Manual of Water Supply Practices

M58

Internal Corrosion Control in Water Distribution Systems

Second Edition

American Water Works Association

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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.

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J. Boxall, University of Sheffield, Sheffield, U.K.
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A. Cantor, Process Research Solutions, LLC, Madison, Wis.
M. Friedman, Confluence Engineering Group, LLC, Seattle, Wash.
R. Giani, CH2M, Lees Summit, Mo.
A. Hill, Confluence Engineering Group, LLC, Seattle, Wash.
C. Hill, Arcadis, Tampa, Fla.
S. Husband, University of Sheffield, Sheffield, U.K.
A. Jacque, Water Quality Investigations, LLC, Mount Horeb, Wis.
B. Lakin, McMillen Jacobs Associates, New York, N.Y.
M. McFadden, M3P Services, LLC, Denver, Colo.
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Chapter 1

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.

Table 1-1 Eight steps to implementing an effective corrosion control program

Step	Discussed in Chapter(s)
1. Develop an understanding of the general concepts behind internal corrosion and metal release in drinking water distribution systems	1, 2
2. Determine the extent and magnitude of corrosion	3
3. Determine the possible causes of corrosion	2, 3
4. Assess corrosion control alternatives	4
5. Develop a corrosion control strategy	4, 5
6. Implement a corrosion control program	3, 6
7. Monitor the effectiveness of the corrosion control program	3, 6
8. Optimize the corrosion control program	5, 6

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

Courtesy of DC Water

Figure 1-1 Red-water sample from a US distribution system

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)

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

	Type of Corrosion			
Characteristic of Corrosion	Uniform Corrosion	Type I Pitting (Cold Water)	Type II Pitting (Hot Water)	Type III Pitting (Soft Water)
Pit shape	No pits	Deep and narrow	Narrower than Type I	Wide and shallow
Type of problem present with corrosion	Blue or green water, high by-product release	Pipe failure	Pipe failure	Blue water, voluminous by-product releases, pipe blockage
Scale morphology on attacked surface	Tarnished copper surface or loose powdery scale	Underlying Cu_2O with overlying malachite, calcite, or other basic copper salts, occasionally CuCl underlies Cu_2O	Underlying Cu_2O with overlying bronchantite ($Cu_4SO_4(OH)_6$), some malachite ($Cu_2CO_3(OH)_2$)	Underlying Cu_2O with overlying bronchantite ($Cu_4SO_4(OH)_6$), some malachite ($Cu_2CO_3(OH)_2$)
Water quality	Low pH (<7.2) or waters with high alkalinity (>250 mg/L)	Hard, cold well waters between pH 7.0 and 7.8, high sulfate relative to chlorides and bicarbonate, high CO_2	Hot waters, pH <7.2, high sulfate relative to bicarbonate, occasional Mn deposits	Soft waters, pH >8.0
Initiating factors	None noted	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	Higher temperatures, high free chlorine residuals, residual aluminum carryover from coagulation process	Stagnation early in pipe life, pH >8.0, residual aluminum carryover from coagulation process, low free chlorine residual
Mitigating factors and treatments	Reduce alkalinity and raise pH or use orthophosphate	Increase bicarbonate and raise pH	Raise pH and/or increase bicarbonate	Avoid stagnation early in pipe life, increase hardness and alkalinity, elevate chlorine residual to >0.5 mg/L

Source: *Adapted from Edwards et al. 1994*

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 (Fe^{2+}) form or ferric (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 to 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 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