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Environmental Protection
Agency

Optimal Corrosion Control Treatment Evaluation Technical Recommendations for Primacy Agencies and Public Water Systems

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Disclaimer

This document provides technical recommendations to primacy agencies and public water systems (PWSs) in determining the most appropriate treatment for controlling lead and copper and complying with the corrosion control treatment (CCT) requirements of the Lead and Copper Rule (LCR) that are in place at the time of document publication.

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Acronyms

AL	Action Level
ANSI	American National Standards Institute
AWWA	American Water Works Association
CCPP	Calcium Carbonate Precipitation Potential
CCT	Corrosion Control Treatment
COC	Chain of Custody
CSMR	Chloride-to-Sulfate Mass Ratio
CWS	Community Water System
DBP	Disinfection Byproduct
DBPR	Disinfection Byproducts Rule
DIC	Dissolved Inorganic Carbon
DO	Dissolved Oxygen
EDS	Energy Dispersive Spectroscopy
EMF	Electromotive Force
EPA	Environmental Protection Agency
HAA5	Haloacetic Acids
ICP-MS	Inductively Coupled Plasma Mass Spectroscopy
LCR	Lead and Copper Rule
LSI	Langelier Saturation Index
LSL	Lead Service Line
LT2ESWTR	Long Term 2 Enhanced Surface Water Treatment Rule
MCLG	Maximum Contaminant Level Goal
MDBPR	Microbial and Disinfection Byproducts Rules
NDWAC	National Drinking Water Advisory Council
NOM	Natural Organic Matter

NPDWR	National Primary Drinking Water Regulations
NSF	NSF International
NTNCWS	Non-transient, Non-Community Water System
OCCT	Optimal Corrosion Control Treatment
ORP	Oxidation-Reduction Potential
OWQP	Optimal Water Quality Parameter
POU	Point-of-use
PWS	Public Water System
RLDWA	The Reduction of Lead in Drinking Water Act of 2011
SDWA	Safe Drinking Water Act
SMCL	Secondary Maximum Contaminant Level
TDS	Total Dissolved Solids
TTHM	Total Trihalomethanes
VOC	Volatile Organic Compound
WQP	Water Quality Parameter
WRF	Water Research Foundation
WWTP	Wastewater Treatment Plant

Chapter 1: Introduction

1.1 Purpose and Audience

The purpose of this document is to provide technical recommendations to help primacy agencies and systems comply with corrosion control treatment (CCT) requirements of the Lead and Copper Rule (LCR), including designation of optimal corrosion control treatment (OCCT).[1] This document summarizes the regulatory requirements, and provides technical recommendations that can assist systems in complying with CCT steps and assist primacy agencies with evaluation of technical information from systems. It also includes background information on corrosion and CCT techniques. This document provides Excel-based ***OCCT Evaluation Templates*** that can be used to organize data and document decisions.

The technical recommendations provided in this document are consistent with previously published corrosion control guidance (USEPA, 1992a; USEPA, 1997; and USEPA, 2003). It is not intended to supersede prior guidance; those resources continue to provide technical information that may be relevant to, and further inform, decision-making. Instead, this document is intended to serve as an added resource, offering supplemental information gleaned from recent developments in the drinking water industry's understanding of lead and copper release and control. This includes:

- Influence of oxidation-reduction potential (ORP) on lead and copper release, and importance of Pb(IV) compounds for systems with lead service lines (LSLs).
- Importance of aluminum, manganese, and other metals on formation of lead scales and lead release.
- Impact of physical disturbances on lead release.
- Mechanisms and limitations of using blended phosphates for corrosion control.
- Target water quality parameters (WQPs) for controlling copper corrosion.
- Impacts of treatment changes, particularly disinfectant changes, on corrosion and corrosion control.

EPA recognizes that research is ongoing, and that the water industry's understanding of corrosion, metals release, and treatment strategies will continue to evolve. EPA will update this document periodically as new information becomes available and as time and resources allow.

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[1] Note that for the purposes of this document, "optimal corrosion control treatment" or "OCCT" is only used when referring to the requirement in section 141.80(d) of the existing LCR for primacy agencies to designate optimal corrosion control treatment. Section 141.2 defines optimal corrosion control treatment as "the 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." The terms "optimal" or "optimized" may also be used in the manual to indicate the best conditions for preventing lead and copper from leaching into water.

1.2 Document Organization

The remainder of this document is organized as follows:

Chapter 2: Background Information provides a history of regulatory actions to reduce lead and copper exposure from drinking water, including efforts since the 1986 Safe Drinking Water Act (SDWA) Amendments to limit the amount of lead in plumbing materials. It also describes the sources of lead in water, including an overview of lead and copper corrosion and release mechanisms, and relative contribution of lead- and copper-containing materials. Lastly, this chapter provides an updated description of water quality and physical factors that influence lead and copper levels in drinking water.

Chapter 3: Corrosion Control Treatment for Lead and Copper describes the available CCT methods and provides approaches that can be used to identify CCT alternatives. The chapter also provides technical recommendations on setting treatment dose and water quality conditions.

Chapter 4: Corrosion Control Treatment Steps under the LCR reviews the CCT requirements under the LCR and provides additional technical recommendations for primacy agencies and systems to consider when meeting these requirements.

Chapter 5: OCCT Start-Up and Monitoring provides technical recommendations on CCT start-up, reviews requirements under the LCR and technical recommendations for follow-up monitoring during the first year of CCT implementation, reviews requirements for establishing optimal water quality parameters (OWQPs) under the LCR, and reviews LCR-required WQP and technical recommendations for additional corrosion control monitoring.

Chapter 6: Impacts of Source Water and Treatment Changes on Lead and Copper in Drinking Water reviews the requirements in the LCR for notification and approval of a source or treatment change. The chapter also provides technical information on how source and treatment changes can affect lead and copper release.

Chapter 7: References provides a full list of references that were used in the development of this document.

These chapters are supported by several appendices:

Appendix A provides a glossary of corrosion terms.

Appendix B provides a lookup table for systems to determine dissolved inorganic carbon (DIC) based on pH and alkalinity.

Appendix C provides technical recommendations on how to conduct investigative sampling and construct lead profiles to help identify the sources of lead and copper in a building water system.

Appendix D provides blank forms for data collection to support a system's OCCT recommendation and/or the corrosion control study.

Appendix E provides blank forms for systems to support OCCT recommendations to their primacy agencies.

Appendix F summarizes desktop and demonstration tools that can be used by systems when conducting a corrosion control study.

Appendix G provides blank forms for systems and technical recommendations for primacy agencies when reviewing system data and designating OWQPs.

1.3 How to Use this Document

Primacy agencies and systems can use the material in Chapters 2 and 3 as a technical reference to help understand corrosion and CCT and to evaluate CCT alternatives. Tools such as the flowcharts in Chapter 3 are intended for screening and are not meant to serve as substitutes for pilot studies and other site-specific investigations. Chapters 4 and 5 provide a review of the LCR regulatory requirements and provide additional technical recommendations to support primacy agencies and systems when a system serving 50,000 or fewer people exceeds the lead or copper action level (AL), or if a system increases its population to more than 50,000 and is subject to the CCT requirements of the LCR for the first time. Chapters 4 and 5 can also be useful for systems serving more than 50,000 people that previously installed CCT but have subsequent AL exceedances. Primacy agencies and systems can use the information in Chapter 6 to review the regulatory requirements related to notification and approval of a source or treatment change. They can also use the technical information in this chapter to determine how treatment changes could impact lead and copper release.

The Excel-based ***OCCT evaluation templates*** mirror the steps and tables in Chapters 4 and 5 and Appendices D through G. Primacy agencies can use the templates to document circumstances around an AL exceedance and review compliance deadlines for individual systems. They can also use the templates to support determinations of whether or not to require a CCT study, what kind of study to require, and to document their decisions. The templates provide electronic versions of the forms in Appendices D through G. Systems can use the forms to organize their data and information electronically and prepare submittals to their primacy agencies.

Chapter 2: Background Information

This chapter provides information on:

- Regulations to control lead and copper in drinking water;
- Sources of lead and copper;
- Water quality characteristics that impact corrosion of lead and copper and release of these metals into the water; and
- Physical and hydraulic characteristics of water systems that impact lead and copper release.

2.1 Regulatory Actions to Control Lead and Copper in Drinking Water

2.1.1 Lead and Copper Regulation

The national primary drinking water regulation that controls lead and copper in drinking water is the 1991 Lead and Copper Rule (LCR) (USEPA, 1991b), as amended. In the 1991 rulemaking, the Environmental Protection Agency (EPA) established maximum contaminant level goals (MCLGs) (zero for lead and 1.3 milligrams per liter (mg/L) for copper) and action levels (0.015 mg/L for lead and 1.3 mg/L for copper) in public water systems (PWSs). (See Exhibit 2.1 for a timeline of lead and copper regulations and related regulatory activities.) The lead or copper action level is exceeded if the concentration in more than 10 percent of water samples (i.e., the 90th percentile level) collected after a minimum stagnation period of 6 hours is greater than the respective action level. Samples from residences must be collected from cold water kitchen or bath taps and those collected from non-residential areas must be collected from interior taps (§141.86(b)(2)).[2] The number of samples to be collected depends on the size of the water system, as specified in the regulation. The 1991 LCR also established requirements that are triggered, in some instances, by exceedances of the action levels. These additional requirements include the installation and maintenance of corrosion control treatment (CCT) and source water monitoring/treatment, lead public education, and lead service line (LSL) replacement.

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[2] Unless otherwise stated, all citations are in Title 40 of the Code of Federal Regulations (CFR).

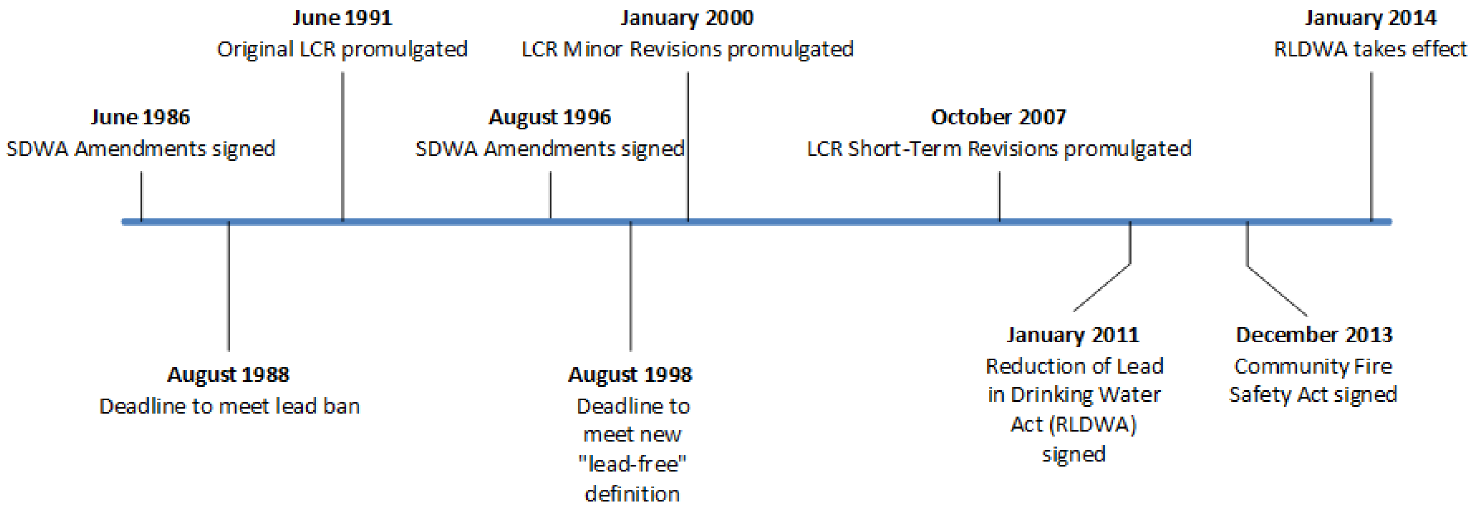

Exhibit 2.1: Timeline of Regulatory Actions Related to Lead and Copper

After the June 1991 LCR, EPA promulgated several technical amendments (USEPA, 1991c; USEPA, 1992b; USEPA, 1994; USEPA, 2004a) as well as more extensive revisions in January 2000 and October 2007 (USEPA, 2000; USEPA, 2007a). The goal of the January 2000 LCR Minor Revisions was to streamline requirements, promote consistent national implementation, and, in many cases, reduce monitoring and reporting requirements (USEPA, 2000). The goal of the 2007 LCR Short-Term Revisions was to enhance the implementation of the LCR in the areas of monitoring, treatment, consumer awareness, and LSL replacement, as well as to improve compliance with the public education requirements of the LCR (USEPA, 2007a).

2.1.2 Control of Lead Content in Plumbing Components

While the LCR regulates the amount of lead and copper in drinking water, the Safe Drinking Water Act (SDWA) also includes provisions aimed at reducing the amount of lead in plumbing components, which could result in lower lead levels in tap samples in the future. This section discusses key changes in SDWA to reduce lead in plumbing components. For additional information, see the references and web links provided herein.

The 1986 SDWA Amendments established requirements to minimize the lead content in source materials that are used in the conveyance and treatment of drinking water. Section 1417 of the 1986 SDWA Amendments banned the use of lead pipe and required the use of "*lead-free*" solders, fluxes, pipes and pipe fittings in the installation or repair of PWSs (also referred to as the "lead ban") (USEPA, 1987). Lead-free materials were defined as:

- Solders and fluxes with a lead content of ≤ 0.2 percent.
- Pipes and pipe fittings with a lead content of ≤ 8.0 percent.

The 1996 SDWA Amendments made it unlawful for anyone to introduce into commerce pipes, pipe or plumbing fittings or fixtures that are not lead free. The 1996 Amendments also required certain plumbing fittings and fixtures (endpoint devices) to be in compliance with a performance standard for lead release for plumbing fittings and fixtures.[3] This standard was satisfied by NSF International/American National Standards Institute (NSF/ANSI) Standard 61, Section 9,[4] which limited the amount of lead that can be leached from endpoint devices used for water intended for human consumption. After August 6, 1998, only those plumbing fittings and fixtures with a lead content of ≤ 8.0 percent that were in compliance with NSF/ANSI Standard 61, Section 9 by an ANSI-accredited certifier could be defined as *"lead-free"* (NSF, 2010).[5]

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[3] For a summary of the 1996 Amendments revisions to the lead ban, refer to Section 118. www.congress.gov/bill/104th-congress/senate-bill/1316.

[4] Devices specifically listed in NSF Standard 61, Section 9 include kitchen and bar faucets, lavatory faucets, water dispensers, drinking fountains, water coolers, glass fillers, residential refrigerator ice makers, supply stops and endpoint control valves. Devices that were not covered by section 9 of NSF 61 were not subject to the NSF performance-based standard, but if they were covered by Section 1417, they were subject to the 8.0 percent lead limit.

[5] This commerce restriction does not apply to pipes used for manufacturing and industrial processing.

Plumbing materials meeting the lead-free definition of ≤ 8.0 percent lead were still found to contribute to lead levels measured at the tap (Sandvig et al., 2008). Thus, efforts to reduce the lead content of materials continued, notably in the States of California, Maryland, Massachusetts, and Vermont. In response, manufacturers developed non-leaded alloys containing very low levels of lead (less than 0.25 percent lead) that can be used in the manufacture of brass faucets, meters, and fittings. Many utilities have also developed their own specifications for non-leaded components (Sandvig et al., 2007).

In 2011, The Reduction of Lead in Drinking Water Act of 2011 (RLDWA) revised Section 1417 to:

(1) Redefine "*lead-free*" in SDWA Section 1417(d) to:
  - Lower the maximum lead content of the wetted surfaces of plumbing products such as pipes, pipe fittings, plumbing fittings and fixtures from 8.0% to a weighted average of 0.25%;
  - Establish a statutory method for the calculation of lead content; and
  - Eliminate the requirement that lead-free products be in compliance with voluntary standards established in accordance with SDWA 1417(e) for leaching of lead from new plumbing fittings and fixtures.

(2) Create exemptions in SDWA Section 1417(a)(4) from the prohibitions on the use or introduction into commerce for:
  - Pipes, fittings and fixtures that are used exclusively for non-potable services where the water is not anticipated to be used for human consumption (SDWA 1417(a)(4)(A)); and
  - "toilets, bidets, urinals, fill valves, flushometer valves, tub fillers, shower valves, service saddles, or water distribution main gate valves that are 2 inches in diameter or larger." (SDWA 1417(a)(4)(B)).

A subsequent Act, The Community Fire Safety Act of 2013, signed on December 20, 2013, exempted fire hydrants from the new lead-free standard, and required EPA to consult with the National Drinking Water Advisory Council (NDWAC) on lead-free issues. Both The RLDWA and Community Fire Safety Act became effective on January 4, 2014. EPA has published a "Summary of The Reduction of Lead in Drinking Water Act and Frequently Asked Questions" that describes both of these Acts in more detail (USEPA, 2013).[6] On January 17, 2017, EPA issued a proposed rule to amend EPA's current regulations and reflect the changes to Section 1417 of SDWA as a result of the RLDWA.

Although the SDWA no longer requires third-party certification, some state or local laws require third-party certification. In addition, third-party certification bodies or agencies may be used by manufacturers to inform consumers which products meet a voluntary standard. One such standard, NSF/ANSI 372 is consistent with the requirements of the RLDWA. A third-party

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[6] This document is available at http://nepis.epa.gov/Exe/ZyPDF.cgi/P100M5DB.PDF?Dockey=P100M5DB.PDF.

certification against this standard could be a useful way to identify a product as meeting the requirements of Section 1417. Products will bear the mark of the laboratory that has independently certified the product as meeting the standard. EPA published a brochure to help the public identify the various marks that indicate a product has been certified as lead-free to satisfy the new requirement of the Act: "How to Identify Lead-Free Certification Marks for Drinking Water System & Plumbing Materials" (USEPA, 2015a).[7] EPA also recommends that PWSs incorporate this NSF/ANSI standard into their contract specifications for materials installed in their treatment and distribution systems, and to encourage their consumers to purchase certified products.

2.2 Sources of Lead and Copper

Lead and copper are rarely present in raw water sources. They are primarily present at the customer's tap due to corrosion of lead and copper-based material. This section:

- Provides an overview of chemical and physical reactions that result in lead and copper release into drinking water (Section 2.2.1); and
- Discusses the relative contribution from supply lines and premise plumbing components (Section 2.2.2).

2.2.1 Corrosion and Metals Release

Corrosion in water systems is defined as the electrochemical interaction between a metal surface such as pipe wall or solder and water. During this interaction, metal is oxidized and transferred to the water or to another location on the surface as a metal ion. Depending on the material there are many forms of corrosion, but usually the most important for drinking water are: (1) uniform corrosion, where the electrochemical interaction occurs along the pipe wall, resulting in a relatively uniform loss of metal across the entire surface; (2) non-uniform corrosion, where metal is lost from a localized point, causing pitting and mounding in some cases; and (3) galvanic corrosion which comes from a coupling of dissimilar metals or internally in metallic alloys. While it is important to understand and control corrosion, the LCR is specifically concerned with controlling ***metals release*** (i.e., release of lead and copper) into the water. Metals release is a function of the reactions that occur between the metal ions released due to corrosion, and the physical, chemical, and biological characteristics of the water and the metal surface.

The form of lead and copper released into the water can be dissolved, colloidal, or particulate (i.e., bound up with other compounds such as iron and aluminum). Of great importance is the ***scale*** that builds up naturally on the metal surface. Pipe scales can be complex and can include two types of compounds: (1) passivating films that form when pipe material and water react directly with each other; and (2) deposited scale material that forms when substances in the water (e.g., iron, manganese, aluminum, calcium) precipitate out or sorb to, and then build up

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[7] This document is available at http://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100LVYK.pdf.

on the pipe surface. Scales can have layers and are influenced by treatment history. The structure and compounds in the existing corrosion scale can influence the effectiveness of CCT.

Researchers have identified many different compounds on lead pipe scales depending on water quality and treatment history:

- In the absence of corrosion inhibitors, lead pipe scales are frequently dominated by compounds that result from the reaction of carbonate and divalent lead compounds (Pb^{++} or Pb(II)),[8] such as hydrocerussite [($Pb_3(CO_3)_2(OH)_2$] and cerussite ($PbCO_3$) (Schock and Lytle, 2011). Plumbonacrite ($Pb_{10}(CO_3)_6(OH)_6O$) has been found to co-occur with Pb(II) carbonate compounds in scales and can be a predominant form in systems with high pH (>10) (DeSantis and Schock, 2014). Lead pipe scales may also include massicot and litharge (which are both forms of PbO) under higher alkalinity conditions (McNeill and Edwards, 2004). Carbonate containing scales are often off-white and slightly chalky when dry (Schock and Lytle, 2011).

- Newer research has confirmed that Pb(IV) compounds, i.e., lead oxide (PbO_2),[9] can be the predominant compounds in lead pipe scales under highly oxidative conditions[10] and under low organic matter conditions (Schock, 2007b; Schock, 2001; Schock and Giani, 2004; DeSantis and Schock, 2014).

- When orthophosphate is used, lead pipe scales are often dominated by crystalline Pb(II) orthophosphate compounds such as hydroxypyromorphite, $Pb_9(PO_4)_6$, or $Pb_3(PO_4)_2$. Scales in systems with blended phosphates do not follow the same trends as orthophosphate and seem to be influenced by calcium concentrations and phosphorus speciation (DeSantis and Schock, 2014).

Copper-based scales usually include cuprite (Cu_2O), cupric hydroxide ($Cu(OH)_2$), tenorite (CuO), and malachite ($Cu_2(OH)_2CO_3$). When orthophosphate is used, various copper phosphate scales may develop (Schock and Sandvig, 2006; Schock and Lytle, 2011)).

The characteristics of the scale and its structure dictate the amount of lead or copper that is released into the water. If conditions favor the formation of insoluble, adherent scale (i.e., scale that adheres well to the pipe wall), the rate of metals release will be low. However, if scales do not adhere well to the pipe wall or they are very soluble, the release of metals may be greater. Other compounds in the water including aluminum, iron, manganese, and calcium can significantly influence scale formation and properties. The type of scale will also dictate how

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[8] Pb^{++}, Pb(II), or divalent lead is the ionic form of lead that is transferred from the material to the water during the corrosion process.

[9] Pb^{++++}, Pb(IV), or tetravalent lead is an ionic form of lead that forms lead oxide (PbO_2), the only Pb(IV) compound that has been identified in lead pipe scales. Throughout this manual, Pb(IV) and PbO_2 are used interchangeably.

[10] For example, systems that have a free chlorine residual of 2 mg/L or greater. See Section 2.3 for more information on how disinfection affects ORP of the water and how this affects the types of lead compounds in the scale.

susceptible it is to releasing particulate lead following physical disturbances (e.g., infrastructure work).

2.2.2 Lead and Copper-Containing Material

The main sources of lead and copper in drinking water are the materials used for supply pipes from the water main to the building (also called "service lines") and premise plumbing. These include lead and copper pipe, lead-based solder, and brass materials used in faucets and fittings.[11] Exhibit 2.2 shows plumbing components that may be potential sources of lead.[12]

Researchers have performed various studies to identify the relative contribution of these materials to lead and/or copper levels measured at the tap in standing samples (Gardels and Sorg, 1989; Lytle and Schock, 1996; Kimbrough, 2001; Kimbrough, 2007; Sandvig et al., 2008; Kimbrough, 2009). They have found that LSLs contribute a significant percentage of the lead in samples collected at the tap (under normal household usage conditions), and that brass may also be a significant source of lead and copper depending on the quality of the drinking water and the composition of and manufacturing process for the brass faucet or fitting. There are, however, many different types of alloys used in brass faucets and fittings. Each may react differently under different water qualities and chemistries, as well as water use patterns, which makes it difficult to identify specific brass components that might cause problems with respect to lead and/or copper release in any given PWS. Appendix C provides methods for diagnostic monitoring that can help pinpoint the source of lead for a specific building.

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[11] Prior to the 1986 SDWA Amendments, 50:50 lead:tin solder could be used for potable applications. Brass alloys comprised of various amounts of copper and lead are used to manufacture pipes, pipe fittings, plumbing fittings, and fixtures (e.g., faucets and meters). As discussed in Section 2.1.2, the RLDWA of 2011 further limits the allowable lead content of these materials.

[12] Although the water utility often owns the portion of the supply pipe from the water main to the property boundary, the homeowner generally owns the portion from the property boundary or meter to the home and is responsible for premise plumbing. This makes lead and copper unique contaminants in that their source is under the control of the individual customer (except in the case of the portion of a LSL owned by the water utility).

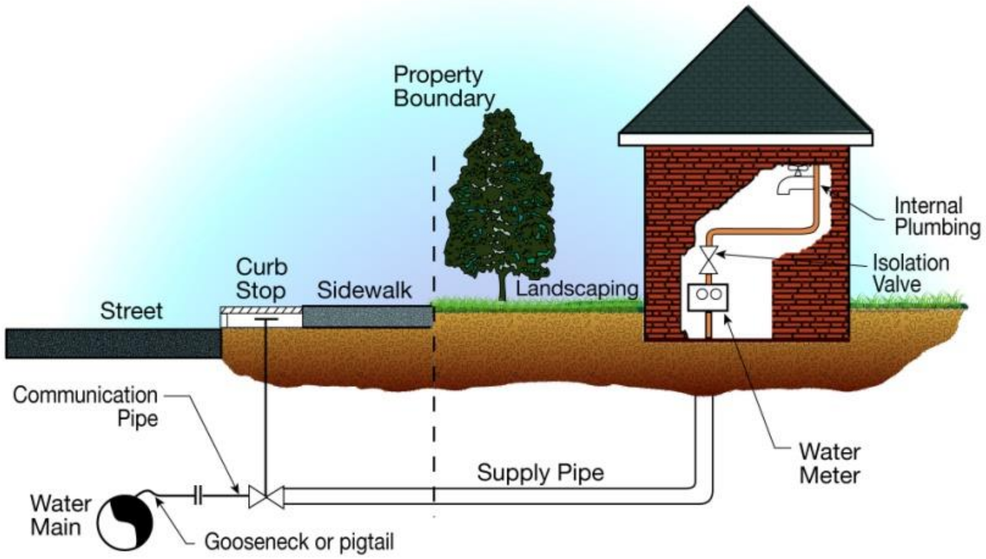

Exhibit 2.2: Typical Water Service Connection that May Provide Sources of Lead (Sandvig et al., 2008)

Copper pipe may be used for both the supply pipe (service line) and the interior piping. Brass fixtures typically are 60 – 90 % copper by weight. Copper release depends on water quality conditions (particularly pH, dissolved inorganic carbon (DIC), and oxidation-reduction potential (ORP)), the age of the copper pipe, and how long the water has been in contact with the pipe. Copper release is typically higher in newer copper plumbing (Cantor et al., 2000; Kimbrough, 2007; Schock and Lytle, 2011). The amount of time required for copper pipes to passivate (i.e., no longer release copper into the water) is highly dependent on water quality, particularly pH, alkalinity, and DIC.

New research has shown that iron and manganese can adsorb other metals such as lead. McFadden et al. (2011) showed that lead released from LSLs was adsorbed onto galvanized iron pipe in homes. Another study showed that iron- and manganese- rich scale provided a source of lead for more than four years after LSLs were fully removed (Schock, Cantor, et al., 2014). Thus, lead released “upstream” (e.g., from an LSL) can accumulate in these scales, providing a long-term source of lead even after LSLs and other lead-containing materials are removed. Residual aluminum in the finished water from the coagulation treatment step can also affect the type and stability of scales formed within LSLs (Schock, 2007b).

2.3 Water Quality Factors Affecting Release of Lead and Copper

New research conducted in recent years has continued to show the influence and importance of water quality on lead and copper levels in drinking water. Water quality can affect the rate of corrosion of lead and copper materials, the formation and characteristics of scales that form on lead and copper based materials, and ultimately, the release of metals into the water. New findings have shed light on the effects on lead and copper levels of natural organic matter (NOM) and metals including iron, aluminum, and manganese. Alkalinity, pH, DIC, and corrosion inhibitors remain critical parameters that directly impact lead release. In addition, new research has shown the importance of ORP in certain types of waters.

Understanding the water quality conditions that impact the release of lead and copper in drinking water provides a foundation for making effective treatment decisions. This section describes the following parameters, how they can be measured or approximated, and how they can affect lead and copper release in drinking water:

- Alkalinity, pH, and DIC.
- Corrosion inhibitors.
- Hardness (calcium and magnesium).
- Buffer Intensity.
- Dissolved oxygen (DO).
- Oxidation reduction potential (ORP).
- Ammonia, chloride, and sulfate.
- Natural organic matter (NOM).
- Iron, aluminum, and manganese.

2.3.1 pH, Alkalinity and DIC

The pH of water is a measure of its acidity, otherwise known as its hydrogen ion concentration (H^+ or H_3O^+). Alkalinity is the capacity of water to neutralize acid. It is primarily the sum of carbonate, bicarbonate, and hydroxide anions in the water as shown in Equation 1 (Stumm and Morgan, 1981).

$$\text{Alkalinity} = 2CO_3^{2-} + HCO_3^- + OH^- - H^+ \qquad \textit{Equation 1}$$

DIC is an estimate of the total amount of inorganic carbon as shown in Equation 2 (Stumm and Morgan, 1981).

$$\text{DIC} = CO_2 + H_2CO_3 + CO_3^{2-} + HCO_3^- \qquad \textit{Equation 2}$$

Alkalinity and DIC are closely related. Most alkalinity comes from bicarbonate and carbonate ions in the water. Although water operators are more familiar with alkalinity, DIC is the parameter more closely related to corrosion because it directly measures the available carbonate species in the water that can react with lead and copper to form the passivating scales. The water's pH influences many other corrosion-related parameters (i.e., buffer capacity, alkalinity, ORP) and has a large influence on corrosion inhibitor effectiveness.

It is best to measure pH in the field at the time of sample collection using a calibrated instrument. EPA Method 150.1 emphasizes the importance of proper sampling technique - the pH of highly purified waters and the pH of waters that are not in equilibrium with the atmosphere are subject to changes as dissolved gases are either absorbed or desorbed. To minimize these impacts, EPA recommends filling sampling containers completely and keeping them sealed prior to analysis (USEPA, 1982). Alkalinity is commonly measured by a certified laboratory and reported as mg/L as calcium carbonate ($CaCO_3$). DIC cannot be measured but can be predicted based on the pH, alkalinity, ionic strength, and temperature of the water, using the table in Appendix B. DIC is usually reported in mg/L as carbon (mg/L as C).There are optimal ranges of pH and DIC that result in the greatest formation of insoluble compounds in the scale, and in this way prevent the release of lead and copper. See Chapter 3 for technical recommendations on adjusting pH/alkalinity/DIC to prevent lead and copper release.

The pH, alkalinity, and DIC of water can be highly variable within the distribution system. The pH can fluctuate due to interactions between water and pipe material, microbiological activity, and changes in disinfectant residual. The water's ability to resist changes in pH is called its buffering capacity (also called buffer intensity). The carbonate and bicarbonate ions in the water provide this buffering; see Section 2.3.4 for additional information.

Regardless of the specific treatment used, understanding the pH and DIC range throughout a distribution system is an important part of maintaining corrosion control and minimizing the release of lead and copper.

2.3.2 Corrosion Inhibitors

Corrosion inhibitors are used not only to control lead and copper release, but also to prevent corrosion of iron pipe and other metals in the distribution system. The most common corrosion inhibitors used by water systems are phosphate-based, which means they have orthophosphate (PO_4^{3-}) in their formulation. Silicate-based corrosion inhibitors, which are mixtures of soda ash and silicon dioxide, have been used in a few cases.

Orthophosphate is commonly used for lead and copper control. Polyphosphates, which are polymers containing linked orthophosphate ions in various structures are used mainly for sequestering iron and manganese. They work by binding or coordinating the metals into their structures so they cannot precipitate on sinks or clothes. Polyphosphates can also sequester lead and copper, keeping them in the water and actually increasing the risk of exposure. Polyphosphates can revert to orthophosphate in the distribution system, but it is difficult to predict if and when this occurs. Research has confirmed that polyphosphates are generally ***not*** effective on their own for controlling the release of lead and copper (Holm and Schock, 1991; Cook, 1992; Dodrill and Edwards, 1995; Cantor et al., 2000). Blended phosphates, which contain a mixture of orthophosphate and polyphosphate, have been used for corrosion control and to sequester iron and manganese. Silicate-based inhibitors have been shown to successfully reduce lead and copper levels in first draw-samples at the tap (Schock, Lytle, et al., 2005), but their full-scale use has been limited.

See Chapter 3 for additional technical recommendations on using orthophosphate, blended phosphates, and silicate-based corrosion inhibitors for controlling lead and copper release.

2.3.3 Hardness (Calcium and Magnesium)

Hardness is primarily the sum of calcium and magnesium in water. It is a common water quality parameter measured in the laboratory and is typically reported as mg/L as $CaCO_3$ (calcium carbonate).

If finished water has high hardness, increasing the pH to control lead release can cause calcium carbonate precipitation, or scaling, in the distribution system. The Langelier Saturation Index (LSI), and other calcium carbonate-related indices such as the Ryznar Index and calcium carbonate precipitation potential (CCPP), can be used as indicators of scaling conditions (Schock and Lytle, 2011).[13] It is critical to note that, while these indices can be used to predict scaling potential as an adverse secondary impact of pH or alkalinity adjustment, they have no value as corrosivity indictors and should ***not*** be used to evaluate lead or copper control. The LSI is only important insofar as it provides information regarding the amount of pH adjustment that can be employed without causing precipitation.

In addition to contributing to scaling, calcium may be a particularly important component of scales laid down by blended phosphate corrosion inhibitors. See Chapter 3 for more information.

2.3.4 Buffer Intensity

Buffer intensity (also called buffer capacity) is a measure of the water's resistance to changes in pH, either up or down. It is defined as the concentration of base required to raise the pH one unit and has units of moles/L/unit pH. Buffer intensity depends on the alkalinity, DIC, and pH of the water. Exhibit 2.3 shows the relationship of pH and buffer intensity at different DIC values, with the highest buffer intensity at a pH of approximately 6.3 and minimum intensity at pH values between 8.0 and 8.5. Thus, waters with pH between 8 and 8.5 and low DIC (less than about 10 mg/L as C) have low buffer intensity and may have more variable pH within the distribution system, whereas waters outside this pH range will have higher buffer intensity and may exhibit less variability in pH levels in the distribution system. Increasing DIC in waters with pH values in the 8 – 8.5 range will not result in appreciable increases in buffer intensity. Additional buffer intensity may result when phosphate or silicate chemicals are dosed at a high concentration relative to DIC.

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[13] The LSI is defined as the comparison between the measured pH of the water with the pH the water would have at saturation with $CaCO_3$.

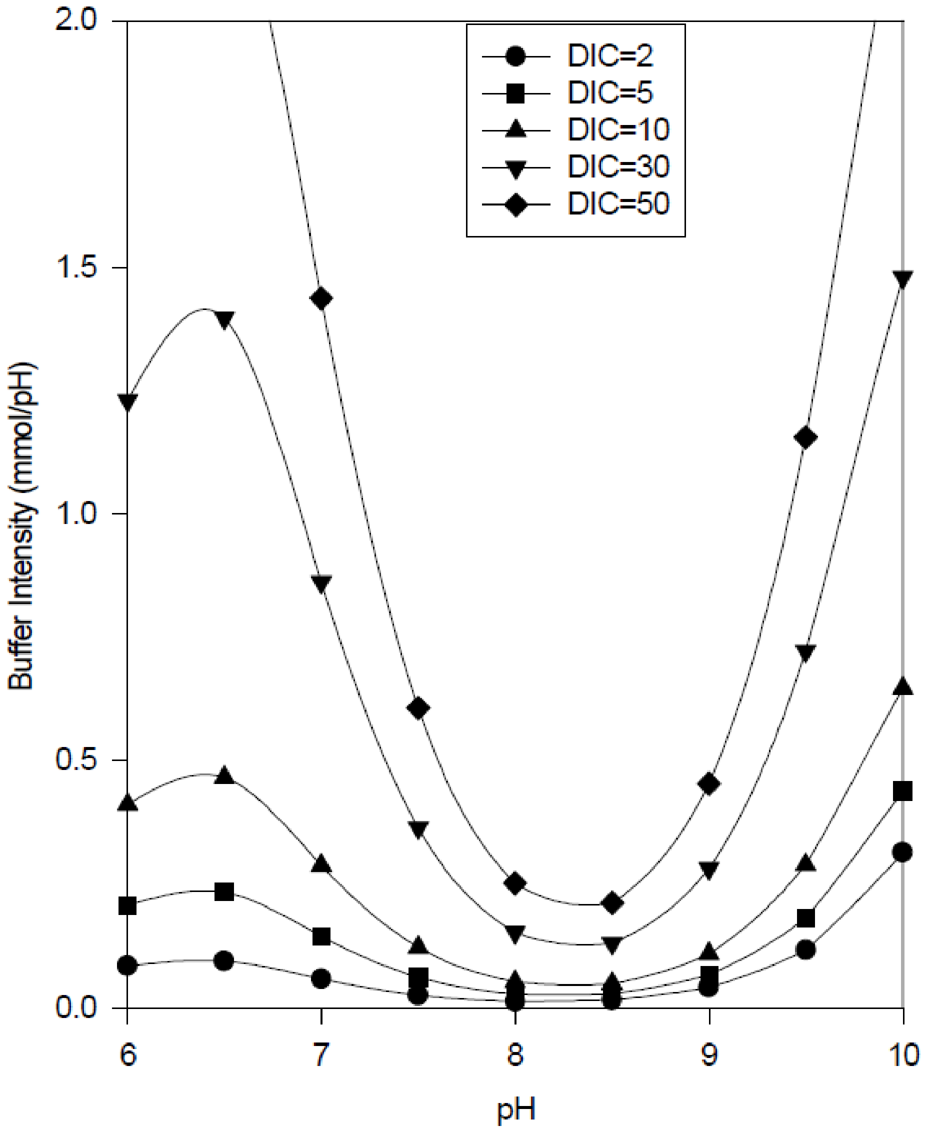

Exhibit 2.3: Buffer Intensity as a Function of pH at Different DIC Values (Clement and Schock, 1998, Figure 1)

2.3.5 Dissolved Oxygen

Oxygen is slightly soluble in water, seldom reaching dissolved concentrations above 15 mg/L. In ground water, DO can vary depending on the geochemistry and hydrogeology of the aquifer. Deep ground water or shallow ground water in areas where the recharge area has silty or clayey soils may have no DO. Shallow ground water in areas with fractured rock or sandy soils may contain higher concentrations of DO. Surface waters are generally more oxygenated, especially flowing sources (i.e., rivers). Stagnant water and waters with low DO content, however, can create oxygen-deficient conditions in some cases. The DO concentration depends on water temperature, but typical well-aerated water will have a DO concentration of about 8 or 9 mg/L. DO concentrations can be measured in the field using a calibrated DO meter.

DO concentration affects the solubility of iron, manganese, lead, and copper. Some ground water systems add dissolved oxygen through aeration processes to oxidize iron and manganese so that they can be removed through precipitation. Increasing DO in the water can increase copper corrosion, converting Cu(I) to Cu(II). However, water with high DO levels may provide corrosion benefits under some circumstances, by facilitating the production of different and more protective lead oxide scales than would have been formed under low DO conditions (see Section 2.3.6 on Oxidation-Reduction Potential for more information).

2.3.6 Oxidation-Reduction Potential

Oxidation-reduction potential, also called redox potential or ORP, is the electric potential required to transfer electrons from one compound (the oxidant) to another compound (the reductant). It is considered a quantitative measure of the state of oxidation in water treatment and distribution systems. Like pH, ORP is a fundamental characteristic of aqueous systems and affects how water interacts with solid substances such as metal pipe material. It is commonly measured using a platinum reference electrode and reported in units of volts (V) or millivolts (mV). Measured ORP values are often normalized with respect to the standard hydrogen electrode and reported as electric potential (E_h) by taking into account a material-specific conversion factor, generally provided by the electrode manufacturer or found in reference textbooks (Copeland and Lytle, 2014).

ORP varies with pH, temperature, and DIC, but is fundamentally driven by the type and concentration of disinfectant in the water (e.g., chlorine or chloramines) and the DO concentration. Laboratory studies by James et al. (2004) and Copeland and Lytle (2014) showed that ORP values are highest for free chlorine and chlorine dioxide, and that ORP decreases with increasing pH from 7 to 9, regardless of the oxidant used. Copeland and Lytle (2014) found an E_h range of 0.51 V (no disinfectant and pH of 9) to 1.02 V (chlorine disinfection and a pH of 7). In general, the influence of free chlorine on ORP is much greater than that of DO. As a result, for systems using a free chlorine residual in the distribution system, DO's influences on ORP are minor.

Under certain conditions, ORP can have a dramatic impact on lead release. Exhibit 2.4 shows the theoretical E_h and pH conditions that favor different dissolved and solid forms of lead. The hatched areas represent lead solids, and the un-hatched areas are lead complexes that are in solution. It is important to note that E_h-pH diagrams are based on theory, and the positions of the boundaries can vary depending upon the data used to construct them. Thus, these diagrams should be used to understand relationships and interpret field data, and not for predicting lead release.

Exhibit 2.4 shows that Pb(II) solids exist theoretically at low E_h values at typical pH levels in drinking water. At higher E_h values (> 0.7 V) and in the absence of corrosion inhibitors or other interfering surface deposits, PbO_2 (a Pb(IV) solid) could form on lead pipe surfaces. PbO_2 is insoluble and would prevent lead from being released to the water. Water quality changes that cause a reduction in pH or ORP from a change in disinfection practices (e.g., switching from chlorine to chloramines in the distribution system), however, can cause PbO_2 to convert to Pb(II) compounds and release lead into the water.

The high E_h values needed for PbO_2 formation may be found in systems that have a high chlorine residual (i.e., > 2 mg/L as free chlorine) for extended periods of time. PbO_2 has been observed to form between pH 7 and 9.5, with formation occurring more quickly at higher pH values. Field testing has shown that the amount of lead released from PbO_2 scales is very low and close to lead levels for non-lead pipes (Schock, Triantafyllidou, et al., 2014; Triantafyllidou et al., 2015).

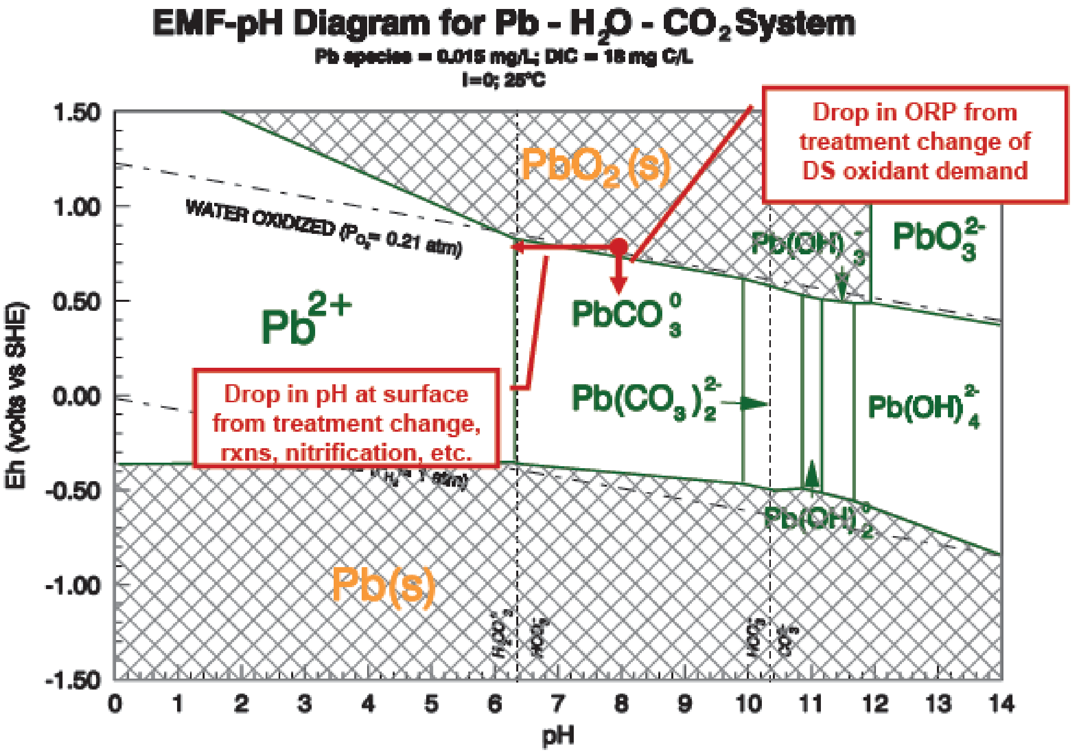

Exhibit 2.4: E_h-pH Diagram for a Lead-Water-Carbonate System. DS oxidant demand in upper box is 'distribution system oxidant demand' (Schock, 2007a; provided by author)

2.3.7 Ammonia, Chloride, and Sulfate

Excess ammonia (NH_3) may occur in the distribution system due to elevated source water ammonia levels and/or if the system uses chloramines for disinfection. The presence of excess ammonia can lead to nitrification in the distribution system. Nitrification occurs when nitrifying bacteria convert ammonia into nitrite and nitrate, which may lower the pH and alkalinity of the water. This can accelerate brass corrosion and cause problems with lead release (Uchida and

Okuwaki, 1999; Douglas et al., 2004). Ammonia may also form compounds with lead and copper, which can interfere with the effectiveness of CCT.

Research has shown that the ratio of chloride (Cl^-) to sulfate (SO_4^{2-}) in the water can be an indicator of potential lead release. An evaluation of LCR tap sampling data from 12 drinking water utilities collected as part of a Water Research Foundation (WRF) project found that all of the water systems with chloride-to-sulfate ratios less than 0.58 met the 90th percentile action level for lead, whereas only 40 percent of the systems with chloride/sulfate ratios greater than 0.58 met the lead action level (Reiber et al., 1997). More recent research has shown that that lead leaching increased when the chloride-to-sulfate mass ratio approached 0.4 to 0.6 (Nguyen et al., 2010; Nguyen et al., 2011); however, further increasing the chloride-to-sulfate mass ratio above 0.7 may not necessarily be an indicator of increased lead release (Wang et al., 2013). Lower chloride-to-sulfate ratios may be indicative of lower lead release due to the formation of an insoluble sulfate precipitate with lead. Higher ratios may result in the formation of a soluble chloride complex, where lead is galvanically connected to another metal such as copper (Nguyen et al., 2010; 2011).

The chloride and sulfate content in water can change with a switch from sulfate-based coagulants (such as aluminum sulfate (alum) and ferric sulfate) to chloride-based coagulants (such as ferric chloride). Conversely, a change from ferric chloride to alum may increase the sulfate content in the water, potentially reducing lead release. Other scenarios that may affect lead release by altering the chloride and sulfate concentration in the water (and hence the chloride-to-sulfate mass ratios) include blending of desalinated seawater, using anion exchange, or brine leaks from on-site hypochlorite generators (Nguyen et al., 2010; 2011). Galvanic connections and galvanic corrosion can occur in the distribution system with the use of lead solder on copper pipes, or from partial lead line replacements (Oliphant, 1983; Gregory, 1985; Reiber, 1991; Singley, 1994; Lauer, 2005; Nguyen et al., 2010; Triantafyllidou and Edwards, 2011; Clark et al., 2013; Wang et al., 2013).

2.3.8 Natural Organic Matter

NOM is a complex mixture of organic compounds that occur in both ground and surface water sources, but are more prevalent in surface water. NOM is difficult to measure, so utilities often use UV_{254} (specific absorption, the ratio of UV absorption to organic carbon concentration) as a surrogate (APHA, AWWA, and WEF, 2005).

The impact of NOM on metals release is unclear. NOM in finished water can help form the protective films that reduce corrosion, but it has also been shown to react with corrosion products to form soluble complexes with lead, which may increase lead levels in the water (Korshin et al., 1996, 1999, 2000, 2005). Organic matter can also provide nutrients for microorganisms, exacerbating problems with biofilm growth and depleting chlorine residuals. This additional microbial growth can cause microbially-induced copper corrosion (pinhole leaks) through localized decreases in pH or, in the case of sulfate-reducing bacteria, through the formation of sulfide (Schock and Lytle, 2011).

2.3.9 Iron, Manganese, and Aluminum

Iron and manganese are present in many ground water sources and in the lower depths of some thermally stratified lakes and reservoirs. While there is no health-based maximum contaminant level for these metals, EPA has established secondary maximum contaminant levels (SMCLs) for iron and manganese of 0.3 mg/L and 0.05 mg/L, respectively. These SMCLs are based on aesthetic issues (red water, staining of clothing). While aluminum occurs naturally in groundwater and soil due to the erosion of aluminum-bearing minerals (USEPA, 2006a), it is more frequently found in drinking waters treated with alum for coagulation. It can also be an impurity in lime. Aluminum can color water, so EPA has set a SMCL of 0.05 to 0.2 mg/L.[14] Iron, manganese, and aluminum are common water quality parameters that can be measured by a certified laboratory.

Systems that increase pH for lead and/or copper control may experience black or red water complaints due to oxidation of iron and manganese in the distribution system. Iron and manganese removal at the treatment plant, or possibly the use of sequestering agents or silicates, can be used in these cases (see Chapter 3 for more information).

New research has shown that manganese and iron can react with dissolved lead and form deposits on lead service lines and other pipes in premise plumbing. In the well-studied case of Madison, WI, manganese that accumulated on pipe scales (up to 10 percent by weight of scale composition) captured dissolved lead and later released it back into the drinking water (Schock, Cantor, et al., 2014). Manganese can also interfere with the formation of PbO_2 and other passivating films (Schock, Cantor, et al., 2014).

Aluminum can interfere with orthophosphate effectiveness by forming aluminum phosphate precipitates, which reduce the amount of orthophosphate available for lead and copper control. Aluminum phosphate precipitates also have the potential to form scales on the interior of piping systems that may reduce the effective diameter of the pipes, resulting in loss of hydraulic capacity and increases in system headloss and operational costs (AWWA, 2005).

The 2006 EPA Report, Inorganic Contaminant Accumulation in Potable Water Distribution Systems notes that, "Based on scale sample analysis from 10 water utilities that practice alum coagulation, Snoeyink et al. (2003) confirmed that aluminum is frequently a major component of lead pipe scale" (USEPA, 2006a). These scales, however, are generally not as stable compared to orthophosphate scales and are prone to sloughing with changes in flow or water quality, or when lead service lines are physically disturbed during routine maintenance and

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[14] "While EPA encourages utilities to meet a level of 0.05 mg/l for aluminum where possible, the Agency still believes that varying water quality and treatment situations necessitate a flexible approach to developing the SMCL. What may be appropriate in one case may not be appropriate in another. Hence, a range was developed for the aluminum SMCL." (USEPA, 1991a).

repair activities. These dislodged scales can release metals that may become entrapped in the interior (premise) plumbing and/or the faucet screen, potentially increasing lead and copper levels in the water (Schock, 2007b).

2.4 Physical and Hydraulic Factors Affecting Release of Lead and Copper

In addition to water quality parameters, physical factors such as pipe disturbances, hydraulics, water use, and water temperature can affect lead and copper levels at the customer's tap. Understanding these factors can help primacy agencies and systems interpret lead and copper data and evaluate the effectiveness of OCCT.

2.4.1 Physical Disturbances

Field sampling has shown that physical disturbances to LSLs related to infrastructure work can result in lead release. Del Toral et al. (2013) found that most lead sampling results above the LCR lead action level of 0.015 mg/L occurred at sites with physical disturbances compared to undisturbed sampling sites.[15] Lower water usage at the disturbed sites may have also been a factor in the higher lead levels found.

Any physical disturbance to the premise plumbing system, from service to tap, can cause lead particulate release. Physical disturbances resulting in lead particulate release can occur during:

- Meter installation or replacement.
- Auto-meter-reader installation.
- Service line repair or partial replacement.
- External shut-off valve repair or replacement.
- Significant street excavation directly in front of the house.
- Repair or replacement of home plumbing fixtures or piping.

When any part of a home plumbing system is drained for repair work, or when infrastructure upgrades or repairs are completed (e.g., main breaks), air may get into the lines and scour deposits from the service lines to the tap. Tap flushing to remove air bubbles can disrupt pipe scales and release lead, copper and other accumulated material in the scales.

2.4.2 Hydraulic Factors

High water velocity can help reduce lead and/or copper by transporting the corrosion inhibitor to pipe surfaces at a higher rate; however, in some cases it can increase lead and/or copper corrosion by increasing the rate at which the oxidants in water come into contact with the metal surface. High water velocity can cause corrosion in copper pipes, and can also mobilize loosely adherent scale and cause sporadic lead release (Schock, 1999). Low water velocity in

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[15] Sampling included first draw and lead profile sampling. The percent of samples with lead levels greater than 0.015 mg/L was 36% for sites with known disturbances (13 sites and 327 samples), 37 % for indeterminate sites where the disturbance could not be verified (2 sites, 81 samples), and 2% for undisturbed sites (16 sites, 372 samples).

areas of low water usage can reduce the effectiveness of the corrosion control inhibitor in forming a passivating scale. Increased water age due to less frequent use can cause water quality changes such as reductions in pH and loss of free chlorine residual that could exacerbate corrosion as well as microbial problems.

Other hydraulic factors that can affect lead and copper release into the customer’s service line or a building’s plumbing include flow reversals and hydraulic pressure transients. Pressure transients may occur when valves are closed to perform maintenance (Friedman et al., 2010) or due to backflow from a cross connection. Residential backflow is more common than previously thought, according to a recent study that identified backflow events in 5 percent of homes with backflow sensing meters (Schneider et al., 2010). Hydraulic pressure transients may occur when there are sudden changes in water velocity due to valves slamming shut, power outages, or pump start/stop cycles (Friedman et al., 2010).

2.4.3 Water Use

The effectiveness of corrosion control inhibitors depends on delivery of the inhibitors to the pipe wall to form the passivating scale. Reductions in water use may adversely affect this process. Also, as stated above, increased water age from less frequent use can cause water quality changes, such as reductions in pH and loss of free chlorine residual, that can exacerbate corrosion as well as microbial problems.

2.4.4 Water Temperature

Water temperature effects are complex and depend on the water chemistry and type of plumbing material. More lead is often mobilized during warmer weather seasons, although temperature effects can vary depending on water quality conditions and plumbing configuration. For example, as reported by Schock and Lytle (2011), orthophosphate reacts more quickly at higher temperatures, so reduction in lead levels may take longer in colder months than in warmer months. Higher temperature can also exacerbate copper corrosion, although elevated temperature has been found in some instances to facilitate a better passivating copper pipe scale (Schock and Lytle, 2011).

Seasonal changes in water temperature can result in significant changes in water quality and can impact lead and copper release. Because of the many reactions happening in the distribution system, it is difficult to generalize temperature’s impacts. Water systems should collect water quality and lead and copper data throughout the year to determine their own trends.

Chapter 3: Corrosion Control Treatment for Lead and Copper

This chapter provides technical information on available corrosion control treatment (CCT) methods for lead and copper (Section 3.1), technical recommendations for identifying treatment alternatives for individual systems (Section 3.2), and technical recommendations for identifying target water quality and dosages for treatment alternatives (Section 3.3). The information in this chapter can be used to support systems and primacy agencies in meeting CCT requirements of the Lead and Copper Rule (LCR). Note that this chapter provides background information and technical recommendations - see Chapters 4 and 5 for a review of the required CCT steps under the LCR and when CCT requirements apply.

3.1 Available Corrosion Control Treatment Methods

Alkalinity and pH adjustment have been used by many systems for corrosion control. The discussion of this method is expanded in this section to include dissolved inorganic carbon (DIC) adjustment because all three parameters are a better indicator of corrosion control effectiveness than pH and alkalinity alone.

Phosphate-based corrosion inhibitors have been widely used to control lead and copper release. Their applications for corrosion control have been updated in this chapter to include more recent information on chemical formulations, optimal pH ranges, and limitations to their use.

Information on the use and effectiveness of silicate-based corrosion inhibitors continues to be limited and more research is needed. They may be effective in reducing lead and copper release in some cases, however, so they are included as a treatment technique in this chapter.

Calcium hardness adjustment is not discussed in this chapter because newer research has shown that calcium carbonate films only rarely form on lead and copper pipe and are not considered an effective form of corrosion control (Schock and Lytle, 2011; Hill and Cantor, 2011). Calcium hardness is important, however, in evaluating the amount of pH adjustment that can be made without causing calcium carbonate precipitation and resultant scaling problems in the distribution system.

New research has found that lead service lines (LSLs) with PbO_2 scales can have very low lead release (levels as low as or lower than those found when orthophosphate treatment is used (Schock, Cantor, et al., 2014; Triantafyllidou et al., 2015)). This new information has significant implications for management of treatment and distribution systems to minimize the release of lead. Questions remain, however, on how systems and primacy agencies can ensure that disinfectant residuals required for the formation and maintenance of PbO_2 scales are maintained in LSLs throughout the distribution system. This may be a particular challenge with homes that go unoccupied for an extended period of time. Therefore, formation of PbO_2 scale is not included in this section as a corrosion control technique. If systems have PbO_2 scales, they should be very careful about making disinfection changes (see Chapter 6 for more information).

The remainder of this sub-subsection describes the specific chemical/physical methods that can be used for pH/alkalinity/DIC adjustment, phosphate-based corrosion inhibitors, and silicate-based corrosion inhibitors.

3.1.1 pH/Alkalinity/DIC Adjustment

As noted in Chapter 2, there are ranges of pH, alkalinity, and DIC that result in formation of insoluble compounds in the scale and in this way prevent the release of lead and copper (see Section 3.3.1 for recommended target pH/alkalinity/DIC ranges). Adjustment of pH/alkalinity/DIC can be accomplished by chemical or non-chemical means. Typical chemicals used for pH/alkalinity/DIC adjustment for corrosion control are listed in Exhibit 3.1. Additional information and guidance on pH adjustment methods are provided in USEPA (1992a) and Hill and Cantor (2011).

In addition to chemical methods, pH/alkalinity/DIC adjustment can be accomplished using limestone contactors or aeration. Limestone contactors, which are enclosed filters containing crushed high-purity limestone, have been used at small systems because they are relatively easy to operate. As the water passes through the limestone, the limestone dissolves, raising the pH, alkalinity, DIC, and calcium of the water. An empty bed contact time of 20 to 40 minutes is typically used to optimize pH and alkalinity adjustment. If a high pH is needed, other media types (e.g., dolomite, dolomitic materials) may be available regionally. The pH can be hard to control in limestone contactors and can depend on initial water quality and type of limestone used. When using limestone contactors, it is important to limit influent water quality to properly control effluent water chemistry. Suggested values for the influent are pH < 7.2, calcium < 60 mg/L, and alkalinity < 100 mg/L (Hill and Cantor, 2011). For influent pH > 7.2, carbon dioxide can be added prior to the contactors. Limiting iron, manganese, and aluminum is also recommended to prevent filter fouling. Limestone contactors can also be used for iron removal but require backwash capabilities to remove iron that accumulates on the limestone. Recommendations on the design and application of limestone contactors can be found on the following Environmental Protection Agency (EPA)-funded website www.unh.edu/wttac/WTTAC_Water_Tech_Guide_Vol2/limestone_intro.html. Calcite filters are a similar treatment that operate using the same principles as limestone contactors, except that they use a finer material that is housed in a cartridge. For the purposes of this document, “limestone contactor” is the generic term used to represent any filtration process of calcite-containing material used to add pH, alkalinity, and DIC to the water.

Aeration is a non-chemical method for adjusting pH where air is introduced into the water. Aeration is the only method that ***reduces*** excess DIC by removing carbon dioxide, which results in an increase in pH. Aeration systems include Venturi injector systems, tray systems, packed tower systems, and diffuse bubble systems. They can be designed to remove other constituents such as iron, manganese, radon, volatile organic compounds (VOCs) and hydrogen sulfide (H_2S). Aeration is most effective when there is an adequate carbon dioxide concentration in the water (4 - 10 mg/L CO_2), and the pH is < 7.2 (Spencer and Brown, 1997; Lytle et al., 1998; Spencer, 1998; AWWA, 1999; Schock et al., 2002; AWWA, 2005).

Exhibit 3.1: Typical Chemical Processes for pH/Alkalinity/DIC Adjustment

Chemical	Use	Composition	Alkalinity Change	DIC Change[1]	Notes
Baking Soda, $NaHCO_3$ (sodium bicarbonate)	Increases alkalinity with moderate increase in pH.	98% purity. Dry storage with solution feed.[2]	0.60 mg/L as $CaCO_3$ alkalinity per mg/L as $NaHCO_3$ [2, 3, 4]	0.14 mg/L as C per mg/L as $NaHCO_3$	Good alkalinity adjustment chemical but expensive.[2]
Carbon Dioxide, CO_2	Lowers pH. Converts hydroxide to bicarbonate and carbonate species.	Pressurized gas storage. Fed either through eduction or directly.[2]	None [2]	0.27 mg/L as C per mg/L as CO_2	Can be used to enhance NaOH or lime feed systems.[2]
Caustic Potash, KOH (potassium hydroxide)	Raises pH. Converts excess carbon dioxide to carbonate alkalinity species.	KOH is available as a 45% solution.[5] Has a low freezing point and may be stored at higher concentrations.	0.89 mg/L as $CaCO_3$ alkalinity per mg/L as KOH [3, 4]	None	pH control is difficult when applied to poorly buffered water.[5] Is a hazardous chemical, requires safe handling and containment areas.
Caustic Soda, NaOH (sodium hydroxide) [6]	Raises pH. Converts excess carbon dioxide to carbonate alkalinity species.	93% purity liquid bulk, but generally shipped and stored at < 50% purity to prevent freezing.[2]	1.25 mg/L as $CaCO_3$ alkalinity per mg/L as NaOH [3, 4]	None	pH control is difficult when applied to poorly buffered water.[2] Is a hazardous chemical, requires safe handling and containment areas.
Hydrated Lime, $Ca(OH)_2$ (calcium hydroxide) [7]	Raises pH. Increases alkalinity and calcium content (i.e., hardness).	95 to 98% purity as $Ca(OH)_2$. 74% active ingredient as CaO. Dry storage with slurry feed.[2]	1.35 mg/L as $CaCO_3$ alkalinity per mg/L as $Ca(OH)_2$ [3, 4]	None	pH control is difficult when applied to poorly buffered water. Slurry feed can cause excess turbidity. O&M is intensive.[2]
Potash, K_2CO_3 (potassium carbonate)	Increases alkalinity with moderate increase in pH.	Dry storage with solution feed.[5]	0.72 mg/L as $CaCO_3$ alkalinity per mg/L K_2CO_3 [3, 4]	0.09 mg/L as C per mg/L as K_2CO_3	More expensive than soda ash but more soluble and easier to handle.[5]

Chemical	Use	Composition	Alkalinity Change	DIC Change[1]	Notes
Soda Ash, Na_2CO_3 (sodium carbonate)	Increases alkalinity with moderate increase in pH.	95% purity. Dry storage with solution feed.[2]	0.94 mg/L as $CaCO_3$ alkalinity per mg/L as Na_2CO_3 [3, 4]	0.11 mg/L as C per mg/L as Na_2CO_3	More pH increase compared with $NaHCO_3$, but less costly.[2] Has increased buffer capacity over hydroxides.
Sodium Silicates, Na_2SiO_3	Moderate increases in alkalinity and pH.	Available in liquid form mainly in 1:3.2 or 1:2 ratios of Na_2O:SiO_2.[8]	Depends on formulation	None	More expensive than other options but easier to handle than lime and other solid feed options. Has additional benefits in sequestering or passivating metals.[8]

Notes and adapted sources:

[1] Calculated by the formula DIC Change = 12 x (moles carbon/mole compound) / molecular weight of compound.

[2] USEPA, 1992a

[3] Wachinski, 2016

[4] Simon, 1991

[5] USEPA, 2003

[6] Caustic potash (KOH), or potassium hydroxide, is an alternative that does not add sodium to water.

[7] Lime is available as hydrated or slaked lime ($Ca(OH)_2$) and quicklime (CaO).

[8] Schock, 1996

3.1.2 Phosphate-Based Inhibitors[16]

As noted in Chapter 2, phosphate-based corrosion inhibitors are chemicals that have orthophosphate in their formulation.[17] Orthophosphate reacts with divalent lead and copper (i.e., Pb^{++} and Cu^{++}) to form compounds that have a strong tendency to stay in solid form and not dissolve into water. The extent to which orthophosphate can control lead and copper release depends on the orthophosphate concentration, pH, DIC, and the characteristics of the existing corrosion scale (e.g., whether it contains other metals such as iron or aluminum).

Orthophosphate is available as phosphoric acid, in salt form (potassium or sodium), and as zinc orthophosphate. Phosphoric acid (H_3PO_4) is a common form that is available in concentrations between 36 and 85 percent. Because it is an acid, it requires special handling and feed facilities. Zinc orthophosphate inhibitors typically have zinc: phosphate weight ratios between 1:1 and 1:10. Recent research found that zinc orthophosphate did not provide additional lead and

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[16] As noted in Chapter 2, polyphosphates, which are used mainly as sequestrants for iron and manganese, have not been found to be effective on their own to control lead and copper release.

[17] Orthophosphate concentration can be measured as P (phosphorus) or PO_4 (phosphate). It is very important to be clear about which measurement is being used. An orthophosphate concentration of 3 mg/L as PO_4 is roughly equivalent to 1 mg/L as P.

copper control compared to orthophosphate (Schneider et al., 2010). The zinc did, however, provide better corrosion protection for cement at low alkalinity/hardness/pH conditions.

Blended phosphates are a mix of orthophosphate and polyphosphate, with the orthophosphate fraction ranging from 0.05 to 0.7. It is possible that blends can provide both sequestration of metals and reduce metals release (Hill and Cantor, 2011). It is important to note that blended phosphates may not function as corrosion inhibitors strictly on the basis of concentration and relative amount of orthophosphate. See Section 3.3 for more information and recommended special considerations for using blended phosphates.

3.1.3 Silicate Inhibitors

Silicate inhibitors are mixtures of soda ash and silicon dioxide. These treatment chemicals are available in liquid or solid form (AwwaRF, 1990; Reiber et al., 1997; USEPA, 2003). They have been shown in a few cases to reduce lead and copper levels in first draw, first liter tap samples (LaRosa-Thompson et al., 1997; Schock, Lytle, et al., 2005). They have not been used in many full-scale plants because they have traditionally been more expensive than phosphate-based inhibitors and can require high doses.

The mechanisms by which silicate inhibitors control lead and copper release have been debated in the literature. Silicates may form an adherent film on the surface of the pipe that acts as a diffusion barrier. Silicates will also increase the pH of the water, which may reduce lead and copper release. The effectiveness of the formation of a diffusion barrier depends on pre-existing corrosion products on the scale to provide a site for the binding of the silicate layer (LaRosa-Thompson et al., 1997).

Silicates are defined by a weight ratio of SiO_2:Na_2O. A ratio of 3.22 is typical, although sodium silicate solutions with ratios as low as 1.6 are commercially available (Schock and Lytle, 2011; Schock, Lytle, et al., 2005).

3.2 Technical Recommendations for Selecting Treatment Alternatives

The process that systems must follow before the primacy agency designates OCCT is established in the LCR and differs in part based on system size. All systems, however, must recommend to the primacy agency a treatment option for designation as OCCT. This section contains technical recommendations to support primacy agencies, water systems, and if applicable, outside technical consultants in evaluating treatment alternatives to control lead and copper release. These technical recommendations may be particularly useful for systems serving 50,000 or fewer people when developing their OCCT recommendation, or for larger systems identifying corrosion control alternatives for further study. See Chapters 4 and 5 for a review of CCT requirements under the LCR.

This section includes flowcharts to support the corrosion control selection process. These flowcharts are based on the 1997 EPA document, *Guidance for Selecting Lead and Copper*

Control Strategies (1997) and the revised guidance with the same name, published in 2003. This section reflects new research related to the control of copper corrosion and blended phosphates, as well as new research related to corrosion control in systems with raw water iron and manganese. These flowcharts are intended to serve as a general screening tool for identifying potential alternatives. They are not meant to substitute for pilot studies and other site-specific investigations or preclude the use of other technologies identified by the system, primacy agency, or technical experts. It is the system and primacy agency's responsibility to assess the pros and cons of each treatment alternative, and to ensure its optimization once installed.

The following technical recommendations are discussed in this section:

- STEP 1. Review Water Quality Data and Other Information.
- STEP 2. Evaluate Potential for Scaling.
- STEP 3. Select One or More Treatment Option(s).
- STEP 4. Identify Possible Limitations for Treatment Options.
- STEP 5. Evaluate Feasibility and Cost.

Section 3.3 follows with technical recommendations on setting dose and target water quality parameters. Special considerations for systems with LSLs, small systems, and systems with multiple sources are provided below.

- Considerations for ***systems with LSLs:*** Systems with LSLs may want to evaluate the feasibility and cost effectiveness of fully removing all LSLs (utility-side and customer-side). Full LSL removal has several operational benefits - for example, systems using orthophosphate may be able to reduce their dose when LSLs have been fully removed. Also, removing the source of lead reduces the vulnerability of the system to unexpected changes in lead release due to future water quality changes.

- Considerations for ***very small community water systems (CWSs) and non-transient, non-community water systems (NTNCWSs):*** Systems that directly control 100 percent of their plumbing fixtures and components may want to consider physically replacing all lead-containing or copper plumbing materials. Systems should verify that the new components are certified *"lead-free"* according to current standards (See Section 2.1 for the definition of "lead-free"). Point-of-use (POU) treatment units, if they meet the SDWA requirements, may be an option in limited circumstances.[18] Note systems that select plumbing replacement or POU devices must continue the CCT steps described in

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[18] For additional information refer to: 1) the preamble to the 2007 LCR Short-Term Revisions (USEPA, 2007a); and 2) *Point-of-Use or Point-of-Entry Treatment Options for Small Drinking Water Systems*, EPA 815-R-06-10 (USEPA, 2006b). https://nepis.epa.gov/Exe/ZyPDF.cgi/P1009UBF.PDF?Dockey=P1009UBF.PDF.

Section 4.1 unless they are deemed optimized.[19] In cases where very small CWSs and NTNCWSs are identifying CCT, it may be beneficial to consider technologies that are easy to operate (e.g., limestone contactors, aeration) and select chemicals that are easy to store and work with, such as baking soda.

- Considerations for ***systems with more than one source:*** Many systems will have unique source and treatment scenarios that make system-wide corrosion control recommendations difficult. It may be prudent for systems with multiple wells or multiple sources, or systems that purchase waters of differing quality that enter the distribution system at various locations, to determine the most appropriate treatment separately for each source then undertake a system-wide evaluation of the most effective way to implement and operate corrosion control.

It is also important to recognize the potential limitations of treatment in chronic low water usage homes and homes that have been unoccupied for extended periods of time. The treatment may not be effective at lowering lead and/or copper levels at these sites, which can pose an ongoing risk to these residents. Systems can consider other potential actions they or residents can take to address the potential risk at these sites.

3.2.1 Technical Recommendations for Reviewing Water Quality Data and Other Information (STEP 1)

Lead and Copper Data

The forms in Appendix D can be used to organize lead and copper tap sampling data for system and primacy agency review. In addition to their own data, systems and primacy agencies should review any additional lead and copper data collected by others (e.g., universities).

Systems and primacy agencies should consider evaluating the dates and locations of individual sample results above the lead or copper action level(s) to determine if there are any spatial or temporal patterns. These results could be compared to water quality data collected at nearby distribution system locations at similar times to determine if they coincided with unusual water quality (e.g., changes in pH, corrosion inhibitor concentration, or microbiological activity). Systems should determine if sample results above the action level(s) coincided with a change in treatment or source. Lastly, systems should compare these sample results to previous rounds of lead and copper tap monitoring to see if there is a reoccurring pattern of lead and/or copper occurrence above the action level(s) at specific locations.

Systems may want to talk to residents where the sample results were above the action level(s) to discuss the resident’s sampling procedure, ask for information on water use patterns and stagnation time prior to sampling, and ask about any physical disturbances that may have

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[19] One way for systems serving 50,000 or fewer people to be deemed to have optimized corrosion control is they conducted lead and copper tap monitoring for two consecutive 6-month monitoring periods without a lead or copper action level exceedance (§141.81(b)(1)).

occurred prior to sampling (e.g., building renovations and other construction work on the property). A good way to collect information ahead of time is on a comprehensive chain of custody (COC) form. The COC form, given to the resident to send in with the sample, can be designed to collect information on sampling procedure, stagnation time, and flushing time. Talking with residents about their sample results provides an opportunity for systems to discuss one-on-one with consumers the public health implications of lead and copper and ways in which residents can reduce their exposure.[20]

For locations with sample results above the action level(s), systems and primacy agencies may want to consider additional sampling[21] to determine the source of the lead so that the system and property owner might consider site-specific remediation in addition to actions required by the regulations. See Appendix C for technical recommendations on investigative sampling methods to determine the source of lead and copper.

Other Water Quality Data and System Information

Systems and primacy agencies should collect and review water quality data and other system information pertinent to corrosion of lead and copper containing materials. Systems can use the forms in Appendix D to organize available water quality data and information and submit it to their primacy agency.

Analysis of a broad range of water quality constituents can be a very cost effective approach to identification of appropriate treatment technologies. For example:

- Having very accurate pH and alkalinity/DIC data is important for assessing the feasibility of such simple treatments as aeration or limestone contactors.
- Having calcium, magnesium, sulfate, iron, manganese, and other water quality data may help define constraints on pH adjustment, phosphate dosing, use of packed tower aerators, membranes or other processes, because of scale buildup issues.
- Knowing whether arsenic or radon is present in the source water will dictate CCTs that are compatible with the removal processes for those contaminants. For example, aeration can be used for radon removal as well as for pH adjustment for corrosion control, potentially reducing or eliminating the need for chemical treatment.
- If iron and/or manganese are present, they can interfere with the effectiveness of CCT. A combination of a removal process or filtration following oxidation (e.g.,

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[20] Note that systems must conduct public education as required by the LCR when they exceed the lead action level (§141.85). Public education guidance for CWSs is provided in the document, "Implementing the Lead Public Education Provisions of the Lead and Copper Rule: A Guide for Community Water Systems" (USEPA, 2008a) and in a similarly titled guidance for NTNCWSs (USEPA, 2008b).

[21] All lead and copper tap sample results from the system's sampling pool collected within the monitoring period must be included in the 90th percentile calculation along with any samples where the system is able to determine that the site selection criteria in §141.86(a)(3)-(8) for the sampling pool are met. Other lead and copper tap data such as from customer requested sampling, investigative sampling, and special studies also must be submitted to the primacy agency (USEPA, 2004c; §141.90(g)).

aeration/disinfection) might be cost-effective and would reduce or eliminate the need for sequestration. Similarly, iron removal processes can often remove arsenic if present.

Primacy agencies and systems can use the information in Chapter 2 to review the data and identify water quality and physical factors that may be contributing to lead and/or copper release. When lead and copper monitoring data appear to be at odds with corrosion control theory, additional unknown factors may be involved. Those critical factors can only be determined by more specific evaluation and studies, such as direct examination of the pipe scales, additional data collection and evaluation, or examining the physical layouts of individual sampling sites.

3.2.2 Technical Recommendations for Evaluating the Potential for Scaling (STEP 2)

The presence of calcium in the water may limit the system's ability to raise the pH due to scaling problems in the distribution system. Scaling can clog pipes, reduce carrying capacity, and cause the water to be cloudy. Before selecting possible treatments, EPA recommends that systems and primacy agencies identify the ***saturation pH*** for calcium carbonate for the system. Maintaining the pH below the saturation pH should help to minimize, although not eliminate, the potential for precipitating calcium carbonate. It is important to note that other constituents in the water such as trace metals, natural organic matter (NOM), ligands, and phosphates can affect calcium carbonate precipitation rates and result in a higher or lower saturation pH.

The steps for determining the saturation pH are as follows:

- Determine the DIC of the water. If DIC data are not available but alkalinity and pH are known, use the table in Appendix B to determine the target DIC (in mg/L as carbon).
- Determine the finished water calcium concentration in mg/L. If this is not known but the system has total hardness data, approximate the calcium concentration by dividing the finished water hardness (as mg/L $CaCO_3$) by 2.5.
- On Exhibit 3.2, find the intersection of DIC on the x-axis (in "mg C/L") and calcium on the y-axis (in "mg Ca/L"). Find the pH curve closest to the intersection. This is the saturation pH for the system.

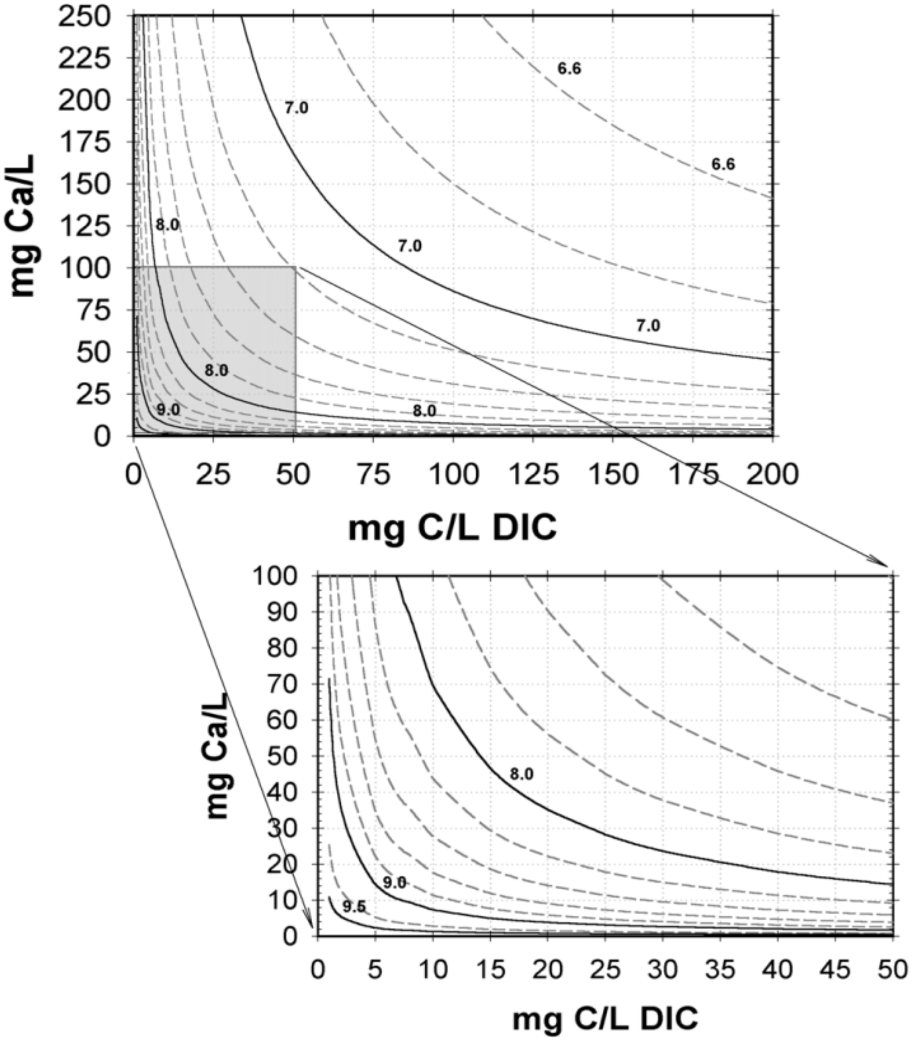


Exhibit 3.2: Theoretical Saturation pH for Calcium Carbonate Precipitation (USEPA, 2003)

Notes:
Solid lines are pH in whole numbers. Dashed lines are pH increments of 0.2
Calcium values are in mg Ca/L. To approximate calcium concentration (in mg Ca/L) from a measured hardness (as mg/L $CaCO_3$), divide the hardness value by 2.5.

3.2.3 Technical Recommendations for Selecting One or More Treatment Option(s) (STEP 3)

Systems and primacy agencies can use Flowcharts 1a through 3b in this section to select candidates for CCT. Exhibit 3.3 is a starting point for systems and primacy agencies to select the most appropriate flowchart for their situation based on whether the system has iron and/or manganese in finished water, is treating for lead and/or copper, and on pH in the distribution system.

These flowcharts were originally developed as a tool for small systems in EPA’s 2003 revised guidance manual on selecting lead and copper corrosion strategies (USEPA, 2003), but they can be useful for all system types. The flowcharts have been updated to reflect new research conducted since 2003.

These flowcharts are a screening tool and are not meant to substitute for pilot studies and other site-specific investigations. They are meant to indicate likely possibilities and do not include information on optimizing any of the treatments. In particular, systems with LSLs should work with their primacy agencies to select treatment that most effectively reduces lead release from the service line and should also consider full LSL replacement as recommended earlier in this chapter. Also, as stated elsewhere in this document, the presence of other chemicals in the finished water such as aluminum, iron, manganese, and calcium may interfere with CCT and point to a need for additional studies and/or alternative control options.

Additional information on setting water quality parameters and dose for the treatment options is provided in Section 3.3.

Exhibit 3.3: Identifying the Appropriate Flowchart for Preliminary CCT Selection

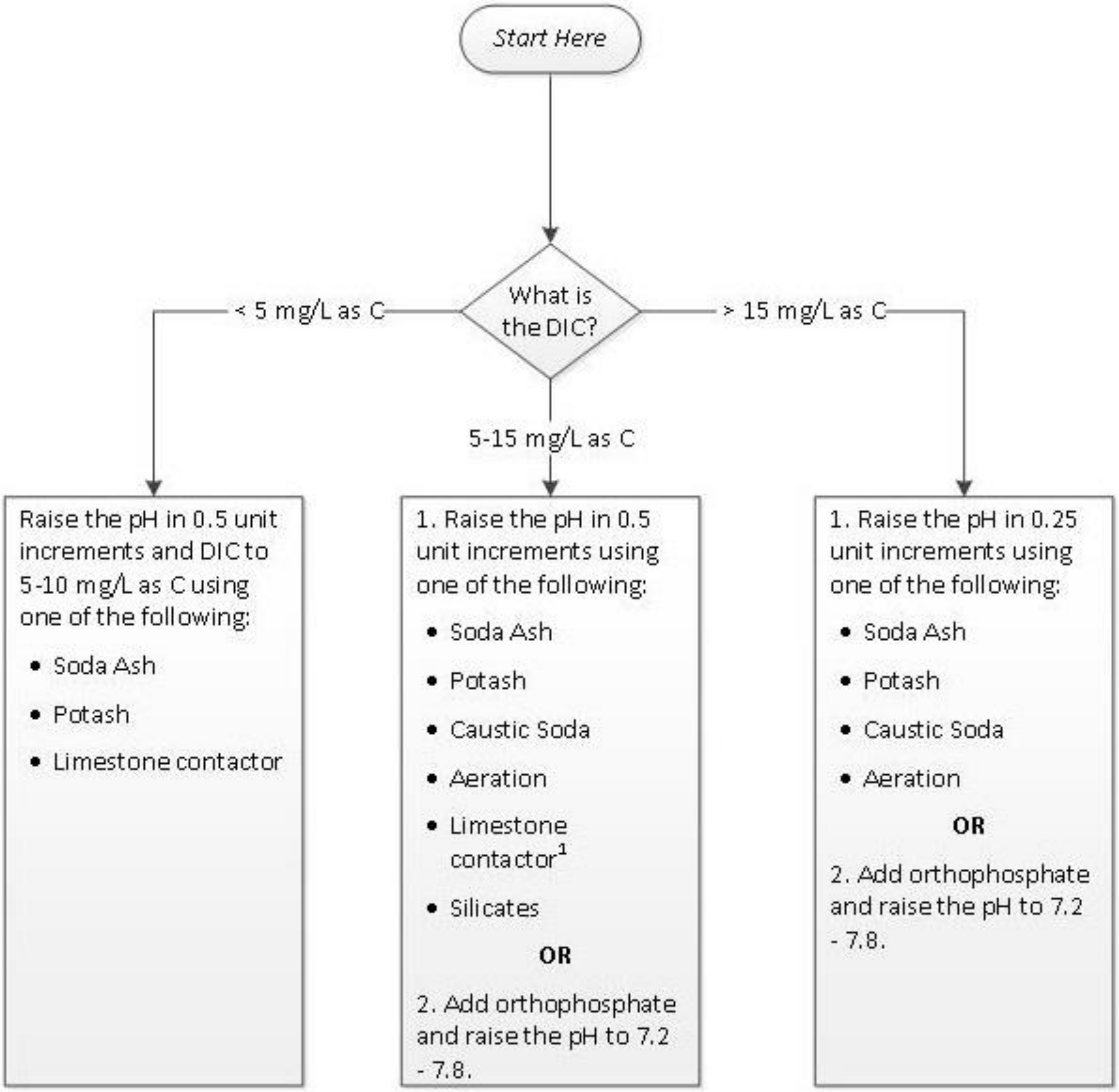
Is iron or manganese present in finished water?[1]	What is the contaminant to be addressed?	What is the finished water pH?	Use This Flowchart[2]
No	Lead only, or Both Lead and Copper	< 7.2	**1a**
		7.2 - 7.8	**1b**
		>7.8 - 9.5	**1c**
		>9.5	**1d**
	Copper only	< 7.2	**2a**
		7.2 - 7.8	**2b**
		>7.8	**2c**
Yes	Lead and/or Copper	< 7.2	**3a**
		≥ 7.2	**3b**

Notes:

[1] Flowcharts 3a and 3b present several treatment options for lead and copper that also reduce iron and manganese. Systems can also consider removing iron and manganese first, then using flowcharts 1a through 2c to control for lead and/or copper.

[2] As discussed in Section 3.1.1, the term “limestone contactor” generically identifies filtration processes where calcite-containing materials are used to add pH, alkalinity, and DIC to water.

Flowchart 1a: Selecting Treatment for Lead only or Lead and Copper with pH < 7.2



Raise the pH in 0.5 unit increments and DIC to 5-10 mg/L as C using one of the following:

- Soda Ash
- Potash
- Limestone contactor

1. Raise the pH in 0.5 unit increments using one of the following:
   - Soda Ash
   - Potash
   - Caustic Soda
   - Aeration
   - Limestone contactor[1]
   - Silicates

OR

2. Add orthophosphate and raise the pH to 7.2 - 7.8.

1. Raise the pH in 0.25 unit increments using one of the following:
   - Soda Ash
   - Potash
   - Caustic Soda
   - Aeration

OR

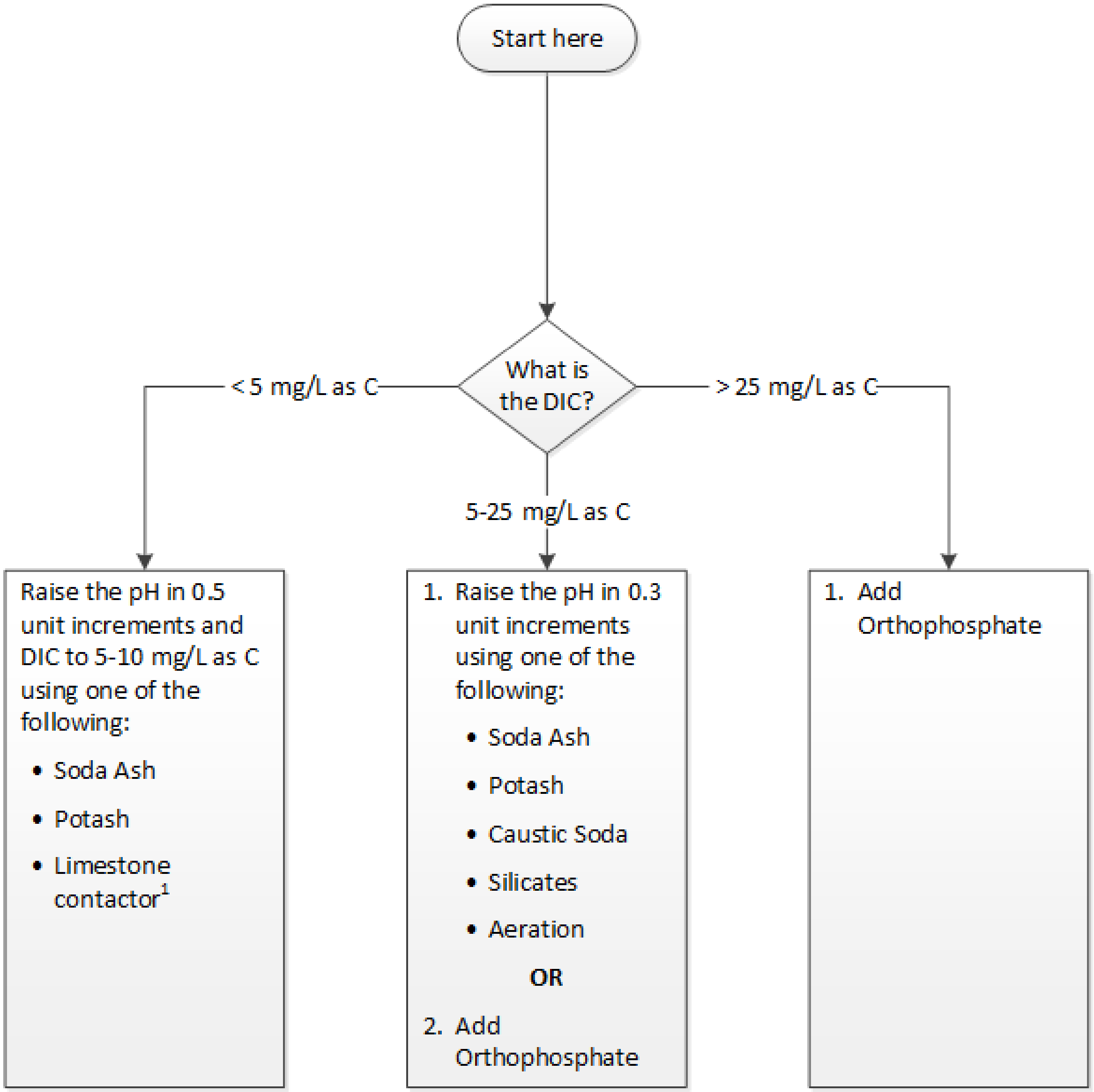
2. Add orthophosphate and raise the pH to 7.2 - 7.8.

KEY:
AL = Action Level
Caustic soda = sodium hydroxide (NaOH)
DIC = Dissolved Inorganic Carbon
mg/L as C = milligrams per liter as carbon
Potash = potassium carbonate (K2CO3)
Soda ash = sodium carbonate (Na2CO3)

Footnotes:

1. Limestone contactors may not be appropriate when DIC > 10mg/L as C.

Flowchart 1b: Selecting Treatment for Lead only or Lead and Copper with pH from 7.2 to 7.8



Raise the pH in 0.5 unit increments and DIC to 5-10 mg/L as C using one of the following:

- Soda Ash
- Potash
- Limestone contactor[1]

1. Raise the pH in 0.3 unit increments using one of the following:
    - Soda Ash
    - Potash
    - Caustic Soda
    - Silicates
    - Aeration

OR

2. Add Orthophosphate

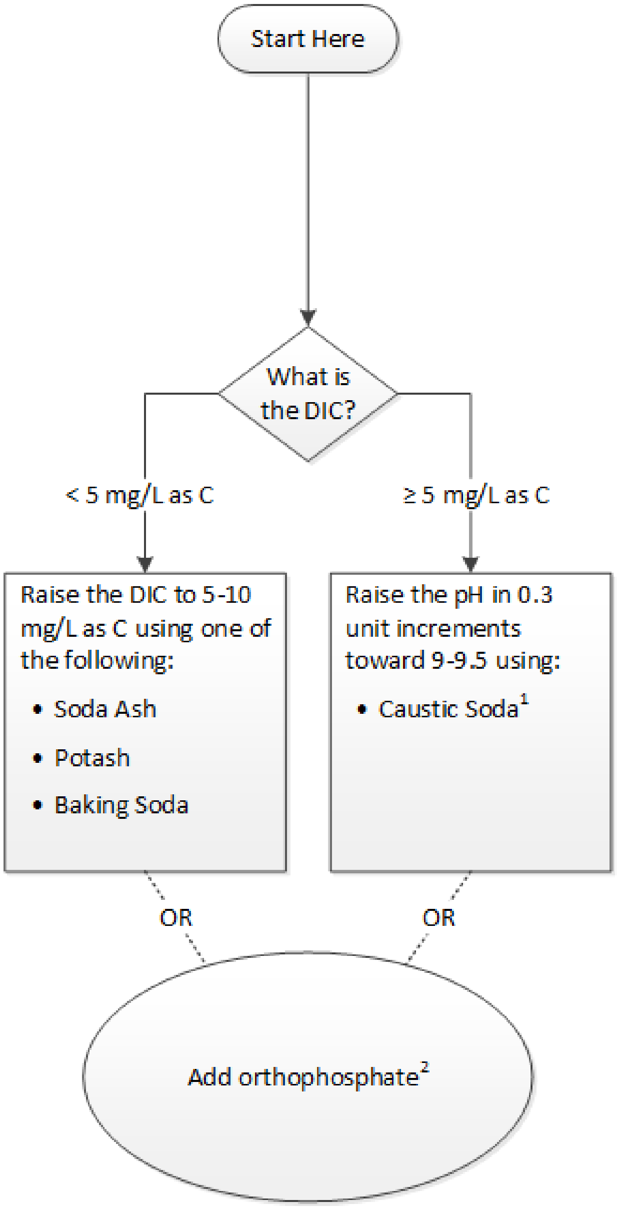
1. Add Orthophosphate

KEY:
AL = Action Level
Caustic soda = sodium hydroxide (NaOH)
DIC = Dissolved Inorganic Carbon
mg/L as C = milligrams per liter as carbon
Potash = potassium carbonate (K_2CO_3)
Soda ash = sodium carbonate (Na_2CO_3)

Footnotes:

1. Carbon dioxide feed before the limestone contactor may be necessary.

Flowchart 1c: Selecting Treatment for Lead only or Lead and Copper with pH > 7.8 to 9.5



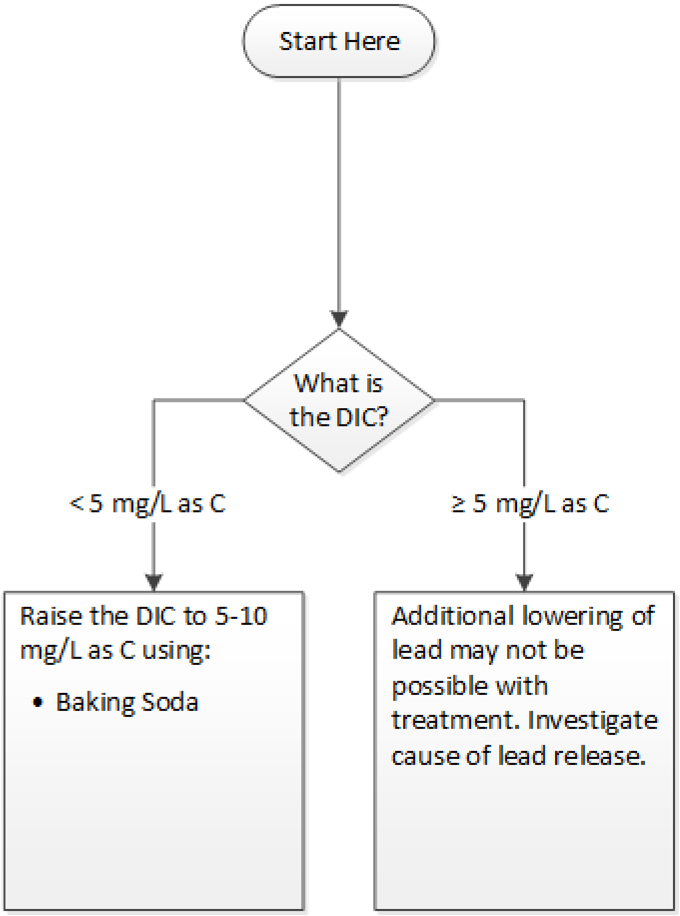
KEY:
AL = Action Level
Baking soda = sodium bicarbonate ($NaHCO_3$)
Caustic soda = sodium hydroxide (NaOH)
DIC = Dissolved Inorganic Carbon
mg/L as C = milligrams per liter as carbon
Potash = potassium carbonate (K_2CO_3)
Soda ash = sodium carbonate (Na_2CO_3)

Footnotes:

[1] Systems with copper plumbing may experience copper pitting problems when operating at pH 9 – 9.5 and DIC of 5 – 15. Orthophosphate may be a better option for these systems.

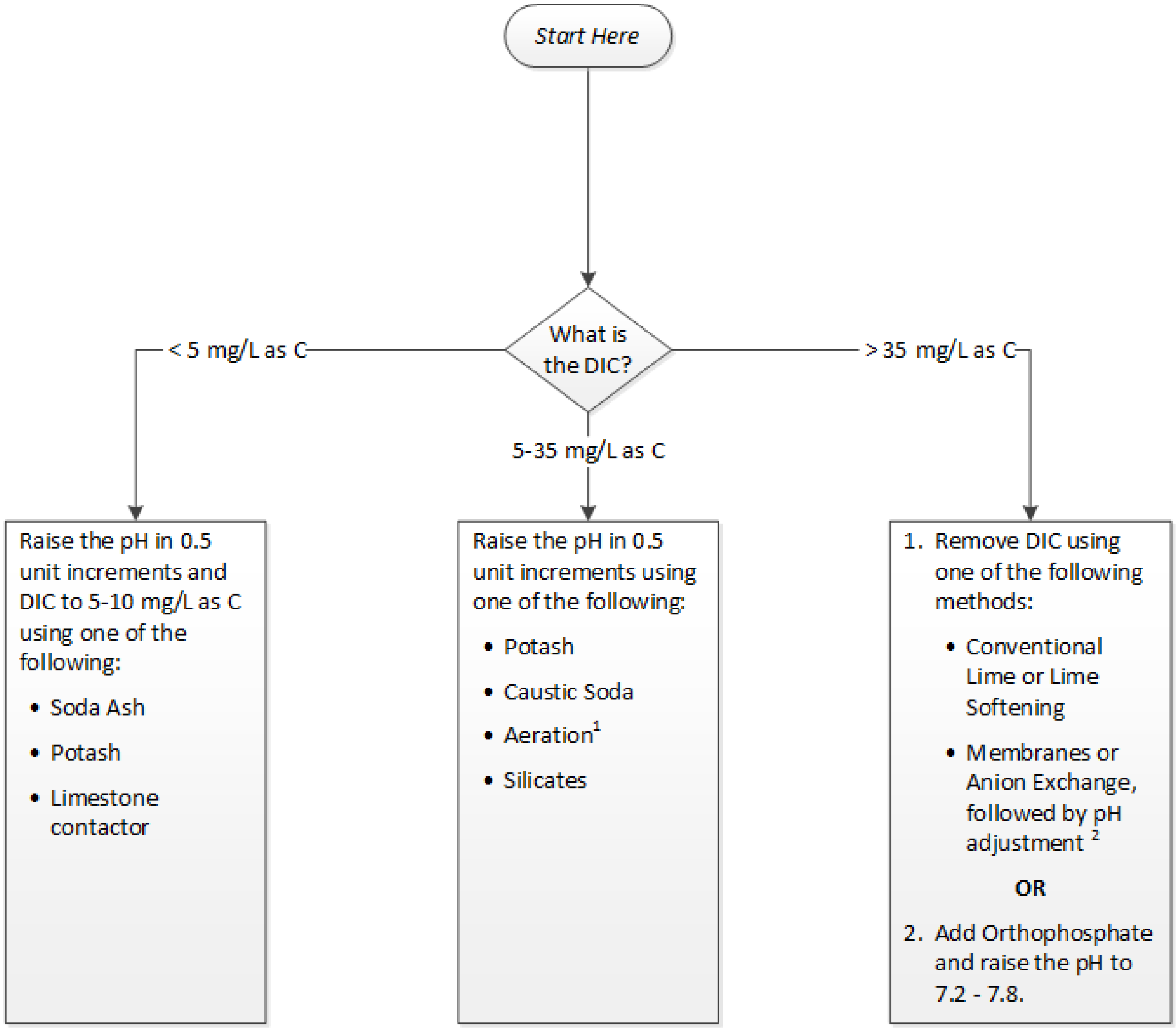
[2] Optimal pH range for orthophosphate is 7.2 - 7.8 but phosphate may be effective at higher pH depending on dose. Orthophosphate effectiveness is lowest in the pH range of 8 – 8.5. Systems should also avoid this range because of inadequate buffering in the distribution system.

Flowchart 1d: Selecting Treatment for Lead only or Lead and Copper with pH > 9.5



KEY:
AL = Action Level
Baking soda = sodium bicarbonate ($NaHCO_3$)
DIC = Dissolved Inorganic Carbon

Flowchart 2a: Selecting Treatment for Copper Only with pH < 7.2

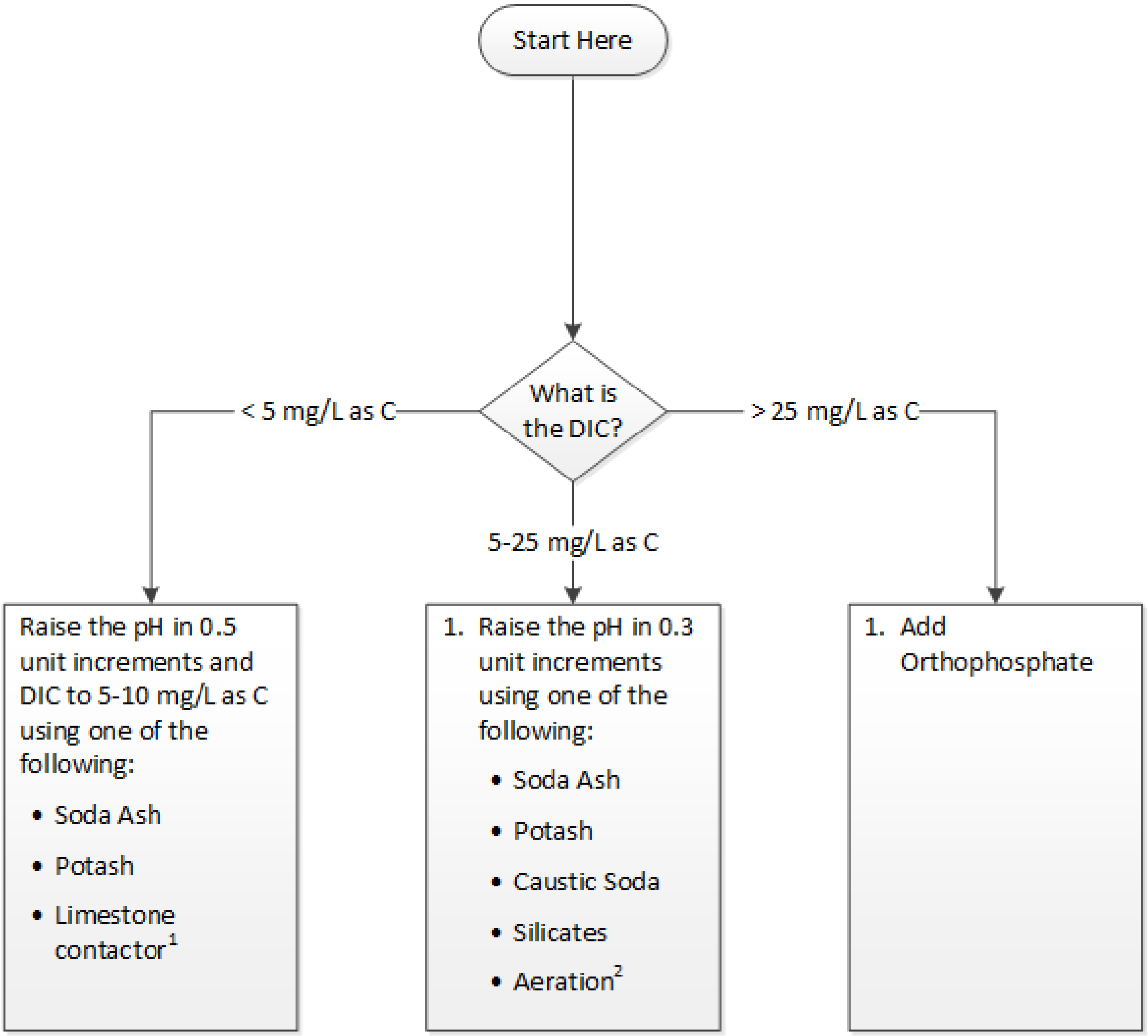


KEY:
AL = Action Level
Caustic soda = sodium hydroxide (NaOH)
DIC = Dissolved Inorganic Carbon
mg/L as C = milligrams per liter as carbon
Potash = potassium carbonate (K_2CO_3)
Soda ash = sodium carbonate (Na_2CO_3)

Footnotes

1. May be most appropriate at higher end of DIC range
2. To achieve optimal levels, consider treating less than 100 percent of the water (i.e., split stream).

Flowchart 2b: Selecting Treatment for Copper Only with pH from 7.2 to 7.8

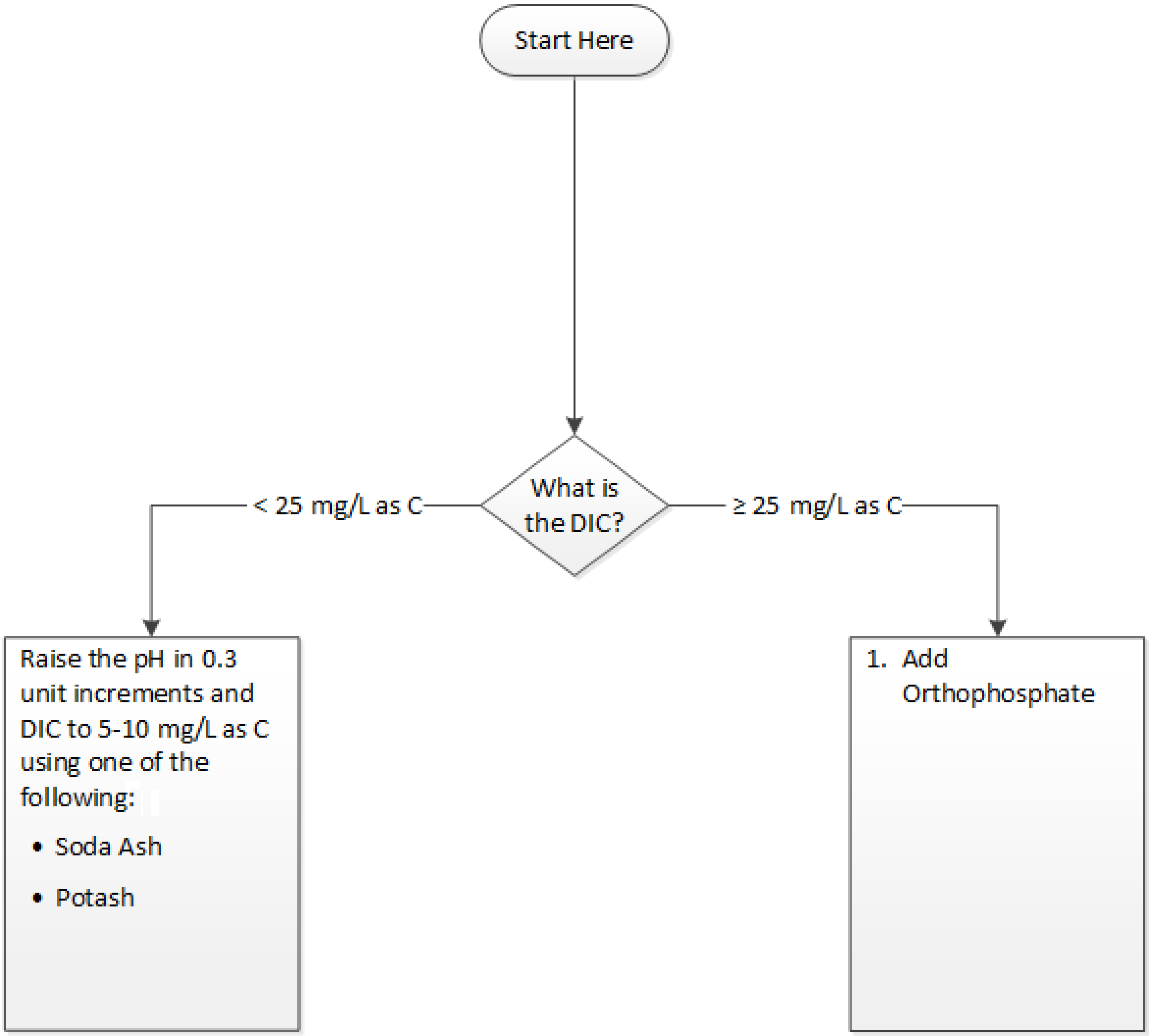


KEY:
AL = Action Level
Caustic soda = sodium hydroxide (NaOH)
DIC = Dissolved Inorganic Carbon
mg/L as C = milligrams per liter as carbon
Potash = potassium carbonate (K_2CO_3)
Soda ash = sodium carbonate (Na_2CO_3)

Footnotes:

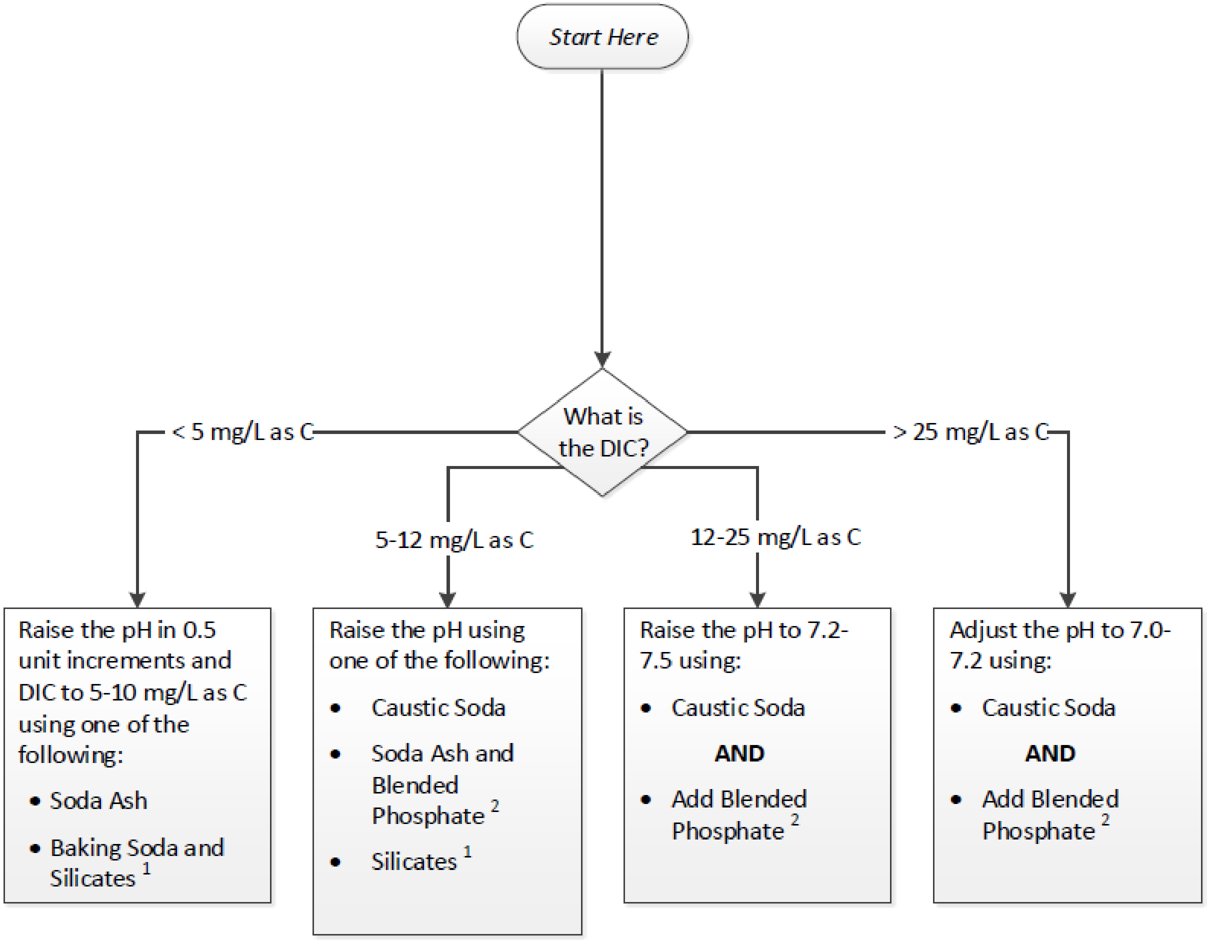
1. Carbon dioxide feed before the limestone contactor may be necessary.
2. May be most appropriate at higher end of DIC range

Flowchart 2c: Selecting Treatment for Copper Only with pH > 7.8



KEY:
AL = Action Level
DIC = Dissolved Inorganic Carbon
mg/L as C = milligrams per liter as carbon
Potash = potassium carbonate (K_2CO_3)
Soda ash = sodium carbonate (Na_2CO_3)

Flowchart 3a: Selecting Treatment for Lead and/or Copper with Iron and Manganese in Finished Water and pH < 7.2

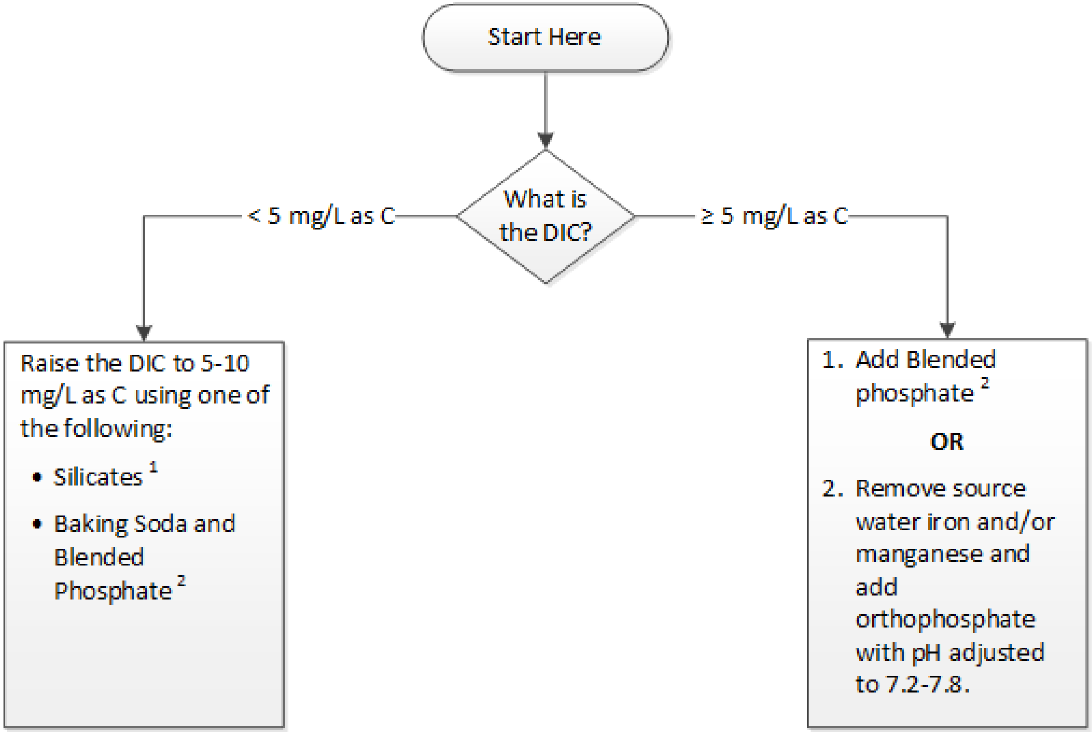


KEY:
AL = Action Level
Baking soda = sodium bicarbonate ($NaHCO_3$)
Caustic soda = sodium hydroxide (NaOH)
DIC = Dissolved Inorganic Carbon
mg/L as C = milligrams per liter as carbon
Soda ash = sodium carbonate (Na_2CO_3)

Footnotes:

1. Silicates are most effective when combined iron and manganese concentrations are less than 1.0 mg/L.
2. The effectiveness of blended phosphate varies based on the formulation. Additional evaluation and/or monitoring is recommended. See Section 3.3.2 for additional discussion.

Flowchart 3b: Selecting Treatment for Lead and/or Copper with Iron and Manganese in Finished Water and pH ≥ 7.2



KEY:
AL = Action Level
Baking soda = sodium bicarbonate ($NaHCO_3$)
DIC = Dissolved Inorganic Carbon
mg/L as C = milligrams per liter as carbon

Footnotes:

1. Silicates are most effective when combined iron and manganese concentrations are less than 1.0 mg/L.
2. The effectiveness of blended phosphate varies based on the formulation. Additional evaluation and/or monitoring is recommended. See Section 3.3.2 for additional discussion. Blended phosphates are less effective for controlling copper at DIC greater than 25 mg/L as C.

3.2.4 Technical Recommendations for Identifying Possible Limitations for Treatment Options (STEP 4)

Once the treatment option(s) are selected from the flowcharts, review the information in this section to identify secondary impacts and possible constraints. Many of these constraints can be overcome with additional treatment modifications at the water treatment plant or wastewater treatment plant (WWTP). Observations and actions to address secondary impacts can be documented using Form E.2 in Appendix E.

Possible Limitations of pH/alkalinity/DIC Adjustment

Although many systems have successfully adjusted pH, alkalinity, and DIC to control lead and copper release, this corrosion control method has secondary impacts that may limit its use. Because silicate addition raises the pH of the water, secondary impacts for this treatment option are similar to the secondary impacts of raising pH for controlling lead and copper release.

Three factors that could limit the use of pH/alkalinity/DIC adjustment and silicates are: (1) optimal pH for other processes, particularly disinfection; (2) calcium carbonate precipitation; and (3) oxidation of iron and manganese. Observations and actions to address secondary impacts can be documented using Form E.2 in Appendix E.

(1) Optimal pH for other processes

Different treatment processes within the plant such as coagulation and disinfection have different target pH ranges. Determining the proper location to add a pH and/or alkalinity adjustment chemical should be considered in light of other process objectives.

Adjusting pH for corrosion control can affect disinfection performance and compliance with Surface Water Treatment Rules and possibly the Ground Water Rule (for those ground water systems that are required to provide 4-log virus inactivation). For systems that use chlorine for primary disinfection, increasing the pH prior to the chlorine contact chamber may reduce disinfection performance and require an increase in chlorine dose or contact time to meet the required CT.[22] For systems that consider contact time in the piping prior to the first customer as part of their CT calculation, a higher chlorine dose may be needed to meet CT. To minimize disinfection impacts, systems should adjust pH for corrosion control after CT has been achieved if possible. A system that plans to make a significant change to its disinfection practice to comply with the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR), such as a change in disinfectant type or process, must develop disinfection profiles and calculate disinfection benchmarks for *Giardia lamblia* and viruses (§§141.708-709).

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[22] CT is chlorine concentration multiplied by contact time. Required CT for chlorine is very dependent on pH, with greater CT required at higher pH levels.

Changing the pH and/or alkalinity may also impact the ability of a system to maintain a disinfectant residual in the distribution system. In most cases however, increasing the pH for corrosion control can help maintain the disinfectant residual because the disinfectant will react at a slower rate with metals being released at the pipe surface.

Changes in pH can also affect formation of disinfection byproducts (DBPs). Total trihalomethanes (TTHM) formation tends to increase at higher pH levels, while formation of haloacetic acids (HAA5) tends to decrease. See the EPA Simultaneous Compliance Guidance Manual for the Stage 2 and LT2 Rules (USEPA, 2007b) for more information on how pH changes can impact DBP formation.

(2) Calcium Carbonate Precipitation

If the finished water has high hardness (specifically the calcium portion of hardness), raising the pH and DIC may cause calcium carbonate to precipitate in the distribution system, clogging hot water heaters and producing cloudy water. Calcium carbonate precipitation is site-specific and depends on many factors; therefore, a system evaluation should be conducted as described in Step 2 above.

If calcium carbonate precipitation is determined to be a potential problem, systems can take one of the following approaches:

- Choose a different CCT method such as using phosphate-based corrosion inhibitor,
- Remove DIC with ion exchange or membrane filtration, or
- Add softening to remove calcium.

(3) Oxidation of Iron and Manganese

Iron and manganese in oxidized form can agglomerate into larger particles causing aesthetic problems in water distribution systems, resulting in black and/or red water complaints. Dissolved oxygen and chemical oxidants such as chlorine may oxidize iron and manganese, and increasing the pH can increase the rate of oxidation. The two standard approaches for these situations are removing iron and manganese at the plant, or sequestering it. Wherever possible, removal of source water iron and manganese is the preferred approach. A common removal strategy is aeration or chlorination followed by filtration. Aeration will also raise the pH so this strategy may meet the system's goals of both iron and manganese removal and pH adjustment for reducing lead and copper release.

Sequestering agents such as polyphosphates and sodium hexametaphosphate may reduce black and/or red water complaints from iron and manganese oxidation, but may also cause increases in lead and copper levels measured at the tap (Schock, 1999; Cantor et al., 2000; Edwards and McNeil, 2002). Vendors often recommend blended phosphates as a lead and copper control strategy for systems with elevated iron and manganese. Blended phosphates include both polyphosphate and orthophosphate in different percentages. Blended phosphates should be used with caution; see Section 3.3 for more information. Silicates can also be used to sequester iron and manganese depending on their concentration in the raw water (Schock et al., 1996; Kvech and Edwards, 2001).

Possible Limitations of Phosphate-Based Corrosion Inhibitors

Although phosphate-based corrosion inhibitors are used widely by water systems, there are limitations to their application. Two factors that could limit the use of phosphate-based corrosion inhibitors are: (1) reactions with aluminum; and (2) impacts on wastewater treatment plants. Observations and actions to address secondary impacts can be documented using Form E.2 in Appendix E.

(1) Reactions with Aluminum

Aluminum can occur in the distribution system as an impurity introduced with lime or when a system uses alum for coagulation. As noted in Section 2.3.9, aluminum can interfere with orthophosphate effectiveness by forming aluminum phosphate ($AlPO_4$) precipitates, which reduces the amount of orthophosphate available for lead and copper control. Aluminum phosphate precipitates can result in smaller pipe diameters, increased head-loss, and increased operational cost (AWWA, 2005). Although aluminum may also provide some protection of lead surfaces by forming films with hydroxide, silicate, or phosphate, these films are prone to sloughing when there are changes in flow or water quality or when LSLs are physically disturbed during routine maintenance and repair activities. These dislodged scales can release metals that may become entrapped in the interior (premise) plumbing, potentially increasing lead and copper levels in the water (Schock, 2007b).

(2) Impacts on Wastewater

Because of problems with nutrient enrichment of surface waters in the United States, there has been concern about adding phosphate-based corrosion inhibitors to drinking water because it 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. Regardless of the situation, it is important that systems 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.

Survey findings from 14 utilities showed that adding a phosphate-based corrosion inhibitor increased the phosphorus load to the wastewater treatment plant by 10 to 35 percent, with a median of 20 percent (Rodgers, 2014). Slightly less than half of the survey's respondents removed phosphorus at the WWTP (Rodgers, 2014). This percentage might increase in the future. Rodgers (2014) reported that in 2013, five states had statewide phosphorus limits for lakes and reservoirs.

Phosphorus can be removed at the WWTP using biological or chemical means. In the District of Columbia, the Blue Plains WWTP added more ferric chloride to chemically remove phosphorus after an orthophosphate corrosion inhibitor was added to drinking water; the additional cost was minor compared to their overall operations budget (Cadmus Group, 2004). Wastewater utilities can also use biological phosphorus removal or a combination of biological and chemical removal techniques.

Prior to selecting a phosphate-based corrosion inhibitor, water systems and primacy agencies should work with wastewater utility personnel to estimate the additional phosphorus load to the WWTP and assess if the load could cause the plant to exceed permit limits or cause other operational problems. Additional information on nutrient enrichment and phosphorus removal strategies can be found in EPA's Nutrient Control Design Manual (USEPA, 2010a).

Use of a zinc orthophosphate corrosion inhibitor can increase zinc loading to the WWTP. Schneider et al. (2011) noted that, based on three case studies, most of the zinc in zinc orthophosphate makes its way into the wastewater treatment stream. Although many systems have successfully used zinc orthophosphate for corrosion control, zinc can inhibit biological wastewater treatment processes, particularly nitrification and denitrification. Moreover, EPA has set limits for zinc in processed sludge that is land applied (USEPA, 2004b). Schneider et al. (2011) notes that "The results of the utility case studies indicate that release of zinc in wastewater residuals and/or receiving streams can be a concern for some utilities." Water systems and primacy agencies should work with wastewater utility personnel to determine if additional zinc loading may be an issue.

3.2.5 Technical Recommendations for Evaluating Feasibility and Cost (STEP 5)

Systems should consider operability, reliability, system configuration, and other site-specific factors when evaluating CCT alternatives. In cases where more than one treatment option can meet the OCCT definition of the rule,[23] systems may want to consider cost factors including costs for capital equipment, operations, and maintenance.

3.3 Setting the Target Dose and Water Quality

This section provides technical recommendations on setting the target dose and water quality for pH/alkalinity/DIC adjustment, phosphate-based corrosion inhibitors, and silicate inhibitors. Note that the recommendations provided in this section are intended as generalized guidelines for the reader's reference. The characteristics of individual systems (e.g., water quality, distribution system configuration, sources of lead and copper, etc.) may warrant considering other values that are distinct from those provided below. For these reasons, they should not be interpreted or prescribed as default minimums and/or maximums.

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[23] As noted in Chapter 1 and Appendix A, the LCR defines OCCT as "the 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." (§141.2)

3.3.1 pH/Alkalinity/DIC Adjustment

As explained previously, the pH, alkalinity, and DIC of the water have a significant influence on lead and copper release. As a reminder, these three parameters are interrelated – if you know two of them, you can estimate the third using the table in Appendix B. The following discussion provides technical recommendations for determining the target pH, alkalinity, and DIC when controlling for lead only or lead and copper, or when controlling for copper only.

To Control for Lead Only or Lead and Copper

The following technical recommendations can assist with the establishment of target pH, alkalinity, and DIC ranges for controlling lead only, or both lead and copper release in drinking water systems. Note that in general, lower pH levels can be used when controlling only for copper release – see the next section for guidelines for those systems that do not have a lead release problem but are targeting copper corrosion control only. Note also that the guidelines below are based on formation of adherent lead carbonate scales based on Pb(II) chemistry[24].

- The target pH should be **8.8 to 10**. Systems with lead service lines that are not using a corrosion inhibitor should consider increasing the pH to **9.0 or greater**. Note that lower pH values, particularly between 8.2 and 8.5, can result in poor buffer intensity of the water (regardless of DIC levels) and wide swings in distribution system pH. See Section 2.3.4 for additional discussion of buffer intensity.

- Sufficient alkalinity and DIC are needed to form the protective scale and provide buffer intensity, but too much can solubilize lead. These factors should be considered when determining a target alkalinity/DIC range. The graph in Exhibit 2.3 can be used to evaluate the effect of DIC on buffer intensity and identify a minimum DIC range for the system's target pH. In general, the higher the pH is in the 8.8 to 10 range, the less DIC is needed to buffer the water. Information on the relationship between DIC and lead solubility is provided in Schock and Lytle (2011) for a modeled water. Lead solubility increases (i.e., more lead is released into the water) with increasing DIC concentrations above approximately 20 mg/L (as C). Schock and Lytle (2011, Figure 20-21) show minimum lead solubility at DIC between 5 and 10 mg/L as C.

As a reminder, increasing the pH to 8.8 – 10 may cause calcium carbonate precipitation if calcium is present, see Section 3.2.2 for additional discussion.

To Control for Copper Only

Adjustment of pH/alkalinity/DIC for copper control can generally be achieved at a lower target pH (as low as 7.8) than the pH needed for lead control. Copper corrosion can be controlled at even lower pH levels (i.e., between 7.0 and 7.8), but alkalinity and DIC become the limiting factors. Schock and Lytle (2011) note that hard, high alkalinity ground waters are often

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[24] For more information on Pb(II) chemistry and also influences of Pb(IV) scale, see Sections 2.2.1 and 2.3.6.

aggressive towards copper and hard to treat with pH adjustment because of calcium carbonate precipitation potential. These waters may not be candidates for pH/alkalinity/DIC adjustment and warrant considering orthophosphate or possibly removal of DIC through ion exchange, membranes, or aeration.

3.3.2 Phosphate-Based Inhibitors

The effectiveness of orthophosphate treatment depends on many factors, including phosphate dose, pH, DIC, and other constituents in the water (e.g., aluminum, iron, manganese). As noted earlier, polyphosphates alone should *not* be used to treat for lead and copper; they are mainly used to sequester iron and manganese. Special considerations for use of blended phosphates are provided at the end of this section.

Conventional wisdom is that orthophosphate treatment for controlling lead and copper should target residual concentrations of **0.33 to 1.0 mg/L as P** (1.0 to 3.0 mg/L as PO_4)[25] at the tap when pH is within the range of **7.2 to 7.8**. ***Higher orthophosphate doses*** (1.0 to 1.2 mg/L as P, or 3 to 3.5 mg/L PO_4 and higher) may be needed under the following circumstances:

- To control lead release from LSLs.
- To control copper corrosion from new copper pipe in high DIC water.
- To mitigate copper pitting in some water qualities.
- If the system has aluminum carry-over from alum coagulation and/or presence of iron, manganese, and/or magnesium in finished water.

While the pH range of 7.2 to 7.8 is still considered optimal, systems ***should not*** automatically reduce the pH of their water if it is 8 or higher when starting orthophosphate treatment. Orthophosphate may be effective at pH as high as 9, although dose requirements may not be the same as for pH from 7.2 to 7.8. Laboratory results suggest that less effective control of lead release occurs between pH 8 and 8.5 than either above or below that range (Schock et al., 1996; Miller, 2014). Systems should therefore avoid operating between pH 8 and 8.5, if possible, to control for lead release. For copper, orthophosphate effectiveness is not strongly affected by pH when pH is between 7 and 8; dose is much more important.

Systems and primacy agencies should also consider the DIC of finished water when determining the target orthophosphate dose. In general, orthophosphate is more effective at low DIC (<10 mg C/L). Also, the pH is less important for lead control in low DIC waters.

Note that the target orthophosphate concentration is the level needed to control corrosion in ***premise plumbing***. Because orthophosphate will react with metals and other compounds, the concentration leaving the treatment plant may need to be higher to achieve the target

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[25] Note that these concentrations are a general point of reference; they are not intended to be interpreted or universally prescribed as default minimums or maximums. Characteristics of individual systems (e.g., water quality, distribution system configuration, sources of lead and copper, etc.) may warrant consideration of other target concentrations, distinct from those provided above. Systems may also benefit from supplemental diagnostic monitoring to verify optimization.

concentration at the tap. In particular, aluminum (e.g., that was carried over from alum coagulation) can react with orthophosphate and reduce the amount available in premise plumbing. During start-up, systems should be prepared to adjust the dose at the treatment plant to meet the target dose at the tap throughout the distribution system. See Chapter 5 for additional recommendations on start-up of orthophosphate treatment.

Some systems have started orthophosphate treatment using a higher passivation dose, followed by a lower maintenance dose for long-term treatment. Hill and Cantor (2011) recommend that the passivation dose be 2 to 3 times higher than the target maintenance dose in order to build up a protective film as quickly as possible. The amount of time needed for the initial passivation dose to form adequate scale is unknown, and will vary depending on the system's specific water quality. Lead levels may continue to decline for years after an optimal orthophosphate dose has been applied, due to the slow rate of scale formation.

Systems with LSLs should evaluate whether the orthophosphate dose is enough to passivate disturbed LSLs in a timely manner. Routine maintenance or repairs such as water main replacements, meter installations, service line and shut-off valve replacements, and leak repairs may disrupt LSL scales and result in high lead levels. When evaluating the success of OCCT, systems and primacy agencies should consider the impact of these physical disturbances on lead levels at the tap (Del Toral et al., 2013). In addition, when establishing a maintenance dosage, it is important to consider other factors such as homes with chronically low water use that have LSLs. Ongoing diagnostic monitoring at these sites before and after treatment installation or adjustment can provide useful information for establishing a proper maintenance dose.

Special Consideration for Blended Phosphates

Blended phosphates have been used for corrosion control and to sequester iron and manganese. Blended phosphates have been shown to be effective for reducing lead levels; however, the lead corrosion scale may not be as robust as the scale created by orthophosphate and, thus, may be more susceptible to physical disturbances and low water use conditions (Del Toral et al., 2013; Wasserstrom et al., 2017). It is unclear if blended phosphates work well to control copper corrosion, especially at high alkalinities.

The effectiveness of blended phosphates cannot be based on the orthophosphate concentration in the blend for the following reasons:

- Blended phosphates control corrosion by creating a barrier film from the interaction of calcium and aluminum in the bulk water with phosphorus containing compounds (Wasserstrom et al., 2017). Thus, calcium and aluminum play a role in effectiveness.

- If the polyphosphate portion of the blend has a high affinity for sequestering lead or copper, it may counteract the benefit of the orthophosphate portion in forming solid lead and copper compounds.

The percent of orthophosphate in the blend can vary widely (from 5 to 70 percent (Hill and Cantor, 2011)). Blended phosphate should contain a minimum orthophosphate concentration of 0.5 mg/L as P (1.5 mg/L as PO_4) as a starting point for evaluation. The orthophosphate ratio in the blend and/or the dose may need to be increased to provide adequate lead control. In some cases, however, simply adding more blended phosphate may not be effective because, if there is excess polyphosphate available beyond what is bound up with other constituents in the water, it can sequester the lead and copper. EPA recommends a demonstration study, additional monitoring, or both for systems that recommend blended phosphates to control lead release.

3.3.3 Silicate Inhibitors

The effectiveness of silicate inhibitors depends on silicate level, pH, and DIC of the water. Adding silicates can raise the pH, so lead and copper level reductions may occur due to an increase in pH as well as passivation. In addition to providing lead and copper control, silicates can sequester iron and manganese if the levels of these constituents are not too high (not greater than 1 mg/L combined) (Schock et al., 1996; Schock, Lytle, et al., 2005).

Many systems have not considered silicate inhibitors for lead and copper control due to the lack of research and field information proving its effectiveness, the estimated operating costs and high dosage rates required, and the time it takes to reduce lead concentrations (Hill and Cantor, 2011).The literature does report a successful case study for a small system in Massachusetts that instituted chlorination and sodium silicate addition in three wells to address LCR compliance and intermittent red water problems (Schock, Lytle, et al., 2005). An initial silicate dosage rate of 25-30 mg/L was effective for reducing lead and copper levels by 55 and 87 percent, respectively, and raised the pH from 6.3 to 7.1. LCR compliance was achieved when the silicate dosage rate was increased to 45-55 mg/L at two wells which raised the pH to 7.5. In another study, Vaidya (2010) found that sodium silicate significantly reduced lead and copper release in bench-scale studies using coupons from 30 to 35-year-old distribution pipes.

Relatively high silicate doses (in excess of 20 mg/L) may be required to control lead release (Schock, Lytle, et al., 2005). A startup dose of 24 mg/L is recommended, followed by a gradual reduction after 60 days to a maintenance dose of 8 to 12 mg/L (Schock and Lytle, 2011; Hill and Cantor, 2011). Chloride, calcium, and magnesium concentrations in the water can affect the optimum dose (Hill and Cantor, 2011). A review of several case studies and literature reports suggested that a pre-existing layer of corrosion products on the pipes was required in order for silicate to properly form a protective layer, at least in copper pipes (LaRosa-Thompson et al., 1997). Similar to phosphate-based inhibitors, it is important to maintain continuous dosing of the silicate inhibitor to ensure effective corrosion control.

Chapter 4: Review of Corrosion Control Treatment Steps under the LCR

Corrosion control treatment (CCT) requirements under the Lead and Copper Rule (LCR) differ depending on the system size (i.e., population served). Most systems serving more than 50,000 people were required to meet a series of deadlines beginning in 1993 to determine optimal corrosion control treatment steps (OCCT) and install OCCT by January 1, 1997.[26] Any system that served 50,000 or fewer people at the time of the LCR, but that grew in population or combined with another system so that they now serve more than 50,000 people (called systems ***newly*** serving more than 50,000 people for the purposes of this document) must also complete CCT steps. Because the regulatory deadlines for systems serving more than 50,000 people have passed, systems newly serving 50,000 people must follow the schedule for systems serving 3,301-50,000 people.[27] Systems serving 50,000 or fewer people are not required to conduct CCT steps under the LCR unless they exceed the lead and/or copper action level (AL).

This chapter presents a review of CCT steps as required by the LCR along with additional technical recommendations to systems and primacy agencies for the following categories of systems:

- Those serving 50,000 or fewer people that exceed the lead and/or copper AL (Section 4.1).
- Systems newly serving more than 50,000 people (Section 4.2).
- Existing systems serving more than 50,000 people that previously installed CCT but have subsequent action level exceedances (Section 4.2).

Chapter 5 follows with a review of LCR requirements and provides additional technical recommendations for CCT installation, startup, follow-up monitoring, and long-term corrosion control monitoring.

These sections are supported by the following appendices:

- Appendix D contains forms that can be used by systems to submit water quality data and system information to the primacy agency.
- Appendix E contains OCCT recommendation forms for systems serving 50,000 or fewer people.
- Appendix F summarizes tools available for conducting a corrosion control study.

Systems and primacy agencies can use the ***OCCT evaluation templates*** to complete many of the tables in the appendices related to their OCCT determination. The templates also provide an

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[26] All systems serving more than 50,000 people are required to conduct CCT steps unless they are deemed to have optimized corrosion control under §141.81(b)(2) or (b)(3).

[27] The schedule for completing CCT was clarified in the guidance manual, *Lead and Copper Rule Monitoring and Reporting Guidance for Public Water Systems* (USEPA, 2010b) as footnote 1 in Exhibit I-1. It specifies that a "system whose population exceeds 50,000 after July 1, 1994, must follow the schedule for medium-size systems, beginning with the requirement to complete a corrosion control study."

opportunity for primacy agencies to customize forms and to enter specific dates for compliance milestones. As a reminder, requirements in this section are based on the LCR as of the date this document was published.

4.1 Corrosion Control Treatment Steps for Systems Serving ≤ 50,000 People

Exhibit 4.1 summarizes the required CCT actions and deadlines when a system serving 50,000 or fewer people exceeds the lead and/or copper action level. The column furthest to the right shows the related section or Chapter where relevant technical recommendations are provided for the system or primacy agency.

It is important to note that in accordance with the LCR, systems serving 50,000 or fewer people have no more than ***6 months*** from the end of the monitoring period in which they had the AL exceedance to recommend OCCT to their primacy agency. The primacy agency then determines if a study is needed. If a study is not required, the primacy agency designates the OCCT within 24 months from the end of the monitoring period in which the system had the AL exceedance for those serving 3,300 or fewer people or within 18 months for those serving 3,301 to 50,000 people. If the primacy agency requires a study, the system must complete the study within 18 months after the primacy agency required the study to be conducted, after which the primacy agency designates the OCCT.

Also note that in accordance with the LCR, systems serving 50,000 or fewer people can discontinue the steps outlined in Exhibit 4.1 whenever their 90th percentile levels are at or below both ALs for two consecutive six-month monitoring periods. However, if these systems then exceed the lead or copper AL, they must recommence completion of the applicable CCT steps beginning with the first treatment step that was not completed in its entirety. The primacy agency may require a system to repeat treatment steps previously completed by the system where the Agency determines that this is necessary to properly implement the treatment requirements.

Exhibit 4.1: Review of CCT Requirements and Deadlines for Systems Serving ≤ 50,000 People (§141.81(e))

Requirement	Timetable for Completing Corrosion Control Treatment Steps[1]	Section Where Technical Recommendations Can Be Found
STEP 1: System exceeds the lead or copper action level (AL).		
STEP 2: System recommends OCCT.	Within 6 months[2]	Section 4.1.1
STEP 3: Primacy agency decides whether system must perform a corrosion control study. If system must conduct a corrosion control study, go to Step 5. If not, go to Step 4.	Within 12 months[2]	Section 4.1.2
STEP 4: Primacy agency designates OCCT for systems that were not required to conduct a study. Go to Step 7.	● Within18 months[2] for systems serving 3,301-50,000 people ● Within 24 months[2] for systems serving ≤ 3,300 people	Section 4.1.3
STEP 5: System completes corrosion control study.[3]	Within 18 months after primacy agency requires that such a study be conducted	Section 4.1.4
STEP 6: Primacy agency designates OCCT.[3]	Within 6 months after completion of Step 5	Section 4.1.5
STEP 7: System installs OCCT.	Within 24 months after the primacy agency designates such treatment	Section 5.1
STEP 8: System conducts follow-up sampling for 2 consecutive 6-month periods.	Within 36 months after the primacy agency designates OCCT	Section 5.2
STEP 9: Primacy agency designates OWQPs.[4]	Within 6 months after completion of Step 8	Section 5.3
STEP 10: System conducts continued WQP and lead and copper tap sampling.	The schedule for required monitoring is based on whether the system exceeds an AL and/or complies with OWQP ranges or minimums	Section 5.4

Notes:

[1] Systems serving 50,000 or fewer people can discontinue these steps whenever their 90th percentile levels are at or below both action levels for two consecutive six-month monitoring periods. However, if these systems then exceed the lead or copper action level, they must recommence completion of the applicable CCT steps.

[2] The required timetable (i.e., number of months) for completing Steps 2, 3, and 4 represent the number of months after the end of the monitoring period during which the lead and/or copper action level was exceeded in Step 1.

[3] These steps only apply to systems that were required to conduct a corrosion control study.

[4] If a small or medium system has installed corrosion control treatment, the primacy agency is obligated to fulfill Step 9. The primacy agency shall review the system's installation of treatment and designate optimal water quality parameters within 6 months after completion of Step 8, in accordance with 141.81(e)(7) and 141.82(f).

4.1.1 System Serving ≤ 50,000 People Makes OCCT Recommendation (STEP 2)

The LCR does not specify precisely how systems serving ≤ 50,000 are required to develop their OCCT recommendation. To help systems evaluate CCT alternatives and make their recommendation, EPA has provided technical information and recommendations in Chapter 3. Systems can use the forms in Appendix D to organize water quality data and other information and forms in Appendix E to document the results of their assessment and submit their data and recommendation to the primacy agency. Note that primacy agencies may also require a system to collect additional data/information under §141.82(a).

4.1.2 Primacy Agency Determines Whether a Study Is Required for System Serving ≤ 50,000 People (STEP 3)

Primacy agencies should review the data provided by the system (using forms in Appendices D and E) for completeness. If data are not sufficient to make a CCT determination, the primacy agency can request additional information from the system.

Once primacy agencies have reviewed the data and OCCT recommendation, they should determine if a study is needed. Exhibit 4.2 provides a checklist to support the primary agency in determining whether or not to require a CCT study. If more than two questions are answered "Yes," the primacy agency should consider requiring a study. Importantly, as stated in EPA's LCR guidance, EPA recommends that primacy agencies require all systems with ***lead service lines*** to conduct a corrosion control study.

If the primacy agency does not require a study, their next step is to designate OCCT (go to Section 4.1.3). Section 4.1.4 provides technical recommendations to support primacy agencies in the event that a corrosion control study is required.

Exhibit 4.2: Recommended Checklist to Support Determination of the Need for a CCT Study for Systems Serving ≤ 50,000 People

Category	Question	Response (YES or NO)
Presence of LSLs	Does the System have lead service lines?[1]	
pH stability	Is the range of pH values measured at the Entry Point > 1.0 pH units (Range = Max entry point pH – Min entry point)?	
	Is the range of pH values measured in the Distribution System > 1.0 pH units (Range = Max pH – Min pH)?	
Iron Deposition Potential	Is average Entry Point iron > 0.3 mg/L?	
	Is average Distribution System iron > 0.3 mg/L?	
Manganese Deposition Potential	Is average Entry Point manganese > 0.05 mg/L?	
	Is average Distribution System manganese > 0.05 mg/L?	
Calcium Carbonate Deposition Potential	Is average Hardness > 150 mg/L as $CaCO_3$? *Entry point of distribution system values may be used.*	
Chloride-to-Sulfate Mass Ratio (CSMR) Issues	Is the CSMR for either Entry Point or Distribution System data > 0.6? *Use Average Chloride Level divided by the Average Sulfate Level.*	
Source Water Changes in the Future	Did the system indicate that there may be source water changes in the future?	
Treatment Process Changes	Did the system indicate that there may be treatment process changes in the future including changes in coagulant?	

Note:

[1] If the system has LSLs, EPA guidance recommends the primacy agency require a study.

4.1.3 Primacy Agency Designates OCCT for System Serving ≤ 50,000 People (STEP 4)

As stated in the LCR, if the primacy agency determines that a study is not required, they must either approve the OCCT option recommended by the system or designate alternative CCT(s) from among those listed in §141.82(c)(1) (§141.82(d)). They must do this ***within 18 months*** after the end of the monitoring period during which the system exceeds the lead or copper AL for systems serving more than 3,300 people, ***and within 24 months*** for systems serving 3,300 or fewer people. Primacy agencies can use information in Chapters 2 and 3 to help make this determination.

The primacy agency must notify the system of its OCCT decision in writing and explain the basis for the determination (§141.82(d)(2)). The primacy agency should work closely with the system to determine the implementation approach and follow-up monitoring (See Chapter 5 for technical recommendations).

4.1.4 System Serving ≤ 50,000 People Conducts Corrosion Control Study (STEP 5)

As stated in the LCR and summarized in Exhibit 4.1, systems are required to complete the corrosion control study ***within 18 months*** of the primacy agency's determination that a study is required. Exhibit 4.3 summarizes corrosion control study requirements for systems from the LCR. Following the exhibit are: (1) technical recommendations for primacy agencies on what type of study to require; (2) technical recommendations for systems on study tools and other considerations; and (3) technical recommendations for systems on corrosion control study reporting.

Exhibit 4.3: Corrosion Control Study Requirements[1]

Corrosion Control Study Component	LCR Requirements
Corrosion Control Study Tools	Systems must evaluate the effectiveness of each CCT specified in §141.82(c)(1) and, if appropriate, combinations of treatments using either pipe rig/loop tests, metal coupon tests, partial-system tests, or analyses based on documented analogous treatments with other systems of similar size, water chemistry, and distribution system configuration (§141.82(a) and (c)(2)).
Monitoring Requirements	Systems must measure the following water quality parameters in any tests before and after evaluating the CCTs: Lead, copper, pH, alkalinity, calcium, conductivity, orthophosphate (when an inhibitor containing a phosphate compound is used), silicate (when an inhibitor containing a silicate compound is used), and water temperature (§141.82(c)(3)).
Identification of Constraints	Systems must identify all chemical or physical constraints that limit or prohibit the use of a particular CCT and document such constraints with at least one of the following (§141.82(c)(4)): • Data and documentation showing that a particular CCT has adversely affected other water treatment processes when used by another water system with comparable water quality characteristics; and/or • Data and documentation demonstrating that the water system has previously attempted to evaluate a particular CCT and has found that the treatment is ineffective or adversely affects other water quality treatment processes.
Effects on Other Treatment Processes	Systems must evaluate the effect of the chemicals used for CCT on other water quality treatment processes (§141.82(c)(5)).
Reporting	On the basis of an analysis of the data generated during each evaluation, the water system must recommend to the primacy agency in writing the treatment option that the corrosion control studies indicate constitutes OCCT for that system. Systems must provide a rationale for their recommendation along with all supporting documentation (§141.82(c)(6)).

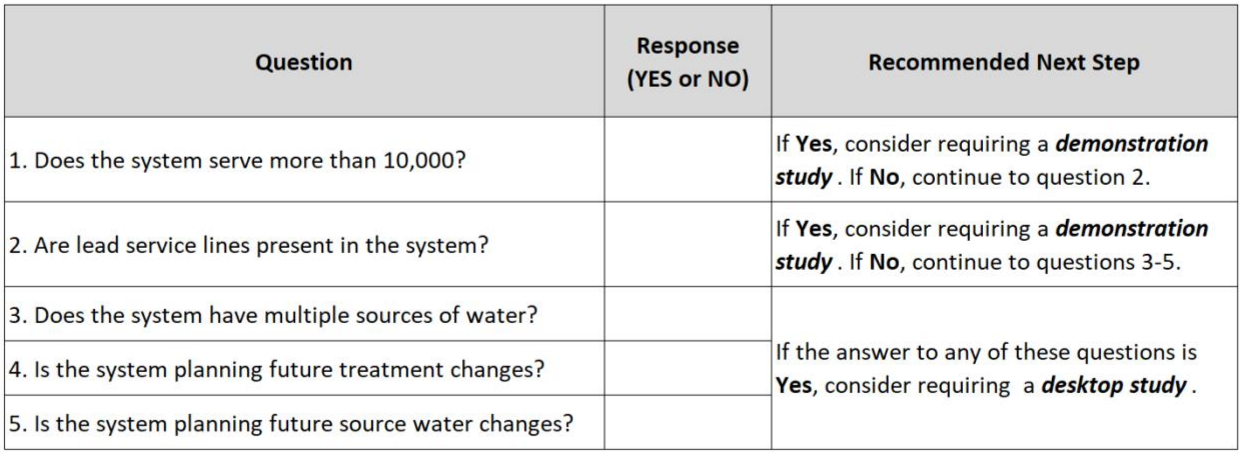
Note:

[1] Corrosion control studies may be required by the primacy agency. If they are, specific requirements for conducting the studies apply regardless of system size. They are from the LCR and are current as of the date of this publication.

(1) Technical Recommendations Regarding Type of Corrosion Control Study

There are several potential approaches to a CCT study. A study can be approached as a "desktop study" based on documented analogous treatments with other systems of similar size, water chemistry, and distribution system configuration, or a "demonstration study" using at least one of the following study tools: pipe rig/loop tests, metal coupon tests, or partial system tests. Systems serving 50,000 or fewer people may be able to satisfy CCT study requirements by performing a desktop study of analogous systems. Exhibit 4.4 provides a recommended checklist for primacy agencies to use when evaluating case-specific factors that may warrant requiring those systems to perform a demonstration study instead.

Exhibit 4.4: Recommended Checklist to Support Primacy Agency Determination of When to Require a Demonstration Study for Systems Serving ≤ 50,000 People



Question	Response (YES or NO)	Recommended Next Step
1. Does the system serve more than 10,000?		If **Yes**, consider requiring a ***demonstration study*** . If **No**, continue to question 2.
2. Are lead service lines present in the system?		If **Yes**, consider requiring a ***demonstration study*** . If **No**, continue to questions 3-5.
3. Does the system have multiple sources of water?		If the answer to any of these questions is **Yes**, consider requiring a ***desktop study*** .
4. Is the system planning future treatment changes?		
5. Is the system planning future source water changes?		

(2) Corrosion Control Study Tools

Appendix F describes tools that can be used for conducting desktop and demonstration corrosion control studies. It includes the study tools required by the rule (analyses based on documented analogous treatments (desktop study); or pipe rig/loop tests, metal coupon tests, or partial-system tests (demonstration studies)) – along with other tools such as pipe scale analysis and models that can be used to supplement the requirements. The appendix is not meant to be exhaustive – other tools might also be useful for determining the most effective CCT for the system.

Note that systems conducting desktop studies must at a minimum evaluate ***analogous treatments at other systems*** of similar size, water chemistry, and distribution system configuration to meet the corrosion control study requirements of the LCR.

(3) Corrosion Control Study Reporting

The system must provide the primacy agency with its recommended OCCT option along with the rationale for its recommendation and supporting documentation as described §141.82(c)(1) – (6). The system must also identify all chemical or physical constraints that limit or prohibit the use of a particular corrosion control treatment and document such constraints with at least one of the following (§141.82(c)(4) and (c)(6)):

- Data and documentation showing that a particular CCT has adversely affected other water treatment processes when used by another water system with comparable water quality characteristics; and/or

- Data and documentation demonstrating that the water system has previously attempted to evaluate a particular CCT and has found that the treatment is ineffective or adversely affects other water quality treatment processes.

The system must also evaluate the effect of the chemicals used for CCT on other water quality treatment processes (§141.82(c)(5) and (c)(6)).

EPA recommends that the system submit to the primacy agency a report that includes the required information identified above and additional data and analyses as follows:

- Options for addressing identified constraints, so that the system would be able to achieve and maintain OCCT, meet other water quality goals, and remain in compliance with all applicable drinking water regulations.
- The corrosion control study's conclusion (i.e., the recommended treatment) and a target level for pH, alkalinity, and corrosion inhibitors (if used).
- Recommended operating ranges for key parameters (pH, alkalinity, and inhibitor (if used)) both at the entry point and in the distribution system.
- Treatment chemicals and dosages that will be used to maintain OCCT, recommendations for quality assurance testing of chemicals, and follow-up monitoring recommendations.
- The system's plan for treatment start-up (see Sections 3.3 and 5.1 for technical recommendations for start-up of pH/alkalinity/dissolved inorganic carbon (DIC) adjustment and phosphate-based corrosion inhibitor treatment).

Exhibit 4.5 and Exhibit 4.6 provide possible outlines for desktop and demonstration study reports, respectively.

Exhibit 4.5: Possible Outline for a Desktop Study Report

Executive Summary

- **I. Introduction**
- **II. Project Background**
- **III. Review of Existing Information**
    - A. Water System Information (provide a system schematic)
    - B. Water Quality Data
        - 1. Raw water
        - 2. Entry Point
        - 3. Distribution system
        - 4. Tap
    - C. Pipeline and Plumbing Materials
    - D. Summary of Water Quality Complaints
    - E. Analogous System Information
- **IV. Potential Causes of Elevated Lead and/or Copper Levels in the System**
- **V. Identification and Assessment of Corrosion Control Alternatives**
- **VI. Evaluation of Corrosion Control Alternatives**
    - A. Performance
    - B. Constraints
    - C. Recommended OCCT

Exhibit 4.6: Possible Outline for a Demonstration Study Report

Executive Summary

- **I. Introduction**
- **II. Project Background**
- **III. Review of Existing Information**
  - A. Water System Information (provide a system schematic)
  - B. Water Quality Data
    - 1. Raw Water
    - 2. Entry Point
    - 3. Distribution System
    - 4. Tap
  - C. Pipeline and Plumbing Materials
  - D. Summary of Water Quality Complaints
  - E. Analogous System Information
- **IV. Special Studies**
  - A. Bench Scale Studies
    - 1. Methods and Materials
    - 2. Results
  - B. Pipe Loop Studies
    - 1. Methods and Materials
    - 2. Results
  - C. Partial System Testing
    - 1. Methods and Materials
    - 2. Results
- **V. Potential Causes of Elevated Lead and/or Copper Levels in the System**
- **VI. Identification and Assessment of Corrosion Control Alternatives**
- **VII. Evaluation of Corrosion Control Alternatives**
  - A. Performance
  - B. Constraints
  - C. Recommended OCCT

4.1.5 Primacy Agency Designates OCCT for Systems Serving ≤ 50,000 People (STEP 6)

Exhibits 4.7 and 4.8 provide technical recommendations for primacy agencies for their review of desktop and demonstration study reports, respectively. Primacy agencies should refer to Chapter 2 for background on sources of lead and copper and impacts of water quality and physical system characteristics on lead and copper release. The information in Chapter 3 can also be used as a reference when evaluating the recommended OCCT option.

Upon its own initiative or in response to a request from a water system, a primacy agency may modify its OCCT determination or optimal water quality control parameters for the system (§141.82(h)). The primacy agency may modify its determination where it concludes that such a change is needed to ensure the water system will continue to provide optimized corrosion control treatment. Such modifications may be appropriate where water systems are contemplating changes to their source water, treatment, or other system components in a manner that could adversely impact their current treatment optimization.

Exhibit 4.7: Recommendations for Primacy Agency Review of Desktop Study

1) Make sure all components of a desktop study are included in the report.
    - → If they are not, coordinate with system to complete study and check against recommended outline of required components for desktop studies.
    - → If they are, continue.
2) Evaluate raw, entry point, and distribution system water quality information.
    - → Evaluate key water quality parameters (pH, alkalinity, conductivity, hardness, other anions and cations) and their impact on lead and/or copper release to water (entry point and distribution system) and treatability (raw water).
    - → Evaluate differences in entry point versus distribution system data for key water quality parameters, particularly variations in pH and DIC.
3) Review regulatory tap monitoring data for lead and copper and other supplemental lead and copper data (e.g., from special studies by universities).
    - → Assess 90th percentile lead and copper levels and that sites selected for regulatory monitoring meet the criteria in the LCR.
    - → Assess available supplemental lead and copper data, if available.
4) Review materials and customer complaint history.
    - → Determine primary sources of lead and copper in drinking water (lead pipe, lead solder, brass, copper pipe).
    - → Identify other materials in the system that may be impacted by CCT (unlined cast iron pipe, asbestos cement pipe, etc.).
5) Review analogous system information.
    - → Ensure that systems described are similar in source, water quality, and materials profiles.
6) Evaluate causes of elevated lead and/or copper levels.
    - → Use water quality and materials information along with corrosion theory to determine primary causes of elevated lead and/or copper levels.
7) Evaluate potential CCT alternatives identified in study.
    - → Evaluate if alternatives have been compared with respect to their abilities to reduce lead and/or copper levels in the system (performance) and the effects that additional CCT will have on water quality parameters (WQPs) and on other water quality treatment processes.
8) Evaluate final recommended OCCT and approve installation if warranted.

Exhibit 4.8: Recommendations for Primacy Agency Review of Demonstration Study

1) Make sure all components of a demonstration study are included in the report.
   - → If they are not, coordinate with system to complete study and check against recommended outline of required components for demonstration studies.
   - → If they are, continue.
2) Evaluate raw, entry point, and distribution system water quality information.
   - → Evaluate key water quality parameters (pH, alkalinity, conductivity, hardness, other anions and cations) and their impact on lead and/or copper release to water (entry point and distribution system) and treatability (raw water).
   - → Evaluate differences in entry point versus distribution system data for key water quality parameters, particularly variations in pH and DIC.
3) Review regulatory tap monitoring data for lead and copper and other supplemental lead and copper data (e.g., from special studies by universities).
   - → Assess 90th percentile lead and copper levels and that sites selected for regulatory monitoring meet the criteria in the LCR.
   - → Assess available supplemental lead and copper data, if available.
4) Review materials and customer complaint history.
   - → Determine primary sources of lead and copper in drinking water (lead pipe, lead solder, brass, copper pipe).
   - → Identify other materials in the system that may be impacted by CCT (unlined cast iron pipe, asbestos cement pipe, etc.).
5) Review analogous system information.
   - → Ensure that systems described are similar in source, water quality, and materials profiles.
6) Evaluate causes of elevated lead and/or copper levels.
   - → **Bench scale/Pipe Rack:** Ensure that materials evaluated are similar to lead and copper source materials in system. Also ensure that water quality conditions are similar to system conditions. For pipe rack studies, ensure that study was conducted long enough for stable scales to form on the pipes.
   - → **Scale Analyses:** Identify if representative pipe specimens were gathered in the field (representative of lead and/or copper source material that is contributing to elevated lead and copper levels in the water) and that scale analyses were completed using appropriate methods with proper quality assurance and quality control.
   - → **Partial System Testing:** Testing area should be selected to represent sites with elevated lead and/or copper levels similar to those used for regulatory compliance sampling under the LCR. Study should continue long enough for CCT to be effective.
   - → **Other:** Any additional sampling should be conducted at sites representative of sites used for LCR compliance sampling.
   - → Results from special studies should be used to inform recommendations on causes of elevated lead and/or copper levels, performance of potential treatment alternatives, and constraints and secondary impacts that may occur with implementation of CCT.
7) Evaluate potential CCT alternatives identified in study.
   - → Evaluate if alternatives have been compared with respect to their abilities to reduce lead and/or copper levels in the system (performance) and the effects that additional CCT will have on WQPs and on other water quality treatment processes.
8) Evaluate final recommended OCCT and approve installation if warranted.

4.2 Corrosion Control Steps for Systems Serving > 50,000 People

As noted earlier in this chapter, most systems serving more than 50,000 people were required to install OCCT by January 1, 1997. Systems that served 50,000 people or fewer at that time may have since experienced population growth, combined with other systems, and/or made other changes so that their new population served is more than 50,000 people. These systems then become subject to the requirements for large systems, including the specific CCT steps applicable to large systems unless they are deemed to have optimized CCT under §141.81(b)(2) or (b)(3).

Exhibit 4.9 summarizes the required actions and deadlines for CCT steps for these systems. It also shows the related section in this document where additional technical recommendations are provided for the system or primacy agency. Those systems serving more than 50,000 people with existing CCT – but that have subsequent lead or copper action level exceedances – can also follow these steps, where applicable, while also complying with the LCR's ALE-triggered source water, public education, and lead service line replacement requirements in §§141.83-85. Note that for these systems, the LCR does not prescribe a schedule for CCT adjustment; instead, one will likely be set by the primacy agency.

Exhibit 4.9: Summary of CCT Requirements and Deadlines for Systems Serving > 50,000 People (§141.81(e))

Requirement[1]	**Timetable for Completing Corrosion Control Treatment Steps**	**Corresponding Section of this Document**
STEP 1: System completes Corrosion Control Study.	Within 18 months after the end of the monitoring period which triggered a study[2]	Section 4.2.1
STEP 2: Primacy agency designates OCCT.	Within 6 months after study is completed	Section 4.2.2
STEP 3: System installs OCCT.[3]	Within 24 months after primacy agency's decision regarding type of treatment to be installed	Section 5.1
STEP 4: System conducts follow-up monitoring for 2 consecutive 6-month periods.	Within 36 months after primacy agency designates OCCT	Section 5.2
STEP 5: Primacy agency designates OWQPs.	Within 6 months of Step 4	Section 5.3
STEP 6: System conducts continued WQP and lead and copper tap monitoring.	The schedule for required monitoring is based on whether the system exceeds an AL and/or complies with OWQP ranges or minimums	Section 5.4

Notes:

[1] This schedule applies to systems newly serving > 50,000 people that are installing CCT. Because the regulatory deadlines for systems serving more than 50,000 people have passed, systems newly serving 50,000 people must follow the schedule for systems serving 3,301-50,000 people.

[2] In other words, the end of the monitoring period in which the system became a system serving > 50,000 people.

[3] For systems with existing CCT, this step would involve adjusting CCT.

4.2.1 Systems Serving >50,000 People Conduct a Corrosion Control Study (STEP 1)

Corrosion control study requirements (e.g., study tools, identification of constraints, reporting) were summarized previously in this Chapter in Exhibit 4.3.

In addition to the corrosion control study and OCCT recommendation, EPA recommends that systems provide their primacy agencies with the water quality and other system-specific information as identified in Appendix D. Primacy agencies may also require a system to collect this additional data/information as per §141.82(a) and (d)(2). The recommended data and information collection forms in Appendix D can be customized for individual systems. Data should be sufficient to characterize raw water, treated water quality (entry point), distribution system water quality, and lead and copper in tap samples. The frequency of data collection should be based on the complexity of the system and how water quality may vary over time and location. Systems should be encouraged to provide multiple years of data that represent different seasons (e.g., quarterly data). Water quality samples should be collected as close in time as possible to lead and copper tap samples. Primacy agencies may be able to verify information using the system's latest sanitary survey report. Recommendations for reviewing water quality data are provided in Section 3.2.1.

As noted in Exhibit 4.3, systems performing corrosion control studies must use either pipe rig/loop tests, metal coupon tests, partial-system tests, or analyses based on documented analogous treatments with other systems of similar size, water chemistry, and distribution system configuration for their CCT study. Because there is less likelihood of truly analogous systems once the population served is more than 50,000 people, EPA recommends that these systems use one of the demonstration study tools (i.e., pipe rig/loop, metal coupon, or partial-system test) to meet CCT requirements. Additional desktop and demonstration study tools can be used to supplement the requirements – see Appendix F for a description of the required and additional CCT study tools. Systems may also find the recommended approach for selecting OCCT (provided in Chapter 3) helpful as a screening tool for identifying which treatments warrant further study.

The system must provide the primacy agency with its recommended OCCT option along with the rationale for its recommendation and supporting documentation as described §141.82(c)(1) – (6). The system must also identify all chemical or physical constraints that limit or prohibit the use of a particular corrosion control treatment and document such constraints with at least one of the following (§141.82(c)(4) and (c)(6)):

- Data and documentation showing that a particular CCT has adversely affected other water treatment processes when used by another water system with comparable water quality characteristics; and/or
- Data and documentation demonstrating that the water system has previously attempted to evaluate a particular CCT and has found that the treatment is ineffective or adversely affects other water quality treatment processes.

The system must also evaluate the effect of the chemicals used for CCT on other water quality treatment processes (§141.82(c)(5) and (c)(6)).

EPA recommends that the system submit to the primacy agency a report that includes the required information identified above and additional data and analyses as follows:

- Options for addressing identified constraints, so that the system would be able to achieve and maintain OCCT, meet other water quality goals, and remain in compliance with all applicable drinking water regulations.
- The corrosion control study's conclusion (i.e., the recommended treatment) and a target level for pH, alkalinity, and corrosion inhibitors (if used).
- Recommended operating ranges for key parameters (pH, alkalinity, and inhibitor (if used)) both at the entry point and in the distribution system.
- Treatment chemicals and dosages that will be used to maintain OCCT, recommendations for quality assurance testing of chemicals, and follow-up monitoring recommendations.
- The system's plan for treatment start-up (see Sections 3.3 and 5.1 for technical recommendations for start-up of pH/alkalinity/DIC adjustment and phosphate-based corrosion inhibitor treatment).

Exhibit 4.5 and Exhibit 4.6, presented earlier in this section, provide possible outlines for desktop and demonstration study reports, respectively.

4.2.2 Primacy Agency Reviews the Study and Designates OCCT for System Serving > 50,000 People (STEP 2)

Primacy agencies can use the checklist in Exhibit 4.8 in Section 4.1.5 to support their review of the study's design and findings. Primacy agencies should refer to Chapter 2 for background on sources of lead and copper and impacts of water quality and physical system characteristics on lead and copper release. The information in Chapter 3 can also be used as a reference when evaluating the recommended OCCT option.

Upon its own initiative or in response to a request from a water system, a primacy agency may modify its OCCT determination or optimal water quality control parameters for the system (§141.82(h)). The primacy agency may modify its determination where it concludes that such a change is needed to ensure the water system will continue to optimize corrosion control treatment. Such modifications may be appropriate where water systems are contemplating changes to their source water, treatment, or other system components in a manner that could adversely impact their current treatment optimization.

Chapter 5: Requirements and Technical Recommendations for OCCT Start-Up and Monitoring

This chapter picks up where Chapter 4 ended – after the primacy agency designates optimal corrosion control treatment (OCCT), the system will install OCCT and conduct follow-up monitoring. The primacy agency will then designate optimal water quality parameters (OWQPs). This chapter is organized as follows:

- Section 5.1 provides technical recommendations for systems on corrosion control treatment (CCT) start-up.
- Section 5.2 discusses required and recommended elements of follow-up monitoring during the first year of OCCT operation.
- Section 5.3 provides requirements and technical recommendations for primacy agencies on evaluating OCCT and setting OWQPs.
- Section 5.4 provides requirements and technical recommendations for comprehensive long-term monitoring for corrosion control.

Systems are encouraged to refer to the document *Lead and Copper Rule Monitoring and Reporting Guidance for Public Water Systems* (USEPA, 2010b) for direction on follow-up and continued lead and copper tap and water quality parameter (WQP) monitoring.[28]

5.1 CCT Start-up

In accordance with the Lead and Copper Rule (LCR), after the primacy agency designates OCCT, the system has 24 months to install it (§141.81(e)(5)).[29] During that time, systems may be adding a new chemical (i.e., a corrosion inhibitor) to the finished water and/or adjusting the finished water pH by adding a new chemical or increasing the dose of an existing chemical. These types of changes can have temporary adverse impacts on water quality in the distribution system (e.g., red water from sloughing of corrosion scale, microbial changes). Therefore, the Environmental Protection Agency (EPA) has provided recommendations in the next two sections for systems to consider when starting pH/alkalinity/dissolved inorganic carbon (DIC) adjustment (5.1.1) and when adding a corrosion inhibitor (5.1.2) to help minimize these potential adverse effects.[30] EPA recommends that systems discuss corrosion control treatment start-up procedures with their primacy agency when the agency is designating OCCT. Additional recommendations for CCT start-up can be found in Hill and Cantor (2011).

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[28] This guidance is available at http://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100DP2P.pdf.

[29] The required time period for installing OCCT (24 months) applies to systems serving ≤ 50,000 people and systems newly serving > 50,000 people. The schedule for CCT adjustment for systems that already have CCT is not prescribed in the LCR. The primacy agency will likely set a schedule for systems serving > 50,000 people that previously installed CCT but have a subsequent action level exceedance.

[30] Silicate-based inhibitors are not included here because information on their use and effectiveness continues to be limited and more research is needed.

5.1.1 Start-up of pH/Alkalinity/DIC Adjustment

Changes in pH/alkalinity/DIC result in a new water quality equilibrium to be established in the distribution system. To minimize adverse impacts (e.g., sloughing of corrosion scale, aesthetic issues), systems should consider raising the pH in increments, e.g., by 0.2 or 0.3 pH units over a 12-month period, or increasing the pH incrementally every 3 months (USEPA, 2007b; MOE, 2009). The approach will be system specific, but consideration should be given to the amount of lead and/or copper reduction that is needed and the potential for secondary impacts as the distribution system equilibrates. The amount of time needed to see results from implementation of pH adjustment will also be system specific. Some systems have seen lead and/or copper reduction within a matter of days following pH adjustment (MOE, 2009); however, other systems have required up to a year to produce a new stable target pH in the distribution system (MWRA, 2010).

5.1.2 Start-up of Phosphate-Based Corrosion Inhibitors

When starting orthophosphate treatment, some systems have gradually increased their orthophosphate doses over time. For example, in a partial distribution system test, an initial orthophosphate dose of 1 mg/L as PO_4 (~0.3 mg/L as P) was gradually increased to 3 mg/L as PO_4 (~1 mg/L as P) over seven months. At three weeks, the orthophosphate concentration reached the target dose at the far ends of the system (MOE, 2009).

Some systems have started orthophosphate treatment with a higher passivation dose, then after a certain time period, switched to a lower maintenance dose for long-term corrosion control. For example, Hill and Cantor (2011) recommend starting inhibitors at 2 to 3 times the maintenance dose in order to more quickly establish a passivating layer. See Section 3.3.2 for technical recommendations related to passivation and maintenance doses.

5.2 Follow-up Monitoring during First Year of Operation

The LCR requires systems to conduct two types of follow-up monitoring during the two consecutive, 6-month periods directly following installation of OCCT (§141.81(d)(5) and (e)(6)):

- Lead and copper tap monitoring; and
- WQP monitoring.

The next two sections summarize follow-up monitoring requirements and recommendations. Systems can use the forms in Appendix G and the forms in the ***OCCT evaluation templates*** to document the results of follow-up monitoring.

As will be discussed in Section 5.3, the primacy agency will use the results of follow-up lead and copper tap monitoring and results from samples collected prior to the system's installation of CCT to determine if the system has properly installed and operated OCCT, and to set OWQPs.

5.2.1 Follow-up Lead and Copper Tap Monitoring

All systems, regardless of size, must conduct two consecutive six-month rounds of follow-up lead and copper tap monitoring at the same number of sites as required for routine monitoring under the LCR (§141.86(c) and (d)(2); see Exhibit 5.1).

Exhibit 5.1: Required Number of Sites for Follow-up Lead and Copper Tap Monitoring

Population Served	Required Number of Sites[1]
≤100	5
101 – 500	10
501 – 3,300	20
3,301 – 10,000	40
10,001 – 100,000	60
>100,000	100

Note:

[1] §141.86(c) and (d)(2). The number of sites is the same as the number of sites required for routine monitoring.

EPA recommends that systems with lead service lines (LSLs) and their primacy agencies consider collecting special tap samples during follow-up monitoring to evaluate the lead released directly from the LSLs. Systems can conduct premise plumbing profiles (see Appendix C for more information), or ask homeowners to collect samples that would capture water from within the LSL for lead analysis. Dissolved and particulate lead should be measured for these special samples. In addition, primacy agencies may wish to consider data from chronically low flow homes and homes with LSL disturbances when evaluating the effectiveness of the CCT.[31]

5.2.2 Follow-up WQP Monitoring

Requirements for WQP follow-up monitoring and recommendations for additional monitoring are summarized in Exhibits 5.2 and 5.3, respectively. Required WQP follow-up monitoring must be conducted at entry points to the distribution system and at tap monitoring locations. Entry point samples must be collected from locations that are representative of each source after treatment. Systems with multiple sources that are combined before distribution must sample at each entry point to the distribution system during periods of normal operating conditions to allow the sample to be representative of all sources being used (§141.87(a)(1)(ii); USEPA 2010b). Tap samples must be representative of water quality throughout the distribution system taking into account the number of persons served, the different sources of water, the different treatment methods employed by the system, and seasonal variability. Tap monitoring

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[31] All lead and copper tap sample results from the system's sampling pool collected within the monitoring period must be included in the 90th percentile calculation along with any samples where the system is able to determine that the site selection criteria in §141.86(a)(3)-(8) for the sampling pool are met. Other lead and copper tap data such as from customer requested sampling, investigative sampling, and special studies also must be submitted to the primacy agency (USEPA, 2004c; §141.90(g)).

locations can be the sites used for coliform monitoring or the sites used for lead and copper tap monitoring (§141.87(a)(1)(i)).

As summarized in Exhibit 5.2, the LCR requires:

- One sample from each entry point at least once every two weeks for:[32]
    - pH;
    - When alkalinity is adjusted, a reading of the dosage rate of the chemical used to adjust alkalinity and the concentration of alkalinity; and
    - When an inhibitor is used, a reading of the dosage rate of the inhibitor used and the concentration of orthophosphate or silicate (whichever is used).
- AND two sets of samples from a specified number of taps (see Exhibit 5.3) during both consecutive 6-month monitoring periods for:
    - pH;
    - Alkalinity;
    - Calcium, when calcium carbonate stabilization is used;
    - Orthophosphate, when a phosphate-based inhibitor is used; and
    - Silica, when a silicate-based inhibitor is used.

Note that the LCR requires systems serving 50,000 or fewer people to conduct follow-up WQP monitoring only during monitoring periods in which they have a lead and/or copper action level exceedance (§141.87(c)). Monitoring is not required if these systems no longer exceed the action level after installing OCCT. However, EPA recommends that primacy agencies consider requiring follow-up WQP monitoring during the first year after OCCT installation regardless of whether the system exceeds the action level in order to demonstrate that the treatment is operating properly.

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[32] Except ground water systems that have primacy agency approval to limit this monitoring to representative sites.

Exhibit 5.2: Follow-up WQP Monitoring Requirements[1] and Recommendations

Type	Parameters	Required [1]		Recommended	
		Number of Sites	**Frequency of Sampling**	**Number of Sites**	**Frequency of Sampling**
Entry point	pH, alkalinity dosage rate and concentration,[2] inhibitor dosage rate and orthophosphate or silicate concentration (whichever is used)[3]	At each entry point[4]	At least once every two weeks	No Change	No Change
Tap (Distribution system samples)[5]	pH, alkalinity, orthophosphate or silica[3], calcium[6]	Number of sites based on system size, See Exhibit 5.3	At least twice per tap every six months (4 sample periods)	At ***more taps than required.*** See Exhibit 5.3.	All parameters: ***Monthly***

Notes:

[1] Required for all systems serving more than 50,000 people (§141.87(c)). Systems serving 50,000 or fewer people are required to conduct follow-up WQP monitoring during any monitoring period in which they exceed either action level or if required by the primacy agency (§141.81(b) and §141.87(c)). Follow-up monitoring occurs during the 12-month period following OCCT installation (§141.81(e)(6) and §141.87(c)).

[2] Required at entry point locations if alkalinity is adjusted as part of corrosion control (§141.87(c)(2)(ii)).

[3] Required if an inhibitor is used. Monitoring for orthophosphate is only required if a phosphate-containing inhibitor is used (§141.87(c)(1)(iii) and (c)(2)(iii)). Monitoring for silica is only required if a silicate-containing inhibitor is used (§141.87(c)(1)(iv) and (c)(2)(iii)).

[4] Ground water systems can limit entry point monitoring to representative sites with approval from their primacy agency (§141.87(c)(3)).

[5] WQP tap samples are collected at locations that are representative of the water quality throughout the distribution system. Systems may sample from sites used for coliform monitoring (§141.87(a)).

[6] Required if calcium carbonate stabilization is used (§141.87(c)(1)(v)).

Exhibit 5.3: Required and Recommended Number of Sites for Follow-up WQP Tap Monitoring

Population Served	Required Number of Sites[1]	Recommended Number Sites
≤100	1	2
101 – 500	1	5
501 - 3,300	2	10
3,301 - 10,000	3	15
10,001 - 50,000	10	20
50,001 - 75,000	10	25
75,001 - 100,000	10	30
100,001 - 500,000	25	40
500,001 - 1,000,000	25	50
>1,000,000	25	>50

Note:

[1] Required each six-month monitoring period for systems serving more than 50,000 people (§141.87(c)). Systems serving 50,000 or fewer people are required to conduct follow-up WQP monitoring during any monitoring period in which they exceed either action level or if required by the primacy agency (§141.81(b) and §141.87(c)).

For follow-up WQP tap monitoring, two samples must be collected from the required number of sites shown in Exhibit 5.3 during both six-month monitoring periods specified in §141.86(d)(2) (§141.87(c)(1)). As shown in Exhibit 5.2, EPA recommends that systems and primacy agencies consider increasing the frequency of WQP tap sampling to ***monthly.*** More frequent monitoring is recommended to capture seasonal variations and influences of temperature on treatment effectiveness.

EPA also recommends that systems and primacy agencies consider follow-up WQP tap monitoring at more locations than required by the LCR (See Exhibit 5.3). Collecting WQP samples at an increased number of tap monitoring locations is especially important for systems that experience fluctuations in distribution system water quality. In particular, pH variations can have a large impact on corrosion control treatment effectiveness. The pH can fluctuate widely in systems with low buffering capacity, high water age (e.g., in dead-end areas), high microbiological activity, and in systems that experience nitrification. It is important that distribution system monitoring represents all pressure and water quality zones to adequately assess treatment effectiveness in all parts of the system. Follow-up WQP samples from tap sites should be collected as close in time as possible to when lead and copper tap samples are collected so that the system can evaluate the influence of water quality fluctuations on lead and copper tap monitoring results.

Primacy agencies and systems may want to consider additional monitoring for iron, manganese, chloride, sulfate, hardness, calcium, total dissolved solids (TDS), and/or oxidation-reduction potential (ORP) if they believe that these parameters may change or were not adequately characterized prior to CCT installation.[33] Primacy agencies can use the forms in Appendix G and electronic versions in the ***OCCT Evaluation Templates*** to document additional follow-up monitoring requirements for systems.

5.3 Evaluating OCCT and Setting Optimal Water Quality Parameters

Primacy agencies are required to evaluate results of follow-up tap and water quality monitoring and results collected prior to the installation of CCT to determine whether the system has properly installed and operated the OCCT and to designate (§141.82(f)):

- A minimum value or a range of values for pH measured at each entry point to the distribution system;
- A minimum pH value, measured in all tap samples, that is equal to or greater than 7.0, unless the primacy agency determines that meeting a pH level of 7.0 is not technologically feasible or is not necessary for the system to optimize corrosion control;
- If alkalinity is adjusted as part of OCCT, a minimum concentration or a range of concentrations for alkalinity, measured at each entry point to the distribution system and in all tap samples;
- If a corrosion inhibitor is used, a minimum concentration or a range of concentrations for the inhibitor, measured at each entry point to the distribution system and in all tap samples, that the primacy agency determines is necessary to form a passivating film on the interior walls of the pipes of the distribution system; and
- If calcium carbonate is used as part of corrosion control, a minimum concentration or a range of concentrations for calcium, measured in all tap samples.

Primacy agencies can designate values for additional water quality control parameters (e.g., free chlorine residual, conductivity, ORP) that reflect optimal corrosion control for the system (§141.82(f)).

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[33] Under §141.82(f), the primacy agency may designate values for additional water quality control parameters determined by the primacy agency to reflect optimal corrosion control for the system. The primacy agency must notify the system in writing of these determinations and explain the basis for its decisions.

EPA recommends that primacy agencies also use results of follow-up monitoring to further evaluate the OCCT and recommend re-evaluation if the results of the treatment are not what were predicted.

Note that the LCR includes a provision (§141.82(h)) for primacy agencies to modify their determination of OCCT or OWQP designations where they conclude that such change is necessary to ensure that the system continues to optimize CCT. Such modifications may be appropriate where water systems are contemplating changes to their source water, treatment, or other system components that could adversely impact their current CCT optimization. A request for modification can also be in response to a written request with supporting documentation from a system or other interested party. The revised determination must be in writing, and include the new treatment requirements, the basis for the primacy agency's decision, and an implementation schedule for completing the treatment modifications.

Appendix G provides technical recommendations for primacy agencies to consider when designating OWQPs for pH/alkalinity/DIC adjustment, orthophosphate treatment, blended phosphate treatment, and use of a silicate inhibitor based on data gathered during the follow-up monitoring.

A recent publication by Cornwell et al. (2015) examined the use of control charts as a diagnostic tool for determining parameter variability and setting acceptable ranges. This approach may be useful to primacy agencies and systems for controlling WQPs and determining when treatment adjustment is needed to bring a parameter back within its goal range.

5.4 Required and Recommended Long-Term Corrosion Control Monitoring

This section describes WQP monitoring required by the LCR once the primacy agency has set OWQPs. It also provides technical recommendations for additional data collection and tracking that could be used to enhance a system's understanding of CCT effectiveness. For the purposes of this document, the combination of required WQP monitoring and additional recommended monitoring is referred to as "long-term corrosion control monitoring."

Generally, systems serving more than 50,000 people must conduct routine monitoring and determine compliance with OWQPs every six months, while systems serving 50,000 or fewer are required to conduct monitoring during periods in which they have a lead and/or copper action level exceedance (§141.87(d)).

Required WQP Monitoring

Systems are required to collect two sets of samples every six months (§141.87(c)(1) and (d)) at the number of WQP tap sampling sites specified for the system size in §141.87(a)(2) (see Exhibit 5.3) for:

- pH;
- Alkalinity;

- Calcium, when calcium carbonate stabilization is used;
- Orthophosphate, when a phosphate-based inhibitor is used; and
- Silica, when a silicate-based inhibitor is used.

They must also collect one set of samples at each entry point (except those ground water systems that can limit entry point monitoring to representative sites) at least once every two weeks for:

- pH;
- When alkalinity is adjusted as part of optimal corrosion control, a reading of the dosage rate of the chemical used to adjust alkalinity and the concentration of alkalinity; and
- When an inhibitor is used, a reading of the dosage rate of the inhibitor used and the concentration of orthophosphate or silicate (whichever is used).

Systems that meet their OWQPs for a specified period of time can qualify for reduced WQP monitoring that allows for fewer and less frequent monitoring at tap locations (§141.87(e)). The LCR does not allow reduced monitoring for WQP samples collected at entry points. Refer to Section III.H in the *Lead and Copper Rule Monitoring and Reporting Guidance for Public Water Systems* (USEPA, 2010b) for additional information.

Technical Recommendations for Additional Monitoring

Additional monitoring could include monitoring for additional WQPs, customer complaint tracking, and monitoring associated with lead source replacement programs.

In addition to required WQP monitoring, systems may want to consider analyzing other water quality parameters that can affect lead and copper release. These may include ORP, ammonia, chloride, sulfate, aluminum, iron, and manganese. See Section 2.3 for discussion of how these water quality parameters influence corrosion.

Customer complaints provide useful information on conditions occurring at customer's taps. Common complaints include red water (iron) and darker tint to the water (manganese), which can indicate an increase in source water levels of iron and manganese or sloughing of scale from cast iron pipe. Complaints of taste/odor issues (earthy or musty flavor) can indicate changes in natural organic matter (NOM) due to algae blooms. Systems can obtain important information from customer complaints of blue water or a metallic taste, which can indicate copper corrosion (customers can begin to notice the taste from copper at concentrations of 3 to 10 mg/L per Dietrich et al., 2008). It is important to note that while customer complaint records can provide information on copper corrosion, lead in drinking water has no taste or color.

Systems should consider additional monitoring to evaluate the effectiveness of lead source replacement programs. The monitoring, whether taken at the tap or directly from the service line, would occur before and after the lead source is removed. Both total and dissolved lead should be analyzed to determine the percentages of particulate and dissolved lead. Replacement of lead sources, such as lead service lines, may increase lead levels (especially particulate lead levels) for a period of time due to the physical disturbance of the system (Sandvig et al., 2008; Muylwyk et al., 2009; Swertfeger et al., 2006; Del Toral et al., 2013). Some disturbances, along with other factors, may elevate lead levels for years (Del Toral et al., 2013). Particulate lead can also be released as part of normal (ongoing) corrosion processes in the system and is common when pipe scales contain substantial amounts of iron, manganese, and other coatings, or when corrosion of brass or solder is galvanically driven.

Recommendations for monitoring programs can be found in Kirmeyer et al. (2000, 2002, 2004); USEPA (2003, 2007d); and MOE (2009).

Chapter 6: Impacts of Source Water and Treatment Changes on Lead and Copper in Drinking Water

Research over the last several years has shed new light on the impacts of source water and treatment changes on lead and copper corrosion control. In particular, for systems with lead service lines, research has shown that lead release is dependent upon many water quality parameters (WQPs), and that treatment change once thought to be independent of corrosion control can have a significant impact on lead release.

Section 6.1 reviews the Lead and Copper Rule (LCR) requirements for maintaining optimal corrosion control treatment (OCCT) and explains when a system is required under the LCR to notify their primacy agency and obtain approval prior to a source or treatment change. Section 6.2 provides technical information on the effects of source water changes and Section 6.3 follows with technical information about the effects of treatment changes on lead and copper levels in drinking water.

6.1 Review of LCR Requirements Related to a Change in Source or Treatment

All systems optimizing corrosion control must continue to operate and maintain the treatment, including maintaining WQPs at or above minimum values or within ranges established by the primacy agency (§141.81(b) and §141.82(g)). Prior to the addition of a new source or any long-term change in water treatment, water systems are required to notify the primacy agency in writing of the change or addition. The primacy agency must review and approve the addition of a new source or long-term change in treatment before it is implemented by the water system. Primacy agencies also have the authority to modify OCCT determinations or OWQP designations upon their own initiative or in response to a request from a water system or other interested party (§141.82(h)). The primacy agency may modify these where it concludes the modifications are necessary to ensure the system will continue to provide optimized corrosion control treatment after changing the source water, treatment, or other system components in such a way that could adversely impact the current optimization.

Switching from purchased water to a new source is an example of source change (USEPA, 2015b). Examples of long-term treatment changes are provided in the LCR and discussed later in this section. The systems that are subject to this requirement are systems that are either: (1) deemed to have optimized corrosion control pursuant to §141.81(b)(3); (2) subject to reduced monitoring under §141.86(d)(4); or (3) subject to a monitoring waiver under §141.86(g). (§141.90(a)(3)).

As described in a November 3, 2015, memorandum from Dr. Peter Grevatt, Director of the Environmental Protection Agency (EPA) Office of Ground Water and Drinking Water (USEPA, 2015b):

1) The LCR requires that any large system (i.e., those serving > 50,000 people) that has met OCCT requirements through the installation of corrosion control treatment to continue

operating and maintaining the treatment and to continue meeting the OWQPs established by the primacy agency (§141.81(b) and §141.82(g)).

2) Systems deemed to have OCCT without the installation of corrosion control treatment are required to notify the primacy agency in writing of any upcoming changes in treatment or source and request that the primacy agency modify its determination of the OCCT and OWQPs applicable to the system. The primacy agency must then review and approve the change and designate OCCT and OWQPs prior to its implementation by the system (§141.81(b)(3)(iii)).

3) Systems subject to reduced monitoring under §141.86(d)(4) or monitoring waivers under §141.86(g) must notify the primacy agency of any upcoming changes in treatment or source and the primacy agency must subsequently review or approve it (§141.90(a)(3)).

EPA recommends that systems that are not subject to a notification requirement also notify the primacy agency prior to the addition of a new source or treatment and request the primacy agency to modify its determination of the OCCT and OWQPs applicable to the system (USEPA, 2015b).

Examples of long-term treatment changes include the addition of a new process or modification of an existing treatment process ((§141.90(a)(3)). Examples of modifications include switching secondary disinfectants, switching coagulants (e.g., alum to ferric chloride), and switching corrosion inhibitor products (e.g., orthophosphate to blended phosphate). Long-term changes can include dose changes to existing chemicals if the system is planning long-term changes to its finished water pH or residual inhibitor concentration. Long-term treatment changes would not include chemical dose fluctuations associated with daily raw water quality changes ((§141.90(a)(3)).

Due to the unique characteristics of each system (e.g., source water, existing treatment processes, distribution system materials) it is critical that public water systems, in conjunction with their primacy agencies and, if necessary, outside technical consultants, evaluate and address potential impacts resulting from treatment and/or source water changes prior to making the change. The evaluation may include a system-wide assessment of source water or treatment modifications to identify existing or anticipated water quality, treatment, or operational issues that may interfere with or limit the effectiveness of corrosion control treatment (CCT) optimization or re-optimization. In addition, systems should conduct ongoing monitoring to ensure compliance with OCCT prior to, during, and after a source or treatment change (USEPA 2015b).

6.2 Impacts of Source Water Changes

Changes in source water can have a significant impact on water quality, corrosion control treatment effectiveness, and lead and copper release. Examples of source changes include:

- Switching from a purchased treated water source to an untreated water source that requires treatment;
- Switching from a purchased treated water source to a different treated source;
- Changing from a ground to surface water source; and
- Adding a new source, such as a new ground water or purchased source, in the distribution system.

Not only can source water changes directly impact corrosion control treatment (e.g., pH, alkalinity, dissolved inorganic carbon (DIC), and corrosion inhibitor concentration), but they can also impact the effectiveness of corrosion control treatment through changes in water quality parameters such as natural organic matter (NOM), metals (e.g., iron and manganese), ions such as chloride and sulfate, oxidation-reduction potential (ORP), and buffer intensity. See Section 2.3 for information on how water quality can impact the release of lead and copper into drinking water.

The literature includes examples of how source water changes have impacted lead and copper release (Boyd et al., 2006; 2008). For example, changes in lead release associated with blending groundwater, treated surface water, and desalinated seawater sources were determined to be a function of temperature, alkalinity, pH, chloride and sulfate (Taylor et al., 2005; Tang et al., 2006). Total copper release has been attributed to changes in temperature, alkalinity, pH, sulfate, and silica (Imran et al., 2006; Xiao et al., 2007). In another study (Zhang et al., 2012), lead release from leaded solder increased with blending of desalinated seawater in pilot-scale pipe loops.

Source water changes can impact trace inorganic contaminant release from deposits or scales in the distribution system (Lytle et al., 2004; Schock, Hyland, and Welch, 2008; Friedman et al., 2010; Peng et al., 2012). As discussed in Section 2.3.9, dissolved lead can react with iron and manganese and form deposits on lead service lines and other pipe materials (Schock, Cantor, et al., 2014). Shifts in water chemistry (e.g., changes associated with blending disparate sources) can potentially affect release and remobilization of these contaminants in the distribution system (Schock, Lytle, et al., 2005; Hill et al., 2010; McFadden et al., 2011; Friedman et al., 2016), which can then impact the formation of passivating scales on lead- and copper-containing materials.

6.3 Impacts of Treatment Changes

Treatment changes that can potentially affect the corrosivity of treated water are identified in several references (USEPA, 2003; USEPA, 2007b; MOE, 2009; Schendel et al., 2009; Grigg, 2010), and discussed in more detail below.

6.3.1 Corrosion Control Treatment

Any proposed change to a system's CCT can have consequences for water quality in the distribution system and corrosion control effectiveness. Even small changes to pH/alkalinity/DIC adjustment processes and inhibitor doses can affect lead and copper levels. If a system proposes changes to any of these key parameters (e.g., lowers pH, lowers or shuts off corrosion inhibitor), there is the potential for increases in lead and/or copper in the water.

Changes in the inhibitor chemical used for treatment can also affect lead and copper release. For example, changing from an orthophosphate chemical to a blended phosphate chemical is significant because the mechanisms by which the two chemicals control lead release are different, and the effectiveness of blended phosphates depends on other constituents in the water (e.g., calcium). Changing to a different manufacturer of blended phosphates can impact lead and copper release, even if the percentage of orthophosphate in the blend is similar (see Chapter 3 for more information on blended phosphates). Systems may design for a specific corrosion control product, but obtain bids for different products with different formulations. Additional drivers for changing the inhibitor chemical include pricing, finished water quality, operational changes, and changes at the receiving wastewater treatment plant (Brown et al., 2013a).

6.3.2 Disinfection

Changing disinfectant from free chlorine to chloramine may destabilize Pb(IV) scales formed under highly oxidizing conditions (high free chlorine residual). This destabilization may cause higher lead levels to be observed (Boyd et al., 2008; Boyd et al., 2009). In order to prevent elevated lead levels, systems can maintain the current conditions where Pb(IV) was the predominant scale, can adjust the pH/alkalinity/DIC to convert scales to Pb(II) passivating films (i.e., pH greater than approximately 9.0 and DIC of 5 to 10 mg/L as C), or can use an orthophosphate inhibitor (optimally at pH in the 7.2 to 7.8 range) (Lytle et al., 2009). There may be a period of time during the conversion from Pb(IV)-based to Pb(II)-based scales where lead levels may increase. A real-world example occurred in the District of Columbia with the DC Water and Sewer Authority (currently known as DC Water) (Schock and Giani, 2004; USEPA, 2007b), in which conversion from free chlorine to chloramines for disinfection, along with pH variations in the distribution system and the presence of lead service lines, contributed to elevated lead levels over a sustained period of time.

Additional monitoring can help determine the typical range of ORP values (i.e., the baseline) in the distribution system prior to disinfectant changes. Special laboratory studies to determine the composition of the lead scales present in the system (e.g., Pb(II) or Pb(IV) scales) can be completed using pipe sections removed from the distribution system (Clement et al., 1998b; Sandvig et al., 2008). Primacy agencies can identify systems that may switch to chloramines or another disinfectant in the future by reviewing compliance with the Stage 2 Disinfection By-products Rule (DBPR).

For systems that use chloramines, nitrification may occur in the distribution system. In a corrosion control guidance manual developed for the Province of Ontario, a case study was presented in which nitrification reduced the pH from approximately 8.5 to 7.8, which resulted in increased lead release. In response, the system raised the finished water pH to 9.2 and observed reductions in lead levels at some sites (MOE, 2009). Nitrification can also be a problem for ground water systems that add chlorine and have high levels of ammonia in their source water.

Important Information about Pb(IV)

Do my lead service lines have Pb(IV) scales?

Pb(IV) (also known as Lead IV or Pb^{++++}) can occur on any lead surface. It forms under highly oxidative conditions. If you have lead service lines with a moderate pH (7 to 8), a consistent free chlorine residual throughout the system (typically 1 to 2 mg/L or higher), no corrosion inhibitor, and no lead problems, you might have predominantly Pb(IV) scales. To help determine if your systems is a candidate for Pb(IV) scales, you can measure ORP of the water. E_h values of 0.7 volts or higher are indicative of Pb(IV) scales. You can also evaluate the scale on exhumed lead service lines to find out for sure.

Can I promote formation of Pb(IV) scales to reduce lead levels?

Although some utilities are targeting the development of a Pb(IV) scale in their systems to control lead release (Brown et al., 2013a), questions remain as to how systems and primacy agencies can ensure that disinfectant residuals required for the formation and maintenance of Pb(IV) scales are maintained within lead service lines throughout the distribution system and to the customer's taps. This may be a particular challenge with homes that go unoccupied for an extended period of time. Therefore, EPA has not included formation of Pb(IV) scale as a corrosion control treatment technique in this document at this time.

What happens if I have Pb(IV) scales and I change treatment?

Changing disinfectant from free chlorine to chloramine for disinfection may destabilize Pb(IV) scales. Systems can use other corrosion control treatments such as pH/alkalinity/DIC adjustment or phosphate-based corrosion inhibitors, but lead levels may increase as the scale is converting from Pb(IV) to Pb(II)-based scale.

The type of chlorine used for disinfection may also have an impact on corrosion. Use of gaseous chlorine lowers the pH of the water resulting in potentially more corrosive water. For systems with low alkalinity water, this effect can be amplified (Schock, 1999). Sodium hypochlorite, a base, can increase the pH of the water.

6.3.3 Coagulation

Switching from a sulfate-based to a chloride-based coagulant may increase the chloride content of the water, increasing the chloride-to-sulfate mass ratio (CSMR). This may aggravate lead release from galvanic connections such as lead solder on copper pipes or partial lead line replacements (Oliphant, 1983; Gregory, 1985; Reiber, 1991; Singley, 1994; Lauer, 2005; Nguyen et al., 2010; Triantafyllidou and Edwards, 2011; Clark et al., 2013; Wang et al., 2013). See Section 2.3.7 for additional discussion on the impacts of changes in chloride and sulfate on lead release.

Changes in pH to optimize the effectiveness of a new coagulant may impact the distribution system pH and cause changes in lead and copper release (USEPA, 2007d; Duranceau et al., 2004). Switching coagulants, or increased use of coagulants to achieve enhanced coagulation will also remove additional NOM. Changes in NOM can impact corrosion control in the distribution system; see Section 2.3.8 for more information.

6.3.4 Water Softening

Changing how softening is practiced at a treatment plant can affect corrosion control. Adding softening will raise the pH and change alkalinity, helping to control lead and copper release, whereas discontinuing softening will change these parameters, which may cause metal release (USEPA, 2007b).

6.3.5 Filtration

Nanofiltration and reverse osmosis remove alkalinity, hardness, and other dissolved compounds but do not remove carbon dioxide, resulting in a lower pH which can cause increases in lead and copper levels measured at the tap. They also remove NOM, which can impact corrosivity of the water (AwwaRF and DVGW-T, 1996; Mays, 1999; Kirmeyer et al., 2000; Duranceau et al., 2004; Schippers et al., 2004; USEPA, 2007b).

Chapter 7: References

APHA, AWWA, and WEF, 2005. *Standard Methods for the Examination of Water and Wastewater, 21st ed.* American Public Health Association. Washington, DC.

Appelo, C.A.J., and Postma, D. 2005. *Geochemistry, Groundwater and Pollution*. CRC Press. New York, NY.

ASTM D2688-11. 2005. *Standard Test Methods for the Corrosivity of Water in the Absence of Heat Transfer (Weight Loss Methods)*. ASTM International.

AWWA. 1993. *Initial Monitoring Experiences of Large Water Utilities under EPA's Lead and Copper Rule.* Water Industry Technical Action Fund (WITAF). AWWA. Denver, CO.

AWWA. 1999. *Water Quality and Treatment, a Handbook of Community Water Supplies*. 5th edition. Raymond Letterman, Editor. AWWA and McGraw-Hill. Denver, CO.

AWWA. 2004. Proceedings of Workshop - Getting the Lead Out: Analysis and Treatment of Elevated Lead Levels in DC's Drinking Water. Water Quality Technology Conference. San Antonio. AWWA. Denver, CO.

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

AwwaRF. 1990. *Lead Control Strategies*. AwwaRF Report #90559. Project #406. AWWA Research Foundation (now Water Research Foundation) and AWWA. Denver, CO.

AwwaRF and DVGW-Technologiezentrum Wasser. 1996. *Internal Corrosion of Water Distribution Systems*. 2nd edition. AwwaRF Order 90508. Project #725. AWWA Research Foundation (now Water Research Foundation) and AWWA. Denver, CO.

Boyd G.R., Dewis, K.M., Sandvig, A.M., Kirmeyer, G.J., Reiber, S.H., and Korshin, G.V. 2006. What Effect Does Background Water Chemistry Have on Metals Release and Galvanic Coupling? Chapter 7 in *Effect of Changing Disinfectants on Distribution System Lead and Copper Release, Part 1 – Literature Review.* AwwaRF Order #91152. Project#3107a. AWWA Research Foundation. Denver, CO.

Boyd, G.R., Dewis, K.M., Korshin, G.V., Reiber, S.H., Schock, M.R., Sandvig, A.M., and Giani, R., 2008. Effects of Changing Disinfectants on Lead and Copper Release. *J. AWWA*, 100(11):75-87.

Boyd, G.R., McFadden, M.S., Reiber, S.H., Sandvig, A.M., Korshin, G.V., Giani, R., and Frenkel, A.I. 2009. *Effect of Changing Disinfectants on Distribution System Lead and Copper Release: Part 2 – Final Report*. WRF Order #3107. Water Research Foundation. Denver, CO.

Boyd, G.R., Tuccillo, M.E., Sandvig, A., Pelaez, M., Han, C., and Dionysiou, D.D. 2013. Nanomaterials: Removal Processes and Beneficial Applications in Treatment. *J. AWWA*, 105(12): E699-E708.

Britton, A., and Richards, W.N. 1981. Factors Influencing Plumbosolvency in Scotland. *J. Inst. Water Engrs. and Scientists*, 35(5):349-364.

Brown, R., McTigue, N., and Cornwell, D.A. 2013a. Strategies for Assessing Optimized Corrosion Control Treatment of Lead and Copper. *J. AWWA*, 105(5): 62-75.

Brown, R., McTigue, N., and Cornwell, D.A. 2013b. LSL Flushing and OCCT Case Studies. In *Proceedings of the AWWA Annual Conference*. AWWA. Denver, CO.

Brown, M.J., Raymond, J., Homa, D., Kennedy, C., and Sinks, T. 2011. Association Between Children's Blood Lead Levels, Lead Service Lines, and Water Disinfection, Washington, DC, 1998–2006. *Environ. Res.,* 111(1): 67-74.

Butler, J.N., and Cogley, D.R. 1998. *Ionic Equilibrium Solubility and pH Calculations*. John Wiley and Sons, New York, NY.

Cadmus Group. 2004. Investigation of Potential Environmental Impacts Due to the Use of Phosphate-Based Corrosion Inhibitors in the District of Columbia. Report Prepared for EPA Region 3.

Cantor, A.F., Denig-Chakoff, D., Vela, R.R., Oleinik, M.G., and Lynch, D.L. 2000. Use of Polyphosphate in Corrosion Control. *J. AWWA*, 92(2):95.

Carlson, K.H., Via, S., Bellamy, B., and Carlson, M. 2000. Secondary Effects of Enhanced Coagulation and Softening. *J. AWWA*. 92(6): 63-75.

Clark, B., Cartier, C., St. Clair, J., Triantafyllidou, S., Prévost, M., and Edwards, M. 2013. Effect of Connection Type on Galvanic Corrosion Between Lead and Copper Pipes. *J. AWWA,* 105: E576-E577.

Clement, J.A., Daly, W.J., Shorney, H.J., and Capuzzi, A.J. 1998a. An Innovative Approach to Understanding and Improving Distribution System Water Quality. *Proceedings of AWWA Water Quality Technology Conference, San Diego, CA*. AWWA. Denver, CO.

Clement, J., Sandvig, A., Snoeyink, V., Kriven, W., and Sarin, P. 1998b. *Analyses and Interpretation of the Physical, Chemical, and Biological Characteristics of Distribution System Pipe Scales*. Water Quality Technology Conference. AWWA. Denver, CO.

Clement, J. A., and Schock, M.R. 1998. *Buffer Intensity: What is It, and Why It's Critical for Controlling Distribution System Water Quality*. AWWA Water Quality Technology Conference, San Diego, CA. AWWA. Denver, CO.

Copeland, A., and Lytle, D.A. 2014. Measuring the Oxidation-Reduction Potential of Important Oxidants in Drinking Water. *J. AWWA*, 106(1): E10-E20.

Cook, J.B. 1992. Achieving Optimum Corrosion Control for Lead in Charleston, S.C.; A Case Study. *Jour. NEWWA*, 111(2):168.

Cornwell, D., Brown, R., and McTigue, N. 2015. Controlling Lead and Copper Rule Water Quality Parameters. *J. AWWA*, 107(2): E86-E96.

Del Toral, M.A., Porter, A., and Schock, M.R. 2013. Detection and Evaluation of Elevated Lead Release from Service Lines: A Field Study. *Environ. Sci. Tech*. 47(16): 9300-9307.

DeSantis, M.K., and Schock, M.R. 2014. Ground Truthing the 'Conventional Wisdom' of Lead Corrosion Control Using Mineralogical Analysis. AWWA Water Quality Technology Conference. November 19, 2014.

Dietrich A.M., Cuppett J.D., and Duncan S.E. 2008. How Much Copper Is Too Much? *OpFlow*, 34(9):8-30.

Dodrill, D.M., and Edwards, M. 1995. Corrosion Control on the Basis of Utility Experience. *J. AWWA*, 87(7):74.

Douglas, I., Guthmann, J., Muylwyk, Q. and Snoeyink, V. 2004. Corrosion Control in the City of Ottawa-Comparison of Alternatives and Case Study for Lead Reduction in Drinking Water. In: *11th Canadian National Drinking Water Conference and 2nd Policy Forum*, W. Robertson and T. Brooks (eds.). April 3-6, Calgary, AB. Canadian Water and Wastewater Association. Ottawa, ON.

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

Edwards, M., and Dudi, A. 2004. Role of Chlorine and Chloramine in Corrosion of Lead-Bearing Plumbing Materials. *J. AWWA*, 96(10):69-81.

Edwards, M., Giani, R., Wujek, J., and Chung, C. 2004. *Use of Lead Profiles to Determine Source of Action Level Exceedances from Residential Homes in Washington, DC*, Sunday Workshop, AWWA Water Quality Technology Conference, San Antonio, TX.

Edwards, M., Jacobs, S., and Dodrill, D. 1999. Desktop Guidance for Mitigating Pb and Cu Corrosion By-Products. *J. AWWA*, 91(5):66-77.

Edwards, M., and McNeill, L.S. 2002. Effect of Phosphate Inhibitors on Lead Release from Pipes. *J. AWWA*, 94(1):79-90.

Edwards, M., Meyer, T.E., Rehring, J., Ferguson, J., Korshin, G., and Perry, S. 1996. *Role of Inorganic Anions, NOM, and Water Treatment Process in Copper Corrosion.* AwwaRF Order #90687. Project #831. AWWA Research Foundation. Denver, CO.

Estes-Smargiassi, S., and Cantor, A. 2006. Lead Service Line Contributions to Lead Levels at the Tap. AWWA Water Quality Technology Conference. Denver, CO. November 2006.

Freeze, R.A., and Cherry, J.A. 1979. *Groundwater*. Prentice Hall, NJ.

Friedman, M., Hill, A., Booth, S., Hallett, M., McNeil, L., McLean, J., Stevens, D., Sorenson, D., Hammer, T., Kent, W., De Hann, M., MacArthur, K., and Mitchell, K. 2016. *Metals Accumulation and Release within the Distribution System: Evaluation and Mitigation,* Project #4509. Water Research Foundation. Denver, CO.

Friedman, M.J., Hill, A.S., Reiber, S.H., Valentine, R.L., Larsen, G., Young, A., Korshin, G.V., and Peng, C.Y. 2010. Assessment of Inorganics Accumulation in Drinking Water System Scales and Sediments. WRF Project #3118. Water Research Foundation. Denver, CO

Gardels, M.C., and Sorg, T.J. 1989. A Laboratory Study of the Leaching of Lead from Water Faucets. *J. AWWA*, 81(7):101-113.

Giani, R., Edwards, M., Chung, C., and Wujek, J. 2004. *Lead Profiling Methodologies and Results*. Presented at Getting the Lead Out: Analysis and Treatment of Elevated Lead Levels in DC's Drinking Water at the AWWA Water Quality Technology Conference. Denver, CO.

Gregory, R. 1985. *Galvanic Corrosion of Lead and Copper Pipework: Phase I, Measurement of Galvanic Corrosion Potential in Selected Waters*. Water Research Centre Engineering, Swindon, England.

Grigg, N.S. 2010. *Secondary Impacts of Corrosion Control on Distribution System and Treatment Plant Equipment*. Project # 4029. Water Research Foundation. Denver, CO. www.waterrf.org/PublicReportLibrary/4029.pdf.

Hayes, C. R., Incledion, S., and Balch, M. 2008. Experience in Wales (UK) of the Optimization of Ortho-Phosphate Dosing for Controlling Lead in Drinking Water. *Journal of Water and Health*, 6 (2), 177-185.

Hill, C.P., and Cantor, A.F. 2011. *Internal Corrosion Control in Water Distribution Systems. AWWA Manual M58, First Edition*. American Water Works Association. Denver, CO.

Hill, A.S., Friedman, M.J., Reiber, S.H., Korshin, G.V., and Valentine, R.L. 2010. Behavior of Trace Inorganic Contaminants in Drinking Water Distribution Systems. *J. AWWA,* 107(7): 107-118.

Holm, T.R., and Schock, M.R. 1991. Potential Effects of Polyphosphate Products on Lead Solubility in Plumbing Systems. *J. AWWA*, 83(7):76-82.

Hu, J., Gan, F., Triantafyllidou, S., Nguyen, C.K., and Edwards, M.A. 2012. Copper-Induced Metal Release from Lead Pipe into Drinking Water. *Corrosion,* 68(11): 1037-1048.

Imran, S.A., Dietz, J.D., Mutoti, G., Xiao, W., Taylor, J.S., and Desai, V. 2006. Optimizing Source Water Blends for Corrosion and Residual Control in Distribution Systems. *J. AWWA,* 98(5): 107-115.

James, C.N., Copeland, R.C., and Lytle, D.A. 2004. Relationships between Oxidation-Reduction Potential, Oxidant, and pH in Drinking Water. In *Proceedings of the AWWA Water Quality Technology Conference*. AWWA. Denver, CO.

Kimbrough, D.E. 2001. Brass Corrosion and the LCR Monitoring Program. *J. AWWA*, *93*(2):81-91.

Kimbrough, D.E. 2007. Brass Corrosion as a Source of Lead and Copper in Traditional and All-Plastic Distribution Systems. *J. AWWA*, *98*(8):70-76.

Kimbrough, D.E. 2009. Source Identification of Copper, Lead, Nickel, and Zinc Loading in Wastewater Reclamation Plant Influents from Corrosion of Brass in Plumbing Fixtures. *Environ. Pollut.,* 157(4):1310-6.

Kirmeyer, G.J., Clement, J. and Sandvig, A. 2000. *Distribution System Water Quality Changes Following Implementation of Corrosion Control Strategies*. AwwaRF Order #90764. Project #157. AWWA Research Foundation. Denver, CO.

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

Kirmeyer, G.J., Murphy, B., Sandvig, A., Korshin, G., Shaha, B., Fabricino, M., and Burlingame, G. 2004. *Post-Optimization Lead and Copper Control Monitoring Strategies*. AwwaRF Order #90996F. Project #2679. AWWA Research Foundation. Denver, CO.

Kirmeyer, G.J., Sandvig, A.M., Pierson, G.L., and Neff, C.H. 1994. *Development of a Pipe Loop Protocol for Lead Control.* AwwaRF Order# 90650. Project #604. AWWA Research Foundation. Denver, CO.

Korshin, G.V., Perry, S.A.L., and Ferguson, J.F. 1996. Influence of NOM on Copper Corrosion. *J. AWWA*, 88(7): 36–47.

Korshin, G.V., Ferguson, J.F., Lancaster, A.N., and Wu, H. 1999. Corrosion and Metal Release for Lead-Containing Materials: Influence of NOM, AwwaRF Report No. 90759. Denver, CO: AWWA Research Foundation.

Korshin, G.V., Ferguson, J.F., and Lancaster. A.N. 2000. Influence of Natural Organic Matter on the Corrosion of Leaded Brass in Potable Water. *Corrosion Science*, 42: 53–66.

Korshin, G.V., Ferguson, J.F., and Lancaster, A.N. 2005. Influence of Natural Organic Matter on the Morphology of Corroding Lead Surfaces and Behavior of Lead-Containing Particles. *Water Research*, 39(5): 811–818.

Kvech, S., and Edwards, M. 2001. Role of Aluminosilicate Deposits in Lead and Copper Corrosion. *J. AWWA*, 93(11):104-112.

LaRosa-Thompson, J., Scheetz, B.E., Schock, M.R., Lytle, D.A., and Delaney, P.J. 1997. Sodium Silicate Corrosion Inhibitors: Issues of Effectiveness and Mechanism. Presented at AWWA Water Quality Technology Conference.

Lauer, W.C. 2005. *Water Quality in the Distribution System*. AWWA. Denver, CO.

Letterman, R.D. 1995. *Calcium Carbonate Dissolution Rate in Limestone Contactors, Research and Development Report*, EPA/600/SR-95/068, Risk Reduction Engineering Laboratory, Cincinnati, OH.

Letterman, R.D. Driscoll, C.T., Haddad, M., and Hsu, H.A. 1986. *Limestone Bed Contactors for Control of Corrosion at Small Water Utilities*. EPA 600/S2-86/099.

Letterman, R.D. Haddad, M. and Driscoll, C.T., Jr. 1991. Limestone Contactors: Steady State Design Relationships. *Jour. Envir. Engrg. Div.- ASCE,* 117(3):339-358.

Letterman, R.D., and Kathari, S. 1996. A Computer Program for the Design of Limestone Contactors. *Jour. NEWWA*, 110(1):42-47.

Lytle, D.A., and Schock, M.R. 1996. S*tagnation Time, Composition, pH and Orthophosphate Effects on Metal Leaching from Brass.* EPA/600/R-96/103. National Risk Management Research Laboratory, Office of Research and Development, USEPA. Cincinnati, OH.

Lytle, D.A., and Schock, M.R. 2005. The Formation of Pb (IV) Oxides in Chlorinated Water. *J. AWWA*, 97(11):102.

Lytle, D.A., Schock, M.R., Clement, J.A., and Spencer, C.M. 1998. Using Aeration for Corrosion Control*. J. AWWA*, 90(3):74-88.

Lytle, D.A., Schock, M.R., and Scheckel, K. 2009. The Inhibition of Pb (IV) Oxide Formation in Chlorinated Water by Orthophosphate. *Environ. Sci. Tech.*, 43(17), 6624-6631.

Lytle, D. A., Schock, M. R., and Sorg, T. J. 1995. Investigation on Techniques and Control of Building Lead and Copper Corrosion by Orthophosphate and Silicate, NACE Corrosion/95, Orlando, FL, 1995; pp 609/1-609/29.

Lytle, D.A., Sorg, T.J., and Frietch, C. 2004. Accumulation of Arsenic in Drinking Water Distribution Systems. *Environ Sci Technol.,* 38(20): 5365.

Mays, L.W. 1999. *Water Distribution Systems Handbook*. AWWA. Denver, CO.

McFadden, M., Giani, R., Kwan, P., and Reiber, S. 2011. Contributions to Drinking Water Lead from Galvanized Iron Corrosion Scales. *J. AWWA,* 103(4):76-89.

McNeill, L.S., and Edwards, M. 2004. Importance of Pb and Cu Particulate Species for Corrosion Control. *J. Environ. Eng.*, 130(2):136-144.

Miller, S.A. Investigation of Lead Solubility and Orthophosphate Addition in High pH Low DIC Water. Master of Science, Department of Biomedical, Chemical, and Environmental Engineering, College of Engineering and Applied Science, University of Cincinnati, Cincinnati, OH, 2014.

MOE. 2009. *Guidance Document for Preparing Corrosion Control Plans for Drinking Water Systems*. Ontario Ministry of Environment. https://ia802301.us.archive.org/18/items/guidancedocument00snsn21738/guidancedocument00snsn21738.pdf.

Montgomery, W.H. 2005. *Water Treatment Principles and Design*. 2nd Edition. John Wiley and Sons.

Muylwyk, Q., Gilks, J., Suffoletta, V., and Olesiuk, J. 2009. *Lead Occurrence and the Impact of LSL Replacement in a Well Buffered Groundwater*. Water Quality Technology Conference Proceedings. AWWA. Denver, CO.

MWRA. 2010. Massachusetts Water Resources Authority 90th Percentile Lead Levels in MWRA System of Fully-Supplied Communities, March 2010. www.mwra.com/watertesting/lead/webgraphs/2010/2010-march-640.jpg.

Nguyen, C., Stone, K., Clark, B., Edwards, M. Gagnon, G., and Knowles, A. 2010. Impact of Chloride:Sulfate Mass Ratio (CSMR) Changes on Lead Leaching in Potable Water. WRF Project #4088. Water Research Foundation. Denver, CO.

Nguyen, C.K., Stone, K.R., and Edwards, M.A. 2011. Chloride-to-Sulfate Mass Ratio: Practical Studies in Galvanic Corrosion of Lead Solder. *J. AWWA*, 103(1): 81-92.

NSF. 2010. *NSF/ANSI 61-2010. Drinking Water System Components – Health Effects*. NSF International. Ann Arbor, Michigan.

Oliphant, R.J. 1983. *Summary Report on the Contamination of Potable Water by Lead from Soldered Joints*. Water Research Center Engineering, Swindon, External Report 125-E.

Peng, C.-Y., Hill, A.S., Friedman, M.J., Valentine, R.L., Larson, G.S., Romero, A.M.Y., Reiber, S.H., and Korshin, G.V. 2012. Occurrence of Trace Inorganic Contaminants in Drinking Water Distribution Systems, *J. AWWA* 104:E181-E193.

Plummer, L.N., and Busenberg, E. 1982. Solubilities of Calcite Aragonite and Vaterite in CO_2-H_2O Solutions Between 0 and 90°C, and an Evaluation of the Aqueous Model for the System $CaCO_3$-CO_2-H_2O. *Geochimica et Cosmochimica Acta (The Journal of The Geochemical Society and The Meteoritical Society),* 46: 1011.

Rego, C.A., and Schock, M.R. 2007. Case Studies in the Integrated Use of Scale Analyses to Solve Lead Problems. Distribution System Research Symposium, AWWA. Denver, CO.

Reiber, S. 1991. Galvanic Stimulation of Corrosion on Lead-Tin Solder-Sweated Joints. *J. AWWA,* 83(7): 83-91.

Reiber, S., Poulsom, S., Perry, S.A.L., Edwards, M., Patel, S., and Dodrill, D.M. 1997. *A General Framework for Corrosion Control Based on Utility Experience*. AwwaRF Order #90712A. Project #910. AWWA Research Foundation, Denver, CO.

Rezania, L.W., and Anderl, W.H. 1996. Copper Corrosion and Iron Removal Plants. *National Conference on Integrating Corrosion Control and Other Water Quality Goals*, Cambridge, MA.

Rezania, L.W., and Anderl, W.H. 1997. Corrosion Control for High DIC Groundwater: Phosphate or Bust. AWWA Annual Conference, Atlanta, GA.

Rodgers, M. 2014. Impact of Corrosion Control on Publicly Owned Treatment Works. In *Proceedings of the Water Quality and Technology Conference*. AWWA. Denver, CO.

Safe Drinking Water Act Amendments of 1996. *Public Law 104-182.* 104th Congress. www.congress.gov/104/plaws/publ182/PLAW-104publ182.pdf.

Sandvig, A.M., Boyd, G., Kirmeyer, G., Edwards, M., Triantafyllidou, S., and Murphy, B. 2007. *Performance and Metal Release of Non-Leaded Brass Meters, Components, and Fittings*. AwwaRF Order # 91174. AWWA Research Foundation. Denver, CO.

Sandvig, A., Kwan, P., Kirmeyer, G., Maynard, B., Mast, D., Trussell, R.R., Trussell, S., Cantor, A., and Prescott, A. 2008. *Contribution of Service Line and Plumbing Fixtures to Lead and Copper Rule Compliance Issues*. AwwaRF Order # 91229. Project #3018. AWWA Research Foundation. Denver, CO.

Schendel, D.B., Chowdhury, Z.K., Hill, C.P., Summers, R.S., Towler, E., Balaji, R., Raucher, R.S., and Cromwell, J. 2009*. Simultaneous Compliance Tool: A Decision Tool to Help Utilities Develop Simultaneous Compliance Strategies*. WRF Order # 91263. Project #3115. Water Research Foundation. Denver, CO.

Schippers, J.C., Kruithof, J.C., Nederlof, M.M., Hofman, J.A.M.H. and Taylor, J. 2004. *Integrated Membrane Systems*. AwwaRF Order #90899. Project #264. AWWA Research Foundation. Denver, CO.

Schneider, O.D. Parks, J., Edwards, M., Atassi, A., and Kashyap, A. 2011. *Comparison of Zinc Versus Non-zinc Corrosion Control for Lead and Copper*. WRF Project #4103. Water Research Foundation. Denver, CO.

Schneider, O.D., Hughes, D.M., Bukhari, Z., LeChevallier, M., Schwartz, P., Sylvester, P., and Lee, J.J. 2010. Determining Vulnerability and Occurrence of Residential Backflow. *J. AWWA*, 102(8):52-63.

Schock, M.R. 1980. Response of Lead Solubility to Dissolved Carbonate in Drinking Water. *J. AWWA*, 72(12):695-704.

Schock, M.R. 1981. Erratum—Response of Lead Solubility to Dissolved Carbonate in Drinking Water. *J. AWWA,* 73(3):36.

Schock, M.R. 1989. Understanding Corrosion Control Strategies for Lead. *J. AWWA,* 81(7):88-101.

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. 1999. Internal Corrosion and Deposition Control. In *Water Quality and Treatment,* 5th Edition. R. Letterman (Ed.). McGraw-Hill Inc. New York, NY.

Schock, M.R. 2001. Tetravalent Lead: A Hitherto Unrecognized Control of Tap Water Lead Contamination. AWWA Water Quality Technology Conference. Denver, CO.

Schock, M.R. 2005. Lead Chemistry Basics, Scale Formation, and Corrosion Control Treatment. Simultaneous Compliance: The Lead/Chloramine Example. April 13, 2005, Virginia Section AWWA, Richmond, VA.

Schock, M.R. 2007a. Distribution System Considerations for Treatment. Workshop on Inorganic Contaminant Issues. August 22, 2007, Cincinnati, OH.

Schock, M.R. 2007b. New Insights Into Lead Corrosion Control and Treatment Change Impacts (with Some Considerations Towards Cu). Presented at Emerging Issues in Water Treatment MI Section, AWWA. May 15, 2007.

Schock, M.R., Cantor, A.F., Triantafyllidou, S., DeSantis, M.K., Scheckel, K.G. 2014. Importance of Pipe Deposits to Lead and Copper Rule Compliance. *J. AWWA.* 106(7): E336-E349.

Schock, M.R., Clement, J.A., Lytle, D.A., Sandvig, A.M., and Harmon, S.M. 1998. Replacing Polyphosphate with Silicate to Solve Problems with Lead, Copper and Source Water Iron. AWWA Water Quality Technology Conference, November 1-4, San Diego, CA.

Schock, M.R., DeSantis, M. K., Metz, D. H., Welch, M. M., Hyland, R.N., and Nadagouda, M.N. 2008. Revisiting the pH Effect on the Orthophosphate Control of Plumbosolvency, *Proceedings of the AWWA Annual Conference and Exposition*, Atlanta, GA.

Schock, M.R., and Fox, J.C. 2001. Solving Copper Corrosion Problems while Maintaining Lead Control in a High Alkalinity Water Using Orthophosphate. AWWA Annual Conference, June 3-7, Washington, DC.

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

Schock, M.R., Holldber, J., Lovejoy, T.R., and Lowry, J. 2002. California's First Aeration Plants for Corrosion Control. *J. AWWA*, 94(3):88-100.

Schock, M.R., Hyland, R., and Welch, M. 2008. Occurrence of Contaminant Accumulation in Lead Pipe Scales from Domestic Drinking Water Distribution Systems. *Environ. Sci. Technol.,* 42(12): 4285-91.

Schock, M.R., and Lemieux, F.G. 2010. Challenges in addressing variability of lead in domestic plumbing. *Water Science & Technology: Water Supply***,** 10(5): 792-798.

Schock, M.R., and Lytle, D.A. 2011. Chapter 20: Internal Corrosion and Deposition Control. In *Water Quality and Treatment.* 6th Edition. AWWA and McGraw-Hill, Inc.

Schock, M.R., Lytle, D.A., Sandvig, A.M., Clement, J., and Harmon, S.M. 2005. Replacing Polyphosphate with Silicate To Solve Lead, Copper, and Source Water Iron Problems. *J. AWWA*, 97(11): 84-93.

Schock, M.R., and Rego, C. 2005. Lead and Copper Corrosion Control Theory Update. New England Water Works Association Conference Spring Exposition and Conference.

Schock, M.R., and Sandvig, A.M. 2006. Long-Term Impacts of Orthophosphate Treatment on Copper. In *Proceedings of the AWWA Annual Conference and Exposition, San Antonio, TX, June 11 - 15, 2006.* AWWA. Denver, CO.

Schock, M.R., Sandvig, A.M., Lemieux, F.G., and Desantis, M.K. 2012. Diagnostic Sampling to Reveal Hidden Lead and Copper Health Risks. 15th Canadian National Conference and 6th Policy Forum on Drinking Water, Kelowna, BC, October 21-24.

Schock, M.R., Scheckel, K.G., DeSantis, M., and Gerke, T.L. 2005. Mode of Occurrence, Treatment and Monitoring Significance of Tetravalent Lead. AWWA Water Quality Technology Conference. Denver, CO.

Schock, M.R., Triantafyllidou, S., and DeSantis, M.K. 2014. Peak Lead Levels and Diagnostics in Lead Service Lines Dominated by PbO_2. In *Proceedings of the AWWA Annual Conference*. AWWA. Denver, CO.

Schock, M.R., Wagner, I., and Oliphant, R. 1996. The Corrosion and Solubility of Lead in Drinking Water. In *Internal Corrosion of Water Distribution Systems*; 2nd edition. AwwaRF Order #90508. Project #725. AWWA Research Foundation/DVGW Forschungsstelle. Denver, CO. 131-230.

Sheiham, I., and Jackson, P.J. 1981. The Scientific Basis for Control of Lead in Drinking Water by Water Treatment. *J. Inst. Water Engrs. and Scientists*, 35(6):491.

Simon, G.P. 1991. Tables and Conversion Factors – Chemical Equivalent Weights and Conversion Factors. In: *Ion Exchange Training Manual*. Springer Science+Business Media. New York.

Singley, J.E. 1994. Electrochemical Nature of Lead Contamination. *J. AWWA*, 86(7): 91-96.

Smith, S.E., Colbourne, J.S., Holt, D.M., Lloyd, B.J., and Bisset, A. 1997. An Examination of the Nature and Occurrence of Deposits in a Distribution System and their Effect on Water Quality. AWWA Water Quality Technology Conference, November 17-21. Denver, CO.

Snoeyink, V., and Jenkins, D. 1980. *Water Chemistry*. John Wiley and Sons. New York, NY.

Snoeyink, V.L., Schock, M.R., Sarin, P., Wang, L., Chen, A.S., Harmon, C., and S.M. 2003. Aluminum-Containing Scales in Water Distribution Systems: Prevalence and Composition. *Journal of Water Supply: Research and Technology —Aqua*, *52* (7): 455-474.

Spencer, C.M. 1998. Aeration and Limestone Contact for Radon Removal and Corrosion Control. *Jour. NEWWA*, 112(1):60-69.

Spencer, C.M., and Brown, W.E. 1997. pH Monitoring to Determine Aeration Effectiveness for Carbon Dioxide and Radon Removal. In *Proceedings of AWWA Water Quality Technology Conference*, November 9-13, Denver, CO.

Stone, K., Nguyen, C. and Edwards, M. 2009. Practical Identification and Resolution of Lead Corrosion Issues Due to Elevated Chloride to Sulfate Mass Ratio. AWWA Annual Conference, June 2009, San Diego, CA.

Stumm, W., and Morgan, J.J. 1981. *Aquatic Chemistry: An Introduction Emphasizing Chemical Equilibria in Natural Waters*. 2nd Edition. John Wiley and Sons, New York.

Swertfeger, J., Hartman, D.J., Shrive, C., Metz, D., and DeMarco, J. 2006. Water Quality Effects of Partial Lead Replacement. In *Proceedings of the AWWA Annual Conference.* AWWA. Denver, CO.

Tang, Z., Hong, S., Xiao, W., and Taylor, J. 2006. Impacts of Blending Ground, Surface and Saline Waters on Lead Release in Drinking Water Distribution Systems. *Water Research*, 40: 943-950.

Taylor, J.S., Dietz, J.D., Randall, A.A., Hong, S.K., Norris, C.D., Mulford, L.A., Arevalo, J.M., Imran, S., Le Puil, M., Liu, S., Mutoti, I., Tang, J., Xiao, W., Cullen, C., Heaviside, R., Mehta, A., Patel, M., Vasquez, F., and Webb, D. 2005. *Effects of Blending on Distribution System Water Quality*. AwwaRF Order #91065F. Project #2702. AWWA Research Foundation. Denver, CO.

Taylor, J.S., Dietz, J.D., Randall, A.A., Norris, C.D., Alsheri, A., Arevalo, J., Guan, X., Lintereur, P., MacNevin, D., Stone, E., Vaidya, R., Zhao, B., Glatthorn, S., and Shekhar, A. 2008. *Control of Distribution System Water Quality Using Inhibitors*. AwwaRF Order #91241F. Project #2702. AWWA Research Foundation. Denver, CO.

Triantafyllidou, S., and Edwards, M. 2010. Contribution of Galvanic Corrosion to Lead in Water after Partial Lead Service Line Replacements. Order #4088b. Project #4088. Water Research Foundation. Denver, CO.

Triantafyllidou, S., and Edwards, M. 2011. Galvanic Corrosion after Simulated Small-Scale Partial Lead Service Line Replacements. *J. AWWA*, 103(9): 85-98.

Triantafyllidou, S., Schock, M., DeSantis, M., and White, C. 2015. Low Contribution of PbO_2-Coated Lead Service Lines to Water Lead Contamination at the Tap. *Environmental Science and Technology*, 49(6): 3746−3754.

Uchida, M., and Okuwaki, A. 1999. Dissolution Behavior of Lead Plates in Aqueous Nitrate Solutions. *Corros. Sci.*, 41(10): 1977-1986.

USEPA. 1982. *EPA Method 150.1, pH (Electrometric).* www.nemi.gov/methods/method_summary/4685/.

USEPA. 1987. Amendments to the Safe Drinking Water Act. *52 FR 20674*, June 2, 1987.

USEPA. 1991a. National Primary Drinking Water Regulations – Synthetic Organic Chemicals and Inorganic Chemicals; Monitoring for Unregulated Contaminants; National Primary Drinking Water Regulations Implementation; National Secondary Drinking Water Regulations. *Federal Register,* 56(20): 3573. January 30, 1991.

USEPA. 1991b. Lead and Copper Rule. Drinking Water Regulations; Maximum Contaminant Level Goals and National Primary Drinking Water Regulations for Lead and Copper; Final Rule. *Federal Register,* 56(110): 26505. June 7, 1991.

USEPA. 1991c. Lead and Copper Rule. Drinking Water Regulations; Maximum Contaminant Level Goals and National Primary Drinking Water Regulations for Lead and Copper; Final Rule. Technical Correction. *Federal Register,* 56(135): 32112. July 15, 1991.

USEPA. 1992a. *Lead and Copper Rule Guidance Manual, Vol. II: Corrosion Control Treatment*. Report No. EPA/811-B-92/002. US Environmental Protection Agency. Washington, DC. https://nepis.epa.gov/Exe/ZyPDF.cgi/91019DM4.PDF?Dockey=91019DM4.PDF

USEPA. 1992b. Lead and Copper Rule. Drinking Water Regulations; Maximum Contaminant Level Goals and National Primary Drinking Water Regulations for Lead and Copper; Final Rule. Technical Correction. *Federal Register,* 57(125): 28785. June 29, 1992.

USEPA. 1994. Lead and Copper Rule. Drinking Water Regulations; Maximum Contaminant Level Goals and National Primary Drinking Water Regulations for Lead and Copper; Final Rule. Technical Correction. *Federal Register,* 59(125): 33860. June 30, 1994.

USEPA. 1997. Interpretation of New Drinking Water Requirements Relating to Lead Free Plumbing Fittings and Fixtures. *Federal Register,* 62(63): 44684. Aug. 22, 1997.

USEPA. 2000. National Primary Drinking Water Regulations for Lead and Copper. *Federal Register*, 65(8): 1950-2015. January 12, 2000. www.gpo.gov/fdsys/pkg/FR-2000-01-12/pdf/00-3.pdf.

USEPA. 2001. *How to Determine Compliance with Optimal Water Quality Parameters as Revised by the Lead and Copper Rule Minor Revisions.* United States Environmental Protection Agency. Office of Water 4606. EPA 815-R-99-019. February 2001. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=901U0100.pdf.

USEPA. 2003. *Final Revised Guidance Manual for Selecting Lead and Copper Control Strategies.* Report No. EPA-816-R-03-001. US Environmental Protection Agency, Washington, DC. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100999U.pdf.

USEPA. 2004a. Lead and Copper Rule. Drinking Water Regulations; Maximum Contaminant Level Goals and National Primary Drinking Water Regulations for Lead and Copper; Final Rule. *Federal Register,* 69(124): 38850. June 29, 2004.

USEPA. 2004b. USEPA *Local Limits Development Guidance*. Office of Wastewater Management 1203. EPA 833-R-04-002A. July 2004. https://nepis.epa.gov/EPA/html/DLwait.htm?url=/Exe/ZyPDF.cgi/300062Q1.PDF?Dockey=300062Q1.PDF.

USEPA. 2004c. *Lead and Copper Rule – Clarification of Requirements for Collecting Samples and Calculating Compliance.* Office of Water (4606). November 23, 2004. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100NEFJ.PDF?Dockey=P100NEFJ.PDF.

USEPA. 2006a. *Inorganic Contaminant Accumulation in Potable Water Distribution Systems.* Office of Water (4601M). December 2006.

USEPA. 2006b. *Point-of-Use or Point-of-Entry Treatment Options for Small Drinking Water Systems*, EPA 815-R-06-10. April 2006. https://nepis.epa.gov/Exe/ZyPDF.cgi/P1009UBF.PDF?Dockey=P1009UBF.PDF.

USEPA. 2007a. National Primary Drinking Water Regulations for Lead and Copper: Short-Term Regulatory Revisions and Clarifications. *Federal Register*, 72 (195) :57782-57820. October 10, 2007. www.federalregister.gov/articles/2007/10/10/E7-19432/national-primary-drinking-water-regulations-for-lead-and-copper-short-term-regulatory-revisions-and.

USEPA. 2007b. *Simultaneous Compliance Guidance Manual for Long Term 2 and Stage 2 DBP Rules*. Office of Water (4601). EPA 815-R-07-017. March 2007. http://nepis.epa.gov/Exe/ZyPDF.cgi/60000E2Q.PDF?Dockey=60000E2Q.PDF.

USEPA. 2007c. *Elevated Lead in D.C. Drinking Water – A Study of Potential Causative Events, Final Summary Report*. Office of Water (4607M). EPA 815-R-07-021. August 2007. http://nepis.epa.gov/Exe/ZyPDF.cgi/P1007ZEI.PDF?Dockey=P1007ZEI.PDF.

USEPA. 2007d. *Lead and Copper Rule 2007 Short Term Revisions and Clarifications State Implementation Guidance*. Office of Water (4606M). EPA 816-D-07-003. December 2007. http://nepis.epa.gov/Exe/ZyPDF.cgi/P100A2A8.PDF?Dockey=P100A2A8.PDF.

USEPA. 2008a. *Implementing the Lead Public Education Provisions of the Lead and Copper Rule: A Guide for Community Water Systems*. Office of Water (4606M). EPA 816-R-08-007. June 2008. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=60001I4N.pdf.

USEPA. 2008b. *Implementing the Lead Public Education Provisions of the Lead and Copper Rule: A Guide for Non-Transient Non-Community Water Systems*. Office of Water (4606M). EPA 816-R-08-008. June 2008. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=60001I2F.pdf.

USEPA. 2008c. *Lead and Copper Rule: A Quick Reference Guide*. Office of Water (4606). EPA 816-F-08-018. http://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=60001N8P.pdf.

USEPA. 2010a. *Nutrient Control Design Manual*. Office of Research and Development. EPA 600/R-10/100. August 2010. http://nepis.epa.gov/Exe/ZyPDF.cgi/P1008KTD.PDF?Dockey=P1008KTD.PDF.

USEPA. 2010b. *Lead and Copper Rule Monitoring and Reporting Guidance for Public Water Systems*. Office of Water (4606M). EPA 816-R-10-004. March 2010. http://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100DP2P.pdf.

USEPA. 2013. *Summary of the Reduction of Lead in Drinking Water Act and Frequently Asked Questions*. Office of Water (4707M) EPA 815-S-13-003. December 19, 2013. http://nepis.epa.gov/Exe/ZyPDF.cgi/P100M5DB.PDF?Dockey=P100M5DB.PDF.

USEPA. 2015a. *How to Identify Lead-Free Certification Marks for Drinking Water System & Plumbing Materials*. EPA/600/F-13/153c. Revised March 2015. http://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100LVYK.pdf.

USEPA. 2015b. Memorandum from Peter C. Grevatt, Director, Office of Ground Water and Drinking Water, to EPA Regional Water Division Directors, Regions I-X. Lead and Copper Rule Requirements for Optimal Corrosion Control Treatment for Large Drinking Water Systems. November 3, 2015. www.epa.gov/sites/production/files/2015-11/documents/occt_req_memo_signed_pg_2015-11-03-155158_508.pdf.

Vaidya, R.D. 2010. The Impact of Corrosion Inhibitors on Iron, Copper, and Lead Surface Scales in Drinking Water. In *Proceedings of the AWWA Annual Conference*. AWWA. Denver, CO.

Wang, Y., Mehta, V., Welter, G.J., and Giammar, D.E. 2013. Effect of Connection Methods on Lead Release from Galvanic Corrosion. *J. AWWA*, 105(7): E337-E351.

Wachinski, A.M. 2016. Tables and Conversion Factors – Common Water Treatment Chemicals. In: *Environmental Ion Exchange: Principles and Design*. 2nd edition. CRC Press. Boca Raton, FL.

Wasserstrom, L., Miller, S., Triantafyllidou, S., DeSantis, M., and Schock, M. 2017. Scale Formation under Blended Phosphate Treatment for a Utility with Lead Pipes. *J. AWWA*, 109(11): E464-E478.

Wilczak, A.J., Hokanson, D.R., Rhodes Trussel, R., Boozarpour, M., and Degraca, A. 2010. Water Conditioning For LCR Compliance and Control Of Metals Release In San Francisco's Water System. *J. AWWA*, 102(3):52-64.

Xiao, W., Hong, S., Tang, Z., and Taylor, J.S. 2007. Effects of Blending on Total Copper Release in Distribution Systems, *J. AWWA,* 99(1): 78-88.

Zhang, Y., Tseng, T.J., Andrews-Tate, C., Cheng, R.C., and Wattier, K.L. 2012. Pilot-Scale Evaluation of Blending Desalinated Seawater into a Distribution System, *J. AWWA,* 104: E416-E429.

Appendix A – Glossary

Term	Definition
90th Percentile	The concentration of lead or copper in tap water that is exceeded by 10 percent of the sites sampled during a monitoring period. For systems collecting five samples, the 90th percentile is the average of the fourth and fifth highest lead or copper result. For systems that are allowed by their primacy agencies to collect fewer than five samples, this value is the highest lead or copper result. The 90th percentile level is compared to the lead or copper action level (AL) to determine whether an AL has been exceeded.
Action Level (AL)	The concentration of lead or copper in tap water which determines whether a system may be required to install corrosion control treatment (CCT), collect water quality parameter (WQP) samples, collect lead and copper source water samples, replace lead service lines (LSLs), and/or deliver public education materials to consumers about lead. The action level for lead is 0.015 mg/L. The action level for copper is 1.3 mg/L.
Action Level Exceedance	Occurs when the 90th percentile lead or copper sample result is above its respective AL.
Aeration	A non-chemical method used for oxidation or adjusting pH where air is introduced into the water. This removes carbon dioxide, which results in an increase in pH.
Alkalinity	The capacity of water to neutralize acid. It is the sum of carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), and hydroxide (OH^-) anions in the water.
Aluminum Carryover	This may occur when a system uses aluminum-containing compounds in their treatment and the aluminum passes through the treatment plant processes into the distribution system. It may affect hydraulic capacity or tie up orthophosphate needed for effective corrosion control treatment.
Analogous Systems	Water systems with similar water quality, treatment, and distribution systems.
Anion	A negative ion; an atom or group of atoms that has gained one or more electrons.
Anode	The component of an electrochemical cell where oxidation occurs and electrons are generated.
Anodic Inhibitor	A substance which can be used to reduce oxidation reactions at the anode.
Buffer Index	The ability of water to provide buffering against a pH increase or decrease caused by a corrosion process or water treatment chemical addition.
Buffer Intensity	Also called buffer capacity, this is a measure of the resistance of water to changes in pH, either up or down. It is related to alkalinity (sum of bicarbonate, carbonate, and hydroxyl ions) but varies with pH.
Cation	A positive ion; an atom or group of atoms that has lost one or more electrons.

Term	Definition
Chloride-to-Sulfate Mass Ratio (CSMR)	The relative ratio of chloride ions (Cl^-) to sulfate ions (SO_4^{2-}) in the water.
Community Water System (CWS)	A public water system (PWS) that serves at least 15 service connections used by year-round residents or regularly serves at least 25 year-round residents.
Corrosion	The physicochemical interaction between a metal and its environment which results in changes in the properties of the metal.
Corrosion Control Treatment (CCT)	A treatment designed to reduce the corrosivity of water toward metal plumbing materials, particularly lead and/or copper.
Corrosion Rate	The rate at which a metal or alloy will deteriorate over time as a result of electrochemical oxidation. The rate will vary according to the specific properties of the metal or alloy and its environmental conditions.
Corrosivity	The ability of a substance to break down (corrode) materials.
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.
Cu	The chemical symbol for copper.
Demonstration Study	A study to evaluate alternative treatment approaches for reducing lead and/or copper levels which includes development and implementation of testing protocols. Demonstration testing can incorporate pipe loops, coupon tests, scale analysis, or partial system testing.
Desktop Study	A study to determine appropriate corrosion control treatment for reducing lead and/or copper levels which includes evaluations of literature, historical data and information, theory, and similar system information.
Dissolved Inorganic Carbon (DIC)	An estimate of the amount of total carbonates in the form of carbon dioxide gas (CO_2 or H_2CO_3), bicarbonate ion (HCO_3^-), and carbonate ion (CO_3^{2-}).
E_h Value	The electrical potential as measured by an oxidation-reduction potential (ORP) probe. The higher the E_h value the more oxidizing the conditions.
Electromotive Force (EMF)	Energy supplied by a source divided by the electric charge transported through the source. For a galvanic cell it is equal to the electric potential difference for zero current through the cell.
Entry Point	Refers to points of entry into the drinking water distribution system from which samples will be representative of each source after treatment.
Finished Water	Water that has been treated and is ready to be delivered to customers.
Flushed Sample	A water sample collected after the water has been allowed to run for a specified period of time.
Galvanic Corrosion	Occurs when two different types of metals or alloys physically contact each other. One of the metals serves as the anode, with its corrosion rate accelerated, while the other serves as the cathode, with its corrosion rate reduced.

Term	Definition
Hardness	A measure of the amount of calcium and magnesium in the water. Hardness is typically reported as "mg/L as $CaCO_3$" (calcium carbonate). Hardness must be taken into consideration when corrosion control is selected and implemented because too much hardness can cause unintended side effects such as increased scaling, either within the pump station/treatment plant or out in the service area.
Ionic Strength	A measure of the concentration of ions in solution.
Langelier Saturation Index (LSI)	The comparison between the measured pH of water with the pH that water would have at saturation with $CaCO_3$. The LSI should only be used to predict scaling potential as an adverse secondary impact of pH or alkalinity adjustment and has no value as a corrosivity indicator for lead and copper.
Large Water System	System serving more than 50,000 people.
LCR	An acronym used to describe the Lead and Copper Rule, which was originally published on June 7, 1991 and also includes subsequent revisions to the rule.
Lead-free	The Reduction of Lead in Drinking Water Act was enacted on January 4, 2011 to amend the Safe Drinking Water Act (SDWA) to redefine the definition of “lead-free.” The bill specifies a maximum weighted average of 0.25 percent for wetted surfaces of pipes, fittings, and fixtures and retains the maximum lead content of 0.2 percent for solder and flux. This revised definition became effective on January 4, 2014.
Lead Service Line (LSL)	A service line made of lead which connects the water main to the building inlet and any lead pigtail, gooseneck, or other fitting which is connected to such lead line (§141.2).
Limestone Contactor	A method for increasing pH, alkalinity, and calcium level by having water flow through a bed of crushed limestone.
Maximum Contaminant Level Goal (MCLG)	The level of a contaminant in drinking water below which there is no known or expected risk to health. It is set at zero for lead and 1.3 mg/L for copper.
Medium Water System	A water system that serves 3,301 to 50,000 people.
Microbial and Disinfection Byproducts Rules (MDBPR)	A series of rules from the Environmental Protection Agency (EPA) designed to protect drinking water supplies from microbial contamination while minimizing health risks from the formation of disinfection byproducts.
Natural Organic Matter (NOM)	Organic material derived from plants and animals in the environment.
Nitrification	Nitrification occurs when nitrifying bacteria convert ammonia (NH_3) into nitrite (NO_2^-) and nitrate (NO_3^-), which may lower the pH and alkalinity of the water, potentially accelerating brass corrosion and causing problems with lead release.

Term	Definition
Non-transient, Non-Community Water System (NTNCWS)	A public water system that is not a community water system and regularly serves at least 25 of the same persons during a minimum of 6 months of each year.
Optimal Corrosion Control Treatment (OCCT)	The corrosion control treatment that minimizes the lead and copper concentrations at users' taps while ensuring that the treatment does not cause the water system to violate any National Primary Drinking Water Regulations (NPDWRs) (§141.2).
Optimal Water Quality Parameters (OWQPs)	Specific ranges or minimums that are determined by the primacy agency for each relevant WQP. OWQPs represent the conditions under which systems must operate their corrosion control treatment to most effectively minimize the lead and copper concentrations at their users' taps while not violating any NPDWRs.
Orthophosphate	The active agent for phosphate-based inhibitor chemicals that, when added to the water, can combine with lead and copper to form several different compounds that have a strong tendency to form a passivating scale, inhibiting lead and copper release into drinking water).
Oxidant	A chemical compound that readily transfers oxygen atoms, or a substance that gains electrons in a redox chemical reaction.
Oxidation-Reduction Potential (ORP)	Also termed redox potential. An electrical measurement that describes the ability of water to oxidize or reduce substances. It affects how the water interacts with solid substances, such as pipe materials in a distribution system, and it affects the thermodynamic stability of minerals.
Partial System Testing	A type of demonstration study in which CCT is evaluated full-scale by applying the treatment to a hydraulically isolated portion of the distribution system.
Passivating Scale	A protective layer comprised of insoluble forms of metals that forms on the pipe surface and helps to prevent the release of lead or copper into drinking water.
Pb	The chemical symbol for lead.
pH	The pH of water is a measure of its acidity, otherwise known as hydrogen ion concentration (H^+ or H_3O^+).
Phosphate Inhibitors	Chemicals used to control lead by forming passivating phosphate-based compounds that help prevent (or inhibit) lead and copper from going into solution. Orthophosphate is the active agent for phosphate-based inhibition.
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.
Point-of-Use (POU) Treatment Unit	Treatment unit applied to a single tap to reduce contaminants in the drinking water at that tap.

Term	Definition
Polyphosphates	Polymers comprised of linked units of orthophosphate that are used to sequester (or bind) iron, manganese, and other constituents in the water to keep them in solution.
Pourbaix Diagram	Also known as a potential-pH diagram, predicts what aqueous species or corrosion by-product solid phases are thermodynamically stable under different conditions of electrochemical potential and pH.
Premise Plumbing	Premise plumbing includes that portion of the potable water distribution system associated with schools, hospitals, public and private housing, and other buildings.
Profile Testing	A type of demonstration study in which several sequential stagnation samples are collected at the tap and analyzed for lead and/or copper. This protocol for sampling can be used to evaluate lead and/or copper release from specific portions of the service line and premise piping system in a residence, and can help identify both the sources of lead and copper and the impact of replacing plumbing materials containing lead and copper.
Public Water System (PWS)	A system that provides piped water for human consumption, which has at least 15 service connections or regularly serves an average of at least 25 individuals daily for at least 60 days of the year. It includes: 1) the collection, treatment, storage, and distribution facilities operated and used by the system, and 2) any collection or pretreatment storage facilities not under the control of the system, but which it primarily uses.
Redox (Lead) Chart	A chart which shows lead speciation as a function of pH and the oxidizing or reducing environment; can be used to identify the potential for changes in ORP to influence lead or copper levels.
Secondary Standards	Non-enforceable federal guidelines regulating contaminants that may cause cosmetic, aesthetic effects (such as taste, odor, or color), or technical effects (corrosion, staining, scaling, and sedimentation) in drinking water. Iron (Fe) and manganese (Mn) are two contaminants with secondary standards (of 0.3 mg/L and 0.05 mg/L, respectively) based on their aesthetic and technical effects.
Sequestering Agents	Chemicals used to absorb metals such as iron and manganese that may interfere with treatment and/or cause customer complaints such as staining or taste problems. Examples include polyphosphates, sodium hexametaphosphate, and silicates.
Silicate Inhibitors	A mixture of soda ash and silicon dioxide that can form metal silicate compounds that serve as anodic inhibitors (i.e., they inhibit the oxidation and dissolution of the metal). They can passivate the surface of lead and copper based materials and help to reduce lead and copper levels. They can also sequester iron and manganese.
Small Water System	A water system that serves ≤ 3,300 people.
Solder	A metallic compound used to seal joints in plumbing. Until the lead ban took effect in 1988, most solder contained about 50 percent lead.

Term	Definition
Solubility (Lead or Copper) Chart	Used to predict the theoretical amount of lead or copper that may be released into water under specific water quality conditions (pH and DIC levels). They can be used as a general indication of the impact that changing water quality conditions may have on lead and copper release and its control.
Soluble/Insoluble	A substance which dissolves in a liquid is termed soluble. A substance that does not dissolve or has very low solubility is termed insoluble.
Standard 61, Section 9	A standard developed by NSF International for American National Standards Institute (ANSI) that limits the amount of lead that can be leached from endpoint devices for water intended for human consumption.
Water Distribution System	Refers to the piping, devices, and related fittings that are used to carry a system's drinking water to its users.
Water Quality Parameters (WQPs)	Used to help systems and primacy agencies determine what levels of CCT work best for the system and whether this treatment is being properly operated and maintained over time. WQPs include: pH, temperature, conductivity, alkalinity, calcium, orthophosphate, and silica.

Appendix B – Estimated Dissolved Inorganic Carbon (mg/L as C) based on Alkalinity and pH (with water temperature of 25 degrees C and TDS of 200)[1, 2, 3]

Total Alkalinity	pH																				
	6.4	**6.6**	**6.8**	**7.0**	**7.2**	**7.4**	**7.6**	**7.8**	**8.0**	**8.2**	**8.4**	**8.6**	**8.8**	**9.0**	**9.2**	**9.4**	**9.6**	**9.8**	**10.0**	**10.2**	**10.4**
0	0																				
2	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0					
4	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0			
6	3	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	0	0		
8	4	3	3	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	0		
10	4	4	3	3	3	3	3	2	2	2	2	2	2	2	2	2	2	1	1	0	
12	5	4	4	3	3	3	3	3	3	3	3	3	3	3	2	2	2	2	1	1	
14	6	5	4	4	4	4	4	3	3	3	3	3	3	3	3	3	2	2	1	1	0
16	7	6	5	5	4	4	4	4	4	4	4	4	4	4	3	3	3	2	2	1	0
18	8	7	6	5	5	5	5	4	4	4	4	4	4	4	4	4	3	3	2	2	1
20	9	7	6	6	5	5	5	5	5	5	5	5	5	4	4	4	4	3	3	2	1
22	10	8	7	6	6	6	6	5	5	5	5	5	5	5	5	4	4	4	3	2	1
24	11	9	8	7	7	6	6	6	6	6	6	6	5	5	5	5	4	4	3	2	2
26	11	10	8	8	7	7	7	6	6	6	6	6	6	6	6	5	5	4	4	3	2
28	12	10	9	8	8	7	7	7	7	7	7	7	6	6	6	6	5	5	4	3	2
30	13	11	10	9	8	8	8	7	7	7	7	7	7	7	6	6	6	5	4	3	2
35	15	13	11	10	9	9	9	9	9	8	8	8	8	8	8	7	7	6	5	4	3
40	18	15	13	12	11	10	10	10	10	10	10	9	9	9	9	8	8	7	6	5	4
45	20	16	14	13	12	12	11	11	11	11	11	11	10	10	10	9	9	8	7	6	5
50	22	18	16	14	14	13	13	12	12	12	12	12	12	11	11	10	10	9	8	7	5
55	24	20	18	16	15	14	14	14	13	13	13	13	13	12	12	11	11	10	9	8	6
60	26	22	19	17	16	16	15	15	15	14	14	14	14	14	13	12	12	11	10	8	7
65	29	24	21	19	18	17	16	16	16	16	15	15	15	15	14	14	13	12	10	9	8

Total Alkalinity	pH																				
	6.4	6.6	6.8	7.0	7.2	7.4	7.6	7.8	8.0	8.2	8.4	8.6	8.8	9.0	9.2	9.4	9.6	9.8	10.0	10.2	10.4
70	31	26	22	20	19	18	18	17	17	17	17	16	16	16	15	15	14	13	11	10	8
75	33	27	24	22	20	19	19	19	18	18	18	18	17	17	16	16	15	14	12	11	9
80	35	29	26	23	22	21	20	20	19	19	19	19	19	18	18	17	16	14	13	12	10
85	37	31	27	25	23	22	21	21	21	20	20	20	20	19	19	18	17	15	14	12	11
90	40	33	29	26	24	23	23	22	22	22	21	21	21	20	20	19	18	16	15	13	11
95	42	35	30	28	26	25	24	23	23	23	23	22	22	22	21	20	19	17	16	14	12
100	44	37	32	29	27	26	25	25	24	24	24	24	23	23	22	21	20	18	17	15	13
125	55	46	40	36	34	32	31	31	30	30	30	29	29	28	27	26	25	23	21	19	17
150	66	55	48	43	41	39	38	37	37	36	36	35	35	34	33	32	30	28	25	23	20
175	77	64	56	51	47	45	44	43	43	42	42	41	41	40	39	37	35	32	30	27	24
200	88	73	64	58	54	52	50	49	49	48	48	47	46	45	44	42	40	37	34	31	28
225	99	82	72	65	61	58	57	56	55	54	54	53	52	51	50	48	45	42	38	35	32
250	110	91	80	72	68	65	63	62	61	60	60	59	58	57	55	53	50	47	43	39	36
275	121	100	88	80	75	71	69	68	67	66	66	65	64	63	61	58	55	51	47	43	39
300	132	110	96	87	81	78	76	74	73	72	72	71	70	68	66	64	60	56	52	47	43
325	143	119	104	94	88	84	82	80	79	78	77	77	75	74	72	69	65	61	56	51	47
350	154	128	112	101	95	91	88	86	85	84	83	82	81	80	77	74	70	65	60	55	51
375	165	137	120	109	102	97	94	93	91	90	89	88	87	85	83	79	75	70	65	59	54
400	176	146	128	116	108	104	101	99	97	96	95	94	93	91	88	85	80	75	69	63	58

Notes:

[1] This table is meant to help primacy agencies and water systems identify potential carbonate precipitation constraints when evaluating CCT alternatives in Section 3.2. DIC values may be up to 20% higher at temperatures as low as 10 degrees C, and may vary slightly at higher and lower TDS.

[2] Shaded cells indicate chemically impossible conditions. May indicate analytical quality or total dissolved solids (TDS) assumption error.

[3] See USEPA (2003) for information on the formula used to calculate the DIC values provided above. Equilibrium constants are referenced from Butler and Cogley (1998); Plummer and Busenberg (1982); Schock (1980); and USEPA (2003).

Appendix C – Investigative Sampling to Determine the Source of Lead and Copper

Investigative sampling can be used to help identify the sources of lead and copper in tap water samples for a specific building. This type of information can help water systems and building owners determine the most effective lead source replacement strategy.

Systems can take two consecutive, first draw, 125-mL standing samples to identify whether the faucet, the brass underneath the faucet, or both components are contributing to lead in a tap water sample. Another method identified in the literature is collecting samples to develop premise plumbing profiles. This method may be used to determine where metals are being released within the premise plumbing and service line and can provide information on the stability and solubility of pipe scales within lead service lines (LSLs). A typical procedure is as follows:

- The water utility first collects pipe material data and estimates the length and diameter of plumbing in the home from the sample tap to the water main.
- After at least 6 hours of stagnation, water utility staff collect sequential 1-liter bottles of water without turning off the tap, typically from a kitchen sink, until all of the estimated volume in the pipe and service line has been collected (up to the water main, typically 10 to 15 bottles). Smaller volumes (e.g., 125 mL) can be collected for the first several samples to isolate potential sources of lead in the faucet from the underlying plumbing materials (connectors, valves).
- As an option, the utility can filter a small volume of water from specific samples (e.g., approximately 200 mL) on-site using a 0.45 micron filter to determine the particulate vs. dissolved portion of lead. A 'water hammer' sample can also be taken by rapidly opening and closing the tap several times to provide an indication of the amount of 'loose' particulate on the pipe walls.
- Analyzing samples for lead, copper, zinc, and iron can provide useful co-occurrence information that can be used to identify potential sources of lead in the plumbing network (Del Toral et al., 2013).

Exhibit C.1 provides an example of a lead profile at a residential home with a LSL, and identifies which portions of the premise plumbing are contributing to elevated lead levels. The home had 8 ft of copper pipe from the kitchen tap to the meter/LSL and 89 ft of LSL following that (Del Toral et al., 2013).

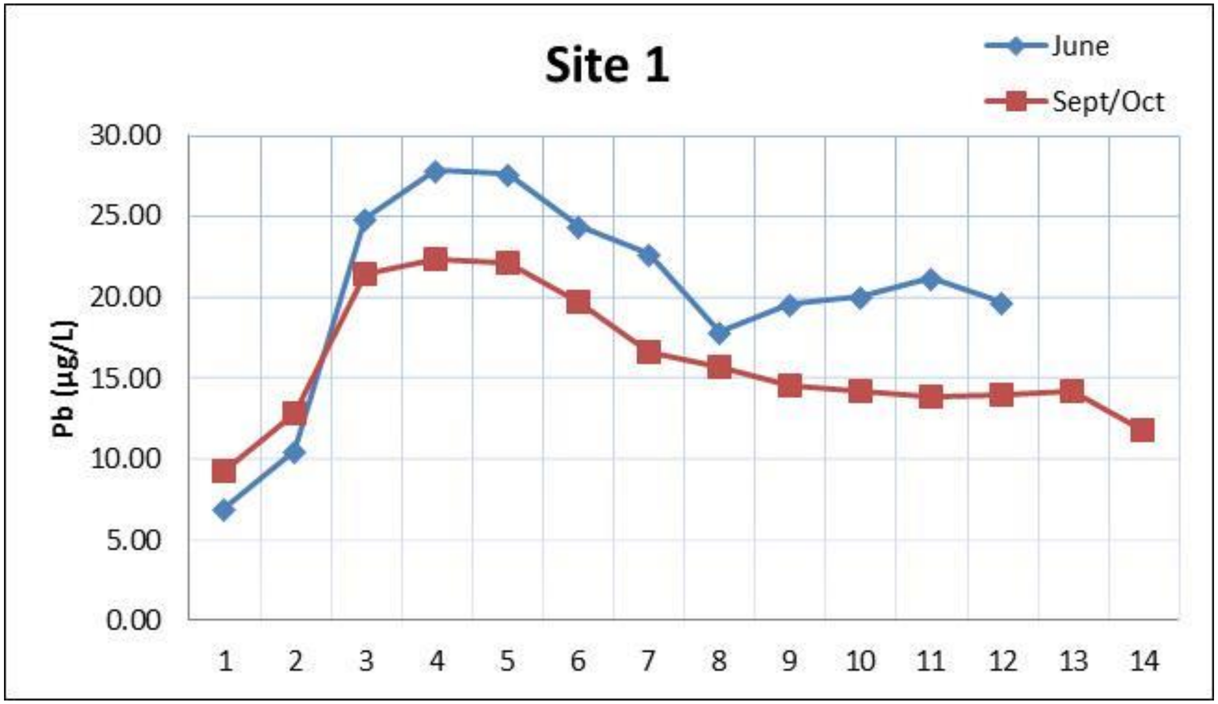

Exhibit C.1: Example of a Lead Profile (Del Toral et al., 2013)

Note: the x-axis represents sequential samples (typically liters)

Appendix D – Water Quality Data and Information Collection Forms

This appendix contains the following forms:

D.1 Water Quality Data – Raw Water
D.2 Water Quality Data – Entry Point
D.3 Water Quality Data – Distribution System
D.4 LCR Data Summary
D.5 Treatment Process Information
D.6 Lead Service Line (LSL) Information
D.7 Distribution System Materials and Operation

These forms and recommended procedures are also available electronically in the ***OCCT Evaluation Templates***.

Important notes about these forms are below.

1) These are technical recommendations only, and can be changed by the primacy agency to reflect system-specific conditions and/or primacy agency needs.

2) These tables can be included in the system's corrosion control treatment (CCT) study report or submitted separately to the primacy agency.

3) Environmental Protection Agency (EPA)-approved analytical methods must be used for regulatory sample analyses (§141.89(a)). Primacy agency approved analytical methods may be used for analysis of additional samples. In some cases, this may include use of field test kits.

Exhibit D.1: Water Quality Data – Raw Water

Exhibit D.1 Water Quality Data - Raw Water[1]													
Source Name (if more than one source, copy this section and complete for each source)													
Source ID													
Source Type													
Parameter	**Required Monitoring**			**Recommended Monitoring**			**System Data**						
	No. of Samples	**Frequency**	**Duration of Sampling**	**No. of Samples**	**Frequency**	**Duration of Sampling**	**No. of Sites**	**No. of Samples**	**Date Range When Samples Were Collected**		**Minimum Value**	**Maximum Value**	**Average Value**
									Start (dd/mm/yyyy)	**End (dd/mm/yyyy)**			
Lead (mg/L)				2	2x/year	1 year							
Copper (mg/L)				2	2x/year	1 year							
pH				6	every other month	1 year							
Alkalinity (mg/L as CaCO$_3$)				4	quarterly	1 year							
Hardness (mg/L as CaCO$_3$)				4	quarterly	1 year							
Temperature (°C)				6	every other month	1 year							
Calcium (mg/L as Ca)				4	quarterly	1 year							
Total Dissolved Solids (mg/L)[2]				4	quarterly	1 year							
Conductivity (as µmho/cm @ 25 °C)[2]				6	every other month	1 year							
Total Chlorine (mg/L as Cl$_2$)				NA	NA	NA							
Free Chlorine (mg/L as Cl$_2$)				NA	NA	NA							
Chloride (mg/L)				2	2x/year	1 year							
Sulfate (mg/L)				2	2x/year	1 year							
Iron (mg/L)				4	quarterly	1 year							
Manganese (mg/L)				4	quarterly	1 year							
Silica (mg/L as SiO$_2$)				4	quarterly	1 year							

[1] Under the Lead and Copper Rule, no raw water monitoring is required. However, if raw water monitoring data are available, this may assist the system in selecting the corrosion control treatment that will work best with the system's water quality.

[2] Either total dissolved solids or conductivity can be measured.

NA = not applicable

Exhibit D.2: Water Quality Data – Entry Point

Exhibit D.2 Water Quality Data - Entry Point[1]													
Source Name (If more than one source, copy this section and complete for each source)													
Source ID													
Source Type													
Parameters	**Entry Point**[4]												
	Required Monitoring under LCR			**Recommended Monitoring**			**System Data**						
	No. of Samples	**Frequency**	**Duration of Sampling**	**No. of Samples**	**Frequency**	**Duration of Sampling**	**No. of Sites**	**No. of Samples**	**Date Range When Samples Were Collected**		**Minimum Value**	**Maximum Value**	**Average Value**
									Start (dd/mm/yyyy)	**End (dd/mm/yyyy)**			
Lead (mg/L)[1]				1	1x/year	1 year							
Copper (mg/L)[1]				1	1x/year	1 year							
pH				12(5)	monthly	1 year							
Alkalinity (mg/L as $CaCO_3$)				12(5)	monthly	1 year							
Orthophosphate (mg/L as P)				12	monthly	1 year							
Hardness (mg/L as $CaCO_3$)				12	monthly	1 year							
Temperature (°C)				12	monthly	1 year							
Calcium (mg/L as Ca)				12	monthly	1 year							
Total Dissolved Solids (mg/L)[2]				6	every other month	1 year							
Conductivity (as µmho/cm @ 25 °C)[2]				12	monthly	1 year							
Disinfectant Residual[3]													
Total Chlorine (mg/L as Cl_2)				12(5)	monthly	2 year							
Free Chlorine (mg/L as Cl_2)				12(5)	monthly	3 year							
Chloride (mg/L)				6	every other month	1 year							
Sulfate (mg/L)				6	every other month	1 year							
Iron (mg/L)				4	quarterly	1 year							
Manganese (mg/L)				4	quarterly	1 year							
Silica (mg/L as SiO_2)				4	quarterly	1 year							

[1] Enter data for each entry point. Copy sheet for multiple entry points.

[2] Either total dissolved solids or conductivity can be measured.

[3] Both total and free chlorine should be measured.

[4] If there is no treatment, then system is only required to sample at the entry point, unless water is piped a significant distance, or stored, between the raw water point and the entry point.

[5] Additional data may be available from the system depending on process control data collection schedules.

Exhibit D.3: Water Quality Data – Distribution System

Exhibit D.3 Water Quality Data - Distribution System													
Source Name (if more than one source, copy this section and complete for each source)													
Source ID													
Source Type													
Parameter	**Required Monitoring under LCR**			**Recommended Data Collection**			**System Data**						
	No. of Samples	**Frequency**	**Duration of Sampling**	**No. of Sites**	**Frequency**	**Duration of Sampling**	**No. of Sites**	**No. of Samples**	**Date Range When Samples Were Collected**		**Minimum Value**	**Maximum Value**	**Average Value**
									Start (dd/mm/yyyy)	**End (dd/mm/yyyy)**			
pH				12(3)	monthly	1 year							
Alkalinity (mg/L as $CaCO_3$)				6	monthly	1 year							
Orthophosphate (mg/L as P)				12(3)	monthly	1 year							
Hardness (mg/L as $CaCO_3$)				6	monthly	1 year							
Temperature (°C)				12(3)	monthly	1 year							
Calcium (mg/L as Ca)				6	monthly	1 year							
Total Dissolved Solids (mg/L)[1]				6	monthly	1 year							
Conductivity (as µmho/cm @ 25 °C)[1]				12	monthly	1 year							
Disinfectant Residual[2]													
Total Chlorine (mg/L as Cl_2)				12 (3)	monthly	1 year							
Free Chlorine (mg/L as Cl_2)				12 (3)	monthly	1 year							
Chloride (mg/L)				4	quarterly	1 year							
Sulfate (mg/L)				4	quarterly	1 year							
Iron (mg/L)				4	quarterly	1 year							
Manganese (mg/L)				4	quarterly	1 year							
Silica (mg/L as SiO_2)				4	quarterly	1 year							

[1] Either total dissolved solids or conductivity can be measured.
[2] Both total and free chlorine should be measured.
[3] Select a combination of sites at various distances from the entry point.

Exhibit D.4: LCR Data Summary

Exhibit D.4 Lead and Copper Rule (LCR) Data Summary

Parameters	First Round of Regulated Tap Samples							
	No. of Samples	Minimum Value	Maximum Value	Average	90th Percentile	# Samples > 0.015 mg/L for lead or > 1.3 mg/L for copper	Sample Period Start Date (dd/mm/yyyy)	Sample Period End Date (dd/mm/yyyy)
Lead (mg/L)								
Copper (mg/L)								

Parameters	Second Round of Regulated Tap Samples							
	No. of Samples	Minimum Value	Maximum Value	Average	90th Percentile	# Samples > 0.015 mg/L for lead or > 1.3 mg/L for copper	Sample Period Start Date (dd/mm/yyyy)	Sample Period End Date (dd/mm/yyyy)
Lead (mg/L)								
Copper (mg/L)								

In the Last 10 Years	How Many Times Has the 90th Percentile of Sampling Results Exceeded the Action Level[1] (indicate the year in which these occurred in parentheses)
Lead (mg/L)	
Copper (mg/L)	

1. Action Levels are 0.015 mg/L for lead and 1.3 mg/L for copper.

Exhibit D.5: Treatment Process Information

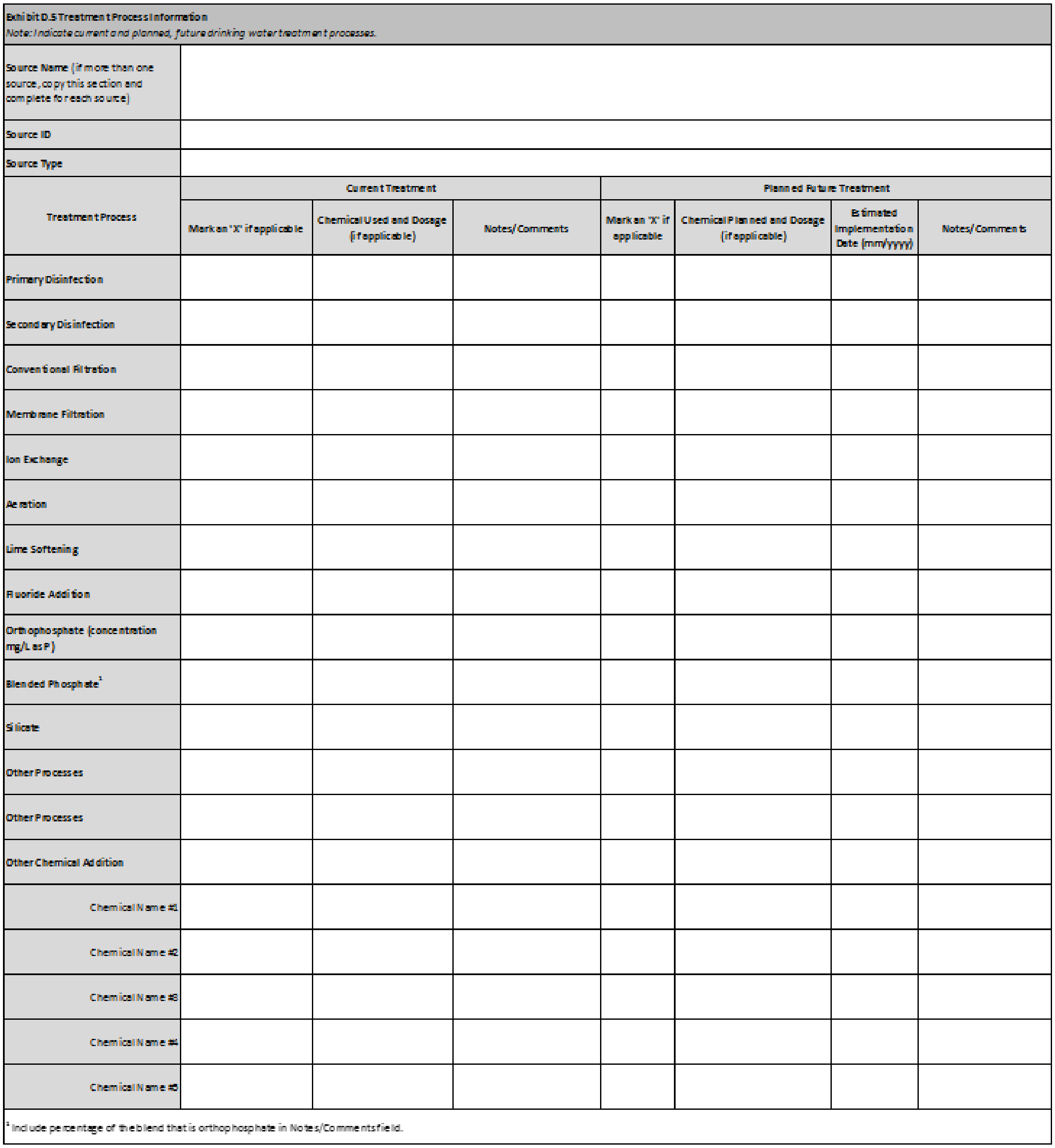

Exhibit D.5 Treatment Process Information
Note: Indicate current and planned, future drinking water treatment processes.

Source Name (if more than one source, copy this section and complete for each source)							
Source ID							
Source Type							
Treatment Process	**Current Treatment**			**Planned Future Treatment**			
	Mark an "X" if applicable	**Chemical Used and Dosage (if applicable)**	**Notes/Comments**	**Mark an "X" if applicable**	**Chemical Planned and Dosage (if applicable)**	**Estimated Implementation Date (mm/yyyy)**	**Notes/Comments**
Primary Disinfection							
Secondary Disinfection							
Conventional Filtration							
Membrane Filtration							
Ion Exchange							
Aeration							
Lime Softening							
Fluoride Addition							
Orthophosphate (concentration mg/L as P)							
Blended Phosphate[1]							
Silicate							
Other Processes							
Other Processes							
Other Chemical Addition							
Chemical Name #1							
Chemical Name #2							
Chemical Name #3							
Chemical Name #4							
Chemical Name #5							

[1] Include percentage of the blend that is orthophosphate in Notes/Comments field.

Exhibit D.6: Lead Service Line Information

Exhibit D.6. Lead Service Line Information	
Question	**Response**
Does your system have **ANY** full[1] or partial[2] lead service lines (YES or NO)?	
If **YES**, approximately how many <u>full</u> lead service lines are in place?	
If **YES**, approximately how many <u>partial</u> lead service lines are in place?	
What was the approximate range of years the lead service lines were installed (YYYY to YYYY)?	

[1] A <u>full</u> lead service line refers to the pipe from the water main to the residence being lead pipe, see illustration below (Source: Sandvig et al., 2008).

[2] A <u>partial</u> lead service line refers to only a portion of the pipe from the main to the residence being lead pipe. This could be the portion of the pipe that is under the control of the utility or the portion of the pipe that is under the control of the property owner, see illustration below (Source: Sandvig et al., 2008).

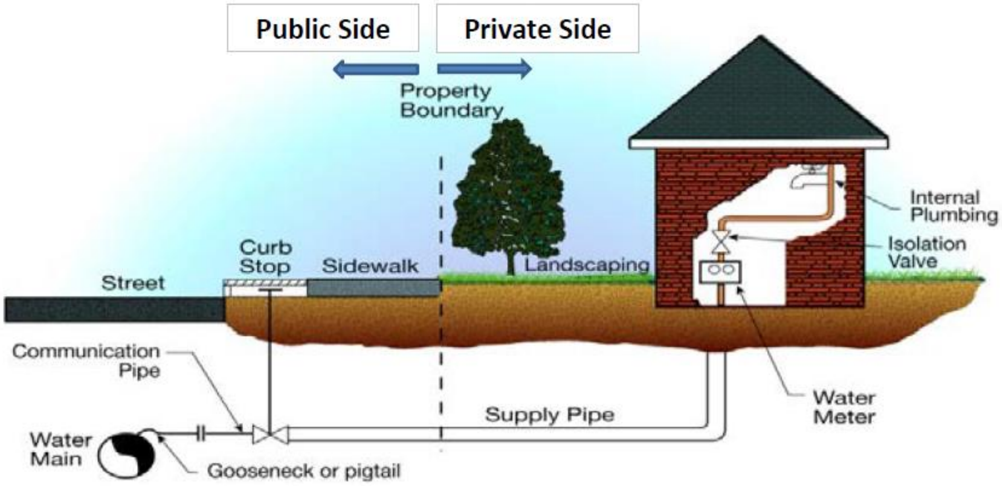

Exhibit D.7: Distribution System Materials and Operation

Exhibit D.7 Distribution System Materials and Operation		
Question	Response	
When was your last material survey completed (40 CFR §141.86(a))?		
What percentage of water mains are unlined cast iron? What is the approximate total length of unlined cast iron mains (feet)?		
Provide any additional comments on distribution system materials (e.g., list all types).		
Do you flush your system (YES or NO)?		
If **YES**, how often do you flush your system?		
Do you have dead-ends in your system that have experienced water quality problems (YES or NO)?		
If you chloraminate, do you use free chlorine periodically during the year (YES or NO)?		
If **YES**, approximately how often do you use free chlorine and at what dose?		
If **YES**, approximately how long is free chlorine used? (i.e. one week, one month, etc...)		
Do you have red water complaints?		
If **YES**, how often do they occur? Rarely (a few times a year), Sometimes (monthly), Regularly (weekly)		
Does your system purchase any water (YES or NO)?		
If **YES**, how much? If it varies by month please list an average per month.		
What is the source of the purchased water?		
Do you have plans to change your source water or purchase water from another system (YES or NO)?		
If **YES**, please describe.		
If applicable, do you have plans to change your coagulant in the near future (i.e. in the next 1-3 years) (YES or NO)?		
If **YES**, please list your current coagulant and the coagulant you plan to use. Please include the planned implementation date.	Current Coagulant	Future Coagulant

Appendix E – OCCT Recommendation Forms for Systems Serving ≤ 50,000 People

Appendix E supports Chapter 4 by providing forms systems can use to identify corrosion control treatment options, evaluate secondary impacts, and document conclusions and rationale for the optimal corrosion control treatment (OCCT) recommendation.

This appendix contains the following forms:

- E.1 Identification of Potential Corrosion Control Treatment Options
- E.2 Evaluation of Secondary Impacts
- E.3 Documentation of OCCT Recommendation

These forms and recommended procedures are also available electronically in the ***OCCT Evaluation Templates***.

Important notes about these forms are below.

1) The procedures in Exhibits E.1 through E.3 are technical recommendations only, and can be changed by the primacy agency to reflect system-specific considerations and/or primacy agency needs.

2) These tables can be included in the system's corrosion control treatment (CCT) study report or submitted separately to the primacy agency.

Exhibit E.1: Identification of Potential Corrosion Control Treatment Options

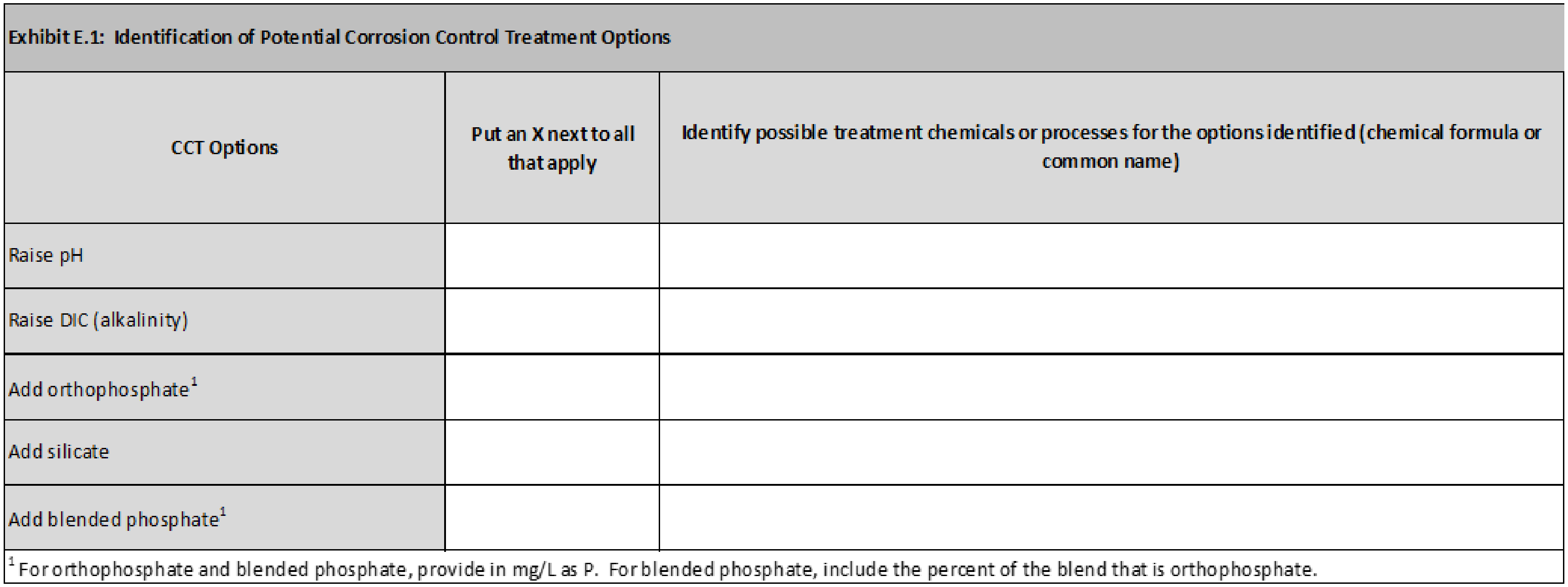

Exhibit E.1: Identification of Potential Corrosion Control Treatment Options

CCT Options	Put an X next to all that apply	Identify possible treatment chemicals or processes for the options identified (chemical formula or common name)
Raise pH		
Raise DIC (alkalinity)		
Add orthophosphate[1]		
Add silicate		
Add blended phosphate[1]		

[1] For orthophosphate and blended phosphate, provide in mg/L as P. For blended phosphate, include the percent of the blend that is orthophosphate.

Exhibit E.2: Evaluation of Secondary Impacts

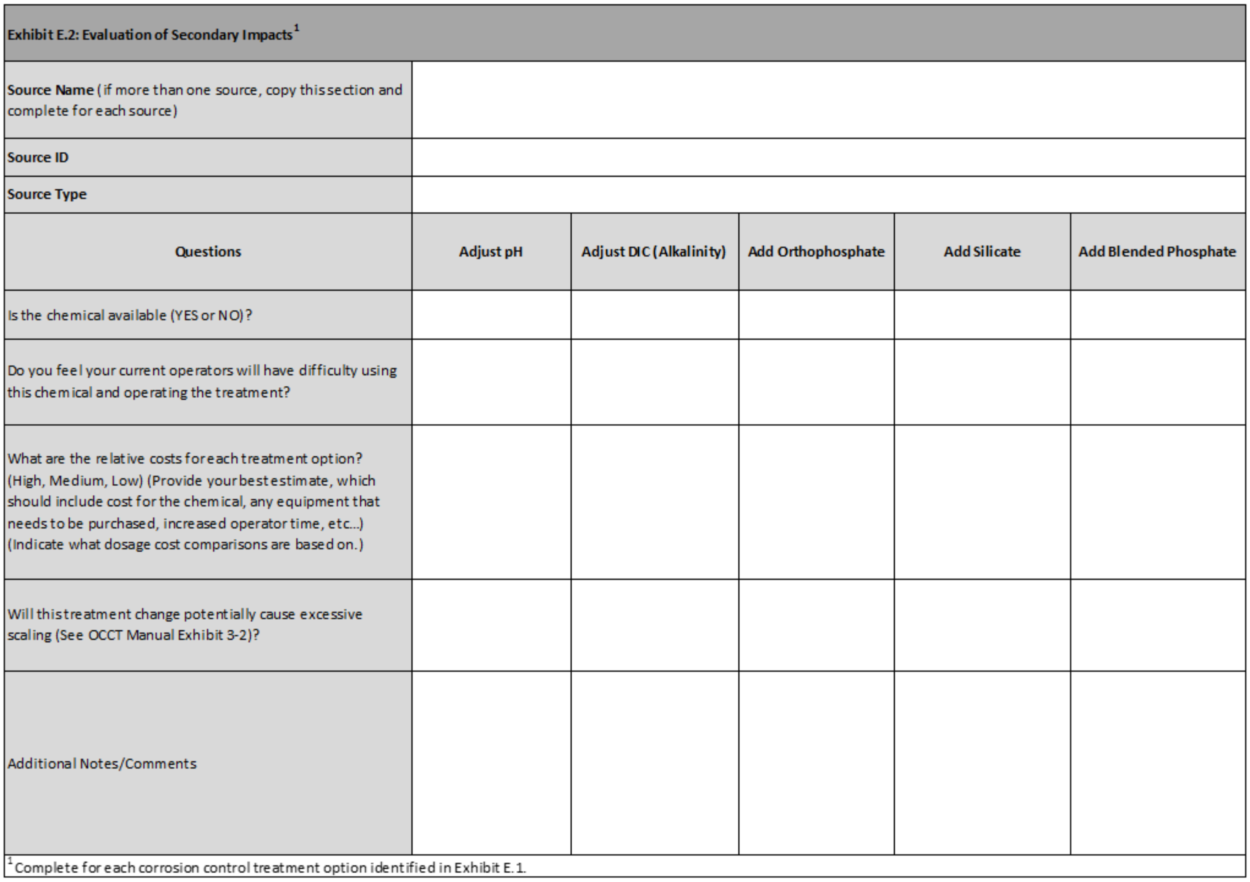

Exhibit E.2: Evaluation of Secondary Impacts[1]					
Source Name (if more than one source, copy this section and complete for each source)					
Source ID					
Source Type					
Questions	**Adjust pH**	**Adjust DIC (Alkalinity)**	**Add Orthophosphate**	**Add Silicate**	**Add Blended Phosphate**
Is the chemical available (YES or NO)?					
Do you feel your current operators will have difficulty using this chemical and operating the treatment?					
What are the relative costs for each treatment option? (High, Medium, Low) (Provide your best estimate, which should include cost for the chemical, any equipment that needs to be purchased, increased operator time, etc...) (Indicate what dosage cost comparisons are based on.)					
Will this treatment change potentially cause excessive scaling (See OCCT Manual Exhibit 3-2)?					
Additional Notes/Comments					

[1] Complete for each corrosion control treatment option identified in Exhibit E.1.

Exhibit E.3: Documentation of OCCT Recommendation

Exhibit E.3: Documentation of OCCT Recommendation					
Source Name (if more than one source, copy this section and complete for each source)					
Source ID					
Source Type					
Identify Recommended Treatment Approach	**Adjust pH**	**Adjust DIC (Alkalinity)**	**Add Orthophosphate**	**Add Silicate**	**Add Blended Phosphate**
Recommended Chemical or Process					
Recommended Dosage					
Recommended Levels at the Entry Point	**pH**	**Alkalinity (mg/L as $CaCO_3$)**	**Inhibitor**[1]		
Minimum					
Maximum					
Average					
Recommended Levels in the Distribution System	**pH**	**Alkalinity (mg/L as $CaCO_3$)**	**Inhibitor**[1]		
Minimum					
Maximum					
Average					

[1] For orthophosphate and blended phosphate, provide in mg/L as P.

PRINTED NAME and Signature of Responsible Party from Public Water System

Date

Appendix F – Tools for Conducting Corrosion Control Studies

This appendix provides a description of tools that can be used to conduct desktop or demonstration-type corrosion control studies. Note that the Lead and Copper Rule (LCR) requires the use of specific types of studies - see Chapter 4 for regulatory requirements. This appendix describes both the required types of studies and additional study tools that can be used to help identify the best corrosion control treatment.

F.1 Desktop Study Tools

Desktop study tools use analogous systems, charts and other information related to corrosion control theory, and models to select appropriate corrosion control treatment strategies. These tools are described below.

Analogous Systems[34]

Drinking water systems can evaluate and compare data from other systems with similar water quality, treatment, and distribution systems (analogous systems) to help identify corrosion control treatment options. A description of the raw source water, water treatment processes, distribution system, source water usage, and the performance of their corrosion control strategy should be included in the corrosion control study report. Systems may want to start with neighboring water systems using the same aquifer or surface source. Systems can also conduct a survey of similar systems to obtain this information; seek technical assistance from engineering consultants or industry associations; or review literature sources, such as the report by The American Water Works Association's (AWWA's) Water Industry Technical Action Fund which provides information on lead, copper, and other water quality information for 400 US water systems (AWWA, 1993). An additional resource is the Distribution System Optimization Program developed by the Partnership for Safe Water and the Water Research Foundation. Participating systems can benchmark their performance against utilities with similar water quality issues.

Corrosion Control Treatment Theory

Chapter 3 contains significant background information on corrosion control treatment. This information can help systems conduct their study and evaluate different treatment strategies.

Models

Modeling software can be used to evaluate corrosion characteristics of water and to predict changes in those characteristics with changes in treatment. However, systems and primacy

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[34] Systems conducting a desktop study (with no demonstration testing) must conduct analyses based on documented analogous treatments with other systems of similar size, water chemistry, and distribution system configuration to meet the requirements of the LCR.

agencies should consider any relevant limitations that may be inherent to the modeled data. Many models are not valid for scaling potential in the presence of phosphates, silicates, or natural organic matter (NOM), and some trace metals that inhibit nucleation and growth of $CaCO_3$. Also, calcite may not be the proper solid phase in some systems. Utilities with corrosion inhibitors or naturally occurring scale-inhibiting factors should consider marble testing or field studies to predict scale potential.

F.2 Demonstration Study Tools

This section describes coupon tests, pipe loop studies, solid and scale analysis, and partial system tests. Several documents can be referenced for more detailed information on the usefulness and relative costs of these tools (USEPA, 2007d; AWWA, 2005; Kirmeyer et al., 2004; USEPA, 1992a; AwwaRF, 1990). A guidance document prepared by the Ontario Ministry of Environment (MOE, 2009) provides a summary of these different tools and recommendations on which to use given a system's size and complexity. This document can be found at https://ia802301.us.archive.org/18/items/guidancedocument00snsn21738/guidancedocument00snsn21738.pdf.

Coupon Studies

Coupon studies use flat metal pieces (i.e., coupons) of lead, copper, iron, or steel to help determine how specific corrosion control treatments (CCTs) may help prevent release of metals from these materials. These coupons can be evaluated using a variety of different protocols (static dump and fill, mounted in a flow-through pipe rig, or mounted in the distribution system) after which they can be taken out and weighed to determine total weight loss. Coupons can also be used to measure the instantaneous corrosion rate of the metal using a variety of electrochemical techniques (ASTM, 2005; AwwaRF, 1990; Schock, 1996; USEPA, 2007d). It is important to note that coupon studies can be useful in determining the corrosion rate, but may have limited use in predicting the concentrations of lead or copper in the water (Schock, 1996).

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 studies can be designed as either flow-through systems (where water flows through the apparatus once and is discharged to waste) or as recirculating systems (where a batch of water is continuously recirculated through the loops for a set period of time). There are several references that provide detailed information on the design and operation of pipe loop systems (Schock and Lytle, 2011; AwwaRF, 1990; and Kirmeyer et al., 1994). Pipe loops may need to be operated for several months or years to develop scales that are similar to what would be found on premise piping in the system, and to measure stable metal levels. One limitation of pipe loops is that they do not provide indication of contribution of lead release from physical disturbances that occur as part of routine system operations, maintenance and repairs.

Scale and Solids Analysis

The analysis of actual pipe scale, and solids released from pipe scales, can provide an understanding of their composition and role in release of lead and/or copper to the water. These types of analyses may be particularly valuable to larger systems with lead service lines (LSLs) that are contemplating a water quality and/or treatment change (particularly a switch from free chlorine to chloramines for disinfection). Many techniques are available to examine the scale: visual inspection, X-ray emission spectroscopy, X-ray diffraction, X-ray fluorescence, Raman spectroscopy, inductively coupled plasma mass spectroscopy (ICP-MS), and scanning electron microscopy with energy dispersive spectroscopy (EDS). There is currently no standardized approach for evaluating pipe scales and solids, but there are references that provide information on the application of these techniques and typical results (Smith et al., 1997; Sandvig et al., 2008; Rego and Schock, 2007).

Partial System Testing

CCTs can be evaluated full-scale by applying the treatment to a hydraulically isolated portion of the distribution system. Systems can collect samples from residential taps for lead and copper analysis and additional water quality parameters in the distribution system. Partial system testing can be relatively expensive, but it does provide a direct means for examining the potential secondary impacts of implementing a particular CCT and for monitoring the implementation timeframes for installation of CCT (i.e., length of time needed for an inhibitor to be effective).

Appendix G – Forms for Follow-up Monitoring and Setting OWQPs

Appendix G supports Chapter 5 by providing data collection forms for follow-up monitoring and technical recommendations for primacy agencies to consider when designating Optimal Water Quality Parameters (OWQPs) for pH/alkalinity/dissolved inorganic carbon (DIC) adjustment, orthophosphate treatment, blended phosphate treatment, and use of a silicate inhibitor.

This appendix contains the following forms:

G.1 Results of Follow-up Lead and Copper Tap Monitoring
G.2 Results of Follow-up WQP Monitoring – Entry Point
G.3 Results of Follow-up WQP Monitoring – Taps
G.4 Setting OWQPs for pH/Alkalinity/DIC Adjustment
G.5 Setting OWQPs for Orthophosphate Inhibitor Addition
G.6 Setting OWQPs for Blended Phosphate Inhibitor Addition
G.7 Setting OWQPs for Silicate Inhibitor Addition
G.8 OWQPs Designated for the System

These forms and recommended procedures are also available electronically in the ***OCCT Evaluation Templates*****.**

Important notes about these forms are below.

1) Environmental Protection Agency (EPA)-approved analytical methods must be used for regulatory sample analyses (§141.89(a)). Primacy agency approved analytical methods may be used for analysis of additional samples. In some cases, this may include use of field test kits.

2) The procedures in Exhibits G.4 through G.7 are technical recommendations only; see Chapter 5 for requirements for primacy agencies in setting OWQPs. Note that the water quality ranges in these exhibits are intended as general guidelines included for the reader's reference. As discussed in Section 3.3, these values may not apply to every situation; therefore, they should not be interpreted or universally prescribed as default minimums and/or maximums.

Exhibit G.1: Results of Follow-up Lead and Copper Tap Monitoring

Exhibit G.1 Results of Follow-up Lead and Copper Tap Monitoring										
Parameter	First Round of Follow-Up Monitoring									
	Required by the Primacy Agency			PWS Data						
	No. of Tap Sites	Frequency	Duration of Sampling	No. of Sites	No. of Samples	Date Range When Samples Were Collected		Minimum Value	Maximum Value	Average Value
						Start (dd/mm/yyyy)	End (dd/mm/yyyy)			
Lead (mg/L)								mg/L	mg/L	mg/L
Copper (mg/L)								mg/L	mg/L	mg/L

Parameter	Second Round of Follow-Up Monitoring									
	Required by the Primacy Agency			PWS Data						
	No. of Tap Sites	Frequency	Duration of Sampling	No. of Sites	No. of Samples	Date Range When Samples Were Collected		Minimum Value	Maximum Value	Average Value
						Start (dd/mm/yyyy)	End (dd/mm/yyyy)			
Lead (mg/L)								mg/L	mg/L	mg/L
Copper (mg/L)								mg/L	mg/L	mg/L

Exhibit G.2: Results of Follow-up WQP Monitoring – Entry Point

Exhibit G.2 Results of Follow-up WQP Monitoring - Entry Point[1]								
Source Name (if more than one source or multiple entry points/source, copy this section and complete for each source/entry point combination)								
Source ID								
Source Type								
Parameter	**Required by the Primacy Agency**		**PWS Data**					
	Frequency	**Duration of Sampling**	**No. of Samples**	**Date Range When Samples Were Collected**		**Minimum Value**	**Maximum Value**	**Average Value**
				Start (dd/mm/yyyy)	**End (dd/mm/yyyy)**			
pH								
Alkalinity (mg/L as $CaCO_3$)								
Inhibitor Concentration (phosphate inhibitor in mg/L as P (not as orthophosphate); silicate inhibitor in mg/L as SiO_2)								
Hardness (mg/L as $CaCO_3$)								
Temperature (°C)								
Calcium (mg/L as Ca)								
Total Dissolved Solids (mg/L)[2]								
Disinfectant Residual Total Chlorine (mg/L as Cl_2)								
Free Chlorine (mg/L as Cl_2)								
Chloride (mg/L)								
Sulfate (mg/L)								
Iron (mg/L)								
Manganese (mg/L)								

[1] Enter data for each entry point. Copy sheet for multiple entry points.

[2] Either Total Dissolved Solids or Conductivity (as µmhos/cm @ 25 C or µS/cm)

Exhibit G.3: Results of Follow-up WQP Monitoring – Taps

Exhibit G.3 Results of Follow-up WQP Monitoring - Tap Samples[1]										
Source Name Associated with tap samples (if there are additional tap samples associated with a different source, copy this section and complete for each source/tap sample set. If multiple sources are associated with the tap samples listed below, list all sources here)										
Source ID(s)										
Source Type										
Parameter	**Required by the Primacy Agency**			**PWS Data**						
	No. of Tap Sites	**Frequency**	**Duration of Sampling**	**No. of Sites**	**No. of Samples**	**Date Range When Samples Were Collected**		**Minimum Value**	**Maximum Value**	**Average Value**
						Start (dd/mm/yyyy)	**End (dd/mm/yyyy)**			
pH										
Alkalinity (mg/L as CaCO$_3$)										
Inhibitor Concentration (phosphate inhibitor in mg/L as P (not as orthophosphate); silicate inhibitor in mg/L as SiO$_2$)										
Hardness (mg/L as CaCO$_3$)										
Temperature (°C)										
Calcium (mg/L as Ca)										
Total Dissolved Solids (mg/L)[2]										
Disinfectant Residual										
Total Chlorine (mg/L as Cl$_2$)										
Free Chlorine (mg/L as Cl$_2$)										
Chloride (mg/L)										
Sulfate (mg/L)										
Iron (mg/L)										
Manganese (mg/L)										

[1] Tap should be flushed prior to collecting samples for all parameters except lead and copper which are standing samples.

[2] Either Total Dissolved Solids or Conductivity (as µmhos/cm @ 25 C or µS/cm)

Exhibit G.4: Setting OWQPs for pH/Alkalinity/DIC Adjustment

Exhibit G.4 Setting OWQPs for pH/Alkalinity/DIC Adjustment		
Step 1: Are the recommended minimums or ranges for pH and/or alkalinity met at the Entry Point and in the Distribution System?[1]	YES	Go to Step 2.
	NO	Work with system to re-evaluate pH and/or alkalinity adjustment process.
Step 2: Is the range of pH values measured at the Entry Point < 0.4 pH units (Range = Max entry point pH - Min entry point pH)?[1]	YES	Go to Step 3.
	NO	The pH range may be too wide for effective control of lead and/or copper levels at the tap. Work with system to re-evaluate pH adjustment process. Review process control charts for pH chemical dosages and resultant pH levels. Evaluate seasonal changes in raw source water quality and impacts on maintenance of pH at the entry point. Also go to Step 3.
Step 3: Is the range of pH values measured in the Distribution System < 0.6 pH units (Range = Max distribution pH - Min distribution pH)?[1]	YES	Identify WQP minimums and ranges based on existing system information (both regulatory WQP monitoring data and additional diagnostic monitoring data if available).
	NO	The pH may be too variable for effective corrosion control. Re-evaluate pH adjustment process and reasons for variability in pH in the distribution system (evaluate buffer intensity, distribution system materials, distribution system operations). If low alkalinity water (< 20 mg $CaCO_3$/L), may need to increase DIC.
[1] The standard deviation is another tool that can be used to evaluate variability of pH measurements, in addition to the minimum, maximum, and range.		

Exhibit G.5: Setting OWQPs for Orthophosphate Inhibitor Addition

Exhibit G.5 Setting OWQPs for Orthophosphate Inhibitor Addition		
Step 1: Is the residual orthophosphate level in the distribution system ≥ 1.0 mg P/L (> 3.0 mg/L PO_4)?	YES	Go to Step 2.
	NO	If system has recommended an orthophosphate residual in the distribution system that is < 1.0 mg P/L, then determine if inhibitor chemical dosage needs to be increased to provide optimal reduction in lead and/or copper levels. If system has recommended an orthophosphate residual in the distribution system that is ≥ 1.0 mg P/L, then evaluate orthophosphate demand in the system (difference between entry point orthophosphate versus residual orthophosphate in the distribution system) and potential for adjusting required dosage to meet recommended residual in the distribution system. Go to Step 2.
Step 2: Are the minimum pH values measured at the Entry Point > 7.2 pH units?	YES	Go to Step 3.
	NO	Minimum pH should be higher for orthophosphate use. Have system re-evaluate pH adjustment process, or raise pH if 7.2 or below.
Step 3: Is the distribution system pH between 7.2 and 7.8 pH units?	YES	Go to Step 4.
	NO	The pH is not in the optimal range for use of orthophosphate inhibitors. Have system re-evaluate the pH control treatment process, pH variability in the distribution system, and adequacy of recommended orthophosphate dosage and residual in the distribution system.
Step 4: Is the range of pH values measured at the entry point < 0.4 pH units (Range = max entry point pH - min entry point pH)?	YES	Go to Step 5.
	NO	The pH may be too variable for effective corrosion control. System should re-evaluate the pH adjustment process (i.e., review process control charts and operations).
Step 5: Is the range of pH values measured in the distribution system < 0.6 pH units (Range = Max distribution pH - Min distribution pH)?	YES	Identify OWQP minimums and ranges based on existing information (both regulatory WQP monitoring data and additional diagnostic monitoring data if available).
	NO	Evaluate causes for pH variability in the system. Evaluate buffer intensity, distribution system materials, and distribution system operations, and adjust treatment and operations to achieve a narrower range of pH and alkalinity.

Exhibit G.6: Setting OWQPs for Blended Phosphate Inhibitor Addition

Exhibit G.6 Setting OWQPs for Blended Phosphate Inhibitor Addition		
Step 1: Is the residual orthophosphate level in the distribution system ≥ 0.5 mg P/L?	YES	Go to Step 2.
	NO	If system has recommended a blended phosphate product dose that results in an orthophosphate residual of < 0.5 mg P/L in the distribution system, then determine if inhibitor chemical dosage needs to be increased to provide optimal reduction in lead and/or copper levels. If system has recommended an orthophosphate residual in the distribution system that is ≥0.5 mg P/L, then evaluate orthophosphate demand in the system (difference between entry point orthophosphate versus residual orthophosphate in the distribution system) and potential for adjusting required dosage to meet recommended residual in the distribution system. Go to Step 2.
Step 2: Are the minimum pH values measured at the entry point > 7.2 pH units?	YES	Go to Step 3.
	NO	Minimum pH should be higher for orthophosphate use. Have system re-evaluate pH adjustment process, or raise pH if 7.2 or below.
Step 3: Is the distribution system pH between 7.2 and 7.8 pH units?	YES	Go to Step 4.
	NO	The pH may not be in the optimal range when using blended phosphate inhibitors, check with the chemical supplier for optimal pH range. Have system re-evaluate the pH control treatment process, pH variability in the distribution system, and adequacy of recommended orthophosphate dosage and residual in the distribution system.
Step 4: Is the range of pH values measured at the entry point < 0.4 pH units (Range = max entry point pH - min entry point pH)?	YES	Go to Step 5.
	NO	The pH may be too variable for effective corrosion control, check with the chemical supplier to verify quality of the product used to adjust pH. System should re-evaluate its pH adjustment process (process control charts and operations).
Step 5: Is the range of pH values measured in the distribution system < 0.6 pH units (Range = max distribution pH - min distribution pH)?	YES	Identify OWQP minimums and ranges based on existing information (both WQP monitoring data and additional diagnostic monitoring data if available).
	NO	Evaluate causes for pH variability in the system. Evaluate buffer intensity, distribution system materials, distribution system operations and adjust treatment and operations accordingly.

Exhibit G.7: Setting OWQPs for Silicate Inhibitor Addition

Exhibit G.7 Setting Optimal WQPs for Silicate Inhibitor Addition		
Step 1: Is the silicate level at the entry point approximately 20 mg/L as SiO_2?	YES	Go to Step 2.
	NO	Silicate addition process should be re-evaluated. Relatively high dosages may be required (in excess of 20 mg/L as SiO_2, depending on the system) for adequate corrosion control.
Step 2: Is the pH at the entry point less than the pH measured in the distribution system?	YES	Go to Step 3.
	NO	Silicate addition process should be re-evaluated. Silicate addition should increase pH in the distribution system, so recommended dosage may not be high enough for adequate corrosion control.
Step 3: Is the range of silicate levels measured in the distribution system from 10 to 20 mg/L as SiO_2?	YES	Identify OWQP minimums and ranges based on existing information (both regulatory WQP monitoring data and additional diagnostic monitoring data if available).
	NO	Re-evaluation of silicate treatment should be completed. Relatively higher dosages may be required (in excess of 20 mg/L) in order to maintain adequate levels in the distribution system for effective corrosion control.

Exhibit G.8: OWQPs Designated for the System

Exhibit G.8 OWQPs Designated for the System				
Parameter[1]	Entry Point		Distribution System	
	Minimum	Maximum	Minimum	Maximum
pH[2]				
Alkalinity[3] (mg/L as $CaCO_3$)				
Inhibitor Concentration (mg/L as P or SiO_2)[4]				

Notes:

[1] In addition to pH, alkalinity, or corrosion inhibitor concentrations, primacy agencies have the authority to designate values for other additional water quality parameters determined by the primacy agency to reflect optimal corrosion control treatment for the system.

[2] Under the Lead and Copper Rule, the minimum pH value measured in all tap samples must be equal to or greater than 7.0, unless the primacy agency determines that meeting a pH of 7.0 is not technologically feasible or is not necessary for the system to optimize corrosion control.

[3] Under the Lead and Copper Rule, primacy agencies must designate a minimum or a range of alkalinity concentrations if it is adjusted as part of the system's optimal corrosion control treatment.

[4] For systems using a corrosion inhibitor as part of the optimal corrosion control treatment.