Internal Corrosion Control in Water Distribution Systems

Second Edition
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Preface

This is the second edition of AWWA Manual M58, *Internal Corrosion Control in Water Distribution Systems*, prepared by the Distribution System Water Quality Committee. It provides practical guidance to aid public water systems in designing, implementing, and maintaining an effective corrosion control program. This manual is intended to help readers understand the factors that influence corrosion, assess corrosion-related impacts, and develop a strategy to implement and maintain effective corrosion control in the water distribution system.

The increased focus surrounding corrosion-related water quality and infrastructure impacts in water distribution systems has generated new research and information in this area. As such, this update of AWWA Manual M58 is a reflection of those advancements, including changes in regulatory requirements, the addition of pertinent case studies and examples, and incorporation of other new material reflective of changes in the industry. In the future, the AWWA Distribution System Water Quality Committee will continue to update this manual as new issues and questions arise.

*Editor’s note:* Throughout this manual, references are made to Awwa Research Foundation (AwwaRF). In 2009, the foundation changed its name to Water Research Foundation. Any publication prior to 2009 will reflect the foundation’s original name.
Overview of Internal Corrosion Impacts in Drinking Water Distribution Systems

Christopher P. Hill, Arcadis

INTRODUCTION

Prior to developing a corrosion control program, it is important to first gain an understanding of the factors that influence internal corrosion and metal release in drinking water distribution systems. Afterward, implementation of an effective corrosion control program can be accomplished in eight steps (Table 1-1).

Selection of an effective corrosion control strategy is not a one-time event. Changes in source water quality, treatment, distribution, operational, or regulatory changes may require a system to reevaluate, revise, optimize, or restore a corrosion control program. To assist the reader in navigating the process described in Table 1-1, this manual is organized accordingly.

PURPOSE OF THIS MANUAL

Internal corrosion of drinking water distribution and home plumbing systems has long been a recognized issue facing the drinking water industry—one that has many health, water quality, and economic implications.
This manual was written with the intent to provide a practical overview of internal corrosion issues, to identify appropriate corrosion response and control methods, and to develop corrosion control monitoring programs. It is not intended to provide detailed summaries of corrosion chemistry. References to additional resources are given where the reader might find more detailed information useful.

Although this manual briefly touches on internal corrosion of nonmetallic pipe surfaces, such as asbestos–cement and cement mortar–lined ductile- or cast-iron pipe, it primarily focuses on corrosion of metal pipe surfaces, solders, and plumbing fixtures, such as those composed of lead, copper, and iron. For the purposes of this manual, the term corrosion refers not only to the electrochemical phenomenon that causes metal loss from pipe surfaces but also to the dissolution of existing pipe scales and corrosion by-products. Internal corrosion—that is, corrosion on the interior surface of metal pipes and fixtures—is the focus of this manual because of the potential for metal release to adversely impact distributed water quality.

**CUSTOMER AND INFRASTRUCTURE IMPACTS OF INTERNAL CORROSION**

Internal corrosion can cause degradation of water quality, infrastructure performance and structural failures, and scaling and reequilibration issues. It may have substantial economic impacts on water utilities and consumers alike. This section discusses the most common issues resulting from internal corrosion of drinking water distribution and home plumbing systems.

**Water Quality Deterioration**

Internal corrosion of distribution system piping and home plumbing may cause several water quality problems, including potential health concerns, discoloration, and taste and odor issues. These problems are primarily the result of corrosion of metal pipe surfaces, pipe solder, and plumbing fixtures or dissolution of existing pipe scales. However, some problems may be attributable to corrosion of nonmetallic system components (e.g., increases in asbestos concentrations).

**Health concerns.** The majority of the health concerns associated with internal corrosion are related to the release of trace metal concentrations (lead, copper, cadmium, etc.) from corroding metal surfaces (ATSDR 2007). However, corrosion can affect the ability to maintain a disinfectant residual in the distribution system, which may result in environments suitable for biofilm growth that may harvest pathogens, such as *Legionella* and various mycobacteria. The potential health concerns related to increased metal concentrations...
in drinking water are discussed further in the “Regulatory Impacts” section later in this chapter.

**Color.** Many of the color issues typically encountered in drinking water are attributable to internal corrosion (Kirmeyer et al. 2000a, 2000b). Corrosion of cast-iron pipe or dissolution of existing scale on cast-iron pipe may result in rust-colored water or red water as a result of the presence of ferric iron (Fe(III)). Red water can stain laundry and plumbing fixtures.

Red water (Figure 1-1) may occur as a result of “hydraulic entrainment” (i.e., the suspension and transport of loose corrosion deposits resulting from changes in flow or direction of flow) or “iron uptake” (i.e., the release of ferrous ions at the pipe surface and subsequent oxidation to ferric iron and precipitation in the bulk water) (Smith et al. 1998). Alternating periods of stagnation, anaerobic conditions, and temperature have been observed to cause red water, as have significant changes in alkalinity and chlorine residual (oxidation–reduction potential [ORP]). Maintaining consistent water quality and maintaining conditions that produce a hard iron scale are critical to minimizing the potential for red water (Smith et al. 1998, Reiber 2006).

Iron corrosion may also result in yellow or black water, which is a consequence of the presence of ferrous iron (Fe(II)). Ferrous iron may occur in waters with low dissolved oxygen concentrations (Kirmeyer et al. 2000a, 2000b). Black water may also be the result of the presence of manganese (Mn) in source waters or contribution from chemicals added during treatment, such as iron-based coagulants.

Copper corrosion may result in blue or green water, which can also stain bathroom fixtures and hair. Blue water may be a consequence of the presence of either dissolved or particulate copper corrosion by-products. Dissolved copper by-products are primarily the result of low pH and can usually be eliminated by raising the pH to above 7.5 (Edwards et al. 2000). Hard, high-alkalinity groundwaters are particularly aggressive toward copper materials (Schock and Lytle 2011). Edwards et al. (1999) found that high-alkalinity waters (>74 mg/L as calcium carbonate) produced the highest 90th-percentile copper levels at pH <7.8.

However, it is often more difficult to determine the cause of particulate copper corrosion by-products, which are found in many home plumbing systems. Particulate copper
corrosion by-products are thought to be primarily the result of microbiological, chemical, or physical factors, or some combination of factors that frequently result in pitting corrosion and/or pipe failure in addition to blue water (Edwards et al. 2000, Bremer et al. 2001).

Gray or black water may also be attributable to hot water heaters. Corrosion of zinc in galvanized piping may result in a milky appearance (Kirmeyer et al. 2000a, 2000b).

**Taste and odor.** Dissolved and particulate iron may cause taste and odor issues at low concentrations. The presence of iron has resulted in metallic taste (Khiari et al. 2002). In addition to metallic taste, cast-iron corrosion may also produce musty tastes and odors (Kirmeyer et al. 2000a, 2000b). Aluminum and zinc may contribute to an astringent mouthfeel, and zinc may also result in a sour taste. Reactions of disinfectants with cement–mortar linings in ductile-iron pipe may also result in astringent, oily (rancid), pine, and phenolic odors (Khiari et al. 2002). High pH may cause the release of phenols from corroding asbestos–cement pipe, which can react with chlorine to form chlorophenols (Kirmeyer et al. 2000a, 2000b).

**Infrastructure Impacts**

In addition to affecting water quality, internal corrosion may also impact distribution and plumbing infrastructure. Most notably, internal corrosion may result in failures of home plumbing systems, causing extensive property damage. Deterioration of distribution system piping and valves as well as other in-line devices may also result from corrosion.

**Home plumbing failures.** The most significant home plumbing failures that occur because of internal corrosion are copper pitting and pinhole leaks. Pitting corrosion, though not well understood, not only damages copper plumbing, but the associated leakage may also cause substantial damage to homes and result in mold growth and other issues that may pose health concerns (Edwards 2004). Table 1-2 summarizes the conditions under which potential copper corrosion has been traditionally thought to occur.

In addition to pitting corrosion, microbiologically influenced corrosion (MIC) of copper piping may also cause pitting and failure of home plumbing (Cantor et al. 2003, 2006) and MIC is often overlooked as a contributor to corrosion of plumbing systems. MIC is more likely to occur in plumbing systems with long stagnation times, in sulfide-containing waters, and in areas in which there is little to no disinfectant residual remaining (Jacobs et al. 1998, Bremer et al. 2001, Cantor et al. 2003).

**Distribution system failures.** Corrosion of distribution system piping may lead to pipe and valve failures resulting in increased water losses. In areas of low or negative pressure, inflow and infiltration are possible, as are bacterial and other contamination from surrounding soils and groundwaters. Failure of corroded valves may also cause operational issues, such as the inability to isolate water mains in the event of a line break, loss of pressure, reduced ability to conduct distribution flushing, and creation of stagnant sections or areas of low flow in the distribution system (e.g., if a valve stem breaks in the closed position). Failures of meters and other in-line devices may reduce system revenues because of inaccurate meter readings and may minimize the ability to accurately determine water loss or identify main breaks.

**Scaling and Reequilibration**

Scaling and reequilibration are two key factors that may impact corrosion and system performance, reequilibration being the transition period following a change in distribution system water quality and lasting until equilibrium is re-established. Formation of protective metal scales is the primary corrosion control mechanism regardless of the technology employed. For example, when pH and alkalinity adjustment are used as the primary lead control strategy, the objective is to form metal solids (e.g., lead carbonate and lead oxides)
INTERNAL CORROSION IMPACTS IN DISTRIBUTION SYSTEMS

The objective of orthophosphate addition is to form a lead phosphate layer (Vik et al. 1996). Controlling the type of scale formed and subsequently maintaining the stability of those scales are key to an effective corrosion control program. Iron scales, for example, are present in either the ferrous ($\text{Fe}^{2+}$) form or ferric ($\text{Fe}^{3+}$) form. Ferrous iron scales are much softer than ferric iron scales and are more likely to contribute to red water (Sarin et al. 2000, Reiber 2006). Creating conditions in which harder ferric iron scales are formed and maintained is ideal for maintaining water quality.

After a protective scale is formed in distribution piping or home plumbing, maintaining scale stability is essential to effective corrosion control treatment. Changes in distribution system water quality may result in reequilibration of existing scales causing red water, increased tap lead or copper concentrations, or other issues.

For example, in 2000, the Washington Aqueduct (Washington, D.C.) switched from free chlorine to chloramine to reduce disinfection by-product concentrations in its

<table>
<thead>
<tr>
<th>Characteristic of Corrosion</th>
<th>Type of Corrosion</th>
<th>Uniform Corrosion (Cold Water)</th>
<th>Type I Pitting</th>
<th>Type II Pitting (Hot Water)</th>
<th>Type III Pitting (Soft Water)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pit shape</td>
<td>No pits</td>
<td>Deep and narrow</td>
<td>Narrower than Type I</td>
<td>Wide and shallow</td>
<td></td>
</tr>
<tr>
<td>Type of problem present with corrosion</td>
<td>Blue or green water, high by-product release</td>
<td>Pipe failure</td>
<td>Pipe failure</td>
<td>Blue water, voluminous by-product releases, pipe blockage</td>
<td></td>
</tr>
<tr>
<td>Scale morphology on attacked surface</td>
<td>Tarnished copper surface or loose powdery scale</td>
<td>Underlying Cu$_2$O with overlying malachite, calcite, or other basic copper salts, occasionally CuCl underlies Cu$_2$O</td>
<td>Underlying Cu$_2$O with overlying bronchantite (Cu$_4$SO$_4$(OH)$_6$), some malachite (Cu$_2$CO$_3$(OH)$_2$)</td>
<td>Underlying Cu$_2$O with overlying bronchantite (Cu$_4$SO$_4$(OH)$_6$), some malachite (Cu$_2$CO$_3$(OH)$_2$)</td>
<td></td>
</tr>
<tr>
<td>Water quality</td>
<td>Low pH (&lt;7.2) or waters with high alkalinity (&gt;250 mg/L)</td>
<td>Hard, cold well waters between pH 7.0 and 7.8, high sulfate relative to chlorides and bicarbonate, high CO$_2$</td>
<td>Hot waters, pH &lt;7.2, high sulfate relative to bicarbonate, occasional Mn deposits</td>
<td>Soft waters, pH &gt;8.0</td>
<td></td>
</tr>
<tr>
<td>Initiating factors</td>
<td>None noted</td>
<td>Stagnation early in pipe life, deposits within pipe such as dirt or carbon fines, high free chlorine residuals, water softeners, residual aluminum carryover from coagulation process</td>
<td>Higher temperatures, high free chlorine residuals, residual aluminum carryover from coagulation process</td>
<td>Stagnation early in pipe life, pH &gt;8.0, residual aluminum carryover from coagulation process, low free chlorine residual</td>
<td></td>
</tr>
<tr>
<td>Mitigating factors and treatments</td>
<td>Reduce alkalinity and raise pH or use orthophosphate</td>
<td>Increase bicarbonate and raise pH</td>
<td>Raise pH and/or increase bicarbonate</td>
<td>Avoid stagnation early in pipe life, increase hardness and alkalinity, elevate chlorine residual to &gt;0.5 mg/L</td>
<td></td>
</tr>
</tbody>
</table>

Source: Adapted from Edwards et al. 1994

Table 1-2 Summary of potential copper corrosion issues, causes, and solutions

on the pipe surface and thereby prevent corrosion, or dissolution, of lead. Similarly, the objective of orthophosphate addition is the formation of a lead phosphate layer (Vik et al. 1996).

Controlling the type of scale formed and subsequently maintaining the stability of those scales are key to an effective corrosion control program. Iron scales, for example, are present in either the ferrous ($\text{Fe}^{2+}$) form or ferric ($\text{Fe}^{3+}$) form. Ferrous iron scales are much softer than ferric iron scales and are more likely to contribute to red water (Sarin et al. 2000, Reiber 2006). Creating conditions in which harder ferric iron scales are formed and maintained is ideal for maintaining water quality.

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For example, in 2000, the Washington Aqueduct (Washington, D.C.) switched from free chlorine to chloramine to reduce disinfection by-product concentrations in its
customer agencies’ systems. As a result of this adjustment, the ORP of the finished water changed, causing a shift in the speciation of the existing lead scales and elevated lead concentrations in the District of Columbia Water (DC Water) service area (USEPA 2007). The conversion to chloramine was just one factor that contributed to the lead release. Many utilities operating chloraminated systems have not experienced similar results.

**Economic Issues**

Internal corrosion may have numerous economic or cost impacts. Excess corrosion can result in tuberculation or excess calcium precipitation, reducing hydraulic capacity, increasing pumping costs, and reducing fire flow capabilities. Failure of distribution system piping and home plumbing may necessitate costly repairs, not only of failed piping but also of other assets damaged because of the pipe failure.

There are also more subtle economic issues associated with corrosion. Increased lead and copper levels may not only result in negative publicity but may also have the potential to bring about litigation. The costs associated with legal action may be substantial. Water quality issues resulting from corrosion (e.g., color, taste and odor, and metals release) may also cause negative customer perceptions and not only affect (reduce) usage but also cost utilities potential future customers.

**REGULATORY IMPACTS**

**Lead and Copper**

In the United States, the Lead and Copper Rule (LCR) was promulgated in 1991 with the purpose of reducing drinking water exposures to lead and copper (56 FR 26460; Federal Register 1991a). The purpose of the LCR is to protect public health by minimizing lead and copper levels in drinking water, primarily by reducing water corrosivity (USEPA 2004a). Lead has been demonstrated to cause delays in physical and mental development in infants and children and has been linked to deficits in attention span and learning abilities, even at low levels (USEPA 2006a, ATSDR 2007). Short-term copper exposure may cause gastrointestinal distress; long-term exposure may cause liver or kidney damage. In individuals with Wilson’s disease, which causes the body to retain copper, copper may cause severe brain damage, liver failure, and death (ATSDR 2004, NIH 2006).

The US Environmental Protection Agency (USEPA) estimates that approximately 20 percent of human lead exposure is from lead in drinking water (USEPA 2006a). The LCR established a maximum contaminant level goal (MCLG) of zero for lead and an MCLG of 1.3 mg/L for copper. The rule established a National Primary Drinking Water Regulation for lead and copper that consisted of a treatment technique requirement including corrosion control treatment, source water treatment, lead service line (LSL) replacement, and public education. The rule set an action level (AL) of 0.015 mg/L for lead and 1.3 mg/L for copper. If the 90th percentile concentration for lead or copper is above the AL, public water systems may be required to initiate water quality parameter monitoring for key corrosion control parameters, install corrosion control treatment, begin source water monitoring or treatment, replace the LSL, or undertake a public education program. USEPA issued guidance to assist utilities in complying with the corrosion control treatment requirements of the LCR in 1992 (USEPA 1992) and provided updated guidance to assist in identification and maintenance of optimal corrosion control treatment in 2016 (USEPA 2016).

Internal corrosion of LSLs, brass meters and plumbing fixtures, and copper plumbing contributes to the concentrations of lead and copper in drinking water. Pure lead pipe (LSLs), lead solder, and brass with greater than 8 percent lead were banned by the 1986 Safe Drinking
Water Act Amendments (Dudi et al. 2005). “Lead-free” brass, however, was allowed to contain as much as 2 to 8 percent lead by weight under this amendment. Greenville Utilities in Greenville, N.C., exceeded the lead AL in 2004 and 2005 even though the system does not contain any LSLs. In this case, the exceedance was attributed to leaching from lead-based solder and plumbing fixtures containing lead (Landers 2006). California banned the use of pipe solder with lead content greater than 0.2 percent in 1987. In 2010, California law defined “lead free” as less than 0.25 percent weighted average and required that all pipes, fittings, and fixtures meet this definition (California DTSC 2009). Similarly, effective January 4, 2014, the federal Reduction of Lead in Drinking Water Act redefined lead-free as containing no more than 0.25% lead as a weighted average on the wetted surface and required “any pipe or plumbing fitting or fixture, any solder, or any flux” used in the installation or repair of any public water system, or any plumbing in a residential or nonresidential facility providing water for human consumption, to be lead free (USEPA 2013a).

In Canada, the low-lead requirements are integrated into plumbing standards that are referenced in the National Plumbing Code of Canada (NPC). In November 2013, a modification of the NPC was approved whereby plumbing standards that required fittings meet the 0.25% weighted average lead limit were added to the 2010 version of NPC as an interim change. The interim change was published in late 2013 (NRCC 2013) and subsequently in the 2015 version of the NPC (NRCC 2015).

Impact of the LCR on tap-water lead concentrations. A review conducted by USEPA of LCR compliance monitoring data for public water systems serving more than 3,300 people shows that since 2000, fewer than 4 percent of those systems have exceeded the lead AL (USEPA 2004b). Prior to 2002, states were not required to report 90th percentile lead concentrations to USEPA unless those values exceeded the AL. Consequently, it is difficult to compare the tap-water lead concentrations in the years following implementation of the LCR to current levels. However, USEPA did evaluate data from 166 large public water systems that exceeded the AL following initial LCR monitoring in 1992 and 1993 (USEPA 2006d). Based on the results of subsequent monitoring conducted by these same utilities between 2000 and 2004, only 15 of those systems continued to exceed the AL (Figure 1-2).

A closer look at the data presented in Figure 1-2 reveals that tap-water lead concentrations have decreased significantly in those systems that initially exceeded the lead AL. Figure 1-3 shows that, for those 166 large systems that exceeded the AL in 1992–1993, the average 90th percentile lead concentration across all 166 systems surveyed decreased from nearly 32 µg/L to 8.2 µg/L. Over that same period, the maximum 90th percentile lead concentration decreased from 211 µg/L to 84 µg/L.

Revisions to the Lead and Copper Rule. USEPA revised the LCR in 2007 (72 FR 57781; Federal Register 2007) with the intent of enhancing implementation in the areas of monitoring, treatment, customer awareness, and LSL replacement. In addition, the 2007 revisions intended to improve public education by providing drinking water customers with “meaningful, timely, and useful information needed to reduce exposure to lead in drinking water.”

The most significant revisions to the LCR provided clarification regarding sample collection and reporting. Specifically, the LCR revisions required that all compliance monitoring results, including those above the required number of samples, be included in the 90th percentile determination and that all samples be taken within the same calendar year for those systems on reduced monitoring. The remainder of the revisions addressed customer notification for those residents in a utility’s sampling program and provisions to address sampling sites with known LSLs that were previously “tested out” due to sample results below the AL.

Long-term revisions to the Lead and Copper Rule. In the years since LCR implementation, a variety of noteworthy research within the drinking water community has provided new insights in lead and copper corrosion and has led to concerns that the
current LCR may systematically underestimate lead and copper levels in drinking water (e.g., Del Toral et al. 2013). The Lead and Copper Rule Working Group (LCRWG) of the National Drinking Water Advisory Council (NDWAC) was formed to provide recommendations to USEPA regarding the Long-Term Revisions to the Lead and Copper Rule. The LCRWG was tasked with addressing the following issues:
Sample site selection criteria
Lead sampling protocols
Public education for copper
Measures to ensure optimal corrosion control treatment
LSL replacement

The LCRWG met between March 2014 and June 2015 and issued its recommendations to USEPA in August 2015 (NDWAC 2015). Among its findings, the Report of the Lead and Copper Rule Working Group to the National Drinking Water Advisory Council concluded that the anticipated Long-Term Revisions to the Lead and Copper Rule represent a significant opportunity for “removing sources of lead in contact with drinking water and for reducing exposure to lead from drinking water.” Further, the LCRWG noted that eliminating the sources of lead in contact with drinking water would require creative funding solutions, as total replacement is expected to cost billions of dollars nationwide. It also concluded that more robust public outreach and education is necessary.

In making its recommendations to USEPA,

The LCRWG took the following considerations, among others, into account in making recommendations for revisions to the current LCR.

There is no safe level of lead. Lead can pose health risks to anyone, but there are heightened risks for pregnant women, infants and young children and other vulnerable populations with both acute and chronic exposures. Effective elimination of leaded materials in contact with water and minimization of exposure to lead in drinking water is a shared responsibility; public water systems (PWSs), consumers, building owners, public health officials and others each have important roles to play. The lack of resources to reduce the sources of exposure in some communities, however, also raises important questions of disparate impact and environmental justice. Thus, creative financing mechanisms will be needed.

The LCR should remain a treatment technique rule, but it can be improved based on the scientific knowledge that has emerged since the current LCR was promulgated. Corrosion control treatment is complicated, and will vary based on specific circumstances in each public water system. Thus, regular updates to guidance by EPA based on the latest science and the creation of a national clearinghouse of information both for the public and for PWSs are needed.

The LCRWG considered but did not quantify the cost implications of its recommendations. An important factor in the group’s deliberations was the principle that PWS and state resources should be focused on actions that achieve the greatest public health protection. Recognizing that lead service line (LSL) replacement programs will be costly in some locations, the LCRWG also encouraged PWSs to incorporate anticipated costs into their capital improvement program as appropriate to their situation, and urges states to include the costs of LSL replacement in their criteria for allocation of Drinking Water State Revolving Funds.

The LCRWG specifically recommends that EPA revise the LCR to:

• Require proactive lead service line replacement programs, which set replacement goals, effectively engage customers in implementing those
goals, and provide improved access to information about LSLs, in place of current requirements in which LSLs must be replaced only after a lead action level (AL) exceedance;

- Establish more robust public education requirements for lead and LSLs, by updating the Consumer Confidence Report (CCR), adding targeted outreach to consumers with lead service lines and other vulnerable populations (pregnant women and families with infants and young children), and increasing the information available to the public;

- Strengthen corrosion control treatment (CCT), retaining the current rule requirements to re-assess CCT if changes to source water or treatment are planned, adding a requirement to review updates to EPA guidance to determine if new scientific information warrants changes;

- Modify monitoring requirements to provide for consumer requested tap samples for lead and to utilize results of tap samples for lead to inform consumer action to reduce the risks in their homes, to inform the appropriate public health agency when results are above a designated household action level, and to assess the effectiveness of CCT and/or other reasons for elevated lead results;

- Tailor water quality parameters (WQPs) to the specific CCT plan for each system, and increase the frequency of WQP monitoring for process control;

- Establish a health-based, household action level that triggers a report to the consumer and to the applicable health agency for follow up;

- Separate the requirements for copper from those for lead and focus new requirements where water is corrosive to copper; and

- Establish appropriate compliance and enforcement mechanisms. (NDWAC 2015)

USEPA is currently considering the LCRWG recommendations and is anticipated to issue a proposed rule in 2017. While not obligated to adopt the working group recommendations, USEPA is likely to include the suggestions, or some form of them, in the revised rule, most notably the recommendations for proactive LSL replacement, enhanced WQP monitoring, and more robust public education.

**Health Canada guidelines.** The safety of drinking water supplies in Canada is a responsibility that is shared between the provincial/territorial, federal, and municipal governments. The day-to-day responsibility of providing safe drinking water to the public generally rests with the provinces and territories while the municipalities usually oversee the day-to-day operations of the treatment facilities. Health Canada develops its *Guidelines for Canadian Drinking Water Quality* in partnership with the provinces and territories. These guidelines are used by every jurisdiction in Canada and are the basis for establishing provincial drinking water quality requirements for all Canadians (Health Canada 2015).

In Canada, the guideline for lead is a maximum acceptable concentration (MAC) of 0.01 mg/L (10 µg/L) based on a provisional tolerable weekly intake of lead established by the World Health Organization (Health Canada 1992). However, Health Canada is reviewing the lead guideline to include the most recent health information as well as sampling and monitoring strategies that address exposure from drinking water (Health Canada 2013). Treatment-based guidance for corrosion control was published in 2009 (Health Canada 2009). The recommended sampling protocol found in this guidance uses stagnation times to capture the highest levels of lead to provide the basis for a system-wide assessment of the corrosion control efficacy.
**Iron and Manganese**

USEPA established secondary maximum contaminant levels (SMCLs) of 0.3 mg/L for iron and 0.05 mg/L for manganese, which represent a “reasonable goal for drinking water quality” (Federal Register 1979, 1991b; USEPA 2013b). SMCLs control contaminants that primarily affect the aesthetic quality of drinking water and are not federally enforceable, although state primacy agencies have the authority to include them in state drinking water regulations. When present at sufficiently high levels, iron may result in rusty color, deposit of sediment, metallic taste, and reddish or orange staining. Similarly, Health Canada’s established aesthetic objective for iron in drinking water is ≤0.3 mg/L (≤300 µg/L). A MAC has not been set for iron (Health Canada 1978).

Much of the iron present in water is because of natural mineral deposits, and when present in source waters at concentrations above the SMCL, iron is frequently removed at the water treatment facility. If not removed, source-water iron may result in red water in the distribution system. However, internal corrosion of unlined cast-iron pipe, galvanized pipe, or dissolution of existing pipe scales in iron pipe may also result in aesthetic issues in drinking water distribution systems.

Iron, manganese, and aluminum scales in water distribution systems have adsorptive properties and can contain substantially higher concentrations of trace metals, such as lead, copper, cadmium, and zinc, than are present in the bulk water entering the system (Friedman et al. 2009, Deshommes et al. 2010, McFadden et al. 2011, Camara et al. 2013, Schock et al. 2014). Release of these metals can occur because of changes in pH and ORP associated with source water blending or source changeovers, treatment process changes, disinfectant residual loss, or biological reactions. These bulk water chemistry changes can cause desorption of contaminants from iron and manganese scales or can result in chemical destabilization of existing scales (Friedman et al. 2009). Physical releases of existing iron scales may trigger red-water events, which may contain elevated concentrations of trace metals. Physical release can be caused by changes in distribution system hydraulics, such as sudden changes in demand, flushing activities, fire flow events, main breaks, or other changes in flow patterns.

**Cadmium**

Short-term exposure to high concentrations of cadmium may result in nausea, vomiting, diarrhea, muscle cramps, salivation, sensory disturbances, liver injury, convulsions, shock, and renal failure. Long-term exposures may cause kidney, liver, bone, and blood damage (USEPA 2006b). Consequently, USEPA has established an MCLG of 0.005 mg/L for cadmium as well as a maximum contaminant level (MCL) of 0.005 mg/L. A MAC of 0.005 mg/L (5 µg/L) for cadmium in drinking water has been established on the basis of health considerations (Health Canada 1986).

Cadmium is primarily present in drinking waters as a result of erosion of natural deposits but may also be present because of leaching from cement–mortar-lined pipes (Guo et al. 1998, Berend and Trouwborst 1999) or from corrosion of galvanized piping. It has also been observed that the amount of lead and cadmium released from galvanized piping decreases with the age of the pipe as a consequence of the formation of a passivating layer on the pipe surface (Meyer 1980).

**Zinc**

Zinc in drinking water is primarily an aesthetic concern because it may result in a metallic taste. Consequently, USEPA has established an SMCL of 5 mg/L for zinc. An aesthetic objective has been established for zinc in drinking water of ≤5.0 mg/L (Health Canada 1987).
Zinc may be present in drinking water due to erosion of natural deposits or from dezincification of brass plumbing fixtures. Several studies of low-alkalinity waters have found that iron and zinc were the principal corrosion by-products of galvanized plumbing (Dangel 1975, JMM 1982).

The zinc coating on galvanized pipe may contain lead, copper, cadmium, chromium, aluminum, barium, and other impurities (AwwaRF and TZW 1996). There are a number of standards regarding galvanized pipe, most notably by ASTM International in the United States. As a result of these impurities, corrosion of galvanized pipe may result in the release of trace metal concentrations.

**Asbestos**

Asbestos in drinking water is most commonly present as a result of degradation of asbestos–cement piping used in drinking-water distribution systems. Though it may be present in natural soils, it does not often migrate to groundwater through soils (USEPA 2006c). Short-term exposure to asbestos in drinking water is not known to cause any health issues; long-term exposure may result in an increased risk of developing benign intestinal polyps. USEPA has established an MCLG of 7 million fibers per liter (MFL) and an MCL of 7 MFL for asbestos.

**Biological Regrowth and Chlorine Demand**

In the United States, the Surface Water Treatment Rule was finalized in 1989 and requires maintenance of a disinfectant residual in the distribution system, among other requirements (54 FR 27486; Federal Register 1989a). The Total Coliform Rule (TCR) imposed monitoring requirements for total coliform as well as for fecal coliform and *Escherichia coli* (54 FR 27544; Federal Register 1989b). The Revised Total Coliform Rule further established an MCL for *E. coli* and uses *E. coli* and total coliforms to initiate a “find and fix” approach to address fecal contamination that could enter into the distribution system (78 FR 10269; Federal Register 2013). It requires public water systems to perform assessments to identify sanitary defects and subsequently take action to correct them. Biological regrowth and chlorine demand may be affected by corrosion in many ways and vice versa. Chlorine and other oxidants impact the ORP, which is a factor in maintaining effective corrosion control. Conversely, corrosion by-products can exert an oxidant demand, diminishing distribution system disinfectant residuals and resulting in increased potential for microbiological regrowth. Microbiological regrowth not only may threaten compliance with the TCR but may also result in increased potential for MIC to occur.

**Release of Trace Metals From Cementitious Coatings**

Barium, cadmium, chromium, and aluminum have been found to leach from cement–mortar lining in distribution piping (Guo et al. 1998, Berend and Trouwborst 1999). While this leaching represents a potential water quality and public health concern, it is not the focus of this manual.

**ADDITIONAL READING**

The reader is advised to become more knowledgeable in the following areas:

- The water quality and operational factors that influence internal corrosion and metal release in drinking water distribution systems
• The potential water quality, health-related infrastructure, and regulatory concerns associated with internal corrosion
• The secondary impacts associated with changes in source-water quality, treatment, or distribution operations and the potential for those changes to affect existing corrosion control effectiveness (i.e., reequilibration of existing pipe scales)

References for this chapter give detailed information on these topics and the other topics discussed. The reader is encouraged to follow up on the referenced material that is publicly available to obtain keener insight into this discussion.

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