The efficiency of pathogen inactivation can also be affected by the pH of the water. At certain pH levels a disinfectant may be transformed into a form that may be more benign to pathogens. Typically,

increasing temperatures will increase the rate of disinfection. Turbidity interferes with disinfection because particles in the water can surround and shield pathogenic microorganisms from the disinfectants. Dissolved organics interfere with disinfection by reacting with the disinfectant to produce compounds with little or no microbiocidal activity, thereby reducing the amount of disinfectant available for pathogen inactivation.

2.1.5 Comparison of Disinfectant Inactivation Values

There is considerable variability in the effectiveness of different disinfectants. Some of the factors affecting disinfection effectiveness are discussed in Table 2-2.

Table 2-2. Summary of Factors that Affect Disinfection

Factor	Description
Disinfectant type	The stronger the disinfectant, the quicker the disinfection process.
Disinfectant dose	Increasing the disinfectant dose will increase the disinfection rate, but may also increase the formation of harmful byproducts.
Type of organism and its physiological condition	A microorganism's susceptibility to disinfection varies according to pathogen group and agent. In general, protozoa are more resistant to disinfectants than are bacteria or viruses.
Contact time	In general, increasing the contact time will decrease the disinfectant dose required for pathogen inactivation.
pH	pH may affect the disinfectant form and, in turn, the efficiency of the disinfectant.
Temperature	Typically, increasing the temperature will increase the rate of disinfection.
Turbidity	Particles responsible for turbidity can surround and shield pathogenic microorganisms from disinfectants and exert a disinfectant demand.
Dissolved organics and inorganics	Dissolved organics can interfere with disinfection by consuming the disinfectants to produce compounds with little or no microbiocidal activity, thereby reducing the amount of disinfectant available for pathogen inactivation.

While there is some promising research on the Ultraviolet (UV) disinfection, there are currently no provisions for its use for regulatory compliance.

One of the most useful ways of characterizing the germicidal efficiency of any disinfectant is the CT factor, a version of the Chick-Watson law (Chick, 1908; Watson, 1908). CT is defined as the product of the residual disinfectant, C, in milligrams per liter (mg/L), and the contact time, T, in minutes.

The CT factor implies that an equivalent level of disinfection can be achieved by different combinations of disinfectant concentrations and contact times. CT factors are typically determined for different levels of pathogen inactivation. Inactivation is usually measured in log base 10, while CT values are usually measured in mg-min/L. The following formula demonstrates how to calculate the different levels of inactivation:

$$X = -\log_{10}(1-N) \text{ or } N = 1 - 10^{-X}$$

where: *X* = level of pathogen removal/inactivation
 N = fraction of pathogen removed/inactivated

The level of inactivation, *X*, is usually expressed as “log removal” or “log inactivation.” For example, a 2-log inactivation is equivalent to a 99 percent pathogen inactivation. Each unit increase in the log removal of pathogens will result in a ten-fold decrease in the fraction of viable pathogens. For example, a 3-log inactivation is equivalent to a 99.9 percent inactivation. When discussing filtration and disinfection, removal levels from filtration can be combined with disinfection inactivation levels to create an overall removal/inactivation level.

EPA has identified CT values for the inactivation of *Giardia* cysts and viruses for various disinfectants. Table 2-3 and Table 2-4 summarize the CT values for the inactivation of viruses and *Giardia* cysts, respectively, using various disinfectants at a water temperature of 10°C and a pH range of 6.0 to 9.0. CT values for chlorine disinfection are based on a free chlorine residual as opposed to a chloramine residual.

Some systems employ different disinfectants to meet their system's demands. These disinfectants are used for primary and/or secondary disinfection depending on the utility's need and the specific disinfectant. Primary disinfection provides the appropriate CT to inactivate microbial pathogens. Disinfectants proven effective for this purpose include free chlorine, chlorine dioxide, and ozone. Secondary disinfection ensures residual protection to control microorganism regrowth or recontamination during water storage and distribution. Either free chlorine, or chlorine plus the addition of ammonia to form chloramine, accomplishes this task (AWWA, 1999).

The most effective chemical disinfectant, overall, in terms of total pathogen inactivation, is ozone. Ozone is an extremely strong disinfectant and has excellent inactivation efficiencies for bacteria, viruses, and *Giardia*. Chlorine and chlorine dioxide are both excellent disinfectants for bacteria. Chlorine is slightly more efficient than chlorine dioxide at inactivating viruses while chlorine dioxide is much better at inactivating *Giardia* cysts. Chloramine is generally not considered a strong disinfectant for bacteria, viruses, or *Giardia* cysts because it requires a high CT value and, therefore, is a poor primary disinfectant, although some systems with long contact times use chloramines for primary disinfection (e.g., Austin, Texas). Chloramine, however, is used because it does not form THMs even after extended contact times and is therefore, an attractive secondary disinfectant for maintaining a residual in the distribution system.

Continuous Wave (CW) Ultraviolet (UV) light is not included in Table 2-3 since it is not allowed under the SWTR and the IESWTR. EPA did not include UV light disinfection in

these two rules since literature data on *Cryptosporidium* inactivation with UV appear controversial because of different experimental protocols used by different investigators (USEPA, 1997b). UV light disinfection also does not provide a residual.

Table 2-3. CT Values for Inactivation of Viruses in Water at 10°C with pH 6.0–9.0

Disinfectant	CT values (in mg-min/L)		
	2-log Inactivation (99.0%)	3-log Inactivation (99.9%)	4-log Inactivation (99.99%)
Chlorine	3	4	6
Chloramine	643	1,067	1,491
Chlorine Dioxide	4.2	12.8	25.1
Ozone	0.5	0.8	1.0

CT values were obtained from Appendix E (AWWA, 1991).

Table 2-4. CT Values for Inactivation of Giardia Cysts in Water at 10°C with pH 6.0–9.0

Disinfectant	CT values (mg-min/L)					
	0.5-log Inactivation (68.0%)	1-log Inactivation (90.0%)	1.5-log Inactivation (96.8%)	2-log Inactivation (99.0%)	2.5-log Inactivation (99.7%)	3-log Inactivation (99.9%)
Chlorine ¹	17	35	52	69	87	104
Chloramine	310	615	930	1,230	1,540	1,850
Chlorine Dioxide	4	7.7	12	15	19	23
Ozone	0.23	0.48	0.72	0.95	1.2	1.43

CT values were obtained from Appendix E (AWWA, 1991).

¹ at pH 7.0 and chlorine residual \leq 0.4 mg/L.

2.1.6 Disinfectant Residual

Disinfectant residual is necessary to inactivate pathogens, maintain water quality, and protect the distribution system against regrowth (Snead et al., 1980). The SWTR provides minimum requirements on the amount of disinfection residual that must exist in treated water.

Specifically, the SWTR requires that filtration and disinfection must be provided to ensure that the total treatment of the system achieves at least a 3-log (99.9 percent) removal/inactivation of *Giardia* cysts and a 4-log (99.99 percent) removal/inactivation of viruses (USEPA, 1989a). In addition, the disinfection process must demonstrate, by continuous monitoring and recording, that the disinfectant residual concentration in water entering the distribution system is never less than 0.2 mg/L and that a detectable residual is maintained in the distribution system.

Although a disinfectant residual is generally necessary to maintain water quality, it is recognized that an excessive amount of disinfectant residual may also pose a threat to health as well as contribute to the increased formation of harmful DBPs. The Stage 1 DBPR sets MRDLs and MRDLGs of 4.0 mg/L for chlorine and chloramines and 0.8 mg/L for chlorine dioxide.

2.2 Stage 1 Disinfectant and Disinfection Byproducts Rule (DBPR)

As mentioned previously, the Stage 1 DBPR finalizes the following:

- MRDLGs for chlorine, chloramines, and chlorine dioxide
- MCLGs for four THMS, two HAAs
- National Primary Drinking Water Regulations (NPDWRs) for
 - Three disinfectants (chlorine, chloramines, and chlorine dioxide)
 - Two groups of organic DBPs (TTHMs and HAA5)
 - Two inorganic DBPs (chlorite and bromate).

Although disinfection plays a crucial role in water treatment, its application does have side effects. In addition to inactivating pathogens, disinfectants react with organic matter to produce DBPs. Numerous researchers have documented that NOM is the principal precursor of DBP formation (Stevens et al., 1976; Babcock and Singer, 1979; Christman et al., 1983).

This section discusses the role of disinfectants in the formation of DBPs, highlighting those disinfectants and DBPs that are of current regulatory interest to EPA. In addition, this section discusses parameters that affect the formation of DBPs and concludes with a discussion of strategies to minimize DBP formation.

2.2.1 Disinfection Byproduct Formation

Natural water contains NOM in the form of humic and nonhumic substances. The precursors of DBP formation are generally naturally occurring organic substances, such as humic and fulvic acids. These acids belong to a family of compounds having similar structure and chemical properties and are formed during the decomposition of vegetation. These natural organic DBP precursors can be subdivided into a hydrophobic (i.e., water repellent) fraction of primarily humic material and a hydrophilic (i.e., water attractive) fraction of primarily fulvic material.

The amount of NOM in water can be estimated by measuring surrogate parameters. Although surrogate parameters have limitations, they are used because they may be measured more easily, rapidly, and inexpensively than the NOM parameter of interest. Estimation of NOM

concentration allows water treatment plant operators to monitor the operation and performance of the water treatment plant. The following surrogate parameters can be used to assess the type and concentration of NOM:

- Total and dissolved organic carbon
- UV light absorbency at 254 nanometer (nm) wavelength (UV-254)
- THM formation potential (THMFP) – a test measuring THM formation with a high dosage of free chlorine and a long reaction time
- THM Simulated Distribution System (SDS) – a test that predicts the total THM concentration at some selected point in a given distribution system, where the conditions of the chlorination test simulate the distribution system at the point desired.

Additional details on NOM type and concentration assessment are available in the *Guidance Manual for Enhanced Coagulation and Precipitative Softening* (USEPA, 1999g).

About 90 percent of total organic carbon (TOC) concentration in a water supply is typically dissolved. The dissolved organic carbon (DOC) concentration is defined as the TOC able to pass through a 0.45 μ m filter. Measurement of UV absorbency is a good technique for assessing the presence of DOC, such as humic substances, because these substances contain aromatic structures that absorb light in the UV spectrum. Oxidative processes can reduce the UV absorbance without changing the DOC concentration, however, the UV/DOC correlation would change after oxidation.

EPA has identified numerous compounds that are of current regulatory interest and pose the greatest health risk based on the frequency of their occurrence and their potential health effects (USEPA, 1992a). The categories of DBPs of interest to EPA include disinfectant residuals, inorganic byproducts, and halogenated organic byproducts, as summarized below, but EPA may add additional DBPs as more information becomes available:

- Disinfection residuals
 - Chlorine
 - Chloramines
 - Chlorine dioxide
- Inorganic byproducts
 - Bromate ion
 - Chlorite ion
- Halogenated organic byproducts
 - THMs
 - Chloroform

- Bromodichloromethane
- Dibromochloromethane
- Bromoform
- Haloacetic acids
 - Monochloroacetic acid
 - Dichloroacetic acid
 - Trichloroacetic acid
 - Monobromoacetic acid
 - Dibromoacetic acid

2.2.1.1 Free Chlorine

Halogenated organic byproducts (such as chloroform) are produced when free chlorine reacts with NOM. In addition, brominated byproducts are formed when source water containing bromide ions is chlorinated. Chlorine oxidizes bromide ions resulting in the formation of free bromine that, in turn, reacts with NOM to produce the brominated analogs of chlorination byproducts. Currently regulated brominated byproducts include bromoform, bromodichloromethane, dibromochloromethane, monobromoacetic acid, and dibromoacetic acid.

2.2.1.2 Chloramine

Application of high-grade chloramine does not generally produce detectable concentrations of THMs. Although detectable concentrations of mono- and dichloroacetic acids can be produced, these are generally significantly lower than corresponding concentrations produced by free chlorine. If chlorine is added prior to ammonia to form chloramines *in-situ* (as often done to insure virus inactivation through free chlorine contact), all of the byproducts associated with the use of free chlorine can be formed (although formation is significantly retarded when ammonia is added). No detectable trihaloacetic acids are produced from chloramination.

2.2.1.3 Chlorine Dioxide

Chlorine dioxide does not produce halogenated DBPs to any significant degree, although it does produce chlorite ion, an inorganic byproduct. Approximately 50 to 70 percent of the chlorine dioxide consumed reduces to chlorite ion (Rav Acha et al., 1995; Werdehoff and Singer, 1987). Moreover, chlorine dioxide generators usually result in some excess free chlorine (typically less than 2 percent by weight in the generator effluent) (USEPA, 1999b). Because chlorine reacts with NOM to produce DBPs, it is important to use high purity chlorine dioxide. The oxidation byproducts of chlorine dioxide treatment have not been studied extensively and until the Chemical Manufacturers Association (CMA) completed a two-generation reproductive rat study in 1996, the public health impact of chlorine dioxide

treatment, has been largely unknown (CMA, 1997). Using sodium chlorite as the test compound, CMA designed the study to evaluate the effects of chlorite on reproduction and pre- and post-natal development when administered orally via drinking water for two successful generations. As a result of this study, an external peer review, and an EPA reassessment, the EPA changed the MCLG for chlorite to 0.8 mg/L and the MRDLG for chlorine dioxide to 0.8 mg/L.

2.2.1.4 Ozone

Although ozone itself does not produce halogenated DBPs, ozonation of waters containing bromide ion can result in the production of brominated DBPs. Ozone will oxidize bromide ion to hypobromous acid which, in turn, reacts with NOM to produce the fully brominated analogs of chlorination byproducts (Cooper et al., 1986; Siddiqui and Amy, 1993). In addition, hypobromite, which is in equilibrium with hypobromous acid, can be oxidized by ozone to produce bromate as an inorganic byproduct. Bromate formation can be controlled by performing ozonation at acidic pH values where hypobromous acid dominates over the hypobromite ion (Siddiqui and Amy, 1993; Krasner et al., 1993), but this may present a significant cost and operational burden for systems. Other bromate control techniques include (USEPA, 1999b):

- Ammonia addition and ozonation to form bromamines
- Manipulating contact time and residual by applying ozone in stages to reduce the ozone residual while maintaining the required CT
- Reducing ambient bromide concentration
- Maintaining a low ozone:DOC ratio.

2.2.2 Factors Affecting DBP Formation

DBP formation is influenced by a number of factors, including precursor concentrations and seasonal variations. According to Singer (1992), the presence of organic precursors and the formation of halogenated DBPs increase as temperature increases. This, in turn, leads to a higher chlorine demand during the warmer summer months or in certain geographical locations in order to maintain effective disinfection residuals.

The pH of the water being chlorinated has an impact on the formation of halogenated byproducts, with the exception of dichloroacetic acid, monochloroacetic acid, and dibromoacetic acid, as shown in Table 2-5. THM formation increases with increasing pH, while the formation of trichloroacetic acid, dichloroacetone, trichloroacetone, and overall total organic halides (TOX) decreases with increased pH (Reckhow and Singer, 1985; Stevens et al., 1988). High pH also

affects chloral hydrate. According to Miller and Uden (1983), chloral hydrate is hydrolyzed and forms chloroform as the decomposition product under high pH conditions.

Table 2-5. Impacts of pH on Organic Halogen Formation During Chlorination

Organic Halogen	pH of Chlorination		
	5.0	7.0	9.4
Total Trihalomethanes	Lower formation		Higher formation
Trichloroacetic Acid	Similar formation	Similar formation	Lower formation
Dichloroacetic Acid	Similar formation - perhaps slightly higher at pH 7		
Monochloroacetic Acid	Concentrations below 5 µg/L, trends not discernible at low levels		
Dibromoacetic Acid	Concentrations below 1 µg/L, trends not discernible at low levels		

Source: Stevens et al., 1988.

Based on chlorination studies of humic material in model systems, high pH tends to favor chlorination formation over the formation of trichloroacetic acid and other organic halides. Accordingly, water treatment plants practicing precipitative softening at pH values greater than 9.5 to 10 are likely to have a higher fraction of TOX attributable to THMs than plants treating surface waters by conventional treatment in pH ranges of 6.0 to 8.0 (Singer and Chang, 1989).

To the extent that the application of chlorine dioxide and chloramines introduces free chlorine into water, any chlorination byproducts would be influenced by pH as discussed above. For a constant chlorine to ammonia dose ratio, the ratio of chloramine to total chlorine increases with increasing pH (AWWA, 1990).

Disinfection of source water containing bromide ions can lead to the formation of brominated DBPs as discussed in Section 2.2.1.1. Increases in the ratios of bromide ion to the chlorine dose and the ratio of the bromide ion to the DOC concentration results in a shift in THM and HAA speciation to the more bromine-substituted species (Krasner et al., 1989; Black et al., 1996). In Krasner's study, the chlorine dose was roughly proportional to TOC concentration. As TOC was removed through the treatment train, the chlorine dose decreased and TTHM formation declined. At the same time, however, the bromide ion to chlorine dose ratio increased and shifted the TTHM concentrations towards brominated THMs. Therefore, improving the removal of NOM prior to chlorination can shift the speciation of halogenated byproducts toward more brominated forms. Ozone application to bromide ion-containing waters at high pH favors the formation of bromate ion, while application at low pH favors the formation of brominated organic byproducts. Since there is some evidence that brominated DBPs may have more significant health effects, absolute levels of DBPs may not be comparable.

2.2.3 DBP Control Strategies

In 1983, the EPA identified the best technologies and treatment techniques that public water systems could use to comply with the MCL for TTHMs (USEPA, 1983). The principal treatment modifications involved moving the point of chlorination downstream in the water treatment plant, optimizing the coagulation process to enhance the removal of DBP precursors, and using chloramines to supplement or replace the use of free chlorine (Singer, 1993).

Moving the point of chlorination downstream in the treatment train proves to be extremely effective in reducing byproduct concentrations because it allows the NOM precursor concentration of the water to be reduced prior to chlorine addition. Replacing prechlorination by preoxidation with an alternate disinfectant that produces less DBPs is an attractive option for reducing the formation of chlorinated byproducts.

Efforts to control the formation of DBPs should focus on:

- Source water selection and control
- DBP precursor removal
- Disinfection strategy selection.

These efforts will affect the types and concentrations of DBPs that are formed. Each of these efforts is briefly discussed below.

2.2.3.1 Source Water Control

Source water control strategies involve managing the source water to lower the concentrations of NOM and bromide ion. Source water control strategies may include changing the water source and blending water high in NOM and bromide ion concentrations with high quality water that is low in NOM and bromide ion concentrations. Research has shown that algal growth leads to the production of DBP precursors (Hoehn et al., 1980; Oliver and Shindler, 1980; Wachter and Andelman, 1984; Karimi and Singer, 1991). Therefore, nutrient and algal management is one method of controlling the DBP formation potential of source waters or presedimentation basins used by systems with highly variable turbidities. Control of bromide ion precursors may be accomplished by preventing brine or salt water intrusion into the water source.

2.2.3.2 DBP Precursor Removal

Raw water can include DBP precursors in dissolved and particulate forms. In conventional treatment, dissolved precursors must be converted to particulate form for subsequent removal during settling and filtering. The potential THM formation generally decreases by about 50 percent through conventional coagulation and settling, indicating the importance of moving the point of chlorine application downstream of coagulation and settling (and even filtration) to

control the formation of TOX and TTHMs (Singer and Chang, 1989). Systems can lower the DBP formation potential of water prior to disinfection by removing precursors with bank filtration, infiltration gallery, enhanced coagulation, granular activated carbon adsorption following filtration, or membrane filtration.

Aluminum (alum) and iron (ferric) salts both have the ability to reduce pH which improves NOM removal. For alum, the optimal pH for NOM removal is in the range of 5.5 to 6.0. The addition of alum decreases pH and may allow the optimal pH range to be reached without acid or base addition. However, waters with very low or very high alkalinities may require the addition of a base or an acid to keep the pH in the range of optimal coagulation (Singer, 1992). Systems will evaluate the optimal combination of coagulant, acid/base, coagulant/filter aids, etc. to remove precursors.

Granular activated carbon (GAC) adsorption can be used following filtration to remove additional NOM. For most applications, empty bed contact times (EBCTs) in the range of 5 to 30 minutes are required, with regeneration frequencies on the order of two- to nine- months (Singer, 1992). Changing the pH, or addition of a disinfectant to the GAC bed, can result in specific reactions in which previously absorbed compounds leach into the treated water. Powdered activated carbon (PAC) can be used seasonally for THM precursor, or TTHM, reduction.

Membrane filtration has been shown to be effective in removing DBP precursors in some instances. In pilot studies, ultrafiltration (UF) with a molecular weight cutoff (MWCO) of 100,000 daltons was ineffective for controlling DBP formation. However, when little or no bromide ion was present in the source water, nanofiltration (NF) membranes with MWCOs of 400 to 800 daltons effectively controlled DBP formation (Laine et al., 1993). In waters containing bromide ion, higher bromoform concentrations were observed after chlorination of membrane permeate (compared with the raw water). TTHMs were lower in the chlorinated permeate than in the chlorinated raw water. However, due to the shift in speciation of THMs toward more brominated forms, bromoform concentration was actually greater in the chlorinated treated water than in the chlorinated raw water. Use of spiral-wound NF membranes (200-300 daltons) more effectively controlled the formation of brominated THMs, but pretreatment of the water was necessary (Laine et al., 1993). Significant limitations in the use of membranes include disposal of the waste brine generated, fouling of the membranes, membrane replacement cost, and total system costs.

2.2.3.3 Disinfection Strategy Selection

In addition to improving the quality of the raw or pre-disinfected water, alternative disinfection strategies may be used to control DBPs. These strategies include the following:

- Use of an alternative or supplemental disinfectant

- Movement of the point of disinfection to reduce TTHM formation
- Use of multiple disinfectants at various points in the treatment plant to avoid DBP formation at locations where precursors are still prevalent.

2.3 Stage 1 Disinfection Byproducts Rule (DBPR)

As noted previously, the Stage 1 DBPR is aimed at limiting the amount of disinfection residual and DBPs in the distribution system. The Stage 1 DBPR is intended to limit the formation of byproducts such as THMs and HAA5 and is directed at PWSs that are CWSs and NTNCWs that treat their drinking water with a chemical disinfectant for either primary or residual treatment. In addition, certain provisions apply to TNCWSs that use chlorine dioxide.

The Stage I DBPR uses two approaches to limit the amount of residual disinfectants and DBPs in distribution systems. First, EPA is requiring the removal of NOM, measured in the form of TOC. Second, EPA is requiring PWSs to reduce the level of TTHMs, HAAs, and bromate ion in distribution systems.

2.3.1 DBP Maximum Contaminant Levels (MCLs)

The Stage 1 DBPR reduces allowable DBPs in PWS distribution systems to the following concentrations:

- TTHMs: 0.080 mg/L (as a running annual average)
- HAA5: 0.060 mg/L (as a running annual average)
- Bromate ion: 0.010 mg/L (as a running annual average)
- Chlorite ion: 1.0 mg/L (as a three-sample set average)

These allowable concentrations may be further reduced in the Stage 2 DBPR or the compliance determination procedure may be changed.

2.3.2 Maximum Residual Disinfectant Levels (MRDLs)

As part of the Stage 1 DBPR, EPA has also set MRDLs and MRDLGs for chlorine, chloramines, and chlorine dioxide. As with MCLs, MRDLs are enforceable limits, whereas MRDLGs, similar to MCLGs, are unenforceable health goals. The MRDLs and MRDLGs, for the three disinfectants are as follows:

	<u>MRDL</u>	<u>MRDLG</u>
• Chlorine:	4.0 mg/L	4.0 mg/L
• Chloramine:	4.0 mg/L	4.0 mg/L
• Chlorine dioxide:	0.8 mg/L	0.8 mg/L

2.3.3 TOC Removal Requirements

The Stage 1 DBPR bases TOC removal requirements on the TOC concentration and alkalinity of the raw water. The required removal is adjusted for alkalinity because the optimal pH for TOC removal is often below 6.0. As a result, waters with high alkalinity require an extensive amount of coagulant and/or pH adjustment to drive the pH into an optimal range. Recent research confirms this situation and has demonstrated that waters with high alkalinity will have a more difficult time meeting the TOC removal requirements as compared to waters with low alkalinity (Krasner and Amy, 1995; White et al., 1997; Arora et al., 1997).

Therefore, the higher cost of chemical addition for waters with high alkalinity has prompted EPA to lower the TOC removal requirements as compared to waters with lower alkalinity. Furthermore, the additional chemicals that would be required to drive the pH into an optimum range might produce byproducts (e.g., sulfuric acid to sulfate) that would become a concern relative to corrosion and/or other public health issues (e.g., gastrointestinal distress).

Table 2-6 outlines the TOC removal requirements of the Stage 1 DBPR (USEPA, 1998a).

Table 2-6. Stage 1 DBPR Percent TOC Removal Requirements

TOC	TOC Removal		
	0 – <60 mg/L Alkalinity	≥60 – <120 mg/L Alkalinity	≥120 mg/L Alkalinity
2.0 – 4.0 mg/L	35%	25%	15%
4.0 – 8.0 mg/L	45%	35%	25%
> 8.0 mg/L	50%	40%	30%

The Stage 1 DBPR also provides for six alternative compliance criteria from the treatment technique requirements provided certain conditions are met. These criteria are independent of the softening requirements and are listed in Section 3.4.1. These criteria differ in the monitoring requirements; they are either determined based on monthly monitoring calculated quarterly as a running annual average of all measurements, on monthly monitoring for TOC and alkalinity or quarterly monitoring for TTHMs and HAA5, calculated quarterly as a running annual average of all measurements, or on monitoring for TTHMs and HAA5, calculated quarterly as a running annual average of all measurements.

It was also agreed during the regulatory negotiation process that specific ultraviolet absorbency (SUVA) should be considered when determinations of exemption status for TOC removal are being made. SUVA is an easily measured indicator of the organic fraction of water that is not amenable to removal through coagulation. It is also a measure of the humic/non-humic

compositions of NOM and, therefore, by including a SUVA provision in the rule, EPA is specifically targeting waters with a NOM fraction that is difficult to remove through enhanced coagulation or enhanced softening. SUVA, is defined as the UV-254 (measured in m^{-1}) divided by the DOC concentration (measured as mg/L).

2.4 Interim Enhanced Surface Water Treatment Rule (IESWTR)

As mentioned previously, the IESWTR focuses primarily on improving particulate removal at drinking water treatment systems. While the “interim” rule applies to systems serving 10,000 people or more, the Long-Term 1 ESWTR (LT1ESWTR) will regulate systems serving fewer than 10,000 people. The overall scope of the LT1ESWTR will depend on the results of the ICR. The LT1ESWTR is expected to be promulgated in the year 2000.

The primary requirements associated with the IESWTR include meeting:

- Filtered effluent turbidity levels (both combined and individual filter effluents)
- Continued *Giardia lamblia* and virus removal/inactivation requirements
- *Cryptosporidium* removal requirements
- Microbial profiling/benchmarking requirements.

2.4.1 Turbidity Requirements

The new turbidity requirements in the IESWTR are as follows (USEPA, 1998b):

- Combined effluent performance requirements for plants using conventional filtration treatment or direct filtration:
 - Combined filtered water effluent turbidity must be less than or equal to 0.3 NTU in at least 95 percent of the measurements taken each month, with measurements taken every four hours of operation; and
 - Combined filtered water effluent turbidity must not exceed 1.0 NTU at any time with measurements taken in four-hour intervals.
- Combined effluent performance requirements for plants using slow sand and diatomaceous earth filtration:
 - The turbidity level of representative samples of a system's filtered water must be less than or equal to 1.0 NTU in at least 95 percent of the measurements taken each month, with measurements taken every four hours of operation; and

- The turbidity level of representative samples of a system's filtered water must at no time exceed 5.0 NTU with measurements taken in four-hour intervals.
- Individual filter performance requirements:
 - Individual filter effluents must be monitored continuously for turbidity
 - Any individual filter with a turbidity level greater than 1.0 NTU, based on two consecutive measurements 15 minutes apart, must be reported to the governing agency
 - Any individual filter with a turbidity level greater than 0.5 NTU at the end of the first four hours of filter operation (following backwash or when off-line filters are put on-line) based on two consecutive measurements 15 minutes apart, must be reported to the governing agency.

A PWS also has the option to use an alternative filtration technology. The PWS may do so if it demonstrates to the State, using pilot plant studies or other means, that the alternative filtration technology, in combination with disinfection treatment that meets the requirements of 40 CFR 141.72(b), consistently achieves 99.9 percent removal and/or inactivation of *Giardia lamblia* cysts and 99.99 percent removal and/or inactivation of viruses, and 99 percent removal of *Cryptosporidium* oocysts, and the State approves the use of the filtration technology.

Depending on the frequency of exceptions, the system may also be required to perform a self-assessment or have the State or a third-party perform a Comprehensive Performance Evaluation (CPE) (USEPA, 1998c).

2.4.2 *Giardia* and Virus Removal/Inactivation Requirements

The IESWTR maintains the existing disinfection requirements as set forth in the 1989 SWTR (USEPA, 1989a). These requirements will be applied to disinfection practices using chlorine, chlorine dioxide, ozone, and chloramines. The concentration/contact time values in the 1989 SWTR continue to apply for *Giardia* and virus removal/inactivation. PWSs are still required to meet a 3-log removal/inactivation of *Giardia* and a 4-log removal/inactivation of viruses, which can be accomplished via filtration followed by disinfection or through disinfection alone. Disinfection credit for compliance with turbidity removal requirements is continued as outlined under the 1989 SWTR.

2.4.3 *Cryptosporidium* Removal Requirements

In addition to *Giardia* and virus removal/inactivation, the IESWTR requires that all surface water systems serving 10,000 people or more, which are required to filter, must achieve at least a 2-log removal of *Cryptosporidium*. This is a new requirement updated from the 1989 SWTR. PWSs using rapid granular filtration (conventional and direct filtration) and meeting

the turbidity requirements outlined above will be considered to be achieving at least a 2-log removal of *Cryptosporidium*, as will systems using slow sand filtration or diatomaceous earth filtration meeting SWTR turbidity requirements (USEPA, 1998b). Systems using alternative filtration technologies must demonstrate to the State that the technology achieves 2-log removal.

2.4.4 Microbial Profiling/Benchmarking Requirements

Another new and primary requirement associated with the IESWTR is microbial profiling and benchmarking. Disinfection profiles must be prepared by PWSs with measured TTHM or HAA5 distribution system levels of 0.064 mg/L or 0.048 mg/L or higher, respectively, as annual averages for the most recent 12 month compliance period. The disinfection profiles will consist of a compilation of daily *Giardia lamblia* log inactivations (or virus inactivations under conditions to be specified), computed over a period of one- to three-years.

Benchmarking is not intended to serve as a regulatory standard. USEPA intends benchmarking to serve as a methodology by which the PWS and State can assure that there are no significant reductions in microbial protection as a result of the system modifying its disinfection practices to meet the Stage 1 DBP MCLs and MRDLs (USEPA, 1998b).

The guidance manual, *Disinfection Profiling and Benchmarking* (USEPA, 1999a) describes the procedures necessary to comply with these requirements, including development of a profile and calculation of a benchmark.

3. SIMULTANEOUS COMPLIANCE ISSUES BETWEEN STAGE 1 DBPR AND IESWTR

3.1 Introduction

As outlined in Chapters 1 and 2, the 1996 Amendments to the SDWA require the EPA to develop regulations for the control and monitoring of microbial pathogens and DBPs in drinking water. Two new rules promulgated in response to the 1996 SDWA Amendments are the Stage 1 DBPR and the IESWTR. These two rules are part of the Microbial and Disinfection Byproduct (M-DBP) cluster of rules discussed in Chapter 1.

The Stage 1 DBPR focuses on minimizing the formation of DBPs in the distribution system of PWSs to reduce the long-term exposure of customers to these potentially carcinogenic compounds through enhanced coagulation or enhanced softening. In contrast, the IESWTR focuses primarily on achieving adequate disinfection and removal of pathogens to protect PWS customers from acute pathogenic exposure that can cause outbreaks of waterborne disease. Since the Stage 1 DBPR is intended to minimize the formation of DBPs and residual disinfectants, this rule may conflict with the IESWTR which specifies levels of treatment techniques required for *Cryptosporidium*.

As a result of the potential conflict inherent in these two rules, EPA sponsored an extensive negotiation process during the development of these regulations. This regulatory negotiation process included extensive input from a variety of stakeholders and resulted in the specific requirements described in Chapter 2.

Both the Stage 1 DBPR and the IESWTR are based on “best available science.” Early in the regulatory negotiation process, the Negotiating Committee agreed that the large amount of information necessary to understand how to optimize the use of disinfectants while concurrently minimizing microbial and DBP risks were unavailable. Some of this information, however, will become available as results from ICR are collected and analyzed. Nevertheless, in the interim, it was agreed that EPA would propose the IESWTR and Stage 1 DBPR to extend coverage to community and nontransient, noncommunity public water systems using disinfectants. The Stage 1 DBPR is applicable to all community and nontransient noncommunity systems, while the IESWTR affects only PWSs serving 10,000 or more people that use surface water or ground water under the direct influence of surface water. EPA will promulgate the Long-Term 1 ESWTR, which will update the IESWTR requirements and extend the regulations to systems serving less than 10,000 persons. Using ICR data and associated research, EPA expects to propose the Stage 2 DBPR and Long-Term 2 ESWTR in late 2000, with promulgation scheduled for May 2002.

This chapter provides technical guidance for addressing many of the issues associated with meeting the different objectives of the Stage 1 DBPR and the IESWTR. Achieving simultaneous compliance for both rules may have significant impacts on many systems. In a few cases, treatment process changes to achieve compliance with one of the regulations may impair a system's ability to meet the requirements of the other regulation unless other changes are made. Conversely, compliance with one regulation may enhance a system's ability to meet the requirements of the second regulation. This chapter highlights many of these potential conflicts between the Stage 1 DBPR and the IESWTR and discusses how compliance can be achieved concurrently.

This chapter focuses on three key regulatory components: profiling and benchmarking, inactivation requirements for non-profiling water systems, and enhanced coagulation considerations relating to turbidity.

3.2 DBPR versus IESWTR Microbial Profiling/ Benchmarking

The IESWTR requires Subpart H¹ systems serving 10,000 or more people to develop a disinfection profile (a compilation of daily *Giardia lamblia* and/or virus log inactivations over a period of a year or more) if the average concentration of TTHMs or HAAs in the distribution system is within 80 percent of the Stage 1 DBPR requirements in the 12 months prior to rule promulgation. According to this standard, applicable PWSs must develop a disinfection profile if either of the following conditions exist:

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

The threshold value of 80 percent of the new MCLs was chosen to identify systems that may have to make significant disinfectant changes to comply with the new MCLs. This excludes systems that experience minor variations in DBP levels due to factors such as seasonal changes in source water quality or water demand. The goal of the IESWTR profiling requirement is to identify a "benchmark" of the existing disinfection level being achieved by the targeted system. The disinfection benchmark is the lowest monthly average value (for systems with one year of profiling data) or average of lowest monthly average values (for systems with more than one year of profiling data) of the monthly logs of *Giardia lamblia* inactivation in each year of profiling data (USEPA, 1998b). The IESWTR requires States to review disinfection profiles when conducting sanitary surveys of their PWSs. If a PWS decides to make a significant change in its disinfection practices, the system will need to consult with the State before

implementing the change. This is especially important if the PWS is also required to develop a disinfection profile since it needs to ensure that the disinfection reached with the new process is not less than the benchmark level. Significant changes to a disinfection process may include the following:

- Moving the point of disinfection application (e.g., from raw water inlet point to post-sedimentation point)
- Changing the type of disinfectant used (e.g., from chlorine to ozone)
- Changing the disinfection process (e.g., changing the contact basin geometry or increasing the pH prior to disinfection by greater than one unit (chlorine only))
- Making any other change designated as significant by the State (e.g., changing the raw water source).

Supporting materials for a State consultation include a description of the proposed change, the disinfection profile, and an analysis of how the proposed change will affect the current disinfection benchmark. For additional information on disinfection profiling and benchmarking, refer to EPA's *Disinfection Profiling and Benchmarking Guidance Manual* (1999a).

Several issues are associated with the significant changes to a disinfection process identified above. These issues affect a PWS's ability to achieve compliance with the Stage 1 DBPR and the profiling requirements of the IESWTR. The following sections highlight and present recommendations for addressing some of these issues. This discussion also includes information on how to use water temperature measurement as a tool to reduce DBP formation.

3.2.1 Moving the Point of Disinfectant Application

3.2.1.1 Issues

Public water systems with a conventional treatment plant might consider moving the application point for their disinfectant downstream to reduce the concentration of DBP precursors in contact with the disinfectant. Raw water can include DBP precursors in both dissolved and particulate forms. In conventional treatment, dissolved precursors must be converted to particulate form during coagulation for subsequent removal during settling and filtering. Depending on the plant, THM formation potential can be decreased by up to 50 percent, as a result of conventional coagulation and settling due to the removal of precursors. This indicates the importance of moving the point of chlorine application after coagulation and settling (and even filtration) in order to control DBP formation (Singer and Chang, 1989).

¹ Subpart H Systems are public water systems that use surface water or ground water under the direct influence of surface water, in whole or in part.

Moving the point of chlorination from pre-rapid mixing to post-rapid mixing may be beneficial in reducing TOX. Solarik et al. (1997) claimed that moving the point of chlorination from pre- to post-rapid mixing was beneficial in six out of 11 waters tested with varying TOX reductions by 1 to 40 percent.

Plants that use conventional water treatment and disinfect raw water prior to filtration generally have adequate contact time to achieve the IESWTR disinfection requirements. When moving the point of disinfection downstream in the treatment process, a PWS must consider the reduced contact time available and the maximum residual concentration that can be maintained under the provisions of the Stage 1 DBPR. Disinfection compliance is measured by CT values (i.e., the residual disinfectant concentration multiplied by the contact time). Increasing CT (and thus inactivation) can be achieved by raising the residual disinfectant concentration through a disinfection zone to compensate for the reduced contact time. Moreover, higher disinfectant doses for the same water disinfectant demand will result in higher residual concentrations, which can cause greater formation of DBPs. However, raising the residual disinfectant concentration has to be within the limits of the MRDL and CT credit is not allowed for chlorine residual levels above 3.0 mg/L.

In addition to evaluating residual disinfectant concentrations, the hydraulic conditions of the downstream processes must be examined to determine if adequate contact time is available. If the disinfectant application point is moved downstream of clarification, filtration units and piping will generally have favorable hydraulic characteristics for contact time, but clearwells, if not properly baffled, might exhibit hydraulic short-circuiting. Therefore, if clearwell contact is needed to maintain disinfection compliance, the clearwells may need to be baffled to eliminate short-circuiting and to achieve adequate contact time. Similarly, the use of storage tanks for contact time might be complicated by fluctuating storage volumes. The amount of contact time achieved is to be based on worst-case conditions, generally considered to be when water in the storage tank is at its lowest level or when storage is bypassed altogether (i.e., during high demand periods).

3.2.1.2 Recommendations

If a PWS opts to move its disinfection point as a control strategy for meeting the Stage 1 DBPR, the following strategies can be implemented to aid the system in maintaining its benchmark for microbial protection and in meeting the requirements of the IESWTR:

- Evaluate the CT that may be achieved downstream of the new application point to ensure that the benchmark CT can be maintained. The evaluation should include a review of temporal changes to understand seasonal impacts on CT as a result of moving the point of disinfection (e.g., during cold weather when higher CT values are needed or during warm weather when the pH of the water drops as a result of runoff). Increased CT can be gained by raising the

residual concentration through the disinfection zone. However, appropriate disinfectant residual concentrations must be determined that will result in an acceptable level of DBP formation and meet the MRDL requirements of the Stage 1 DBPR.

- Examine hydraulic conditions so as to maximize contact time, which will decrease the required disinfectant residual concentration. If disinfection is moved downstream of clarification, contact time can be achieved in filters, piping, and clearwell storage tanks. However, clearwells may have to be modified (e.g., baffling and/or improved inlet and outlet structures added) to improve their hydraulic performance. Constructing additional storage or dedicated disinfection contact basins can allow the system to gain additional contact time.
- Evaluate the operational impacts on coagulation, filter fouling, algal growth, oxidation of iron and manganese, control of tastes and odors, and other issues. Systems may not be able to completely eliminate pre-disinfection but may be able to reduce levels or use alternative oxidants. This is discussed in greater detail in the *Alternative Disinfectants and Oxidants Guidance Manual* (USEPA, 1999b) and the *Guidance Manual for Enhanced Coagulation and Precipitative Softening* (USEPA, 1999g). It is important to note that the oxidation of iron and manganese can be accomplished without maintaining a disinfectant residual (or even maintaining a minimum residual), and DBPs will not always form to appreciable levels in the absence of a disinfectant residual.

3.2.2 Changing the Type of Disinfectant(s) Used

3.2.2.1 Issues

The formation of DBPs and the reactions between the different disinfectants and the precursors present in water are complex. A comprehensive discussion of the factors dictating the formation of DBPs by the various disinfectants can be found in EPA's *Alternative Disinfectants and Oxidants Guidance Manual* (1999b). In general, halogenated organic byproducts are formed when NOM reacts with free chlorine or free bromine present in the water. Free bromine results from the oxidation of bromide ion in the source water by chlorine, chlorine dioxide, or ozone. The factors affecting the formation of both halogenated and brominated DBPs include the:

1. Type and concentration of natural organic matter present
2. Disinfectant type and dosage
3. Contact time
4. Bromide ion concentration
5. pH
6. Temperature

7. Mixing conditions of the water and disinfectant.

Nonhalogenated DBPs can also form when strong oxidants react with various compounds found in the water. Ozone can oxidize organics to form aldehydes, aldo- and keto-acids, organic acids, and brominated organics in the presence of bromide ion (Singer, 1992). Many of these byproducts are simple organic compounds that are more available as a substrate to microorganisms and appear as biodegradable dissolved organic carbon (BDOC) and assimilable organic carbon (AOC) in the treated water. AOC, or the fraction that is assimilated by specific strains of heterotrophic organisms, namely *Pseudomonas fluorescens* and *Spirillum NOX*, contributes to the growth of biofilms in the distribution system, while BDOC is defined as the carbon in dissolved organic compounds that are biodegradable by microorganisms (e.g., carboxylic acids and carbohydrates). The presence of AOC or BDOC creates a water quality issue, as it may lead to the presence of opportunistic pathogens in drinking water. In addition, chlorine dioxide forms the inorganic DBPs chlorite ion and chlorate ion upon oxidation of compounds in water.

EPA and the Association of Metropolitan Water Agencies funded a two-year study of 35 water treatment facilities to evaluate DBP production. Among four of the facilities, 11 alternative disinfection strategies were investigated to evaluate the difference in DBP production from the plants' previous disinfection strategies (or base disinfection conditions). Three reports (Metropolitan and Montgomery, 1989; Jacangelo et al., 1989; USEPA, 1992a) analyzed and documented different aspects of the study.

Table 3-1 presents the ten potential strategies that may be used for primary and secondary disinfection. Table 3-2 lists the changes in DBP production observed in the four plants after new disinfection strategies were implemented.

Table 3-1. 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
Chloramine/Chloramine	Ozone/Chloramine
Ozone/Chlorine	Ozone/Chloramine

Note: Disinfectants are listed as primary disinfectant/secondary disinfectant

As can be seen from Table 3-2, changing primary and secondary disinfectants might not lead to reductions in DBP levels for all systems, the table does demonstrate how changes in disinfection practices at several different Utilities resulted in a reduction (or no change) in TTHM and HAAs formation. These results may differ depending on the water quality.

In general, the EPA study found that by carefully selecting the primary and secondary disinfectant based on source water quality and by avoiding long contact times and high dosages of DBP-forming disinfectants, the total DBP formation declined. However, it is important to understand that when changes are made in the disinfectants used, each disinfectant has different pathogen inactivation mechanisms, resulting in variations in inactivation effectiveness. As a result, the CT requirements for the various disinfectants can be radically different. For instance, the CT required for chloramines to achieve 1-log inactivation of *Giardia* is about 18 times greater than the CT required for free chlorine. Therefore, if a PWS is considering changing from chlorine to chloramines, CT will have to be achieved either by raising the residual concentration in the disinfection zone or by increasing the contact time. As described in the previous section, the MRDLs included in the Stage 1 DBPR can limit the levels to which the disinfectant residual can be raised.

If a PWS evaluates its current disinfection strategy and decides to modify the type of disinfectant used, the evaluation should ensure that the disinfection requirements of the SWTR and IESWTR are also met.

Selection of the most appropriate disinfectant requires balance between the following three key factors:

- Meeting the disinfection requirements
- Avoiding the production of excessive levels of DBPs
- Balancing the formation of DBPs from different disinfectants
- Maintaining a disinfectant residual in the distribution system without increasing DBP formation.

If a new disinfectant is evaluated, DBP precursors, primarily in the form of TOC and bromide ion concentration, should be examined along with the required log inactivation required to meet the disinfection requirements. High levels of TOC and bromide ion concentrations indicate a high potential for DBP formation.

Table 3-2. Impacts of Disinfection Practice on DBP Formation

Changes in Disinfection Practices (Primary/Secondary)	Change in DBP Formation				
	Chlorine/Chlorine To Chlorine/Chloramines	Chlorine/Chlorine To Ozone/Chlorine		Chlorine/Chloramines to Ozone/Chloramines	Chlorine/Chlorine to Chloramines/Chloramines
Disinfection By-Product	Utility #7	Utility #19	Utility #36	Utility #7	Utility #36
Total Trihalomethanes	Decrease	Decrease	No change	Decrease	Decrease
Haloacetic Acids	Decrease	Decrease	No change	Decrease	Decrease
Haloacetonitriles	Decrease	Decrease	No change	Decrease	Decrease
Haloketones	Decrease	No change	Increase	Increase	Decrease
Aldehydes	Not analyzed	Not analyzed	Increase	Not analyzed	Decrease
Chloropicrin	No change	Increase	Increase	Decrease	No change
Cyanogen Chloride	No change	Not analyzed	No change	No change	Increase

Changes in Disinfection Practices (Primary/Secondary)	Change in DBP Formation				
	Ozone/Chlorine To Ozone/Chloramines	Chloramines/Chloramines To Ozone/Chloramines		Chlorine/Chlorine To Ozone/Chloramines	
Disinfection By-Product	Utility #36	Utility #25	Utility #36	Utility #7	Utility #36
Total Trihalomethanes	Decrease	Decrease	No change	Decrease	Decrease
Haloacetic Acids	Decrease	Decrease	No change	Decrease	Decrease
Haloacetonitriles	Decrease	No change	No change	Decrease	Decrease
Haloketones	Decrease	No change	Increase	Decrease	Decrease
Aldehydes	Decrease	Increase	Increase	Not analyzed	Increase
Chloropicrin	Increase	Increase	Increase	Decrease	Increase
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: USEPA, 1992a; Jacangelo et al., 1989; Metropolitan and Montgomery, 1989.

If ozone is selected as the primary disinfectant, the potential for biological regrowth in the distribution system should also be evaluated closely. As stated previously, ozone can change the nature of the TOC present in the water and increase the biodegradable portions of the TOC (measured as BDOC and AOC). These two measurements evaluate the portion of the TOC in the water that can be utilized readily as food by microorganisms. Elevated BDOC and AOC levels can result in significant biological regrowth in a distribution system, and, hence, provisions must be made to minimize biological activity in the distribution system or remove the AOC during treatment. AOC reduction is often accomplished by the use of biologically active filtration or carbon filtration after ozonation.

In addition, if the primary disinfectant is changed, the use of an alternative oxidant in the raw water may be required. Raw water oxidants have uses other than disinfection. They are often used to achieve the following:

- Control nuisance Asiatic clams and zebra mussel
- Oxidize iron and manganese
- Remove tastes and odors
- Improve coagulation and filtration efficiency
- Prevent algal growth in the treatment plant prior to disinfection.

EPA's *Alternative Disinfectants and Oxidants Guidance Manual* (1999b) includes a discussion of many alternative oxidants for raw water and their effectiveness for accomplishing treatment objectives other than disinfection.

If a new secondary disinfectant is contemplated, the major considerations for implementation are DBP formation potential and distribution system retention time. Free chlorine continues to form DBPs until precursors are exhausted or the chlorine residual is diminished. Distribution systems with long retention times can cause elevated DBP levels. Long retention times with chlorine dioxide residuals can generate elevated chlorite ion and chlorate ion levels. Chloramines, which are weaker disinfectants, do not form appreciable DBPs and are often used as secondary disinfectants to control DBP formation when residence time is long.

3.2.2.2 Recommendations

If a PWS is considering a change in disinfectants, it should consider the following strategies during evaluation and implementation of the change:

- For facilities that add chlorine early in the treatment process (e.g., to the raw water) and form excessive levels of DBPs, strong consideration should be given to eliminating or reducing this practice and focusing on the addition of free chlorine after TOC reduction by coagulation. If a pre-disinfectant or oxidant is required to meet CT requirements or accomplish other treatment

requirements, consideration should be given to an alternative disinfectant such as chlorine dioxide or ozone, both of which can achieve disinfection and provide chemical oxidation for taste and odor and inorganic pollutant control.

- If a change in disinfectant strategy is desired, the new strategy should be bench-tested and piloted. Table 3-3 presents a summary of the treatment properties of eight different disinfectants to help assist PWSs in the selection of new primary and/or secondary disinfectants. The information in Table 3-3 serves as a basis for selecting the most appropriate disinfectant and addresses many of the key technical and regulatory issues that must be assessed. The characterizations in Table 3-3 are based on typical disinfectant applications. Thus, even though chlorine is considered to be prone to THM formation, the table does not address the degree or amount of THMs produced. Similarly, more than 2-log inactivation could be achievable for some disinfectants, but the high dose required may not be a reasonable. Detailed information on the properties and use of alternative disinfectants is provided in EPA's *Alternative Disinfectants and Oxidants Guidance Manual* (1999b).
- A disinfection strategy that may become more attractive to many PWSs involves the use of chlorine dioxide as a primary disinfectant (within allowable concentrations) and chloramines as a secondary disinfectant. Chlorine dioxide provides rapid inactivation of pathogens and some preliminary oxidation benefits without the formation of halogenated DBPs. However, chlorine dioxide dosage is limited by the formation of the inorganic DBPs chlorite ion and chlorate ion. Under the Stage 1 DBPR, the use of chlorine dioxide requires additional monitoring to address the acute risk associated with the use of chlorine dioxide. Chlorine dioxide must be measured daily at the entrance to the distribution system. Chlorite must be monitored in the distribution system three times per month. Chloramines serve to maintain a long-term distribution system residual without forming high levels of DBPs (refer to EPA's *Alternative Disinfectants and Oxidants Guidance Manual*, 1999b).

Table 3-3. Summary of Disinfectant Properties

Condition	Chlorine	Ozone	Chlorine Dioxide	Permanganate ¹	Chloramine	Ozone/Peroxide ¹	Ultraviolet ¹
Produce THM with TOC	y	s	n	n	y	s	n
Produce oxidized organics	s	y	s	s	n	y	s
Produce halogenated organics	y	s	n	n	y	s	n
Produce inorganic byproducts	n	s	y	n	n	s	n
MRDL applies	y	n	y	n	y	n	n
Lime softening impacts	y	n	n	n	y	n	y
Turbidity impacts	n	s	n	n	n	s	y
Meet <i>Giardia</i> - <2.0 log	y	y	y	n	n	n	n
Meet <i>Giardia</i> - >2.0 log	n	y	y	n	n	n	n
Meet <i>Crypto</i> - <2.0 log	n	y	y	n	n	n	n
Meet <i>Crypto</i> - >2.0 log	n	y	n	n	n	n	n
Meet Virus - <2.0 log	y	y	y	n	n	n	y
Meet Virus - >2.0 log	y	y	y	n	n	n	y
Secondary disinfectant	y	n	s	n	y	n	n
Operator skill (1=low; 5=high)	1	5	5	1	3	5	3
Applicable to large utilities	y	y	y	y	y	y	n
Applicable to small utilities	y	n	n	y	y	n	y

y = yes, n = no, s = sometimes

¹ Not approved for compliance with SWTR inactivation requirements

3.2.3 Temperature Effects on Chlorine and DBP Formation

3.2.3.1 Issues

In general, as temperature increases, a greater potential for DBP formation normally results. This occurs as a result of chlorine being more effective at higher temperatures, resulting in faster chemical reactions. Also, at higher temperatures chlorine is a more effective disinfectant because of the disinfection kinetics. Warm surface waters also typically support more organic growth and thus have elevated levels of NOM. Conversely, the increase in chlorine effectiveness at higher temperatures can be beneficial to the disinfection process since less chlorine or less contact time is required to provide adequate log inactivations of *Giardia* and viruses. This characteristic allows the reduction of chlorine dosage or contact time in warm weather without compromising microbial protection, which can assist in limiting DBP formation.

3.2.3.2 Recommendations

If elevated levels of DBPs are formed in a warm water source, PWSs may employ the following strategies:

- In all cases, PWSs should closely monitor DBP formation at higher water temperatures to ensure that the MCLs are not exceeded. If increased monitoring shows that DBP formation is not a concern at higher temperatures, then monitoring at regular intervals should suffice.
- Since chlorine effectiveness increases at higher temperatures, PWSs should consider reducing the disinfectant dose in warm weather to reduce the formation of DBPs. However, the disinfectant dosage may not be lowered below the point of compliance with all other rules, such as what is dictated by the SWTR (USEPA, 1989a).
- If DBP production cannot be controlled by the reduction of disinfectant dosage in warm water, PWSs should consider other modifications to the disinfection scheme such as moving the point of disinfection application or the use of an alternative disinfectant for primary or secondary disinfection. Systems may be able to use these strategies on a seasonal basis.

3.2.4 pH Effects on Chlorine

3.2.4.1 Issues

As discussed in Chapter 2, the pathogen inactivation of free chlorine is dependent on disinfection pH. Therefore, the pH maintained in the treatment process can impact the level of inactivation achieved. However, pH changes also can have wide ranging impacts on treatment chemistry and should be evaluated carefully. Typical impacts of pH changes can include changes in coagulation chemistry, floc settling characteristics, sludge dewatering, and corrosion potential.

Since the CT required for disinfection is lower at reduced pH levels, the required chlorine dose is lower, thus reducing the amount of free chlorine available for DBP formation. As a result, DBP formation may be reduced as pH is lowered (which may not be true for specific DBPs such as HAAs). The formation of some DBPs, such as HAAs, increases at lower pH levels, however, the low CT required at the lower pH may be partially offset by this increase.

3.2.4.2 Recommendations

pH adjustments may be made to stabilize finished water, aid inorganic constituent removal, and enhance coagulation to achieve TOC removal. Strategies for maintaining adequate disinfection levels include:

- Maintaining a low pH after chlorine application and during the required disinfection contact time. Since chlorine is more effective at lower pHs, the benchmark CT can be achieved with a lower chlorine dosage, thus generally reducing the formation of DBPs (although some may be increased). This strategy may result in corrosion impacts at locations with depressed pH levels, such as in clearwells and piping, unless the system takes adequate precautions.
- Carefully evaluating pH adjustment prior to implementation. Variation of pH levels can affect treatment chemistry and result in impacts to coagulation, settling, and sludge dewatering. Variations in pH can also create problems with the solubility of inorganic constituents and result in impacts such as increased iron and manganese levels in the treated water or the reformation of insoluble calcium carbonate particles in lime softened waters. Both of these effects are aesthetic issues and can result in increased finished water turbidity and precipitation in piping.

3.2.5 Case Study

Case Study No. 1 presents an example of how the DBP MCLs were met after changing the disinfectant and manipulating pH levels and contact times while also achieving the required pathogen inactivation.

Case Study No. 1: Simultaneous Compliance between DBPR and SWTR by Changing the Disinfectant and Manipulating pH Levels and Contact Time

Background

The following case study describes how Plant A could simultaneously comply with the DBPR, the IESWTR, and the SWTR. The design parameters (including treatment processes), and raw and finished water quality of Plant A (serving 25,000) people are provided below.

Source Type:	Surface Water
Flow Rate:	Average Daily Flow - 2 mgd Design Flow - 4 mgd
Treatment System:	Rapid Mix Coagulation/Flocculation (alum, 20 mg/L; theoretical detention time - 1 hour) Sedimentation (theoretical detention time - 3 hours) Filtration (No. of units - 5, single media, loading rate 2 gpm/ft ²) Clearwell (theoretical detention time - 30 min) Disinfection points of application <ul style="list-style-type: none">- raw water inlet (maximum chlorine dose - 5.0 mg/L)- clearwell water inlet (maximum chlorine dose - 5.0 mg/L)
Raw Water Quality:	TOC - 3.0 mg/L pH - 7.8 Alkalinity - 100 -120 mg/L as CaCO ₃ Turbidity - 20 to 110 NTU
Finished Water Quality:	TOC - 1.8 (40 percent removal) pH - 7.1 Residual Chlorine - 2 mg/L Alkalinity - 70 to 95 mg/L as CaCO ₃ Turbidity - 0.1 NTU
Distribution System Water Quality:	TTHM - 0.095 mg/L (Running Annual Average)* HAA5 - 0.050 mg/L (Running Annual Average)*

* profiling required

Simultaneous Compliance Issues

Stage 1 DBPR. The Stage 1 DBPR requires a TOC removal of 25 percent (based on influent TOC and alkalinity conditions). The TOC removal achieved was 40 percent, which is greater than the minimum percent removal of TOC required. TTHM level in the distribution system is required to be below the specified MCL of 80 µg/L. The residual chlorine is required to be below the specified MRDL of 4.0 mg/L.

SWTR. The SWTR requires Plant A to achieve 3-log inactivation/removal of *Giardia* and a 4-log inactivation/removal of viruses. The State credits this plant with a 2.5-log removal for *Giardia* for conventional filtration. Plant A must maintain a CT of 25 mg-min/L to achieve the additional 0.5-log inactivation of *Giardia* with chlorine at 10°C with pH 7.1. The CT value of 25 mg-min/L corresponds to pH 7.5 (i.e., the conservative approximation method is used to determine CT value rather than the linear interpolation method). Disinfection profiling and benchmarking are required and any significant change in the treatment must be preceded by consultation with the State.

Potential Conflicts. Reducing chlorine dose levels to achieve the desired DBP levels and MRDL levels may jeopardize meeting the required CT levels. Lower free chlorine levels make it difficult to meet CT requirements. Enhanced coagulation will require the coagulant dosage to be increased or the coagulant changed (e.g., ferric chloride) resulting in a lower pH level than that of the raw water. Excess coagulant and pH adjustment might affect disinfectant efficacy. Additionally, problems with biofouling of distribution network may occur causing the TTHM MCL to be exceeded. Moreover, the system making significant changes in disinfection practices may choose under State guidance to develop an alternative disinfection benchmark and must consult with the State prior to making any significant modifications.

Steps to Resolve Conflicts and Results Achieved

Plant A makes three modifications to its treatment practices so that it may simultaneously comply with the SWTR and the Stage 1 DBPR.

In the first modification, the plant switches to chloramine as the secondary disinfectant during the summer months when the water is the warmest and biological growth is the highest. Because chloramines do not react with NOM to form significant amounts of TTHMs, the plant is able to comply with the Stage 1 DBPR. The plant is also able to meet the 0.5-log *Giardia* inactivation CT requirement for chlorine at the higher temperature using a dose of 3.5 mg/L. The Stage 1 DBPR MRDL for chloramine of 4.0 mg/L is also not exceeded.

In the second modification, the plant operator reduces the pH level by adding an acid and employing enhanced coagulation. It should be noted that the system already meets the TOC removal requirements. The plant operators employ enhanced coagulation to further reduce DBP precursors and save money as a result of reduced chlorine demand. Because chlorine is more effective as a disinfectant at lower pH levels, the system achieves the required inactivation. The lower chlorine dose results in reduced DBP levels and the system is in compliance with both the DBPR and the SWTR. However, low pH and alkalinity (due to enhanced coagulant dosage), together with an increase in the chloride concentration (if ferric chloride is used) could result in a potential LCR compliance problem.

In the third modification, Plant A moved the point of primary disinfectant application to the filter discharge, and improved the baffle conditions in the clearwell to increase the disinfectant contact time to attain the required CT. The plant is able to meet the required CT of 25 using a free chlorine residual of 3.0 mg/L. Also, since disinfection takes place after the NOM is removed, the TTHM level is considerably reduced to below the MCL.

3.3 DBP MCLs and Inactivation Requirements for Non-Profiling Water Systems

As discussed previously, PWSs with DBP levels below 0.064 mg/L for TTHM and 0.048 mg/L for HAA5, based on annual averages, are not expected to make significant modifications to their disinfection process to comply with the Stage 1 DBPR. Therefore, the Stage 1 DBPR does not require disinfection profiles for these water systems. As a result, only a few potential challenges exist in complying with the Stage 1 DBPR and maintaining microbial protection.

3.3.1 Issues

The Stage 1 DBPR establishes MRDLs for the various disinfectants. PWSs cannot exceed these concentration levels in the water distribution system based on a running average of the last 12 monthly averages. This running annual average is computed every 3 months. While not experiencing significant DBP formation, some systems may have large distribution systems with long residence times. Systems that use free chlorine as a residual disinfectant may experience significant residual concentration decay in areas of the distribution system with long detention times due to such factors as corrosion and regrowth. As a result, some systems may have historically maintained disinfectant residual concentrations at very high levels in the distribution system to achieve the required minimum residual concentration levels at all locations in the system. It is possible that these high concentrations can exceed the MRDLs.

3.3.2 Recommendations

To reduce the amount of disinfectant needed to maintain the minimum required levels in all areas of the distribution system, the utility should consider the following activities:

- Implementation of an aggressive flushing program in the long-detention time areas of the system. Flushing can purge the system of “old” water as well as scour the piping to remove biogrowth.
- Evaluating distribution system corrosion potential to ensure that the corrosion of ferrous surfaces is not causing elevated disinfectant demand. If corrosion appears to be a problem, a corrosion control plan may be required.
- Evaluating the use of booster disinfection at key locations in the distribution system rather than maintaining high concentration levels in the finished water.

3.4 Stage 1 DBPR Enhanced Coagulation and IESWTR Turbidity Requirements

Subpart H PWSs using conventional treatment (i.e., coagulation, sedimentation, and filtration) or precipitative softening to meet the MCL and MRDL requirements of the Stage 1 DBPR must also comply with the TOC removal requirements listed in the rule. Typically, enhanced coagulation or enhanced softening is used to meet TOC requirements in these instances. Enhanced coagulation includes the addition of higher levels of a coagulant to achieve TOC removal and may include lowering of the coagulation pH. Enhanced coagulation has shown to be an effective strategy for reduction of DBP precursors by reducing a portion of the NOM prior to disinfectant addition for many systems (Krasner and Amy, 1995). However, the effect of enhanced coagulation on pathogen removal/inactivation has not been widely investigated. Recent work indicates that moving from conventional to enhanced coagulation tends to improve particulate and microbial removal.

The remainder of this section defines the issues related to enhanced coagulation and how these issues relate to particulate and microbial control. Following this introduction, specific impacts and conflicts that might result from implementation of enhanced coagulation are presented.

3.4.1 DBP Control

One of the best methods to minimize DBP formation is to remove DBP precursors (e.g., natural organic material) prior to adding a disinfectant. As noted above, EPA has determined that “enhanced coagulation” is an effective technique for DBP precursor removal.

Chemical coagulation with aluminum (i.e., alum) and iron (i.e., ferric) salts is most often utilized for turbidity removal. These two coagulants can also remove certain portions of the NOM present in water, if dosage and pH conditions are optimized. Typically, enhanced coagulation can remove the hydrophobic portions of the NOM, which generally consist of the humic substances found in the water. The hydrophilic portion of the NOM, which are generally the fulvic substances, is much more difficult to remove by coagulation. Therefore, the effectiveness of TOC removal by enhanced coagulation is dependent on the relative portions of hydrophobic and hydrophilic materials present in the water.

For alum, the optimal pH for NOM removal ranges from 5.5 to 6.0, while the optimum pH range for ferric salts is slightly lower. Ferric salts appear to perform better for TOC removal for equivalent doses of the metal coagulant than alum in some situations. In addition, the ferric salts are stronger acids and tend to lower pH more per mass dose of coagulant than alum, thereby reducing the amount of coagulant required to achieve the optimum pH range. However, waters with very high alkalinity may require the addition of an acid, while very low

alkalinity waters may require the addition of a base to reach the optimal NOM coagulation pH (Singer, 1992)

The NOM removal required under the Stage 1 DBPR is based on the surrogate parameter TOC. The TOC removal percentages, summarized in Chapter 2, depend on the amount of TOC and alkalinity present in the raw water. Since the removal of TOC is dependent on the make-up of the organics present, the character of the NOM present will dictate the amount of TOC actually removed.

As required under the Stage 1 DBPR, Subpart H systems using conventional treatment must use enhanced coagulation or enhanced softening to remove TOC unless they meet one of the following alternative compliance criteria:

- The system's source water or treated water TOC level, is < 2.0 mg/L.
- The system's source water TOC level, prior to any treatment, is < 4.0 mg/L; the alkalinity is > 60 mg/L; and the TTHM annual average is 0.040 mg/L and the HAA5 annual average is 0.030 mg/L or the system has made an irrevocable financial commitment to achieve these levels.
- The system's TTHM annual average is 0.040 mg/L and the HAA5 annual average is 0.30 mg/L and the system uses only chlorine for primary disinfection and maintenance of a disinfectant residual.
- The system practices softening and removes at least 10 mg/L of magnesium hardness (as CaCO_3), except for systems that use ion exchange (applicable for systems that use enhanced softening only).
- The system has a source water or treated water SUVA 2.0 mg/L-m. If a PWS can demonstrate that the NOM present has a SUVA of less than this level (which indicates that the NOM present is primarily hydrophilic), the system does not have to comply with the TOC removal requirements in the rule.
- The system has lowered the treated water alkalinity to < 60 mg/L as CaCO_3 (applicable for systems that use enhanced softening only).

In instances where little TOC can be removed by coagulation, the Stage 1 DBPR allows a system to comply with the TOC removal requirements by achieving a "point of diminishing return" (PODR). The PODR is the coagulant dose beyond which less than 0.3 mg/L of TOC is removed for every additional 10 mg/L alum dosage (or equivalent ferric dose).

According to some studies (Krasner and Amy, 1995; White et al., 1997; Arora et al., 1997), many facilities will have a difficult time meeting the TOC removal criteria due to the characteristics of the NOM present. Based on available research, the difficulty in removing TOC appears to be particularly applicable to waters low in TOC and high in alkalinity. Jar tests have shown that waters high in TOC and low in alkalinity had the highest probability of meeting the TOC removal requirements, while waters low in TOC and high in alkalinity typically reached the PODR before meeting the criteria (Krasner and Amy, 1995; White et al., 1997; Arora et al., 1997).

To assist PWSs in achieving optimum coagulation for TOC removal, it may be beneficial to consider the addition of an acid to reduce the pH prior to adding a coagulant. By doing so, the optimal pH level for NOM removal can be achieved with a lower quantity of coagulant needed to meet TOC removal requirements. Since acids are typically more economical than coagulants, it may be cheaper to use the coagulant only for coagulation purposes and use an acid for pH reduction. In addition, water with low alkalinity may need to have alkalinity added, as chemical coagulation and certain acids, such as sulfuric acid and other acids that are likely to be used to adjust pH in a water treatment design, will consume alkalinity from the water.

3.4.2 Pathogen Inactivation/Removal

Traditionally, filtration and disinfection have been the mechanisms by which pathogens have been removed and/or inactivated in potable water. Disinfection has been characterized by the log inactivation achieved under specific disinfection conditions. Research has shown that sedimentation alone following coagulation may provide only small reductions of viruses and moderate (i.e., 20 to 35 percent) removals of bacteria and coliforms (Abbaszadegan et al., 1997). The removal of microorganisms is primarily due to the adsorption of the microbial contaminants onto the coagulant, the floc formed in the coagulation process, and through physical removal during the settling of flocs.

Most studies dealing with enhanced coagulation have focused on NOM and/or TOC removal as outlined above. As a result, little is known of the effect of enhanced coagulation on pathogen removal. One recent study indicated that the overall average of microbial log removal under optimized coagulation conditions for viruses, parasites, and bacteria were higher than the baseline practices with the same coagulant type (Abbaszadegan et al., 1997). Therefore, it might be expected that enhanced coagulation practices could improve pathogen removal. This outcome is likely the result of pathogens adsorbing onto larger metal hydroxide flocs which are subsequently removed by sedimentation and filtration.

3.4.3 Issues and Recommendations for Simultaneous Compliance

Employing enhanced coagulation and/or other alternative TOC removal technologies should improve the overall water treatment process, as many DBP precursors will be removed. By doing so, less disinfectant will be needed for pathogen inactivation as less DBP precursors will be present to be oxidized (i.e., lower disinfectant demand). Furthermore, enhanced coagulation should also improve the sedimentation of microbial particles, as the additional coagulant will provide an opportunity for larger particle growth and more spatial area coverage of settling flocs. As a result, properly implemented enhanced coagulation may improve compliance with both the Stage 1 DBPR and the IESWTR.

However, there are some specific simultaneous compliance issues with respect to the IESWTR that result from optimizing TOC removal with enhanced coagulation for Stage 1 DBPR compliance. Many of these issues and subsequent recommendations are presented in the following subsections.

3.4.3.1 Enhanced Coagulation and Turbidity Requirements

Issues

As mentioned previously, the IESWTR has new, more restrictive turbidity requirements for surface water or GWUDI systems that use conventional filtration treatment or direct filtration and serve 10,000 or more people. The primary purpose of the turbidity requirements is the improved removal of particulates, especially pathogens. High levels of turbidity exert an oxidant demand and may prevent inactivation by shielding the pathogens.

The available research suggests that enhanced coagulation generally improves overall filtration performance by reducing particle loading on the filter media. Enhanced coagulation may improve the capture of small previously unfilterable particles due to the larger floc formation. Care should be taken, however, since excess coagulant can form a film on the filter surface or solubilize/precipitate upon final pH adjustment.

In addition, pH adjustment to acceptable levels (i.e., between pH 6 and 8.5) can also cause solubility problems with several inorganic contaminants. If pH adjustment is not carefully planned, systems may experience increased levels of turbidity from iron and manganese precipitation. Lime softening plants can also cause calcium carbonate to precipitate after pH adjustment, which will also affect turbidity. However, the rule does allow the acidification of turbidity samples that will dissolve calcium carbonate which may have formed after pH adjustment.

Recommendations

In general, employing enhanced coagulation should assist facilities in meeting the turbidity requirements set forth in the IESWTR. Meeting the required turbidity levels will improve disinfection by limiting the effluent water disinfectant demand. It also appears that the turbidity requirements associated with the IESWTR are achievable for most PWSs, especially if filter-to-waste is employed for ripening filters (McTigue and Cornwell, 1997).

In cases where facilities do not meet the combined filter effluent turbidity requirements after backwashing, consideration should be given to a filter-to-waste period for the first 30 to 60 minutes after backwashing individual filters. If filter-to-waste cannot be provided, post-backwash turbidity spikes can also be controlled by reducing the start-up filtration rate or by adding coagulant polymer or a coagulant aid to the backwash water to facilitate ripening.

To ensure that the proper coagulant dose is applied and to minimize overdosing, extensive bench and/or pilot studies should be performed to determine the coagulant dose required for enhanced coagulation under various operating conditions. The coagulant feed should then be flow paced to ensure that the proper coagulant concentration is provided through all flow regimes. Other strategies for maintaining optimal coagulant dosages include:

- Careful evaluation of pH adjustment prior to implementation. Variation of pH levels can affect treatment chemistry and the effectiveness of chlorine and result in impacts to settling and sludge dewatering. Variations in pH can also create problems with the solubility of inorganic constituents and result in impacts, such as increased iron and manganese levels or the recalcification of lime softened waters, resulting in increased turbidity.
- Maximizing turbidity removal by continually seeking to optimize the treatment process (refer to EPA's *Guidance Manual for Compliance with the Interim Enhanced Surface Water Treatment Rule: Turbidity Provisions* (1999e)).
- Using acid to lower pH into the optimum range for TOC removal in lieu of overdosing coagulant, which can be more expensive and impact turbidity, particle removal, and sludge handling.
- Using jar tests regularly to maintain proper coagulant dose for enhanced coagulation.
- If applicable, switching coagulants. In some cases, ferric salts have proven to be more effective than aluminum salts in the removal of microorganisms by enhanced coagulation.
- Using filter aids/polymers during coagulation. Synthetic organic polymers can be used in addition to or in place of alum and ferric salts based on the results of bench pilot tests.

Strategies are discussed in greater detail in the *Guidance Manual for Enhanced Coagulation and Precipitative Softening* (USEPA, 1999g). This manual also discusses operational problems that may occur.

3.4.4 Case Study

Case Study No. 2 presents an example of how compliance issues for the TOC removal requirements of the DBPR were met using enhanced coagulation while also achieving the turbidity removal requirements of the IESWTR.

Case Study No. 2: Simultaneous Compliance between TOC Removal and Turbidity

Background

The following case study describes how Plant B could simultaneously comply with the TOC removal requirements of the DBPR and the turbidity removal requirements of the IESWTR. The design parameters (including treatment processes), and raw and finished water quality of Plant B (serving 700,000) people are provided below.

Source Type:	Surface Water
Flow Rate:	Average Daily Flow - 50 mgd Design Flow - 100 mgd
Treatment System:	Rapid Mix Coagulation/Flocculation (alum, 20 mg/L) Sedimentation (theoretical detention time - 3 hours) Filtration (No. of units - 50, single media, loading rate 2 gpm/ft ²) Clearwell (theoretical detention time - 30 min) Disinfection (maximum chlorine dose - 5.0 mg/L, point of application - raw water inlet)
Raw Water Quality:	TOC - 7.0 mg/L pH - 7.3 Alkalinity - 60 to 80 mg/L as CaCO ₃ Turbidity - 45 to 110 NTU
Finished Water Quality:	TOC - 4.9 (30 percent removal) pH - 6.5 Alkalinity - 40 to 60 mg/L as CaCO ₃ Turbidity - 0.2 NTU Residual Chlorine - 2.0 mg/L
Distribution System Water Quality:	TTHM - 0.090 mg/L (Running Annual Average)* HAA5 - 0.045 mg/L (Running Annual Average)*

* profiling required

Simultaneous Compliance Issues

IESWTR. The IESWTR requires the combined filtered water effluent turbidity to be less than 0.3 NTU in at least 95 percent of the measurements taken each month, with measurements being taken at continuously at 4-hour intervals, and less than 1 NTU at all times. Disinfection profiling and benchmarking are required and any significant change in the treatment must be preceded by consultation with the State.

Stage 1 DBPR. The Stage 1 DBPR requires a TOC removal of 35 percent (based on influent TOC and alkalinity conditions). The TTHM in the finished water is required to be below the specified MCL of 80 µg/L and residual chlorine is required to be below the specified MRDL of 4.0 mg/L. Enhanced coagulation, which requires the coagulant dosage to be increased, will remove DBP precursors and limit the formation of DBPs to within the MCLs.

Potential Conflicts. Increased coagulant dosage and pH adjustment after coagulation may cause an increase in turbidity. Excess coagulant can form a film on the filter surface, and which may solubilize and then precipitate upon post-filtration final pH adjustment.

Steps to Resolve Conflicts and Results Achieved

To comply with Stage 1 DBPR requirements for TOC, Plant B employed enhanced coagulation. The coagulant dosage was increased to 30 mg/L which helped achieve a 40 percent reduction in TOC from 7.0 mg/L to 4.2 mg/L but resulted in a decrease in pH to 6.5. A pH adjustment was necessary after treatment to raise the finished water pH to its previous level at 7.3. Due to the additional removal of DBP precursors, a lower chlorine dose of 4.0 mg/L was sufficient to meet chlorine demand and provide a chlorine residual of 2.0 mg/L. The TTHM in the finished water was reduced to 60 µg/L which is below the MCL.

To meet the turbidity requirements for the IESWTR, the operators ensured that the coagulant dosage applied for enhanced coagulation was proper and hence, minimized overdosing. Bench and pilot studies were performed initially to determine the appropriate dose, and the dose was checked regularly through additional jar tests. Operators also ensured that the coagulant feed is flow paced and proper coagulant concentration is provided at all times.

3.4.4.1 Enhanced Coagulation and Cryptosporidium Removal

Issues

As stated previously, most research on enhanced coagulation reports that particulate removal is usually improved under enhanced coagulation conditions as compared to conventional coagulation. However, some research has indicated that overdosing coagulant chemicals to maximize TOC removal may reduce *Cryptosporidium* removal (Ollier et al, 1997). As a result, until further research either confirms or contradicts the results of the Ollier study, PWSs should closely monitor turbidity to ensure particle removal is maintained throughout enhanced coagulation practices. Particle counting can also be used to monitor the size range of the

particles passing through the filter to ensure that particles in the *Cryptosporidium* size range are removed.

Recommendations

Some strategies available to maintain *Cryptosporidium* removal during enhanced coagulation include the following:

- Maximize turbidity removal by continually seeking to optimize the treatment process.
- Use acid to lower pH into the optimum range for TOC removal in lieu of overdosing the coagulant, which can impact turbidity.
- Use jar tests regularly to maintain proper coagulant dose for enhanced coagulation and turbidity removal.
- Use particle counters to monitor the size of particles passing through the filters to ensure that *Cryptosporidium*-sized particles are being removed. Note that particle counting cannot be used as a surrogate for pathogens but it can provide information on changes in particle size distribution and removal.
- Particle counters may also detect particle breakthrough well in advance of increased headloss and be used to optimize the filtration process.
- Employ enhanced coagulation and, if applicable, consider switching to a ferric salt coagulant, as this has proven to be more effective, in some cases, in the removal of microorganisms.

3.4.4.2 pH and Chlorine Effectiveness

Issues

Due to a variety of factors, the effectiveness of chlorine as a disinfectant is enhanced at lower pH levels. Thus, the CT values required for *Giardia* decrease as pH levels decrease (AWWA, 1991). If chlorine is used as a disinfectant, the impact of pH changes resulting from enhanced coagulation (both pH depression during coagulation and pH adjustment prior to distribution) should be considered if the adjustment occurs in a chlorine disinfection zone.

The pH of the water being chlorinated has an impact on the formation of halogenated byproducts (Reckhow and Singer, 1985; Stevens et al., 1989). Since the application of chlorine dioxide and chloramines introduces free chlorine into water, chlorination byproducts that may be formed would be influenced by pH. Although many DBPs do not exhibit any changes relating to water pH, THM formation increases with increasing pH and the formation of trichloroacetic acid, dichloroacetonitrile, and trichloropropanone decreases with increasing pH. Overall, TOX formation decreases with an increase in pH.

High pH tends to favor chloroform formation over the formation of trichloroacetic acid and other organic halides (Singer and Chang, 1989). Ozone application to bromide ion-containing waters at high pH favors the formation of bromate ion, while application at low pH favors the formation of brominated organic byproducts. Table 3-4 discusses how the pH of water being chlorinated impacts the formation of halogenated byproducts.

Recommendations

To maintain the effectiveness of chlorine as a disinfectant, the following pH control strategies are available:

- Keep pH low after chlorine application and during the required contact time. Since chlorine is more effective at lower pH levels, the required CT can be achieved with a lower chlorine dosage. The rate of TTHM formation should be reduced, but HAA5 levels may not be reduced.
- Carefully evaluate pH adjustment prior to implementation. Variation of pH levels can affect treatment chemistry and result in impacts to settling and sludge dewatering in addition to the effects on chlorine. Variations in pH can also create problems with the solubility of inorganic constituents and result in impacts such as increased iron and manganese levels or, in the treated water, the recalcification of lime softened waters resulting in increased turbidity and levels of copper and lead in the treated water.
- Evaluate pH effects on the treatment plant (i.e., pipes, tanks, etc.).

Table 3-4. Conditions of Formation of DBPs

Byproduct	Conditions of Formation		
	Chlorination at pH 5.0	Chlorination at pH 7.0	Chlorination at pH 9.4
Total Trihalomethanes	Lower formation		Higher formation
Trichloroacetic Acid	Similar formation	Similar formation	Lower formation
Dichloroacetic Acid	Similar formation - perhaps slightly higher at pH 7.0	Similar formation - perhaps slightly higher at pH 7.0	Similar formation - perhaps slightly higher at pH 7.0
Monochloroacetic Acid	At concentrations <5 µg/L, trends not discernible	At concentrations <5 µg/L, trends not discernible	At concentrations <5 µg/L, trends not discernible
Dibromoacetic Acid	At concentrations <1 µg/L, trends not discernible	At concentrations <1 µg/L, trends not discernible	At concentrations <1 µg/L, trends not discernible
Chloral Hydrate	Similar formation	Similar formation	Forms within 4 hours; decays over time to <5 µg/L
Chloropicrin	At concentrations <1 µg/L, trends not discernible	At concentrations <1 µg/L, trends not discernible	At concentrations <1 µg/L, trends not discernible
Dichloroacetonitrile	Higher formation	Forms within 4 hours; decays over time to <5 µg/L	Concentrations <2 µg/L, trends not discernible
Bromochloroacetonitrile	At concentrations <2 µg/L, trends not discernible	At concentrations <2 µg/L, trends not discernible	At concentrations <2 µg/L, trends not discernible
Dibromoacetonitrile	At concentrations <.5 µg/L, trends not discernible	At concentrations <.5 µg/L, trends not discernible	At concentrations <.5 µg/L, trends not discernible
Trichloroacetonitrile	Not detected	Not detected	Not detected
1,1,1-Trichloropropanone	Higher formation	At concentrations <2 µg/L, trends not discernible	Not detected

Source: Stevens et al., 1989

Case Study

Case Study No. 3 presents an example of how the pathogen removal/inactivation requirements were met under high pH conditions while also complying with lime softening requirements.

Case Study No. 3: Simultaneous Compliance between Lime Softening and DBP MCLs

Background

The following case study describes how Plant C could simultaneously comply with lime softening requirements and meet the DBPR MCLs using chlorine as the disinfectant. The design parameters (including treatment processes), and raw and finished water quality of Plant C (serving 200,000 people) are provided below.

Source Type:	Surface Water
Flow Rate:	Average Daily Flow - 20 mgd Design Flow - 40 mgd
Treatment System:	Rapid Mix Coagulation/Flocculation (alum, 20 mg/L, lime softening, detention time 45 min) Sedimentation (theoretical detention time - 6 hours) Filtration (No. of units - 20, single media, loading rate 2 gpm/ft ²) Clearwell (theoretical detention time - 30 min) Disinfection (maximum chlorine dose - 12 mg/L, point of application - raw water inlet)
Raw Water Quality:	TOC - 7.0 mg/L pH - 7.3 Alkalinity - 50 to 60 mg/L as CaCO ₃ Turbidity - 45 to 110 NTU Total Hardness - 140 mg/L as CaCO ₃
Finished Water Quality:	TOC - 4.2 (40 percent removal) pH - 8.5 Alkalinity - 90 to 100 mg/L as CaCO ₃ Turbidity - 0.2 NTU Total Hardness - 60 mg/L as CaCO ₃ Residual Chlorine - 4.0 mg/L
Distribution System Water Quality:	TTHM - 0.090 mg/L (Running Annual Average)* HAA5 - 0.045 mg/L (Running Annual Average)*
* profiling required	

Simultaneous Compliance Issues

SWTR. The SWTR requires Plant C to achieve 3-log removal of *Giardia* and 4-log removal of viruses. The State credits the system with 2.5-log removal for *Giardia* for conventional filtration. Plant C must maintain a CT value determined by the State at 65 mg-min/L.

Lime Softening. Lime softening is used by PWSs to reduce the total hardness of the treated water. Because lime softening occurs at pH values above 9, the finished water from softening plants often has an elevated pH. Disinfection may not be effective at high pH conditions.

Stage 1 DBPR. The Stage 1 DBPR reduces the MCL of TTHMs in the finished water to 80 µg/L; the current TTHM concentration at Plant C is 90 µg/L. Also, the MRDL for chlorine is set at 4.0 mg/L. Plant C also needs to reduce the residual chlorine level. Plant C determined high chlorine dosages are used under high pH conditions to achieve the desired pathogen inactivation.

Potential Conflicts. High CT values are required for effective chlorine disinfection in waters with elevated pH levels during lime softening. High chlorine doses required under these high pH conditions may result in formation of DBPs and excess chlorine residuals. However, no CT credit is given for the chlorine residuals greater than 3.0 mg/L.

Steps to Resolve Conflicts and Results Achieved

Plant C is currently adding chlorine for disinfection at the raw water inlet. Disinfection is not effective at the high pH (9.5 to 11.5) required for lime softening. The plant determined that changing the point of application to after lime softening and pH adjustment increased the disinfection effectiveness. The plant is required to consult with the State prior modifying its disinfection practice and disinfection profiling and benchmarking also is required. Hydrochloric acid was used to decrease the pH to 8.5 prior to filtration. The hydraulic performance of the clearwell storage tank was improved by adding baffles to increase the contact time. The plant reduced the chlorine dose to 5.0 mg/L while still achieving the CT disinfection requirements. Adequate contact time was achieved in the filters, piping, and the clearwell storage tanks. Additional storage tanks or contact basins were not necessary.

The pH adjustment reduced the finished water pH to 8.5 which allowed Plant C to reduce the chlorine residual concentration to 2.0 mg/L. This reduced chlorine dose also helped reduce the TTHM concentration to 62 µg/L, which is within the required level of 80 µg/L.

3.4.4.3 Prechlorination and TOC Removal

Issues

Prechlorination, which is chlorine addition prior to sedimentation and/or filtration, is often practiced to increase the available CT, and thus, the log inactivation of *Giardia* and viruses. This process often improves coagulation processes, and it often improves water quality by

increasing taste and odor control and inorganic contaminant removal through the oxidation of both organic and inorganic constituents. All of the effects of adding chlorine prior to enhanced coagulation are not well documented. It is known, however, that during prechlorination, free chlorine will react with the organic material in the raw water to form DBPs. Therefore, since some precursors in the raw water are converted into DBPs, prechlorination may conflict with the purpose of enhanced coagulation, which is the removal of precursors before DBPs are formed. In addition, research suggests that prechlorination can also impact TOC removal in lime softening processes (AWWA, 1990).

Recommendations

Where prechlorination is reducing the effectiveness of enhanced coagulation for TOC removal and/or is increasing the distribution system DBPs to levels above Stage 1 DBPR requirements, the following strategies are available to address the issues associated with enhanced coagulation:

- Change the predisinfectant from chlorine to an alternate disinfectant such as chlorine dioxide, ozone, or another oxidant. These chemicals are strong oxidants, as well as very effective disinfectants, that can in certain instances reduce DBP formation. PWSs, however, should be aware of other issues associated with the use of these disinfectants. For example, chlorine dioxide forms the inorganic DBPs, chlorite and chlorate. Ozone can form a variety of DBPs depending on water quality. In addition, ozone can increase the biodegradable portion of TOC remaining in the water, which can lead to biological regrowth in the distribution system. Similarly, water systems may opt to use chloramine to disinfect and maintain a residual. If the system intends on switching to ozone or chloramine for primary disinfection, disinfection profiling and benchmarking for virus disinfection is required. Also, systems switching to chlorine dioxide should strongly consider profiling and benchmarking for virus disinfection. All systems switching to an alternative disinfectant are required to consult with the State prior to changing disinfection practices. A more detailed discussion of alternative disinfectants available for use can be found in the *Alternative Disinfectants and Oxidants Guidance Manual* (USEPA, 1999b). A more detailed description of disinfection and profiling requirements can be found in the *Disinfection Profiling and Benchmarking Guidance Manual* (USEPA, 1999a).
- Consider eliminating prechlorination (during certain seasons) and relying on disinfection downstream of clarification. This approach will require recalculation of the available CT to ensure that adequate disinfection is maintained. If the available CT does not meet the log inactivation requirements, the facility can consider increasing the free chlorine residual (within the limit of the MRDLs) to meet the required CT value or maintain a lower pH in the disinfection zone as discussed previously, or increase contact time by adding storage or changing the baffling conditions in the clearwells. Note that if prechlorination is discontinued, the system may need to consider an alternate raw water oxidant (e.g., potassium

permanganate) or other treatment technology to control tastes and odors or enhance iron and manganese removal.

- If prechlorination is not impeding a system from achieving TOC removal requirements and maintaining distribution DBP levels, then a facility is not required to modify any of their disinfection practices. However, in this case, a facility should closely monitor DBP levels to ensure continued compliance with DBP requirements. The system may wish to profile to better understand inactivation and DBP formation relationships and then be able to modify operations.

3.4.4.4 Enhanced Coagulation and Distribution System Surfaces

Issues

As mentioned previously, enhanced coagulation typically includes lowering the coagulation pH to levels optimal for TOC removal. An additional pH adjustment is required to stabilize the water chemistry and bring the water to acceptable pH levels prior to distribution. However, any changes in the pH levels historically maintained in the distribution system can disrupt any films and scales that have accumulated on natural corrosion surfaces. These films and scales have formed over long periods of time and serve to passivate the corrosion process from further development. A pH change can disrupt these surfaces releasing inorganic contaminants as well as microbes and TOC trapped in the films and scales, and increase corrosion release rates.

Although disruption of the corrosion surfaces in the distribution system may not result in a direct violation of either the Stage 1 DBPR or the IESWTR, the disruption could cause aesthetic problems or the release of microbes and pathogens. However, if TOC is released from the corrosion surfaces, the TOC could react with free chlorine to form more chlorinated DBPs, which could cause a violation of the Stage 1 DBPR. In addition, the release of microbes could cause a violation of the Total Coliform Rule, and further corrosion could impact compliance with the Lead and Copper Rule. These latter impacts are addressed in Chapters 4 and 5 of this guidance manual, respectively.

Recommendations

The primary strategies available for addressing the impacts of enhanced coagulation on distribution systems are as follows:

- Attempt to maintain the distribution system pH (and alkalinity) at historic levels after implementing enhanced coagulation. The pH adjustment prior to distribution should be designed to return the water chemistry to a stable, or slightly scaling, condition that is similar to the historic finished water quality. This approach will significantly reduce the potential for attack on corrosion surfaces from a more aggressive water that may result from a pH change.

- If it is difficult to maintain the distribution system pH at current levels after enhanced coagulation is employed, a program can be implemented to strategically flush the distribution system to scour biofilms and remove dissolved encrustation materials before they are released into the water. After flushing, the system should evaluate the corrosion potential and either stabilize water chemistry or institute a corrosion control program to ensure that the continuation of corrosion and the associated dissolution of corrosion surfaces is minimized.

3.5 Summary and Recommendations

In summary, compliance with the Stage 1 DBPR will, in many instances, enhance a system's ability to comply with the IESWTR. However, in some cases, simultaneous compliance will involve systems performing a delicate balancing act between many issues and may require significant treatment modifications to be made. Alternative technologies for TOC removal may be required, as well as an evaluation of current disinfection strategies. PWSs should consider the following items when complying with both the Stage 1 DBPR and the IESWTR:

- Practice enhanced (or optimized) coagulation. Enhanced coagulation will remove DBP precursors and help improve disinfection efficiency. Optimize the coagulation process for maximum turbidity removal.
- Conduct rigorous monitoring of the treatment process, including jar testing, DBP monitoring, and TOC measurement, to ensure that proper coagulation is occurring and impacts to other treatment processes are being minimized.
- Evaluate alternative treatment technologies for TOC removal compliance and additional DBP precursor removal.
- Consider modifying disinfection strategy. Strategies such as the use of free chlorine, chlorine dioxide, or ozone followed by chloramination may provide the benefit of pretreatment oxidation and pathogen inactivation with reduced formation of DBPs.
- Monitor turbidity levels and particle counts to evaluate filter performance and minimize impacts to particle removals. Consider filter-to-waste or other backwash treatment strategies to limit turbidity spikes during the filter ripening period after backwashing.
- Continually seek to optimize water treatment processes to balance particle removal, disinfection of pathogens, and control of DBPs.

*3. SIMULTANEOUS COMPLIANCE ISSUES BETWEEN STAGE 1 DBPR AND
IESWTR*

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4. SIMULTANEOUS COMPLIANCE ISSUES BETWEEN THE STAGE 1 DBPR, THE IESWTR, AND LEAD AND COPPER RULE

Conflicts between the Stage 1 DBPR, IESWTR, and the LCR can occur when the chemical stability of drinking water is affected. Lead and copper are released into drinking water by corrosion, specific chemical measures such as pH and alkalinity adjustment and the addition of corrosion inhibitors are employed. Certain actions that may be necessary for PWSs to comply with the Stage 1 DBPR, such as enhanced coagulation, can upset the established operating chemistry in a system by lowering the pH. Similarly, certain actions that may be necessary for PWSs to comply with the IESWTR, such as removing additional turbidity, can be affected by the addition of chemicals that inhibit corrosion.

This chapter briefly discusses the LCR and presents several potential conflicts between the Stage 1 DBPR, the IESWTR, and the LCR. It includes discussion of the following topics:

- pH impacts
- Turbidity issues
- Microbial re-growth issues
- Enhanced coagulation issues
- Disinfection strategy issues.

Under each topic area, issues are presented and possible solutions for resolving these conflicts are provided. PWSs have recently had to determine the actions they would take to comply with the LCR. Compliance with the Stage 1 DBPR and IESWTR will complicate corrosion control issues. Additional research into these issues are needed. Systems intending to make “significant changes” to the treatment process, such as disinfection or coagulation changes, may wish to employ coupon tests in the distribution system before and after the changes are made to better understand the impact of change on corrosion control.

4.1 Overview of the Lead and Copper Rule

The 1986 Amendments to the SDWA required EPA to promulgate drinking water standards for contaminants that impose potential adverse health risks. Lead and copper were specifically listed in the 1986 SDWA amendments for mandatory development of a National Primary Drinking Water Regulation. EPA responded to this mandate by promulgating the LCR (USEPA, 1991). The stated goal of the LCR is to “minimize lead and copper at users’ taps while ensuring that the treatment does not cause the system to violate any national primary

drinking water regulation” (USEPA, 1991). This goal will be accomplished through the application of corrosion control strategies (i.e., varying pH levels, alkalinity levels, and inhibitor requirements). The corrosion control steps are necessary for a PWS to minimize lead and copper concentrations at its customers’ taps.

The LCR action levels for lead and copper are 0.015 mg/L and 1.30 mg/L, respectively, at the 90th percentile of the samples measured at customer taps. Monitoring for a variety of water quality parameters is required. In addition to monitoring, all large PWSs (i.e., those systems serving more than 50,000 people) are required to conduct corrosion studies to determine optimal lead and copper corrosion control strategies. For smaller PWSs, corrosion control studies are not required unless the action limits are exceeded.

4.1.1 Lead and Copper Corrosion Control Strategies

Under the LCR, the action level triggers steps to be taken by the PWS to remain in compliance with the LCR. The PWS is required to explore:

1. Public education
2. Source water treatment
3. Corrosion control practices, and, if corrosion control treatment fails,
4. Lead pipe replacement.

As part of the corrosion control study, the LCR mandates PWSs to consider the following three basic approaches for achieving corrosion control:

- pH/alkalinity adjustment
- Corrosion inhibitor addition
- Calcium adjustment (i.e., CaCO₃ deposition).

When tailoring a program to meet the specific needs of a particular PWS, characterization of corrosion controls is necessary. Corrosion control technologies can be characterized by two very general mechanisms, each of which has a multitude of variations that carry specific advantages and disadvantages. These mechanisms are:

- Barrier Protection – The deposition of a precipitate film on plumbing surfaces to prevent oxidizing agents in the water from reaching the plumbing surface and/or oxidized metals on the plumbing surface from leaching into the water.
- Passivation – The manipulation of the water chemistry so that the plumbing material and a number of soluble water constituents react to form protective surface compounds that limit the

release of metal into the water. The degree of passivation is a function of the electrical properties of the surface compounds formed.

Passivation occurs at a specific anodic overpotential (i.e., a deviation from the equilibrium corrosion potential) called the passivation potential (i.e., E_{pp}) and is characterized by a sudden drop/reversal in the anodic current density with a very slight increment in the anodic overpotential. This transformation of the anodic current behavior occurs over a 5-10 mV range. Beyond this overpotential value, there is a zone where anodic current density is virtually becomes independent of overpotential. About 40-100mV above E_{pp} (depending on the water chemistry, surface film characteristics etc.), the passivated surface becomes unstable and the anodic current density thus starts increasing with increasing overpotential, once again. The key to this form of protection is to be able to control the applied anodic potential to about 20-40 mV above E_{pp} .

Table 4-1 summarizes the various chemical treatment systems available to promote barrier protection and/or passivation. Each of these approaches must be evaluated relative to dosage range and specific water quality concerns. Moreover, it should be realized that a particular treatment approach will not be universally effective on all metal types and that corrosion control must be tailored to the plumbing material of interest (i.e., lead or copper) and water characteristics.

Table 4-1. Summary of Corrosion Control Approaches

Treatment Approach (Control Mechanism)	pH/Alkalinity Adjustment (Passivation)	Corrosion Inhibitor Addition (Passivation)	Calcium Carbonate Adjustment (Barrier)
Key Water Quality Parameters	pH, alkalinity, Total Dissolved Solids (TDSs), temperature	pH, metals, hardness, temperature	Calcium, pH, alkalinity, TDS, temperature
Potential Chemical Feed Systems	Lime (Calcium Oxide) Soda Ash (Sodium Carbonate) Potassium Carbonate Sodium hexa-metaphosphate Sodium Bicarbonate Sodium Hydroxide (Caustic Soda) Potassium hydroxide Carbon Dioxide	Orthophosphate Polyphosphate Phosphate blends Silicates Silicate/phosphate blends	Lime (Calcium Oxide) Soda Ash (Sodium Carbonate) Sodium Bicarbonate Sodium Hydroxide (Caustic Soda) Carbon Dioxide

Adjusting the pH or alkalinity of the water offers “passive” protection from corrosion. Moderate increases in pH/alkalinity normally induce the formation of less soluble hydroxyl-

carbonate compounds on the lead or copper piping material. If the alkalinity of the water is increased to high levels (usually > 250 mg/L of CaCO₃) corrosive conditions for copper are recreated. This is due to the high propensity of cupric ions (Cu²⁺) to form carbonate and hydroxy-carbonate complexes and the consequent shift in the equilibrium of the following reaction to the right.



The corresponding lead complexes are less soluble and hence form a protective scale that results in better protection from high alkalinity waters.

The addition of corrosion inhibitor chemicals also reduces the corrosion potential of the water by forming a protective passivating film. Adding orthophosphate, blended phosphates, silicate, or a blend of these chemicals induces the formation of a less soluble compound that reduces corrosion or slows metal release from the targeted piping material (i.e., lead or copper).

In addition, calcium and/or carbonate additions elevate the pH level of the finished water. For corrosion protection, enough calcium and/or carbonate must be added to achieve the supersaturation and precipitation of calcium carbonate (CaCO₃) in the water. The precipitation collects on the piping material and acts as a barrier between the piping material from potentially corrosive conditions. Care must be taken not to over-precipitate calcium carbonate as this can result in pipeline plugging. Compared to lime or caustic addition, raising pH by aeration has several inherent advantages for copper corrosion control in low-pH, high alkalinity waters. These advantages are attributed to lower final alkalinity and a reduced likelihood of over-precipitation of calcite. Conversely, insufficient amounts of calcium carbonate precipitate may cause spotty surface coatings and lead to localized corrosion.

When selecting a lead and copper corrosion control strategy, it is important to understand the chemistry of the finished water. Important water quality parameters influencing lead and copper corrosion include the following (AWWA, 1990; AWWARF, 1985):

- pH
- alkalinity
- dissolved inorganic carbonate
- hardness
- conductivity/ionic strength
- reduction/oxidation (redox) potential
- residual chlorine
- temperature
- dissolved oxygen
- calcium
- magnesium
- sodium
- potassium
- bicarbonate
- sulfate
- chloride
- nitrate
- total dissolved solids

The relationships among these water quality parameters are such that changing one parameter will directly or indirectly impact the effect of the other chemicals on corrosion control (AWWA, 1990). For example, systems may increase the buffering capacity of their waters to control copper release. Buffering is provided in most distribution systems by dissolved inorganic carbon species (represented by $C_t = [\text{CO}_3^{2-}] + [\text{HCO}_3^-] + [\text{CO}_2(\text{aq})]$) and orthophosphate. There are however a number of trade-offs that need consideration. For example, the increase in C_t affects the aqueous phase chemical speciation of lead and copper, which in turn influences the corrosion reaction kinetics and equilibria. Moreover, addition of phosphoric acid or dissolved inorganic carbon (DIC) species increases the conductivity of the water, which could increase reaction kinetics and copper release by decreasing the chances of cuprous/cupric ion build-up at the metal-water interface. The increased conductivity results in increased copper by-product release and reduced scale formation. The above clearly demonstrates how various water quality parameters that influence lead/copper corrosion, are intricately interconnected.

4.1.2 LCR Compliance Relationships with the Stage 1 DBPR and the IESWTR

The control measures for LCR compliance consist of chemical additions to raise pH and alkalinity, and/or the addition of corrosion inhibitors. In general, control strategies for achieving compliance with the Stage 1 DBPR and IESWTR favor:

- Lowering pH to enhance coagulation to improve DBP precursor removal and chlorine disinfection efficiency; and
- Employing filtration and disinfection to improve microbial inactivation and to minimize DBP formation.

Table 4-2 summarizes the potential impact of LCR control strategies on the compliance requirements of the Stage 1 DBPR and IESWTR. Table 4-3 summarizes the potential impacts of control strategies for Stage 1 DBPR and IESWTR on LCR compliance requirements. These potential impacts are discussed in detail in the following sections.

4.2 pH Impacts on the LCR and the Stage 1 DBPR and the IESWTR

The pH adjustment presents compliance issues for the LCR and the Stage 1 DBPR and IESWTR in the following areas of water treatment and distribution:

- Coagulation
- DBP formation

4. SIMULTANEOUS COMPLIANCE ISSUES BETWEEN M-DBP RULES AND LEAD AND COPPER RULE

- Chlorine CT values.

This section presents issues and recommendations in these areas relative to pH levels.

Table 4-2. LCR Impacts on Stage 1 DBPR and IESWTR Requirements

Corrosion Control Treatment for LCR	Impacts on IESWTR Compliance	Impacts on Stage 1 DBPR Compliance
Increase pH	<ul style="list-style-type: none"> • Requires higher CT values for chlorine disinfection • Use of coagulants at higher pHs may increase residual aluminum concentrations 	<ul style="list-style-type: none"> • Increased THM formation • Higher CT requirement may increase disinfectant dosage and increase DBP formation potential
Alkalinity adjustment	<ul style="list-style-type: none"> • Coagulant chemical dosage may need to be adjusted to achieve optimal pH 	<ul style="list-style-type: none"> • None
Orthophosphate and/or Polyphosphate/blended phosphate addition	<ul style="list-style-type: none"> • May need to reduce optimum pH for aluminum precipitation • Turbidity increase from zinc carbonate precipitate, if zinc orthophosphate is used • Potential to stimulate regrowth in the distribution system. However, recent research indicates improved management of biological regrowth with the use of orthophosphates¹ • Increased turbidity from algae blooms in open finished water reservoirs is possible 	<ul style="list-style-type: none"> • None
Silicate addition	<ul style="list-style-type: none"> • High silica levels can form precipitates, causing increased turbidity 	<ul style="list-style-type: none"> • None

¹ There has been a lot of speculation about the ability of orthophosphate and/or blended phosphates to stimulate regrowth in the system. Systematic studies documenting this fact are almost non-existent. However, post 1990 research conducted, by LeChavallier et al. (1993), shows improved disinfectant stability and less regrowth. Moreover, in most cases, carbon has been identified as the limiting nutrient and not phosphorous (C:N:P=100:20:10 is the optimal nutrient ratio that favors the growth of micro-organisms). Source: AWWARF, 1990c.

Table 4-3. Stage 1 DBPR and IESWTR Impacts on LCR Requirements

Stage 1 DBPR and IESWTR Control Strategy	LCR Impact
Increase disinfectant dose to meet CT requirements Enhance DBP precursor removal by optimizing coagulation Change disinfectants	Variable—Alters water chemistry for the treated water, which impacts the corrosion rate and metal release for lead and copper

Source: AWWARF, 1990b.

4.2.1 Coagulation

As stated in Chapter 3, chemical coagulation with aluminum (alum) and iron (ferric) salts can be an effective strategy for reducing DBP precursors (in the form of NOM) prior to disinfection. The optimal pH for NOM removal with alum is in the range of 5.5 to 6.0. Using ferric salts, the pH range is slightly lower (Singer, 1992).

4.2.1.1 Issues

Issues arise when pH and alkalinity levels are altered to achieve optimum NOM removal. Coagulants themselves consume alkalinity. For example, 0.5 mg alkalinity (as CaCO_3) is consumed per mg alum (Culp/Wesner/Culp, 1986). The changes in pH and alkalinity levels due to enhanced coagulation may impact the existing corrosion control scheme for lead and copper in the distribution system and may impact LCR compliance

Alternatively, the pH levels typically associated with lead and copper corrosion control reduce the effectiveness of coagulation. Ineffective coagulation may impact Stage 1 DBPR compliance (in addition to other operating problems). When coagulation or enhanced coagulation results in low pH or is practiced at low pH, the finished water pH level needs to be revised before being pumped to consumers. Coagulation and enhanced coagulation conducted at low pH levels often produce water that is supersaturated with carbon dioxide. For waters with sufficient levels of carbonate alkalinity, aeration (carbon dioxide stripping) could be an attractive low-cost option and could provide the flexibility to raise the pH without precipitating calcite or altering the alkalinity (Edwards et al., 1996). Also, caustic compounds, as detailed below, can be used to shift the system from carbon dioxide to bicarbonate/

4.2.1.2 Recommendations

Potential resolutions to the conflicts between the pH levels needed to minimize lead and copper corrosion and to enhance coagulation include:

- Adjusting pH prior to coagulation to optimize coagulation, sedimentation, and filtration.
- Readjusting pH levels in the finished water by chemical addition (see Table 4-1) following coagulation and filtration to pH and alkalinity levels prior to optimized coagulation. Several chemicals can be added to increase both pH and alkalinity levels in the finished water. Table 4-4 presents the chemicals commonly used for pH/alkalinity adjustment.
- Monitoring lead and copper corrosion rates in the distribution system and implementing an LCR compliance strategy (see Section 4.7 of this Chapter).

Table 4-4. Chemicals for pH Adjustment or Alkalinity Addition

pH/Alkalinity Adjustment Chemical	Alkalinity Added¹ (as mg CaCO₃ per mg dose)
Sodium Hydroxide (50% solution)	1.25
Lime, as Ca(OH) ₂	1.35
Soda Ash, Na ₂ CO ₃	0.94
Sodium Bicarbonate, NaHCO ₃	0.59

¹Sodium hydroxide and lime add hydroxide alkalinity only.

Soda ash and sodium bicarbonate add carbonate or bicarbonate alkalinity, depending on pH.

Source: AWWA, 1990.

4.2.2 DBP Formation

The pH of water has an impact on DBP formation when chlorine is used. Higher rates of TTHM formation occur at a pH level of 9.4, while HAA formation tends to remain constant or decrease with increasing pH level (Stevens et al., 1989). Lower pH levels decrease bromate ion formation while increasing brominated organic compound formation (Song et al., 1997).

4.2.2.1 Issues

When pH levels are increased in the finished water as a LCR compliance strategy, TTHM levels will increase in the distribution system if chlorine is used as the secondary disinfectant. The increase in TTHM levels in the distribution system may exceed the TTHM MCL of the Stage 1 DBPR.

4.2.2.2 Recommendations

Potential resolutions to the conflicts between pH and DBP formation include:

- Limiting pH levels in the distribution system to less than 8.2 to limit TTHM formation (Reiber et al., 1997). Four LCR compliance strategy case studies showed that TTHM increases were less than 20 percent if the pH shift implemented for lead and/or copper corrosion control was from near neutral to less than 8.2. When the pH was shifted from near neutral to greater than 8.5, TTHM production increased as much as 40 percent. At one plant, TTHM increases due to pH adjustment ranged from 2 percent at a pH of 8.1 up to 43 percent at a pH of 8.7. HAA production was shown to decrease (about 10 percent) for all of the pH increases implemented (Reiber et al., 1997).
- Switching the secondary disinfectant to a chemical producing fewer DBPs such as monochloramine, which does not produce DBPs to any significant degree.
- Implementating an alternative LCR compliance strategy using corrosion inhibitors or a combination of pH and alkalinity adjustment instead of just pH adjustment (see Table 4-1).

While increasing alkalinity in poorly-buffered waters helps, except for a few odd cases with lead, alkalinity adjustment alone is not often helpful, and may be counter-productive for copper.

4.2.3 Chlorine CT Values

CT values for *Giardia* inactivation by chlorine disinfection are pH dependent. For a given level of inactivation, the higher the pH, the higher the CT value required.

4.2.3.1 Issues

If pH increases for LCR compliance are implemented prior to disinfection, the chlorine CT values required for *Giardia* inactivation will be increased. Increased chlorine CT values require an increase in disinfection detention time and/or chlorine residual. For example, if the pH is increased from 6.0 to 9.0 prior to disinfection, then the CT value (at 0.6 mg/L residual chlorine and 10°C) will increase from 13 to 36 mg-min/L for 0.5 log *Giardia* inactivation (AWWA, 1991). To meet this increased CT value, the T_{10} ¹ must be increased from 22 to 60 minutes. If additional contact volume is not available, a chlorine residual of 2.0 mg/L is required corresponding to a CT of 44 mg-min/L, representing an increase in chlorine residual of more than three times the original residual level. Note that the chlorine residual increase (from 0.6 mg/L to 2.0 mg/L) is greater than the T_{10} increase (from 22 to 60 minutes) because the CT value required depends on chlorine residual level. Increasing chlorine residual levels or extending contact time may increase the rate of DBP formation and may cause DBP MCLs to be exceeded under the Stage 1 DBPR.

4.2.3.2 Recommendations

Potential resolutions to the conflicts between pH, chlorine CT values, DBP formation, and compliance with the LCR include:

- Relocating the application point for pH adjustment to a point after disinfection CT is achieved.
- Switching to an alternative primary disinfectant that is not pH dependent between the pH levels of 6.0 and 9.0 (e.g., chlorine dioxide, ozone, or monochloramine). Since ozone does not maintain an appreciable residual level, another chemical must be added for secondary disinfection (i.e., chlorine or monochloramine).
- Implementing an alternative LCR compliance strategy using corrosion inhibitors or a combination of pH and alkalinity adjustment (see Table 4-1).

¹ T_{10} is based on the detention time that is equaled or exceeded by 90 percent of the water passing through the basin. T_{10} is developed by measuring the peak hourly flow rate and using other plant hydraulic information.

4.2.4 Case Study

Case Study No. 4 presents an example of how the IESWTR pathogen removal/inactivation requirements were met while also achieving the LCR requirements.

Case Study No. 4: Simultaneous Compliance between Pathogen Removal/Inactivation and Lead and Copper Control

Background

The following case study describes how Plant D could simultaneously comply with the *Giardia* removal/inactivation requirements of the IESWTR and the lead and copper concentration requirements of the LCR. The design parameters (including treatment processes), and raw and finished water quality of Plant D (serving 500,000 people) are provided below:

Source Type:	Surface Water
Flow Rate:	Average Daily Flow - 40 mgd Design Flow - 80 mgd
Treatment System:	Rapid Mix Coagulation/Flocculation (alum, 20 mg/L) Sedimentation (theoretical detention time: 3 hours) Filtration (No. of units: 40, single media, loading rate 2 gpm/ft ²) Clearwell (theoretical detention time: 30 min) Disinfection (maximum chlorine dose: 7.0 - 8.0 mg/L, point of application - raw water inlet)
Raw Water Quality:	TOC - 3.0 mg/L pH - 6.5 Alkalinity - 20 to 40 mg/L Turbidity - 40 to 100 NTU
Finished Water Quality:	TOC - 2.1 mg/L (30 percent removal) pH - 6.0 Alkalinity - 20 to 35 mg/L Turbidity - 0.2 NTU Residual Chlorine - 1.0 mg/L
Distribution System Water Quality:	TTHM -0.090 mg/L* HAA5 -0.050 mg/L*

* profiling required

Simultaneous Compliance Issues

IESWTR. The IESWTR requires a 3-log removal/inactivation of *Giardia*. This is a total log removal/inactivation requirement which can be achieved by filtration and disinfection or disinfection alone. The IESWTR also requires the combined filtered water effluent turbidity to be less than 0.3 NTU in at least 95 percent of the measurements taken each month, with measurements being taken at 4-hour intervals, and less than 1 NTU at all times. Disinfection profiling and benchmarking are required and any significant change in the benchmark must be preceded by consultation with the State.

LCR. The LCR action level requirements for lead and copper are 0.015 mg/L and 1.30 mg/L, respectively, in 10 percent or more of the samples measured at customer taps. In addition, Plant D is required to conduct corrosion studies to determine optimal lead and copper corrosion control strategies.

Potential Conflicts. CT values for *Giardia* inactivation by chlorine disinfection are pH dependent. The CT required for disinfection is lower at reduced pH levels which reduces the chlorine dose. A lower dose of chlorine would likely result in a reduced amount of free chlorine available for DBP formation. However, low pH levels may result in increased lead and copper corrosion rates. Also, the additional chemicals that would be required to raise the pH to an optimum range might produce byproducts that would become a concern.

Steps to Resolve Conflicts and Results Achieved

To comply with IESWTR requirements for pathogen removal, Plant D employed primary disinfection at the raw water inlet at a pH level of 6.5. Enhanced coagulation was also applied to reduce TOC concentration by at least 35 percent, as required by the Stage 1 DBPR. The process of enhanced coagulation, however, reduced the pH level to 5.5. As such, a pH adjustment was necessary to raise the finished water pH to 7.5.

To comply with the LCR action level requirements for lead and copper, the operators planned on adding lime somewhere in the treatment train to increase pH to 7.5. The operators knew that adding lime may create a precipitate in the system that may either place additional load on the filters (possibly causing an IESWTR turbidity violation) or become a problem in the distribution system. Rather than creating a problem within the distribution system, plant operators decided to add lime prior to filtration and assess feed systems, mixing conditions and flow loading rates. The operators set up a bench scale test apparatus to demonstrate the amounts and the effectiveness of adding lime to the finished water and how often the filters need to be backwashed. In addition, the pH levels and turbidity in the finished

4.3 Turbidity

Filtered water turbidity levels must be maintained as required under the IESWTR. The maximum turbidity limits were developed to certify filter performance and provide high quality water for disinfection. Addition of the following chemicals can have a negative impact on filtered water turbidity:

- Zinc orthophosphate and silicate-based corrosion inhibitors
- Lime.

The following subsections present the issues and recommendations in these areas.

4.3.1 Corrosion Inhibitor Addition

Zinc orthophosphate and silicate-based corrosion inhibitors may slightly increase the turbidity of the finished water. The turbidity increase due to corrosion inhibitor addition is most likely a function of site-specific water quality parameters and the type of corrosion inhibitor used. Some of the products now sold as corrosion inhibitors were originally developed as sequestering agents for iron and manganese. The sequestering nature of the corrosion inhibitor may lead to increases in the turbidity of the water.

4.3.1.1 Issues

If zinc orthophosphate or silicate-based corrosion inhibitors are added prior to filtration, turbidity requirements of the IESWTR may be exceeded. This exceedance may be caused by either an inhibitor turbidity that cannot be removed by filtration or additional filter loading leading to premature filter breakthrough. Additional research in this area is needed.

4.3.1.2 Recommendations

Potential resolutions to the turbidity impacts of corrosion inhibitor addition include:

- Relocating the application point for zinc orthophosphate and silicate-based corrosion inhibitors downstream of filtration and disinfection contact. Moving the application beyond the point at which disinfection is complete reduces the impact of inhibitor turbidity on disinfection.
- Implementing an alternative LCR compliance strategy using other corrosion inhibitors or pH/alkalinity adjustment.

4.3.2 Lime Addition

Lime addition for LCR compliance or softening may slightly increase the turbidity of the water due to calcium carbonate precipitation.

4.3.2.1 Issues

Lime addition prior to filtration may create a precipitate that will place additional load on the filters. This additional load can lead to premature filter breakthrough and require more frequent backwashing. The extra load on the filters may cause the turbidity requirements of the IESWTR to be exceeded.

Lime addition after filtration may cause a precipitate in the distribution system. If the precipitate attaches to the walls of the pipe, barrier corrosion protection may be provided. If the precipitate remains in solution, it can lead to consumer complaints.

4.3.2.2 Recommendations

- Potential resolutions to the turbidity impacts of lime addition include:
- Recognizing the impact of the additional load due to lime precipitates on the operation of the filters. This recognition will require more frequent backwashing of the filters.
- Relocating the application point for lime downstream of filtration and disinfection. (This action may move the precipitate problem to the distribution system or the consumers' tap.)
- Implementing an alternative LCR compliance strategy using corrosion inhibitors or pH/alkalinity adjustment with a non-calcium chemical (such as sodium hydroxide).

4.4 Microbial Regrowth

Secondary disinfectant residual levels are maintained throughout the distribution system to prevent regrowth of microbes in the distribution system.

4.4.1 Phosphate Corrosion Inhibitor Addition

The addition of orthophosphate or polyphosphate corrosion inhibitors may stimulate regrowth in distribution system, which may impact TCR compliance. Similarly, phosphate based corrosion inhibitor addition to systems utilizing open finished water reservoirs can increase the potential for algae blooms (AWWARF, 1990c). However, post 1990 research has shown that there could be significant improvements in preventing biological regrowth by exercising good corrosion control in the distribution system. LeChavallier et al. (1993) have examined the relationship between iron corrosion and the disinfection of biofilm bacteria. Increased corrosion rates were found to reduce biofilm disinfection efficiency for both chlorine and monochloramine. For free chlorine, corrosion rates greater than 1 mpy (mils per year) reduced disinfection efficiencies to near zero. Monochloramine was less dramatically affected by corrosion with disinfection efficiencies dropping 10-fold for every 10-fold increase in the corrosion rate. The South Central Connecticut Regional Water Authority (SCCRWA) modified its corrosion program in September 1988, following several years of excessive coliform levels in the distribution system. Coliform growth was especially prolific in the iron tubercles within the distribution system pipelines. The utility increased the concentration of zinc metaphosphate from 1 to 2 mg/L (Smith et al., 1989). Total phosphorous concentrations in the distribution system increased from 0.31 to 0.43 mg PO₄-P/L (phosphate as phosphorous per liter of water). Although no immediate effect was observed, weekly coliform levels

significantly decreased from 12 percent to 5.1 percent over the following two-year period. Turbidity levels in the distribution system also decreased from 0.10 NTU to 0.04 NTU after the increase in the corrosion inhibitor dosage.

Several investigators (Opheim et al., 1988; Emde et al., 1992) have reported the occurrence of coliform bacteria in corrosion tubercles on iron pipes. Lowther and Mosher (1984) reported that levels of coliform bacteria decreased within a few weeks following the application of zinc orthophosphate in the Seymour, Indiana distribution system. Zinc orthophosphate also has been successfully used at other Indiana operations to control coliform occurrences (unpublished data). The need to achieve low corrosion rates for effective inactivation of biofilm bacteria demonstrates the importance of maintaining consistent corrosion control. Fluctuations in the water quality variables (pH, chlorine residuals and temperature) at the Swimming River treatment plant (American Water Works Service Co., NJ) probably made consistent corrosion control difficult despite addition of zinc orthophosphate and polyphosphate inhibitors (LeChavallier et al., 1987). Coliform bacteria were isolated from iron tubercles within this distribution system. One occurrence of coliform bacteria in the Swimming River distribution network followed the breakdown of the lime system. Although the connection between feeding lime and coliform bacteria was not understood at that time (i.e., 1985), subsequent research by LeChavallier et al. (1993) appear to indicate that corrosivity resulting from lower calcium carbonate levels would provide a better environment for bacterial growth. The elimination of distribution system coliform bacteria was due, in part, to improvements in the consistency of the operations at the Swimming River treatment plant.

4.4.1.1 Issues

Typically, the regrowth of microorganisms in the distribution system is nutrient-limited. In other words, the distributed water may contain limited amounts of phosphorous, nitrogen, and trace elements (such as potassium, magnesium, etc.) required for growth (Gaudy and Gaudy, 1980). Systems that use monochloramine as a secondary disinfectant increase the nitrogen content of the water through the addition of ammonia. Phosphorous can be added for corrosion control in the form of orthophosphates or polyphosphates. The addition of phosphorous increases the potential for regrowth in the distribution system, especially where monochloramine is used for secondary disinfection.

For example, nitrification was observed during demonstration testing of LCR control strategies at one plant. During one monitoring episode, chloramine residual levels were found to drop from 3.2 to 0.2 mg/L across a short pipe distance. This finding was attributed to the growth of nitrifying bacteria, which were limited until introduction of the phosphate-based corrosion inhibitor addition (Reiber et al., 1997).

Orthophosphate addition for the control of lead and copper corrosion in a low-DIC water at a pH of 7.5 will have a significant impact on reducing lead solubility. However, it may not improve copper control beyond that afforded by raising pH to 7.5 (Schock et al, 1995). For water systems not encountering lead material problems, however, doses of orthophosphate at 1.5 mg PO₄-P/L may be effective in controlling copper levels in new plumbing, at pH values less than 8.

4.4.1.2 Recommendations

- Potential resolutions to the regrowth impacts of phosphate-based corrosion inhibitor addition include:
 - Lowering the phosphate-based corrosion inhibitor dose to the practical minimum.
 - Implementing an alternative LCR compliance strategy using silicate-based corrosion inhibitors or pH/alkalinity adjustment.
 - Increasing secondary disinfectant residual levels in the distribution system to limit regrowth. (Increasing the disinfectant dose may increase DBP formation.)
- Minimizing sediment build-up and tuberculation in the distribution system will help to reduce disinfectant demand. This may require cleaning and flushing of distribution system sections and adjusting hardness, alkalinity and pH. Sediment from a system experiencing coliform regrowth episodes was shown to contain high levels of heterotrophic plate count (HPC bacteria (greater than 8×10^6 CFU/gm) and coliform organisms (LeChavallier et al., 1987). The sediment in this system was also covered by a layer of post-precipitation from improperly applied treatment chemicals. The control of sediment accumulation in distribution system pipelines by routine and aggressive flushing is important because even recalcitrant organic compounds can be slowly biodegraded in the sediments and provide an endogenous supply of nutrients. In another study by LeChavallier et al. (1996), involving seven free-chlorinating systems, the majority of the systems that had low occurrence rates for coliforms (< 0.5 percent of the samples tested positive for coliforms), flushed 100 percent of the distribution on an annual basis. Dead ends and points of stagnation in the distribution system are especially prone to microbial growth and consequent loss of disinfectant residuals.
- Where chloramines are used as a residual disinfectant, the system should practice optimization of the chlorine to ammonia feed ratio to minimize ammonia content in the finished waters.

4.5 Enhanced Coagulation

Enhanced coagulation can have the following general effects on lead and copper corrosion:

- Decrease pH levels in the finished water (see Section 4.2.1).

- Decrease NOM levels in the finished water. NOM levels less than 2.0 mg/L result in a substantial increase in lead corrosion rates, especially in brass (Korshin et al., 1998).
- Change coagulant dosages and/or type of chemical used. Altering sulfate and chloride concentrations (as the anionic portion of the coagulant) impacts lead and copper corrosion rates.
- Reduction in residual aluminum levels may occur.

Issues and possible solutions in these areas relative to lead and copper corrosion are presented in the following paragraphs.

4.5.1 NOM Removal

Enhancing coagulation for NOM removal is required by the Stage 1 DBPR. Of all the parameters that impact metal corrosion in potable water, NOM is one of the least studied. Removal of NOM during enhanced coagulation alters the lead corrosion rate for lead-containing brass, pipe, and solder. The effects of NOM levels are dependent upon the type of corroding material. In waters with neutral pH and low alkalinity, lead release from brass is significantly increased with NOM concentrations between 0 and 2.0 mg/L as carbon. NOM concentrations greater than 2.0 mg/L as carbon do not impact brass corrosion rates. The corrosion of lead pipe and solder is initially increased due to reduced NOM concentrations. However, once surface scales form a barrier in reduced NOM water, the lead corrosion rate decreases and stabilizes (Korshin et al., 1998).

Several investigators have studied the interaction between Cupric ion and dissolved NOM (Cabaniss and Shuman, 1988; Davis, 1984; Holm, 1990). The composition of NOM is extremely diverse and greatly depends upon its source. As a result, these interactions cannot be generalized. NOM is mainly composed of humic and fulvic substances and its interaction with cupric ions is usually characterized empirically by statistical models that describe the binding of metals with one or several theoretical ligands under specific experimental conditions such as pH, ionic strength, etc. (Cabaniss and Shuman, 1988). The degree to which NOM impacts copper corrosion has not been determined conclusively. Research indicates that NOM may reduce pitting attack and possibly alter some scale formation characteristics of uniform copper corrosion (Edwards et al, 1994). Rehring (1994) found that copper corrosion rates increased with NOM concentration at pH 6, whereas at pH 7.5 and 9 it had less significant effects. The uncoiling of NOM macromolecules at high pH values (due to repulsion between specific charged groups on account of de-protonation), can significantly increase the number of sites that could bind with cupric ions and result in more copper being bound in the form of Cu-NOM complexes. This in turn would affect corrosion rates and copper release. Palit and Pehkonen (1998) studied the correlation between copper release as well as corrosion rates (measured

electrochemically) and the ratio of UV absorbance to TOC. Using UV₂₅₄:TOC in L/mg-min and the BDOC:DOC ratio as surrogates for copper release, Palit and Pehkonen (1988) found that there was a greater occurrence of corrosion with lower the BDOC levels in waters and a higher UV₂₅₄:TOC ratio.

4.5.1.1 Issues

NOM levels are reduced during enhanced coagulation for Subpart H systems using conventional treatment as required by the Stage 1 DBPR. The increase in lead corrosion rates associated with low NOM levels may impact LCR compliance. This impact from NOM removal may be most evident during tap sampling from brass faucet fixtures (Korshin et al., 1998).

4.5.1.2 Recommendations

Potential resolutions to the NOM removal impact on lead corrosion rates include:

- Increasing pH levels and/or orthophosphate levels in the finished water. Reduced NOM levels only slightly increase lead released from brass in high pH water. Similar results have been observed with orthophosphate addition (Korshin et al., 1998).
- Monitoring lead and copper corrosion rates in the distribution system and implementation of a LCR compliance strategy, if required.

4.5.2 Coagulant Changes

The optimization of coagulation may alter the existing coagulant dose or even result in a change in coagulant types. The changes in coagulant (dose and/or type) impact the overall water quality, which impacts the rate of lead and copper corrosion (AWWARF, 1985). In addition to the impacts on pH described in Section 4.2, changes in coagulant type may also impact the amount of chloride and sulfate ions present in the finished water. Utilities, that are changing the coagulant or practicing enhanced coagulation, may want to restore finished water chemistry as much as possible to its historical levels to avoid corrosion control problems.

There is some evidence to suggest that the sulfate to chloride mass ratio is important for predicting pitting corrosion in copper. A sulfate to chloride mass ratio greater than 1:2 may increase the potential for copper pitting (AWWARF, 1985). Alternatively, in case studies at 22 water utilities, all 12 utilities with sulfate to chloride mass ratios of more than 1:1.7 met the action level for lead. In contrast, 6 of the 10 utilities with sulfate to chloride ratios of less than 1:1.7 failed to meet the action limit for lead (Reiber et al., 1997). In relation to copper corrosion, the results of these studies on copper and lead corrosion suggest that a sulfate to

chloride mass ratio of 1:2 may increase the ability to meet the action level for lead without increasing the potential for copper pitting corrosion.

Recent research, however, indicates that the sulfate to chloride mass ratio may be relatively unimportant in these predictions and that the presence of sulfides may be a better indicator of copper pitting (Jacobs et al., 1998). As a consequence of the possible role of sulfides in copper pitting, it has been suggested by Jacobs et al. that the best predictor may be the presence of sulfates and the conditions in the distribution system (such as low dissolved oxygen) that may reduce sulfates to sulfides.

4.5.2.1 Issues

Enhanced coagulation requirements of the Stage 1 DBPR may alter the coagulant dose or result in changes in coagulant chemicals. These changes may result in changes in relative sulfate and chloride ion levels alter lead and copper corrosion rates that may, in turn, affect a system's ability to comply with the LCR.

4.5.2.2 Recommendations

Systems, which must change coagulants or coagulant dosages to comply with enhanced coagulation requirements, can control potential increases in lead and copper corrosion by:

- Adjusting the pH of the finished water (see Section 4.2.1);
- Adding lime or another source of calcium so that the finished water is saturated with calcium carbonate and forms a protective coating on the pipes; or
- Adding a corrosion inhibitor (i.e., a substance that is phosphate- or silica-based) to the finished water to form a protective coating on the pipes.

One of the earliest steps would be to consider as close a pH, hardness and DIC match to pre-Enhanced Coagulation conditions as possible. If that is not feasible, then a new corrosion control optimization study would be warranted to evaluate the best new treatment. Whenever possible, the best objective would be to retain successful water chemistry and to minimize distribution system water quality fluctuations as much as possible.

4.5.3 Case Study

Case Study No. 5 presents an example of how enhanced coagulation requirements of the Stage 1 DBPR were met while also achieving the LCR requirements.

Case Study No. 5 (An Actual Water Utility): Simultaneous Compliance between the Stage I DBPR and the LCR

Background

The following is a case study that describes the experience of a real Water Utility X (names of the treatment plants and the utility withheld at the request of the Utility) in its attempt to reduce THMs by changing the coagulant. In the process, the system exceeded the action level for lead at customer taps; 0.015 mg/L. This case study documents the steps taken to remedy the situation and thus enable plant operators to simultaneously comply with the DBPR and LCR.

Prior to the establishment of the 100 ppb THM standard, the utility practiced pre-chlorination at the intake. The finished water pH level was approximately 9.5 and THM levels ranged from 200-250 ppb. Research by the Utility staff determined that by eliminating pre-chlorination and reducing the finished water pH to a level between 7.5 and 8.0, compliance with the 100 ppb standard could be achieved. The THM running annual average for Plants 1 and 2 were 60-70 ppb and 70-80 ppb, respectively. However, there were several adverse impacts associated with removing the pre-chlorination step and reducing the pH. These impacts included:

- (a) Each plant lost 24 hours of chlorine contact time
- (b) Coagulation was not considered to be as effective by the plant operators
- (c) Algal blooms occurred in the treatment basins (causing more particulate loading on the dual media filters)
- (d) The finished water became corrosive (precipitation of calcium carbonate is precluded below a pH of 8.3).

Additional research determined that zinc-orthophosphate (ZOP) was effective in reducing the corrosiveness of the finished water. Consequently, ZOP was added to the treatment regimen in 1981 to protect distribution system piping and customer plumbing.

Simultaneous Compliance Issues

LCR. Utility X has completed four rounds of LCR monitoring at high-risk sites, under worst-case conditions in the distribution system. Two rounds were completed in 1992 and two rounds were completed in 1997. These results are shown below

Lead Monitoring Results Summary at High Risk Areas

Round No.	Period	Phosphate conc.	90 th percentile Lead conc.
1	Jan.-June 1992	0.16 mg/L	15 ppb
2	July-Dec. 1992	0.18 mg/L	116 ppb
3	Jan.-June 1997	0.58 mg/L	33 ppb
4	July-Dec. 1997	1.45 mg/L	3 ppb

City Y (a master-metered suburb receiving Utility X water) has completed four rounds of LCR monitoring. The results from four of those are rounds are listed below.

Lead Monitoring Results Summary at City Y

Round No.	Period	Phosphate conc.	90 th percentile Lead conc.
1	July-Dec. 1992	0.18 mg/L	19 ppb
2	Jan.-June 1995	1.00 mg/L	8 ppb
3	July-Dec. 1995	0.80 mg/L	7 ppb
4	Jan.-July 1997	0.58 mg/L	46 ppb

During the 1992 and 1995 monitoring periods, the Utility used alum as the coagulant in Plants 1 and 2. During the 1997 monitoring period, ferric chloride was used as the coagulant. After 1992, the phosphate concentration was increased substantially which resulted in lowering the 90th percentile lead concentration, as demonstrated in monitoring rounds 2 and 3 at City Y. The increase in the 90th percentile lead concentration during round 4 at both sites was very dramatic. A plausible explanation for this result is discussed below.

Distribution system monitoring during January through June 1997, resulted in a lead concentration of 33 ppb at the 90th percentile. This result surprised operators since elevating the phosphate concentration after the 1992 monitoring periods had lowered the 90th percentile lead levels substantially. A literature search revealed that if the sulfate to chloride mass ratio is greater than 0.58, then typically the lead action level would be exceeded, regardless of the water quality. The chloride to sulfate ratio of the Water Utility X finished water was calculated to be: (a) Alum coagulation: 0.29-0.49 (b) Ferric chloride coagulation: 0.82-1.50. Apparently, the switch from alum to ferric chloride had shifted the chloride to sulfate ratio into a range that nullified the effectiveness of the ZOP corrosion inhibitor. Thus, an attempt to comply with the Stage I THM standard had created a situation that lead to the exceedance of the LCR action level. In order to lower the lead solubility before the July through December, 1997, LCR distribution system monitoring, the coagulant was switched from ferric chloride back to alum, and a corrosion inhibitor with a 5:1 phosphate to zinc ratio was utilized (normally an inhibitor with a 3:1 phosphate to Zn ratio was used), to allow an additional increase in the phosphate level without increasing the Zn concentration. As a result, the 90th percentile lead concentration dropped to 3 ppb during the July through December, 1997, monitoring period.

Section IV of USEPA (1997b) does not discuss the same effects on lead solubility as noted above. Utility X has the capacity to adjust pH and alkalinity into the optimal range prior to entry into the distribution system.

Apparently, the reduction in lead solubility resulted from an appropriate chloride to sulfate ratio, which enabled the corrosion inhibitor to be effective, and not from any pH or alkalinity induced changes in the water quality. The finished water pH and alkalinity were very similar during the use of both alum and ferric chloride.

IESWTR. In order to increase CT and flexibility at the plants, six clearwells were constructed (at a cost of \$23 million) in 1995. This additional clearwell capacity increased the plant detention time by 16 hours. As expected, the THM RAA increased from a historic concentration of 70-80 ppb to 90 ppb. This RAA increase expedited another cycle of research to evaluate treatments that would reduce THM precursors more effectively. Coagulation with ferric chloride proved to be the most efficient and plausible treatment to lower THM RAA, obviating major capital construction/operation costs. Alum coagulation (used historically) removed TOC sufficiently to meet the percent removal criteria of the ESWTR, but did not remove THM precursors as effectively as ferric chloride.

Stage 1 DBPR. Compliance with the Stage I THM (80 ppb) RAA concentration was attainable at one of the two plants, with alum coagulation. However a similar compliance was not achieved at the other water treatment plant using alum as the coagulant. Coagulant was changed from alum to ferric chloride at Plant 1 (August 1995) and at Plant 2 (September 1996). This resulted in a 43 percent decrease in THM RAA at Plant 1 (from 70 ppb to 40 ppb) and a 33 percent reduction in THM RAA at the plant 2 (from 90 ppb to 60 ppb). Compliance with Stage I THM concentration was assured at both treatment plants while compliance with Stage II THM concentration (40 ppb) was feasible at one of them alone. With ferric chloride coagulation as the only treatment change, it was not feasible at the water treatment Plant 2.

Concluding Remarks

The Utility has resolved the lead solubility issue, but is still faced with the Stage I DBPR issue, since the THM RAA is expected to rise again. The Utility is also concerned with bacterial regrowth in the system due to elevated phosphate levels.

4.6 Disinfection Strategy

4.6.1 Switching Disinfectants

Compliance with the DBPR may require changing the chemical used for secondary disinfection. Changes of the secondary disinfectant may impact the redox potential of the water as well as overall water quality. Changes in water quality, and especially in redox potential, impact lead and copper corrosion rates (AWWA, 1990). Moreover, the feasibility of the switch to an alternate disinfectant may depend on how well it can be managed and the compatibility of the scheme with consecutive systems.

4.6.1.1 Issues

The use of chloramines as a secondary disinfectant (to provide a residual in the distribution system) could result in a significant reduction in TTHM formation potential in the distribution system. The chloramination process needs to be optimized in order to provide adequate distribution system residual and at the same time minimize the possibility of nitrification. Nitrification could be controlled by reducing the detention time, keeping water temperatures low, increasing the chlorine to ammonia ratio, checking the ammonia concentration and maintaining chloramine residuals > 2 mg/L. The activity of nitrifying bacteria can be detected by monitoring HPC concentrations, chloramine residuals and nitrite and nitrate concentrations. Nitrite is an intermediate in the nitrification process, which has a very high chlorine demand. This accelerates the destruction of the chloramine residual. Nitrification can lower the pH of the water in the distribution system and consequently prove detrimental for lead and copper release control.

Changes in lead and copper corrosion rates due to changes in secondary disinfectants may impact LCR compliance. Corrosion products and tubercles interfere with the disinfection of coliforms and HPC bacteria. Norton and LeChevallier (1997) have conducted several studies at the Indiana-American Water Company (Muncie, IN) to investigate the effect of chloramination on the distribution system water quality. At Muncie, pH and alkalinity were used for corrosion control and corrosion rates and Larson's indexes were low throughout the project. However, the water entering the Muncie distribution system had a propensity for pitting corrosion. After that study, phosphoric acid was fed as a corrosion inhibitor (orthophosphate concentration between 2.0 and 2.5 mg/L was maintained). Even after 16 months of orthophosphate addition, only one of 1,246 chloraminated distribution system samples tested positive for coliform bacteria.

4.6.1.2 Recommendations

Systems that must switch to a different secondary disinfectant may minimize increases in the rate of lead and copper corrosion by:

- Adding lime or another source of calcium to the finished water to saturate it with calcium carbonate and form a protective coating on the pipes
- Adding a corrosion inhibitor (i.e., a substance that is phosphate- or silica-based) to the finished water to form a protective coating on the pipes.

4.6.2 Ozonation and Unfiltered Systems

Following ozonation, the treated water contains increased levels of dissolved oxygen. Filtration reduces the level of dissolved oxygen to acceptable levels. Unfiltered systems (both

surface and ground water) deliver the increased dissolved oxygen into the distribution system. Increased dissolved oxygen levels may increase the rate of lead and copper corrosion and encourage nitrification (AWWA, 1990).

4.6.2.1 Issues

Implementing ozone disinfection for Stage 1 DBPR compliance at unfiltered water treatment systems can lead to changes in lead and copper corrosion rates due to increased dissolved oxygen (DO) that may impact LCR compliance. Besides increasing the DO, another drawback of ozonation is the formation of acidic functional groups like carboxylic acids, aldehydes, keto-acids etc., which could reduce the pH of the water significantly. According to Palit and Pehkonen (1998), ozonation followed by biofiltration resulted in an increase and a 30 to 40 percent decrease in the copper release rate. Ozonation followed by biofiltration ensures the removal of the biodegradable component of the NOM (e.g., BDOC), thus minimizing the potential for microbial regrowth in the distribution system. Furthermore, according to bench scale studies conducted by Palit and Pehkonen (1998), a low BDOC:DOC ratio could significantly increase the formation of the particulate copper (fraction of the copper byproduct release that is retained by a 0.45 μ m cellulose acetate filter). The significance of converting copper release into a particulate copper (also lead release into a lead particulate) relies on the potential to filter these particulates out using point-of-entry (POE) or point-of-use (POU) filters.

4.6.2.2 Recommendations

Unfiltered systems that switch to ozone disinfection may manage increased corrosion because of increased dissolved oxygen, by:

- Adding lime or another source of calcium to the finished water to saturate it with calcium carbonate and form a protective coating on the pipes
- Adding a corrosion inhibitor (i.e., a substance that is phosphate- or silica-based) to the finished water to form a protective coating on the pipes.

4.7 Summary

The compliance relationships between the Stage 1 DBPR, IESWTR, and LCR are numerous. Prior to promulgation of the Stage 1 DBPR and IESWTR, most water systems should have already achieved compliance with the LCR. This compliance may include the implementation of LCR control strategies as well as the conduct of ongoing monitoring to demonstrate that lead and copper levels remain below their respective action limits. Implementation of the Stage 1 DBPR and IESWTR may require changes that affect current LCR compliance. Therefore, compliance relationships between these rules and the LCR must be analyzed. The following

two sections present decision trees for simultaneous compliance based on whether the changes are initiated by the Stage 1 DBPR or the IESWTR.

4.7.1 DBP Controls Required

Figure 4-1 presents a decision tree showing the steps that should be taken if DBP controls are required. As discussed in Chapter 3, DBP controls may be required for any one of the following reasons:

1. TOC level exceeds 2.0 mg/L in the raw water
2. DBP levels in the finished water exceed the current MCL
3. Disinfectant residual levels in the finished water exceed the current MRDL
4. DBP levels in the finished water exceed 80 percent of the current MCL which initiates disinfection profiling and may require DBP controls.

Once the changes required for DBP control are developed, a study should be performed to determine the impact of the DBP controls on LCR compliance. If the results of the study indicate that no impact on LCR compliance is expected, the DBP control strategy can be implemented.

As shown in Figure 4-1, the results of the study show that there are impacts on LCR compliance as expected (i.e., changes in finished water pH), a study should also determine if mitigation of the DBP control is feasible and identify mitigation actions to assure LCR compliance (i.e., pH adjustment). If the impact of DBP control on LCR compliance cannot be mitigated, then an alternative DBP control strategy will be required.

A desktop study should determine the impact of LCR mitigation on IESWTR and TCR compliance (i.e., CT impacts or distribution system regrowth) and if the impact of DBP control on LCR compliance can be mitigated. If the LCR mitigation actions do not impact IESWTR and TCR compliance, the effectiveness of the LCR mitigation actions should be demonstrated in bench or pilot scale tests. Both the DBP control strategy and the associated LCR mitigation actions can be implemented if the demonstrations are successful.

As shown in Figure 4-1, when the LCR mitigation actions impact either IESWTR or TCR compliance, further studies are required to determine if other alternatives are available to avoid the conflicts and assure simultaneous compliance. An alternative LCR mitigation or alternative DBP control strategy may be required if the impacts cannot be avoided. When the LCR mitigation action impact on the IESWTR and TCR can be mitigated, the DBP control strategy and the associated LCR, IESWTR, and TCR control strategies can be implemented (following demonstration testing of the LCR mitigation actions).

4.7.2 IESWTR Controls Required

Figure 4-2 presents a decision tree showing the steps that should be taken if IESWTR controls are required. As discussed in Chapter 2, IESWTR controls may be required for one of the following reasons:

- Filtered water turbidity exceeds the treatment technology level
- CT values are less than required.

Once the changes required for IESWTR control are developed, a LCR desktop study (e.g., a study conducted based on computer simulation or modeling without laboratory testing) may be performed to determine the impact of IESWTR controls on LCR compliance. If results of the desktop study demonstrate no impact on LCR compliance is expected, the IESWTR control strategy can be implemented (Chapters 3 and 5 identify conflicts with the DBPR and TCR, respectively).

As shown in Figure 4-2, when the results of the desktop study show that impacts on LCR compliance are expected (i.e., changes in finished water pH), the desktop study should determine if mitigation of the IESWTR control is feasible and identify mitigation actions to assure LCR compliance (i.e., pH adjustment). If the impact of IESWTR control on LCR compliance cannot be mitigated, then an alternative IESWTR control strategy is required. When the impact of IESWTR control on LCR compliance can be mitigated, the desktop study should determine the impact of LCR mitigation on DBPR and TCR compliance (i.e., distribution system pH increases or distribution system regrowth). The effectiveness of the LCR mitigation actions should be demonstrated in bench or pilot scale tests if the LCR mitigation actions do not impact DBPR and TCR compliance. When the demonstrations are successful, both the IESWTR control strategy and the associated LCR mitigation actions can be implemented.

4. SIMULTANEOUS COMPLIANCE ISSUES BETWEEN M-DBP RULES AND LEAD AND COPPER RULE

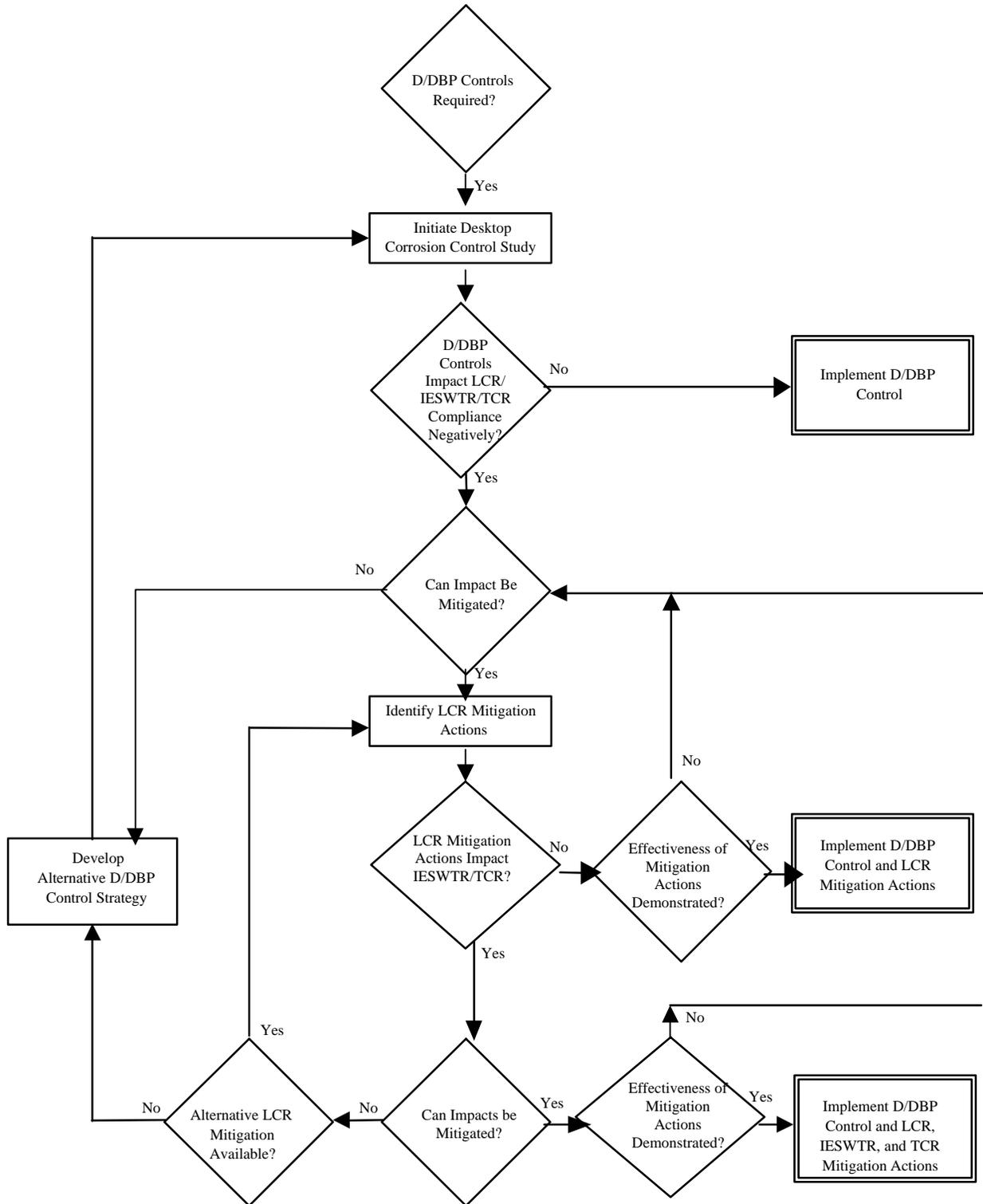


Figure 4-1. DBP Control Decision Tree

4. SIMULTANEOUS COMPLIANCE ISSUES BETWEEN M-DBP RULES AND LEAD AND COPPER RULE

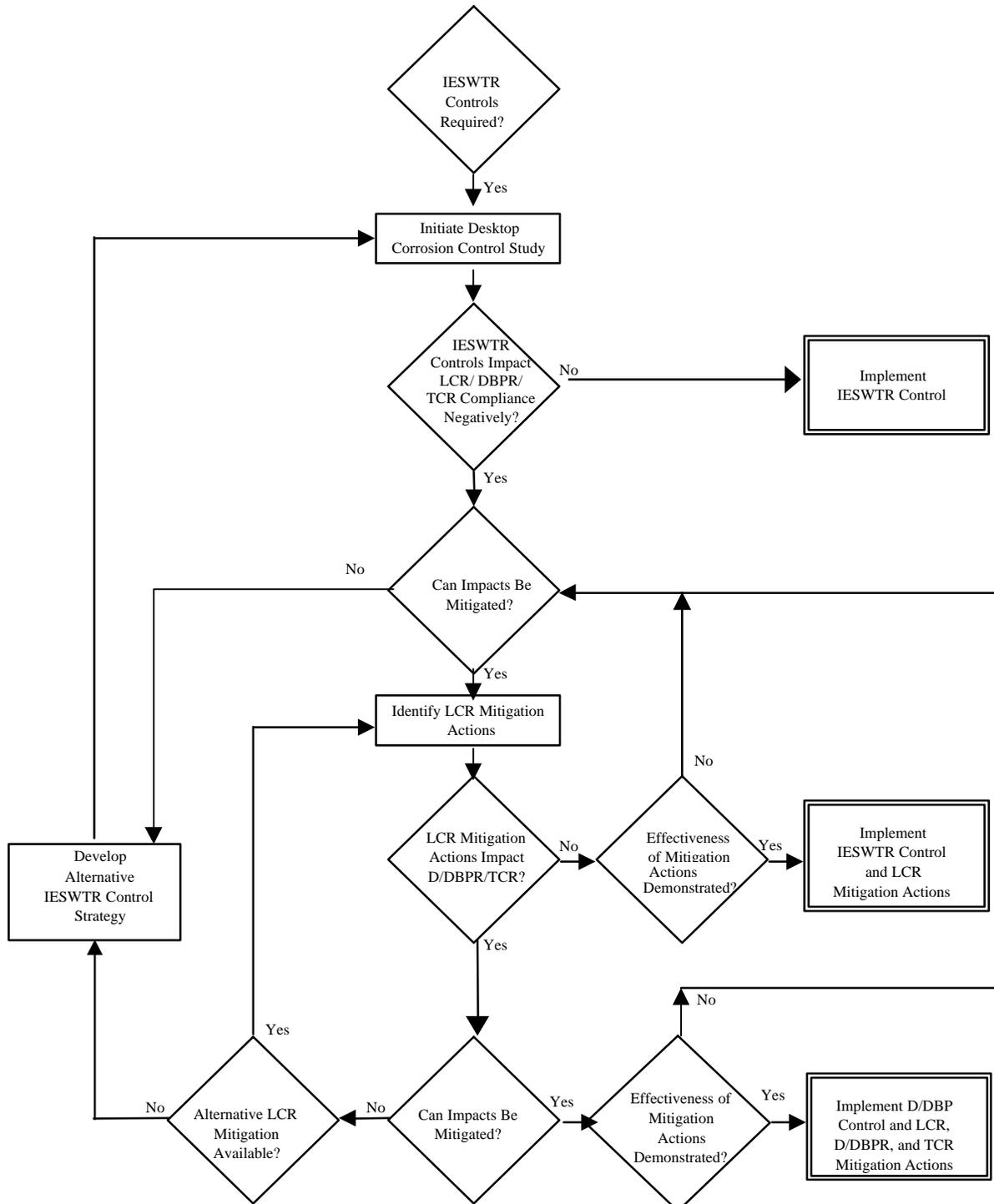


Figure 4-2. IESWTR Control Decision Tree

4. SIMULTANEOUS COMPLIANCE ISSUES BETWEEN M-DBP RULES AND LEAD AND COPPER RULE

As shown in Figure 4-2, when the LCR mitigation actions impact either DBPR or TCR compliance, further study should determine if mitigation of the conflicts is feasible and identify mitigation actions to assure simultaneous compliance. An alternative LCR mitigation or alternative IESWTR control strategy may be required if the impacts cannot be mitigated. When the LCR mitigation action impact on the DBPR and TCR can be mitigated, the IESWTR control strategy and the associated LCR, DBPR, and TCR mitigation actions can be implemented (following demonstration testing of the LCR mitigation actions).

5. TOTAL COLIFORM RULE AND ISSUES ON COMPLIANCE WITH THE STAGE 1 DBPR AND IESWTR

In published case studies involving the modification of disinfection practices to control DBPs, PWSs have generally been successful in maintaining bacteriological safety as DBP levels were reduced (AWWARF, 1990b). This chapter discusses the circumstances in which PWSs may have difficulty in simultaneously meeting the regulatory requirements of the TCR, Stage 1 DBPR and the IESWTR. For each situation discussed, approaches are described which may be useful in achieving simultaneous compliance with the rules. These approaches involve modifications of both disinfection and treatment practices.

5.1 Requirements of the TCR and Compliance Issues

5.1.1 TCR Requirements

The TCR became effective on December 30, 1990 (USEPA, 1989b) and is intended to ensure that drinking water remains safe from microbial contamination. Coliforms are bacteria naturally present in the digestive tracts of warm-blooded animals. There are also coliforms that are native to the soil and decaying vegetation (Peavy et al., 1985). While generally not harmful to human health, coliforms are often present in water contaminated with human or animal waste, which may contain other disease-causing organisms. Total coliforms are therefore used as indicators of the possible presence of these disease-causing microbes. For purposes of the TCR, EPA assumes that the treatment methods that produce coliform-free water will also prevent the occurrence of these other microbial pathogens.

Major requirements of the TCR include the following:

- PWSs must collect a specified number of routine samples per month, dependent upon populations served. The number of samples increases with increasing population and the sample locations must be representative of the PWS's distribution system.
- The maximum total coliform-positive samples each month must total less than 5 percent (or no more than one positive if the system collects fewer than 40 samples per month).
- If a sample is total coliform-positive, repeat samples must be taken at the original location, as well as upstream and downstream of the original location within 24 hours and within five service locations of the original location.
- If a sample is total coliform-positive, it must also be tested for the presence of fecal coliforms or *E. coli*. The State must be notified if any fecal coliforms or *E. coli* samples in the water

system are positive. An acute violation of the TCR occurs when a repeat sample is fecal coliform-positive or *E. coli*-positive or if a fecal coliform-positive or *E. coli*-positive original sample is followed by a total coliform-positive repeat sample.

- All utilities must develop a written bacteriological sampling plan that is subject to review and revision by the State.

Chlorine, chloramines, and chlorine dioxide are typically used to maintain a disinfectant residual in the distribution system. In the Stage 1 DBPR, maximum residual disinfectant levels (MRDLs) were promulgated for chlorine (4.0 mg/L), chloramine (4.0 mg/L), and chlorine dioxide (0.8 mg/L). Therefore, the fact that the disinfectant residual concentration is limited may (in poorly operated systems) result in failure to meet the TCR by not having sufficient oxidizing ability. Although much smaller doses of disinfectants are needed, the residence times in distribution systems can be large (i.e., on the order of days). However, the above should not be a problem for most well operated systems. Maintaining microbial protection through the use of secondary disinfection while limiting the concentrations of DBPs requires simultaneous compliance with the TCR, Stage 1 DBPR, and the IESWTR.

5.1.2 Issues

The TCR's primary intention is to protect systems against microbial contamination from regrowth or outside sources such as a pipeline break or cross-connection with wastewater piping. A disinfectant residual alone will not ensure the absence of a coliform regrowth problem; however the absence of a residual indicates a problem. The TCR, however, addresses the occurrence of coliforms since coliforms are indicators of contamination. An acute violation of the TCR occurs when a repeat sample is fecal coliform-positive or *E. coli*-positive or if a fecal coliform-positive or *E. coli*-positive original sample is followed by a total coliform-positive. As a result of this lack of source discrimination, the TCR can respond to coliforms resulting from regrowth due to disinfectant resistance or reactivation of injured bacteria (AWWARF, 1990a). There can also be events during which bacteria shed from the pipe surface release coliforms within biofilms. Such events may be a more common source of coliform detection than fecal source contamination (Camper et al., 1996; Camper, 1996).

Microbial contamination can result from two principal sources. The first and historically most significant source is from cross-connections with wastewater piping or other external sources such as pipe breaks or breakthroughs at the treatment plant (i.e., viable, but perhaps injured, bacteria pass through the disinfection process). These external sources of microbial contamination are due to transport phenomena rather than cell growth, which is a biochemical reaction process. The second source of microbial contamination is growth of bacteria in the distribution system, which may have originated outside of the system. An event of microbial contamination, regardless of the source, is monitored under the TCR. However, the distinction

between the two types of sources assists in understanding the potential conflicts that can arise between the TCR, Stage 1 DBPR, and IESWTR. Table 5-1 categorizes these conflicts in terms of the source of microbial contamination.

Table 5-1. TCR, Stage 1 DBPR, and IESWTR Conflicts Resulting from the Source of Microbial Contamination

Source of Microbial Contamination	Potential TCR, Stage 1 DBPR, and IESWTR Conflict
Growth of bacteria in distribution system	<ul style="list-style-type: none"> • Change in primary disinfectant to ozone • Change in primary/secondary disinfection practices • Enhanced coagulation/softening increased turbidity
External source of bacteria	<ul style="list-style-type: none"> • Maximum disinfectant residual concentration • Enhanced coagulation/softening increased turbidity

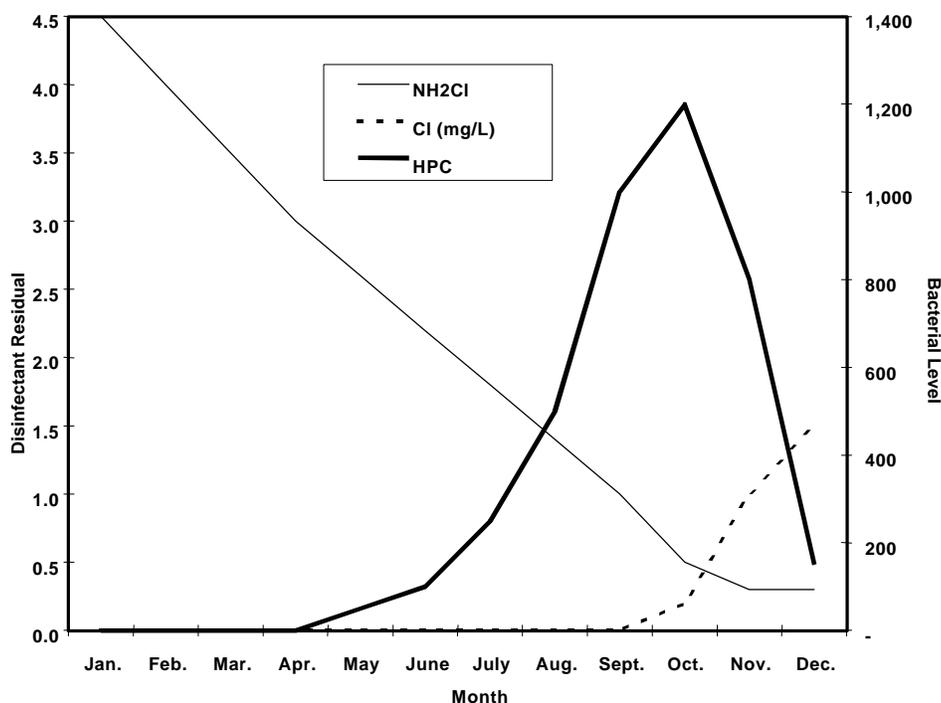
Although the TCR requires maintenance of a disinfectant residual in the distribution system, the presence of a residual does not guarantee the prevention of bacterial occurrences. Biofilms on the inside lining of distribution pipe can contain coliforms and other bacteria. Biofilms can be described as the accumulation of microbial cells at the pipe surface (Characklis et al., 1988). Occurrence of a biofilm begins when microbial cells being carried in the liquid medium become entrapped or adsorbed at the surface of the pipe. Metabolism can occur if an energy source (e.g., AOC and other nutrients) and other essential nutrients are available. With metabolism comes growth and the population forming the biofilm can increase (Characklis et al., 1988).

5.2 Coliform Growth in Distribution System When Secondary Disinfectant is Changed to Chloramine

5.2.1 Occurrences of Coliform Growth

Chloramines have been shown to be effective secondary disinfectants, which also minimize the formation of DBPs. According to EPA (1992b) and Jacangelo et al. (1987), chloramine is better able to penetrate the biofilm layer and inactivate attached organisms because it is more limited, than chlorine, in the types of compounds with which it will react. Studies conducted by LeChevallier et al. (1990) suggest that biofilm control can be achieved using chloramine levels ranging from 2 to 4 mg/L. Another study, conducted to determine the effects of maintaining a chloramine residual on distribution system water quality found that distribution system water samples testing positive for coliform bacteria dropped from 56.1 percent to 18.2 percent after conversion to chloramine (MacLeod and Zimmerman, 1986). More than 70 utilities in the U.S. effectively use chloramines for disinfection of distribution water supplies (Kreft et al., 1985).

There are some disadvantages with the use of chloramine as a disinfectant. One of the major disadvantages is that, with the presence of ammonia, there is a potential for biological nitrification with chloramination. Nitrification is inversely proportional to the chloramine residual, which can increase coliform growth and increase the growth of heterotrophic bacteria. Also, when certain control practices are implemented, destruction of biofilms may result in coliforms being released (Wilczak et al., 1996). As such, changing the secondary disinfectant to chloramine to comply with the Stage 1 DBPR and IESWTR can cause potential compliance conflicts with the TCR. Figure 5-1 shows an example of the relationships among the chloramine residual, HPC bacterial growth, and free chlorine residual during a nitrification episode when free chlorine was used to control nitrification (Skadsen, 1993). As nitrates increase and chloramine is depleted, increases in coliform and HPC growth occur.



Modified from Skadsen, 1993

Figure 5-1. Example of Disinfectant Residual/Bacterial Relationship During a Nitrification Control Episode

5.2.2 Nitrification

Nitrification can have various adverse effects on water quality, including a loss of total chlorine and ammonia residuals, consumption of dissolved oxygen, and increase in nitrate levels, and an increase in HPC bacteria concentration, creating the potential for violation of the TCR (Kirmeyer, et al., 1995). Nitrification in chloraminated drinking waters is usually partially due to excess ammonia present in the distribution system (Skadsen, 1993). The excess ammonia encourages the growth of nitrifying bacteria which convert ammonia to nitrates. An

intermediate step in this conversion results in a small amount of nitrite being formed. Research has shown that a chlorine demand of 5.0 mg/L is exerted by 1.0 mg/L of nitrite (Cowman and Singer, 1994). The nitrites rapidly reduce free chlorine, accelerate decomposition of chloramines, and can interfere with the measurement of free chlorine (Skadsen, 1993). If nitrification episodes are allowed to continue, very low (or zero) total chlorine residual concentration levels may occur. Loss of chlorine residual allows an increase in HPC bacteria and potential increases in total coliforms resulting in a positive sample (Cowman and Singer, 1994).

5.2.2.1 Biology

Nitrification occurs in two phases, with the oxidation of ammonia to nitrite followed by the oxidation of nitrite to nitrate. Ammonia-oxidizing bacteria (AOB) facilitate the conversion to nitrite. Nitrite causes a high free chlorine demand which accelerates the destruction of the chloramine residual (Wolfe, 1990). Lieu et al. (1993) suggested that control of nitrification in the distribution system could be optimized by inactivating AOB. This research demonstrated how AOB inactivation was primarily dependent on chloramine dosage.

Several possible factors have been implicated as contributing to nitrification. These factors include low chlorine to ammonia ratio, long detention times, and high (25°C - 30°C) temperatures (Wolfe et al., 1988 and 1990). Though some articles note that low chloramine dosages may lead to nitrification, other research has reported nitrification occurring at chloramine concentrations greater than 5.0 mg/L (Kirmeyer et al., 1995). Nitrifying bacteria are more resistant to disinfection by chloramine than by free chlorine (Wolfe et al., 1990). The optimum conditions for nitrification consist of a water system with free-ammonia, a pH of 7.5 to 8.5, dissolved oxygen, a water temperature of 25°C to 30°C, and a dark environment. Nitrifying bacteria, or nitrite-oxidizing bacteria (NOB), exhibit slow growth and are inhibited by sunlight. NOB has been found in higher numbers in the sediment of distribution systems than in the biofilm (Wolfe et al., 1988 and 1990).

5.2.2.2 Occurrence

If the water storage reservoirs in the distribution system are covered and have low disinfectant residuals, partial nitrification may occur (White, 1992). Covering a reservoir may cause proliferation of nitrifying bacteria that generate nitrites. Eventually, the reservoir may become biologically unstable, and disagreeable tastes and odors may result. All surface water and GWUDI systems serving 10,000 or more people are required to cover newly constructed treated water reservoirs (USEPA, 1998b). EPA also recommends covering old storage reservoirs. It is important to shock disinfect newly uncovered and newly constructed reservoirs before use and to maintain an adequate residual disinfectant in the stored reservoir water to inhibit nitrifying bacteria and prevent nitrification.

5.2.3 Recommendations

Mechanisms for controlling the occurrence of coliform growth and nitrification include higher chloramine residuals, higher chlorine:ammonia-nitrogen ratios, periodic switching to free chlorine (particularly during warmer months), more frequent turnover in storage reservoirs, and distribution systems flushing (AWWARF, 1993). The use of free chlorine to control nitrification has been correlated with increased HPC bacteria without a violation of the TCR (Skadsen, 1993). Nitrification may be controlled by taking corrective action when chloramine residuals are depleted in the distribution system. This can be done by monitoring the monochloramine and dichloramine residuals at strategic locations throughout the distribution system (White, 1992). Also, as stated earlier, monitoring water, pH, and temperature is important in determining when conditions favorable for nitrification are occurring in the distribution system, and specifically, at a pH between 7.5 and 8.5 and a water temperature above 20°C. Therefore, to prevent coliform occurrence, “high” levels of nitrites, loss of chloramine residual, elevated levels of HPC, and associated taste and odor problems, good chloramines management is required. This includes, in addition to the above-mentioned mechanisms, control of corrosion and the elimination of stagnant areas in the distribution system (AWWARF, 1995).

The stability of the chloramine free residual is increased throughout the distribution system as a result of microbial contaminant control and decreased bacterial concentrations in the raw water. Recommended approaches to prevent and control nitrification in the distribution system include (Cowman and Singer, 1994):

- Decreasing the detention time
- Increasing the chlorine to ammonia ratio
- Decreasing the excess ammonia concentration.

Kirmeyer et al. (1995) also recommends removing organic compounds at the treatment plant. The distribution system should be evaluated to identify the low-flow or dead-end sections. The detention times in the system should be operationally minimized (Skadsen, 1993). Additional recommendation for monitoring parameters and locations for the control of coliform growth and nitrification follows.

5.2.3.1 Monitoring Parameters

Nitrification is suspected in chloraminated water systems when chloramine residuals are rapidly depleted. Primary monitoring parameters include:

- Chemical balance of nitrogen species: This can be determined by measuring the free and total ammonia, nitrate and nitrite concentrations, and calculating the differences

between the treatment plant finished water and a given point in the distribution system.

- Heterotrophic Plate Counts using R2A agar: Standard plate counts may be useful, but they are not as sensitive to changes as counts using the R2A agar. AWWA (1995) recommends the use of R2A agar for HPC analysis for all utilities practicing chloramination.

Secondary monitoring parameters (i.e., those which should not be used without corroboration with a primary parameter) include the following:

- Chloramine (or total chlorine) residual: A sharp decrease in the chloramine residual could signal the onset of nitrification. However, caution needs to be exercised since chloramine residuals degrade over time in open reservoirs, in the presence of biofilm and under other distribution system conditions, such as backflow incidents.
- Dissolved Oxygen (DO): Decreases in DO levels frequently correlate with nitrification in some utilities.
- Alkalinity: Very few utilities report a strong correlation between alkalinity decreases and nitrification (AWWA, 1995).

5.2.3.2 Monitoring Locations

- Raw water: Sampling data should include baseline information on ammonia, nitrate and nitrite concentration, and TOC concentration.
- Treatment plant finished water: AWWA recommends that utilities monitor the chlorine to ammonia ratios as mg/L of Cl per mg/L of N. This ratio can be directly measured, or the applied ratio can be adjusted for the chlorine demand.
- Reservoirs: Measurements in reservoirs should evaluate nitrate and nitrite concentrations, free ammonia, HPC, temperature, DO, and total disinfectant residual. Turnover rates for the reservoir's water should also be routinely monitored.
- Dead-end mains: Nitrate and nitrite concentrations, HPC, DO, temperature, and disinfectant residual should be monitored at dead-end main locations. Accurate flushing records should also be maintained and system detention times should be estimated on a seasonal basis.
- Designated coliform monitoring locations: These locations should be routinely sampled for nitrate, nitrite, HPC, and chloramine residual concentrations.

5.2.4 Case Study

Case Study No. 6 presents an example of how TCR requirements were met while also achieving the DBP MCLs by using chloramine as a secondary disinfectant alternative.

Case Study No. 6: Simultaneous Compliance between TCR and DBP MCL Using Chloramine as the Alternative Secondary Disinfectant

Background

The following case study describes how Plant F could simultaneously comply with the TCR requirements and meet the DBPR MCLs using chloramine as the alternative secondary disinfectant. The design parameters (including treatment processes), and raw and finished water quality of Plant F (serving 400,000 people) are provided below:

Source Type:	Surface Water
Flow Rate:	Average Daily Flow - 40 mgd Design Flow - 60 mgd
Treatment System:	Rapid Mix Coagulation/Flocculation (alum, 20 mg/L) Sedimentation (theoretical detention time - 3 hours) Filtration (No. of units - 30, single media, loading rate 2 gpm/ft ²) Clearwell (theoretical detention time - 30 min) Disinfection (maximum chlorine dose - 5.0 mg/L, point of application raw water inlet)
Raw Water Quality:	TOC - 7.0 mg/L pH - 6.8 Alkalinity - 60 to 80 mg/L Turbidity - 45 to 110 NTU
Finished Water Quality:	TOC - 4.9 (30 percent removal) pH - 6.5 Alkalinity - 40 to 60 mg/L Turbidity - 0.2 NTU Residual Chlorine - 2.0 mg/L Total coliforms - No of samples collected per month - 210 No. of samples positive per month - 5
Distribution System Water Quality:	TTHM -0.090 mg/L (Running Annual Average)* HAA5 -0.050 mg/L (Running Annual Average)*

* profiling required

Simultaneous Compliance Issues

Stage 1 DBPR. The Stage 1 DBPR reduces the MCL of TTHMs in the finished water to 80 µg/L which is 10 µg/L lower than the current TTHM concentration at Plant F. Plant F determined that changing the secondary disinfectant from chlorine to chloramine will prevent the formation of TTHMs above the MCL.

TCR. For Plant F, serving 400,000 people, the TCR requires 200 routine samples to be collected per month, out of which no more than 10 samples (5 percent) may be positive for total coliform bacteria. None of the total coliform-positive routine samples may be positive for fecal coliform or *E. coli*.

Potential Conflicts. Chlorine reacts with NOM to produce a variety of DBPs, including THMs, haloacetic acids (HAAs), and brominated products (if bromide ion is present). Use of chloramine as an alternative secondary disinfectant can reduce the formation of DBPs to comply with the DBPR requirements. However, the presence of ammonia from using chloramine increases the potential for biological nitrification in the distribution system. Nitrification can cause a loss of total chlorine and ammonia residuals, and an increase in bacteria. The greater number of bacteria increases the potential for TCR violation. The system must conduct disinfection profiling.

Steps to Resolve Conflicts and Results Achieved

After conducting bench- and pilot- scale studies, Plant F switched the secondary disinfectant from chlorine to chloramine to meet the TTHM requirement. Using a chlorine concentration of 4 mg/L and ammonia concentration of 1.0 mg/L (chlorine-to-ammonia ratio of 4:1), the plant was able to reduce the TTHM to 70 µg/L and thus comply with the DBPR MCL for TTHM. The chloramine residual was 2.5 mg/L and excess ammonia was 0.2 mg/L under these conditions. The system is required to consult with the State and disinfection profiling and benchmarking is required.

Operational mechanisms implemented by Plant F to control the coliform growth and nitrification included maintaining a high chloramine residual (monochloramine preferred) and a high chlorine-to-ammonia ratio. Monitoring of monochloramine and dichloroamine residuals was conducted at strategic locations throughout the distribution system. The chlorine-to-ammonia ratio was optimized to maintain adequate chloramine residual and low excess ammonia. Increasing the ratio further to 5:1 would help control the nitrification problem by decreasing the amount of ammonia in the distribution system, but would increase the potential of a chlorine overdose that would reduce the chloramine residual levels that are desired in the distribution system. Therefore, the higher dose was used only in the summer months during the highest potential for biological growth.

Additional steps implemented by the plant were periodic switching to free chlorine, and more frequent turnover in storage reservoirs and the distribution system. Once a year, Plant F uses chlorine past the breakpoint to allow a free residual for 30 days. This is simply done by turning off the ammonia addition temporarily to ensure that free chlorine is the secondary disinfectant. The increased chlorine oxidizes any nitrite or nitrifying bacteria and eliminates the excess ammonia in the system. Using higher chlorine dose was found to be more effective than a flushing program for the storage reservoirs and the distribution systems that produced only temporary results. The plant is able to maintain the number of coliform-positive samples to the MCL of less than 5 percent and thus comply with the TCR requirements.

5.3 Coliform Growth in Distribution System When Primary Disinfectant is Changed to Ozone

Ozone is a powerful oxidant that is able to achieve disinfection with less contact time and concentration than other disinfectants, such as chlorine (DeMers and Renner, 1992). Ozone, however, can only be used as a primary disinfectant since it cannot maintain a residual in the distribution system. Thus, ozone disinfection must be coupled with a secondary disinfectant, such as chlorine or chloramines, for a complete disinfection system.

5.3.1 Occurrence

A principal advantage of ozone use as a primary disinfectant is THM and HAA5 control. This advantage, however, can be offset in terms of DBP formation since ozone can react with NOM to produce unregulated organic byproducts such as ketones and aldehydes. In the presence of bromide, ozone can react with organic matter to form bromate ion, a contaminant regulated under the Stage 1 DBPR. In terms of the TCR, ozonation can increase organic matter which can be biodegraded and can promote bacterial growth/regrowth in the distribution system (Langlais et al., 1991). Bacterial growth can occur when cellular metabolism in biofilms or suspended bacteria is increased due to the additional nutrients available from AOC. AOC is a byproduct of ozonation in water containing sufficient NOM.

5.3.2 Recommendations

Application of ozone disinfection appears most favorable for systems with low-TOC waters or where biological filtration is practiced at the treatment facility to reduce biodegradable organic matter. However, the decision by a PWS to change to ozone as the primary disinfectant is usually made to lower TTHMs or HAA5, a problem with high (not low) TOC waters.

5.3.2.1 Applicability of Ozone

Ozone can be effective in partially oxidizing organics in the water to biodegradable compounds that can be removed by biological filtration (DeMers and Renner, 1992). This partial oxidation gives rise to lower molecular weight compounds that are more easily biodegradable. Just as the more easily biodegradable organics are effectively removed by biofiltration, they can become a substrate for the microbial population in the distribution system, if not removed. This increase in the biodegradable fraction of organic carbon occurs as a result of moderate levels of ozonation. These ozone levels are typical of the doses commonly applied for disinfection.

The organic acid and aldehyde byproducts of ozonation discussed above are readily biodegradable and are a component of the AOC or BDOC. Ozonation can increase the BDOC

by oxidation. Therefore, if water disinfected with ozone is treated by a biologically active process (i.e., biological active carbon), removal of these biodegradable byproducts can be expected following the development of a biomass. The use of biologically active filters, maintained by not applying disinfectant prior to the filters, has been shown to successfully remove aldehydes and other compounds representing a portion of the BDOC in a water (Bablon et al., 1988; Rittman, 1990; Reckhow et al., 1992). Oxidation of chlorinated DBP precursors using ozone has been shown to be effective at low ozone doses (Shukairy et al., 1992).

The wide-scale conversion from chlorination to ozonation in previously biologically stable distribution systems in the Netherlands provides lessons for PWSs in the United States changing to ozone as their primary disinfectant. Van der Kooij (1997) reported that the introduction of ozonation to replace chlorination in previously biologically stable water was followed by regrowth phenomena in a distribution system in the Netherlands. Research showed that biodegradable low molecular weight compounds were formed when ozone oxidized humic and fulvic acids. HPC values directly correlated with AOC concentrations greater than 10 µg/L carbon (Van der Kooij, 1997). Thus, monitoring and reduction of AOC levels could be a tool to maintain compliance with the TCR.

5.3.2.2 Biological Treatment

Incorporating biological treatment into the water treatment process when changing to ozone as a primary disinfectant could have benefits for the distribution system beyond removing AOC created by ozonation (Hozalski et al., 1995). Research has been shown that a very little EBCT is required for high levels of AOC removal in biological filters. Prevost reported that as little as 2 minutes of EBCT provided up to 90 percent AOC removal (Prevost et al., 1992). An EBCT of 2 minutes is an atypical EBCT for a filter; to further remove the biodegradable portions of TOC for the additional benefit of distribution system water quality required 15-20 minutes of EBCT. Thus, while AOC can be removed in an existing unit process such as the filter beds, once it is made biologically active, a new process with more EBCT can result in a significant reduction in the entire biodegradable fraction of TOC (Prevost et al., 1992).

It is desirable to achieve biological filtration with the same filtration system used to remove turbidity (Krasner et al., 1990). This removal can be accomplished in unit filtration processes which are already in place in the plant such as sand filters, sand filters with GAC, and post-filtration GAC. Biofiltration, however, does not appear to be equivalent to chemical removal. In parallel studies, biofiltration removed 8 to 12 percent of TOC, whereas physicochemical processes removed 28 to 68 percent (Prevost et al., 1992).

5.3.3 Summary and Recommendations

In summary, possible strategies for controlling bacterial growth in distribution systems when the primary disinfectant is changed to ozone are as follows:

- Ozonation in the absence of biological or GAC treatment may result in adding biodegradable organic carbon, which then leads to regrowth of bacteria in the distribution system. In low-TOC waters or with biological treatment following ozone addition, biologically stable water should be produced minimizing distribution system coliform presence.
- Establishing the lower limit of AOC concentration, which prevents bacterial regrowth, can assist the PWS in monitoring for and effectively removing enough AOC to maintain biological stability.

5.3.4 Case Study

Case Study No. 7 presents an example of how bacterial growth requirements under the TCR were met while also achieving the Stage 1 DBPR requirements by using ozone as an alternative primary disinfectant.

Case Study No. 7: Complying with the Total Coliform Rule and the Stage 1 DBPR Using Ozone as the Primary Disinfectant

Background

The following case study describes how Plant G could simultaneously comply with the DBPR by switching to ozonation as a primary disinfectant and with the TCR by taking steps to prevent biological regrowth in the distribution system. The design parameters (including treatment processes), and raw and finished water quality of Plant G (serving 15,000 people) are provided below.

Source Type:	Surface Water
Flow Rate:	Average Daily Flow - 2.2 mgd Design Flow - 4.0 mgd
Treatment System:	Coagulation/Flocculation (alum, 20 mg/L) Sedimentation (theoretical detention time - 3 hours) Filtration (4 rapid sand filters, loading rate 2 gpm/ft ²) Primary Disinfection (maximum chlorine dose 5.0 mg/L, point of application - prior to coagulation/flocculation) Secondary Disinfection (maximum chlorine dose 2.0 mg/L, point of application - following filtration)
Raw Water Quality:	TOC - 10 mg/L pH - 6.5 Alkalinity - 50 to 70 mg/L Turbidity - 10 to 40 NTU
Finished Water Quality:	TOC - 7.0 mg/L (30 percent removal) pH - 6.5 Alkalinity - 40 to 60 mg/L Turbidity - 0.2 NTU Residual Chlorine - 0.2 mg/L at the furthest point in the distribution system Total coliforms - No of samples collected per month - 20 - No. of samples positive per month - 0
Distribution System Water Quality:	TTHM -0.090 mg/L (Running Annual Average)* HAA5 -0.050 mg/L (Running Annual Average)*

* profiling required

Simultaneous Compliance Issues

Stage 1 DBPR. The Stage 1 DBPR sets the TTHM MCL at 80 µg/L which requires a 10 µg/L reduction from Plant G's existing finished water TTHM concentration. Plant G determined that because of the high concentration of TOC in its raw water, it must change its primary disinfectant to ozonation to prevent the formation of TTHMs.

TCR. The TCR requires Plant G, serving 15,000 people, to collect 15 samples from the distribution system per month. No more than 1 of those samples may test positive for the presence of total coliform bacteria and none of the samples which test positive for total coliform may test positive for fecal coliform or *E. coli*.

Potential Conflicts. By switching from chlorination to ozonation as the primary disinfectant, Plant G does not eliminate its ability to provide a disinfectant residual, because it still maintains a chlorination system following the filters. However, ozonation of the raw water would result in the partial oxidation of the organic matter into biodegradable organic carbon (BDOC). These biodegradable organics could provide nutrients for bacteria and promote biological regrowth in the distribution system. The biological regrowth within the distribution system could result in an increased number of total coliform bacteria detections. An additional problem is the potential for continued formation of TTHMs by reaction of the organics and the chlorine disinfectant.

Steps to Resolve Conflicts and Results Achieved

Plant G determines that it must reduce the biodegradable organic carbon (BDOC) in the water prior to applying the chlorine disinfectant. Systems switching their primary disinfectant to ozone are required to consult with the State and profile and benchmark for virus disinfection. To accomplish this, Plant G modifies its existing sand filters to achieve biological filtration by increasing the filter media depth reducing the frequency of the filter backwash. The filter media depth was increased by the system from 2.5 feet to four feet, resulting in an EBCT of 15 minutes. The frequency of backwash was decreased substantially by the operators thus resulting in filter run times which may lower filtered water rates. To improve the filtration rate, the operators used surface water wash more frequently than before the filters were used as biofilters. Backwashes were performed as the filters became plugged or turbidity breakthrough occurred. The decreased frequency of backwash, promoted biological growth on the filters. The biologically active filters consumed the BDOC and further reduced the TOC levels. This resulted in the reduction of TTHM formation to levels below the TTHM MCL and in the continued control of biological regrowth, as measured by the lack of coliform bacteria in the distribution system. There could be problems with media carryover during backwash. Also, the biofilm formed over the media has the tendency to slough off from time to time, resulting in sudden turbidity breakthroughs, unless the process is properly managed.

5.4 Coliform Growth in the Distribution System Resulting from Changes to Primary and Secondary Disinfection Practices

This section provides a summary of potential TCR compliance issues resulting from changes in disinfection practices, including a summary of the issues addressed in the previous two sections. There is relatively little information available that describes distribution system compliance issues with the TCR following changes in disinfection practice. The discussions in the previous two sections, however, suggest that potential TCR compliance issues could arise (e.g., nitrification). Table 5-2 outlines potential TCR control strategies for addressing distribution system responses to disinfectant changes.

5.4.1 Change from Chlorine/Chlorine to Chlorine/Chloramine

Section 5.2 contains a brief discussion about coliform growth in distribution systems when the secondary disinfectant is changed from chlorine to chloramine. In summary, the use of chloramines as a secondary disinfectant has been shown to be effective in protecting the distribution system from microbial contamination while at the same time minimizing the formation of DBPs. Chloramines, on the other hand, can cause methemoglobinemia and adversely affect the health of kidney dialysis patients (USEPA, 1999b). The presence of ammonia indicates that the potential for biological nitrification exists. For a more thorough discussion about the chemistry, primary uses, points of application, DBP formation, and pathogen inactivation and disinfection efficacy of chloramines please refer to the *Alternative Disinfectants and Oxidants Guidance Manual* (USEPA, 1999b).

5.4.2 Change from Chlorine/Chlorine to Ozone/Chlorine

Section 5.3 discusses coliform growth in distribution systems when changing the primary disinfectant to ozone. This section provides a discussion of recent data on byproduct formation when changing to ozone as a primary disinfectant. For a more thorough discussion about the chemistry, primary uses and points of application, DBP formation, and pathogen inactivation and disinfection efficacy of ozone refer to the *Alternative Disinfectants and Oxidants Guidance Manual* (USEPA, 1999b).

The ozone/chlorine strategy may result in brominated DBPs (note that brominated DBPs have health implications). However, the main benefit derived from using ozone as the primary disinfectant is for controlling THM formation. This is because free chlorine is applied later in the treatment process after the precursors have been removed.

The cities of Phoenix (1989) and San Diego (1990) have, however, reported that substituting ozone for chlorine as a primary disinfectant, when not practicing pre-chlorination, resulted in an increased THM formation in the finished water (USEPA, 1999b).

Table 5-2. TCR Control Strategies Following Changes in Disinfection Practice

Change in Disinfection Practice	TCR Control Strategies
Chlorine/Chlorine to Chlorine/Chloramine	Control nitrification through: <ol style="list-style-type: none"> 1. Decreasing detention time 2. Increasing the chlorine to ammonia ratio 3. Decreasing the excess ammonia concentration
Chlorine/Chlorine to Ozone/Chlorine	Control NOM after ozonation through: <ol style="list-style-type: none"> 1. Active biological filtration 2. Limiting ozone dosage 3. Alternative low-TOC water supply 4. Ozonation: Results in the formation of smaller and more easily volatilizing compounds (like CH_3CHO, HCHO, glyoxal, etc.) and hence, results in lowering the TOC in many cases. In some cases, ozone may oxidize the NOM all the way to CO_2 (i.e., mineralize), resulting in lower TOC values.
Chlorine/Chlorine to Ozone/Chloramine	Control NOM after ozonation through: <ol style="list-style-type: none"> 1. Active biological filtration 2. Limiting ozone dosage 3. Alternative low-TOC water supply 4. Ozonation: Results in the formation of smaller and more easily volatilizing compounds (like CH_3CHO, HCHO, glyoxal, etc.) and hence, results in lowering the TOC in many cases. In some cases, ozone may oxidize the NOM all the way to CO_2 (i.e., mineralize), resulting in lower TOC values. Control nitrification through: <ol style="list-style-type: none"> 1. Decreasing detention time 2. Increasing the chlorine to ammonia ratio 3. Decreasing the excess ammonia concentration
Chlorine/Chlorine to Chlorine Dioxide/Chlorine Dioxide	Increase distribution system residuals: <ol style="list-style-type: none"> 1. Add chlorine/chloramine remotely in system 2. Eliminate free chlorine in distribution system
Chlorine/Chloramine to Ozone/Chloramine	Control NOM after ozonation through: <ol style="list-style-type: none"> 1. Active biological filtration 2. Limiting ozone dosage 3. Alternative low-TOC water supply 4. Ozonation: Results in the formation of smaller and more easily volatilizing compounds (like CH_3CHO, HCHO, glyoxal, etc.) and hence, results in lowering the TOC in many cases. In some cases, ozone may oxidize the NOM all the way to CO_2 (i.e., mineralize), resulting in lower TOC values. Control nitrification through: <ol style="list-style-type: none"> 1. Decreasing detention time 2. Increasing the chlorine to ammonia ratio 3. Decreasing the excess ammonia concentration

Table 5-2. TCR Control Strategies Following Changes in Disinfection Practice (Continued)

Change in Disinfection Practice	TCR Control Strategies
Chlorine/Chloramine to Chlorine Dioxide/ Chloramine	Increase distribution system residuals: <ol style="list-style-type: none"> 1. Add chlorine/chloramine remotely in system 2. Eliminate free chlorine in distribution system Control nitrification through: <ol style="list-style-type: none"> 1. Decreasing detention time 2. Increasing the chlorine to ammonia ratio 3. Decreasing the excess ammonia concentration
Ozone/Chlorine to Ozone/Chloramine	Control nitrification through: <ol style="list-style-type: none"> 1. Decreasing detention time 2. Increasing the chlorine to ammonia ratio 3. Decreasing the excess ammonia concentration

Source: USEPA, 1994.

Research regarding the disinfection of a low-bromide water with ozone/chlorine suggests that THMs, HAAs, and chloral hydrates (currently unregulated) are formed during disinfection (LeBel et al., 1995). Raw and treated water characteristics from this study are shown in Table 5-3, and DBP speciation is shown in Table 5-4. The study plant uses flocculation, sedimentation, chlorination (in summer only to improve CT and minimize biofilm growth potential in the network), sand filtration, ozonation, and post-chlorination for processing water.

Table 5-3. Raw and Treated Water Quality at a Plant Using Ozone/Chlorine

Parameter	Raw Water	Treated Water
pH	6.8-7.6	7.2-8.5
TOC, mg/L	3.4-5.8	1.8-3.0
TOX, µgCl ⁻ /L	NA	13-210
Bromide ion, mg/L	<0.002	<0.002
TKN, mg/L	<0.1	<0.1
Color, TCU	27.4	1.7
Turbidity, NTU	3.4	0.3
Hardness, mg/L as CaCO ₃	20	31
Alkalinity, mg/L as CaCO ₃	12	12

Table 5-4. DBP Speciation at a Plant Using Ozone/Chlorine

Parameter	Mean (µg/L)	Maximum (µg/L)
Chloroform	29.6	100.1
Bromodichloromethane	1.5	3.2
Chlorodibromomethane	0.1	0.2
Bromoform	<0.1	<0.1
Total THMs	31.2	103.4
HAA5	19.8	78.6
Chloral Hydrate	8.9	23.4

Seasonally, the highest concentrations occurred from July through October, and concentrations increased with time through the water system (from raw water through the furthest sampling point in the distribution system). Clearly, even from a relatively low TOC water, the ozone/chlorine disinfection practice can cause MCLs to be exceeded. However, the mean values indicate generally good results.

At plants where published data are available, there appear to be no distribution system impacts resulting from the ozone/chlorine disinfection practice change (AWWARF, 1990b).

5.4.3 Change from Chlorine/Chlorine to Ozone/Chloramine

The primary impact of this disinfection practice change results from the effects of ozone oxidation of organics coupled with the change from chlorine to chloramine. Distribution system problems associated with the use of combined chlorine residual, or no residual, have been documented in several instances (AWWARF, 1990b). In these cases, the use of combined chlorine is characterized by an initial satisfactory phase in which chloramine residuals are easily maintained throughout the system and bacterial counts are very low. However, problems may develop over a period of years including increased bacterial counts, declines in combined chlorine residual, increased taste and odor complaints, and reduced transmission main carrying capacity. Conversion of the system to free-chlorine residual produces an initial increase in consumer complaints of taste and odors resulting from oxidation of accumulated organic material, and difficulty in maintaining a free-chlorine concentration at the ends of the distribution system (AWWA, 1990).

A byproduct of ozonation, acetaldehyde, is a known precursor for chloral hydrate (neither is currently regulated), a byproduct of chlorination. Enhancement of chloral hydrate has not been observed when monochloramine is applied as the secondary disinfectant or if biologically active filtration is used following ozonation and prior to chlorination (Singer, 1992). These compounds are not currently regulated.

5.4.4 Change from Chlorine/Chlorine to Chlorine Dioxide/ Chlorine Dioxide

A change in primary disinfectant from chlorine to chlorine dioxide and a change in secondary disinfectant from chlorine to chlorine dioxide would likely cause a large reduction in TTHMs, particularly where high efficiency chlorine dioxide generators are used. However, there is no literature available where such a change has occurred and it is very unlikely that a system will find chlorine dioxide as a feasible secondary disinfectant. A more likely scenario, for systems seeking drastic reduction in TTHMS, is to replace a chlorine/chlorine system with a chlorine dioxide/chloramine system.

The main concern with the use of chlorine dioxide as both the primary and secondary disinfectant remains in the formation of the chlorite ion, an inorganic byproduct. Another concern with the use of chlorine dioxide is meeting the chlorine dioxide MRDL and chlorite MCL while maintaining a residual throughout the system.

According to Singer (1992), the oxidation products of chlorine dioxide have not been studied extensively, therefore, the public health impact related to the use of chlorine dioxide is largely unknown. The impact of the use of chlorine dioxide on the distribution system is speculative at best. Although chlorine dioxide is expected to protect public health and the distribution system from microbial contamination, the high reactivity of chlorine dioxide suggests that it might, like ozone, create more biodegradable organic compounds that would enhance biofilms and bacterial regrowth, particularly at remote sites in the distribution system and in unlooped lines.

5.4.5 Change from Chlorine/Chloramine to Ozone/Chloramine

The change to ozone as a primary disinfectant and chloramine remaining as a secondary disinfectant will impact TCR compliance due to the action of ozone on NOM. Having already established distribution system practices for biofilm growth in chloraminated distribution water, PWSs making this disinfection practice modification will focus on the biological stability of the distribution system water.

In cases where the use of ozone as the primary disinfectant increases levels of AOC, biological stability in the distribution system could be disrupted even though chloramination has been practiced. As previously discussed in Section 5.3, AOC provides nutrient value for cell metabolism. In a previously chloraminated system, control of nitrification may be achieved using one or more of the techniques listed in Table 5-2. However, the additional nutrients in AOC may require modification to the practices. Alternatively, biological filtration can be used to effectively reduce nutrient levels.

5.4.6 Change from Chlorine/Chloramine to Chlorine Dioxide/Chloramine

A change in primary disinfectant from chlorine to chlorine dioxide while continuing chloramination as the secondary disinfectant would likely be undertaken to dramatically reduce TTHMs. No instance could be found in the literature where this change has occurred. Therefore, it is not known from experience what the possible conflicts or problems might be. However, speculation on the high reactivity of chlorine dioxide would suggest that there would be concern for creation of biodegradable organic compounds in the same way ozone creates aldehydes and AOC. If more biodegradable organic compounds are created, additional nutrients could be available in the distribution system that were not present when chlorination was the primary disinfectant. A greater amount of nutrients in the distribution system could result in enhanced biofilms and enhanced bacterial re-growth. It is possible under this hypothetical scenario that a violation of the TCR could occur. However, a comparison of the oxidation potentials of chlorine dioxide, ozone and free chlorine (i.e., ClO_2 oxidation potential = 0.95V, $\text{O}_3 = 2.07\text{V}$, $\text{HOCl} = 1.36\text{V}$) suggests that the formation of easily biodegradable compounds would not be of much concern. Additional research is needed to verify the speculation and hypotheses described above.

Mitigating this hypothetical problem is expected to utilize biologically active filters to effectively remove the more biodegradable organics created by chlorine dioxide destruction of NOM.

5.4.7 Change from Ozone/Chlorine to Ozone/Chloramine

The primary effect of this change results from the change from chlorine as a secondary disinfectant to chloramine. Current literature demonstrates that such a shift may create a problem in maintaining a chlorine residual in the network (AWWA, 1990). The problems associated with using chloramine develop over time and are manifested by increases in bacterial counts, taste and odor problems, a decrease in residual levels, and reduced transmission carrying capacity due to biofilm formation (AWWA, 1990). These problems can be solved through the occasional use of free chlorine as a secondary disinfectant and a GAC filter following ozonation.

5.5 Coliform Growth in the Distribution System Which Could Result From Alternative Disinfection Benchmarking

Disinfection benchmarking is a methodology and process by which PWSs and States, working together, ensure that there will be no significant reduction in microbial protection when

disinfection practices are modified to meet new standards for DBPs under the Stage 1 DBPR. The *Disinfection Profiling and Benchmarking Guidance Manual* (USEPA, 1999a) provides a more detailed discussion of benchmarking procedures.

The competing aims of ensuring protection against microbial pathogens while modifying disinfection practices to comply with forthcoming rules requires a process which is based on cooperation between States and utilities. Disinfection benchmarking attempts to establish a historic level of disinfection effectiveness through the analysis of previous daily log inactivation levels of *Giardia* or viruses. An alternative benchmark is a level of disinfection effectiveness that the PWS and the State have determined provides microbial protection when the disinfection practice changes substantially. One example of the need for an alternative benchmark is when the historic log inactivations are so high that they fail to provide meaningful representation of the risks involved. In a case like this, the PWS and the State could agree to allow reduction in the level of log inactivations. The subsequent reduction in the amount of disinfection could adversely affect the biological stability in the distribution system.

With daily information on the disinfectant residuals, temperature, pH, and contact times, a PWS can determine the daily log inactivation. By recording log inactivation over a year or a period of years, the PWS can determine the minimum log inactivation during which zero microbial contamination events occurred. This level of log inactivation can then become the “benchmark.” Thus, since the benchmark is determined from interchangeable values, a PWS can modify disinfectant practices and still achieve log inactivation levels above the benchmark, as long as the CT values of the disinfectant are known. However, if a PWS has been disinfecting at a level which produces, for example, 50 logs of *Giardia* or virus inactivation, the PWS may want to apply for a lower level and work with the State to establish an alternative benchmark.

Systems changing their disinfectants from chlorine to other alternative disinfectants (for example, ozone or chloride dioxide) will be required to develop a virus profile and benchmark (please refer to the *Disinfection Profiling and Benchmarking Guidance Manual* (USEPA, 1999a) for more details). When a new benchmark is set, coliform growth in the distribution system is not expected to occur because the State-approved alternative benchmarks will maintain the current level of public health protection against *Giardia* and viruses, which are generally more resistant to disinfection than coliforms.

5.6 Coliform Growth in the Distribution System Which Could Result from Enhanced Coagulation or Enhanced Softening

Enhanced coagulation and enhanced softening can indirectly influence coliform growth in the distribution system by lessening disinfectant effectiveness when pH is changed.

5.6.1 Occurrence

The relationship described above is complex, since the removal of the constituents of TOC during enhanced coagulation and enhanced softening serves to reduce disinfectant demand. Because microbial protection will generally be maintained at the treatment plant through the profiling and benchmarking processes, the system should focus on the secondary disinfectants with regards to lessening disinfectant effectiveness. Table 5-5 describes the general relationships between changes in pH and the subsequent impact(s) on secondary disinfectant effectiveness.

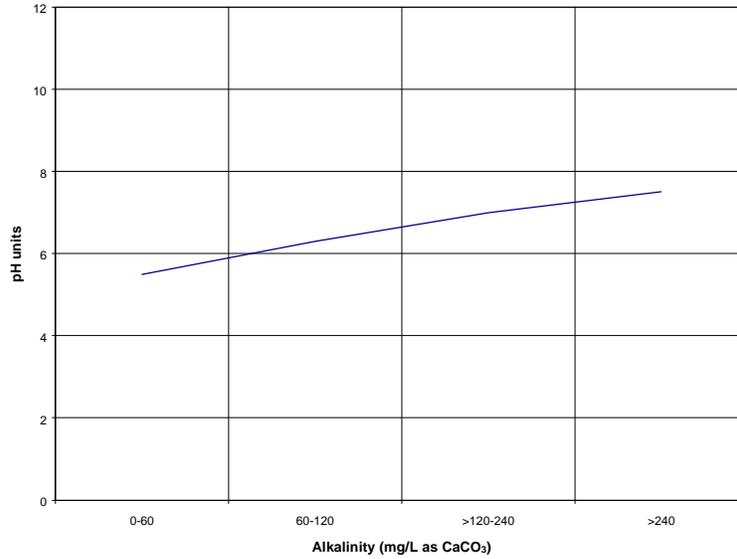
Table 5-5. Generalized Relationships between pH and Effectiveness of Disinfectants Used for Secondary Disinfection

Enhanced Process	pH Impact	Secondary Disinfectant Effectiveness ¹		
		Chlorine	Chlorine Dioxide	Chloramines
Coagulation	↓	↑	↓	↓
Softening	↑	↓	↑	↑

¹ Ozone not included due to its practical limits as a secondary disinfectant.

5.6.2 Enhanced Coagulation

Enhanced coagulation occurs at lower pH levels than most waters. As shown in Figure 5-2, the target pH for enhanced coagulation decreases with decreasing alkalinity. Unfortunately, secondary disinfectant effectiveness decreases for both chloramines and chlorine dioxide, as well. Chloramines are destabilized at lower pH levels, resulting in a lower proportion of the mono-species, and more of the di- and tri- species. Another indirect effect can involve an increase in the corrosivity of chloramines, which can impact the corrosion scale containing bacterial populations. Therefore, a PWS contemplating enhanced coagulation and using chloramines or chlorine dioxide as secondary disinfectants should evaluate the need to adjust pH to prevent corrosion and remain in compliance with the LCR. Also, the system may need to evaluate the impact on biological stability in the distribution system.



Source: USEPA, 1994

Figure 5-2. Relationship Between Target pH and Alkalinity for Enhanced Coagulation Enhanced Softening

Enhanced softening has the opposite effect on disinfectant effectiveness. The higher pH required for this practice will enhance the effectiveness of chloramines and reduce that of chlorine.

5.7 Summary and Recommendations

Modifying treatment practices to comply with the Stage 1 DBPR and IESWTR may cause violations of the TCR. These problems can arise from a number of changes to the chemistry and biology of the distribution system. Chief among the changes are the following:

- pH changes resulting from Stage 1 DBPR compliance that can affect the disinfection effectiveness of chlorine and chloramines
- Increases in the amount of substrate available for biological regrowth in the distribution system when the primary disinfectant is changed to ozone and, perhaps, chlorine dioxide
- Changes in disinfectants to comply with TTHM limits, such as chloramines for secondary disinfection. Chloramines can provide the ammonia for regrowth if the process is not controlled.

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6. OPERATIONAL ISSUES

Promulgation of the IESWTR and the Stage 1 DBPR may have significant impacts on the operation of existing water treatment facilities. These two rules lower the MCL for TTHMs, set new MCLs for HAA5, bromate, and chlorite; increase the requirements for turbidity removal; define the removal requirements for *Cryptosporidium*; and set requirements for the removal of TOC. These changes may result in the use of enhanced treatment, including increased coagulant dosages and pH depression. To comply with these new rules, treatment facilities may also be forced to make changes in the types and dosages of oxidants and disinfectants, the types and dosages of coagulants, and the pH of coagulation. These changes may present several operational problems for treatment facilities including:

- Corrosion of both treatment structures and equipment due to pH changes and oxidant/disinfectant changes
- Changes in the type of chemical feed equipment and the location of chemical dosage points
- Changes in the process equipment distribution system
- Increased need for staff training regarding operational and maintenance issues
- Impacts on the volume and characteristics of treatment residuals
- Changes in water taste and odor due to the use of new oxidants and disinfectants
- Changes in water aesthetics due to changes in the coagulant type
- Changes in process chemistry that may result in distribution system impacts such as nitrification and biological regrowth when chloramines are used as a residual disinfectant, or the formation of chlorite ion when chlorine dioxide is used.

This chapter discusses some of the operational issues described above which are associated with the implementation of enhanced coagulation and the use of alternative disinfectants. Potential problems are identified along with possible solutions to allow a facility to achieve simultaneous compliance with the regulations. This chapter is organized into the following sections:

- Construction Materials
- Treatment Equipment
- Operations and Maintenance Staff Training
- Impact of Enhanced Coagulation on Process Residuals
- Taste and Odors.

6.1 Construction Materials

The construction materials in an existing treatment facility may be subject to significant corrosion and attack as a result of several of the treatment system changes that may occur to meet the new regulations. Changes in coagulation pH to meet the enhanced treatment requirements, or the use of stronger oxidants, may result in aggressive attacks on concrete and steel tankage, as well as submerged treatment equipment and piping.

6.1.1 Impact of Enhanced Coagulation

The major impact on materials of construction in treatment facilities will result from the Stage 1 DBPR requirements for enhanced treatment to achieve TOC removal. Research has shown that to remove additional NOM during the treatment process, coagulant dosages may have to be increased and the pH of the water adjusted. Coagulation with metal salts has been demonstrated to yield optimal NOM removals at pH levels of 5.0 to 6.0 (White et al., 1997). Depending on the required TOC removal to be achieved, some treatment facilities may have to increase coagulant dosages and reduce the pH levels in the coagulation and flocculation basins. The slightly acidic water in these basins increases the rate at which concrete and steel corrode.

Typical dosages of metal salts result in slightly acidic water. Acidic waters can dissolve the calcium carbonate in the concrete and corrosion (rusting) of steel materials may occur. Lime added for softening raises the pH and can promote the development of scale. As a result, coagulation and flocculation treatment steps have been accomplished in unlined concrete tanks, or in coated steel structures or pipelines. Submerged treatment equipment, such as mixers, flocculators, and pumps, have been also been coated to inhibit corrosion by preventing contact between the process water and any ferrous (steel, iron, etc.) surfaces.

The potential process changes implemented in response to enhanced coagulation may result in water in the coagulation flocculation tanks with a much lower pH. These waters may be corrosive enough to attack concrete surfaces and some protective coatings that may have been used in the past. If enhanced treatment is required, and the appropriate bench and pilot scale process testing determine that the pH must be lowered significantly below 7.0 (e.g., pH of 5.5 to 6.5), the treatment facility should evaluate all construction materials that will come in contact with the lower pH water. The coatings on existing equipment, pipe linings, gaskets, and structures should all be investigated to ensure that deterioration will not occur. The investigation should also include an evaluation of the chemical resistance of the existing surfaces to the treatment chemicals and oxidants to be used. This evaluation may even include long-term exposure coupon tests to analyze corrosive attack.

If the evaluation demonstrates that additional protection is required, a variety of commercially available coatings can be used to protect both ferrous and concrete surfaces. Possible coatings

include epoxy, polyurethane, and vinyl paints that may be applied to both ferrous surfaces and concrete. In addition, several cementitious coatings are available for application on concrete to provide a sacrificial and replaceable mortar coating on the concrete surface.

The areas in the treatment train where pH will be depressed will determine the locations for additional corrosion protection. Particular attention should be given to the application point of the acid used for lowering pH, since very low pH areas may exist in a process stream until the acid is thoroughly mixed into the flow. Since residual streams from sedimentation (i.e., sludge) and filtration (i.e., filter backwash washwater) may be created prior to raising the pH, corrosion protection may be required in the residual processing and dewatering facilities of the plant.

Depending on the particular treatment configuration, chemical addition to raise the pH after coagulation may occur some distance downstream, even after filtration. Many existing treatment plants are constructed with common wall construction. This configuration will make pH adjustment after coagulation difficult without a break in the hydraulic gradient.

The *Guidance Manual for Enhanced Coagulation and Precipitative Softening* (USEPA, 1999g) provides additional information that can be used to assist utilities in implementing, monitoring, and complying with the treatment technique requirements in the final Stage 1 DBPR and to provide guidance to State staff responsible for implementing the treatment requirements.

6.1.2 Impact of Disinfectant Changes

The Stage 1 DBPR also lowers the MCLs for TTHMs and sets a MCL for HAA5. As a result, many facilities may begin to utilize alternative disinfectants and oxidants to produce fewer DBPs, but maintain microbial protection. Some alternative disinfectants and oxidants, such as ozone and chlorine are very strong oxidants and can cause localized corrosion at or near their injection point. When changes in disinfectants or oxidants are contemplated, all construction materials and equipment that will come in contact with the process water should be evaluated. Application of coatings as described in the previous section would be an appropriate method of corrosion protection, should it be warranted.

More detailed information on alternative disinfectants is provided in EPA's *Alternative Disinfectants and Oxidants Guidance Manual* (1999b).

6.2 Treatment Equipment

In addition to the impacts on construction materials discussed above, many facilities may also experience impacts to existing treatment equipment due to changes in coagulants and disinfectants. Changes in the treatment chemicals used at a facility may require significant

changes in chemical storage and feed equipment. Obviously, the addition of new process treatment units to accommodate the addition of ozone as a disinfectant may require major structural modifications, as this addition could include ozone generators, contact chambers, off-gas control, and biologically active filtration. However, it is less obvious that seemingly minor changes in coagulants, such as the change from ferrous sulfate to ferric sulfate, may also require substantial modifications to existing chemical storage facilities due to ferric sulfate's greater specific gravity and lower pH. In other instances, various chemicals may have differing freeze characteristics or viscosity, differing unloading and storage requirements, or be incompatible with existing construction materials used in the storage, conveyance, feed, and chemical piping systems.

Enhanced treatment for TOC removal may also require greater coagulant dosages, making existing chemical storage and feed facilities inadequate. If modifications to the chemical feed systems are contemplated, a complete evaluation of the existing storage and feed systems should be performed to determine all modifications required after the chemicals to be used, dosages, and injection locations have been determined.

The monitoring requirements of the IESWTR for filter effluent turbidity could also require new process instrumentation as well as data management and retrieval equipment. Facility operators may also consider automation to provide additional process monitoring of coagulant dosage control (e.g., zeta potential, streaming current, or raw water turbidity), pH, disinfectant residual, and turbidity at several points in the treatment process to better monitor overall plant performance.

6.3 Operations and Maintenance Staff Training

As with any modification to a treatment process, requirements for increased staff and staff training must be addressed. The addition of new disinfectants/oxidants, or the integration of enhanced treatment, will require additional staff training not only to operate the new equipment and treatment technologies, but also to maintain the new equipment. The addition of process monitoring instrumentation may require additional staff training to interpret the new data being received. As with any plant modification, the overall treatment plant Operations and Maintenance Manual must be updated to provide the information necessary for plant staff to operate the plant effectively and safely.

Additional staff may also be needed by treatment facilities that currently utilize labor-intensive operations, such as sludge drying beds with short rotation periods. These facilities may need more staff to process an increased volume of residual solids caused by a change in coagulants or the implementation of enhanced treatment.

Likewise, facilities which have little automation, limited in-line monitoring, and manual process control may require additional manpower to monitor and maintain new process variables (such as chemical feed controls) included in a new treatment process. The requirements of the IESWTR for disinfection profiling and the increased monitoring of individual filter performance could also add significantly to an operator's administrative duties.

6.4 Impact of Enhanced Coagulation on Process Residuals

Facilities that implement enhanced coagulation may experience significant changes in both the volume and characteristics of process residuals. An increase in coagulant dosage could increase the volume of residual solids created, and a change in coagulant types or coagulation pH could alter the dewatering characteristics of existing residual streams.

6.4.1 Solids Volume

The production of residual solids is related to water production, coagulant dosage, raw water suspended solids, and polymer dosage. If treatment facilities make changes in coagulant types or add/modify polymer addition, significant changes may be expected in the amount of solids produced. The following formulas can be used to estimate the amount of residual solids that might be produced from a metal hydroxide coagulation treatment scheme (AWWA and ASCE, 1998):

For aluminum coagulant sludge: $S = Q(0.44 Al + SS + P)(8.34 \text{ lb/mil gal/mg/L})$

For ferric chloride sludge: $S = Q(2.9 Fe + SS + P)(8.34 \text{ lb/mil gal/mg/L})$

Where:

- S = solids produced, pound dry solids per day
- Q = water production, million gallons per day
- Al = alum dosage, mg/L as solution (alum 17.1% solution)
- SS = suspended solids concentration, mg/L
- Fe = ferric chloride dosage, mg/L (dosage as Fe)
- P = polymer dosage, mg/L

A similar equation has been developed for lime softening solids (AWWA and ASCE, 1998):

$S = Q(2.0Ca + 2.6Mg)(8.34 \text{ lb/mil gal/mg/L})$

Where:

- Ca = calcium hardness removed as CaCO_3 , mg/L
- Mg = magnesium hardness removed as CaCO_3 , mg/L

When changes in coagulants are contemplated, the results of these equations may be compared to actual solids production experienced with the current coagulant for verification purposes. The equations can then be used to estimate solids production expected with a new coagulant, or a change in coagulant dosage. If significant increases in solids volume are expected to result from changes in coagulants, the capacity of the facility's residual management system should be evaluated. This evaluation can be performed by developing a complete mass balance of the solids passing through the treatment plant. The solids in the raw water should be included in the calculation, along with solids recycled to the head of the plant and floc produced in the treatment process.

Alum produces 0.44 mg/L of solids for each mg/L of alum added to the process. Likewise, iron salts produce 2.9 mg/L of solids for each mg/L of coagulant added (AWWA and ASCE, 1998). It is evident that a change in coagulants from alum to iron salts as a coagulant will produce more solids for similar dosages.

Increases in sludge wasting can also increase residual hydraulic rates which can have substantial impacts on surface water disposal systems, or facilities that discharge solids to a sanitary sewer. Surface water discharge may require revisions to existing discharge permits with limits on maximum flow rates or other parameters such as total solids and pH. Sanitary sewer discharges may exceed permitted levels, or require expansion of pretreatment measures already in place. If permit limits are expected to be exceeded, a permit revision may be in order. Facilities which face limits on the maximum flow rate or total volume of discharge may need to explore ways of reducing sludge volumes by the addition of treatment steps such as gravity thickening or floatation prior to discharge. These treatment methods, however, will not decrease the solids levels.

Increases in solids loading rates on existing unit processes may also exceed the capacity of existing residual treatment system, resulting in effluent sludge which may not meet the requirements for landfilling, land application, or reuse. Residual solids are typically treated by a variety of processes, including thickening, dewatering, or drying. All of these processes can include chemical conditioning for optimal performance.

Thickening processes usually concentrate hydroxide residual streams to 1 to 8 percent solids by weight, and lime sludges up to 25 percent solids (AWWA and ASCE, 1998). Thickening can be accomplished by the use of gravity thickening basins, gravity belt thickeners, or flotation processes. Gravity thickening basins are typically loaded directly from sedimentation basin blowdown at 100 to 200 gpd/ft² for hydroxide sludges, and 60 to 200 lb solids per ft² per day for lime sludges (AWWA and ASCE, 1998). Typical solids loadings for gravity belt thickeners vary by manufacturer, but are published and available with the equipment documentation.

Flotation thickening processes usually are operated in continuous feed mode, and can accommodate solids loadings of 10 to 30 lb/day/ft² (AWWA and ASCE, 1998).

Dewatering processes include mechanical systems such as filter presses, belt presses, centrifuges, vacuum-assisted drying beds, and filtration, as well as nonmechanical treatment systems including drying beds, freeze-assisted sand beds, solar drying beds, wedgewire beds, and lagoons. Loading rates for these processes are variable, and are affected by regional and climatic factors, as well as depth of application and length of drying time before removal. Typical guidelines for the various processes can be found in the references AWWA and ASCE (1998) and ASCE/AWWA/USEPA (1997).

In all cases, chemical conditioning can be used to optimize existing dewatering processes. Anionic polymers are typically added to influent streams to aid in the formation of very dense and large floc, which has better settling characteristics. Lime and bentonite clay are also used to condition and add bulk to coagulant sludges.

6.4.2 Residual Solids Dewatering Characteristics

Changes in coagulants or coagulation and flocculation conditions can have significant impacts on the characteristics of residual solids. Hydroxide sludges produced from aluminum and iron salts are generally gelatinous in nature, non-compactible, and difficult to dewater. In contrast, sludges from lime softening treatment processes are generally easier to dewater. The presence of magnesium hydroxide in softening sludges can impact dewatering, making it more difficult to achieve high percent solids sludge cake. As a result, facilities that practice enhanced softening and change their treatment scheme to remove additional magnesium may experience difficulty in maintaining dewatering efficiency.

Changes in pH that may be required to achieve enhanced coagulation may also change the dewatering characteristics of some sludges. These changes may improve or degrade the ease with which the sludges can be concentrated. pH changes can also impact facilities that have requirements on dewatering facility effluent or discharge to surface water bodies or sanitary sewers.

In addition, the additional NOM removed by enhanced coagulation will be present in the residual stream and may present problems with discharge limitations, pre-treatment requirements, or reuse requirements. The recovered solids, as well as the decanted liquids, may have a very different quality and may lose some value for reuse, recycling, or discharge. These solids may also require stabilization.

The expected variation in dewatering characteristics will depend largely on the character of the raw water source and the treatment scheme utilized. Bench- and pilot- scale testing can be

used to develop data to give general indications of the impacts on dewatering characteristics. Thickening can be evaluated using settling tests, flotation tests, and capillary suction time tests (Burriss and Smith, 1996). Dewatering processes can be evaluated using time-to-filter tests, filter leaf tests, capillary suction tests, and settling tests (Burriss and Smith, 1996). It should be noted that bench-scale tests may not provide direct correlation to full-scale performance. Bench- and pilot- scale tests can, however, be useful in evaluating the magnitude of expected changes and the effectiveness of treatment modifications.

As stated previously, chemical conditioning of residual streams can greatly improve the performance of dewatering processes. The addition of anionic polymers has proven to aid in the formation of large, dense floc, which is more easily separated as concentrated solids. Lime and clay have also been used to condition hydroxide sludges and improve dewatering. The advice and documentation available from dewatering equipment manufacturers may also provide useful information in defining treatment modifications.

6.5 Tastes and Odors

Changes in oxidants or disinfectants used in a treatment process to control the formation of DBPs may also result in the formation of new tastes and odors in the finished water. The implementation of process modifications can change the intensity and character of historic tastes and odor episodes, or change the way a facility must treat a chronic taste and odor problem. It has been well documented that there are many causes of tastes and odors in finished water, and the intensity and character of specific taste and odor episodes have proven to be highly variable and often difficult to trace (AWWARF and Lyonnaise des Eaux, 1995). Tastes and odors are common in surface water sources, and are typically caused by decaying vegetation, algae, or industrial and municipal wastes. Finished water tastes and odors can also be caused by biological activity in distribution systems and in-storage reservoirs.

The treatment of tastes and odors is commonly accomplished by either the application of an oxidant to raw water prior to treatment, or by the use of an adsorbing media such as activated carbon. The chemicals used for pre-oxidation may also be the primary disinfectant used for microbial inactivation. Many odor causing compounds present in surface water, such as 2-methylisoborneol (MIB) and geosmin, are resistant to oxidation and can have competing chemical reactions with certain oxidants that can create new tastes and odors or worsen existing conditions. DBPs such as aldehydes, phenols, chlorophenols, and trihalomethanes can also impart distinct tastes and odors (AWWARF and Lyonnaise des Eaux, 1995).

Most of the disinfectants and oxidants in use today are effective in reducing and controlling specific taste and odor episodes. Stronger oxidants like ozone, potassium permanganate, and chlorine dioxide are more effective in oxidizing odor-causing compounds, but may form

additional tastes and odors at high residual concentrations, or form byproducts. Chloramines have proven more effective in controlling tastes and odors when strong taste and odor precursors are present.

6.5.1 Taste and Odor Sources

Tastes and odors are caused by many sources. Geosmin and MIB result in earthy and musty odors in water supplies. These compounds are naturally occurring, and are primarily formed by the metabolism of many forms of algae (AWWARF and Lyonnaise des Eaux, 1995).

Tastes and odors can also be created in the distribution system by a variety of causes including biological sources like fungi and bacteria from biofilms, or chemical sources like disinfectants, construction materials, corrosion, and DBPs. System design and operation can also lead to tastes and odors created in areas with long residence times, or by the blending of differing sources and by the presence of cross-connections.

Chlorine has also been the source of many taste and odor complaints. The tastes and odors are often described as bleach-like, or similar to swimming pool odors, resulting from the use of free chlorine or chloramines (AWWARF and Lyonnaise des Eaux, 1995). Monochloramine rarely has been found to result in significant taste and odor problems, but it is not as easy to detect as dichloramine and trichloramine. Dichloramine has been described as a swimming pool or bleach odor, while trichloramine has been described as chlorinous and fragrant (AWWARF and Lyonnaise des Eaux, 1995). These two chloramines are prevalent at lower pH levels.

In addition to the tastes and odors imparted by free chlorine and chloramines, tastes and odors can be created from byproducts produced when these disinfectants are applied to water. The reaction of free chlorine with amino acids or organic nitrogen present in water can form aldehydes, which have been associated with taste and odor. Aldehydes have complex tastes and odor characteristics, but have been described as chlorinous, earthy, stale, disinfectant, bitter, ammonia, organic, muddy, moldy, and bleach-like (AWWARF and Lyonnaise des Eaux, 1995). Phenols present in water can also react with chlorine to produce chlorophenol, which have medicinal tastes and odors. In addition, trihalomethanes can have strong medicinal tastes and odors.

Chloramines can have the same reactions with amino acids, organic nitrogen, and phenols to create taste and odor causing compounds. Since chloramines are much weaker oxidants than free chlorine, the reaction time to form taste and odor causing compounds is much longer, resulting in a reduced potential for taste and odor production.

Chlorine dioxide can form detectable tastes and odors when residual concentrations reach 0.20 mg/L to 0.25 mg/L (AWWARF and Lyonnaise des Eaux, 1995). Secondary odors have also been reported due to reactions between chlorine dioxide and household products and from the gaseous release when taps are opened.

Ozone is effective in oxidizing organic compounds responsible for many tastes and odors, and is highly effective when combined with hydrogen peroxide or UV light to form an advanced oxidation process. However, ozone has been reported to impart an “oxidant” or “ozonous” odor to waters, even when an ozone residual is not present. Aldehyde byproducts formed from the reaction of ozone in water have also been associated with odors ranging from fruity to sickening. Tastes and odors have not been identified with other ozone byproducts (AWWARF and Lyonnaise des Eaux, 1995).

6.5.2 Taste and Odor Controls

Taste and odor episodes respond in various ways to different treatments. Free chlorine application or ozonation can effectively remove some odors, such as those characterized as fishy. Other constituents like geosmin and MIB are difficult to oxidize. In planning for the implementation of any process modifications, incorporating flexibility in the treatment process to allow the application of differing oxidants at various points in the treatment process for the control of tastes and odors should be considered.

Bench-scale and pilot studies may be required to develop treatment schemes that will minimize byproduct formation and provide taste and odor control without reducing the microbial protection. Chemical analyses can also be performed to determine the causes of tastes and odors. The Flavor Profile Analysis (FPA) approach can be used to define sensory responses to tastes and odors to better understand their character and intensity. Once known, treatment and control strategies can be developed to address specific applications. Further information describing taste and odor identification and treatment strategies can be found in the publications *Identification and Treatment of Tastes and Odors in Drinking Water* (AWWARF, 1996) and *Advances in Taste and Odor Treatment and Control* (AWWARF and Lyonnaise des Eaux, 1995).

In addition to oxidation, treatment schemes utilizing activated carbon may be necessary to control tastes and odors and minimize byproduct formation. Activated carbon is typically applied as powdered activated carbon (PAC) or as granular activated carbon (GAC). Activated carbon is an adsorbent, and its efficiency is determined by contact time and the presence of organic constituents in the water competing for adsorbent sites.

PAC is generally injected into raw water as a slurry prior to treatment, and is useful for occasional control of recurring taste and odor events. The PAC is captured through

sedimentation, regenerated, and recycled. GAC is typically used after sedimentation, and typically in a GAC-filled basin used as a contactor. GAC contactors are normally used for control of chronic tastes and odors. It should be noted that activated carbon has other uses in water treatment, including the removal of natural organic matter and synthetic organic compounds.

Activated carbon has been proven effective for the control of many tastes and odors, but the effectiveness and economic impacts are application-specific. Bench and or pilot testing is normally required to determine the recommended configuration, especially for the design of GAC contactors.

Biological treatment has also been examined in Europe, but has not received wide attention in the United States. Biological treatment utilizes slow sand filtration and attempts to control tastes and odors by achieving biological stability of water through the removal of biological organic matter. Biological treatment may have other benefits by controlling biological regrowth in the distribution system, thus reducing the requirements for secondary disinfectants. The effectiveness and application of biological treatment is not fully known at this time, but research continues to examine its use and evaluate the benefits to be gained in the control of tastes and odors.

6.5.3 Recommendations

Tastes and odors in the distribution system and treatment facility should be continually monitored to ensure that high quality, stable water is being delivered. Systems should consider the following to control taste and odor problems:

- Reviewing customer complaints to best determine the cause of tastes and odors so that corrective action can be taken
- Considering changing the secondary disinfectant to control regrowth
- Making a pH adjustment or applying a corrosion inhibitor to address corrosion problems
- Rehabilitating water mains to replace existing, unlined corrosion surfaces in the distribution system
- Examining the construction materials used in the distribution system, including coatings and linings in both piping and storage facilities
- Revising the system operations to reduce residence times in storage facilities
- Implementing a water main flushing program
- Maintaining an adequate disinfectant residual to control regrowth.

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