Simultaneous Compliance Workbook:

KEY QUESTIONS TO CONSIDER WHEN ADDING OR CHANGING TREATMENT— *A SIMPLIFIED APPROACH*

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Abbreviations and Acronyms

AOC	Assimilable Organic Carbon
As^{+5}	Arsenate
AWWA	American Water Works Association
C	Disinfectant Residual Concentration in milligrams per liter (mg/L) (in CT calculations)
$CaCO_3$	Calcium Carbonate
CCT	Corrosion Control Treatment
CCPP	Calcium Carbonate Precipitation Potential
CFR	Code of Federal Regulations
CO_2	Carbon Dioxide
CT	The Product of Disinfectant Residual Concentration and Contact Time
DBP	Disinfection Byproduct
DBPR	Disinfectants and Disinfection Byproducts Rule
DIC	Dissolved Inorganic Carbon
DOC	Dissolved Organic Carbon
GAC	Granular Activated Carbon
HAA	Haloacetic Acid
IESWTR	Interim Enhanced Surface Water Treatment Rule
IX	Ion Exchange
LCR	Lead and Copper Rule
LSI	Langelier Saturation Index
LT1ESWTR	Long Term 1 Enhanced Surface Water Treatment Rule
LT2ESWTR	Long Term 2 Enhanced Surface Water Treatment Rule
MCL	Maximum Contaminant Level
MF	Microfiltration
NF	Nanofiltration
NH_2Cl	Monochloramine
NOM	Natural Organic Material
NPDES	National Pollutant Discharge Elimination System
O&M	Operation and Maintenance
OCCT	Optimal Corrosion Control Treatment
ORP	Oxidation Reduction Potential
PAC	Powdered Activated Carbon
PACl	Polyaluminum Chloride
Pb	Lead

Pb^{2+}	Plumbous Ion or Lead (II)
Pb^{4+}	Plumbic Ion or Lead (IV)
PbO_2	Lead Oxide
POTW	Publicly Owned Treatment Works (i.e., WWTP)
PWS	Public Water System
RO	Reverse Osmosis
RTCR	Revised Total Coliform Rule
SDWA	Safe Drinking Water Act
SUVA	Specific Ultraviolet Absorbance
SWTR	Surface Water Treatment Rule
T	Contact Time in Minutes (in CT calculations)
TDS	Total Dissolved Solids
THM	Trihalomethane
TOC	Total Organic Carbon
UF	Ultrafiltration
USEPA	U.S. Environmental Protection Agency
UV	Ultraviolet Light
WWTP	Wastewater Treatment Plant

Introduction

Simultaneous Compliance planning is the comprehensive assessment and implementation of processes and practices that promote compliance with **all** Safe Drinking Water Act (SDWA) regulations. Without careful planning and proper implementation, actions intended to improve one aspect of regulatory compliance can produce conflicts (or at least pose challenges) in other areas of water quality performance. Wholesalers should communicate with their consecutive systems before making treatment changes to give the consecutive systems enough time to prepare and ensure continued compliance with all SDWA regulations within their own systems. The purpose of this workbook is to provide a summary of potential simultaneous compliance and operational planning issues that can arise when water utilities choose to implement or change the following treatment technologies:

- Modifying Existing Chlorination Practices
- Seasonal Reductions in Chlorine Dosage
- Conversion to Chloramines for Secondary Disinfection
- Conversion to Chlorine Dioxide for Primary Disinfection
- Enhanced or Modified Coagulation
- Ion Exchange (IX) Processes
- Microfiltration (MF) and Ultrafiltration (UF)
- Nanofiltration (NF) and Reverse Osmosis (RO)
- Corrosion Control Treatment (CCT)
- Ozone Treatment
- Ultraviolet Light (UV) Disinfection

This workbook includes issues associated with each technology, along with suggestions about assessment tools and possible ways that simultaneous compliance issues can be addressed. Most of the technologies are addressed in detail later in this workbook; ozone and UV are discussed briefly at the end of this section. These two technologies and their simultaneous compliance issues are discussed in greater detail in the *Simultaneous Compliance Guidance Manual for the LT2ESWTR and Stage 2 DBP Rules* (USEPA 2007). This workbook is not intended to provide comprehensive technical guidance for systems making treatment modifications. Instead, systems are encouraged to use this document in combination with other suggested reading and reference documents as technical resources (some listed at the end of each section) to identify potential issues and possible solutions.

The suggestions in this workbook are intended to inform public water system (PWS) decision making, but they should not be used in place of system-specific data collection and economic analysis. In many cases, a complete assessment of a selected treatment technology requires the assistance of a licensed design professional. Often, pilot plant or full-scale treatability data must be collected in accordance with state primacy agency requirements. Systems should consider source water characteristics, existing treatment processes, distribution system issues, available resources, and other system-specific information in determining the best compliance approach.

How to Use This Workbook

Specific simultaneous compliance solutions are unique to the characteristics of each water system. Each section of this workbook provides a brief description of a specific treatment technology, its advantages and disadvantages, and typical applications, as well as potential waste or wastewater management considerations. Simultaneous compliance and pivotal operational issues are then summarized for each approach. Finally, a list of questions that utilities should consider before implementing or modifying each technology is presented to frame the compliance and operational issues and help utilities identify key challenges and solutions most applicable to their water systems.

The following are examples of technology-specific simultaneous compliance issues.

Modifying existing chlorination practices

Modifying chlorination practices can be an effective strategy to reduce formation of disinfection byproducts (DBPs). One of the simplest methods of reducing DBP formation is to defer chlorine addition until as much natural organic material (NOM) as possible has been removed. Because chlorine is used by water utilities in so many different ways, modifying chlorination practices has the potential to introduce a wide array of both simultaneous compliance issues and unintended consequences. Modified chlorination practices could create shifts in pH and alkalinity levels and negatively affect CCT. Changing the location of chlorine addition could reduce the ability to meet disinfection requirements in the treatment process. Changes from free chlorine to chloramines for secondary disinfection can, under some conditions, result in an increase in lead or copper solubility. Disinfection changes could necessitate re-optimization of CCT under the Lead and Copper Rule (LCR).

Seasonal reductions in chlorine dosage

By reducing chlorine dosages when water temperatures are higher, systems might be able to reduce overall formation of DBPs. Systems could potentially achieve comparable pathogen inactivation with less chlorine and a reduction in DBP formation by reducing the chlorine residual at the treatment plant during warm water conditions. Disinfectant residuals should never be lowered below primary disinfection requirements dictated by the Surface Water Treatment Rule (SWTR), the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR), the prescribed residual level if on a reduced monitoring schedule under the Revised Total Coliform Rule (RTCR), and a water system’s primacy agency.

Conversion to chloramines for secondary disinfection

Chloramines are often an alternative to chlorine for secondary disinfection because it is more stable and persistent in the distribution system and minimizes the formation of trihalomethanes (THMs) and haloacetic acids (HAAs). Simultaneous compliance issues and potential unintended consequences include nitrification and the destabilization of pipe scales;

when pipe scales are stable, they can provide corrosion control benefits. Wherever chloramination is practiced, utilities should follow a nitrification action plan including monitoring of ammonia, free chlorine, and total chlorine residuals in the distribution system. Conversion to chloramines can also decrease pH, change microbial conditions, and reduce oxidation reduction potential (ORP) in the distribution system, causing a shift in existing metallic-scale species and increases in dissolved lead and other metal concentrations.

Conversion to chlorine dioxide for primary disinfection

Chlorine dioxide is an alternative to chlorine for primary disinfection but is rarely used for secondary disinfection, in part due to acute health risks associated with high concentrations of chlorine dioxide and additional health concerns related to the DBP chlorite. One simultaneous compliance issue is formation of DBPs including chlorite and chlorate. Unintended consequences are dependent upon the location of the chemical feed point as well as system-specific water quality and operating conditions. For example, if chlorine dioxide is used for primary disinfection after filtration, the chlorine dioxide may oxidize iron and manganese present in the filtered water causing them to form precipitates that could potentially affect distribution system water quality.

Enhanced or modified coagulation

Increased removal of DBP precursors is frequently employed as a treatment technique to lower DBP formation. *Enhanced coagulation* refers to adding excess coagulant (at correct pH, alkalinity and temperature conditions) to improve removal of DBP precursors by conventional water treatment. Changes in coagulation practices can cause a wide variety of simultaneous compliance issues and potential treatment interactions, including decreased finished water pH and total organic carbon (TOC) and changes in the chloride-to-sulfate mass ratio. Failing to plan for pH shifts that typically accompany enhanced coagulation (either by adjusting the finished water pH or modifying the CCT) is likely to have negative effects on tap water lead and copper levels. Changes in pH may also affect the primary and secondary disinfection processes and the integrity of pipe scales in the distribution system. Corrosion and release of pipe scales may occur in the distribution system.

Ion exchange processes

IX is generally used to remove specifically targeted ions and other charged species from water such as hardness, nitrate, fluoride, perchlorate, uranium, selenium, arsenic, sulfate, NOM, and radionuclides. Competition for adsorption sites on the IX resin can greatly reduce its efficiency in removing specifically targeted ions or contaminants. Significant demineralization (resulting from combined anion and cation exchange) can have a significant effect on total dissolved solids (TDS) and alkalinity and can produce a water that is highly corrosive. High levels of TDS, chlorides, or other target contaminants in IX waste streams can complicate disposal or possibly trigger more stringent hazardous or radioactive waste requirements.

Microfiltration and ultrafiltration

MF and UF are low-pressure membrane processes increasingly used in drinking water treatment. MF and UF are typically employed to achieve high removals of turbidity, bacteria, *Giardia*, and *Cryptosporidium*. This often allows for a lower disinfectant dosage and reduced formation of DBPs. Very few simultaneous compliance or unintended consequences are associated with MF and UF, although modifications to pretreatment and post-treatment can introduce complexities. Proper operational practices are typically sufficient to address such issues, although additional operator training could be needed.

Nanofiltration and reverse osmosis

NF and RO are used for softening, removing DBP precursors or other dissolved contaminants, and desalination. They also provide a barrier for most cysts and viruses. NF can be effective in removing arsenic, nitrate, radionuclides, and many other dissolved contaminants. As with IX, NF can have a significant effect on TDS and alkalinity and can produce a lower pH water that is more corrosive. Often 10 to 30 percent of treated water will be lost to concentrate and cleaning solutions where NF treatment is being used for contaminant removal.

Corrosion control treatment

CCT has historically been applied to meet multiple water quality objectives. Under the LCR, CCT is narrowly defined as minimizing dissolution of lead and copper into drinking water without compromising other health-related water quality goals. In practice, optimizing and maintaining CCT inevitably requires a careful balance between sometimes conflicting water quality objectives for pH, lead solubility, coagulation, softening, disinfection, DBPs, copper, phosphorus, and other water quality constraints. Even where a system has successfully implemented CCT and conducted follow-up monitoring as required by the LCR, seemingly unrelated changes in source water conditions, treatment practices, and distribution system operation and maintenance (O&M) can affect lead solubility and existing distribution system scale deposits. Utilities should carefully evaluate the effect(s) of any pH/alkalinity shifts on corrosion and re-optimize LCR CCT if necessary.

Ozone treatment and ultraviolet light disinfection

Water systems are implementing additional treatment modifications including ozone or UV disinfection. Ozone is an alternative to chlorine for preoxidation and primary disinfection. It is not used as a secondary disinfectant because it decays rapidly and cannot maintain a residual in the distribution system. Similarly, UV disinfection does not produce a disinfectant residual; therefore, another disinfectant is usually required to accomplish secondary disinfection.

One simultaneous compliance issue with using ozone is formation of regulated (bromate) and unregulated DBPs. Another possible unintended consequence of using ozone is that other ozonation byproducts, such as aldehydes and organic acids, are more readily biodegradable and may contribute to assimilable organic carbon (AOC) and biological growth (e.g., biofilm) in the distribution system. Also, dissolved oxygen produced during treatment may increase corrosion.

Ozone and UV are not discussed further in this workbook. For additional information about related simultaneous compliance issues and unintended consequences of using ozone or UV, refer to the *Simultaneous Compliance Guidance Manual for the Long Term 2 Enhanced Surface Water Treatment Rule and Stage 2 Disinfectants and Disinfection Byproduct Rule* (USEPA 2007).

Additional Reference Documents

In conjunction with promulgation of the Interim Enhanced Surface Water Treatment Rule (IESWTR), Stage 1 Disinfectants and Disinfection Byproducts Rule (DBPR), Long Term 1 Enhanced Surface Water Treatment Rule (LT1ESWTR), LT2ESWTR, and the Stage 2 DBPR, U.S. Environmental Protection Agency (USEPA), the American Water Works Association (AWWA), and the Water Research Foundation (WRF) have published the following guidance manuals that could assist PWSs with resolving potential conflicts:

Disinfection

- *AWWA Manual M20 Water Chlorination and Chloramination Practices and Principles, Second Edition* (AWWA 2006).
- *AWWA Manual M65 On-Site Generation of Hypochlorite, First Edition* (AWWA 2015).
- *Alternative Disinfectants and Oxidants Guidance Manual* (USEPA 1999).
- *Disinfection Profiling and Benchmarking Guidance Manual* (USEPA 2020).

Nitrification

- *AWWA Manual M56 Nitrification Prevention and Control in Drinking Water, Second Edition* (AWWA 2013).

Corrosion Control

- *AWWA Manual M58 Internal Corrosion Control in Water Distribution Systems, Second Edition* (AWWA 2017).
- *Managing Change and Unintended Consequences—LCR Corrosion Control Treatment* (AWWA 2005).
- Friedman, M.J., A.S. Hill, S.H. Reiber, R.L. Valentine, G. Larsen, A. Young, G.V. Korshin, and C.Y. Peng. 2010. *Assessment of Inorganics Accumulation in Drinking Water System Scales and Sediments*. Denver, Colo.: WRF.
- Friedman, M., A. Hill, S. Booth, M. Hallett, L. McNeill, J. McLean, D. Stevens, D. Sorensen, T. Hammer, W. Kent, M. DeHaan, K. MacArthur, and K. Mitchell. 2016. *Metals Accumulation and Release Within the Distribution System: Evaluation and Mitigation*. Denver, Colo.: WRF.
- *Revised Optimal Corrosion Control Treatment Evaluation Technical Recommendations for Primacy Agencies and Public Water Systems* (USEPA 2019).

Distribution System Operations and Management

- *AWWA Manual M68 Water Quality in Distribution Systems, First Edition* (AWWA 2017).

- *ANSI/AWWA Standard G200-09. Distribution Systems Operation and Management* (AWWA 2009).

<u>Regulatory Compliance</u>

- *Complying with the Long Term 2 Enhanced Surface Water Treatment Rule: Small Entity Compliance Guide* (USEPA 2007).
- *Complying with the Stage 2 Disinfectants and Disinfection Byproduct Rule: Small Entity Compliance Guide* (USEPA 2007).
- *Enhanced Coagulation and Enhanced Precipitative Softening Guidance Manual* (USEPA 1999).
- *Handbook: Optimizing Water Treatment Plant Performance Using the Composite Correction Program* (USEPA 1998).
- *Lead and Copper Rule Guidance Manual, Volume II: Corrosion Control Treatment* (USEPA 1992).
- *Membrane Filtration Guidance Manual* (USEPA 2005).
- *Simultaneous Compliance Guidance Manual for the Long Term 2 Enhanced Surface Water Treatment Rule and Stage 2 Disinfectants and Disinfection Byproduct Rule* (USEPA 2007).

Modifying Existing Chlorination Practices

Why add chlorine to drinking water?

The SWTR, IESWTR, and LT2ESWTR establish disinfection requirements for water systems. While alternatives exist, most United States water systems employ chlorine for either primary or secondary disinfection.

At surface water treatment plants, chlorine can be added for prechlorination at either the raw water intake or flash mixer, for intermediate chlorination ahead of the filters, for post-chlorination at the clearwell, and for distribution system disinfectant residual in the distribution system.

While inactivation of pathogenic organisms is still the primary function of chlorine, it is often used in drinking water treatment for other purposes including:

- Controlling nuisance Asiatic clams and zebra mussels
- Oxidizing iron and manganese
- Improving coagulation
- Controlling taste and odor
- Preventing algal growth in sedimentation basins and filters
- Removing color

The typical uses for each chlorine application point are summarized below:

Table 1: Typical Chlorine Points of Application and Uses

Point of Application	Typical Uses
Raw Water Intake	Zebra mussel and Asiatic clam control, control biological growth
Flash Mixer/Rapid Mix Flocculation (prior to sedimentation)	Prechlorination, iron and manganese oxidation, improved coagulation, taste and odor control, oxidation of hydrogen sulfide, algae control
Filter Influent/ Settled water	Prechlorination, control biological growth in filter, iron and manganese oxidation, taste and odor control, color removal
Filtered Water	Primary disinfection
Finished Water Prior to Entry Point to the Distribution System	Secondary disinfection
Finished Water in the Distribution System	Booster disinfection

Source: *Alternative Disinfectants and Oxidants Guidance Manual*, USEPA 1999.

What are potential disadvantages of chlorine?

Chlorine reacts with natural organic material (NOM) to produce DBPs:

Free Chlorine + NOM = DBPs (trihalomethane [THMs], haloacetic acid [HAAs])

DBPs are regulated contaminants in drinking water because they are possible carcinogens and have been shown to cause adverse reproductive or developmental effects in laboratory animals. One of the simplest methods of reducing DBP formation is to defer chlorine addition (to the extent practical) until as much NOM as possible has been removed by preceding treatment processes.

How can chlorination practices be modified to reduce DBPs?

Modifying chlorination practices can be an effective strategy to reduce formation of DBPs. This strategy can generally be broken into four basic approaches:

- Eliminating/reducing prechlorination
- Moving the initial point of chlorine addition downstream
- Optimizing/reducing overall chlorine dosages
- Reducing pH to enhance primary disinfection

One of the simplest methods of reducing DBP formation is to defer chlorine addition until NOM levels have been reduced.

Eliminating/reducing prechlorination

Eliminating or reducing prechlorination dosages can be very effective for controlling DBPs. However, failure to replace chlorine with an alternative pre-oxidant, such as potassium permanganate, chlorine dioxide, or ozone, could result in other water quality problems. Algae, taste and odor, iron and manganese, and contaminants whose removal is often facilitated by prechlorination could pass through the treatment process unless a substitute oxidant is used.

In addition, if primary disinfection credit under the suite of SWTRs is partially achieved via prechlorination, such credit would be less if prechlorination were decreased or eliminated. Shifts in the oxidizing conditions within granular media filters commonly used in water treatment can cause desorption of metal-oxides (e.g., manganese dioxide) and subsequent release of previously removed inorganic contaminants. Finally, substitute oxidants such as chlorine dioxide or ozone should not be introduced without careful evaluation because their use can create new simultaneous compliance issues or negative unintended consequences.

Moving the initial point of chlorine addition downstream

Water utilities employing conventional treatment could consider moving the application point for chlorine downstream within the plant to a point after more DBP precursors have been removed. Depending on the treatment plant, THM formation potential can be decreased by up to 50 percent as a result of precursor removal during coagulation and sedimentation (Singer and Chang 1989). DBP concentrations in the finished water can often be reduced by moving the initial point of chlorination downstream in the treatment process, which can also allow for a reduction in the overall dosage of disinfectant needed for primary disinfection.

Optimizing/reducing overall chlorine dosages

If the initial point of chlorine application is moved downstream of where a significant amount of organic matter has been removed, the chlorine demand of the water is lower. In some cases, the system might be able to take advantage of the reduced chlorine demand to lessen the overall chlorine dose needed to achieve primary disinfection. The system would benefit not only from lower chemical costs but could also reduce operational costs if the system decreases its number of chlorine injection points.

Reducing pH to enhance primary disinfection

The efficacy of free chlorine for inactivation of bacteria, viruses, *Giardia lamblia*, and other microbial pathogens is pH dependent. Operating unit treatment processes that contribute to primary disinfection at lower pH often allows chlorine dosages to be reduced without loss of disinfection credit. However, because other unit processes are also sensitive to shifts in pH, the site-specific benefits of pH reduction should be carefully weighed against possible negative effects on other treatment processes (e.g., coagulation, corrosion control).

Simultaneous Compliance Issues Associated with Modifying Chlorination Practices

Many systems benefit from using chlorine as both an oxidant and a disinfectant. Chlorine can oxidize iron and manganese, improve coagulation, enhance color removal, improve taste and odor, and control biological growth at various stages of treatment/disinfection. Because chlorine has many applications, modifying chlorination practices has the potential to introduce both simultaneous compliance issues and unintended consequences as listed below.

Modifying chlorination practices has the potential to introduce both simultaneous compliance issues and unintended consequences.

- Affect primary disinfection CT performance
- Reduce coagulation effectiveness
- Affect iron and manganese removal
- Shift pH and alkalinity
- Increase algae growth and filter fouling within treatment plants
- Impact extracellular cyanotoxin concentrations
- Limit control of zebra mussels or Asiatic clams
- Form chlorate when generating hypochlorite onsite

Changes in pH, chlorine dosage, or application point(s) will usually affect primary disinfection CT performance under the SWTR and could affect lead and copper corrosion and CCT effectiveness under LCR.

Affect primary disinfection CT performance

The SWTR requires that systems achieve 3-log (99.9%) removal/inactivation of *Giardia lamblia* and 4-log (99.99%) removal/inactivation of viruses through a combination of disinfection and filtration. Primary disinfection requirements are based on the concept of C times T, or *CT*, which is the product of residual disinfectant concentration (C, in milligrams per liter [mg/L]) multiplied by contact time (T, in minutes) during which the flow is in contact with the disinfectant. SWTR CT requirements and performance are highly dependent on pH, water temperature, tank configuration, and residual disinfectant concentration. Thus, any changes in pH, chlorine dosage, or application point(s) affects primary disinfection CT performance.

Chlorine gas cylinders

If a PWS receives CT credit for contact time before filtration and then moves the point of chlorination further downstream in the treatment process, the system may have to increase its disinfectant concentration to accommodate reduced contact time. Systems must complete disinfection benchmarking and profiling before modifying existing chlorination practices to ensure primary disinfection is not compromised (40 CFR 141.708). USEPA provides guidance in the *Disinfection Profiling and Benchmarking Guidance Manual* (USEPA 2020).

Reduce coagulation effectiveness

Coagulation is often affected by the degree of pre-oxidation that occurs upstream, particularly where coagulant dosages are dictated by higher levels of NOM in the water. If pre-oxidation or chlorination practices are changed upstream of coagulation, higher coagulant dosages might be needed to achieve the same degree of particle destabilization. Systems could consider alternate pre-oxidants (e.g., permanganate, ozone) to support effective particle destabilization when changing chlorination practices upstream of coagulation.

Affect iron and manganese removal

Systems should be careful to consider how changes to prechlorination or pre-oxidation could affect iron and manganese removal mechanisms during treatment. Iron and manganese often cause staining and aesthetic problems. Raw water iron and manganese are often treated by oxidation to produce a solid that is subsequently removed by sedimentation and filtration. Where pre-oxidation is used to control high manganese, a manganese coating often develops on granular filter media and other downstream surfaces. That layer can dissolve if pre-oxidation is discontinued or if the pH drops, which would tend to release slugs of manganese and potentially increase filtered water turbidity.

Some systems might be able to substitute an alternative oxidant or reduce their prechlorination dose for iron or manganese removal. The oxidation of iron and manganese can sometimes be achieved by maintaining only a minimum residual. Potassium permanganate might be an effective alternative oxidant to chlorine for iron and manganese removal and does not react with NOM to form THMs or HAAs. Various alternatives are discussed in greater detail in the *Alternative Disinfectants and Oxidants Guidance Manual* (USEPA 1999) and the *Guidance Manual for Enhanced Coagulation and Precipitative Softening* (USEPA 1999).

Shift pH and alkalinity

The use of gaseous chlorine typically decreases pH, whereas adding liquid sodium hypochlorite may increase water pH. Water systems that also use a coagulant should consider whether eliminating prechlorination and the resulting shift in pH and alkalinity would require adjustment of the coagulant dosage or addition of other chemicals to control pH. Utilities should carefully evaluate the effect of any pH/alkalinity shifts on corrosion, and re-optimize LCR corrosion control treatment (CCT) if necessary as discussed in more detail later in this workbook.

> Utilities should carefully evaluate the effect of any pH/alkalinity shifts on corrosion, and if necessary, re-optimize LCR CCT.

Increase algae growth and filter fouling within treatment plants

Reducing or eliminating prechlorination to lower DBP formation may also have unintended consequences related to O&M. Prechlorination is sometimes used to minimize operational problems associated with biological growth and fouling inside water treatment plants. Many surface water treatment facilities have historically maintained a low chlorine residual through flocculation, sedimentation and filtration to prevent growth of algae in conduits, launders, and filters. Reducing or eliminating this low chlorine residual could potentially result in increased algal growth, clogging, and turbidity problems in filters.

Prechlorination is also used to prevent slime formation on filters, pipes, and tanks, and reduce associated maintenance and potential taste and odor problems. Utilities that practice prechlorination should carefully consider these operational constraints in addition to the simultaneous compliance issues. Depending on temperature and other raw water conditions, some systems might need to continue low-level prechlorination when microbial fouling is more likely to occur, such as when there is algal growth in the source water. Other conventional systems might be constrained to moving chlorine addition no further downstream than the settled water (upstream of filtration).

Impact extracellular cyanotoxin concentrations

Oxidants, such as chlorine, ozone or potassium permanganate, applied to raw water that contains intact cyanobacteria cells can lyse the cells or stimulate the release of intracellular toxins in un-lysed cells, resulting in the release of cyanotoxins. However, the amount of oxidant dosed may not be sufficient to oxidize the released toxins (USEPA 2015).

Limit control of zebra mussels or Asiatic clams

Many water systems add chlorine at their intakes to control Asiatic clams and zebra mussels. The Asiatic clam (*Corbicula fluminea*) was introduced to the United States from Southeast Asia in 1938 and now inhabits almost every river system south of 40E latitude. The zebra mussel (*Dreissena polymorpha*) population in the United States has also expanded rapidly since being introduced into the lower Great Lakes Basin in the late 1980s. Both these mollusks have invaded many United States source waters, clogging raw water transmission systems, valves, screens, and meters; damaging centrifugal pumps; and indirectly causing taste and odor problems.

Systems that add chlorine to their raw water to control Asiatic clams or zebra mussels and have problems with elevated THM or HAA concentrations might need to consider using an alternative oxidant (e.g., monochloramine, permanganate, ozone, chlorine dioxide). Some synthetic organic polyelectrolytes certified to NSF International Standard 60 as coagulants/ coagulant aids have also shown promise as biocidal agents for zebra mussel control. Biocides should only be applied for the uses they are registered for under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). For additional guidance on FIFRA as it pertains to drinking water disinfectants, see the *Quick Guide for Disinfectant Products for Drinking Water Use by Public Water Systems: Understanding Your Responsibility under FIFRA and How FIFRA Approval Relates to SDWA* (USEPA 2017). The biocidal effectiveness of alternative oxidants for controlling such nuisance organisms likely requires careful study, along with an assessment of potential effects on other treatment and compliance objectives. Other *non-chemical* approaches to mollusk control consist of the following:

- Use of electrical fields to kill larval stage of mollusk development
- Ultrasonic methods to interfere with settlement and attachment
- Oxygen deprivation
- Raw water sand infiltration beds
- Thermal control techniques

Additional information on treatment strategies for zebra mussel control is available in Banerjee (2016).

Form chlorate when generating hypochlorite onsite

Many water systems are replacing chlorine gas with onsite generation of sodium hypochlorite due to safety and security concerns. Compared to chlorine gas, hypochlorite solutions contain more impurities such as chlorate, chlorite, bromate, and perchlorate. Perchlorate formation can be minimized by storing generated hypochlorite as a dilute solution for no more than two days and controlling the air temperature in the chemical storage room.

☆ Questions/Issues to Consider

Will modified chlorination dosages and application points meet primary disinfection CT criteria under all source water conditions? Is finished water storage sized correctly for disinfection?

Complete disinfection benchmarking and profiling before modifying existing chlorination practices to ensure primary disinfection is not compromised (see the *Disinfection Profiling and Benchmarking Guidance Manual* [USEPA 2020]).

To what degree will DBP formation be reduced? How will DBP speciation shift?

To answer these questions, systems can conduct treatability testing or use existing predictive models. Reductions in DBP levels and changes in the types of DBP species are dependent upon system-specific water quality and operational conditions. These tools can help the system determine the best time for initiating seasonal changes in disinfection practices and the disinfectant dosage rate that provides optimal benefits.

How will modified chlorination practices affect CCT in the distribution system?

Disinfection changes could create shifts in pH and alkalinity levels, and could negatively affect CCT. Changes from free chlorine to chloramines for secondary disinfection could, under some conditions, result in an increase in lead or copper solubility or both. Disinfection changes might make it necessary to re-optimize CCT under the LCR.

Will modified chlorination practices affect iron and manganese levels?

Chlorine pre-oxidation often contributes to removal of iron and manganese via filtration. In addition, manganese dioxide deposits in filters could dissolve if pre-oxidation practices are changed or discontinued.

Will modified chlorination practices affect taste and odor?

Chlorine pre-oxidation can contribute to taste and odor control in subsequent treatment processes.

Does prechlorination contribute to control of Asiatic clams or zebra mussels?

Alternative biocidal chemical or other measures might be needed to protect intakes and raw water pumping and pipeline facilities.

How many new chlorine application points will be needed? Can existing chemical feed facilities serve new chlorine application points?

The cost of new piping, pumping, and control instrumentation can complicate implementation of modified chlorination practices. The system engineering related to relocating chlorine application points can be complex, and site-specific access and other physical constraints could limit alternatives for moving chlorine addition downstream.

Will modified chlorination practices affect algae or slime growth within the treatment plant?

Chlorine pre-oxidation often mitigates seasonal biological growths in basins, pipelines, and filters.

Bibliography

Banerjee, R. 2016. How to effectively control zebra mussels. *Environmental Science & Engineering*. April 2016.

Becker, W.C., K. Au, C.R. O'Melia, and J.S. Young Jr. 2004. *Using Oxidants to Enhance Filter Performance.* AwwaRF Report 90998. Project #2725. American Water Works Association Research Foundation, Denver, CO.

Cantor, A.F., J.K. Park, and P. Vaiyavatjamai. 2003. Effect of chlorine on corrosion in drinking water systems. *Journal of American Water Works Association* 95(5):112–123.

Cohen, Y.K. 1998. Forming chloramine and maintaining residual. *Opflow* 24(9):1–5.

Duranceau, S.J., D. Townley, and G.E.C. Bell. 2004. *Optimizing Corrosion Control in Distribution Systems.* AwwaRF Report 90983. Project #2648. American Water Works Association Research Foundation, Denver, CO.

Gates, D., G. Ziglio, and K. Ozekin. 2009. *State of the Science of Chlorine Dioxide in Drinking Water*. Water Research Foundation and Fondazione AMGA.

Krasner, S.W., S.R. Rajachandran, J.E. Cromwell III, D.M. Owen, and Z.K. Chowdhury. 2003. *Case Studies of Modified Treatment Practices for Disinfection By-Product Control*. AwwaRF Report 90946F. Project #369. American Water Works Association Research Foundation, Denver, CO.

Lytle, D.A., and M.R. Schock. 2005. Formation of Pb(IV) oxides in chlorinated water. *Journal of American Water Works Association* 97(11):102–114.

Schock, M.R., S.M. Harmon, J. Swertfeger, and R. Lohmann. 2001. Tetravalent Lead: A Hitherto Unrecognized Control of Tap Water Lead Contamination. In *Proceedings of AWWA 2001 Water Quality Technology Conference, Nov. 11-14, 2001, Nashville, TN*. American Water Works Association, Denver, CO.

Singer, P.C., and S.D. Chang. 1989. Correlations between trihalomethanes and total organic halides formed during water treatment. *Journal of American Water Works Association* 81(8):61–65.

Snyder, S.A., B.D. Stanford, A.N. Pisarenko, G. Gordon, and M. Asami. 2009. *Hypochlorite – An Assessment of Factors that Influence the Formation of Perchlorate and Other Contaminants*. Denver, Colo.: AWWA and WRF.

Stanford, B.D., A.N. Pisarenko, D.J. Dryer, J.C. Ziegler-Holady, S. Gamage, O. Quiñones, B.J. Vanderford, and E.R.V. Dickenson. 2013. Chlorate, perchlorate, and bromate in onsite-generated hypochlorite systems. *Journal of American Water Works Association* 105(3):E93–102.

USEPA. 2015. *Recommendations for Public Water Systems to Manage Cyanotoxins in Drinking Water*. EPA 815-R-15-010. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

USEPA. 2017. *Quick Guide for Disinfectant Products for Drinking Water Use by Public Water Systems*: *Understanding Your Responsibility under FIFRA and How FIFRA Approval Relates to*

SDWA. U.S. Environmental Protection Agency, Office of Pesticide Programs, Washington, DC.

USEPA. 2020. *Disinfection Profiling and Benchmarking Guidance Manual*. EPA 815-R-20-003. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

Wert, E.C., D.J. Rexing, and R.E. Zegers. 2005. Manganese Release from Filter Media During the Conversion to Biological Filtration. *2005 AWWA Annual Conference and Exposition, Jun. 12-17, 2005,* San Francisco, CA. American Water Works Association, Denver, CO.

White, G.C. 1999. *Handbook of Chlorination and Alternative Disinfectants*. 4th ed. Van Nostrand Reinhold Co., New York.

Seasonal Reductions in Chlorine Dosage

Why seasonally reduce chlorine addition?

In general, as temperatures increase, chlorine reaction kinetics also increase. Systems that use the same chlorine dose throughout the year could be over-chlorinating during warmer summer months. This could occur more frequently in temperate regions with large seasonal changes in source water temperature. Such systems might be able to provide sufficient primary disinfection CT in warmer months using lower dosages of free chlorine and still provide inactivation of *Giardia* and viruses. Faster chlorine reactions mean that disinfection effectiveness improves but also that trihalomethanes (THMs) and haloacetic acids (HAAs) form more quickly. By reducing chlorine dosages when water temperatures are higher, systems might be able to reduce overall formation of disinfection byproducts (DBPs). Of course, water age, natural organic material (NOM) levels and pH always remain important factors in DBP formation.

By reducing chlorine dosages when water temperatures are higher, systems may be able to reduce formation of DBPs.

By reducing the chlorine residual at the treatment plant during warm water conditions, systems could achieve comparable pathogen inactivation with less chlorine and a reduction in DBP formation.

Simultaneous Compliance Issues Associated with Seasonal Reduction of Chlorine Dosage

Disinfectant residuals should never be lowered below primary disinfection CT requirements dictated by the SWTR. Systems should carefully evaluate their disinfection profiles to ensure that they meet benchmarking requirements and refer to guidance provided in the *Disinfection Profiling and Benchmarking Guidance Manual* (USEPA 2020). Utilities should also review any plans to change disinfection practices with their state primacy agency before implementation.

Disinfectant residuals should never be lowered below primary disinfection CT requirements dictated by the SWTR.

Simultaneous compliance issues potentially associated with reducing chlorine dosages under warm temperature conditions include:

- Addressing seasonal variability of source water pathogen concentrations
- Maintaining disinfectant residuals in the distribution system
- Lead releasing caused by shifts in oxidation reduction potential (ORP)

Addressing seasonal variability of source water pathogen concentrations

Pathogen concentrations can increase in some surface water sources during the summer months. Concentrations of viruses and enteric bacteria are of concern, especially if the source water is also used for recreational activity. Seasonal blooms of blue-green algae can give rise to the production of toxins that can contaminate source water. Other pathogens such as

Cryptosporidium have been found to peak during spring runoff. Systems should evaluate their source water and examine historical data to determine if a trend in pathogen occurrence exists in the warmer months. Systems should also consider consulting with their state and neighboring utilities to leverage source data collected by others. Many systems have expanded data on *Cryptosporidium* or *E. coli* or both as a result of the LT2ESWTR source water monitoring requirements.

Maintaining disinfectant residuals in the distribution system

Lower finished water residual levels combined with the faster decay rate of chlorine in the warmer months might make it difficult for some systems to meet the SWTR requirement of maintaining a detectable residual throughout the distribution system. In cases in which systems do not add supplemental chlorine after primary disinfection, reducing the chlorine dose during warmer months could result in lower finished water chlorine residual concentrations. Distribution systems are also more susceptible to microbial growth and coliform re-growth during periods of warmer water temperature.

If systems are having difficulty maintaining their chlorine residual in the distribution system to meet secondary disinfection requirements, they should control microbial growth and ensure compliance with the Revised Total Coliform Rule (RTCR). They might want to enhance distribution system operational practices to reduce water age. Supplemental disinfection might also be a good strategy for maintaining a residual in remote areas of the distribution system.

Lead releasing caused by shifts in oxidation reduction potential (ORP)

Disinfectant changes can affect ORP, which controls the oxidation state of mineral species in pipe scales. A reduction in chlorine concentration generally results in a lower ORP in water. At higher ORP values, lead scales are more likely to be present as $Pb4^+$ species, which are harder and more stable than $Pb2^+$ scales. If the oxidation state of the water varies enough, scales adapted to one set of conditions may be disrupted and become unstable (Brown et al., 2013).

Under some conditions where lead oxide (PbO_2) compounds have formed on lead service lines or home plumbing, ORP reductions can cause dissolution of PbO_2, representing a shift to more soluble lead species and a possible increase in lead solubility (Lytle and Schock 2005; Schock and Giani 2004). Reductions in ORP can also cause manganese deposits on pipes to dissolve, potentially re-depositing on plumbing fixtures and staining laundry.

☆ Questions/Issues to Consider

How do primary disinfection requirements change under seasonal temperature variations? Are there seasonal increases in chlorine-resistant pathogens?

Removal and inactivation goals for all microbiological contaminants must be established on the basis of SWTR and LT2ESWTR requirements. Utilities should verify inactivation credit with their state primacy agencies, along with any demonstration requirements.

Will modified chlorination dosages meet primary disinfection CT criteria under all source water conditions?

Complete disinfection benchmarking and profiling before modifying chlorination practices to ensure primary disinfection is not compromised. Refer to the *Disinfection Profiling and Benchmarking Guidance Manual* (USEPA 2020) for additional guidance on this issue.

To what degree will DBP formation be reduced?

Systems can conduct testing or use existing predictive models to better understand the benefits of seasonal reductions in disinfectant dosages. These tools can help the system determine the best time for initiating seasonal changes in disinfection practices and the disinfectant dosage rate that provides optimal benefits.

How will modified chlorination practices affect CCT in the distribution system?

Modified chlorination practices could create shifts in pH and alkalinity levels and negatively affect CCT. Changes from free chlorine to chloramines for secondary disinfection can, under some conditions, result in an increase in lead or copper solubility. Disinfection changes could necessitate re-optimization of CCT under the LCR, which should be considered prior to implementing changes in treatment.

Will modified chlorination practices affect iron and manganese levels?

Chlorine oxidizes iron and manganese and forms chemical precipitates that should be removed by sedimentation and filtration processes. If the chlorine application point or dosage rate changes, the effectiveness of this pre-oxidation process may change. For example, manganese dioxide deposits in filters can dissolve if pre-oxidation practices are changed or discontinued.

Will reduced chlorine addition affect secondary disinfection?

Reduced chlorine addition will most likely affect secondary disinfection. Utilities should modify finished water chlorine residuals, if necessary, to maintain target disinfectant residuals throughout the distribution system.

Bibliography

Brown, R.A., N.E. McTigue, and D.A. Cornwall. 2013. Strategies for assessing optimized corrosion control treatment of lead and copper. *Journal of American Water Works Association* 105(5):62–75.

Cantor, A.F., J.K. Park, and P. Vaiyavatjamai. 2003. Effect of chlorine on corrosion in drinking water systems. *Journal of American Water Works Association* 95(5):112–123.

Friedman, M., A. Hill, S. Booth, M. Hallett, L. McNeill, J. McLean, D. Stevens, D. Sorensen, T. Hammer, W. Kent, M. DeHaan, K. MacArthur, and K. Mitchell. 2016. *Metals Accumulation and Release Within the Distribution System: Evaluation and Mitigation*. Denver, Colo.: WRF.

Friedman, M.J., A.S. Hill, S.H. Reiber, R.L. Valentine, G. Larsen, A. Young, G.V. Korshin, and C.Y. Peng. 2010. *Assessment of Inorganics Accumulation in Drinking Water System Scales and Sediments*. Denver, Colo.: WRF.

Krasner, S.W., S.R. Rajachandran, J.E. Cromwell III, D.M. Owen, and Z.K. Chowdhury. 2003. *Case Studies of Modified Treatment Practices for Disinfection By-Product Control*. AwwaRF Report 90946F. Project #369. American Water Works Association Research Foundation, Denver, CO.

Lytle, D.A., and M.R. Schock. 2005. Formation of Pb(IV) oxides in chlorinated water. *Journal of American Water Works Association* 97(11):102–114.

Schock, M.R., S.M. Harmon, J. Swertfeger, and R. Lohmann. 2001. Tetravalent Lead: A Hitherto Unrecognized Control of Tap Water Lead Contamination. In *Proceedings of AWWA 2001 Water Quality Technology Conference, Nov. 11-14, 2001, Nashville, TN*. American Water Works Association, Denver, CO.

Schock, M.R., and R. Giani. 2004. Oxidant/disinfectant Chemistry and Impacts on Lead Corrosion. In *Proceedings of AWWA 2004 Water Quality Technology Conference, Nov. 8-11, 2004, San Antonio, TX*. American Water Works Association, Denver, CO.

USEPA. 2020. *Disinfection Profiling and Benchmarking Guidance Manual*. EPA 815-R-20-003. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

Wert, E.C., D.J. Rexing, and R.E. Zegers. 2005. Manganese release from filter media during the conversion to biological filtration. *2005 AWWA Annual Conference and Exposition, Jun. 12-17, 2005,* San Francisco, CA. American Water Works Association, Denver, CO.

White, G.C. 1999. *Handbook of Chlorination and Alternative Disinfectants*. 4th ed. Van Nostrand Reinhold Co., New York.

Conversion to Chloramines for Secondary Disinfection

Why use chloramines instead of chlorine?

Chloramination is an attractive alternative to chlorine for secondary disinfection because it is more stable and persistent in the distribution system, and minimizes the formation of THMs and HAAs.

United States water utilities have been employing chloramines to maintain a disinfectant residual in their distribution systems (i.e., secondary disinfection) for most of the last century. Chloramines are a family of oxidants formed by the reaction of chlorine and ammonia. Chloramination is often an attractive alternative to chlorine for secondary disinfection because it is more stable and persistent in the distribution system and minimizes the formation of trihalomethanes (THMs) and haloacetic acids (HAAs). Many utilities changed from free chlorine to chloramines for secondary disinfection to comply with the Stage 1 DBPR. More systems can be expected to switch to chloramines to meet requirements of the Stage 2 DBPR. While monochloramines are primarily used as a secondary disinfectant to provide a residual in the distribution system, chloramination is occasionally used for SWTR primary disinfection. Many consumers reportedly prefer the taste and smell of chloramines to chlorine.

Ammonia used to form chloramines

The ratios at which chlorine and ammonia are fed control the species of chloramines present. Monochloramine (NH_2Cl) is the preferred chloramine species because it is a somewhat more powerful oxidant and less likely than dichloramine ($NHCl_2$) and trichloramine (NCl_3, or nitrogen tri-chloride) to cause taste and odor problems in water distribution systems. However, NH_2Cl is a much weaker oxidant than free chlorine and generally provides only limited inactivation of microorganisms or oxidization of DBP precursors or both. Nonetheless, NH_2Cl has been shown in many cases to help reduce the occurrence of *Legionella* bacteria in institutional premise plumbing. Because a weaker oxidant is more persistent, monochloramine is sometimes found to be more effective in controlling distribution system biofilm. As with free chlorine, the effectiveness of chloramination is dependent on dose, contact time, pH, and temperature.

Simultaneous Compliance Issues Associated with Chloramine Conversion

Many simultaneous compliance issues and potential unintended consequences can be associated with conversion to chloramines for secondary disinfection. The most significant include nitrification and short-term destabilization of existing pipe scales (i.e., corrosion control impacts).

Simultaneous compliance issues that can be related to conversion to chloramines include nitrification and destabilization of pipe scales.

Increased nitrification potential

Nitrification occurs when ammonia-oxidizing bacteria convert free ammonia to nitrite (partial nitrification) and when nitrite is subsequently oxidized by bacteria to nitrate. Some free ammonia is usually present in distribution systems using monochloramines for secondary disinfection, although excess free ammonia could be present as a result of chloramine degradation or poor control of the chlorine-to-ammonia ratio or both. Maintaining good control of the chlorine-to-ammonia feed ratio at the treatment plant is essential in preventing nitrification. A chlorine-to-ammonia ratio between 3.5:1 and 5:1 is generally recommended depending on pH. Some researchers have suggested that nitrification is less likely to occur in systems where chlorine dioxide is used for oxidation or primary disinfection because chlorite is toxic to many forms of ammonia-oxidizing bacteria (McGuire et al. 2006).

Systems with high water age, poorly mixed storage facilities, low storage facility volume turnover, and warm water temperatures (> 20 degrees Celsius [°C] or > 68 degrees Fahrenheit [°F]) are generally more susceptible to nitrification. The cleanliness of finished water storage facilities and distribution piping are also important factors. Comprehensive system flushing should be conducted on a regular basis; and sediment should be removed from storage facilities periodically depending on system water quality and operations. Improving volume turnover and mixing in distribution system storage facilities substantially reduces the potential for nitrification. Flushing system dead ends to minimize water age and maintaining a NH_2Cl residual can also help to reduce the potential for nitrification. The extent to which water age impacts water quality depends on numerous factors, including the microbial and chemical stability of the water, disinfectant type and dose, and distribution system operating conditions (Friedman et al., 2010).

Wherever chloramination is practiced, utilities should carefully monitor ammonia, free chlorine, and total chlorine residuals and ensure that an appropriate chlorine-to-ammonia ratio is maintained.

In poorly buffered waters (i.e., those with low alkalinity), nitrification can also result in increased corrosion. The nitrification process consumes alkalinity (as bicarbonate) and produces carbonic acid. In low alkalinity waters, it has the potential to cause localized depression of pH and increase iron, lead, and copper corrosion. It can also lead to dissolution of cement-mortar linings in distribution system piping.

Mixing chloraminated water and water having a free chlorine residual is not generally recommended because it can cause frequent shifts in the chlorine-to-ammonia ratio, pH, alkalinity, and other changes in distribution biochemistry. Blending that results in excess free chlorine can contribute to increased DBP formation. If blending waters with chloramines and free chlorine residuals is unavoidable, utilities should determine the residuals in both waters and carefully assess the chlorine-to-ammonia ratio of the resulting mixture. If blending raises the chlorine-to-ammonia ratio above 5:1, $NHCl_2$ and NCl_3 form and the associated odors cause customer complaints. Breakpoint reactions occur at a chlorine-to-ammonia ratio of 7.6:1 or higher, which can lead to rapid loss of disinfectant residual. Wherever chloramination is practiced, utilities should carefully monitor ammonia, free chlorine, and total chlorine residuals and ensure that the correct chlorine-ammonia ratio is maintained.

Destabilization of existing pipe scales

Chloramination can also affect existing pipe scale stability because of its lower ORP relative to free chlorine. Free chlorine, particularly at higher doses, has a higher ORP than NH_2Cl, which in turn controls the oxidation state of existing metal pipe scales. At higher ORP values, iron is more likely to be present in ferric forms (Fe^{3+}), which are generally harder and more stable than ferrous iron (Fe^{2+}) species. Similarly, at higher ORP values, lead scales are more likely to be present as Pb^{4+} species, which are harder and more stable than Pb^{2+} scales. If the oxidation state of the water varies enough, scales adapted to one set of conditions may be disrupted and become unstable (Brown et al., 2013).

Under some conditions where PbO_2 compounds have formed on lead service lines or home plumbing, ORP reductions can cause dissolution of PbO_2, representing a shift to more soluble lead species and possible increases in lead solubility (Lytle and Schock 2005; Schock and Giani 2004).

> Conversion to chloramines can reduce ORP in the distribution system, which could increase dissolved lead concentrations.

Conversion to chloramines can reduce ORP in the distribution system causing a shift in existing metallic-scale species and result in increases in dissolved metal concentrations. For example, ORP reductions can cause manganese deposits on pipes to dissolve, potentially re-depositing on plumbing fixtures and staining laundry. Using an orthophosphate-based corrosion inhibitor (e.g., phosphoric acid or zinc orthophosphate) changes the metallic (i.e., iron and lead) precipitates on pipe surfaces and can help to minimize the potential for increased metals to be released as a result of conversion to chloramines. Changes to pipe scale can require months or even years to fully take effect and stabilize, so it is important for systems to consider the long-term implications of making any changes that will affect pipe scale.

Chloramines can negatively affect kidney dialysis patients where blood might come in contact with water across semi-permeable membranes. That could permit small amounts of chloramines to enter blood vessels of a kidney dialysis patient, which would be toxic to certain blood cells. Chloramines are also toxic to fish, and therefore, should be removed from water before it is discharged to natural fish habitats or used in fresh water aquariums. It can also affect water customers who produce foods, beverages, and pharmaceuticals.

Other potential consequences of chloramination include the production of unregulated DBPs including N-nitrosodimethylamine (NDMA) and iodoacids.

☆ Questions/Issues to Consider

To what degree will DBP formation be reduced?

Systems can conduct testing or use existing predictive models to better understand how DBPs would be reduced and how other critical water quality conditions might change when converting to monochloramine for secondary disinfection.

What is the potential for nitrification to occur?

The potential for nitrification occurrence is dependent upon system-specific operating conditions (e.g., water age, disinfectant residual, water temperature). Nitrification occurs when ammonia-oxidizing bacteria convert free ammonia to nitrite (partial nitrification) and when nitrite is subsequently oxidized by bacteria to nitrate. This process is more likely to occur during summer months when the water is warmer. Some free ammonia is usually present in systems using NH_2Cl for secondary disinfection, although excess free ammonia could be present as a result of chloramine degradation or poor control of the chlorine-to-ammonia ratio or both.

How will nitrification be controlled if it does occur?

After a nitrification event is well developed, there are limited effective control strategies (AWWA 2017). The preferred approaches are to either prevent nitrification from occurring or to detect it at an early stage. The most common responses to halting a nitrification event include: a temporary conversion to free chlorine, distribution system flushing, and storage tank flushing and disinfection (AWWA 2017).

Will periodic use of free chlorine still be necessary to help prevent nitrification under warmer water temperatures?

Yes, a seasonal switch to free chlorine is recommended, typically in the spring before the water warms up (AWWA 2017, 2013). Each system should decide the most effective timing and duration of this free chlorine disinfection period.

How will chloramination affect CCT in the distribution system?

Converting disinfection practice from chlorine to chloramines can reduce ORP in the distribution system causing a shift in existing metallic-scale species and result in increases in dissolved metal concentrations. LCR CCT might need to be re-optimized.

Will chloramination practices affect iron and manganese levels?

Changes in ORP could also affect the stability of iron or manganese deposits within existing pipe scales.

What distribution system operational practices will need to be changed to successfully practice chloramination? What special operational procedures and monitoring will need to be done during conversion?

Chloramination typically necessitates new monitoring and operational procedures to prevent nitrification and minimize water age. In addition, systems should carefully plan for supplemental water quality monitoring, operational measures, and customer communications before and during actual conversion from free chlorine to chloramines.

What additional operator training is needed?

Additional training should be given for new monitoring and operational procedures. Chloramination often needs more careful operation of the distribution system and increased operator attention as compared to free chlorine.

Will chloramination practices affect taste and odor?

Customers usually notice a change in taste and odor, especially during the initial transition period. Public information and outreach might be necessary to ensure confidence in the water supply.

Are there any consecutive systems? How will implementing chloramines affect them?

Consecutive systems that purchase finished water from a system using surface water supplies should maintain a disinfectant residual throughout the distribution system (USEPA 1989). Consecutive systems that purchase finished water from a system using ground water with chemical disinfection should maintain a disinfectant residual as required by the state. When chloramination is used for secondary disinfection by the wholesale system, consecutive systems should take proactive measures to prevent nitrification from occurring. If the consecutive system adds chlorine to increase the disinfectant residual (i.e., booster disinfection), they should avoid blending waters with the different disinfectant residuals. When chlorinated water mixes with chloraminated water, the free chlorine combines with the ammonia and forms $NHCl_2$ and NCl_3, which are weaker disinfectants and cause taste and odor problems. This mixing effect can also reduce the total chlorine residual in the chloraminated water to non-detectable levels and can cause bacteria regrowth and nitrification.

Bibliography

AWWA. 2013. *Manual M56 Nitrification Prevention and Control in Drinking Water*, Second Edition. Denver, CO. AWWA.

AWWA. 2017. *Manual M68 Water Quality in Distribution Systems*, First Edition. Denver, CO. AWWA.

Boyd, G.R., K.M. Dewis, A.M. Sandvig, G.J. Kirmeyer, S.H. Reiber, and G.V. Korshin. 2006. *Effect of Changing Disinfectants on Distribution System Lead and Copper Release*, Part 1—Literature Review. AwwaRF Report 91152. Project # 3107. American Water Works Association Research Foundation, Denver, CO.

Brown, R.A., N.E. McTigue, and D.A. Cornwall. 2013. Strategies for assessing optimized corrosion control treatment of lead and copper. *Journal of American Water Works Association* 105(5): 62–75.

Cantor, A.F., J.K. Park, and P. Vaiyavatjamai. 2003. Effect of chlorine on corrosion in drinking water systems. *Journal of American Water Works Association* 95(5):112–123.

Duranceau, S.J., D. Townley, and G.E.C. Bell. 2004. *Optimizing Corrosion Control in Distribution Systems*. AwwaRF Report 90983. Project #2648. American Water Works Association Research Foundation, Denver, CO.

Friedman, M., A. Hill, S. Booth, M. Hallett, L. McNeill, J. McLean, D. Stevens, D. Sorensen, T. Hammer, W. Kent, M. DeHaan, K. MacArthur, and K. Mitchell. 2016. *Metals Accumulation and Release Within the Distribution System: Evaluation and Mitigation*. Denver, Colo.: WRF.

Friedman, M.J., A.S. Hill, S.H. Reiber, R.L. Valentine, G. Larsen, A. Young, G.V. Korshin, and C.Y. Peng. 2010. *Assessment of Inorganics Accumulation in Drinking Water System Scales and Sediments*. Denver, Colo.: WRF. Friedman, M., Kirmeyer, G., Lemieux, J., LeChevallier, M., Seidl, S., and Routt, J., 2010. *Criteria for Optimized Distribution Systems*. Water Research Foundation, Denver.

Kirmeyer, G.J., M. LeChevallier, H. Barbeau, K. Martel, G. Thompson, L. Radder, W. Klement, and A. Flores. 2004a. *Optimizing Chloramine Treatment*. AwwaRF Report 90993. Project #2760. American Water Works Association Research Foundation, Denver, CO and American Water Works Association, Denver, CO.

Lytle, D.A., and M.R. Schock. 2005. Formation of Pb(IV) oxides in chlorinated water. *Journal of American Water Works Association* 97(11):102–114.

McGuire, M.J., M.S. Pearthree, N.K. Blute, K.F. Arnold, and T. Hoogerwerf. 2006. Nitrification control by chlorite ion at pilot scale. *Journal of American Water Works Association* 98(1):95–105.

Reiber, S. 1991. *Corrosion Effects by Chloramines*. American Water Works Association Research Foundation, Denver, CO.

Schock, M.R., S.M. Harmon, J. Swertfeger, and R. Lohmann. 2001. Tetravalent Lead: A Hitherto Unrecognized Control of Tap Water Lead Contamination. In *Proceedings of AWWA 2001 Water Quality Technology Conference, Nov. 11-14, 2001, Nashville, TN.* American Water Works Association, Denver, CO.

Schock, M.R., and R. Giani. 2004. Oxidant/disinfectant chemistry and impacts on lead corrosion. In *Proceedings of AWWA 2004 Water Quality Technology Conference, Nov. 8-11, 2004, San Antonio, TX*. American Water Works Association, Denver, CO.

Conversion to Chlorine Dioxide for Primary Disinfection

Why use chlorine dioxide?

Chlorine dioxide is effective for the inactivation of *Giardia*, *Cryptosporidium*, and viruses. It also has a high oxidation potential and can be maintained over a wide pH range. Other applications include taste and odor control, and iron and manganese oxidation. Chlorine dioxide is rarely used for secondary disinfection; chlorine and NH_2Cl are the preferred secondary disinfectants based on cost, chemical stability, and taste and odor issues.

Simultaneous Compliance Issues Associated with Adding Chlorine Dioxide

Systems should consider the possible health effects associated with chlorine dioxide addition (briefly discussed below). In addition, introducing chlorine dioxide may change the oxidation reduction potential of the water, can disrupt passivating layers (depending on current treatment and what treatment changes are being made), and can result in NOM reduction.

Disinfection byproduct formation

Chlorite and chlorate are the major byproducts of chlorine dioxide disinfection. Chlorite is regulated by USEPA with a maximum contaminant level (MCL) of 1.0 mg/L due to potential health concerns. Chlorate is currently unregulated in the United States. Chlorite may cause anemia in some people and affect the nervous systems of infants, young children, and fetuses of pregnant women. Ongoing exposure to chlorate ion can lead to an enlarged thyroid (USEPA 2012).

Acute concerns related to high chlorine dioxide dosages

Chlorine dioxide can cause acute health effects and has a maximum residual disinfectant level (MRDL) of 0.8 mg/L. The most common adverse health effects are destruction of red blood cells and elevated blood levels of methemoglobin, a form of hemoglobin. Children and infants may experience nervous system problems.

Chlorine dioxide can cause acute health effects. Adverse health effects include destruction of red blood cells and elevated blood levels of methemoglobin, as well as nervous system problems in infants and children.

☆ Questions/Issues to Consider

To what degree will DBP formation change?

Chlorine dioxide provides a good alternative to chlorine for systems that are trying to lower the formation of THMs or HAAs. Most chlorine dioxide generators produce some chlorine as a byproduct, so THMs and HAAs may still be formed; however, it is likely their concentrations will be lower than when chlorine alone is used as a primary disinfectant. The reduction of THM or HAA formation due to changing disinfectants varies based on system water quality and operational conditions. The DBP of greater concern when chlorine dioxide is used is chlorite, which has a 1.0 mg/L MCL. Chlorate is another DBP formed when chlorine dioxide is used and was included in EPA's Third Unregulated Contaminant Rule monitoring program. Systems can conduct testing or use existing predictive models to better understand how DBPs would be formed, and how other critical water quality conditions might change when converting to chlorine dioxide for disinfection.

How will chlorine dioxide disinfection affect CCT in the distribution system?

Because chlorine dioxide is also a strong oxidant, systems that change from chlorine to chlorine dioxide will have similar ORP levels in the distribution system (Lytle and Schock 2005). Therefore, it is not likely there will be a shift in existing metallic-scale species or dissolved metal concentrations.

Will chlorine dioxide treatment practices affect iron and manganese levels?

Chlorine dioxide is a strong oxidant and can oxidize iron and manganese in the water. The oxidation process will form iron and manganese precipitates that can be removed by sedimentation and filtration processes.

What distribution system operational and maintenance practices will need to be changed if chlorine dioxide is used?

Membrane-based analytical systems need routine maintenance to assure effective operation and data accuracy. Operators may need to replace sensor membranes and the electrolytic solution on a monthly to semi-annual basis to minimize fouling. Operators can consult manufacturer's instructions for suggested sampling rates and then conduct routine inspections to confirm that sampling rates are within the preferred range. On-line sensors should be routinely calibrated as recommended by the manufacturer.

What monitoring practices will need to be changed to successfully practice chlorine dioxide disinfection?

For primary disinfection, associated regulatory and operational monitoring would be conducted before and after the clearwell or pipeline used for disinfection contact time.

Any PWS using chlorine dioxide is required to monitor daily at each entry point to the distribution system to ensure they are not exceeding the MRDL (USEPA 1998). If the daily chlorine dioxide measurement at the entry point exceeds 0.8 mg/L, three follow-up distribution system chlorine dioxide samples must be measured the following day. Chlorite must be monitored daily at the entry point to the distribution system, in addition to being measured in a three-sample set each month in the distribution system.

What additional operator training is needed?

Operators may need training on both regulatory and operational monitoring procedures specific to chlorine dioxide. When using on-line sensors, the operators may need to contact the sensor manufacturer for assistance with developing and implementing monitoring protocols. When using a spectrophotometric analytical method, the sampler may need to pass an initial demonstration of capability by analyzing known standards and blanks, and checking that the measured values are within a certain percentage of the known value.

Will chlorine dioxide disinfection practices affect taste and odor?

Compared to chlorine and NH_2Cl, chlorine dioxide has more objectionable tastes and odors at concentrations necessary for secondary disinfection (> 0.2 mg/L in North America) (Gates et al. 2009). Although the odor threshold of chlorine dioxide in tap water is not well-documented in the literature, general practice indicates that concentrations from 0.2 to 0.4 mg/L are easily detected (Gates et al. 2009).

Are there any consecutive systems? How will chlorine dioxide disinfection affect them?

Consecutive systems that purchase finished water from a system using surface water supplies should maintain a disinfectant residual throughout the distribution system (USEPA 1989). Consecutive systems that purchase finished water from a system using ground water supplies with chemical disinfection should maintain a disinfectant residual as required by the state. Wholesale systems that use chlorine dioxide for primary disinfection often use chloramines for secondary disinfection. Consecutive systems that do not add a chemical disinfectant to the water but deliver water that has been treated with a disinfectant other than UV light must meet the requirements of the Stage 2 DBPR (40 CFR 141.620). Specifically, consecutive systems should monitor the residual disinfectant concentration using approved methods at the same time and location as total coliform samples are collected. Consecutive systems should also calculate the MRDL and report it to the primacy agency along with other monitoring results.

Bibliography

AWWA. 2017. *Manual M68 Water Quality in Distribution Systems*, First Edition. Denver, CO. AWWA.

Clarke, S.H., and W. Bettin. 2006. *Chlorine Dioxide Disinfection in the Use of Individual Water Purification Devices*. Technical Information Paper #31-007-0306. U.S. Army Center for Health Promotion and Preventive Medicine.

Duranceau, S.J., D. Townley, and G.E.C. Bell. 2004. *Optimizing Corrosion Control in Distribution Systems*. AwwaRF Report 90983. Project #2648. American Water Works Association Research Foundation, Denver, CO.

Gates, D., 1998. *The Chlorine Dioxide Handbook*. Water Disinfection Series. AWWA, Denver, CO.

Gates, D., G. Ziglio, and K. Ozekin. 2009. *State of the Science of Chlorine Dioxide in Drinking Water*. Water Research Foundation and Fondazione AMGA.

Holden, G.W. 2017. Chlorine dioxide preoxidation for DBP reduction. *Journal of American Water Works Association* 109(7):36–43.

Lytle, D.A., and M.R. Schock. 2005. Formation of Pb(IV) oxides in chlorinated water. *Journal of American Water Works Association* 97(11):102–114.

USEPA. 1989. National Primary Drinking Water Regulations: Filtration, Disinfection, Turbidity, *Giardia lamblia*, Viruses, *Legionella* and Heterotrophic Bacteria; Final Rule. 54 FR 27486. (June 29, 1989).

USEPA. 1997. National Primary Drinking Water Regulations: Disinfectants and Disinfection By-products Notice of Data Availability; Proposed Rule. 62 FR 59388. (November 3, 1997).

USEPA. 1998. National Primary Drinking Water Regulations: Disinfectants and Disinfection Byproducts; Final Rule. 63 FR 69390. (December 16, 1998).

USEPA. 1999. *Alternative Disinfectants and Oxidants Guidance Manual*. EPA 815-R-99-014. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

USEPA. 2006. *National Primary Drinking Water Regulations: Stage 2 Disinfectants and Disinfection Byproducts Rule*; Final Rule. 71 FR 388. (January 4, 2006).

USEPA. 2010. *Stage 2 Disinfectants and Disinfection Byproducts Rule Consecutive Systems Guidance Manual*. EPA 815-R-09-017. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

USEPA. 2012. *The Third Unregulated Contaminants Monitoring Rule (UCMR3): Fact Sheet for Assessment Monitoring of List 1 Contaminants*. EPA 815-F-12-003. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

World Health Organization (WHO). 2011. *Drinking Water Guidelines*. 4th Edition. Geneva, Switzerland.

Zhang, Z., J.E. Stout, V.L. Yu, and R. Vidic. 2008. Effect of pipe corrosion scales on chlorine dioxide consumption in drinking water distribution systems. *Water Research* 42(2008):129–136.

Enhanced or Modified Coagulation

What is coagulation?

Coagulation is one of the most common chemical processes used in water treatment. Small particulates, colloids (organic and inorganic), and tiny mineral precipitates are mostly held in solution by electrostatic repulsion. Coagulation in water treatment generally refers to the addition or formation of chemical species with opposite charges so that previously *stabilized* substances can approach closely enough to allow collision and aggregation into larger, more removable particles. Coagulation is primarily used for removing turbidity, particulate, and microbial contaminants (bacteria, viruses, cysts, and o-ocysts), although natural organic material (NOM) removal is also routinely an objective of coagulation.

As described previously in this workbook, NOM often reacts with chlorine during treatment to produce disinfection by products (DBPs):

Free Chlorine + NOM = DBPs (trihalomethanes [THMs], haloacetic acids [HAAs])

For that reason, NOM is often referred to as a *DBP precursor*. DBPs are regulated drinking water contaminants because they are possible carcinogens and have been shown to cause adverse reproductive or developmental effects in laboratory animals. Removal of NOM is frequently employed as a treatment technique to lower DBP formation. Total organic carbon (TOC) and specific ultraviolet light absorbance (SUVA) are common surrogate measures used to approximate the NOM levels.

Enhanced or modified coagulation

Enhanced coagulation refers to adding excess coagulant (under correct pH, alkalinity, and temperature conditions) to improve removal of DBP precursors by conventional water treatment. The removal of organic matter and other precursor materials by enhanced coagulation is an important element of compliance with disinfection by product requirements. Under the Stage 1 DBPR, enhanced coagulation is defined as a *treatment technique* achieving a specific percentage of TOC removal during treatment (USEPA 1999). Enhanced coagulation can also improve the removal of arsenate and some radionuclides.

During jar testing, coagulant concentrations can be compared to determine the coagulant dose that results in the greatest removal of DBP precursors.

Enhanced coagulation is a regulatory term describing how the coagulation process can be modified to improve DBP precursor removal. Coagulation is also modified for treatment purposes other than enhanced DBP precursor removal, including improving removal of turbidity, particulates, some types of inorganics, and other color-causing compounds. Coagulation modifications may be dictated by source conditions, seasonal variations, and the treatment processes that occur upstream and downstream of coagulant chemical addition.

Increased removal of DBP precursors is frequently employed as a treatment technique to lower DBP formation.

Enhanced/modified coagulation practices often consist of the following:

- Increased coagulant dosages
- Lower coagulation pH
- Switching primary coagulant chemicals
- Adding a synthetic organic polymer as a coagulant aid
- Combinations of the above

pH range for enhanced coagulation

The optimal pH range for enhanced coagulation is usually about 6.2–6.8 when using aluminum sulfate as a coagulant and about 5.5–6.5 when using iron salt coagulants. Such metal salt coagulants are routinely added to water in an acidic (lower pH) chemical formulation, although more pH-neutral forms are also available. For higher alkalinity water, higher coagulant dosages are sometimes used to lower the pH to a more optimal range. In such cases, it is sometimes beneficial to use acid, in addition to the selected coagulant, to reduce the amount of coagulant needed and effectively lower chemical costs.

Best pH Ranges for Enhanced Coagulation:
- Aluminum sulfate: 6.2–6.8
- Iron salt coagulants: 5.5–6.5

Simultaneous Compliance Issues Associated with Enhanced or Modified Coagulation

Changes in coagulation practices cause a wide variety of simultaneous compliance issues and potential treatment interactions. This section discusses several of the most common consequences including shifts in finished water pH, changes in the finished water chloride-to-sulfate mass ratio, and reduction in other contaminants (e.g., NOM). It is particularly significant that pH changes invariably cause a shift in lead and copper solubility and the tendency of the water to form protective scales in distribution system piping. Thus, such shifts in pH can have profound effects on corrosion control treatment (CCT). Failing to plan for the pH decrease that typically accompanies enhanced coagulation (either by adjusting the finished water pH or modifying CCT) is likely to have negative effects on tap water lead and copper levels.

Key Simultaneous Compliance Issues
- Changes in finished water pH
- Changes in finished water chloride-to-sulfate mass ratio
- Increases in finished water lead or copper levels due to less effective corrosion control treatment (CCT)

Shifts in finished water pH

The hydrolysis reactions that occur when common metal salt coagulants (alum, ferric chloride, and ferric sulfate) are added to water generally consume alkalinity and lower pH. Changing the coagulant from alum to a ferric-based coagulant can decrease alkalinity and make the pH unstable. The pH drop is greater in low-alkalinity waters. In poorly buffered (i.e., low-alkalinity) waters, the use of partially neutralized, pre-hydrolyzed polyelectrolytes such as polyaluminum chloride (PACl) can help to minimize the pH reduction, which could result from conventional metal salt coagulants and still achieve significant NOM removal.

Shifts in lead/copper solubility

Changes in coagulant to improve NOM removal and ultimately reduce DBPs can also cause shifts in lead and copper solubility and affect tap water concentrations of the corrosion byproducts (depending on what CCT is being employed). It has also been reported that the finished water chloride-to-sulfate ($Cl:SO_4$) mass ratio has an effect on lead corrosion. Edwards and Reiber (1997) reported that in a survey of 24 utilities, 100 percent of the utilities with $Cl:SO_4$ ratios less than 0.58 met the 0.015 mg/L Pb action level. However, of those facilities with $Cl:SO_4$ ratios greater than 0.58, only 36 percent met the action level.

Coagulation changes to improve NOM removal and reduce DBPs can also cause shifts in lead and copper solubility - and increase tap water concentrations of these metals.

NOM removal can also affect lead and copper corrosion

The NOM or precursor concentration could also have an effect on lead and copper corrosion, although that is not always the case. Under certain conditions, NOM has been shown to form complexes with lead and copper, form protective coatings on pipe surfaces, and reduce dissolved lead and copper concentrations. In other instances, NOM has been demonstrated to have a negative effect on lead and copper corrosion particularly in stagnant pipes. What is known is that the effect of NOM on lead and copper corrosion in a system is largely dependent on water chemistry, characteristics of the NOM present, and other system hydraulic conditions. Changes in coagulation that affect finished water NOM concentrations or characteristics might therefore have an effect on CCT efficiency.

Increased concentrations of dissolved aluminum and iron

Increased coagulant doses sometimes cause increased concentrations of dissolved aluminum and iron that can potentially pass through filters and enter the distribution system. Excess iron can precipitate in the distribution system and lead to red water problems. Residual aluminum can result in post-precipitation of aluminum hydroxide causing reduced hydraulic capacity, potential valve damage and increased operations costs. Aluminum can interfere with orthophosphate-based corrosion control treatment by forming aluminum phosphate precipitates, which reduce the amount of orthophosphate available for lead and copper control. Residual aluminum has also been implicated as a factor in increased copper pitting and pinhole leaks in home plumbing (Rushing and Edwards 2004).

Residuals impacts

Because more coagulant is added and more NOM is being removed, enhanced coagulation likely results in the production of more residual waste or sludge. Systems will likely experience higher costs with managing an increased residual load. Depending on how water treatment residuals are managed, additional facilities might need to be constructed or new permits might be necessary. The handling, dewatering, and disposal of water treatment plant sludge should be reviewed and the potential for increased costs of waste disposal should be factored into a system's decision.

If the source water has concentrations of hazardous contaminants, such as arsenic, the waste residuals could concentrate those contaminants to the extent that the waste is considered unfit for disposal in a sanitary landfill. Some states have stricter limits on toxics concentrations in waste residuals disposed of in sanitary landfills; and exceeding any of those limits could cause the waste to be classified as hazardous. Systems should properly analyze the sludge that results from enhanced coagulation for increased metals and other contaminants that could create issues with final sludge disposal. If hazardous chemicals are concentrated in the residuals, systems should consult with their state regulatory agency regarding disposal of those residuals.

Questions/Issues to Consider

What coagulants and dosages will be needed for enhanced coagulation? To what degree will DBP formation be reduced? What will be the pH of coagulation?

Systems might need to conduct bench-scale testing or use existing predictive models to understand the optimal enhanced coagulation dosages for their water and the impacts of those dosages on pH.

How will enhanced coagulation affect disinfection?

The efficacy of disinfection and kinetics of DBP formation are both pH-dependent. Utilities should evaluate how pH shifts affect CT performance and residual decay rates, as well as the formation of DBPs.

Will TOC removal under modified coagulation practices meet treatment technique requirements as defined under the Stage 1 DBPR (USEPA 1999)?

Enhanced coagulation requirements under the Stage 1 DBPR are specific. Utilities considering enhanced coagulation for Stage 1 DBPR compliance should verify demonstration requirements with their state primacy agency before implementing changes in coagulation practices.

How will enhanced coagulation affect granular media filtration?

Solids loading onto filters could increase, and systems might need to adjust filtration rates and backwash procedures.

How will enhanced coagulation affect CCT in the distribution system?

Enhanced coagulation affects alkalinity and pH levels, and it can negatively affect CCT. If existing CCT has been designated as optimal or the system has been deemed as optimized without adding treatment under the LCR, OCCT may need to be reevaluated.

Will enhanced coagulation increase filtered water aluminum or iron levels?

Shifts in pH or using partially neutralized iron and aluminum salt coagulants could increase residual concentrations of those metals, which could cause post-precipitation in the distribution system.

What are the consequences of switching coagulants?

Changing the coagulant used during water treatment to improve DBP precursor removal can impact water quality in several ways. For example, the extent that lead and copper leach into water in the distribution system may increase; a coagulant switch can change the finished water Cl:SO4 ratio, which may impact lead corrosion. Impacts of changing coagulant on LCR CCT, turbidity removal and additional treatment and operational issues should be carefully considered and investigated before making a treatment change (AWWA 2005).

How will water treatment residuals (i.e., sludge) be affected?

Increased primary coagulant dosages increase production of water treatment residuals or sludge. Additional sludge handling or treatment facilities might need to be constructed or new permits might be necessary. The handling, dewatering, and disposal of water treatment plant sludge should be carefully reviewed.

Bibliography

AWWA. 2005. Managing Change and Unintended Consequences: Lead and Copper Rule Corrosion Control Treatment. American Water Works Association, Denver, CO.

Chang, S.D., H. Ruiz, W.D. Bellamy, C.W. Spangenberg, and D.L. Clark. 1994. “Removal of Arsenic by Enhanced Coagulation and Membrane Technology.” *Proceedings, 1994 National Conference on Environmental Engineering*, ASCE. New York, NY.

Edwards, M., and S. Reiber. 1997. *A General Framework for Corrosion Control Based on Utility Experience*. AwwaRF Report 90712A. Project #910. American Water Works Association Research Foundation, Denver, CO.

Kirmeyer, G.J., M. Friedman, K. Martel, G. Thompson, A. Sandvig, J. Clement, and M. Frey. 2002. *Guidance Manual for Monitoring Distribution System Water Quality*. AwwaRF Report 90882. Project #2522. American Water Works Association Research Foundation, Denver, CO and American Water Works Association, Denver, CO.

Kornegay, B.H. 2000. *Natural Organic Matter in Drinking Water: Recommendations to Water Utilities*. AwwaRF Report 90802. Project #2543. American Water Works Association Research Foundation, Denver, CO.

Krasner, S.W., and G. Amy. 1995. Jar-test evaluations of enhanced coagulation. *Journal of American Water Works Association* 87(10):93–107.

Lovins, W.A., III, S.J. Duranceau, R.M. Gonzalez, and J.S. Taylor. 2003. Optimized Coagulation Assessment for a Highly Organic Surface Water Supply. *Journal of American Water Works Association* 95(10):94–108.

Rushing, J.C., and M. Edwards. 2004. Effect of aluminum solids and chlorine on cold water pitting of copper. *Corrosion Science* 46(12):3069–3088.

USEPA. 1999. *Enhanced Coagulation and Enhanced Precipitative Softening Guidance Manual*. EPA 815-R-99-012. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

Ion Exchange Processes

What is ion exchange?

IX is generally used to remove dissolved ions and other charged species from water, such as hardness (calcium and magnesium), nitrate, fluoride, perchlorate, uranium, selenium, arsenic, sulfate, NOM, and radionuclides.

Ion exchange (IX) is generally used to remove dissolved ions and other charged species from water. Removal is accomplished through adsorption of contaminants onto a resin exchange medium. The resin surface is designated as either cationic (positively charged) or anionic (negatively charged). IX processes are reversible chemical reactions that remove dissolved contaminants from a solution and replace them with other similarly charged ions. Because those reactions are reversible, IX is very sensitive to the presence of competing ions. High concentrations of competing minerals can decrease removal of target contaminants and profoundly affect the cost-effectiveness of IX.

In drinking water treatment, the most common IX process is cation exchange softening in which calcium and magnesium hardness is removed. Radium can also be removed from drinking water by cation exchange. Anion exchange can be used to remove contaminants such as nitrate, fluoride, perchlorate, chromium, uranium, selenium, arsenic, sulfate, natural organic material (NOM), and others. IX is often the best choice for small systems that need to remove radionuclides.

Typical water systems with IX consist of pretreatment, IX, disinfection, storage, and distribution elements. Water is often pretreated before IX to remove suspended solids and total dissolved solids (TDS). Methods of pretreatment consist of the following:

- Filtration
- Coagulation and filtration
- Microfiltration (MF) and Ultrafiltration (UF)
- Precipitative softening
- Reverse osmosis (RO)
- Combinations of the above

When the capacity of an IX resin is exhausted, it is necessary to use a saturated solution of the exchange ion (e.g., sodium chloride) to restore the capacity of the resin and return it to its initial condition. The resin exchange capacity is typically expressed in terms of weight per unit volume of the resin. The effective service life of an IX system is generally dependent on the resin exchange capacity, the influent contaminant concentration and the desired effluent quality.

Simultaneous Compliance Issues Associated with Ion Exchange Processes

Competition for adsorption sites on the IX resin can greatly reduce its efficiency in removing specific ions or contaminants. Generally ions with higher valence, greater atomic weights, and smaller radii are preferentially absorbed by IX resins and adsorption media. For example, raw water with high hardness competes with other cations (positive ions) for space on the resin exchange medium, requiring the IX bed to be regenerated more frequently. In general, anion IX processes preferentially remove sulfate over most other target contaminants (Water Research Foundation 2011) which can change the Cl:SO_4 ratio and may result in increased lead corrosion in some distribution systems. High concentrations of competing minerals can decrease removal of target contaminants and profoundly affect IX media longevity and regeneration requirements. Rapid shifts in water chemistry (e.g., sodium, sulfate, chloride) can also result in displacement and release of target contaminants such as arsenic, uranium, and nitrates.

IX softening is a cation exchange process involving the exchange of dissolved calcium and magnesium for sodium ions. Cation exchange does not generally affect lead and copper solubility because it causes no significant changes in pH, dissolved carbonates and alkalinity (parameters that have the most effect on lead and copper corrosion). Cation exchange softening can actually cause slight (0.2–0.3) increases in pH, which can have a slightly beneficial effect on lead and copper concentrations. Although cation exchange does not typically increase lead and copper corrosion, waters that need softening often have high alkalinity and carbonate concentrations, which can be more corrosive than softer waters. In addition, removing sulfate and increased chloride concentrations can increase the chloride-to-sulfate mass ratio, which can cause an increase in lead corrosion in some distribution systems.

Demineralization via IX can have a significant effect on TDS and alkalinity, which can produce water that is highly corrosive.

Anion exchange or demineralization (combined anion and cation exchange) can have a significant effect on TDS and alkalinity. Such demineralization removes both dissolved cations (e.g., calcium, magnesium) and anions (e.g., carbonate, sulfate, silicate), which can produce water that is highly corrosive. Blending treated demineralized water with water that has bypassed the IX treatment might be an appropriate solution to minimize the corrosivity in such cases. Where possible, the blending ratio should be determined with key corrosion parameters (i.e., pH, alkalinity, calcium, phosphate) taken into consideration. The finished water chemistry should be adjusted appropriately when blending is not an option because specific contaminants, such as arsenic or nitrate, need the entire or a significant portion of the flow to be treated and result in a water that is corrosive. Under such circumstances, systems should consider orthophosphate or another corrosion inhibitor addition as a corrosion control technology.

In practice, optimizing and maintaining CCT inevitably necessitates a careful balance between water quality objectives for pH, TDS, alkalinity, lead solubility, disinfection, DBPs, and removal of inorganic contaminants. Treatment using cationic IX to soften water will remove calcium and magnesium but generally does not remove TDS or alkalinity. Therefore, utilities should use diagnostic tools or supplemental monitoring (or both) to carefully consider how treatment changes like softening can affect their distribution system corrosion control practices. Those tools are in Appendix D of the *Simultaneous Compliance Guidance Manual for the LT2ESWTR and Stage 2 DBP Rules* (USEPA 2007) and consist of the following:

- Desktop studies
- Water quality monitoring
    - Expanded baseline monitoring
    - Supplemental tap water quality monitoring
- Blending analysis
- Solubility models
- Laboratory and field testing
    - Treatment simulation
    - Pipe loop testing
    - Coupon studies
    - Electrochemical measurement techniques
    - Scale and solids analysis
    - Partial system testing

> High levels of TDS, chlorides, or other target contaminants in IX waste streams can complicate disposal, or possibly trigger more stringent hazardous or radioactive waste requirements.

IX waste streams (i.e., brine) are highly concentrated in TDS and target contaminants and need careful handling and disposal. New National Pollutant Discharge Elimination System (NPDES) or sewer use permits are often needed. When radionuclides are present, concentration of radioactivity could require the use of specially licensed contractors for transportation and disposal of spent IX resins.

☆ Questions/Issues to Consider

What type of IX resin is needed for target contaminants?

Treatability testing might be necessary to determine whether cation, anion, or mixed-bed IX is most appropriate.

How frequently will IX resin need to be regenerated?

IX media longevity and regeneration requirements are uniquely site specific and depend on throughput and concentrations of non-target, inorganic contaminants. Sulfates, nitrates, and many other dissolved minerals compete for IX bed capacity. High concentrations of those competing minerals decrease removal of target contaminants and profoundly affect the cost-effectiveness of IX.

What percentage of the source water needs to be treated?

The percentage of source water that needs to be treated depends on source water concentrations and treated water goals for target contaminants. Side stream or partial treatment might be sufficient for lower concentrations of certain contaminants. Higher concentrations need more of the source water to be treated.

Will pretreatment be needed?

Some form of pretreatment is almost always needed ahead of IX. Pre-oxidation might enhance the removal of certain contaminants including arsenic.

Is source water prone to wide deviations in mineral concentration?

Rapid shifts in feed stream chemistry (e.g., sodium, sulfate, chloride) could result in displacement and release of target contaminants such as arsenic, uranium, and nitrates, potentially posing a risk to public health.

How will IX affect CCT in the distribution system?

Optimizing and maintaining CCT inevitably needs a careful balance between sometimes conflicting treatment objectives for pH, TDS, alkalinity, lead solubility, and inorganic contaminants. Cationic IX softening removes calcium and magnesium, but does not generally remove TDS or alkalinity. Although cation exchange does not typically increase lead and copper corrosion, waters that need softening often have high alkalinity and carbonate concentrations, which can be more corrosive than softer waters. Waters with very high alkalinities (> 175 mg-$CaCO_3$/L) could require more robust CCT.

What is the disposal plan for waste streams?

High levels of TDS, chlorides, or other target contaminants can complicate brine disposal. New NPDES or sewer use permits might be required. In some cases, IX process residuals or spent media could trigger more stringent hazardous or radioactive waste disposal requirements.

Bibliography

Amy, G.L., M. Edwards, M. Benjamin, K. Carlson, J. Chwirka, P. Brandhuber, L. McNeill, and F. Vagliasindi. 2000. *Arsenic Treatability Options and Evaluation of Residuals Management Issues*. AwwaRF Report 90771. Project #153. American Water Works Association Research Foundation, Denver, CO.

Sorg, T.J. 1988. Methods for removing uranium from drinking water. *Journal of American Water Works Association* 80(7):105–111.

USEPA. 2001. *Controlling Disinfection By-Products and Microbial Contaminants in Drinking Water*. EPA/600/R-01/110. U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC.

USEPA. 2005. *A Regulator's Guide to the Management of Radioactive Residuals from Drinking Water Treatment Technologies*. EPA 816-R-05-004. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

Water Research Foundation. 2011. Technology Primers for the Simultaneous Compliance Tool. Supplement to Water Research Foundation Project 91263. Water Research Foundation, Denver, CO.

Microfiltration and Ultrafiltration

What are microfiltration and ultrafiltration?

Microfiltration (MF) and ultrafiltration (UF) are low-pressure membrane processes commonly used in drinking water treatment. The membranes remove particulate matter larger than the membrane pore size (MF 0.1-1 µm; UF 0.01-0.1 µm). The primary difference between MF and UF is the pore size of the membranes. MF membranes generally operate at slightly lower pressure and have larger pore sizes than UF membranes. Particulates removed include suspended solids, turbidity, some colloids, bacteria, protozoan cysts, and viruses (only UF membranes have been demonstrated to remove viruses to any significant degree). MF and UF are typically employed for removing particulate and some microbial contaminants, and are frequently selected as an alternative to granular media filtration in conventional treatment and softening applications. MF and UF units are often supplied on skid-mounted assemblies that include sensors and other equipment needed for unattended automatic operation.

MF and UF are typically employed to achieve high removals of turbidity, bacteria, *Giardia* and *Cryptosporidium*. This often allows for a lower disinfectant dosage and reduced formation of DBPs.

The primary advantage of MF and UF is their ability to achieve high removals of turbidity, bacteria, *Giardia* and *Cryptosporidium*. This often allows a system to lower its disinfectant dosage and possibly reduce formation of disinfection byproducts (DBPs). If surface water systems use MF or UF instead of chemical disinfection to get inactivation/removal credit, they need to add a disinfectant such as chlorine or chloramines to inactivate viruses and to maintain a disinfectant residual in the distribution system. MF and UF units that are challenge-tested before installation and undergo membrane integrity tests might qualify for additional *Cryptosporidium* removal credit under the LT2ESWTR. Systems should consult with their state primacy agency to determine applicable credits and demonstration requirements.

MF and UF membrane systems frequently need chemical and physical pretreatment to prevent unacceptable fouling. The form of pretreatment needed depends on the feed water quality and membrane attributes. Surface water generally needs more extensive pretreatment than ground water. Inorganic chemicals (e.g., phosphorus, hardness, particulate arsenic, metals) can be removed by MF and UF with suitable pretreatment. Some removal of dissolved organics can occur with specific MF and UF pretreatment (e.g., coagulation), which can result in lower DBP formation.

MF and UF membranes do not have a small enough molecular cutoff weight to remove dissolved or colloidal arsenic. The removal depends on the size distribution of particles to which the arsenic is bound and the pore size of the membrane. A coagulation step before the membranes might be necessary to provide for arsenic removal.

A skid of microfiltration filters

Temperature has a significant effect on MF and UF membrane performance. As the viscosity and density of the water increase, the trans-membrane pressure required to pass the water through the membrane also increases. MF and UF membrane systems always need routine backwashing to remove foulants from the membrane surfaces. Backwash frequency and duration depend on the membrane system and specific feed water quality and operational conditions. Chemical clean-in-place is necessary to control membrane fouling and maintain target hydraulic loading rates.

Residuals generated from MF and UF systems include the spent backwash and spent cleaning solutions. Spent backwash can be recycled to the process to increase system recovery, reduce chemical doses, and improve overall treatment performance. Otherwise disposal of spent backwash is generally accomplished by discharge to a sanitary sewer or receiving stream after appropriate treatment, much the same way spent backwash from a rapid sand filter would be handled. Spent cleaning solutions are generally acidic in nature and sometimes need neutralization before disposal. MF and UF cleaning streams and concentrated process residuals could require special permits for disposal or sewer discharge. Systems considering MF and UF should confer with their state primacy agency to establish residuals handling, dewatering, and disposal requirements.

Simultaneous Compliance and Operational Issues Associated with MF and UF

Very few simultaneous compliance or operational problems are associated with MF and UF, although modifications to pretreatment and post-treatment can introduce new complexities. Improved operational practices are normally sufficient to address such issues.

Changes in disinfection practices

Systems that install MF and UF will likely receive increased removal credit for *Giardia* and *Cryptosporidium*, as determined by the state. UF membranes also are capable of removing some viruses, and certain states may grant virus removal credit with adequate demonstration. That can result in less stringent primary disinfection CT requirements in conjunction with MF and UF treatment. Systems will likely need to implement operational practices and monitoring changes to realize the full benefits of MF and UF. Often post-membrane disinfection criteria are dictated solely by virus inactivation and maintaining residual chlorine/chloramine concentrations in the distribution system (i.e., secondary disinfection).

Membrane fouling

Membranes can be fouled by organic matter, iron, manganese, and carbonate deposits. MF and UF foulants can result from source water constituents or compounds introduced by reactions with treatment chemicals. Ground water systems that do not treat their water before it passes through the MF and UF unit can have problems with iron, manganese, and other minerals. Systems with high total organic carbon (TOC) can reduce fouling by placing the MF and UF downstream of the coagulation-sedimentation-filtration processes. TOC removal can be improved by using enhanced coagulation techniques. Bench-scale testing might be needed to determine optimal coagulation pH and dosages. Iron-based coagulants can contribute to fouling/scaling of certain MF and UF membranes. Systems that aerate their ground water to oxidize iron, manganese, or other compounds should remove any precipitated minerals before the water reaches the MF and UF unit to prevent fouling.

Loss of process water

MF and UF processes produce both backwash water and chemical clean-in-place waste streams. Sometimes the amount of process wastewater to be handled is greater than that produced by conventional treatment. Despite recent advances in MF and UF efficiency, some systems lose as much as 15 percent of the process water as a waste stream. To handle the MF and UF units’ higher quantities of process wastewater, systems might need to increase the capacity of their process waste stream storage and residuals processing facilities.

Additional training

MF and UF membranes are significantly different to operate than other water treatment units. The monitoring and control parameters are different, and state primacy agencies sometimes require additional training or certification for operators.

☆ Questions/Issues to Consider

What is the Cryptosporidium removal credit for MF and UF?

The LT2ESWTR does not prescribe a specific removal credit for membrane filtration systems. Instead, removal credit is based on system performance results from a product-specific challenge test and site-specific testing. Systems should consult with their primacy agency to determine applicable removal credits and demonstration requirements. Systems using MF and UF might want to perform validation testing before installation and should provide for membrane integrity testing to qualify for *Cryptosporidium* removal credit under the LT2ESWTR.

How will virus inactivation/removal be accomplished?

UF membranes are capable of removing some viruses, and certain states may grant virus removal credit with adequate demonstration. MF cannot remove viruses. If surface water systems use MF or UF, they must add a disinfectant such as chlorine or chloramines to inactivate viruses to comply with the SWTR. NF and RO are capable of significant virus removal, however some level of virus inactivation through disinfection is usually required by the state.

What pretreatment will be needed for MF and UF processes?

Some form of pretreatment is often needed upstream of MF and UF to prevent fouling by particulates, iron, or dissolved organics or to promote the removal of DBP precursors. Surface water generally contains more particles that need to be removed during pretreatment than ground water in order to maintain MF or UF filter efficacy.

Will MF and UF pretreatment create any effect on CCT? pH change?

Very few simultaneous compliance or unintended consequences are associated with MF and UF, although modifications to pretreatment and post-treatment can introduce complexities. Any shifts in pH or alkalinity associated with MF and UF pretreatment can negatively affect CCT. LCR CCT might need to be re-optimized.

Are MF and UF membranes tolerant of any pre-oxidants?

Polypropylene membranes are incompatible with chorine. Systems should verify specific oxidant tolerance with membrane manufacturers.

How will water lost during production affect overall capacity requirements?

Some MF and UF systems lose as much as 15 percent of the process water as a waste stream. To handle the MF and UF units' higher quantities of process residuals, utilities may need to increase the capacity of their supply, waste stream storage, and residuals processing facilities.

How will process residuals streams be disposed?

Handling and disposal of MF and UF residuals is generally accomplished by discharge to a sanitary sewer or receiving stream, similar to the way spent backwash from a rapid sand filter would be handled. Spent membrane cleaning solutions are generally acidic in nature and sometimes need neutralization before disposal. MF and UF cleaning streams and concentrated process residuals might require special permits for disposal or sewer discharge. Systems considering MF and UF should confer with their state primacy agency to establish residuals handling, dewatering, and disposal requirements.

What supplemental operator certifications or training are needed?

The primacy agency could require new certifications for operators of MF and UF facilities. Systems should consult with their primacy agency.

Bibliography

Amy, G., M. Clark, and J. Pellegrino. 2001. *NOM Rejection by, and Fouling of, NF and UF Membranes*. AwwaRF Report 90837. Project #390. American Water Works Association Research Foundation, Denver, CO.

Duranceau, S.J. 2001. *Membrane Practices for Water Treatment*. American Water Works Association, Denver, CO.

Glucina, K., A. Alvarez, and J.M. Laine. 2000. "Assessment of an integrated membrane system for surface water treatment." *Proceedings, International Conference on Membranes in Drinking and Industrial Water Production*. Italy. 2:113–122.

HDR Engineering, Inc. 2001. *Handbook of Public Water Systems.* 2nd ed., John Wiley & Sons, Inc., New York.

Mallevialle, J., P.E. Odendaal, and M.R. Wiesner. 1996. *Water Treatment Membrane Processes.* AwwaRF Report 90716. Project #826. American Water Works Association Research Foundation, Denver, CO.

USEPA. 2001. *Low-Pressure Membrane Filtration for Pathogen Removal: Application, Implementation, and Regulatory Issues*. EPA 815-C-01-001. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

USEPA. 2005. *Membrane Filtration Guidance Manual*. EPA 815-R-06-009. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

USEPA. 2010. *Long Term 2 Enhanced Surface Water Treatment Rule: Toolbox Guidance Manual*. EPA 815-R-09-016. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

Nanofiltration and Reverse Osmosis

What are nanofiltration and reverse osmosis?

NF membranes are typically used for hardness and DBP precursor removal. RO membranes are usually used for more aggressive removal of TDS and monovalent ions (e.g., seawater desalting, fluoride and chloride). Both treatments provide absolute barriers for most cysts and viruses.

Nanofiltration (NF) and reverse osmosis (RO) are physical separation processes in which properly pretreated source water is delivered at moderately high pressures against a semi-permeable membrane. NF and RO *reverse* the so-called natural osmotic process by using pressure to force water through membranes, against the natural osmotic gradient. The membrane rejects most soluble ions and molecules while allowing water of very low mineral content to pass through. As a result, the dissolved contaminant concentrations are higher on the feed side of the membrane. The primary difference between NF and RO is the size of dissolved contaminants that are removed, which is related to pressure and the type of membrane employed. NF is sometimes referred to as *loose RO*.

NF membranes are often used for hardness and natural organic material (NOM) (i.e., DBP precursor) removal and provide a barrier for most cysts and viruses. NF can also be effective in removing arsenic, nitrate, radionuclides, chromium, and many other dissolved contaminants. In contrast, RO membranes are typically used for more aggressive removal of TDS and monovalent ions (e.g., seawater and brackish water desalting, fluoride and chloride). Like other membrane systems, NF and RO include three basic flow streams: the feed, permeate or product, and concentrate or waste stream. A treatment process generally consists of multiple stages in which the concentrate from the prior stage becomes the feed for the subsequent stage. The permeate from each stage is blended together for the final product stream.


A skid of reverse osmosis filters

NF and RO systems typically need pretreatment to prevent membrane fouling by dissolved inorganics or biological constituents. The type of pretreatment depends on the feed water quality and membrane type. For some surface waters pretreatment can be extensive and include coagulation, sedimentation, pH adjustment, MF, granular activated carbon (GAC) adsorption, and other oxidation or removal processes. NF and RO post-treatment typically includes degasification for carbon dioxide (if excessive) and hydrogen sulfide removal (if present), pH and alkalinity adjustment for corrosion control, and using either free chlorine or monochloramine for secondary disinfection in the distribution system.

Simultaneous Compliance and Operational Issues Associated with NF and RO

NF and RO are used for softening, desalination, and removing NOM or other dissolved contaminants (e.g., arsenic or radionuclides). These membrane filtration processes can have a significant effect on CCT effectiveness if the new water chemistry is not properly adjusted. Alkalinity removal associated with NF and RO often results in lower pH and increased dissolved carbon dioxide, which can affect corrosion control and scale stability in the distribution system. Without some form of blending or split treatment, re-optimization of CCT most likely requires degasification (air stripping to remove dissolved carbon dioxide) and pH/alkalinity adjustment before distribution (AMTA 2007). Significant decreases in finished water alkalinity (> 15 percent) can cause increased corrosion of iron, lead, and copper—particularly in low-alkalinity waters. Using an orthophosphate-based corrosion inhibitor (e.g., phosphoric acid or zinc orthophosphate) can also help to minimize the potential for increased metals release.

NF and RO remove TDS and alkalinity and can produce water that is more corrosive.

To prevent corrosion of cement-mortar linings in distribution piping, a positive Langelier Saturation Index (LSI) should generally be maintained. LSI is the pH change required to bring water to equilibrium. Water with an LSI of 1.0 is one pH unit above saturation. LSI is useful for measuring the tendency of water to dissolve or precipitate calcium carbonate; but it is not a reliable means of predicting LCR compliance or lead solubility (AWWA 2005). LSI values greater than 0.5 can promote excessive precipitation of calcium carbonate in the distribution system. Similarly, a finished water calcium carbonate precipitation potential (CCPP) of 4 to 10 will help to prevent dissolution of cement-mortar linings; but values in excess of 10 can result in excessive precipitation.

Residuals generated from NF and RO systems include the concentrate from the membrane processes and the spent cleaning chemicals. Concentrate or *reject* water disposal can be challenging because it is highly regulated by USEPA or state government agencies. Often 10–30 percent of water will be lost to concentrate and cleaning solutions where NF treatment is used for ionic contaminant removal; as much as 75 percent of water may be lost during RO treatment. NF and RO concentrate is typically a high-TDS waste stream and should have a comparatively large body of water for discharge, or it should be discharged to a wastewater treatment plant (WWTP) or via deep-well injection. Spent chemical cleaning solutions are generally acidic in nature and should be neutralized before disposal.

Often 10–30 percent of water will be lost when NF treatment is being used for contaminant removal; the percentage of water lost during RO treatment can be much higher.

☆ Questions/Issues to Consider

What pretreatment will be needed?

NF and RO typically needs pretreatment to prevent fouling by particulates, dissolved organics, or high mineral concentrations.

What are post-treatment considerations after NF or RO treatment?

Water that has been treated with NF or RO is likely to require subsequent treatment for residual disinfection and corrosion control. Degasification and/or air stripping may also be needed to remove gases present in the permeate.

How will water lost during production affect overall capacity requirements?

NF systems can lose as much as 30 percent of the process water as a waste stream when used for ionic contaminant removal. Utilities considering NF or RO should evaluate increasing their raw water supply capacity as well as effects on waste stream storage and residuals processing facilities.

How will increased corrosivity and scaling potential of treated water be managed? Will CCT need to be re-optimized?

Demineralization by NF and RO typically increases corrosivity, which could require more aggressive CCT to avoid negative effects on existing pipe scales. Blending of NF or RO permeate with other waters might be needed for optimal corrosion control, to promote scale stability and to avoid customer *dirty water* complaints. Removal of sulfate and increased chloride concentrations can increase in the chloride-to-sulfate ratio, which can increase lead corrosion in some distribution systems. LCR CCT will almost certainly need to be re-optimized.

What is the disposal plan for the reject waste stream with high TDS?

Reject stream disposal options are usually limited to publicly owned treatment works (POTW) discharge or deep-well injection, unless the facility is located near an ocean.

What type of membrane integrity testing will be provided?

NF or RO system development must include integrity testing to receive credit for *Cryptosporidium* removal under LT2ESWTR.

Bibliography

AMTA (American Membrane Technology Association). 2007. *Nanofiltration and Reverse Osmosis (NF/RO)*. (FS-3) Feb. 2007, American Membrane Technology, Stuart, FL.

Amy, G., M. Clark, and J. Pellegrino. 2001. *NOM Rejection by, and Fouling of, NF and UF Membranes*. AwwaRF Report 90837. Project #390. American Water Works Association Research Foundation, Denver, CO.

Amy, G.L., M. Edwards, M. Benjamin, K. Carlson, J. Chwirka, P. Brandhuber, L. McNeill, and F. Vagliasindi. 2000. *Arsenic Treatability Options and Evaluation of Residuals Management Issues*. AwwaRF Report 90771. Project #153. American Water Works Association Research Foundation, Denver, CO.

AWWA. 1999. *Reverse Osmosis and Nanofiltration*. AWWA Manual M46. American Water Works Association, Denver, CO.

AWWA. 2005. *Managing Change and Unintended Consequences: Lead and Copper Rule Corrosion Control Treatment*. American Water Works Association, Denver, CO.

Duranceau, S.J. 2001. *Membrane Practices for Water Treatment*. American Water Works Association, Denver, CO.

Glucina, K., A. Alvarez, and J.M. Laine. 2000. “Assessment of an integrated membrane system for surface water treatment.” *Proceedings, International Conference on Membranes in Drinking and Industrial Water Production*. Italy. 2:113–122.

USEPA. 2001. *Low-Pressure Membrane Filtration for Pathogen Removal: Application, Implementation, and Regulatory Issues*. EPA 815-C-01-001. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

USEPA. 2005. *Membrane Filtration Guidance Manual*. EPA 815-R-06-009. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

USEPA. 2010. *Long Term 2 Enhanced Surface Water Treatment Rule: Toolbox Guidance Manual*. EPA 815-R-09-016. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

Corrosion Control Treatment

What is corrosion control treatment?

Optimizing and maintaining OCCT necessitates a careful balance among sometimes conflicting water quality objectives for coagulation, softening, disinfection, removal of inorganics such as arsenic, and DBP control.

The term *corrosion control treatment (CCT)* has historically been applied to a variety of treatment techniques, which in practice are used to meet distinctly different objectives. Before the LCR was promulgated in 1991, drinking water corrosion control practices were often targeted to improve aesthetics of the drinking water, to protect a pipeline's hydraulic capacity, and/or extend its service life. Those remain worthy objectives even though they are peripheral to *optimal corrosion control treatment (OCCT)*, which is more narrowly defined as corrosion control treatment that minimizes the lead and copper concentrations at users' taps while insuring that the treatment does not cause the water system to violate any national primary drinking water regulations. OCCT approaches are discussed in greater detail in the EPA's *Revised Optimal Corrosion Control Treatment Evaluation Technical Recommendations for Primacy Agencies and Public Water Systems* (herein referred to as *OCCT Technical Recommendations Document*) (USEPA 2019).

Metals release is a function of the reactions that occur between the metal surface (e.g., pipe, solder) and the water and is affected by the physical, chemical, and biological characteristics of the water and the metal surface. A very important factor in metals release is the *scale* that builds up on the metal surface. Pipe scale generally reduces metal release, and the extent of this reduction depends on a number of factors. Scale can be complex and contain a mix of passivating films and deposited materials such as iron, manganese, aluminum, and calcium. Scales can have layers and are influenced by treatment history. The structure and compounds in the scale can influence the effectiveness of CCT (USEPA 2019). Changes to pipe scale can require months or even years to fully take effect and stabilize, so it is important for systems to consider the long-term implications of making any changes that will affect pipe scale.

For most utilities, OCCT under the LCR consists of employing one of the following (USEPA 2019):

- **pH/alkalinity/dissolved inorganic carbon adjustment** refers to modifying pH, alkalinity, and/or dissolved inorganic carbon (DIC) to induce the formation of insoluble compounds (i.e., carbonate compounds) on the metal surface. This method often requires a high pH (generally 8.8 or greater but 9.0 or greater for systems with lead service lines). Alkalinity/DIC is needed to form the protective scale and provide buffer capacity, but too much can solubilize lead. Copper control can generally be achieved at a lower target pH (as low as 7.8).
- **Corrosion inhibitor addition** refers to applying a substance capable of reducing the corrosivity of water toward metal plumbing materials, especially lead and copper, by forming a protective layer on the interior surface of those materials. The most common corrosion inhibitor for controlling lead and copper is orthophosphate. Orthophosphate is available in many forms including phosphoric acid and zinc orthophosphate, and is

typically added to finished water so that residual concentrations at the tap are 1.0 to 3.0 mg/L as phosphate (PO_4). Higher or lower doses may be needed for water falling outside of the pH range of 7.2 to 7.8. Blended phosphates, which are combinations of orthophosphate and polyphosphates, can be effective depending on the amount of orthophosphate in the blend. Note that polyphosphates do not control lead and copper release, but they can be used as a sequestering agent for iron and manganese. Silicates have also been shown in a few cases to effectively reduce lead and copper concentrations at customer's taps. The effectiveness of corrosion inhibitors depends on the concentration of the inhibitor, pH, DIC, and characteristics of the existing corrosion scale.

Although calcium hardness adjustment was used in the past with the intent to control corrosion, research since the promulgation of the LCR has shown that calcium carbonate films only rarely form on lead and copper pipe and are not considered an effective form of corrosion control for lead and copper.

For OCCT, utilities should select and implement the most effective control of lead and copper possible while maintaining compliance with regulatory requirements and other water quality constraints. In practice, maintaining OCCT inevitably requires a careful balance between sometimes conflicting water quality objectives for coagulation, softening, removal of inorganics such as arsenic, disinfection, and disinfection byproducts (DBP) control.

Even where a utility has successfully implemented OCCT, changes in source conditions, treatment, or distribution system O&M can affect pipe scales and cause lead and copper release.

Adding phosphate-based corrosion inhibitors to drinking water will increase the phosphorus loading to the wastewater treatment plant. Some wastewater utilities have stringent limits on the amount of phosphorus that can be discharged to receiving waters and remove it at the plant using biological and/or chemical treatment. Systems should communicate with wastewater treatment personnel and evaluate potential impacts of adding phosphate-based corrosion inhibitors before making the final treatment selection and setting the target dose.

Simultaneous Compliance and Unintended Consequences of Changes Related to CCT

Changes in source water, treatment practices, and distribution system O&M have the potential to compromise CCT and jeopardize LCR compliance if not properly managed. Preventing negative effects of these changes on CCT necessitates a comprehensive evaluation of each change *before* it is implemented. This could include discussions with the state primacy agency, establishing new water quality criteria for OCCT, and conducting an evaluation of the effect of possible changes on finished water quality. In some cases, system-specific conditions (e.g., presence of lead service lines, extensive unlined cast-iron pipe) could warrant further investigation to preemptively determine the effect of changes on CCT effectiveness. In these cases, coupon studies and pipe loop testing might help to establish optimum water quality and CCT conditions. Where CCT is not currently practiced or may have been compromised and the cause of the increase in lead or copper corrosion is unknown, a review of existing data (and supplemental data collection, in some cases) will be extremely useful in identifying the possible cause and determining the best course of action.

Source water changes

Source water characteristics have a significant influence on finished water corrosivity. Changes in source water that affect pH, alkalinity, and/or DIC are likely to affect metals release in the distribution system. For example, reductions in alkalinity and DIC will reduce the buffering capacity of the water. Poorly buffered waters may have more variable pH in the distribution system, which can negatively impact CCT effectiveness regardless of the method used. Changes in source water quality that affect other finished water quality parameters such as natural organic material (NOM) and ammonia can affect biological activity in the distribution system as well as metal surface reactions. Therefore, it is essential to understand and plan for how changes in source water could affect CCT and other treatments *before* switching sources. Systems can then manage changes in source water to prevent deterioration of finished water quality and maintain OCCT or re-optimize CCT to address new conditions and constraints. Effective and consistent CCT is more easily accomplished when providing and maintaining a source water with consistent quality or when providing adequate treatment to address variations in raw water quality.

What treatment changes affect CCT?

Changes in water treatment practices can have unintended consequences if not properly implemented. Failure to proactively manage such changes in treatment can produce negative effects on CCT and LCR compliance.

Oxidants are used in water treatment to accomplish a variety of objectives, most notably disinfection. Free chlorine is by far the most common oxidant chemical employed in water treatment, although ozone, chloramines, chlorine dioxide, and potassium permanganate are also common. Alternatives to primary and secondary disinfection using free chlorine have become increasingly common since the 1980s to help reduce the formation of DBPs. Oxidant changes have the potential to alter the stability of existing passivation scales and associated corrosion rates for lead and copper. Oxidant/disinfectant changes include:

- **Modified free chlorine dosages** or relocating chlorine application points including booster chlorination
- **Switch from chlorine gas to sodium hypochlorite** because of health and safety concerns and risk management requirements related to storing chlorine gas
- **Conversion from free chlorine to chloramines** for secondary disinfection to reduce formation of DBPs within the distribution system
- **Pre-ozonation** for conversion of NOM, taste and odor control, or to promote biological treatment
- **Use of chlorine dioxide** to reduce DBP formation, control taste and odor, or replace free chlorine

Almost any change to an existing oxidation/disinfection strategy has the potential to affect CCT. Modifications to free chlorine dosages, application points, or both have the potential to alter metal oxidation rates and the nature of the existing scale deposits. Changing from free chlorine to chloramines for secondary disinfection may destabilize lead oxide scale in the distribution system. For guidance on identifying situations in which lead oxide exists and strategies to prevent lead release when changing from chlorine to chloramines, see Chapter 6 of the *OCCT Technical Recommendations Document* (USEPA 2019).

Changes in treatment that change the finished water alkalinity and pH can cause a shift in lead and/or copper solubility and the nature of passivation scales that provide corrosion control. Coagulation, softening, membrane processes such as NF and RO, and ion exchange (IX) are processes that are likely to affect these parameters. Reducing pH to optimize coagulation can result in lower finished water pH, which will likely affect corrosion control effectiveness. Also, switching from a sulfate-based to chloride-based coagulant may increase the chloride content of the water, increasing the chloride-to-sulfate mass ratio. This may result in increased lead release (USEPA 2019).

Alkalinity and pH are the water quality parameters that most influence lead and copper solubility, or the nature of passivation scales that provide corrosion control.

Adding enhanced softening may raise pH and alkalinity, which is generally a positive factor for controlling lead and copper, whereas removing or discontinuing softening can have the opposite effect. NF and RO remove alkalinity, hardness, and some dissolved compounds but do not remove carbon dioxide, resulting in a lower pH. IX can have a similar impact of removing alkalinity and other dissolved compounds in the water. Other treatments such as GAC and biological filtration can change the amount of NOM in the water, which could potentially cause shifts in corrosion scale formation. See Table 2 for an overview of potential impacts of treatment changes on CCT. For more information, refer to the *Simultaneous Compliance Guidance Manual for the LT2ESWTR and Stage 2 DBP Rules* (USEPA 2007) and the *OCCT Technical Recommendations Document* (USEPA 2019).

Table 2: Treatment Changes Affecting CCT

Treatment Change	Compliance Concerns
Changing from chlorine to chloramines	• Potential lead release from lead oxide scales • Change in microbial conditions • Localized reductions in pH due to nitrification
Adding ozone	• Increased dissolved oxygen • Increased microbial growth • NOM reduction
Enhanced coagulation	• Decreased pH • Decreased NOM

Treatment Change	Compliance Concerns
Coagulant change (alum to ferric)	• Increased chloride-to-sulfate mass ratio, which could impact lead release • Potentially reduced aluminum carry-over and improved orthophosphate treatment
Enhanced softening (DBP control)	• Higher pH • Decreased corrosion rate • Formation of calcium carbonate scale • NOM reduction
Adding NF or RO	• Alkalinity and hardness removal • Lower pH

Refer to the *Simultaneous Compliance Guidance Manual for the LT2ESWTR and Stage 2 DBP Rules* (USEPA 2007) and the *OCCT Technical Recommendations Document* (USEPA 2019) for more information.

How do CCT changes affect other water quality goals?

The following modifications to CCT to improve its effectiveness may have negative impacts on other water quality goals:

- **Increasing pH to increase buffer capacity promotes increased formation of insoluble scales.** Increasing pH to improve CCT effectiveness can also affect DBP speciation or formation kinetics (i.e., increase HAA formation but decrease THM formation). Further, increasing the pH can also affect the efficacy of the secondary disinfectant. Both free chlorine and monochloramine are more effective at lower pH values. However, chloramine residual stability improves as pH increases, so pH goals for monochloramine should be carefully established to avoid nitrification while balancing corrosion control, disinfection, and DBP compliance issues. In addition to these impacts, pH increase can cause calcium carbonate precipitation, which can cause cloudy water and decrease the carrying capacity of pipes. Increasing pH can also cause oxidation of iron and manganese, triggering red or dirty water complaints.
- **Changes in corrosion inhibitor chemicals or dosage.** Utilities should carefully examine the impact of switching inhibitors or dosages before making the change. Increasing the orthophosphate dose can increase the phosphorus loading to the wastewater treatment plant (WWTP). Switching from orthophosphate to zinc-orthophosphate can potentially cause problems with biological treatment processes (particularly nitrification) at WWTPs and impact the WWTP's ability to meet discharge permit requirements for metals. Switching to a blended phosphate for corrosion control can help sequester iron and manganese, but it is important that the blend continue to minimize lead and copper concentrations at the tap. While blended phosphates have been shown to be effective for reducing lead levels, the lead corrosion scale may not be as robust as the scale created by orthophosphate and may be more susceptible to physical disturbances and low water use conditions. Blended phosphates may not work well to control copper

corrosion, especially at high alkalinities, and the effectiveness of blended phosphates cannot be based on the orthophosphate concentration in the blend. EPA recommends a demonstration study, additional monitoring, or both for systems that recommend blended phosphates to control lead release.

Utilities should carefully consider using diagnostic tools or supplemental monitoring to assess how source and treatment changes can affect distribution system corrosion control. Appendix F of the *OCCT Technical Recommendations Document* (USEPA 2019) provides a description of the various tools that can be used to conduct a desk top study (e.g., using theory and analogous systems) and demonstration study (e.g., pipe loops, coupons, scale analysis, partial system tests). Additional water quality monitoring of key parameters including pH, alkalinity, biological indicators such as HPC, and corrosion inhibitor can be very helpful in characterizing variability in key finished water and distribution system water quality. For more information see Appendix C of the *OCCT Technical Recommendations Document* (USEPA 2019) and Appendix D of the *Simultaneous Compliance Guidance Manual for the LT2ESWTR and Stage 2 DBP Rules* (USEPA 2007).

☆ Questions/Issues to Consider

In practice, optimizing and maintaining CCT necessitates a careful balance between sometimes conflicting water quality objectives for coagulation, softening, disinfection, and DBPs. The following questions will help a system identify simultaneous compliance challenges and a possible need for adjusting or modifying operations and/or treatment.

How was LCR OCCT established? What has changed?

Many source or treatment changes could cause the system to need to re-optimize CCT. New data collection might be needed to understand the corrosion implications of some changes.

Has there been any increase in historical 90th percentile lead or copper tap water concentrations during the last 5 years? 75th percentile? 50th percentile?

Increases in lead or copper tap water concentrations can indicate that CCT is not fully optimized, even if the system does not have an action level exceedance under the LCR.

Are the target water quality parameters (e.g., pH, alkalinity, TDS, PO_4) associated with LCR OCCT being consistently maintained?

Daily or weekly variations in pH, alkalinity or TDS can create scale instability, which can compromise CCT or cause dirty water complaints. Alkalinity and pH should be kept as consistent as possible. Increases or decreases in tap water pH could also indicate a need to re-optimize CCT even if the 90th percentile concentrations of lead and copper have remained unchanged or below the LCR action levels.

Has there been a conversion from free chlorine to chloramines?

Under certain conditions, changes from free chlorine to chloramines for secondary disinfection can result in an increase in lead solubility.

What is the effect of CCT pH on secondary disinfection?

The efficacy of free chlorine to inactivate microorganisms is highly pH dependent. A change in pH may somewhat affect the ability of secondary disinfection to protect water in the distribution system. However, since inactivation of pathogens takes place predominantly during primary disinfection, this should not be a substantial concern if the water system has a properly protected distribution system.

What is the effect of CCT pH on the formation of DBPs in the distribution system?

Increasing pH to improve CCT effectiveness could affect DBP speciation or formation kinetics (i.e., increase HAA formation but decrease THM formation).

What is the chloride-to-sulfate ($Cl:SO_4$) mass ratio?

Finished water chloride-to-sulfate mass ratios have been statistically linked to LCR action level exceedances. Edwards and Reiber (1997) reported that in a survey of 24 utilities, 100 percent of the utilities with Cl:SO4 ratios less than 0.58 met the 0.015 mg/L Pb action level. However, of those facilities with Cl:SO4 ratios greater than 0.58, only 36 percent met the action level.

Are there any consecutive systems? How will implementation changes to your OCCT affect them?

Consecutive systems receive some or all of their finished water from one or more wholesale systems. Delivery may be through a direct connection or through the distribution system of one or more consecutive systems. It is important for wholesale and consecutive systems to establish a communication process so the consecutive systems are aware of any water quality and operational changes being made by the wholesale systems.

Is a phosphate-based corrosion inhibitor being used?

Verify that pH is correct for the type of inhibitor chemical being used. Systems should communicate with WWTPs and evaluate potential impacts of adding phosphate-based corrosion inhibitors before making the final treatment selection and setting the target dose.

Bibliography

AWWA. 2005. *Managing Change and Unintended Consequences: Lead and Copper Rule Corrosion Control Treatment.* American Water Works Association, Denver, CO.

Duranceau, S.J., D. Townley, and G.E.C. Bell. 2004. *Optimizing Corrosion Control in Distribution Systems.* AwwaRF Report 90983. Project #2648. American Water Works Association Research Foundation, Denver, CO.

Economic and Engineering Services, Inc., and Illinois State Water Survey. 1990. *Lead Control Strategies.* American Water Works Association Research Foundation and American Water Works Association, Denver, CO.

Edwards, M., and T. Holm. 2001. *Role of Phosphate Inhibitors in Mitigating Lead and Copper Corrosion.* AwwaRF Report 90823 Project #2587. American Water Works Association Research Foundation, Denver, CO.

Edwards, M., and S. Reiber. 1997. *A General Framework for Corrosion Control Based on Utility Experience.* AwwaRF Report 90712A. Project #910. American Water Works Association Research Foundation, Denver, CO.

Estes-Smargiassi, S., J. Steinkrauss, A. Sandvig, and T. Young. 2006. "Impact of lead service line replacement on lead levels at the tap." *Proceedings, AWWA Annual Conference and Exposition*, American Water Works Association. San Antonio, TX.

Kirmeyer, G.J., G. Pierson, J. Clement, A. Sandvig, V. Snoeyink, W. Kriven, and A. Camper. 1999. *Distribution System Water Quality Changes Following Corrosion Control Strategies*. AwwaRF Report 90764. Project #157. American Water Works Association Research Foundation, Denver, CO.

Lytle, D.A., and M.R. Schock. 2005. Formation of Pb(IV) oxides in chlorinated water. *Journal of American Water Works Association* 97(11):102–114.

Schock, M. 1996. Corrosion inhibitor applications in drinking water treatment: Conforming to the Lead and Copper Rule. Presented at *NACE Corrosion 1996 Conference*.

Schock, M.R., and R. Giani. 2004. Oxidant/Disinfectant Chemistry and Impacts on Lead Corrosion. In *Proceedings of AWWA Water Quality Technology Conference*. American Water Works Association, Denver, CO.

Schock, M.R., S.M. Harmon, J. Swertfeger, and R. Lohmann. 2001. "Tetravalent Lead: A Hitherto Unrecognized Control of Tap Water Lead Contamination." *Proceedings, AWWA Water Quality Technology Conference*, American Water Works Association. Denver, CO.

Schock, M.R., I. Wagner, and R. Oliphant. 1996. The Corrosion and Solubility of Lead in Drinking Water. In *Internal Corrosion of Water Distribution Systems*. 2nd edition. AwwaRF and DVGW TZW Cooperative Research Report. AwwaRF Report 90508. Project #725. American Water Works Association Research Foundation, Denver, CO.

USEPA. 1992. *Lead and Copper Rule Guidance Manual, Volume II: Corrosion Control Treatment*. EPA 811-B-92-002. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

USEPA. 2003. *Revised Guidance Manual for Selecting Lead and Copper Control Strategies*. EPA 816-R-03-001. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

USEPA. 2019. *Revised Optimal Corrosion Control Treatment Evaluation Technical Recommendations for Primacy Agencies and Public Water Systems*. EPA 816-B-16-003. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

Glossary

Application point. The precise location within a sequential water treatment process where chemicals are injected or introduced.

Assimilable organic carbon (AOC). The fraction of organic carbon that can be used by specific microorganisms and converted to cell weight. AOC also represents a potential for biological regrowth in distribution systems. Ozone can convert organic matter in water to AOC, whereas biological filtration can reduce the AOC level.

Bicarbonate (HCO_3^-). An inorganic monovalent anion usually found in natural water.

Calcium carbonate ($CaCO_3$). A colorless or white crystalline compound that occurs naturally as chalk, limestone, marble, and other forms. Pure calcium carbonate exists in two distinct crystalline forms: the trigonal solid, calcite; and the orthorhombic solid, aragonite. $CaCO_3$ is a sparingly soluble salt, the solubility of which decreases with increasing temperature. It has the potential to cause scaling if it is concentrated to supersaturation.

Calcium carbonate precipitation potential (CCPP). A theoretical measure of the amount of calcium carbonate ($CaCO_3$) that can precipitate as water equilibrates.

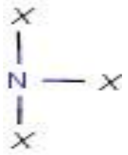
Carbonate passivation. A corrosion control technique that causes pipe materials to create metal/hydroxide/carbonate compounds that form a film on the pipe wall to protect the pipe.

Carbonate precipitation. In the context of corrosion control, the shifting of chemical equilibrium to cause the formation of a solid protective layer of $CaCO_3$ on interior pipe surfaces.

Carbon dioxide (CO_2). A colorless, odorless, incombustible gas that is a normal component of natural waters. It can enter surface water and ground water by absorption from the atmosphere or biological oxidation of organic matter.

Chloramination. The process of disinfecting water with chloramines.

Chloramines. Disinfectants produced from the mixing of chlorine (Cl_2) and ammonia (NH_3). The general formula is NH_xCl_y, where x can be 0, 1, or 2 and y can be 1, 2, or 3. Typically, monochloramine (NH_2Cl) and a small percentage of dichloramine ($NHCl_2$) are formed depending on the pH and the chlorine-to-ammonia ratio that reacts. Under certain circumstances, nitrogen trichloride (trichloramine, NCl_3) can be formed. In the presence of organic nitrogen, organic chloramines can also form; however, they are not considered to be disinfectants.



Chloramines, where one to three of the Xs are chlorine atoms and the rest are hydrogen atoms.

Chloride-to-sulfate mass ratio ($Cl:SO_4$). A water quality index that can reveal the potential for higher levels of lead release through galvanic corrosion of lead–tin solder at copper pipe joints.

Water utilities should guard against inadvertently altering the $Cl:SO_4$ of their water through their coagulant choice.

Coagulation. The process of destabilizing charges on particles in water by adding chemicals (coagulants). Natural particles in water have negative charges that repel other material and thereby keep it in suspension. In coagulation, positively charged chemicals are added to neutralize or destabilize the charges and allow the particles to accumulate and be removed by physical processes such as sedimentation or filtration. Commonly used coagulants include aluminum salts, iron salts, and cationic polymers.

Concentrate or reject water. The concentrated solution containing constituents removed or separated from the feed water by a membrane water treatment system. It is commonly in the form of a continuous flow stream. Concentrate is also called reject, brine, retentate, or blow-down depending on the specific membrane process.

Contact time (T). For disinfection CT calculations, the time in minutes that it takes for water to move from the point of disinfectant application or the previous point of disinfectant residual measurement to the point where residual disinfectant concentration (C) is measured.

Conventional treatment or **Conventional surface water treatment.** The use of coagulation, flocculation, sedimentation, filtration, and disinfection, together as sequential unit processes in surface water treatment.

Corrosion control treatment (CCT). Treatment to minimize the loss of metal from the pipe and/or appurtenance, and the uptake of the metal by the water during delivery to consumers. Two general corrosion control treatment approaches exist: precipitation and passivation. Precipitation involves forming a chemical precipitate in the finished water that deposits onto the pipe wall to create a protective coating. Passivation involves an interaction between the pipe material and the finished water such that metal compounds are formed on the pipe surface, creating a film of less soluble material.

Coupon Study. Study that uses metal pieces (i.e., coupons) of lead, copper, iron, or steel to help determine how specific water treatments may help prevent release of metals from these materials.

Cryptosporidium. A widespread intestinal coccidian protozoan parasite about 3.5 micrometers in diameter that can cause diarrhea and is capable of infecting mammals (including humans), birds, fish, and snakes. It is often responsible for waterborne disease outbreaks.

CT. The product of the residual disinfectant concentration (C) in mg/L determined before or at the first customer, and the corresponding disinfectant contact time (T) in minutes.

Disinfectants and Disinfection Byproducts Rule (DBPR). A national primary drinking water regulation promulgated by the USEPA to regulate drinking water disinfectants and byproducts of disinfection.

Disinfectant residual concentration (C). The concentration of a disinfectant after a given contact time. Under SWTR, primary disinfection credit is based on achieving specified $C \times T$

values, where *C* is the concentration of the disinfectant in milligrams per liter and *T* is the corresponding contact time in minutes.

Disinfection. (1) The process of destroying or inactivating pathogenic organisms (bacteria, viruses, fungi, and protozoa) by either chemical or physical means. (2) In water treatment, the process in which water is exposed to a chemical disinfectant—chlorine (HOCl, OCl^-), chloramines ($NHCl_2$ or NH_2Cl), chlorine dioxide (ClO_2), iodine, or ozone (O_3)—for a specified period to kill pathogenic organisms.

Disinfection benchmarking. The disinfection benchmark is a water system's lowest monthly average log inactivation, and is determined using the data collected weekly for the disinfection profile. To determine the benchmark, the system should first calculate the average log inactivation for each calendar month of the disinfection profile. The monthly average log inactivation is calculated by adding the weekly log inactivation values for a particular month and dividing that value by the number of weekly values for that particular month. The month with the lowest monthly average log inactivation is the benchmark.

Disinfection byproduct (DBP). A chemical byproduct of the disinfection process. DBPs are formed by the reaction of the disinfectant, NOM, and the bromide ion (Br^-). Some DBPs are formed through halogen (e.g., chlorine or bromine) substitution reactions (i.e., halogen-substituted byproducts). Other DBPs are oxidation byproducts of NOM (e.g., aldehydes—RCHO). Concentrations are typically in the microgram per liter or nanogram per liter range.

Disinfection byproduct precursor (DBP precursor). A substance that can be converted into a DBP during disinfection. Typically, most of these precursors are constituents of NOM.

Disinfection profile. A compilation of daily *Giardia* and/or virus log inactivation over a period of one year or more. The IESWTR requires water systems to develop a disinfection profile if they exceed certain DBP levels in their distribution system.

Dissolved inorganic carbon (DIC). An estimate of the amount of total carbonates in the form of carbon dioxide gas or carbonic acid (CO_2 or H_2CO_3, respectively), bicarbonate ion (HCO_3^-), and carbonate ion (CO_3^{2-}) (USEPA 2019).

Dissolved organic carbon (DOC). That portion of the organic carbon in water that passes through a 0.45-micrometer pore-diameter filter. For most drinking water sources, the DOC fraction represents a very high percentage of the TOC pool. It is composed of individual compounds and nonspecific humic material, although humic substances account for a large portion of dissolved organic matter in natural waters. Typically, the DOC level provides some indication of the amount of DBP precursors in a water source. After filtration, DOC is determined in the same manner as TOC. Organic carbon concentrations should be reported as DOC only if the sample has been filtered through a 0.45 micrometer pore-diameter filter before analysis.

Dissolved oxygen (DO). The concentration of oxygen in aqueous solution, often expressed in units of milligrams per liter. It is usually determined by one of two methods: a DO probe or Winkler titration.

Distribution system. A system of conduits (laterals, distributaries, pipes, and their appurtenances) by which a primary water supply is distributed to consumers. The term applies particularly to the network of pipelines in the streets in a domestic water system.

Enhanced coagulation. The addition of excess coagulant for improved removal of DBP precursors by conventional coagulation-sedimentation-filtration treatment. In the DBPR, the removal of TOC is used as a performance indicator for the removal of DBP precursors. The DBPR does not require conversion to optimized coagulation practices, but rather enhancement of an existing process to remove specified levels of TOC on the basis of influent water quality. Enhanced coagulation can also be used to remove arsenic during the coagulation process.

Finished water. Completely treated drinking water at a location immediately upstream of entry into a water distribution system.

Flash mixer/Rapid mixer. A device for quickly dispersing chemicals uniformly throughout a liquid.

Flocculation. The water treatment process following coagulation that uses a slow mixing rate to bring suspended particles together so they form larger, more removable particles called floc.

Free chlorine. The amount of chlorine available as dissolved gas (Cl_2), hypochlorous acid (HOCl) and hypochlorite ion (OCl^-), that is not combined with ammonia (NH_3) or other compounds in water.

Granular activated carbon (GAC). A form of particulate carbon manufactured with increased surface area per unit mass to enhance adsorption of soluble contaminants. GAC is used in fixed-bed contactors in water treatment and is removed and regenerated (reactivated) when the adsorption capacity is exhausted. In some applications GAC can be used to support a biological population for stabilizing biodegradable organic material.

Granular media filtration. A process by which water is filtered through a medium consisting of grains of sand or other granular material.

Ground Water Rule (GWR). A SDWA regulation that establishes a risk-targeted approach to identify PWSs using ground water supplies that are susceptible to fecal contamination. The GWR requires corrective action to address significant deficiencies and source water fecal contamination in public ground water systems.

Ground water under the direct influence of surface water (GWUDI). Water defined by USEPA in the SWTR as any water beneath the surface of the ground that has: (1) significant occurrence of insects or other macroorganisms, algae, organic debris, or large diameter pathogens such as *Giardia lamblia,* or (2) significant and relatively rapid shifts in water characteristics—such as turbidity, temperature, conductivity, or pH—that closely correlate with climatological or surface water conditions. The IESWTR and LT1ESWTR amend the first item of this definition to include *Cryptosporidium*.

Haloacetic acid (HAA). CX_3COOH, where X = chloride or bromide, in various combinations as mono-, di-, or tri-halogenated acetic acids. A class of DBPs formed primarily during the chlorination of water containing NOM. When bromide (Br^-) is present, a total of nine chlorine-, bromine-and-chlorine-, or bromine-substituted species can be formed. THMs and HAAs are the two most prevalent classes of byproducts formed during chlorination and they are subject to regulation under the DBPR.

Haloacetic acid sum (HAA5). The sum of the concentrations, in milligrams per liter, of five HAA compounds: monochloro-, dichloro-, trichloro-, monobromo-, and dibromoacetic acid. The DBPR regulates the sum of these five species; sufficient data were not available on the occurrence and control of the other four HAA species during the rule-making process.

Heterotrophic plate count (HPC). A bacterial enumeration procedure used to estimate bacterial density in an environmental sample, generally water. Other names for the procedure include total plate count, standard plate count, plate count, and aerobic plate count.

Inactivation. The effective treatment technique to achieve the death, injury, or inability of microbial contaminants to infect drinking water.

Langelier Saturation Index (LSI). The most common of the calcium carbonate ($CaCO_3$) saturation indexes. The formula for the LSI is based on a comparison of the measured pH of a water (pH*a*) with the pH the water would have (pH*s*) if at saturation with $CaCO_3$ (calcite form) given the same calcium hardness and alkalinity for both pH cases. Many of the other indexes found in the water treatment and corrosion literature are less accurate.

Lead and Copper Rule (LCR). A rule promulgated by USEPA on June 7, 1991 (*Federal Register*, 56(110):26460-26564) that set National Primary Drinking Water Regulations for lead and copper.

Legionella. A genus of bacteria of the family *Legionellaceae.* It consists of at least 70 distinct serogroups and more than 50 species.

Maximum contaminant level (MCL). A value defined under SDWA section 1401(3) as the maximum permissible level (concentration) of a contaminant in water delivered to any user of a PWS. MCLs are the legally enforced standards in the United States.

Microbial contaminants. Microbiological contaminants of any sort. This is also the definition for microbials.

Microfiltration (MF). A pressure-driven membrane process that separates micrometer-diameter and submicrometer-diameter particles (down to an approximately 0.1-micrometer-diameter size) from a feed stream by using a sieving mechanism. The smallest particle size removed is dependent on the pore size rating of the membrane.

Monochloramine (NH_2Cl). A chloramine species produced from the mixing of chlorine (in the form of hypochlorous acid, HOCl) and ammonia (NH_3). Typically, monochloramine and a small percentage of dichloramine ($NHCl_2$) are formed. Monochloramine is used as a disinfectant, especially for distribution system residual maintenance.

Nanofiltration (NF). A pressure-driven membrane separation process that generally removes substances in the nanometer size range. Its separation capability is controlled by the diffusion rate of solutes through a membrane barrier and by sieving and is dependent on the membrane type. In potable water treatment, NF is typically used to remove nonvolatile organics larger than the 200–500-dalton molecular weight cutoff (e.g., natural and synthetic organics, color, DBP precursors) and multivalent inorganics (for softening).

National Pollutant Discharge Elimination System (NPDES) Permit. The regulatory agency document issued by either a federal or state agency that is designed to control all discharges of pollutants from point sources into United States waterways. The permits regulate discharges into navigable waters from all point sources of pollution including industries, municipal WWTPs, sanitary landfills, large agricultural feedlots, and return irrigation flows.

Natural organic material (NOM). A heterogeneous mixture of organic matter that occurs ubiquitously in both surface water and ground water, although its magnitude and character differ from source to source. NOM contributes to the color of a water and could also represent DBP precursors in the presence of such disinfectants as chlorine. Humic substances (e.g., fulvic acid) represent a significant fraction of NOM in surface water sources.

Nephelometric turbidity unit (NTU). A unit for expressing the cloudiness (turbidity) of a sample as measured by light scattering using a nephelometric turbidimeter.

Nitrification. The process of formation of nitrate (NO_3^-) from reduced inorganic nitrogen compounds. Nitrification in the environment is carried out primarily by autotrophic bacteria and some chemoorganotrophic bacteria.

Operation and maintenance (O&M). The ongoing process of carrying out activities necessary to fulfill the mission of an organization and to keep a system in such condition as to be able to achieve those objectives. Operations represent organized procedures for enabling a system to perform its intended function; maintenance represents organized procedures for keeping the system (equipment, plants, facilities) in such condition that it is able to continue performing its intended function.

Optimal corrosion control treatment (OCCT). For the purposes of the LCR, the treatment that minimizes the lead and copper levels at users' taps while ensuring that the treatment does not cause the water system to violate any national drinking water regulations.

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

Oxidation-reduction potential (ORP, pE). The potential required to transfer electrons from oxidant to reductant, or a qualitative measure of the state of oxidation in treatment systems. The more positive the value the more oxidizing the solution. More negative values represent more reducing conditions.

Pathogen. An organism capable of causing infection or infectious disease.

Pipe Loop Testing. Pipe loops consist of pipes or pipe sections made of a variety of materials, including lead pipe (new or excavated); copper pipe; copper pipe with lead soldered joints; or brass components (faucets or meters). Pipe loop testing is used to evaluate the ability of corrosion control treatments to reduce the presence of metals in drinking water.

Polyaluminum chloride (PACl). A hydrolyzed form of aluminum chloride ($AlCl_3$) that is used for coagulation, typically in low-turbidity waters. As a result of its polymeric form lower dosages can be used compared to metal coagulants.

Powdered activated carbon (PAC). Activated carbon composed of fine particles and providing a large surface area for adsorption. PAC is typically added as a slurry on an intermittent or continuous basis to remove taste- and odor-causing compounds or trace organic contaminants and is not reused.

Prechlorination. Chlorination of source water before other unit processes (e.g., before coagulation). The location where the chlorine (Cl_2) is added should be specified to avoid confusion, e.g., source water chlorination, pre-filtration chlorination.

Precipitative softening. A unit process by which the dissolved minerals in water, particularly calcium and magnesium are removed during lime or lime-soda ash softening through deliberate formation of a precipitate. Precipitative softening can be used for the removal of DBP precursors (i.e., TOC or NOM), a process referred to as enhanced softening.

Precursor. A compound or mixture that can be converted to a specific substance. For example, upon disinfection DBP precursors are converted to DBP.

Primacy agency. The agency that has the primary responsibility for administering and enforcing federal regulations.

Primary disinfection. A regulatory-defined treatment technique to protect consumers against the adverse health effects from exposure to *Giardia lamblia*, *Cryptosporidium*, viruses, *Legionella,* and heterotrophic bacteria in drinking water. The SWTR and LT2ESWTR establish microbial inactivation and removal requirements for primary disinfection, depending upon site-specific source and treatment conditions.

Public water system (PWS). As defined in section 1401(4) of SDWA, this is a system for providing to the public water for human consumption through pipes or other constructed conveyances.

Publicly-owned treatment works (POTW). A wastewater treatment facility owned by a municipality or local government authority.

Radionuclides. A material with an unstable atomic nucleus that spontaneously decays or disintegrates, producing radiation.

Raw water. The untreated source of supply for a public or private water utility. Raw water is usually treated before distribution to consumers, although some ground water is of such a quality that it can be distributed untreated.

Residuals. Any gaseous, liquid, or solid byproduct of a treatment process that ultimately must be disposed of. Solid residuals are often referred to as *sludge*. For example, in conventional treatment, floc particles that settle in sedimentation basins, filter backwash water, and solids in the backwash water are all considered to be residuals. These residuals differ from disinfectant residuals (see “disinfectant residual concentration” above).

Reverse osmosis (RO). A pressure-driven membrane separation process that removes ions, salts, and other dissolved solids and nonvolatile organics. The separation capability of the process is controlled by the diffusion rate of solutes through a membrane barrier and by sieving and is dependent on the membrane type. In potable water treatment, RO is typically used for desalting, specific ion removal, and natural and synthetic organics removal. It is no longer commonly called hyperfiltration.

Revised Total Coliform Rule (RTCR). USEPA rulemaking that sets an MCL for *E. coli* and uses *E. coli* and total coliforms to initiate a "find and fix" approach to address fecal contamination that could enter into the distribution system. The rule was promulgated February 13, 2013, (78 *Federal Register* 10269).

Safe Drinking Water Act (SDWA). Public Law 93-523, enacted December 16, 1974, establishing Title XIV of the U.S. Public Health Service Act, codified generally as 42 U.S.C. 300f-300j -11. It required USEPA to set national primary (health-related) drinking water regulations that were the first to apply to all public water systems, as defined by the act, in the United States.

Secondary disinfection. The practice of maintaining a free chlorine or monochloramine residual in a water distribution system to protect against microbial contamination.

Simultaneous compliance. The comprehensive assessment and implementation of processes and practices that promote compliance with all SDWA regulations. Without careful planning and proper implementation, actions intended to improve one aspect of regulatory compliance can produce conflicts (or at least pose challenges) in other areas of water quality performance.

Source water. The supply of water for a water utility. Source water is usually treated before distribution to consumers, but some ground waters are of such a quality that they can be distributed untreated.

Specific ultraviolet absorbance (SUVA). The ultraviolet absorbance at 254 nanometers (measured in units of per meter) divided by the DOC concentration (in milligrams per liter). Typically, a SUVA less than 3 liters per meter-milligram corresponds to largely non-humic material, whereas a SUVA in the range of 4–5 liters per meter-milligram corresponds to mainly humic material. Because humic materials are more easily removed through coagulation than non-humic substances, higher SUVA values should indicate a water that is more amenable to enhanced coagulation.

Supervisory Control and Data Acquisition (SCADA). A computer monitored alarm, response, control, and data acquisition system used by drinking water facilities to monitor their operations.

Surface Water Treatment Rule (SWTR). The common name for the USEPA regulation first promulgated June 29, 1989, that sets maximum contaminant level goals for *Giardia lamblia*, viruses, and *Legionella*, as well as National Primary Drinking Water Regulations for PWSs using surface water sources or ground water under the direct influence of surface water. The regulation includes (1) criteria under which filtration (including coagulation and sedimentation, as appropriate) are required and procedures by which the states are to determine which systems must install filtration and (2) disinfection requirements.

Synthetic organic chemicals (SOC). An organic compound that is commercially made. Some SOCs are contaminants in drinking water and are regulated by USEPA. The regulated SOCs include pesticides, herbicides, polychlorinated biphenyls, and polynuclear aromatic hydrocarbons.

Synthetic organic polyelectrolytes. Often referred to as a "polymer." A class of commercially produced organic treatment chemicals commonly used in water treatment as coagulants or coagulant aids, or to enhance settling and thickening of solids.

Total dissolved solids (TDS). The weight per unit volume of solids remaining after a sample has been filtered to remove suspended and colloidal solids. The solids passing the filter are evaporated to dryness. The filter pore diameter and evaporation temperature are frequently specified.

Total organic carbon (TOC). A measure of the concentration of organic carbon in water, determined by oxidation of the organic matter into carbon dioxide (CO_2). TOC includes all the carbon atoms covalently bonded in organic molecules. Most of the organic carbon in drinking water supplies is DOC, with the remainder referred to as particulate organic carbon. In natural waters TOC is composed primarily of nonspecific humic materials. TOC is used as a surrogate measurement for DBP precursors, although only a small fraction of the organic carbon reacts to form these byproducts.

Total trihalomethanes (TTHM). The sum of the four chlorine- and bromine-containing trihalomethanes (i.e., chloroform, bromodichloromethane, dibromochloromethane, and bromoform). USEPA regulates the sum of these four species on a weight-concentration basis.

Trihalomethane (THM). Any of numerous organic compounds named as derivatives of methane (CH_4) in which the three halogen atoms (chlorine, bromine, iodine, singly or in combination) are substituted for three of the hydrogen atoms. THMs are formed during the disinfection of water with free chlorine. Because of their carcinogenic potential and other possible health effects, these compounds are regulated by USEPA.

Trihalomethane formation potential (THMFP). The amount of THMs formed during a test in which a source or treated water is (1) dosed with a relatively high amount of disinfectant (normally chlorine) to produce a residual at the end of the test of about 3 milligrams per liter and (2) incubated or stored under conditions that maximize THM production (e.g., neutral to alkaline pH, warm water temperature, contact time of 4 to 7 days). This value is not a measure of the amount of THMs that would form under normal drinking water treatment conditions, but rather an indirect measure of the amount of THM precursors in a sample.

Ultrafiltration (UF). A pressure-driven membrane process that separates submicron particles (down to 0.01-micrometer size or less) and dissolved solutes (down to a molecular weight cutoff of approximately 1,000 daltons) from a feed stream by using a sieving mechanism that is dependent on the pore size rating of the membrane.

Ultraviolet light (UV). Radiation having a wavelength shorter than 390 nanometers (the shortest wavelength of visible light) and longer than 10 nanometers (the longest wavelength of x-rays). UV can be used as a disinfectant or in combination with chemical oxidants to create more broadly reactive hydroxyl radicals (OH-).

Unintended consequences. Actions intended to improve one aspect of regulatory compliance, which produce conflicts (or at least pose challenges) in other areas of water quality performance.

Volatile organic compounds (VOC). A class of organic compounds that includes gases and volatile liquids. Many VOCs are used as solvents. A number of these compounds are regulated by USEPA.

References

40 CFR 141. *National Primary Drinking Water Regulations*. United States Environmental Protection Agency, Washington DC.

AWWA. 2001. *The Drinking Water Dictionary*. McGraw-Hill, New York.

USEPA. 2019. *Revised Optimal Corrosion Control Treatment Evaluation Technical Recommendations for Primacy Agencies and Public Water Systems*. EPA 816-B-16-003. United States Environmental Protection Agency, Office of Water, Washington DC.