

Lead and Copper Corrosion: An Overview of WRF Research

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THIS SUMMARY OF relevant Water Research Foundation (WRF) research projects, both completed and ongoing, provides a basic understanding of the issues surrounding lead and copper corrosion and the Lead and Copper Rule (LCR).

BACKGROUND

IN 1991, THE U.S. Environmental Protection Agency (EPA) published the LCR, which established that all community water systems (CWSs) and non-transient non-community water systems (NTNCWSs) would be subject to the rule requirements. The primary purpose of the LCR is to protect public health by minimizing lead (Pb) and copper (Cu) levels in drinking water. Pb and Cu enter drinking water mainly from corrosion of Pb- and Cu-containing plumbing materials. A unique aspect of the LCR is that lead and copper have action levels (AL) of 0.015 mg/L for lead and 1.3 mg/L for copper, and therefore do not have Maximum Contaminant Levels (MCLs). The action level for lead is a screening technique for optimal corrosion control based on treatment feasibility, and is not a health-based threshold. The action level for copper does have a health reference based on the prevention of nausea. Copper also has a secondary MCL (SMCL) of 1.0 mg/L, which is based on aesthetics (taste and staining). Table 1 highlights the different regulatory levels of Pb and Cu.

Table 1. Lead and copper regulatory framework		
	Copper	Lead
AL (mg/L)	1.3	0.015
Health Based Action Level	Yes	No
MCL	N/A	N/A
MCLG (mg/L)	1.3	0
SMCL (mg/L)	1.0	N/A

The LCR requires a one-liter first draw sample to be taken after a minimum six-hour stagnation time, and homeowners are allowed to take this sample at the customer tap. The LCR has a sample site tiering system, prioritizing the selection of sampling sites based on the likelihood of the sites to release lead and copper. If an action level is exceeded in more than ten percent of samples collected at customers’ taps, then further action is required. These additional actions can include source water monitoring and treatment, public education, and lead service line replacement. The EPA provides more information on the Lead and Copper Rule [on their website](#).

Since the late 1980s, WRF has funded over 45 research projects related to lead and copper corrosion valued at more than \$16 million. All projects with Pb and Cu corrosion implications are described below. This paper is updated annually and includes a brief summary of each project. The last three pages of this paper contain a list of all of the projects with

links to the webpages where project reports and executive summaries can be viewed and downloaded.

ORGANIZATION

Section 1) List of published and ongoing research projects

THIS SECTION PROVIDES a list of both published and ongoing research projects. The title of each report is hyperlinked to the project page of the WRF website. From this page, you can view general project information and download reports for completed projects. If available, you can also view project updates, the scope of work, webcasts, and other project-related resources.

Section 2) Ongoing WRF Projects

THIS SECTION LISTS ongoing research projects that are not yet completed. The objectives, approach, and expected completion year are listed for each project.

Section 3) WRF Project Summaries

THIS SECTION SUMMARIZES the objectives, general research approaches, and major findings of WRF projects that have examined various aspects of lead and copper corrosion. The project report summaries are organized under the following topic areas:

- General overview
- Corrosion control effects on water quality and corrosion
- Treatment process effects on lead and copper corrosion
- Specific water chemistry effects on lead and copper corrosion
- Material effects on lead and copper release

Section 4) Summary of Common Themes

THIS SECTION SUMMARIZES common themes and lessons learned from the results of relevant WRF research reports. The results are organized under the following general topic areas:

- General overview
- Corrosion control effects on water quality and corrosion
- Treatment process effects on lead and copper corrosion
- Specific water chemistry effects on lead and copper corrosion
- Material effects on lead and copper release

SECTION 1) LIST OF PUBLISHED AND ONGOING RESEARCH PROJECTS

Report Title	Year Published	Project #	Principal Investigator
Full Lead Service Line Replacement Guidance	research ongoing	4713	Brown (Cornwell Engineering)
Evaluation of Electrical Resistance Lead Pipe Detection Methods	research ongoing	4698	Roy (Altran)
Service Line Material Identification Techniques	research ongoing	4693	Venkatesh (American Water)
Processes Controlling the Time for Orthophosphate to Achieve Effective Corrosion Control	research ongoing	4686	Giammar (Washington University in St Louis)
Corrosion of Nonleaded Pump Impeller Alloys in Chlorinated Potable Water	research ongoing	4658	Edwards (Virginia Tech)
Evaluation of Flushing to Reduce Lead Levels	research ongoing	4584	Cornwell (EET)
Optimization of Phosphorus-Based Corrosion Control Chemicals Using a Comprehensive Perspective of Water Quality	research completed, to be published in early 2018	4586	Cantor (Process Research)
Evaluation of Lead Service Line Lining and Coating Technologies	2017	4351	Randtke (University of Kansas)
Evaluation of Lead Line Sampling Strategies	2015	4569	Cornwell (EET)
Controlling Lead in Drinking Water	2015	4409	Brown (EET)
Non-Intrusive Methodology for Assessing Lead and Copper Corrosion	2014	4317	Edwards (Virginia Tech)
The Performance of Non-Leaded Brass Materials	2014	4191	Klinger (TZW)
Application of Filters for Evaluating Lead and Copper Concentrations in Tap Water	2013	4415	Cantor (Process Research Solutions)
Galvanic Corrosion Following Partial Lead Service Line Replacement	2013	4349	Welter (O'Brien and Gere)
Distribution System Water Quality Control Demonstration	2012	4286	Cantor (Process Research Solutions)
Is NSF 61 Relevant for Chloraminating Utilities?	2012	4243	Sandvig (The Cadmus Group)
Lead (IV) Oxide Formation and Stability in Drinking Water Distribution Systems	2012	4211	Giammar (Washington University in St Louis)
Comparison of Zinc vs. Non-Zinc Corrosion Control for Lead and Copper	2011	4103	Schneider (American Water)
Copper Pitting and Brass Dezincification: Chemical and Physical Effects	2011	4289	Edwards (Virginia Tech)
Lead and Copper Corrosion Control in New Construction	2011	4164	Edwards (Virginia Tech)
Chloride to Sulfate Mass Ratio (CSMR): Changes from Water Treatment and Its Impact on Lead Leaching in Potable Water	2010	4088	Edwards (Virginia Tech)
Water Chemistry Effects on Dissolution Rates of Lead Corrosion Products	2010	4064	Giammar (Washington University)
Contribution of Galvanic Corrosion to Lead in Water After Partial Lead Service Line Replacements	2010	4088b	Edwards (Virginia Tech)
Secondary Impacts of Corrosion Control on Distribution System and Treatment Plant Equipment	2010	4029	Grigg (Colorado State University)
An Investigation of Stannous Chloride as an Inhibitor of Lead Corrosion	2010	3174	Hozalski (University of Minnesota)
The Role of Free Chlorine, Chloramines, and NOM on the Release of Lead into Drinking Water	2009	3172	Valentine (Iowa State University)
Decision Tool to Help Utilities Develop Simultaneous Compliance Strategies	2009	3115	Schendel (Malcolm Pirnie, Inc.)
Impact of Phosphate Corrosion Inhibitors on Cement-Based Pipes and Linings	2008	4033	Atassi (CDM) and Edwards (Virginia Tech)
Performance and Metal Release of Non-Leaded Brass Meters, Components, and Fittings	2007	3112	Sandvig (HDR/Economic and Engineering Services, Inc.)

Report Title	Year Published	Project #	Principal Investigator
Effect of Changing Disinfectants on Distribution System Lead and Copper Release Part 1 (Literature Review) Part 2 (Research Results)	Part 1-2006 Part 2-2010	Part 1-91152 Part 2-3107	Boyd (HDR)
Non-Uniform Corrosion in Copper Piping - Monitoring Techniques	2008	3109	Edwards (Virginia Tech)
Contribution of Service Line and Plumbing Fixtures to LCR Compliance Issues	2008	3018	Kirmeyer (HDR/Economic and Engineering Services, Inc.)
Assessment of Non-Uniform Corrosion in Copper Piping	2008	3015	Edwards (Virginia Tech)
Enhanced Coagulation Impacts on Corrosion of Water Treatment Plant Infrastructure	2004	2687	Edwards (Virginia Tech)
Optimizing Chloramine Treatment (2nd Edition)	2004	2760	Kirmeyer (Economic and Engineering Services, Inc.)
Optimizing Corrosion Control in Water Distribution Systems	2004	2648	Duranceau (Boyle Engineering Corp.)
Post-Optimization Lead and Copper Monitoring Strategies	2004	2679	Kirmeyer (Economic and Engineering Services, Inc.)
Role of Phosphate Inhibitors in Mitigating Lead and Copper Corrosion	2001	2587	Edwards (Virginia Tech)
Distribution System Water Quality Changes Following Corrosion Control Strategies	2000	157	Kirmeyer (Economic and Engineering Services, Inc.)
Lead Pipe Rehabilitation and Replacement Techniques	2000	465	Kirmeyer (Economic and Engineering Services, Inc.)
Corrosion and Metal Release for Lead-Containing Plumbing Materials: Influence of NOM	1999	182	Korshin (University of Washington)
A General Framework for Corrosion Control Based on Utility Experience (includes Control of Pb and Cu Corrosion By-products Using CORRODE Software)	1997	910	Reiber (HDR Engineering)
Internal Corrosion of Water Distribution Systems	1996	725	N/A
Role of Inorganic Anions, NOM, and Water Treatment Processes in Copper Corrosion	1996	831	Edwards (University of Colorado – Boulder)
Innovative Techniques for Lead Service Line Location	1995	813	Weston Solutions, Inc.
Development of a Pipe Loop Protocol for Lead Control	1994	604	Kirmeyer (Economic and Engineering Services, Inc.)
Chloramine Effects on Distribution System Materials	1993	508	Reiber (HDR Engineering)
Evaluation of the Effects of Electrical Grounding on Water Quality	1994	714	CH2M Hill
Lead Control Strategies	1990	406	EES, Inc.

SECTION 2) ONGOING WRF PROJECTS

4584 - Evaluation of Flushing to Reduce Lead Levels

THIS PROJECT WILL evaluate the impact of high velocity flushing on the removal of particulate lead from service lines and premise plumbing, and the subsequent impact on “at the tap” lead concentrations. The goal of the project is not only to see if high velocity flushing can successfully reduce lead levels at the tap, but also to see how frequently the flushing may need to be repeated in order to maintain any observed lead reduction. This project is scheduled to be completed in 2018. Tailored Collaboration partner: DC Water.

4658 - Corrosion of Nonleaded Pump Impeller Alloys in Chlorinated Potable Water

THIS PROJECT IS intended to collect corrosion performance data for current metal alloys recommended for pump impellers. This project will also quantify the performance of several new and emerging lead-free alloys that are attempting to break into the municipal water market. This data will allow water utilities to make better-informed pump design decisions. The recommendations of this project will provide guidance to pump impeller end users and could refine existing alloy manufacturing methods to develop more lasting materials for these applications. This project is scheduled to be completed in 2018. Tailored Collaboration partner: San Jose Water Company.

4686 - Processes Controlling the Time for Orthophosphate to Achieve Effective Corrosion Control

THIS PROJECT WILL provide new scientific insights into lead phosphate nucleation, aggregation, and deposition that will enable efficient application of phosphate to control both dissolved and total lead concentrations in water. The specific objectives are to (1) identify factors that control the behavior of lead phosphates in solution and quantify the effects of water chemistry on those processes, (2) determine the rates of precipitation and deposition of lead phosphate particles on scales that form on pipe surfaces, and (3) enable optimization of phosphate application strategies that can be tailored to a particular water chemistry and scale type. The project is funded through a Memorandum of Understanding (MOU) between WRF and the National Science Foundation (NSF). Under the MOU, WRF will fund Task 3 of the study, while the NSF will fund Tasks 1 and 2. The researchers will publish the results as a single final report. This project is scheduled to be completed in 2018. Research partner: NSF.

4693 - Service Line Material Identification Techniques

THIS PROJECT WILL evaluate technologies capable of remotely determining the material composition of water service lines. The specific objectives are to (1) review current literature, utility practices, and prospective technologies; (2) perform field demonstrations of promising technologies; and (3) develop case studies of existing practices and approaches

for identifying service line material. This project is scheduled to be completed in 2018.

4698 - Evaluation of Electrical Resistance Lead Pipe Detection Methods

THIS PROJECT WILL determine if electrical measurements would be sufficiently sensitive to detect various piping types. Resistance measurement has been preliminarily identified as the most likely candidate for this determination. Brief literature searching will be performed to see if other measurement techniques could be used for pipe identification. Additionally, inspection tools that go beyond lead pipe detection will be reviewed to determine if length of lead pipe, discontinuities, and other features can be detected. This project is scheduled to be completed in 2018. Research partner: Massachusetts Water Resources Authority.

4713 - Full Lead Service Line Replacement Guidance

THIS PROJECT WILL evaluate strategies to reduce lead exposure after conducting full lead service line replacements (FLSLRs). The research will provide accurate and easily understood guidance and reference materials for staff at any U.S. or Canadian water system to use when planning and implementing FLSLRs. The research team will conduct a literature review of current information related to limiting lead release following lead service line disturbances, and evaluate the effectiveness of flushing to reduce lead exposure following FLSLRs at single-family homes. The research will also identify lessons learned from case studies, if available, of utilities that have monitored lead release following FLSLR. Participating utilities will conduct field studies at over 100 locations during the course of this project. This project is scheduled to be completed in 2020.

SECTION 3) WRF PROJECT SUMMARIES

General Overview

4286 - Distribution System Water Quality Control Demonstration (2012)

THIS PROJECT DEMONSTRATES the use of three tools for process control in water systems. One is a simple data management tool for making sense of complicated systems: Shewhart control charts used in industrial quality control. Another tool is a relatively simple means of tracking water quality at consumers' taps: standardized monitoring stations that are abstractions of consumers' plumbing systems. The third tool is a monitoring strategy that identifies key information linking components of a water system together.

For lead, the monitoring station data were shown to be equivalent to residential water samples taken directly from lead service lines. In lead service lines, the lead-surface-area-to-water-volume ratio is similar to that in a monitoring station. However, this ratio is lower in a first-draw residential sample

where plumbing materials other than lead exist. Therefore, the monitoring station lead concentration data are higher than first-draw residential sample data. The same similarity applies to the copper concentrations found in the monitoring stations. However, there are typically more copper components associated with a first-draw residential sample. Therefore, it is expected that monitoring station copper concentration data and first-draw residential sample copper concentration data will be closer in magnitude than the comparative lead data.

3115 - Decision Tools to Help Utilities Develop Simultaneous Compliance Strategies (2005)

UTILITY MANAGERS AND staff are required to make decisions about competing water quality objectives in the context of rapidly changing regulations and increasingly rigorous customer expectations. Without careful planning and proper implementation, utility actions originally intended to improve compliance can instead produce adverse unintended consequences.

The research focus of this project was to develop a web-deployed decision-making assistance tool, which allows utilities to more simply identify and assess potential simultaneous compliance conflicts and other negative unintended consequences. The Simultaneous Compliance Tool (SCTool) developed under this project is intended to assist utilities in evaluating appropriate technology choices to comply with multiple and/or conflicting water quality goals. Potential compliance issues with the Lead and Copper Rule were evaluated as part of this research.

The SCTool is intended to be usable by utility personnel who are not water quality experts. The SCTool is not a design tool and it will not generate final solutions or recommendations. Rather, the interface prompts the user to enter water quality data and system attributes sufficient to identify when conflicts and consequences are in play.

A webcast for this project is available for download on the WRF website.

725 - Internal Corrosion of Water Distribution Systems, Second Edition (1996)

THIS REPORT SERVES as a guidance manual on corrosion control for drinking water systems that covers corrosion principles, corrosion of materials, mitigation of corrosion impacts, assessment technologies, and approaches to corrosion control studies. Various chapters address lead- and copper-related corrosion issues.

813 - Innovative Techniques for Lead Service Line Location (1995)

THIS REPORT EVALUATED lead water service line location techniques. This objective was met by:

- Identifying and evaluating any emerging techniques or technologies available through a thorough search of literature

- Developing potential direct methods through the use of emerging or existing techniques, and conducting bench scale and field tests for performance evaluation
- Developing indirect methodologies to determine probability of lead service lines by analyzing utility records and databases, and using statistical methods

406 - Lead Control Strategies (1990)

THIS REPORT WAS published during the time that the LCR was first being introduced in the United States. At the time, EPA guidance on LCR treatment plans (i.e., pipe loop studies, analysis of data, start-up, and monitoring of treatment) had not yet been developed or published. The manual provides a body of knowledge to help utilities develop lead control strategies.

This project identified potential sources of lead coming from customer plumbing as being goosenecks, lead service lines, lead plumbing, lead lined iron piping, lead tin solder, and brass faucets. Many variables control the rate of leaching and lead in water samples, including the age and type of material, workmanship, size of pipe, water quality, size of the water sample, standing time, and whether a water sample has been running or standing.

As a part of this project, the research team contacted utilities that had conducted lead studies to improve water quality for their customers. The studies included water quality tap sampling, pipe loop studies, lead materials investigations and replacement programs, and lead treatment programs. The case studies provided a good basis for developing viable lead control strategies at the time.

The manual also provided the theory and practical considerations for controlling lead leaching from chemical treatment processes. The researchers determined the most important water quality parameters for lead solubility to be pH, alkalinity, dissolved inorganic carbonate, and orthophosphate levels. The manual recommended controlling lead with pH adjustment, carbonate adjustment, orthophosphate addition, silicate addition, and calcium carbonate deposition.

Corrosion Control Effects on Water Quality and Corrosion

4586 - Optimization of Phosphorus-Based Corrosion Control Chemicals Using a Comprehensive Perspective of Water Quality (2017)

THE OBJECTIVES OF this project were to measure the effects of lead and copper orthophosphate and carbonate compounds in the complex chemical and microbiological environment of drinking water systems, to observe the effects on lead and copper orthophosphate and carbonate compounds as some of the chemical and microbiological factors were removed from the water environment, and to assess the impact of phosphates on the environment and on wastewater treatment facilities after the phosphates have left the drinking water system.

The project found that passivating barriers are not guaranteed to form on pipe walls. Lead and copper carbonates, expected by the carbonate solubility models used as a foundation for the Lead and Copper Rule, formed on the test chamber metal surfaces, but many other chemical compounds and biofilms did as well. In studying the accumulations on the metal surfaces in the test chambers, there was not just one lead or copper carbonate compound as idealized by the carbonate solubility models. Instead, there were mixtures of types of lead or copper carbonate compounds as well as lead or copper oxides. Forming passivating barriers with orthophosphate addition was also studied. As with a carbonate-based passivating barrier, it was physically difficult to form a uniform barrier against metal surfaces where other chemical scales and biofilms were forming and to compete with the other influencing factors. It should not be assumed that using orthophosphate provides guaranteed protection from exposure to lead or copper for consumers.

In general, the findings in this project emphasized a comprehensive perspective for control of distribution system water quality issues, including lead and copper release. In this perspective, water quality is shaped by complex interactions of drinking water, which is a potpourri of natural and treatment chemicals and naturally-occurring microorganisms, with pipe wall accumulations of various chemical scales and biofilms. No scientific formula can predict the characteristics of the final water quality. All distribution system water quality issues (discolored water, disinfection byproducts, presence of pathogens, release of lead and copper, etc.) are interrelated; they are all manifestations of the complex interactions between a complex solution of water and a complex composition of pipe wall accumulations.

If contemplating using a phosphate-based corrosion control chemical, begin a dialogue with the associated wastewater treatment facility personnel. Chapter 12 of the report lists steps for evaluating the impact of the corrosion control strategy on meeting phosphorus discharge limits. A portion of phosphate-dosed water also runs directly into natural bodies of water when used for outdoor or industrial cooling purposes. Consider the impact of the phosphate on the receiving body of water, especially using the phosphorus discharge limits determined by regulatory agencies.

4103 - Comparison of Zinc vs. Non-zinc Corrosion Control for Lead and Copper (2011)

THIS PROJECT EVALUATED if there are corrosion control and metal release performance differences between “zinc orthophosphate” (ZOP) and non-zinc orthophosphate corrosion inhibitor formulations under realistic distribution system and domestic plumbing conditions. While many communities nationwide use ZOP, it is expensive and the zinc becomes concentrated in wastewater sludge, which can be an environmental concern. An alternative to ZOP is orthophosphoric acid (non-zinc orthophosphate), which has been successfully

used for corrosion control at a number of utilities nationwide. However, there is a lack of scientifically valid data comparing the performance of ZOP and non-zinc corrosion inhibiting compounds (CICs) for controlling the rate of corrosion and levels of metal release from iron, lead, brass, and copper piping and plumbing devices.

The project team utilized a multiphase approach to address these issues. The first phase was a series of bench-scale experiments performed to examine the impact of corrosion variables including pH, orthophosphate dose, and chloride to sulfate mass ratio (CSMR) on lead and copper release. Experiments were also performed to examine the impact of corrosion variables on cement. The second phase of the research consisted of pilot testing at five systems that currently use orthophosphate. The third phase of the research involved the collection of historical and operational data from utilities that use ZOP, along with analysis of samples from distribution systems to examine the fate of zinc and orthophosphate in the distribution system.

The results from the statistical approach suggest that, for general corrosion of lead and copper in most locations, there does not appear to be a significant difference in performance between ZOP and non-zinc orthophosphate. This conclusion is based on analyses of electrochemical measurements, dissolved metal release, and particulate metal release. Bench studies have shown that zinc may be beneficial for preventing some types of copper pitting corrosion. Furthermore, results of this study suggest that addition of a zinc-containing CIC is beneficial in reducing cement degradation and aluminum release to water when treated water is low in calcium and alkalinity. There appears to be little advantage in adding zinc to treated water high in calcium and alkalinity as non-zinc orthophosphate alone can inhibit calcium carbonate scaling of cement. If zinc dosing is discontinued, calcium leaching from cement can return to levels that correspond to those present when no zinc protective scale is present in as little as five weeks.

Based upon calcium and aluminum leaching results, it appears that a 0.1 mg/L zinc dose is sufficient to provide continued corrosion protection once a protective zinc-containing scale layer has been formed. The results of these studies should be interpreted with caution however, and bench-scale and/or pilot studies should be conducted to determine if zinc addition is beneficial for a specific water quality condition. Additionally, a cost/benefit analysis should be conducted concerning the benefit of adding zinc (to increase the life of concrete infrastructure) versus the cost of zinc treatment and disposal. Non-cost factors, such as the environmental impact of zinc, should also be included in the evaluation.

3174 - An Investigation of Stannous Chloride as an Inhibitor of Lead Corrosion (2010)

THIS PROJECT EVALUATED the mechanism by which stannous chloride (SnCl_2) decreases the corrosion of lead and the

corresponding release of Pb into the water supply. The specific objectives of the research were to improve the understanding of tin chemistry in drinking water, investigate the toxicity of tin to both planktonic and biofilm bacteria, and determine the mode of action of SnCl₂. Batch experiments were performed to investigate the reactivity of stannous ion with drinking water oxidants, followed by determination of the toxicity of stannous and stannic chloride to planktonic and biofilm bacteria. Finally, batch experiments with lead coupons were performed to investigate the effects of tin on lead corrosion.

Results showed that measured chlorine consumption coupled with the low recommended dose for water treatment indicate that use of stannous chloride will result in a minor chlorine demand. Stannous chloride was highly toxic to laboratory strains of heterotrophic bacteria, but not as toxic to a laboratory strain of nitrifiers. Compared to the lab strains, environmental bacteria were significantly more resistant to Sn toxicity. Depending on the dose, stannous chloride can inhibit *P. aeruginosa* biofilm formation and remove established biofilms.

Aged and new coupons were employed in semi-batch reactors to investigate the role of microbially-influenced corrosion (MIC) and the effects of stannous chloride on lead corrosion. Bacteria and biofilms were prevalent on the lead coupons at the end of the lead corrosion experiment for all conditions, suggesting that MIC may be important for lead. Furthermore, stannous chloride did not decrease the accumulation of biofilm on the coupons or the concentrations of dissolved and total lead released from the coupons.

Utilities considering use of stannous chloride for lead corrosion control should proceed slowly and with caution. In previous pipe loop studies, stannous chloride showed some benefit with respect to reducing lead and bacterial levels, but the chemical did not decrease lead release or biofilm accumulation in the batch experiments with lead coupons performed in this work. Coupon, and possibly pipe loop, studies are recommended for utilities considering use of stannous chloride to evaluate whether the chemical might be effective for the given water quality conditions.

157 - Distribution System Water Quality Changes Following Corrosion Control Strategies (2000)

THIS PROJECT DOCUMENTED distribution system secondary water quality impacts of implementing lead and copper corrosion control strategies. The researchers also developed mitigation strategies to preclude, minimize, or eliminate problem areas that resulted from LCR treatment.

The researchers found that the interplay of the water quality of the distributed water, types of materials present in the distribution system, and the hydraulic conditions in the distribution system all lead to secondary water quality impacts. Most impacts occurred when the distribution system water quality was unstable, either because of multiple finished water quality changes over short periods of time or because of wide fluctuations in pH levels. Wide fluctuations in pH largely

occurred because of inadequate buffering in the distribution system or because large changes occurred in finished water quality conditions. For systems controlling pH and/or alkalinity, few adverse secondary impacts occurred when consistent distribution pH levels and adequate buffering intensity were maintained.

The researchers recommended that utilities establish and implement procedures for corrosion control treatment, including:

- Designing corrosion control facilities with appropriate pH adjustment controls. Low buffer intensity can result in pH fluctuations that can produce scales on pipe surfaces that are less adherent. Large pH fluctuations can also cause solubilization and precipitation of scales.
- Ensuring that distributed water quality remains stable by maintaining adequate buffering and consistency of treatment.
- Avoiding other treatment changes during the period of time when corrosion control is initiated (such as changing disinfectants, changing coagulants, or adding new treatment processes).
- Making incremental changes to finished water quality during start up to avoid exposing the distribution system to large finished water quality changes over a short period.
- Responding to localized water quality problem areas with a flushing program.
- Evaluating the potential for secondary impact based on water quality data evaluations, assessments of piping conditions and hydraulic information, and review of historical treatment information.
- For systems using orthophosphate inhibitors, maintaining adequate residuals in the distribution system and applying the inhibitors at the pH range that is optimal for lead and copper control (7.3 to 7.8).
- Implementing a distribution system monitoring program to provide information to assess and respond to secondary impacts that might occur. Monitoring programs should include:
 - Standing lead and copper levels (more frequently than required by the LCR)
 - Water quality parameter measurements to assess the secondary impacts of corrosion treatment and to evaluate the amount of time needed for lead, iron, copper, and other materials to re-equilibrate to new water quality conditions
 - Orthophosphate and/or silicate levels
 - pH and alkalinity levels

910 - A General Framework for Corrosion Control Based on Utility Experience (1998) and Control of Pb and Cu Corrosion By-Products Using CORRODE Software (1995)

THIS PROJECT IS a compilation of utility experiences with mitigation of lead and copper corrosion by-product release under provisions of the LCR. Corrosion by-products include aqueous, dissolved, and solid species associated with lead and copper ions. This project report provides a list of publications that synthesize utility experiences with corrosion control, information on how to conduct desktop corrosion control studies, corrosion control case studies, and a software program that simplifies predictions of lead and copper solubility. This manual is meant to be used at two different levels. Utility managers, staff, and regulators could review the report to gain insights into corrosion control approaches and strategies. On another level, the report provides more specific utility experiences under the LCR, providing insight for mitigation of corrosion by-products.

The software product provided with this report is a tool to simplify predictions of maximum soluble lead and copper corrosion by-product release in pipes under different water quality conditions. It also addresses the impacts of aeration on pH and lead and copper solubility, as well as the effects of mixing on water quality. It should be noted that due to gaps in knowledge regarding the fundamental science of corrosion by-product release and the fact that many corrosion by-products are particulates and not soluble, the software is somewhat limited. Despite those limitations, solubility predictions are an important component of corrosion desktop studies, and were considered one of the best predictive tools for utilities at the time this report was published.

Some key points presented in this manual are:

- The 1995 Water Industry Technical Action Fund (WITAF) database referenced in this report provides a comprehensive compilation of utility experiences that allows utilities to compare their own experiences with those of other water utilities with similar water qualities.
- Differences in sampling rigor can cause substantial differences in the outcome of a tap sampling program. Monitoring programs should stress that samples be acquired following the minimum standing water period and using low flow rates during the sample draw.
- Before proceeding with the implementation of a corrosion control program, it is critical to establish representative metal release rates in the distribution system.
- Pipe loop protocols are proven to provide useful information in several corrosion control assessment programs; however, they required a substantial investment of resources and time. Additionally, the data they yield are often difficult to analyze and not always predictive of distribution system performance.

- The secondary impacts of corrosion control are usually relatively minor:
 - Utilities that attempted to define whether corrosion control treatments produced noticeable changes in the taste and odor profile of the distributed water were unable to demonstrate any difference relative to the unmodified baseline water.
 - The pH shifts associated with most corrosion control strategies produced only minor changes in the concentration of disinfection by-products.
- Solubility models have value in terms of predicting metal release trends and for examining mechanisms of passivation and corrosion scale accumulation. However, while the models accurately reflect equilibrium conditions, they do not take into account solubility kinetics, the heterogeneity of plumbing surfaces, or the issue of particulate shedding versus soluble metal release.
- Some electrochemical screening techniques can accurately determine the underlying rate of corrosion on lead and copper surfaces, as well as on the surfaces of their alloys.
- Copper corrosion control is easier to achieve than lead release control. Copper corrosion is almost exclusively chemical, while lead release is governed by a combination of chemical, hydraulic, and other mechanical factors.
- Stability of pH is necessary for controlling the release of lead. Distribution system pH changes that drop the pH by greater than 0.5 units, even for brief periods, appear to disrupt the effective passivation of corrosion surfaces, especially on brass and lead/tin solder surfaces.
- There is evidence that opportunistic organisms can exploit corrosion scales as colonization sites. By doing so they create a microenvironment that may influence the rate and morphology of corrosion on the underlying metal.

2587 - Role of Phosphate Inhibitors in Mitigating Lead and Copper Corrosion (2001)

THIS PROJECT SUMMARIZES the effects of phosphate-based corrosion inhibitor chemicals on lead and copper corrosion. Experiments were conducted to examine the complexation of copper and lead, solid dissolution rates, and solid precipitation in the presence of polyphosphate.

Fundamental Chemistry Experiments. For the polyphosphate tested in this study, every 1 mg/L of phosphate inhibitor dosed (as P) had the potential to hold 2 mg/L of lead in solution. This could be considered a maximum capacity for lead dissolution, as this high of a value would rarely be achieved in practice due to the effects of calcium, magnesium, kinetic limitations, and other factors. Lead complexation is not as strong in the presence of calcium (40 mg/L) but is still relatively important. These experiments also indicated that hexametaphosphate increases the rate of dissolution from lead scales [including

PbCO_3 and $\text{Pb}_3(\text{CO}_3)_2(\text{OH})_2$]. Precipitation of lead from solutions containing NaHCO_3 was inhibited by sodium metaphosphate. The final dissolved lead concentration was roughly equal to the metaphosphate complexing capacity. Higher metaphosphate concentrations resulted in higher dissolved lead concentrations. This led to the conclusion that polyphosphate can influence the kinetics of scale formation in pipes.

Copper Corrosion. With a few exceptions, dosing of orthophosphate and hexametaphosphate inhibitors had beneficial effects on copper release. The exceptions are for very new pipes at pH 7.2, in which hexametaphosphate had very significant adverse short-term effects, and for well-aged pipes at pH 7.2 and alkalinity 300 mg/L as CaCO_3 . In the latter case, although the orthophosphate had dramatic short-term benefits, a few years of aging caused marked decreases in release when inhibitors were absent.

Lead Corrosion. Orthophosphate dosing often produced significant benefits for lead. This was true for every stagnation time and water quality tested at 6 months' pipe age. The project also examined the role of phosphate inhibitors in controlling soluble lead release, as opposed to total lead. In every instance, soluble lead concentrations were lower in the presence of orthophosphate than in an equivalent system without inhibitor. Conversely, with few exceptions, soluble lead concentrations were higher in systems dosed with hexametaphosphate than without inhibitor. Orthophosphate has an enormous advantage over hexametaphosphate when comparing soluble lead release. Hexametaphosphate demonstrated an increase in soluble lead in every instance when compared to an equivalent dose of orthophosphate. This led to the conclusion that hexametaphosphate substantially increases problems with soluble lead.

Lead and Copper Corrosion By-Products. Significant fractions of particulate and colloidal lead and copper were found in participating utilities' tap water samples. Copper was mostly soluble when total copper levels were high. In contrast, most of the lead found in the tap samples was in the particulate form.

Zinc Orthophosphate. The addition of zinc did not enhance the performance of orthophosphate. In all cases, zinc tended to detract from the benefits of orthophosphate. This led the researchers to conclude that zinc orthophosphate cannot be recommended for copper or lead corrosion control when compared to orthophosphate alone.

4033 - Impact of Phosphate Corrosion Inhibitors on Cement-Based Pipes and Linings (2009)

THIS PROJECT INVESTIGATED the interactions between water chemistry, temperature, cavitation, and phosphate corrosion inhibitors with cement-based pipes and linings in order to understand scale formation, lime leaching, and bulk water quality implications in the distribution system. The research team used field data from 19 water utilities in combination

with bench-scale testing in order to understand the relationship between water quality factors and cement-based pipe failures.

The case studies from the participating utilities demonstrate the diversity and complexity of corrosion control issues. The bench-scale test results generally correlate with utility experience and demonstrate the effectiveness of corrosion inhibitors in the protection of concrete and cement-based pipes. It is important to note that it is unlikely for a utility to have one type and material of pipe in its distribution system, which further complicates a utility's corrosion control program.

General trends were observed from the water quality conditions that were tested at bench-scale:

- Low alkalinity (~20 mg/L as CaCO_3) and low pH (~7.0) can be extremely aggressive to concrete and can cause rapid degradation of concrete by lime leaching into the bulk water.
- High alkalinity (~200 mg/L as CaCO_3) and high pH (~8.3) are non-aggressive to concrete, but scaling of pipes by calcite precipitation can be a major concern to utilities due to the potential impacts on the hydraulic capacity of the distribution system.
- Higher concentrations of magnesium and silicon can be effective at preventing concrete corrosion, but only at higher bulk water pH of about 9.5.
- The kinetics of concrete corrosion degradation reactions increase at higher temperatures, but this effect is countered by reduced calcite solubility in waters with higher pH/higher alkalinity (with no inhibitor added).
- Gaseous cavitation did not increase concrete corrosion, but vaporous cavitation can be extremely detrimental to concrete.
- Both zinc and non-zinc phosphate inhibitors (orthophosphate and polyphosphate) were effective at reducing concrete corrosion at near neutral pH. At a pH of 8.3, neither orthophosphate nor polyphosphate was effective at reducing corrosion.

Prior to making any changes to corrosion control programs, utilities should consider undertaking bench-scale or pipe loop tests for baseline (control) in comparison to different corrosion inhibitors and pH/alkalinity adjustment conditions to confirm the results and develop a corrosion control strategy that meets their goals. Utilities should also continuously monitor water quality changes in the distribution system to ascertain if changes may be due to corrosion of concrete or cement-lined pipes. Continuously monitoring hydraulic changes in the distribution system to assess changes in hydraulic capacity caused by lower than expected C-values can help a utility determine if those changes are due to deposition or scaling forming on distribution system pipe walls. Utilities should also evaluate surge conditions in the distribution system to avoid vaporous cavitation conditions that could be detrimental to concrete- or cement-lined pipes. Based on the results of bench or pipe loop testing and all of the monitoring data, a utility can

assess its current corrosion control practices and whether they are effective for protection of distribution system infrastructure and LCR compliance.

4029 - Secondary Impacts of Corrosion Control on Distribution System and Treatment Plant Equipment (2010)

THIS PROJECT USED a literature review; technical workshop; utility and regulator survey; and interviews with utility engineers, operators, regulators, and researchers to assess distribution system and treatment plant equipment failures or problems that occur from water quality changes made for corrosion control. The focus is specifically on the secondary effects on valves, meters, impellers, and pumps.

While corrosion, scaling, and precipitation occur on a widespread basis, most utilities do not focus on these issues until problems occur. It is difficult to find utility employees with knowledge of these effects, and the responsible managers are likely to be treatment and water quality staff or operations managers for both treatment and distribution systems. Most utilities are concerned with their ability to meet demands and are aware of clogging and the need to flush and renew pipes, but are not aware of the qualitative reasons behind impeded flow conditions. The general assumption is that scaling and impeded flow are inevitable and utilities use maintenance and renewal to avoid these issues. Utilities that use pH control to create calcium scales to passivate pipe surfaces seem to have a better handle on secondary effects from corrosion control.

Secondary effects are clustered around dominating distribution system material metal species—calcium, aluminum, iron, and manganese—and include pipe scaling and clogging; inoperable valves, pumps, and meters; water quality changes causing red, yellow, or black water; release of constituents; and transport of release materials. Calcium effects are most common in corrosion control treatment, but aluminum effects can also occur from changes in pH and from the use of inhibitors. While iron and manganese effects do not always result directly from corrosion control treatment, they are interrelated with other effects on corrosion and deposition.

The ability of calcium compounds to remain in solution is very sensitive to pH changes and the few serious calcium problems that were identified occurred suddenly due to pH shifts. Aluminum scaling can also occur from water quality adjustments used in corrosion control programs and can cause significant loss of capacity in water pipes.

Recommendations for utilities to detect and remediate the secondary effects of corrosion control include:

- Implement effective condition assessment programs as part of utility asset management systems.
- Designate a single manager at a utility to be in charge of and evaluate scaling problems.
- Conduct a study to evaluate corrosion effects, loss of pipe capacity, valve problems, pump seizures, impaired

hydrant function, colored water, hot water problems, plugged injectors, and other symptoms. This can be done with pilot- or full-scale studies of treatment changes using pipe loops with pipe coupons.

- Use multiple approaches, including uni-directional flushing, pH adjustment, change in chemical additives, re-plumbing of systems, cleaning and lining, and pipe replacement. Of course, selecting among these options requires careful consideration of the benefits and costs of each in terms of utility objectives—including water quality, hydraulics, customer service, and workforce utilization.

2679 - Post-Optimization Lead and Copper Monitoring Strategies (2004)

THIS PROJECT DEVELOPED a monitoring program for drinking water utilities that have already achieved optimized corrosion control. Alternative monitoring methods were developed to demonstrate to regulatory primacy agencies that corrosion control is being maintained when treatment techniques and/or source waters are altered.

Utilities have been struggling with variability in monitoring data, shrinking sample pools (due to home remodeling or lack of customer interest), increasing costs associated with monitoring programs, and the differing needs of utilities verifying optimization and corrosion control versus those trying to achieve optimization in the first place. The monitoring protocol recommended in this report simultaneously addresses the control of data variability and attrition of sample pools by recommending the sampling of fewer sites more often. It also provides utilities and regulators with tools to continue to collect statistically sound data in the face of fewer qualified sample locations.

The research team conducted regulator and utility surveys to develop both in-home tap and on-line corrosion monitoring protocols that were then field tested by four participating utilities. From this research, the team developed a proposed alternative lead and copper corrosion control monitoring strategy. Included are a proposed in-home tap sampling protocol and statistical evaluation methodologies and an evaluation of the applicability of on-line corrosion cell predictive technologies.

Alternative In-Home Tap Monitoring Protocol. A detailed summary of the alternative tap monitoring protocol can be found in the published report. It outlines, for both lead and copper, the number of sites recommended for sampling, the number of samples per site, a quarterly evaluation period, site selection criteria, and data collection and analysis criteria.

On-line Corrosion Monitoring Protocol. The development of the on-line corrosion cell (OLCC) addressed many of the challenges associated with the initial design of a functioning corrosion cell. After several attempts, the Narrow Rectangular Cell (NRC) design showed that the Corrosion Potential-Stagnation/Flow (CPSF) theory could be verified in the laboratory and in the field. In its current level of development, the NRC OLCC is

not widely applicable to utility use, and data interpretation can be difficult for a typical utility operator. However, the OLCC design and findings reported are significant first steps to future investigation into this type of corrosion cell.

An automated sampling device was developed to a prototype stage and tested in the field. Data collected using the devices was comparable to manually collected samples. Future investigation will require design revision and more extensive field-testing.

Finally, the investigation of lead and copper pipe loops as a tool for tracking corrosion control changes demonstrated that there is potential for their use. However, due to the time required for pipe loops to stabilize, the feasibility of their use is limited to utilities that have operable pipe loop racks in inventory or under operation. The data provided by the pipe loop racks evaluated did not justify the time and associated financial commitment required for the development of such a tool for an already optimized utility.

2648 - Optimizing Corrosion Control in Water Distribution Systems (2004)

THIS PROJECT DEVELOPED and tested an online, real-time electrochemical sensor to screen corrosion inhibitors for drinking water treatment. It also demonstrated the use of electrochemical noise (EN) in development for corrosion control applications.

The results of this study were successful in demonstrating the use of a multi-element sensor, electrochemical technique for instantaneously monitoring and optimizing corrosion in water distribution systems. Additional findings from the study include:

- The EN technique was shown to be a sensitive tool for identifying electrochemical corrosion phenomena, and it allowed low rates of pitting to be accurately detected and monitored.
- EN corrosion rate calculations appeared to follow changes in process parameters such as use of inhibitors, water flow past electrodes, and water temperatures.
- Electrochemical noise measurements in the field detected corrosion rates over a wide range, and characterized the degree of localization.
- EN monitoring can be implemented with informed but minimal effort. New monitoring techniques can be effective if the process is kept fairly simple.
- Although EN signals could not be directly correlated to water quality concentrations, the value of using EN is having the ability to monitor changes in corrosion environments and having the ability to identify pitting and crevice corrosion regimes.

Treatment Process Effects on Lead and Copper Corrosion

4164 - Lead and Copper Corrosion Control in New Construction (2008)

NEW PLUMBING SYSTEMS can contribute to lead and copper corrosion and cause aesthetic problems. This purpose of this project was to develop guidance to install and commission new building plumbing systems and specifically answer the following questions:

1. What flushing recommendations would remove ammonia, zinc, and high chloride due to flux from plumbing lines, along with metallic debris and solvents?
2. Can more frequent flushing assist in passivation of lead leaching from new brass?
3. To what extent do residual PVC solvents and flux contribute to initiation of nitrification in premise plumbing?
4. Do current shock chlorination practices damage plastic and/or copper plumbing systems?

The following are conclusions from the project:

- If lead leaching is an issue in a newly commissioned plumbing system, a multi-faceted approach that includes comprehensive testing may be necessary to remediate problems since the root cause may be a result of installation procedures, plumbing system design, lead leaching propensity of the installed brass devices, corrosivity of the water relative to new brass, or commissioning procedures. Factors that contribute to lead problems include high lead content of brass valves, relatively high corrosivity of water towards leaded brass valves or solder, trapped lead-bearing particulates on strainers, aerators, or in the plumbing system, or nitrification because the resulting lower pH might result in excessive metal leaching or reduced rates of passivation.
- The improper use of petroleum-based flux in plumbing systems, or failure to promptly flush flux from the plumbing lines, can cause a variety of problems with drinking water affecting aesthetics, health, and corrosivity due to high metal leaching and possible promotion of microbial growth.
- Flushing of ASTM B813 compliant flux and metallic debris can be accomplished using water at or above 3.6 fps; however, petroleum-based flux cannot be flushed from plumbing systems with ambient temperature water, which can create long-term problems.
- The inadequate flushing of flux from a plumbing system can lead to the proliferation of nitrifying bacteria. Nitrification can create higher levels of lead and copper at the tap and allow higher levels of microbial growth within the plumbing system.
- One time 50 to 200 mg/L shock chlorination does not seriously damage plastic piping or copper tube; however, repeated shock chlorination events are not recommended because significant deterioration may occur.

- Pipe material has a strong influence on the level of chlorine demand and associated ability to meet required levels of disinfectant residual after shock chlorination. In a comparison of copper, brass, cross-linked polyethylene (PEX), and chlorinated polyvinyl chloride (CPVC), copper exerts the highest chlorine demand while CPVC exerts the lowest. Copper exerts a higher demand because chlorine is a strong oxidizer and the copper is subject to some oxidation whereas the CPVC is not. Chlorine is consumed as it is reduced.
- When shock chlorination is employed to disinfect plumbing waters with pH levels 9 and above, chlorine residuals tend to be held better than with waters at lower pH levels. Orthophosphate addition significantly reduced the rate at which chlorine disappears from some waters.

A brochure was produced as part of this project. This brochure provides guidance to plumbers, building managers, regulatory agencies, and code administrators on installation of premise plumbing for new construction. A strategy is outlined to test, remediate, and mitigate plumbing issues in new buildings. A webcast for this project is available for download on the WRF website.

3107 - Effect of Changing Disinfectants on Distribution System Lead and Copper Release (2010)¹

PART 1 – Literature Review. The literature review identified many of the key issues with regard to predicting effects of disinfectant change on lead and copper corrosion and metals release into drinking water supplies. This literature provides information related to the following questions:

- How does a change in disinfectant impact lead release?
- How does a change in disinfectant affect copper release?
- Does galvanic coupling affect metals release with the change in disinfectant?
- How does the change in disinfectant affect the nature of protective scales formed on plumbing materials?
- Historically, what have been the effects of various forms of treatment on galvanic coupling corrosion and metals release after disinfectant changes in the distribution system?
- What effect does background water chemistry have on metals release and galvanic coupling?
- What effect does a change in disinfectant have on redox?

The findings of the literature review indicated the importance of chemical and electrochemical properties that are fundamental to our understanding of the response of corroding

metals and alloys to transitions from free chlorine to chloramines, and vice versa.

Part 2 – Research Results. The objective of this research was to determine effects of changing disinfectants from free chlorine to chloramines and vice versa on metals leaching rates and leaching levels from lead, brass, and copper components in the distribution system. This project also studied the effects of galvanic coupling on metals release. This investigation produced a body of data regarding metal release and passivation under a variety of conditions that provides valuable guidance for engineers and utility operators seeking to make disinfectant conversions without endangering public health. While the results of this project are especially applicable to distribution systems with lead components, the implications of this research extend to newer distribution systems containing other lead-bearing materials.

The researchers made the following conclusions:

- For lead plumbing materials that do not have extensive accumulation of surface scales containing PbO₂, changes in disinfectant are not likely to significantly impact lead leaching.
- For lead plumbing materials that are passivated and likely to have developed scales that are rich in PbO₂, changes in disinfectant—that is, conversion to chloramines or some other low ORP conditions—are likely to cause a notable increase of lead leaching when conversion to chloramines is implemented.
- Copper leaching can be temporarily increased due to chlorine/chloramines transition (or vice versa). However, in most cases the increase in copper leaching is followed by a sustained decrease in leaching rates.
- Because the sensitivity of copper leaching to the presence of a disinfectant does not appear to be disinfectant-specific, disinfectant conversions in distribution systems probably do not run the risk of substantial increases in copper concentrations at household taps.
- Lead leaching from bronze appears to exhibit trends similar to those seen from lead. Lead corrosion products appear to rapidly form on lead phase existing on the alloy surface, ultimately suppressing lead release.
- Copper leaching from bronze can be promoted by the presence of a disinfectant. However, like copper leaching from copper materials, this effect is transient and tends to be followed by a decreasing leaching.
- Effects of changing disinfectants on metal leaching from bronze plumbing materials are minimal.
- Galvanic effects appear to be very sensitive to initial chlorine/chloramines (or vice versa) transitions. However, the effect is highly transient. Under steady state conditions, the shock of initial exposure quickly wanes.
- In general, disinfectant conversion does not appear to have long-term significant impact on galvanic effects. However, background water quality conditions or particular mineral passivating scales that were not

1. Projects #3107 and #4088b produced conflicting results on lead release. A later WRF project, #4349, *Galvanic Corrosion Following Partial Lead Service Line Replacement*, examined these results. Please refer to page 22 of this document for details on project #4349.

explored in this investigation may produce different results.

Additionally, based on the findings of this research, guidelines for before and after the disinfectant change were developed for utilities faced with potential consequences of lead and copper release.

4088 - Impact of Chloride: Sulfate Mass Ratio (CSMR) Changes on Lead Leaching in Potable Water (2010)

THIS PROJECT INVESTIGATED the potential effects of coagulant changeover on lead release from plumbing components, with emphasis on changeover from aluminum sulfate to ferric chloride, ferric sulfate, polyaluminum chloride, and various polymer coagulants. Additional project goals were to investigate the finished water chemistry resulting from coagulant changeover, how distribution system scales are affected and how this affects lead release, and the magnitude of lead release after different stagnation times.

The work was performed in three phases. In Phase 1, the fundamental chemistry of galvanic corrosion attack on lead-copper joints was evaluated, and experiments examined impacts of high Chloride: Sulfate Mass Ratio (CSMR) on the integrity of soldered joints. Utility case studies were evaluated in the second phase of work to examine effects of CSMR on galvanic corrosion in a number of potable waters. Specifically, questions regarding the effects of coagulant changeover, desalination, and anion exchange treatment on lead solder and leaded brass corrosion were evaluated. The roles of alkalinity, pH, and corrosion inhibitors to potentially mitigate corrosion in high CSMR waters were also examined. Finally, in a third phase of work, re-circulating loops were used to evaluate the impacts of chloride, sulfate, and flow rate on corrosion of lead plumbing.

Some of the key conclusions that came out of this study are listed below:

- The corrosion rate of and the release of lead and/or tin from solder alloys was greater in high CSMR water. The pH at the solder surfaces was measured to be as low as pH 3.0.
- Generally, increasing the CSMR of the water results in higher lead levels in water when copper:lead solder or copper:lead pipe galvanic couples are present. There could be higher chloride and lower sulfate in the water due to road salt entering the water supply from runoff, coagulant type (chloride-based vs. sulfate-based), desalination, chloride-based anion exchange treatment, brine leak from hypochlorite generation system.
- For the utilities evaluated in this project, leaded brass leached relatively low levels of lead to the water, even in situations with high CSMR. In contrast, corrosion of lead solder in simulated copper joints contributed to very high amounts of lead in test waters. Thus, while leaded brass is impacted somewhat by CSMR, the issues associated with lead solder can occasionally achieve hazardous waste levels (>5,000 ppb) of lead in water under

worst-case scenarios. As a result, lead solder and lead pipe galvanically connected to copper are the primary concern when effects of higher CSMR are considered.

- The galvanic connection of copper to the lead materials evaluated in the study significantly increased lead leaching when compared to the situation when there was no electrical connection to copper pipe. In some waters, however, galvanic connections had little effect on lead leaching.
- Problems that occur in coagulant changeovers could usually be mitigated by controlling the type of coagulant and keeping CSMR below about 0.5. However, this is not always an option when CSMR was increased via arsenic treatment, anion exchange or desalination. For these case studies, adding orthophosphate when the CSMR was high did not reduce lead leaching or the extent of the problem.

A second phase of this project was conducted to examine effects of CSMR and galvanic corrosion on lead leaching to potable water after partial lead service line replacements.

4088B - Contribution of Galvanic Corrosion to Lead in Water After Partial Lead Service Line Replacements (2010).²

DUE TO PROPERTY ownership issues, partial lead service line replacements (and not full replacements) are widely implemented in the United States, with a primary goal of reducing lead exposure at the tap. During a partial-pipe replacement, a portion of the lead service line is typically replaced with copper pipe. These dissimilar metallic pipe materials are then connected to restore drinking water service. This process creates an electrochemical or galvanic cell, which can accelerate corrosion of the lead pipe. In this work, the adverse effects of such connections in the context of lead leaching were confirmed in experiments of simulated lead service line replacements.

The results of this research found that under stagnant water conditions, galvanic connections between lead pipe (either new or old) and copper pipe increased lead release into the water, compared to a full length of lead pipe alone. The extent of galvanic corrosion observed was dependent on drinking water quality. Exposure to synthetic water of high CSMR (i.e., CSMR of 16) increased lead release from the Pb:Cu test rigs by 3–12 times, compared to low CSMR water (i.e., CSMR of 0.2). Higher galvanic currents between lead and copper were measured when the CSMR was high, mechanistically explaining the trends in lead release. Even Under stagnant water conditions, galvanic connections between lead pipe (either new or old)

2. Projects #3107 and #4088b produced conflicting results on lead release. A later WRF project, #4349, *Galvanic Corrosion Following Partial Lead Service Line Replacement*, examined these results. Please refer to page 22 of this document for details on project #4349.

and copper pipe increased lead release into the water, compared to a full length of lead pipe alone. The extent of galvanic corrosion observed was dependent on drinking water quality. Key aspects of this study are also available in the March 16, 2010 Webcast.

604 - Development of a Pipe Loop Protocol for Lead Control (1994)

THIS PROJECT PROVIDES drinking water utilities with a standard protocol for use of the AwwaRF pipe rack to evaluate the effectiveness of various treatment options in controlling lead and copper levels at the tap. The protocol provided is a practical, hands-on approach with construction, operation, and data evaluation recommendations based on results from several utilities that tested the AwwaRF pipe rack in their plants.

The AwwaRF pipe rack is designed to evaluate lead and copper leaching characteristics in a flow-through system that simulates household plumbing. Each rack is designed to contain several individual pipe loops for which various metal levels could be evaluated for specific water qualities. The pipe rack is designed to help utilities perform corrosion rate studies and metals leaching determinations for compliance with the LCR.

The LCR requires that all utilities serving over 50,000 customers conduct corrosion control optimization studies and demonstrate optimal treatment for lead and copper. The 1992 USEPA guidance manual for the LCR specifies a framework for conducting corrosion studies. The AwwaRF pipe rack can be used as a demonstration testing device for comparing the effect of corrosion treatments on metals levels and for testing secondary impacts of treatment changes on water quality and regulatory compliance.

Proper planning and operation of pipe rack studies are crucial for a successful pipe rack study: proper fabrication, adequate mixing of chemical feed solutions, adequate preconditioning, proper disinfection of sample ports (to prevent high heterotrophic bacteria counts), and monitoring of pipe rack operations. The operation can be divided into three phases: startup, preconditioning, and corrosion testing operations. With startup, a standard protocol for flushing is recommended in the manual. The manual also recommends a four-week preconditioning phase before chemical treatments are started. This allows verification that the pipe loops are constructed in a similar fashion and yield similar results with a common starting point for evaluating treatment effects on leaching. For the actual corrosion testing, the manual recommends a daily on-off cycle to simulate flow in a typical home, collection of standing samples for measuring corrosion-related parameters, and collection of running samples for determining influent water quality characteristics and operational consistency. At a minimum, lead, copper, temperature, alkalinity, total and free chlorine, and pH are recommended for analysis on first flush, standing water quality samples. The manual recommends frequency of collection of standing samples based on the

expected variability of the results and the length of time over which samples will be collected.

The manual recommends that utilities run pipe rack studies for three distinct periods: a conditioning period, a transition period, and a stability period. The conditioning period consists of a rapid drop in metals levels, followed by a transition period where metals levels decrease at a slower rate. In the stability period, metals levels stabilize. Utilities must run the pipe rack studies long enough to ensure data represent the stabilization period. The utilities that tested the pipe rack for this study found that it took six to nine months for lead to stabilize in lead loops; three to eight months for lead to stabilize in lead-soldered copper loops. Copper levels stabilized in two to eight months. The manual recommends utilities operate the pipe rack long enough for the metals levels to stabilize. Longer periods may be required if data collected are highly variable or a greater degree of statistical confidence is required.

In 1994, when this study was published, an AwwaRF pipe rack cost \$10,000 to \$13,000 in materials and labor to build. For several water quality conditions to be tested, one rack would be needed for each treated water condition. Operation costs may require up to one full-time operator for a two to four-week period, with routine operations up to 20 hours/week.

Noted drawbacks with the AwwaRF pipe rack study include:

- For statistically meaningful and valid results, the study may have to be run for as long as 18 months to obtain adequate data.
- Metals levels measured are impacted by the nature and consistency of source water quality.
- The stability of metals may not be observed if seasonal source water quality changes happen during the course of a pipe rack study.
- The cost of building a pipe rack system may be cost prohibitive for small utilities.
- Variability measured in the lead and copper data from the pipe racks used in the study was high. However, non-parametric methods are available with which to evaluate the variable data in a statistically valid manner.

Although the results from the AwwaRF pipe rack must be considered a relative evaluation of treatment impacts on metal levels, the data can be used for demonstrating optimization.

508 - Chloramine Effects on Distribution System Materials (1994)

THE PURPOSE OF this project was to investigate corrosion and degradation of elastomers and some metals with chlorine and chloramine disinfection.

For elastomers, the results pointed to accelerated elastomer failure after changeover to chloramination. Accelerated life cycle testing of tension mounted thermoplastic coupons showed that with few exceptions solutions of chloramines produced greater material swelling, deeper and dense surface cracking, a rapid loss of elasticity, and loss of tensile strength than equivalent concentrations of free chlorine. Elastomers

more susceptible to degradation are those formulated with natural or synthetic isoprenes. Newly engineered synthetic polymers performed well in the chloramines exposure tests.

For metals, the researchers exposed seven metals (copper, brass, bronze, three types of solders, and mild steel) to varying levels of pH (6–8), chlorine (0.5 and 5.0 mg/L), chloramines (0.5 and 5.0 mg/L) and ammonia (<10 mg/L). Corrosivity was measured using weight methods, electrochemical analysis, and galvanic current on coupons or pipe segments exposed to disinfectants. The researchers made the following conclusions:

- Both chlorine and chloramines accelerate the corrosion of copper and its alloys at pH 6 but cause minimal corrosion at pH 8.
- An increase in disinfectant concentration can increase corrosion of copper and its alloys at pH 6.
- Corrosion of copper and copper alloys by free or combined chlorine was greatest for brass, followed by copper, and then bronze.
- The presence of free or combined chlorine did not lead to pitting type corrosion on copper or copper alloy surfaces under the conditions tested in this project.
- The presence of ammonium ions produced no discernible increase in corrosion on copper or copper alloy surfaces.
- Neither leaded nor lead-free solders are substantially influenced by the presence of free or combined chlorine at pH levels common to distribution systems.
- In equal concentrations, free chlorine is slightly more corrosive than chloramines on copper and its alloys. However, residual concentrations are higher in systems that disinfect with combined chlorine, compared to free chlorine. As a result, systems that convert to chloramine disinfection may experience higher rates of corrosion depending on pH levels.

2760 - Optimizing Chloramine Treatment, Second Edition (2004)

IN 1993, WRF funded the first edition of this report, which is a manual on the use of chloramines and the role they play in water quality improvements for drinking water utilities. This second edition of the report provides updated information gathered from 68 utilities by documenting their experience with chloramination use. Using the information from the utility survey, the researchers identified critical parameters for controlling chloramination and formulated a chloramination optimization strategy.

The report provides key evaluation criteria when evaluating a switch to chloramines, a process for determining if chloramines are the right choice for a utility, a process and operating procedures for optimizing chloramines treatment, ammonia storage and feed facility considerations, chloramination start up considerations, distribution system issues, parameters to monitor, and customer relations issues to consider.

The researchers did not find that the utilities surveyed had experienced any general trends of lead and copper corrosion issues with chloramine use. Through the literature review for this project, the researchers found that many corrosion studies conducted on chlorinated and chloraminated water systems included evaluations of copper; however, very few rigorous studies exist that make a direct comparison of the corrosive effects of chlorine and chloramines.

One case-study utility conducted a comprehensive corrosion study on their soft, slightly buffered water sources. The utility evaluated the corrosivity of chlorine and chloramines using flow through pipe loops for a 12-month period. According to the results, copper thinning rates decreased as the pH was increased. At each of the different levels, chloramines caused more copper thinning than chlorine, with the exception of three control loops. It is important to note that the utility did not compare equivalent levels of chlorine and chloramines. As such, the utility results, which indicate that chloramine was more corrosive to copper than chlorine, are not direct comparisons of corrosivity between the two disinfectants.

2687 - Enhanced Coagulation Impacts on Corrosion of Water Treatment Plant Infrastructure (2004)

THIS PROJECT EXAMINED the effects of enhanced coagulation (lower coagulation pH and higher coagulant doses) on water treatment plant infrastructure. This project focused specifically on corrosion of treatment plant infrastructure to include concrete, internal plant piping, pumps, and valves.

The research team conducted a utility survey and case studies to determine the effects of enhanced coagulation on water treatment plant infrastructure. Additionally, the team conducted experiments on inhibitor compatibility with enhanced coagulation and a comparison of alum, ferric, and PACl coagulants in the degradation of concrete.

Some key findings of this research are:

- Free chlorine is highly corrosive to plant infrastructure. However, few utilities anticipate increased problems from free chlorine when coagulation pH is lowered, even though such changes are known to enhance release of Cl₂ gas from water. Painting plant infrastructure provides a simple means of slowing the rate of attack.
- Metallic plant infrastructure, such as pumps and pipes, bear close monitoring for pinhole or pitting-type corrosion.
- Coagulation at the treatment plant can cause discoloration and change corrosion of materials in the distribution system. Whenever a change in coagulant type or pH is implemented, the corrosivity of the water is fundamentally changed. Even small changes in the pH of distributed water can have noticeable impacts on corrosion of distribution system materials.
- If inhibitors are used to protect components in the treatment plant, they need to be compatible with coagulation goals. Since phosphate or polyphosphate inhibitors

are removed by, and likely interfere with, coagulation, they do not appear to be a good option for protecting plant infrastructure.

831 - Role of Inorganic Anions, NOM, and Water Treatment Processes in Copper Corrosion (1996)

THIS PROJECT STUDIED the effects of water quality on copper corrosion using both conventional and electrochemical aging methods. In addition to natural organic matter (NOM), the researchers focused on the effects of five common anions: sulfate, chloride, bicarbonate, perchlorate, and nitrate.

Some general implications for water treatment practices were discovered. Utilities delivering high-alkalinity (> 100 mg/L as CaCO₃) and low pH (<7.7) waters can expect a high likelihood of problems with copper corrosion. A small pH increase to about 8.0 may alleviate or eliminate copper corrosion problems. The research team recommends on-site corrosion studies to accurately define the pH increase necessary to gain the desired benefits.

In waters with NOM in the range of 1–4 mg/L (typical for surface source waters), NOM removal by coagulation or adsorption, or both, cause little change in copper corrosion and release.

With enhanced coagulation, waters treated with alum were more aggressive towards copper than those treated with ferric chloride. Alum also caused longer-term corrosion rates. The choice between using aluminum sulfate and ferric chloride as coagulants is very important for copper corrosion control. Although chloride has beneficial effects and sulfate has adverse effects, it is not known whether these effects are magnified at increased concentrations, nor are the combined interactions understood. Once again, corrosion studies are imperative to determine whether the benefits, if any, would be worth the cost of changing coagulants.

Adsorption with GAC had a negative impact on copper corrosion while ozonation had no significant effects on copper corrosion.

Specific Water Chemistry Effects on Lead and Copper Corrosion

4409 – Controlling Lead in Drinking Water (2015)

THIS PROJECT PROVIDES recommendations for controlling lead in drinking water. In order to accomplish this, it is important to understand why lead is present at the tap and how lead release can be prevented. The chemistry of the water that determines both of these factors is described in this report. Control strategies used by water utilities are described, including a detailed discussion of lead service line replacement. In addition, case studies showing how six utilities have approached lead and copper corrosion control are listed under project resources.

Chapter 1 focuses on the important characteristics of lead chemistry in water. Lead in drinking water at the customer tap

is almost exclusively the result of water contact with lead containing components in the distribution system or household plumbing. If these lead-containing materials are present in the system, and the water causes corrosion through contact, lead can be released in a soluble or insoluble form, depending on the water chemistry.

Chapter 2 describes how these water quality characteristics can be manipulated or accounted for in drinking water systems to control lead levels at the customer tap. The most common methods to minimize lead in drinking water are:

- Adjusting the water chemistry to produce stable water quality conditions that inhibit lead release
- High velocity flushing (especially inside the home) to remove particulate lead
- Removing service lines and plumbing materials that contain lead

Chapter 3 describes an example of a lead service line replacement strategy.

4317 - Non-Intrusive Methodology for Assessing Lead and Copper Corrosion (2014)

THIS PROJECT DEVELOPED a corrosion test rig (CER) to gauge the effectiveness of corrosion control efforts. The test rig is designed to provide reproducible lead and copper readings to discern trends in lead and copper release. Data from the test rig allows analysis of lead pipe connected to copper pipe, leaded solder, and leaded brass in isolation, thereby assisting interpretation of lead leaching problems.

The test rig contained nine lengths of parallel pipe. These lengths are divided into three duplicate lengths of (1) copper pipe with lead solder (copper-solder), (2) PVC with brass rod inserts (brass), and (3) lead pipe galvanically connected to copper tube (lead-copper). The project was conducted over three phases. Phase I and II consisted of rig design and testing. Phase III consisted of full-scale field testing at the five participating utilities. Each of the participating utilities had one CER installed at their water treatment plant and one CER at a more distant point in their distribution system where the water quality may be different.

The following conclusions were reached:

- The highest lead leaching propensity was for lead-copper pipe, relative to copper solder and to leaded brass. The leaded brass consistently leached low levels of lead across all five utilities. Lead leaching from the copper-solder changed depending on the utility
- Particulate lead was a large component of the measured lead levels. Between 49 and 99% of measured lead was in particulate form.
- Particulate copper had less of an influence on the copper measurements compared to lead. Particulate copper accounted for 2 to 34% of measured copper levels.
- For copper leaching, the copper-solder always leached the most copper, followed by the lead-copper pipe. The brass always leached the least copper.

- CERs may provide a more consistent measure of a water's corrosivity and a utility's corrosion control effectiveness.
- Two participating utilities, which shared the same source, water but had different water processes had different results for lead and copper leaching, reinforcing the significance of treatment differences and water chemistry in corrosion control.

4211 - Lead (IV) Oxide Formation and Stability in Drinking Water Distribution Systems (2012)

PbO₂ SOLIDS FORM at the high oxidation reduction potential induced by residual free chlorine, and such solids have been observed as constituents of scales of lead corrosion products that develop on lead pipes. The PbO₂ solids have low solubility. As long as a sufficiently high oxidation-reduction potential is maintained, dissolved lead concentrations remain at low levels. However, when the oxidation reduction potential is lowered the PbO₂ is no longer stable and its reduction releases lead to the water. Even when oxidizing conditions are present, the actual solubility of PbO₂ phases is imprecisely known. Information on the dissolution rates of PbO₂ is particularly valuable as water suppliers consider process changes that affect water chemistry such as switching disinfectant type or dose, adjusting pH, or adding a corrosion inhibitor.

The project was divided into three integrated research objectives. The tasks progressed from (1) the formation of PbO₂, to (2) the stability of PbO₂ in equilibrated systems, and finally to (3) the rates of dissolution of PbO₂.

Key findings with respect to formation, equilibrium dissolved lead concentrations, and PbO₂ dissolution rates are provided in the report. Findings of particular interest include:

- PbO₂ can only form in the presence of free chlorine, and the threshold free chlorine concentration for producing PbO₂ is less than 4 mg Cl₂/L.
- The formation of PbO₂ is accelerated by the presence of dissolved inorganic carbon.
- Dissolved lead concentrations from equilibration of PbO₂ in water with free chlorine were orders of magnitude higher than predicted from published thermodynamic data.
- The dissolution rate and not the equilibrium solubility of PbO₂ will control dissolved lead concentrations in waters that are in contact with PbO₂ as a corrosion product for most relevant stagnation times.
- The rate of PbO₂ dissolution rate decreased with increasing pH. This is in contrast to the dissolved lead concentrations after multi-day equilibration that increased with increasing pH.
- Orthophosphate inhibited PbO₂ dissolution with its effects limited to near-neutral pH.

Lead(IV) oxides (PbO₂) can be an important component of corrosion products on pipe scales for utilities that have lead service lines in their distribution systems and that currently

use or have used free chlorine as the secondary disinfectant. PbO₂ can only form in systems with free chlorine present; however, because of the low solubility of this phase and the complexity of pipe scales, PbO₂ may persist well after a switch from free chlorine to chloramine. The rate of PbO₂ formation and consequently the likely extent of PbO₂ formation on lead service lines is strongly affected by the water chemistry of the distribution system. The dissolution rate of PbO₂ is a very strong function of the water chemistry, and orders of magnitude differences can occur in the rates depending on the composition. Utilities should be aware of conditions that could accelerate the dissolution of PbO₂ and the release of lead from this potential reservoir of unstable lead in scales on lead service lines. This is particularly important for systems that have recently switched from using free chlorine to chloramine as the secondary disinfectant. The most significant parameter affecting PbO₂ dissolution rates is the concentration and identity of species that can act as chemical reductants to accelerate PbO₂ dissolution. These species include natural organic matter, dissolved iron(II) and manganese(II), and iodide.

4243 - Is NSF 61 Relevant for Chloraminating Utilities? (2012)

THE NSF INTERNATIONAL and the American National Standard Institute (NSF/ANSI), Drinking Water System Components—Health Effects, was developed to establish minimum requirements for the control of potential adverse human health effects from products that contact drinking water or drinking water treatment chemicals. NSF/ANSI Standard 61 is concerned about the potential extraction of any chemical, including lead and copper. Release of lead and copper from these testing protocols currently uses exposure waters containing free chlorine as the disinfectant

The main objectives of this project were to directly compare the leaching characteristics of typical utility service connection and premise plumbing devices under relevant NSF 61 Section 8 and 9 protocols (both chlorinated and chloraminated conditions) in order to assess whether the standard predicts lead and copper release with sufficient accuracy to meet the public health and regulatory needs of utilities that use chloramines. A second objective was to develop a knowledge base of utility experience using NSF 61 certified appurtenances with chloramines disinfection.

Laboratory results of this study indicated that for lead release for Section 9 devices, there was very little difference seen between the chlorinated and chloraminated versions of the Section 9 test water. Evaluation of all test water conditions and all Section 9 products indicated that the current Section 9 test water was found to be the most appropriate condition for certification of Section 9 products for lead release. However, for certification of Section 8 products for lead release, the current NSF Standard 61 Section 8 test waters were not the most aggressive. When comparing lead release from all the test water conditions and devices evaluated, the chloraminated

version of the current Section 9 test water yielded the highest normalized lead release for Section 8 devices. The difference in lead release from Section 8 products between the current chlorinated Section 9 test water and the chloraminated version was minimal however, and may have been due to variability in products tested versus differences in the extraction water. Therefore, for utilities that chloramine, instituting testing protocols that incorporate chloramines, or incorporate dual evaluation of chlorinated and chloraminated exposure waters, will likely not be more predictive of extraction of lead from Section 8 products than testing with a chlorinated extraction water alone. Based on the variable laboratory results seen through the Section 8 analyses, the standard for Section 8 products would be improved by the addition of a requirement mandating a sample size greater than 1, and the exposure water for lead release for Section 8 brass or bronze containing devices should be re-assessed.

4289 - Copper Pitting and Brass Dezincification: Chemical and Physical Effects (2009)

COPPER PITTING AND brass dezincification are types of localized, or non-uniform, corrosion, which can impact the service life of premise plumbing systems. Only a few studies have succeeded in replicating either copper pitting or brass dezincification in the laboratory as it occurs in practice. This project conducted a comprehensive literature review on brass dezincification in potable water systems. Experimental work was conducted to meet three objectives:

1. Evaluate the effects of water quality parameters and common chemical constituents, and physical factors on rates of copper pitting
2. Evaluate the effects of water quality parameters and common chemical constituents on severity and selectivity of brass dezincification
3. Evaluate the effects of physical factors on type, severity, and selectivity of brass corrosion

The first and third objectives were met by conducting long-term, large-scale tests in pipe loops. Tests to meet the second objective were carried out in stagnant, bench-scale apparatuses constructed of copper tubes and brass rods, which were filled with various test waters.

A wide range of chemical and physical factors was indeed found to influence copper pitting and brass dezincification. Temperature and physical exposure conditions were also found to affect other types of brass corrosion (i.e., lead leaching and pitting). Specific results can be found in the final report.

A decision tree was developed to assist utilities in determining how to avoid or mitigate copper pitting problems associated with aggressive water (see Figure ES.1 in the report). For utilities concerned with avoiding copper pitting problems, it is recommended that proactive efforts be made to maintain non-aggressive water qualities. Thus, proposed changes to water treatment should be carefully considered and tested to evaluate if finished water quality will be rendered aggressive.

For utilities with known copper pitting problems, dosing phosphate or silica corrosion inhibitors are the only recommended strategies for mitigation of significant “outbreaks” or widespread problems. If pinhole leak failures are isolated to systems known to have high flow velocities or galvanic connections between copper and other metals, problems could be mitigated by repairing or re-plumbing affected systems to remediate the contributing factors. In such cases, utilities should closely monitor failure reports to make certain that more pervasive problems do not exist.

At this time, a mitigation strategy for brass dezincification based on modifications to water quality cannot be recommended. Although it is clear that higher alkalinity and lower chloride may reduce dezincification tendencies, threshold values for inhibiting dezincification have not been determined. Furthermore, conventional corrosion inhibitors like phosphates or silica do not appear to have long-lasting effects. Thus, avoiding and mitigating dezincification failures in aggressive water is probably best accomplished by use of dezincification resistant (DZR) brass alloys. To this end, it is recommended that utilities determine if their finished water quality is, in fact, aggressive, and relay this information to consumers and developers. For utilities concerned about lead contamination, it is also recommended that brasses installed in hot water lines be considered as a lead source.

4064 - Water Chemistry Effects on Dissolution Rates of Lead Corrosion Products (2006)

THE INTERNAL CORROSION of lead-containing pipe, fittings, and solder in premise plumbing is the most significant source of lead to drinking water. The primary objective of this project was to provide new information to the water supply community that advances understanding of lead corrosion product dissolution and transformation rates. The research approach was divided into three corresponding research tasks. Task 1 was a literature review evaluating the dissolution rates of lead(II) carbonate, lead(II) phosphate, and lead(IV) oxide precipitates. Task 2 was a systematic experimental investigation of the dissolution rates of three important lead corrosion products. Task 3 extended the study of dissolution rates of pure solids to release rates from pipe scales. Tasks 2 and 3 involved bench-scale laboratory experiments with integrated analysis of the aqueous solutions and the solid phases.

Information on the specific water chemistry and corrosion products is valuable in predicting and controlling lead release from scales on lead service lines. When collecting samples for compliance with the LCR, utilities could gain insights into processes controlling lead concentrations by measuring pH, dissolved inorganic carbon concentrations or alkalinity, free and/or combined chlorine concentrations, and orthophosphate concentrations. Information on the identity of the corrosion products can be gained by sampling and analyzing portions of pipe scales when lead service lines are removed from a system.

This study found that the effectiveness of corrosion control strategies will vary depending on the source water chemistry and the composition of the pipe scales. Generally, less lead is released at higher pH values and the addition of orthophosphate dramatically decreased rates of lead release from both plattnerite and hydrocerussite. A webcast on this project was presented on April 29, 2010.

3172 - Role of Free Chlorine, Chloramines, and NOM on the Release of Lead into Drinking Water (2008)

THIS PROJECT INVESTIGATED the release of lead in the presence of NOM, free chlorine, and chloramine by means of the dissolution and passivation of lead oxide (PbO₂) in the distribution system.

The researchers found that lead oxide is relatively unstable in water. It is reduced to Pb(II) by the water itself, but only very slowly at or near neutral pH values. It is also reduced by NOM. The reductive capacity of the NOM is reduced if it is pre-oxidized by free chlorine. However, when free chlorine was present with NOM, lead oxide is not reduced because it would oxidize any released Pb(II) back to lead oxide.

Monochloramine, generally considered an oxidant, reduced lead oxide. The amount of Pb(II) formed was related to the amount of monochloramine that decomposed via auto-oxidation. This suggests that the reaction mechanism involves a reaction of intermediates produced from the auto-decomposition of monochloramine, which act as potent reductants of lead oxide. Because NOM was also slowly oxidized by monochloramine, the effect of mixtures of monochloramine and NOM led to more complex behavior as each component did not act independently.

Water treatment processes that can alter the oxidation potential of the treated water need to be carefully evaluated for lead release from lead oxide or other lead bearing materials, such as brass meters or valves. Water systems that have adopted or are contemplating adoption of chloramination for secondary disinfection should conduct a more thorough lead monitoring program after switching disinfectants. Additionally, pre-oxidizing NOM or removing NOM should reduce the potential for lead release from lead oxide.

3015 - Assessment of Non-Uniform Corrosion in Copper Piping (2008)

THIS PROJECT INVESTIGATED the extent and implications of copper pitting and pinhole leaks for residential potable water plumbing systems. The research team also investigated suspected causes of copper pitting and pinhole leaks through case studies at participating communities.

Non-uniform corrosion—also known as copper pitting—that manifests itself as a pinhole leak greatly shortens the usable lifespan of potable plumbing pipes. The resulting leaks can damage customer housing infrastructure and possibly lead to mold growth. Although customer plumbing and property is not the jurisdiction of local utilities, utilities need to

be aware of the extent and possible causes of copper pitting in the communities they serve.

Through a national survey of plumbers, homeowners, businesses, and corrosion experts, as well as a review of a database of copper pitting failures covering 30 years of data, the research team determined that approximately 8.1 percent of homeowners in the U.S. have experienced at least one pinhole leak. Between 21 and 60 percent of homes in certain communities have experienced pinhole leaks. The total cost of pinhole leaks and pinhole leak prevention in the U.S. is estimated to be \$967 million annually, with the largest proportion of cost (\$564 million) in single-family homes (particularly devoted to repairs). About 58 percent of responding utilities reported corrosion inhibitors, and annual costs of dosing corrosion inhibitors per customer (connection) ranged from \$0.10 to \$5.72 with an average of \$1.16.

Case studies at communities experiencing pinhole leaks were designed to confirm suspected pinhole leaks and identify mechanisms that cause those leaks. Three water chemistry and microbiological factors emerged with strong links to pinhole leaks:

- high pH and high levels of disinfectant, exacerbated by aluminum and other particles
- local production of H₂S in and around pits by sulfate reducing bacteria (SRB)
- erosion corrosion in hot water recirculation systems

Of course, there are other factors believed to influence copper pitting corrosion, and further research will need to be done to identify and confirm those.

The team developed a protocol to help utilities assess the extent of pinhole leaks in their community. The report includes a CD ROM that contains the results of the detailed case studies from the participating communities. The case studies include detailed information on the hydrological, biological, and aqueous chemical factors that led to copper pitting failures.

3109 - Non-Uniform Internal Corrosion in Copper Piping – Monitoring Techniques (2009)

THIS PROJECT EVALUATED the accuracy of several electrochemical monitoring techniques in predicting pitting propensity of copper tubing in potable water supplies. For this study, the research team tested corrosion potential (E_{Corr}), electrochemical noise (ECN), pit wires, and coupon testing. Four water qualities of well-established pitting propensities were used to assess the four corrosion monitoring techniques—a proven pitting water, a biologically active water suspected to cause pitting, a non-pitting water, and a pitting water that also produces blue water events. Each of the corrosion monitoring techniques selected for this study had artifacts or insurmountable problems relative to tracking pitting propensity in the test waters and were found to be highly imperfect and of limited value.

This research makes it very clear that existing electrochemical tests of copper pitting propensity are largely tracking

measurements of solution redox potential and oxidant levels, with some undetermined modification by surface scale or rust layers. The electrochemical tests are also influenced by, and in some cases controlled by, flow phenomenon. Specifically, turning a pump on and off, or long-term continuous flow, can control the electrochemical measurements that are made. Therefore, ECorr and ECN, as applied in past research, provide very little or no direct insight to pitting phenomena without extensive prior testing and experience with the water in question.

Understandably, researchers and utilities will likely continue to use electrochemical techniques to predict pitting propensity in the future despite the major limitations discovered in this study, because it is unacceptable to do nothing and because the alternatives to electrochemical techniques have their own deficiencies. However, utilities are probably better served by conducting detailed forensic evaluations of pitting failures, and then trying to relate patterns of pitting in a given system to changes in oxidant chemistry, microbial activity, and other monitored water chemistry variables throughout the distribution system. Changes in these parameters that occur in premise plumbing including pH, dissolved oxygen, disinfectant levels, and microbial communities (including SRB and nitrifiers) may provide useful insights into factors that contribute to pitting. Utilities can then consider changes in distribution system operations such as booster chlorination, reducing pH or dosing an inhibitor—which have a strong likelihood of reducing copper pitting while also achieving other desirable water quality objectives.

182 - Corrosion and Metal Release for Lead-Containing Plumbing Materials: Influence of NOM (1999)

THIS PROJECT INVESTIGATED the effects of natural organic matter (NOM) on the corrosion of lead-containing materials (i.e., leaded brass, lead-tin solder, and lead pipe) in drinking water. The researchers found that the effects of NOM were dependent on the properties of the corroding material. The primary conclusion of this research confirmed the suspicion that the presence of NOM may be a major factor affecting lead release from lead pipe, lead-tin solder, and leaded brass or bronze. The adverse effects of NOM were exacerbated in low-pH, low-alkalinity waters. Increasing pH and alkalinity can alleviate the adverse effects of NOM. Chlorination and ozonation did not diminish the lead leaching associated with NOM on the short term, but may alleviate NOM effects associated with lead release in the end. NOM did exhibit some corrosion-inhibiting action for brass and decelerate the dezincification of the brass, but it did not stop or inhibit selective lead oxidation and leaching caused by the galvanic coupling of the lead microphase with the copper-based matrix. The researchers concluded their report with a recommendation that all lead-containing copper-based alloys be eliminated in potable water applications.

Material Effects on Lead and Copper Release

4351 - Evaluation of Lead Service Line Lining and Coating Technologies (2017)

THE PRIMARY OBJECTIVES of this research project were: (1) to evaluate lead service line (LSL) lining and coating technologies as alternatives to full or partial LSL replacement, and as a means of protecting and repairing copper service lines (CSLs); and (2) to provide information and recommendations to water utilities, engineering consultants, consumers, property owners, state and provincial regulators, and other stakeholders to assist them in making informed decisions regarding lining and coating of both lead and copper service lines.

The research concluded that three currently available lining or coating technologies can effectively reduce or eliminate release of lead from LSLs, are expected to have long service lives, and can potentially result in significant cost savings and other benefits relative to LSL replacement, depending on site-specific conditions. Other possible benefits include fewer and shorter disruptions of vehicular and pedestrian traffic; reduced damage to landscaping, trees, sidewalks, and driveways; less potential for damage to other utility lines (gas, electric, phone, cable, sewers); and facilitating delay of LSL replacements until they can be more efficiently and more cost-effectively performed in concert with future main rehabilitation or replacement projects. Thus, lining and coating technologies are potentially useful tools for reducing public exposure to lead in drinking water. Public water systems and property owners should be encouraged to evaluate their use, to the extent permitted by applicable regulations, in situations where significant cost savings and/or other benefits can be realized; and, where applicable, to incorporate their use into well-organized, system-wide LSLR programs to help minimize costs and maximize benefits.

Three technologies are deemed to be especially promising and are therefore recommended for consideration by both public water systems and property owners: PET lining, epoxy coating, and polyurea/polyurethane coating. Each can effectively reduce or eliminate lead release, is commercially available, and is, or has been, certified for use in contact with potable water in the United States, Canada, and/or the UK. Each of these technologies involves materials that could potentially affect water quality by leaching certain constituents into the water; but that is true of every material that is used, or could conceivably be used, in water service lines. This issue has been effectively addressed for many years by requiring any material that may come into contact with potable water in a public water system to be certified as meeting NSF/ANSI Standard 61.

4569 - Evaluation of Lead Line Sampling Strategies (2015)

THIS PROJECT CONDUCTED a side-by-side comparison of five lead sampling techniques. Each strategy's effectiveness at detecting peak total lead levels was evaluated. These strategies were compared to results collected during a minimum 12-L profile on each sampling date. The five sampling strategies are listed below:

1. Run tap water until a temperature change is detected and then sample
2. Collect a full profile during a one-time sampling event at each location, determine the profile volume with the peak lead concentration, and collect future samples for lead at this peak profile volume (the "initial peak" method)
3. Sample a fixed sample volume (e.g., the 5th liter)
4. Sample the middle of the service line (SL) or lead service line (LSL) based on site specific calculations
5. Collect a composite sample (e.g., the first gallon or first ~4 liters)

Key findings of the five sampling strategies are as follows:

- No sampling method was particularly proficient at finding the peak lead level compared to doing a full profile for each sampling event.
- The figure below summarizes the sampling method results from the study, characterizing the results by the percentage of observations that produced a total lead result within 70 percent of the peak total lead value. The peak total lead value was the highest lead level found during each profile sampling event.

A webcast for this project is available for download on the WRF website.

4191 - The Performance of Non-Leaded Brass Materials (2014)

THIS PROJECT IDENTIFIES and prioritizes key water quality characteristics and changes that might adversely impact the performance and leaching of non-leaded brass drinking water distribution system components over typical component lifetimes. This project determined the water quality impacts on short- and long-term performance of non-leaded brass components and determined the inorganic compounds (i.e., Se, Bi, Pb, Cu and Sb) likely to be released from the non-leaded brass components under a variety of water quality conditions.

This project tested four non-leaded brasses and one leaded brass (the control) for long-term performance for corrosion and leaching under the following different water quality conditions typical for North American utilities:

- Hard water, high chloride, high alkalinity
- High pH, low alkalinity, chlorinated
- High pH, low alkalinity, chloraminated
- High TOC, moderate alkalinity, groundwater
- Low alkalinity, low pH, mountain runoff

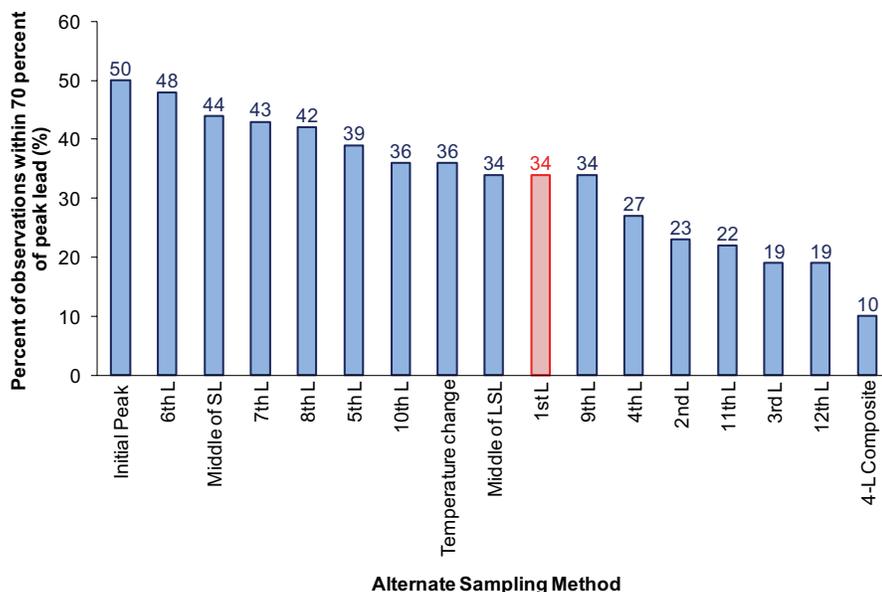
The alloys were tested for leaching of copper, zinc, lead, and nickel as well as other relevant elements such as tin, manganese, bismuth, selenium, and antimony. The materials were also tested according to NSF/ANSI Standard 61, Section 9, for lead leaching. Other performance measures tested included dezincification resistance, stress corrosion cracking, and erosion corrosion resistance.

The findings from the tests revealed, in principle, all four tested nonleaded brasses are suitable for use in drinking water. Nevertheless, in local waters with a significant dezincification potential (waters with low alkalinity, high chloride, and/or high sulfate concentrations), it is recommended to perform long-term tests to confirm the performance of the provided materials.

4349 - Galvanic Corrosion Following Partial Lead Service Line Replacement (2013)

THIS PROJECT PROVIDES an unbiased third-party review of the two previous WRF reports on lead corrosion (#3107 and #4088b). It developed guidance for water utilities on strategies for minimizing lead release from partial LSLRs on the basis of experiments conducted with commercially available transition couplings and field harvested pipes. The project also explores post replacement sampling conducted by two participating utilities as part of regularly specified sampling and special studies. The literature review comparing previous research on this topic is available in the final report as well as a stand-alone project paper. The tailored collaboration partner for the project is DC Water.

The laboratory experiments, conducted for a six-week period, indicate that galvanic corrosion



can cause statistically significant increases in lead concentrations. The extended timeframe pilot experiments (16 to 57 week durations) also had elevated lead concentrations following connections of lead pipe to copper tubing, but the findings were not conclusive as to how much of this increase is attributable to galvanic mechanisms. The pilot experiments, which were conducted with sample flow rates similar to or somewhat greater than typical kitchen faucet use, exhibited Pb concentrations that declined to stable lower values after durations that ranged from about four months to ten months. Field observations from two large LSLR programs summarized in this report suggest that elevated concentrations may abate in a period of four to six months.

Non-conductive plastic couplings always released less lead than the conductive metal couplings. Consideration should be given to use of non-conductive couplings where partial LSLRs must be undertaken. If a plastic coupling is used, it is recommended that a plastic spacer be inserted in the center of the assembly to assure that there is no contact between the two pipes. If a dielectric or plastic coupling is used, consideration will have to be given to alternative means of grounding the household electrical wiring system.

4415 - Application of Filters for Evaluating Lead and Copper Concentrations in Tap Water (2013)

THIS PROJECT EVALUATED if a commercially available carbon-based filter is capable of capturing the mass of lead and copper from a faucet's flow of drinking water, thereby creating a composite sample representing the total mass of these metals that the consumer would have been exposed to. A method to quantify the capture of lead and copper in the filter was also explored in this study. Desired characteristics of a filter to be used as a composite sampler for particulate and dissolved lead and copper were also provided.

Some point of use water filters are effective at removing dissolved and particulate metals.

If the volume of flow can be determined, the filters do provide an accurate estimate of potential exposure to contaminants in drinking water. A method to calculate lead and copper in the filter was developed. Using carbon filters as composite samplers to measure the total amount of lead and copper released to the tap can be accomplished but several issues with the filters need to be better defined before this can become a practical technique.

3018 - Contribution of Service Line and Plumbing Fixtures to Lead and Copper Rule Compliance Issues (2008)

THE IMPLEMENTATION OF the LCR has resulted in significant reductions in the first liter standing lead levels measured at the tap. However, there are utilities that have implemented optimal treatment that continue to experience lead levels at or near the action level for lead. There are also utilities that would like to go a step further in reducing lead levels measured in

their system by proactively replacing lead source materials. This project was initiated to help understand the contributions that various lead-based materials in premise plumbing may have on lead levels measured at the tap. Specifically, the research team investigated the contributions of premise piping, service lines, faucets, and meters.

The researchers found that lead source contributions are influenced by the physical characteristics of the source (i.e., length, diameter, surface area, etc.), water quality conditions, water use and hydraulic patterns, and mixing and dilution effects as the water flows during sampling. The team hypothesized that the presence of a lead service line at an individual site may elevate the contribution of individual sources by providing an additional source of lead, either by seeding the premise plumbing system with lead, or introducing lead derived from the service line at the start of the stagnation period.

The most effective way to reduce the total mass of lead measured at the tap is to replace the entire lead service line, followed by replacing lead sources in the premise plumbing, the faucet, and then the meter. Replacement of faucets and end-use fittings may or may not improve lead levels at the tap; however, it may be appropriate at sites without lead service lines that experience elevated lead levels in first-draw samples. Elevated lead levels may occur immediately after lead source replacement and may persist for longer periods, dependent on the materials and water quality at each site, and the amount of disturbance during replacement.

Corrosion control is still the best and most cost-effective way to comply with the requirements of the LCR. However, the customer's portion of the lead service line—which is beyond the jurisdiction of local water utilities—remains an important unresolved source of lead. Common sense tells us that, in the end, lead source removal is the most certain route to eliminating lead in drinking water. The water industry has learned a great deal about methods of minimizing the release of lead from lead surfaces exposed to water, and it has made a great deal of progress in removing lead service lines. These project results clearly demonstrate that the customer's portion of the lead service line remains an important unresolved source of lead. This issue is beyond the jurisdiction of local water utilities and other resources will be required if it is to be resolved.

The report includes a CD ROM that contains the extensive results obtained from the national survey of lead source characteristics and jurisdictional issues, case studies, pilot and field evaluations, and scale analyses.

3112 - Performance and Metal Release of Non-Leaded Brass Meters and Fixtures (2007)

THIS PROJECT PROVIDES definition and structure to the issues surrounding the current state of knowledge, testing protocols, performance, regulatory environment, and research gaps pertaining to the widespread use of residential sized non-leaded brass materials in drinking water systems. Historically, leaded

brasses have been used in drinking water systems; however, they were found to leach lead under certain circumstances. Because of this, alternative non-lead brass materials were developed that have a lead content between 0.1 and 0.25 percent lead by weight. Consequently, water utilities throughout the United States have begun to specify these non-lead brass materials for their systems. This project synthesized the current state of knowledge through a series of topic papers, and then convened an expert workshop to develop research needs and priorities for the drinking water industry to address.

The topic papers are included in the report by title:

- *Description of the Composition, Lead Content, and Mechanical Properties of New Non-Leaded Brasses*: Three families of non-lead brass alloys are commercially available: Envirobrass, FederAlloy, and ECO BRASS. All three range from 0.1 to 0.25 percent lead by weight. These alternative brasses were developed to be comparable to their leaded counterparts in terms of mechanical strength.
- *Potential Health Effects of Non-Leaded Brass Alloys*: Non-lead brasses contain a variety of metals that may be released into drinking water, including bismuth, selenium, copper, tin, nickel, antimony, zinc, and lead. While there are currently no U.S. drinking water regulations for bismuth and tin, the other metals listed above are all known to cause negative health consequences and therefore have MCLGs and MCLs as regulated by the EPA.
- *Potential of Non-Leaded Brasses to Release Lead and Copper and Other Metals (Bismuth and Selenium) into Drinking Water*: The potential for non-lead brasses to leach lead, copper and other metals has not been adequately examined. Preliminary tests studying corrosion and dezincification behavior of non-lead brasses have been aimed more at their practical performance rather than for health effects. More work needs to be undertaken to gain a better understanding of leaching propensity of these alloys.
- *The American Society for Testing and Materials (ASTM) Specifications for New Non-Leaded Brasses*: No specifications have been developed by ASTM that focus specifically on non-lead brass alloys. Some of the new alternative alloys have already been listed in existing ASTM standards for copper alloy applications, whereas some others are currently under evaluation for ASTM listing.
- *Summary of Current State Experience with Non-Leaded Brass Materials*: Action has been taken by a few states in order to eliminate lead use in drinking water components (e.g., California) or to promote use of components with lower lead content (e.g., Massachusetts).
- *Utility Motivations and Experience with Non-Lead Brass Components*: In 2000, Asarco commissioned a survey of U.S. water utilities to identify utility plans for replacement of leaded components with non-lead components.

They received 301 responses from utilities; 20 percent of utilities had plans to replace their lead containing brass components. Twenty one percent indicated they were not aware that non-lead brass options were available.

- *Potential Impacts to Manufacturers*: Manufacturers who use bismuth and/or selenium in their non-lead brasses may face competing European and Japanese demands for bismuth and selenium supplies. The new alloys may exhibit lower ductility and lower impact strength. Finally, the need to comply with NSF/ANSI Standard 61 is causing manufacturers to consider alternative strategies for production of brass water meters and other components, including: reducing the surface area available for water contact, using a different material for water contact with platings or coatings, or removing lead from the surface of the water contact component.
- *Impacts to Plumbing Industry*: Several options can be considered to facilitate the complex interaction among manufacturers, certification organizations, inspectors, and installers of brass materials. These include code revisions and code enforcement, coordination between federal, state, and local regulatory agencies, education and training of plumbers, and standardization of terminology between the various groups.
- *Impacts to Utility Operations and Maintenance Procedures*: There is little documented information on the material performance of non-lead components that have been installed in the field; however, limited information indicates no observed differences in structural performance. Costs of non-lead materials are currently higher than their leaded counterparts (20–30%), but when material costs are evaluated in perspective to the entire cost of installation, the overall increase in costs is significantly less (2–5%).
- *Alternative Materials for Fittings and Components*: Possible approaches to reduce human exposure to lead in brass include using alternatives to lead to fabricate the components and designing changes to existing manufacturing processes to eliminate lead leaching.

714- Evaluation of the Effects of Electrical Grounding on Water Quality (1994)

THIS PROJECT DETERMINED the effects of electrical grounding on water quality in residential plumbing. The objectives were to determine if electrical currents from grounding cause an increase in tap water metals concentrations and, if an effect was observed, to identify the levels of current that are problematic. The project included a literature review, an initial field survey, full-scale testing on a specially constructed model house, and field verification.

Overall, this study verified that, in the area of corrosion control, no one factor can be identified as the sole cause of elevated copper concentrations in tap water. Water quality,

stray current, electrical transients (i.e., lightning), fixtures, and construction practices were all identified as possible contributors to copper concentrations.

465 - Lead Pipe Rehabilitation and Replacement Techniques (2000)

THIS PROJECT TESTED and evaluated existing and emerging technologies for rehabilitation or replacement of lead pipes distribution systems. The LCR requires that a water system that exceeds the 90th percentile action level for lead after installing optional corrosion control and source water treatment is required to replace lead service lines that contribute more than 0.015 mg/L to total standing tap water lead levels. Although replacement or rehabilitation is an efficient method to remove lead sources in the distribution system, it is usually the most costly alternative for reducing lead levels at the tap (as opposed to corrosion control and source water treatment). This manual provides utilities with a tool for assessing and selecting lead pipe rehabilitation and replacement technologies. It provides descriptions of the various techniques, where those techniques can be applied, and factors that should be considered for successful application of each technique. The manual includes cost estimates (estimated in 1998) for comparison between the various techniques.

The research team used a utility survey, case studies, and field-testing to document utility experience with several lead pipe rehabilitation and replacement techniques. Technology categories tested included:

- Open-trench replacement
- Replacement along existing route (discarded pipe is left in the ground and new pipe is installed along a different route using a trenchless method)
- Replacement along a new route (existing lead pipe is removed or displaced while simultaneously replacing it with a new pipe)
- Slip lining (existing pipe is lined with a loose or tight fitting liner made of plastic material)
- Pipe coating (existing pipe interior is coated with epoxy or other polymer material)

For each technology category, the manual describes various techniques needed to apply the technology. Twenty-eight techniques were addressed in this manual. Technology profiles are detailed in the manual and facilitate a direct comparison between the various techniques.

Comparison of technologies:

- In general, the open-trench replacement technology is the most versatile and adaptable but the costs can be very high compared to other technologies (due to the typically high costs associated with site restoration).
- Replacement-along-existing-route technology is commonly applied in the United States, but not in Canada or Europe. The technology is straightforward to apply and costs are generally lower than open trench technology, provided conditions are favorable below grade. It does

tend to cause longer interruptions in water service because the water must be disconnected during replacement of the existing lead pipe.

- The replacement-on-new-route technology enables new service pipes to be installed at lower costs compared to open-trench and with minimum disruption to the environment and customers. It is commonly used in North America and Europe and is considered the most preferable technology choice for installation of replacement service pipes by many utilities surveyed for this project.
- The slip-lining technology is applied mostly in Holland and the U.K. Limited testing of this technology has been conducted in North America, but it is not applied routinely. This technology can be used to rehabilitate lead pipes where replacement-along-existing-route and replacement-on-new-route technologies are not suitable. This technology would not be suitable for lead pipes that follow a convoluted route or have significant breaks or restrictions. Costs are relatively high compared to other technologies due to the cost of the lining material and high capital cost of the equipment.
- The pipe-coating technology is not used routinely in North America or Europe to rehabilitate lead pipes. It is used in the United States to coat small diameter potable water pipes within buildings and ships. It can also be used to coat the inside of pipes around bends and through pipe restrictions. The major advantage of this technology is its ability to complete multiple installations at a reduced cost. The major disadvantage is the extended interruption in water service due to the long time required for the resin to cure.

SECTION 4) SUMMARY OF COMMON THEMES

ONE OF THE most important lessons learned from the WRF research on lead and copper corrosion is that every utility's lead and copper corrosion challenges are unique to its source water quality, treatment processes, distribution system configuration, and materials. There is no standard recipe for lead and copper corrosion control that every utility can apply for corrosion control strategies or distribution system management. Below are some lessons learned from this body of research that do apply to most or all drinking water utilities, and that can be helpful in addressing lead and copper corrosion issues.

General Overview

- Stand-alone monitoring stations can help predict lead and copper release trends at the tap and water quality impacts on metal release. However, the metal concentrations from pipe rigs or monitoring stations may not represent the actual concentrations at the tap due to variation in pipe materials and configurations.
- The Simultaneous Compliance Tool (SCTool) is intended to assist utilities in evaluating appropriate technology

choices to comply with multiple and/or conflicting water quality goals.

- Test results showed that indirect and direct methods can differentiate between various service line materials (lead, copper, and galvanized iron pipes).

Corrosion Control Effects on Water Quality and Corrosion

- With phosphate-based and carbonate-based passivating barriers, it can be difficult to form a uniform barrier against metal surfaces where other chemical scales and biofilms are also forming and to compete with the other influencing factors.
- It should never be assumed that using orthophosphate provides guaranteed protection from exposure to lead or copper for consumers.
- If contemplating using a phosphate-based corrosion control chemical, begin a dialogue with the associated wastewater treatment facility personnel.
- For general corrosion of lead and copper in most locations, there does not appear to be a significant difference in performance between zinc orthophosphate and non-zinc orthophosphate. Addition of a zinc containing corrosion inhibiting compound is beneficial in reducing cement degradation and aluminum release to water when treated water is low in calcium and alkalinity. Bench-scale and/or pilot studies should be conducted to determine if zinc addition is beneficial for a specific water quality condition and pipe material.
- Utilities considering use of stannous chloride for lead corrosion control should proceed slowly and with caution. Coupon and possibly pipe loop studies are recommended to evaluate whether the chemical might be effective for the given water quality conditions.
- Most negative water quality impacts occur when the distribution system water quality is unstable, either because of multiple finished water quality changes over short periods of time or because of wide fluctuations in pH levels in the distribution system.
- To minimize adverse water quality impacts, maintain a consistent distribution system pH with adequate buffering intensity. Distribution system pH changes that drop the pH by greater than 0.5 units, even for brief periods, can disrupt the effective passivation of corrosion surfaces, especially on brass and lead/tin solder surfaces.
- Utilities should make incremental changes to finished water quality during start up to avoid exposing the distribution system to abrupt changes. It is also advisable to avoid making other treatment changes during start up (i.e., changing disinfectants, changing coagulants, or adding new treatment processes).
- When using orthophosphate inhibitors, maintain adequate residuals in the distribution system and apply

those inhibitors at the pH range that is optimal for lead and copper control (7.3 to 7.8).

- Look to other similar utilities' experiences concerning corrosion control. The report, *A General Framework for Corrosion Control Based on Utility Experience* (AwwaRF #90712B, 1997), provides a compilation of utility experiences with mitigation of lead and copper corrosion byproduct release under the LCR. The report also references a 1995 WITAF database that provides a compilation of utility experiences that allows utilities to compare their own experiences with those of other water utilities with similar water qualities.
- In general, copper corrosion control is easier to achieve than lead release control. Copper corrosion is almost exclusively chemical, while lead release is governed by a combination of chemical, hydraulic, and other mechanical factors.
- *Post Optimization Lead and Copper Monitoring Strategies* (WRF #2679) outlines a monitoring program for drinking water utilities that have already achieved optimized corrosion control. The program includes a proposed in-home tap sampling protocol (number of sites to sample, number of samples per site, a quarterly evaluation period, site selection criteria, and data collection/analysis criteria) and statistical evaluation methodologies.

Treatment Process Effects on Lead and Copper Corrosion

- While the WRF body of research did not specifically investigate the effect on lead release of changing from chlorine to chloramines, it did look preliminarily at copper release. It was determined that residual concentrations of free chlorine are higher in systems that disinfect with combined chlorine (chloramines), as opposed to systems that disinfect with free chlorine alone. As a result, systems that convert to chloramines may experience higher rates of copper corrosion, depending on pH levels.
- CSMR can affect lead release. CSMR can be affected by road salt entering the water supply from runoff, coagulant type (chloride-based vs. sulfate-based), desalination, chloride-based anion exchange treatment, and brine leak from hypochlorite generation systems.
- Problems that occur in coagulant changeovers could usually be mitigated by controlling the type of coagulant and keeping CSMR below about 0.5. However, this is not always an option.
- Changing disinfectants can affect metals leaching from lead, brass, and copper components in the distribution system. Utilities should evaluate these potential metal release changes that might occur before fully implementing a disinfectant change.
- The effectiveness of corrosion control strategies will vary depending on the source water chemistry and the

composition of the pipe scales. Generally, less lead is released at higher pH values.

- Information on the specific water chemistry and corrosion products is valuable in predicting and controlling lead release from scales on lead service lines. When collecting samples for compliance with the LCR, utilities could gain insights into processes controlling lead concentrations by measuring pH, dissolved inorganic carbon concentrations or alkalinity, free and/or combined chlorine concentrations, and orthophosphate concentrations.
- Both chlorine and chloramines accelerate the corrosion of copper and its alloys at pH 6 but cause minimal corrosion at pH 8. In equal concentrations, free chlorine is slightly more corrosive than chloramines on copper and its alloys.
- In *Optimizing Chloramine Treatment, Second Edition* (AwwaRF #90993, 2004), the utilities surveyed did not experience any general trends of lead and copper corrosion issues with chloramine use. Through the literature review, the researchers found that many corrosion studies conducted on chlorinated and chloraminated water systems included evaluations of copper. However, very few rigorous studies exist that make a direct comparison of the corrosive effects of chlorine and chloramines.
- With enhanced coagulation, waters treated with alum are generally more aggressive towards copper than those treated with ferric chloride. The choice between using aluminum sulfate versus ferric chloride as coagulants is very important for corrosion control. Corrosion studies are imperative to determine whether the benefits, if any, would be worth the cost of changing coagulants.
- In waters with NOM in the typical range for surface source waters (1–4 mg/L), NOM removal by coagulation and/or adsorption causes little change in copper corrosion and release.
- Concrete corrosion can be an important concern in a utility's overall corrosion control strategy because concrete or cement-lined pipes make up over 50 percent of drinking water distribution system infrastructure in the United States. Prior to making any changes to corrosion control programs, utilities should consider undertaking bench-scale or pipe loop tests for baseline (control) in comparison to different corrosion inhibitors and pH/alkalinity adjustment conditions to confirm the results and develop corrosion control strategies that meet their goals. *Impact of Phosphate Corrosion Inhibitors on Cement-Based Pipes and Linings* (WRF #4033, 2009) presents a decision tree to provide utilities with a general direction on the type of inhibitors or corrosion control strategies that can be developed to avoid unintended consequences in the distribution system. This tool can also be used to evaluate the aggressiveness of a given water

condition towards concrete or cement-lined transmission and distribution main infrastructure.

- The AwwaRF pipe loop protocol (604) offers a practical, hands-on approach to evaluating lead and copper leaching characteristics in a flow-through system that simulates household plumbing. It is a useful tool for corrosion-rate studies and determinations of metals leaching for compliance with the LCR, but is expensive and time-consuming to use.

Specific Water Chemistry Effects on Lead and Copper Corrosion

- The most common methods to minimize lead in drinking water are adjusting the water chemistry to produce stable water quality conditions that inhibit lead release, high velocity flushing (especially inside the home) to remove particulate lead, and removing service lines and plumbing materials that contain lead.
- Pipe loop rigs can complement LCR testing results, which largely depend on nuances of home plumbing systems beyond the control of water utilities. Pipe loop rigs may provide a more consistent measure of a water's corrosivity and a utility's corrosion control effectiveness. However, it is important to remember that lead and copper release data is intrinsically highly variable.
- PbO_2 can only form in the presence of free chlorine, and the threshold free chlorine concentration for producing PbO_2 is less than 4 mg Cl_2/L .
- The formation of PbO_2 is accelerated by the presence of dissolved inorganic carbon.
- Dissolved lead concentrations from equilibration of PbO_2 in water with free chlorine can be higher than predicted from published thermodynamic data.
- The dissolution rate and not the equilibrium solubility of PbO_2 will control dissolved lead concentrations in waters that are in contact with PbO_2 as a corrosion product for most relevant stagnation times.
- NSF 61 Section 9 test water was found to be the most appropriate condition for certification of Section 9 products for lead release regardless of disinfection type (chlorine, chloramine).
- NSF 61 Section 8 testing protocols that incorporate chloramines, or dual evaluation of chlorinated and chloraminated exposure waters, will likely not be more predictive of extraction of lead from Section 8 products than testing with a chlorinated extraction water alone.
- A wide range of chemical and physical factors can influence copper pitting and brass dezincification. Temperature and physical exposure conditions can affect other types of brass corrosion.
- Lead oxide is relatively unstable in water. It is reduced to Pb(II) by the water itself, but only very slowly at, or near, neutral pH values. It is also reduced by NOM.

Pre-oxidizing, or removing, NOM should reduce the potential for lead release from lead oxide.

- Utilities delivering water of high alkalinity (>100 mg/L as CaCO₃) and low pH (<7.7) can expect a high likelihood of problems with copper corrosion. A small pH increase to about 8.0 may alleviate or eliminate copper corrosion problems. On-site corrosion studies can help to accurately define the pH increase necessary to gain the desired benefits of a pH change.
- The presence of NOM may be a major factor affecting the release of lead from lead pipe, lead-tin solder, and leaded brass or bronze. The adverse effects of NOM are exacerbated in low-pH, low-alkalinity waters.
- While customer premise plumbing is not in the jurisdiction of local utilities, utilities need to be aware of the extent and possible causes of copper pitting in the communities they serve. *Assessment of Non-Uniform Corrosion in Copper Piping* (AwwaRF #3015, 2008) developed a protocol to help utilities assess the extent of pinhole leaks in their communities. Three water chemistry and microbiological factors show strong links to non-uniform copper corrosion and pinhole leaks in customer premise plumbing:
 - high pH and high levels of disinfectant, exacerbated by aluminum and other particles
 - local production of H₂S in and around pits by sulfate reducing bacteria (SRB)
 - erosion corrosion in hot water recirculation systems
 Of course, there are other factors believed to influence copper pitting corrosion, and further research is needed to identify and confirm those.
- Utilities should not rely on electrochemical monitoring techniques (corrosion potential, electrochemical noise, etc.) to predict the pitting propensity of copper tubing in the distribution system or customer premises. Each of the corrosion monitoring techniques selected for study in *Non-Uniform Corrosion in Copper Piping – Monitoring Techniques* (WRF #3109, 2009) were found to be highly imperfect and of limited value.

Material Effects on Lead and Copper Release

- Three technologies are deemed to be especially promising for lead service line lining/coating and are therefore recommended for consideration by both public water systems and property owners: PET lining, epoxy coating, and polyurea/polyurethane coating. Each can effectively reduce or eliminate lead release, is commercially available, and is, or has been, certified for use in contact with potable water in the United States, Canada, and/or the UK. Public water systems and property owners are encouraged to evaluate their use, to the extent permitted by applicable regulations, in situations where significant cost savings and/or other benefits can be realized; and, where applicable, to incorporate their use into

well-organized, system-wide LSLR programs to help minimize costs and maximize benefits.

- When alternative (i.e., different than first liter) lead sampling strategies were analyzed, no sampling method was particularly proficient at finding the peak lead level compared to doing a full profile for each sampling event.
- Many non-leaded brasses are suitable for use in drinking water. Long-term water quality tests are recommended for potentially corrosive water and to confirm the performance of the provided materials.
- Galvanic corrosion can lead to elevated lead levels at the tap. Lab, pilot, and field experiments exhibited variability in the duration and concentration of lead levels. However, lead levels typically dropped to stable lower values in approximately four to ten months.
- Non-conductive plastic couplings always released less lead than the conductive metal couplings. Consideration should be given to use of non-conductive couplings where partial LSLRs must be undertaken. If a plastic coupling is used, it is recommended that a plastic spacer be inserted in the center of the assembly to assure that there is no contact between the two pipes. If a dielectric or plastic coupling is used, consideration will have to be given to alternative means of grounding the household electrical wiring system.
- No one factor can be identified as the sole cause of elevated copper concentrations in tap water. Water quality, stray current, electrical transients (i.e., lightning), fixtures, and construction practices were all identified as possible contributors to copper concentrations.
- Some point of use water filters are effective at removing dissolved and particulate metals. If the volume of flow can be determined, the filters do provide accurate estimates of potential exposure to contaminants in drinking water.
- Using carbon filters as composite samplers to measure the total amount of lead and copper released to the tap can be accomplished, but several issues with the filters need to be better defined before this can become a practical technique.
- The most effective way to reduce the total mass of lead measured at the tap is to replace the entire lead service line, followed by replacing lead sources in the premise plumbing, the faucet, and then the meter. Replacement of faucets and end-use fittings may or may not improve lead levels at the tap; however, it may be appropriate at sites without lead service lines that experience elevated lead levels in first-draw samples. Elevated lead levels may occur immediately after lead source replacement and may persist for longer periods, dependent on the materials and water quality at each site, and the amount of disturbance during replacement.
- Corrosion control is still the best and most cost-effective way to comply with the requirements of the LCR.

However, the customer's portion of the lead service line—which is beyond the jurisdiction of local water utilities—remains an important unresolved source of lead.

- New plumbing systems can contribute to lead and copper corrosion and cause aesthetic problems. Flushing of ASTM B813 compliant flux and metallic debris can be accomplished using water at or above 3.6 fps; however, petroleum-based flux cannot be flushed from plumbing systems with ambient temperature water, which can create long-term problems. One time 50 to 200 mg/L shock chlorination does not seriously damage plastic piping or copper tube; however, repeated shock chlorination events are not recommended because significant deterioration may occur.
- New non-lead brass materials (0.1–0.25 percent lead by weight) are commercially available to help get the lead out of drinking water systems. While these materials show promise for helping utilities to comply with the LCR, these materials are relatively new and there are questions about the short- and long-term performance of these materials that need to be researched. *Performance and Metal Release of Non-Leaded Brass Meters and Fixtures* (AwwaRF #3112, 2007) includes a series of summary papers that describe what the drinking water industry currently knows about the performance of these materials, and it provides a research agenda to investigate the knowledge gaps about the use of these materials.
- The LCR requires that a water system that exceeds the 90th percentile action level for lead after installing optional corrosion control and source water treatment replace lead service lines that contribute more than 0.105 mg/L to total standing tap water lead levels. *Lead Pipe Rehabilitation and Replacement Technologies* (AwwaRF #465, 2000) is a tool for assessing and selecting lead pipe rehabilitation and replacement techniques to meet this requirement.



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