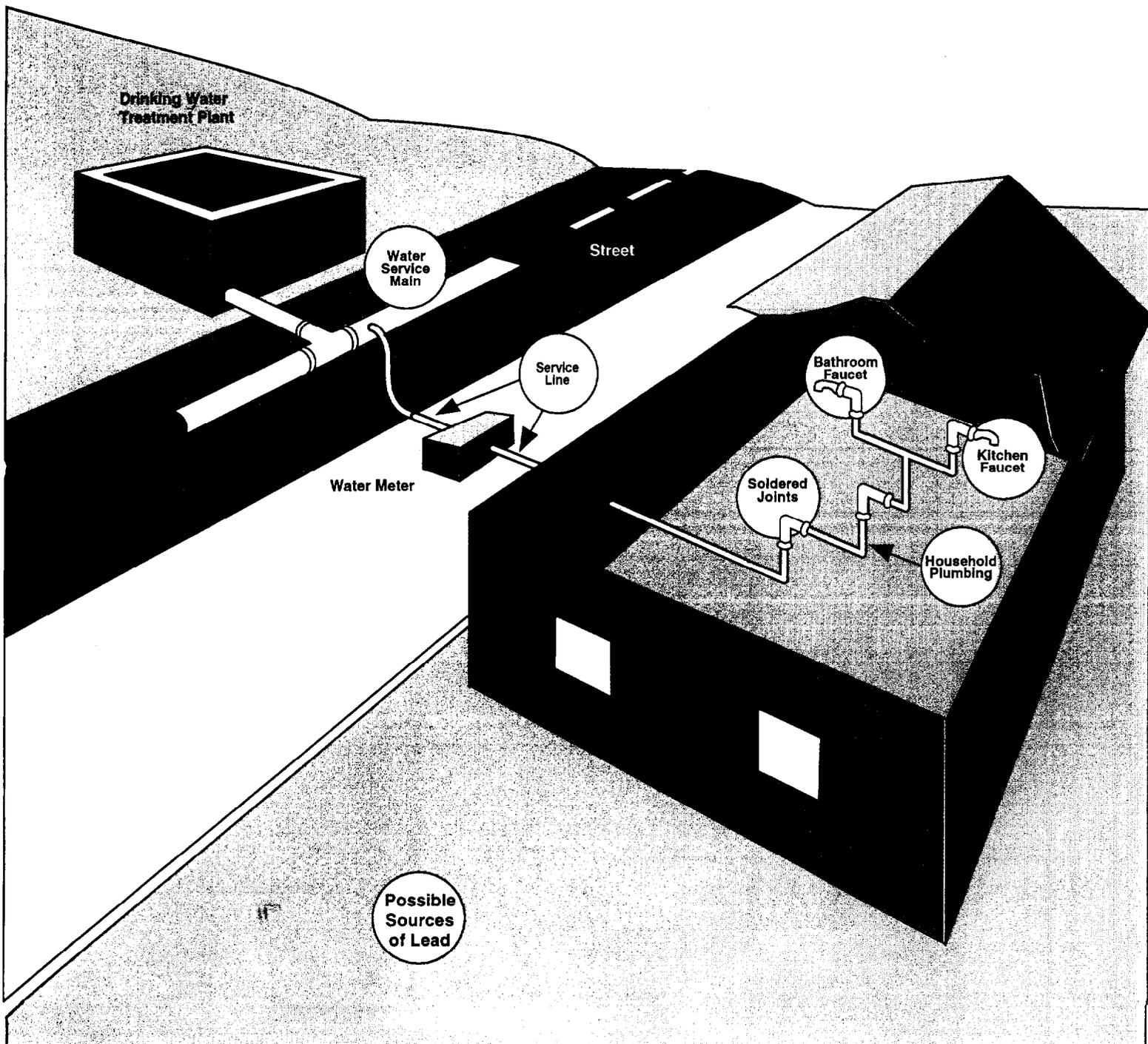




Seminar Publication

Control of Lead and Copper in Drinking Water



Seminar Publication:

**Control of Lead and Copper in
Drinking Water**

Office of Research and Development
Washington, DC 20460

Notice

This document has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for publication. The mention of trade names, commercial products, or services does not convey, and should not be interpreted as conveying, official EPA approval, endorsement, or recommendation.

Acknowledgments

This document is based in part on presentations made at the September 1991 U.S. Environmental Protection Agency/American Water Works Association National Workshop on Lead and Copper in Drinking Water. The agenda and names of presenters from the Workshop are listed in Appendix A. Appreciation is expressed to those individuals for making presentations and providing written materials for the Workshop and for this document, and to EPA Region 5 and Jon DeBoer of the American Water Works Association for their work in arranging the Workshop. Appreciation is expressed to the following individuals for contributing their work to this publication:

| | | |
|---------------|--|---|
| Chapter One | 1.1 | Jeff Cohen, U.S. Environmental Protection Agency |
| | 1.2 | William Parrish, Maryland Department of the Environment |
| Chapter Two | | Vernon Snoeyink, University of Illinois |
| Chapter Three | 3.1 | William Richards, Roy F. Weston, Inc. |
| | 3.2 | Jack Dice, Denver, Colorado Water Department |
| | 3.3 | Douglas Neden, Greater Vancouver Regional District |
| | 3.4 | Jack DeMarco, Cincinnati Water Works |
| | 3.5 | Thomas Bailey, Durham, North Carolina Department of Water Resources |
| Chapter Four | 4.1 | Michelle Frey and Leland Harms, Black & Veatch, Inc. |
| | 4.2 | Chester Neff, Kent Smothers, Mark Brooks, and Mark Warnock, Illinois State Water Survey |
| | 4.3 | Anne Sandvig and Boris Prokop, Economic and Engineering Services, Inc. |
| | 4.3 | Michael Schock, U.S. Environmental Protection Agency |
| | 4.4 | Steve Reiber, University of North Carolina at Charlotte |
| Chapter Five | 5.1 | Michael Schock, U.S. Environmental Protection Agency |
| | 5.2 | Richard Moser, American Water Works Service Company, Inc. |
| | 5.3 | Jonathan Clement, Black & Veatch, Inc. |
| | 5.4 | Albert Ilges, Champlain, Vermont Water District |
| | 5.5 | John Allen, Chippewa Falls, Wisconsin |
| | 5.5 | William Barry, Ayres Associates |
| | 5.6 | Thomas Sorg, Michael Schock, and Darren Lytle, U.S. Environmental Protection Agency |
| 5.7 | Rita Gergely, Iowa Department of Public Health | |

Appreciation is expressed to the following individuals for providing guidance, review, and/or helpful suggestions for this document: Ronnie Levin, Michael Schock, and Thomas Sorg, all of the U.S. Environmental Protection Agency.

Dr. James E. Smith, Jr. of EPA's Center for Environmental Research Information managed the preparation of this document, with assistance from Richard Scharp. Jennifer Helmick and other staff members of Eastern Research Group, Inc. provided overall editing and document preparation. Jonathan A. Clement of Black & Veatch, Inc. served as technical editor.

Contents

| | |
|--|-----------|
| Introduction | xiii |
| Chapter 1 Regulatory Issues..... | 1 |
| 1.1 EPA's New National Primary Drinking Water Regulation for Lead and Copper | 1 |
| 1.1.1 Introduction | 1 |
| 1.1.2 Tap Water Monitoring for Lead and Copper | 1 |
| 1.1.3 Monitoring for Water Quality Parameters | 1 |
| 1.1.4 Corrosion Control Optimization..... | 2 |
| 1.1.5 Source Water Treatment | 2 |
| 1.1.6 Public Education | 2 |
| 1.1.7 Lead Service Line Replacement..... | 5 |
| 1.1.8 Regulatory Schedule..... | 5 |
| 1.1.9 Impacts of the Lead and Copper Rule..... | 5 |
| 1.2 A Smaller State's Perspective..... | 5 |
| Chapter 2 Corrosion Characteristics of Materials | 9 |
| 2.1 The Corrosion Cell | 9 |
| 2.2 Uniform Corrosion and Pitting | 10 |
| 2.3 Passivation..... | 10 |
| 2.4 Galvanic Corrosion..... | 10 |
| 2.5 Corrosion Rate vs. Metal Uptake..... | 12 |
| Chapter 3 Monitoring Design and Implementation..... | 13 |
| 3.1 Characterizing the System: Baseline Monitoring | 13 |
| 3.1.1 Introduction..... | 13 |
| 3.1.2 Characterizing the Water System..... | 13 |
| 3.1.3 The Materials Survey | 14 |
| 3.1.4 Information Sources | 14 |
| 3.1.5 Conclusions..... | 15 |
| 3.2 Selection of an Analytical Laboratory..... | 15 |
| 3.2.1 Introduction..... | 15 |
| 3.2.2 The Regulation | 15 |
| 3.2.3 Decision Time | 15 |
| 3.2.4 Selection Criteria..... | 17 |
| 3.2.5 Conclusions..... | 17 |
| 3.3 "At the Tap" Monitoring | 17 |
| 3.3.1 Materials Surveys and Site Selections..... | 17 |
| 3.3.2 Sample Collection..... | 18 |
| 3.3.3 Other Water Quality Parameters..... | 18 |
| 3.3.4 Case Study One—Greater Vancouver Water District Experience..... | 18 |
| 3.4 Monitoring Program Design Using Utility Employees and Customers..... | 18 |
| 3.4.1 Introduction..... | 18 |
| 3.4.2 Case Study Two—The Cincinnati Water Works System | 19 |
| 3.5 Integrating Water Testing and Occupancy Certification | 22 |
| 3.5.1 Case Study Three—Durham, North Carolina | 22 |
| Chapter 4 Corrosion Control Assessment | 27 |
| 4.1 Basics of a Corrosion Control Study..... | 27 |
| 4.1.1 Regulatory Requirements | 27 |

| | |
|---|-----------|
| 4.1.2 Study Components | 27 |
| 4.1.3 Desktop Evaluations | 29 |
| 4.1.4 Corrosion Study Organization | 36 |
| 4.1.5 Demonstration Testing | 36 |
| 4.1.6 Data Handling and Analysis | 40 |
| 4.1.7 Secondary Testing Programs | 40 |
| 4.1.8 Quality Assurance/ Quality Control Programs | 40 |
| 4.1.9 Example of Selecting Optimal Treatment | 41 |
| 4.1.10 Example of a Flow-Through Demonstration Testing Program | 41 |
| 4.2 Design Considerations and Procedures for Coupon Tests | 43 |
| 4.2.1 Summary of Method | 43 |
| 4.2.2 Basic Corrosion Measurement Considerations | 44 |
| 4.2.3 Purchasing and Preparation of Corrosion Specimens | 44 |
| 4.2.4 Duration Guidelines for Corrosion Studies | 45 |
| 4.2.5 Processing of Corroded Specimens | 47 |
| 4.2.6 Chemical Cleaning Procedures | 47 |
| 4.2.7 Evaluation of Localized Corrosion | 48 |
| 4.2.8 The Corrosion Rate Calculation | 48 |
| 4.2.9 Interpretation of the Corrosion Data | 48 |
| 4.2.10 Summary | 50 |
| 4.3 Design Considerations for Pipe Loop Testing | 50 |
| 4.3.1 Introduction | 50 |
| 4.3.2 Pipe Loop Design and Construction Considerations | 50 |
| 4.3.3 Pipe Loop Operational Considerations | 51 |
| 4.3.4 Characteristics of Pipe Loop Data | 52 |
| 4.3.5 Data Evaluation Considerations | 52 |
| 4.4 Electrochemical Methodologies for Corrosion Measurement in the Distribution System | 52 |
| 4.4.1 Polarization Techniques | 53 |
| 4.4.2 Electrical Resistance and Electrochemical Noise | 54 |
| 4.4.3 Summary | 54 |
| 4.5 References | 54 |
| Chapter 5 Control Strategies | 57 |
| 5.1 Overview of Control Strategies for Lead in Drinking Water | 57 |
| 5.1.1 Chemical Treatment Strategies | 57 |
| 5.1.2 Selection Criteria | 63 |
| 5.1.3 Treatment Chemicals | 64 |
| 5.1.4 Summary | 65 |
| 5.2 Secondary Effects and Conflicts with Lead Corrosion Control Strategies | 66 |
| 5.2.1 Carbonate Passivation | 66 |
| 5.2.2 Corrosion Inhibitors | 67 |
| 5.2.3 Materials | 68 |
| 5.2.4 Conclusions | 68 |
| 5.3 Full-Scale Performance Testing of Sodium Silicate to Control the Corrosion of Lead, Copper, and Iron: York, Maine | 68 |
| 5.3.1 Introduction | 68 |
| 5.3.2 Findings | 69 |
| 5.3.3 Recommendations | 69 |
| 5.3.4 Methodology | 70 |
| 5.3.5 Results and Discussion | 71 |
| 5.4 Assessing Zinc Orthophosphate vs. pH Adjustment: Champlain, Vermont | 74 |
| 5.4.1 Introduction | 74 |
| 5.4.2 Materials and Methods | 75 |
| 5.4.3 Results | 79 |
| 5.4.4 Discussion | 80 |
| 5.4.5 Conclusions | 83 |
| 5.4.6 Recommendations | 83 |
| 5.5 Reducing Corrosion Products in Municipal Water Supplies: Chippewa Falls, Wisconsin | 83 |
| 5.5.1 Background | 83 |
| 5.5.2 Water System | 84 |
| 5.5.3 Regulations | 84 |

| | |
|---|-----|
| 5.5.4 Hot Water Flushing | 84 |
| 5.5.5 Aging of Service Pipe | 86 |
| 5.5.6 Chemical Stabilization | 86 |
| 5.5.7 Administrative Order | 86 |
| 5.5.8 Referendum | 86 |
| 5.5.9 Legal Action | 87 |
| 5.5.10 Pilot Study | 87 |
| 5.5.11 Goals of the Pilot Study | 87 |
| 5.5.12 Implementation of the Pilot Study | 89 |
| 5.5.13 Decision to Treat | 89 |
| 5.5.14 Implementation of Central Treatment | 89 |
| 5.5.15 Facilities Constructed | 90 |
| 5.5.16 Monitoring | 90 |
| 5.5.17 Sampling Protocol | 91 |
| 5.5.18 Feed Rates | 93 |
| 5.5.19 Operation and Maintenance Costs | 93 |
| 5.6 Evaluating a Chemical Treatment Program to Reduce Lead in a Building: A Case Study | 94 |
| 5.7 Iowa's Lead in Schools' Drinking Water Program: More Than Just a Monitoring Program | 97 |
| 5.7.1 Introduction | 97 |
| 5.7.2 Requirements of the LCCA | 97 |
| 5.7.3 More Than a Monitoring Program | 98 |
| 5.7.4 Implementation in Iowa: Monitoring Results | 98 |
| 5.7.5 Implementation in Iowa: Technical Assistance Program | 98 |
| 5.7.6 Test Results from Iowa's Program | 98 |
| 5.7.7 Example of a Solution: Finding a Solution for New Hampton High School | 99 |
| 5.7.8 General Observations from Investigations | 100 |
| 5.8 References | 100 |
| Appendix A Workshop Agenda: EPA/AWWA National Workshop on Control of Lead and Copper in Drinking Water | 103 |
| Appendix B Units and Conversions | 105 |

Figures

| Number | | Page |
|--------|--|------|
| 1-1 | Tap water monitoring (lead and copper)..... | 2 |
| 1-2 | Monitoring for water quality parameters | 2 |
| 1-3 | Implementation pathways for large public water systems | 3 |
| 1-4. | Implementation pathway for medium-sized and small public water systems..... | 4 |
| 1-5 | Regulatory schedules for large, medium-sized, and small systems..... | 6 |
| 2-2 | Typical anodic (a) and cathodic (b) reactions..... | 9 |
| 2-1 | A diagram of the corrosion cell..... | 9 |
| 2-4 | Corrosion rate as a function of time | 11 |
| 2-5 | Scale composition on the surface of iron pipe | 11 |
| 2-3 | The oxygen concentration cell (a) and pitting and tuberculation for iron pipe (b) | 11 |
| 2-6 | A micrograph of a cross-section of brass (x100)..... | 12 |
| 3-1 | Tier One sampling site requirements..... | 14 |
| 3-3 | Tier Three sampling site requirements | 14 |
| 3-2 | Tier Two sampling site requirements | 14 |
| 3-4 | Copper levels from the Greater Vancouver Water District monitoring program | 18 |
| 3-5 | Lead levels from the Greater Vancouver Water District monitoring program | 18 |
| 3-6 | Cincinnati Water Works: Schematic of treatment system for the Ohio River supply (a) and lime softening treatment system for the ground water supply (b)..... | 19 |
| 3-7 | Percent of samples failing lead, copper, coliform, and standard plate count tests | 23 |
| 3-8 | Percent of samples failed for lead (a) and copper test (b)..... | 23 |
| 3-9 | Percent samples failed and passed for copper, coliform, and standard plate count tests..... | 24 |
| 3-10 | Number of samples exceeding 50 vs. 15 µg/L..... | 25 |
| 4-1 | Logic diagram for evaluating alternative corrosion control approaches | 30 |
| 4-2 | Suggested corrosion control approaches based on water quality characteristics | 32 |
| 4-3 | Conceptual layout of flow-through testing schemes | 37 |
| 4-4 | Reduction in metal concentrations (a) and coupon weight-loss (b) by alternative treatments | 41 |
| 4-5 | Corrosion specimen data form..... | 46 |
| 4-6 | Planned-interval pipe insert exposure during EPA/ISWS corrosion study | 49 |
| 4-7 | Corrosion of galvanized steel specimens at Site 302..... | 49 |
| 4-8 | Corrosion of copper specimens at Site 307 | 49 |
| 4-9 | Effect of water corrosivity on galvanized steel | 50 |
| 5-1 | Stagnation lead levels..... | 58 |
| 5-2 | Alkalinity/DIC relationships | 58 |
| 5-4 | Lead speciation for 25°C, I = 0.01, DIC = 50 mg/L..... | 60 |
| 5-3 | Lead speciation for 25°C, ionic strength (I) = 0.01, dissolved inorganic carbonate (DIC) = 3 mg/L | 60 |
| 5-5 | Lead solubility (I = 0.01, 25°C) | 60 |
| 5-6 | Variation in lead solubility (pH 7.0) as a function of orthophosphate dosage for different alkalinities | 61 |
| 5-7 | Variation in lead solubility (pH 7.5) as a function of orthophosphate dosage for different alkalinities | 61 |
| 5-8 | Variation in lead solubility (pH 8.0) as a function of orthophosphate dosage for different alkalinities | 61 |
| 5-9 | Zinc solubility (I = 0.01)..... | 62 |
| 5-10 | Zinc solubility (pH 7.5, I = 0.01, 25°C)..... | 62 |
| 5-11 | Path of lead response to treatment changes | 65 |

| Number | | Page |
|--------|---|------|
| 5-12a | Distribution of HOCl and OCl ⁻ in water as a function of pH | 66 |
| 5-12b | Effects of pH and oxidant dosage on the formation of TOX and THMs (CHCl ₃) at 20°C in distilled water solutions of 5 mg humic acid/L | 67 |
| 5-13 | Corrosion rate vs. pH, 114-hour laboratory test with aerated tap water | 67 |
| 5-14 | Tricalcium phosphate saturation..... | 68 |
| 5-15 | Map of the York Water District distribution system..... | 71 |
| 5-16 | Temperature of the filtration plant finished water (a) and monthly water production (b) | 72 |
| 5-17 | Average monthly silica dosages and raw water silica concentrations | 72 |
| 5-18 | Average pH (a) and alkalinity (b) from the distribution sampling events..... | 72 |
| 5-19 | Silica concentrations from selected sites within the distribution system (a) and in first- and second-draw samples (b) | 73 |
| 5-20 | Average lead concentrations in the first-draw samples (a) and the number of samples exceeding specified concentrations in first-draw samples (b) | 73 |
| 5-22 | Average copper concentrations in the first-draw samples..... | 74 |
| 5-21 | Average iron concentrations in the first- and second-draw samples | 74 |
| 5-23 | Coupon studies on corrosion rates in four cell units | 76 |
| 5-24 | Comparison of municipal and regional water treatment using the same source waters (Lake Champlain, Vermont) | 77 |
| 5-25 | Schematic of Champlain Water District water treatment process..... | 78 |
| 5-26 | Champlain Water District laboratory coupon procedure change (06/01/89) | 78 |
| 5-27 | Well locations, Chippewa Falls, Wisconsin..... | 85 |
| 5-28 | Pilot test area, Chippewa Falls, Wisconsin | 88 |
| 5-29 | pH, copper, and lead at the 461 A Street copper services during pilot study | 89 |
| 5-30 | pH, iron, and zinc at the 467 Chippewa Street galvanized service | 89 |
| 5-31 | Lead levels in samples collected at 1301 Waldheim Road..... | 91 |
| 5-32 | Copper levels in samples collected at 1301 Waldheim Road..... | 91 |
| 5-33 | pH, lead, and copper at 1301 Waldheim Road | 92 |
| 5-34 | pH, lead, and copper at 43-45 Stump Lake Road | 92 |
| 5-35 | Annual operation and maintenance costs for the chemical feed system | 93 |
| 5-36 | Cost of caustic soda per anhydrous ton..... | 93 |
| 5-37 | Lead (a) and zinc (b) concentrations in samples collected sequentially (Room 3329)..... | 95 |
| 5-38 | Lead (a) and zinc (b) concentrations in samples collected sequentially (Room 1618)..... | 95 |
| 5-39 | Water usage study—lead concentrations over time in Room G402..... | 96 |
| 5-40 | Water usage study—lead concentrations over time in Room 3325 | 96 |
| 5-41 | Water usage study—average lead concentrations from the ground floor..... | 96 |
| 5-42 | Water usage study—average lead concentrations from the third floor | 97 |
| 5-43 | Water usage study—number of samples with less than 50 µg/l and 15 µg/l lead from the ground floor..... | 97 |
| 5-44 | Water usage study—number of samples with less than 50 µg/l and 15 µg/l lead from the third floor..... | 97 |

Tables

| Number | | Page |
|--------|--|------|
| 2-1 | Examples of Galvanic Corrosion | 10 |
| 3-1 | Analytical Methods | 16 |
| 3-2 | Water Main Materials | 19 |
| 3-3 | Joint Materials | 20 |
| 3-4 | Service Branch Materials | 20 |
| 3-5 | Lead Levels in First-Draw Samples as Part of Employee Monitoring Program | 20 |
| 3-6 | Outline for Implementation | 21 |
| 3-7 | Lead and Copper List of Monitoring Questions for Ohio EPA | 21 |
| 3-8 | Lead Concentrations in Samples Collected as Part of Durham Lead Survey | 22 |
| 4-1 | Recommended Corrosion Control Study Components for Large PWSs Based on Lead Levels | 28 |
| 4-2 | Source Water Treatment Guidelines | 29 |
| 4-3 | Schedule of Drinking Water Regulatory Activity: 1990–2000 | 34 |
| 4-4a | Constraints Worksheet for pH/Alkalinity or Calcium Adjustment Treatment Alternatives | 35 |
| 4-4b | Constraints Worksheet for Inhibitor Treatment Alternatives | 35 |
| 4-5 | Organization of the Major Components in Corrosion Control Studies | 36 |
| 4-6 | Pipe Volumes by Tubing Length and Diameter | 39 |
| 4-7 | Corrosion Control Treatment Performance Ranking Matrix | 42 |
| 4-8 | Final Corrosion Control Treatment Selection Matrix | 42 |
| 4-9 | Lead Concentrations from Pipe Loop Testing | 42 |
| 4-10 | Skewness Coefficients for Lead Data | 43 |
| 4-11 | Calculated Student's t Values | 43 |
| 4-12 | Suppliers of Corrosion Specimens and Pipe Loops | 44 |
| 4-13 | Typical Coupon and Pipe Loop Costs | 45 |
| 4-14 | Typical Corrosion Rates for Pipe Inserts in Illinois Waters | 45 |
| 4-15 | Density of Selected Metals | 48 |
| 4-16 | Significance of Coupon Weight Loss Measurements | 49 |
| 5-1 | Langelier Index (LI) vs. Calcium Carbonate Precipitation Potential (CCPP) | 59 |
| 5-2 | Average Finished Water Quality Summary | 71 |
| 5-3 | Corrosion Rate Reductions of Laboratory Steel Coupons 84 days exposure time | 79 |
| 5-4 | Corrosion Rate Reductions of Laboratory Lead Coupons 84 days exposure time | 79 |
| 5-5 | Corrosion Rate Reductions for the Distribution System Steel Coupons | 79 |
| 5-6 | Corrosion Rate Reductions for the Distribution System Lead Coupons | 79 |
| 5-7 | Lead Concentrations in Sequential Samples | 80 |
| 5-8 | Average Lead Concentrations at Consumer Taps Conc. $\mu\text{g/L}$ (number of samples) | 82 |
| 5-9 | Hot Water (140°F) Flushing Results (lead in $\mu\text{g/L}$) | 86 |
| 5-10 | Construction Costs | 90 |
| 5-11 | Lead Levels in the Samples Collected at 1301 Waldheim Road ($\mu\text{g/L}$) | 91 |
| 5-12 | Lead and Copper Levels in the Samples Collected at 1301 Waldheim Road | 91 |
| 5-13 | Lead and Copper Levels in Samples Collected at 47 Stump Lake Road | 91 |
| 5-14 | Lead and Copper Levels in Samples Collected at 1100 West River Street | 91 |
| 5-15 | Chemical Feed Rates of Caustic Soda | 93 |
| 5-16 | Annual Operation and Maintenance Costs | 93 |
| 5-17 | Caustic Soda Costs | 93 |
| 5-18 | Water Quality Characteristics | 94 |
| 5-19 | Lead Levels in Samples of Flushed and Static Water from Various Locations | 94 |
| 5-20 | Percentage of Lead in Solder Samples | 94 |

| Number | | Page |
|--------|--|------|
| 5-21 | Lead Baseline Data Collected at the Ground Floor and at the Third Floor | 96 |
| 5-22 | Summary of Lead Levels Found by Institutions..... | 99 |
| 5-23 | Number of Facilities Reporting Lead Levels Above 20 µg/L and the Highest Lead Levels Recorded from those Facilities | 99 |

Introduction

On September 23, 24, and 25, 1991, the U.S. Environmental Protection Agency (EPA) and the American Water Works Association (AWWA) held a national workshop on control of lead and copper in drinking water. The objectives of the workshop were to help participants:

- Become familiar with EPA's new national primary drinking water regulation for lead and copper and its anticipated impact on utilities.
- Learn investigative requirements and control strategies.
- Learn methodologies for implementation.
- Share field experience.
- Become familiar with laboratory and pilot testing procedures.

The workshop speakers included individuals from EPA, states, industry, academia, AWWA and the AWWA Research Foundation, consulting firms, and utilities. More than 300 participants heard presentations on regulatory issues, corrosion characteristics of materials, monitoring design and implementation, and control strategies (see Appendix A, Workshop Agenda). Two breakout sessions addressed design considerations and procedures for pipe loop and coupon testing. This

publication is based in part on the information presented at the 1991 national workshop, updated and supplemented with additional material.

How To Use This Document

Chapter One of this publication discusses *regulatory issues*, presenting both an overview of the new federal requirements and a state perspective on implementing these requirements. *Chapter Two* presents information about the *corrosion characteristics of materials*. *Chapter Three* discusses the design and implementation of a corrosion *monitoring* program. Topics include baseline monitoring, selecting an analytical laboratory, monitoring at the customer's tap, designing a monitoring program using utility employees and customers, and integrating water testing and occupancy certification. *Chapter Four* focuses on *corrosion control assessment*, including coupon tests, pipe loop tests, and electrochemical methodologies for corrosion measurement. Section 4.1, Basics of a Corrosion Control Study, presents recommendations for states and utilities for performing and evaluating corrosion control studies. Finally, corrosion control strategies are addressed in *Chapter Five*, which includes an overview of *control strategies* as well as secondary effects. Throughout, the document presents the experience of utilities in monitoring, assessment, and control strategies.

Chapter 1

Regulatory Issues

On June 7, 1991, EPA promulgated maximum contaminant level goals (MCLGs) and national primary drinking water regulations (NPDWRs) for lead and copper in drinking water. The MCLG for lead is zero, and the MCLG for copper is 1.3 milligrams per liter (mg/L). EPA promulgated an NPDWR for lead and copper consisting of a treatment technique requirement that includes corrosion control, source water treatment, lead service line replacement, and public education.

This chapter presents an overview of EPA's new NPDWR for lead and copper. In addition, it discusses implementation of the rule at the state level, from the perspective of the state of Maryland.

1.1 EPA's New National Primary Drinking Water Regulation for Lead and Copper

1.1.1 Introduction

EPA's final rule for lead and copper in drinking water (see *Federal Register*, June 7, 1991, 56 FR 26460) is part of a federal effort to reduce lead exposure from all sources. The rule was one of the most controversial regulations ever proposed by the Agency, receiving more than 3,000 comments. The final lead rule was developed through a cooperative effort by EPA's regulatory staff, the American Water Works Association (AWWA), and others. This process resulted in a regulation based on the practical realities faced by water utilities as well as the need to protect human health.

Although drinking water generally does not contain high concentrations of lead, it can be a source of lead to which a large number of people are exposed. In addition, recent scientific evidence shows that children, in particular, suffer adverse health effects from lower levels of lead exposure than previously thought harmful. The potential health effects of lead in children can include impaired mental development, reduced IQ, shortened attention span, diminished hearing, lowered birth weight, and altered heme synthesis and vitamin D metabolism. In adults, the health effects include increased blood pressure.

Because of these health effects, EPA has set an "action level" for lead in drinking water of 15 µg/L, measured at the 90th percentile (e.g., if there are 100 samples, no more than 10 may exceed the action level). In contrast, the maximum contaminant level (MCL) for lead (which was promulgated as an interim drinking water regulation in 1975 and was effective

until December 7, 1992) was 50 µg/L in samples obtained at the point of entry into the distribution system. The action level is not an enforceable standard, but it triggers corrosion control treatment. EPA also has set an action level for copper of 1.3 mg/L (also at the 90th percentile).

The final rule for lead and copper applies to community and nontransient, noncommunity systems. The rule includes requirements for tap water monitoring (lead and copper, water quality parameters), corrosion control optimization, source water treatment, public education, and replacement of lead service lines.

1.1.2 Tap Water Monitoring for Lead and Copper

The dates by which tap water monitoring for lead and copper must begin are shown in Figure 1-1(a); the number of sites required for additional monitoring are shown in Figure 1-1(b). If a system complies with the action levels, the state may reduce the monitoring requirements, as shown in Figure 1-1(c).

Targeted high-risk homes include those homes with lead solder installed after 1982, lead pipes, and lead service lines. A tiered approach, worked out between the system and the state, should be used to select the sample sites.

The samples should be first flush, 6-hour standing time, 1 liter. The system can furnish bottles to residents and train those residents to collect the samples. Acid preservative need not be added until the water sample reaches the laboratory. Acidification may be done up to 14 days after the sample is collected.

1.1.3 Monitoring for Water Quality Parameters

Systems serving more than 50,000 people, as well as small and medium-sized systems that exceed action levels, must monitor for water quality parameters to identify optimal treatment and to determine compliance. These parameters include pH, alkalinity, calcium, conductivity, orthophosphate (if used in treatment), silica (if used in treatment), and water temperature.

Figure 1-2(a) shows the number of samples required for initial monitoring of water quality parameters. Reduced monitoring, as shown in Figure 1-2(b), may be authorized by the state. The sampling site locations for water quality parameters may be different from those for lead and copper, but they should

(a) Start Dates for Monitoring

| System Size (Population) | Start Dates |
|--|--------------|
| Large Systems (more than 50,000) | January 1992 |
| Medium-Sized Systems (3,301 to 50,000) | July 1992 |
| Small Systems (3,300 or fewer) | July 1993 |

(b) Initial Monitoring (Samples collected every 6 months.)

| System Size (Population) | Number of Sampling Sites |
|--------------------------|--------------------------|
| More than 100,000 | 100 |
| 10,001 to 100,000 | 60 |
| 3,301 to 10,000 | 40 |
| 501 to 3,300 | 20 |
| 101 to 500 | 10 |
| 100 or fewer | 5 |

(c) Reduced Monitoring

| System Size (Population) | Number of Sampling Sites |
|--------------------------|--------------------------|
| More than 100,000 | 50 |
| 10,001 to 100,000 | 30 |
| 3,301 to 10,000 | 20 |
| 501 to 3,300 | 10 |
| 101 to 500 | 5 |
| 100 or fewer | 5 |

Figure 1-1. Tap water monitoring (lead and copper).

(a) Initial Monitoring (Two samples every 6 months.)

| System Size (Population) | Number of Tap Sampling Sites |
|--------------------------|------------------------------|
| More than 100,000 | 25 |
| 10,001 to 100,000 | 10 |
| 3,301 to 10,000 | 3 |
| 501 to 3,300 | 2 |
| 101 to 500 | 1 |
| 100 or fewer | 1 |

(b) Reduced Monitoring

| System Size (Population) | Number of Tap Sampling Sites |
|--------------------------|------------------------------|
| More than 100,000 | 10 |
| 10,001 to 100,000 | 7 |
| 3,301 to 10,000 | 3 |
| 501 to 3,300 | 2 |
| 101 to 500 | 1 |
| 100 or fewer | 1 |

Figure 1-2. Monitoring for water quality parameters.

be representative taps (e.g., they may be the same as those for coliform monitoring). In addition, one sample must be collected at every point of entry to the distribution system.

1.1.4 Corrosion Control Optimization

Optimal corrosion control treatment (required as shown in Figures 1-3 and 1-4) minimizes lead and copper in drinking water at the tap while ensuring that the system does not violate the NPDWRs. The system must identify constraints for different treatments and fully document its treatment recommendation. Elements of corrosion control optimization are:

- Laboratory study. A laboratory study is used to evaluate alternative treatments (e.g., pH and alkalinity adjustment, calcium adjustment, and use of corrosion inhibitors).
- Recommendation to the state.
- Treatment installation. After the system makes a recommendation, the state approves the recommendation or designates an alternative. The system has 24 months to install the treatment and 12 months for follow-up monitoring.
- Follow-up monitoring. Different tests are allowed (e.g., pipe loops, coupons, partial systems, and analyses based on analogous systems).
- State-specified operating parameters. These parameters (e.g., pH, alkalinity, calcium, orthophosphate, and silica) become compliance measures.
- Compliance with specified parameters.

1.1.5 Source Water Treatment

If the tap action level is exceeded, it becomes necessary to monitor for lead and copper in the source water. If the source water contains lead or copper, the water system must investigate treatment alternatives. The system makes a recommendation, and the state either approves the recommendation or designates an alternative course of action. Treatment alternatives for source water include ion exchange, reverse osmosis, lime softening, and coagulation/filtration. The system has 24 months to install the treatment system and 12 months for follow-up monitoring. The state designates the maximum permissible lead and copper concentrations for finished water entering the distribution system.

1.1.6 Public Education

EPA has developed a package of public education materials that the system must use if action levels are exceeded. This package provides the minimum materials for public education as specified in the rule: an introduction, information about health effects and sources of lead, and steps that can be taken at home to reduce lead levels in water. The system may add information to this package.

Public education program delivery must begin within 60 days after the lead action level is exceeded. Program delivery

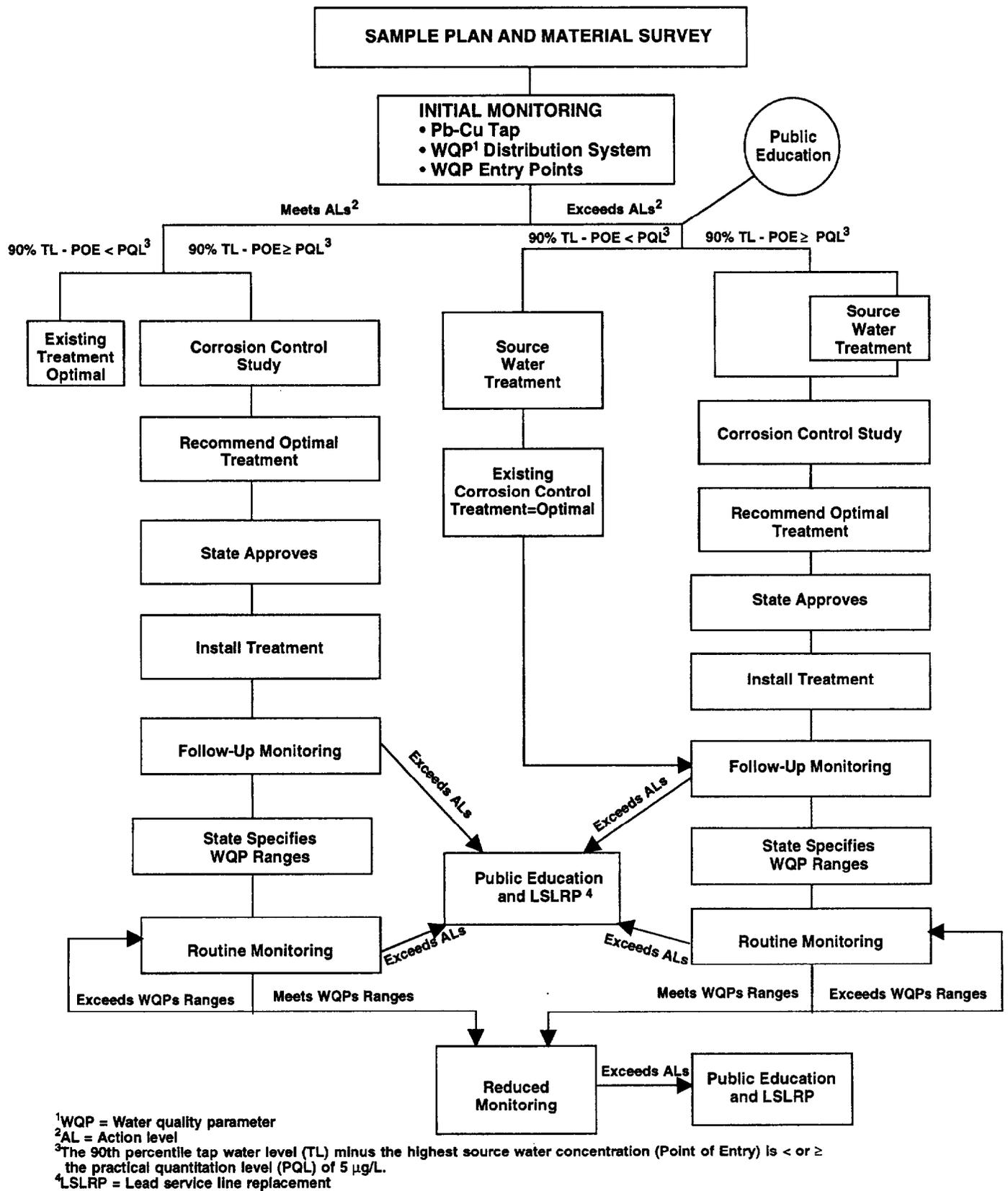
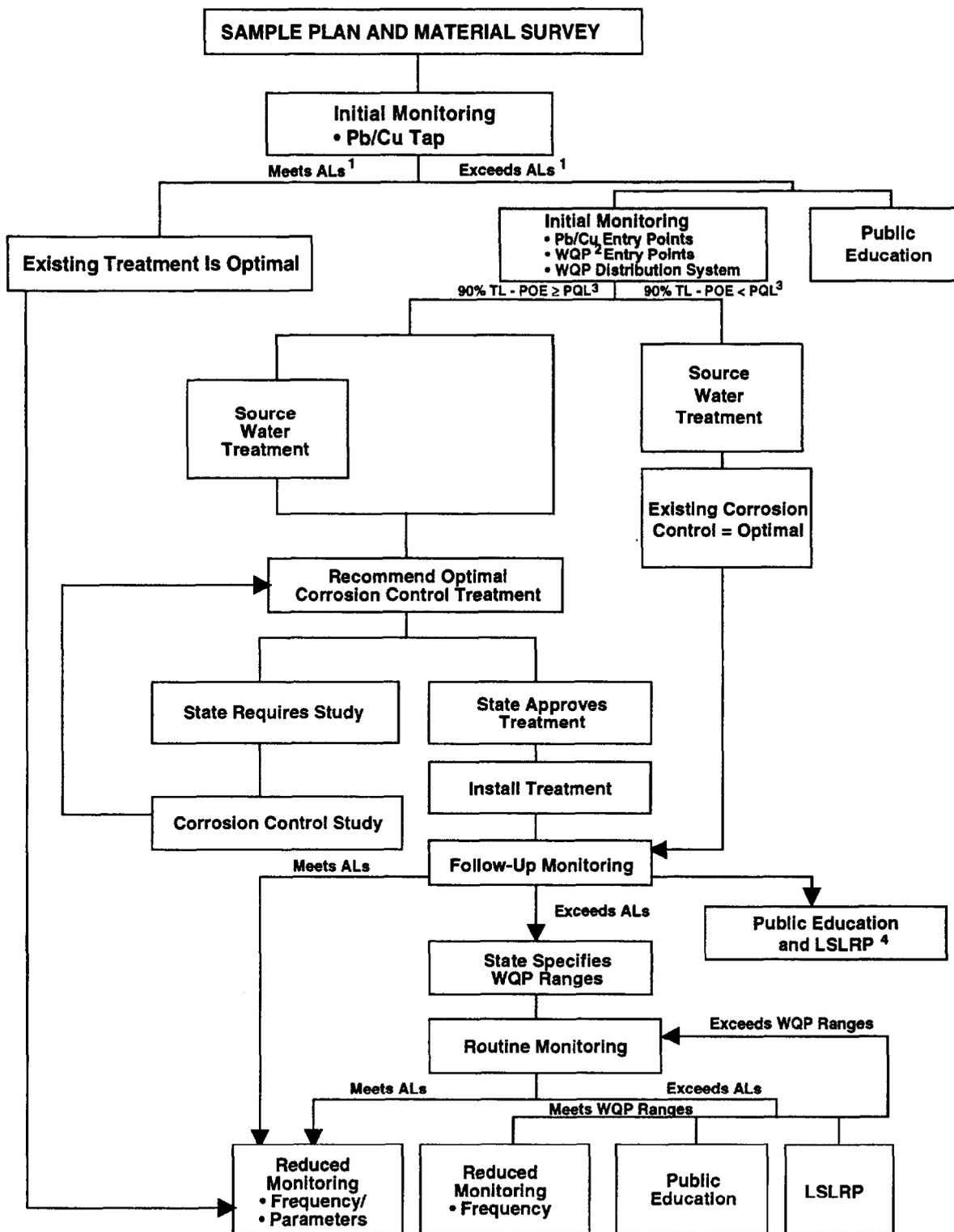


Figure 1-3. Implementation pathways for large public water systems.

Source: U.S. EPA, *Lead and Copper Rule Guidance Manual, Volume 2* (1992).



¹AL = Action level

²WQP = Water quality parameter

³The 90th percentile tap water level (TL) minus the highest source water concentration (Point of Entry) is < or ≥ the practical quantitation level (PQL) of 5 µg/L. A second round of Pb/Cu-Tap and Pb/Cu-POE would be required for this condition.

⁴LSLRP = Lead service line replacement

Figure 1-4. Implementation pathway for medium-sized and small public water systems.

Source: U.S. EPA, *Lead and Copper Rule Guidance Manual, Volume 2* (1992).

must include bill stuffers, pamphlets to selected groups (such as pediatricians), notices to major newspapers, and public service announcements (PSAs) to local radio and television stations. These must be delivered every 12 months for as long as the lead action level is exceeded (with the exception of the PSA, which must be delivered every 6 months).

1.1.7 Lead Service Line Replacement

If corrosion control and source water treatment do not work for systems containing lead service lines, and the system continues to exceed lead action levels, the lead service lines must be replaced. The rule requires that 7 percent be replaced each year (over a 15-year period); only those lines that are under system control, however, must be replaced. Control, as defined by state statutes, municipal ordinances, or public service contracts, is the authority to set standards for construction, repair, or maintenance; the authority to replace, repair, or maintain; or ownership. No replacement is required for an individual line if the lead concentration in all service line samples from that line is less than or equal to 15 µg/L. Monitoring methods include (1) tapping into the water line, (2) measuring temperature changes, and (3) determining flush volume between the end of the line and the tap.

1.1.8 Regulatory Schedule

The regulatory schedules for large, medium-sized, and small systems are shown in Figure 1-5; the steps that water systems must take are shown in Figures 1-3 and 1-4. Deadlines are set for the initial monitoring period, the completion of studies, state approval, treatment installation, and follow-up monitoring.

1.1.9 Impacts of the Lead and Copper Rule

The total capital costs are estimated to be between \$2.9 and \$7.6 billion; operation and maintenance costs, \$240 million per year; and total annualized costs, between \$500 and \$790 million. Corrosion control treatment required by the rule is estimated to cost \$1 per household per year for large systems and \$2 to \$20 per household per year for smaller systems. Tap water monitoring will be required for 79,000 community and nontransient, noncommunity water systems. Monitoring costs are estimated to be \$40 million per year nationwide. Total annualized costs for lead service line replacement are estimated to be between \$80 and \$370 million. State implementation costs are estimated to be \$40 million per year.

1.2 A Smaller State's Perspective

This section presents the progress and plans made by the state of Maryland in preparing for implementation of the lead and copper rule. It discusses the results of an assessment prepared for upper-level management in Maryland's Department of the Environment Water Supply Program. This assessment examines monitoring, treatment, lead service line replacement, compliance and enforcement, training, and resources.

In Maryland and throughout the United States, EPA's NPDRs likely will have a substantial impact on small system

compliance. Training will be essential for educating the industries, especially the small systems that lack technical staff and resources.

Maryland has a population of 4.8 million, 80 percent (3.2 million) of whom are served by public water supplies. Approximately 8 percent of those are served by Washington's Urban Sanitary Commission and the Baltimore Metropolitan Water Supply System. Approximately 530 community water supply systems and 520 nontransient, noncommunity water supply systems, primarily schools and day care centers, serve the remaining 92 percent. About 980 systems serve a population of fewer than 3,300. The 50 to 60 medium-sized and large systems are not expected to have problems implementing the rule. The small systems, however, almost certainly will have problems, primarily with monitoring and costs, and this is where the state's resources will be used most.

The assessment looked at the impact that monitoring will have on water supplies in the state. A survey determined that 44 state-certified laboratories were available for lead and copper analyses; about half of those are out-of-state laboratories. A question therefore arises concerning whether adequate capacity for the analyses will be available, especially in the final phase of the rule, when the systems that serve fewer than 3,300 people are required to monitor. Therefore, the state has made plans to spread out the workload over time.

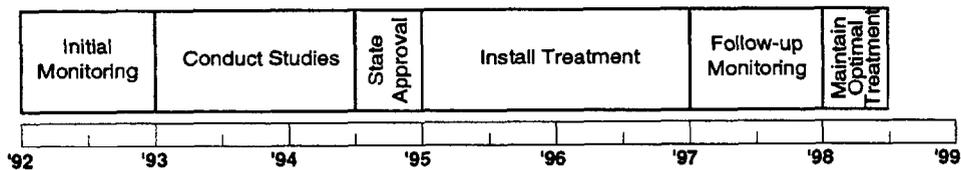
The laboratory survey identified representative costs for lead and copper monitoring, with an upper limit of about \$65 per sample. This monitoring included collection by the utility, transport to the laboratory, analysis, and recording of the results. Analyses for water quality parameters would at least double that figure per sample. For larger systems, the total cost estimated for lead and copper monitoring was between \$8,000 and \$13,000 per year; for small systems, between \$650 and \$1,300 per year. Sample costs, including those for water quality parameters, increase these costs to approximately \$1,300 to \$2,600 per year. Many smaller utilities will incur significant costs in conducting corrosion control studies. At the time of the assessment, the estimated cost was between \$10,000 and \$15,000, although a study in the District of Columbia's system cost more than \$300,000. It is hoped that most systems will not incur such expenses, and some of the earlier studies provide valuable lessons in controlling costs.

Treatment costs probably will not have a significant impact on larger utilities because many of these utilities have been practicing corrosion control for many years. For the small systems, treatment costs probably will include purchasing feeders, chemical storage tanks, and other related work. Costs for these systems are approximately \$5,000. About 70 percent of the systems in the state will require treatment for lead and copper, with an estimated total of \$3 million statewide for capital costs.

Operation and maintenance (O&M) costs are another factor to consider. O&M costs for corrosion control treatment are approximately \$1,500 per year. This cost is not large for a system serving a population of 3,300, but it is a major expense for small systems of approximately 15 connections.

Regulatory Schedule for Large Systems

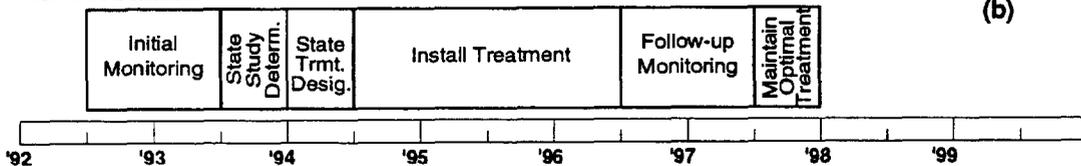
(a)



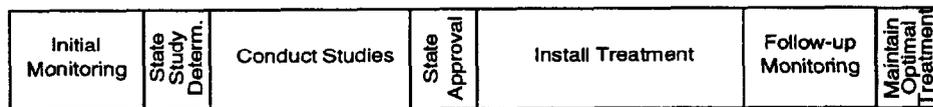
Regulatory Schedule for Medium-Sized Systems

Without Studies

(b)



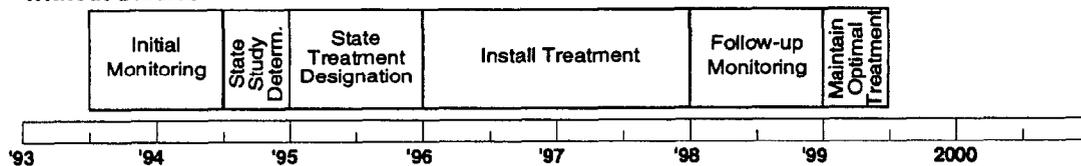
With Studies



Regulatory Schedule for Small Systems

Without Studies

(c)



With Studies

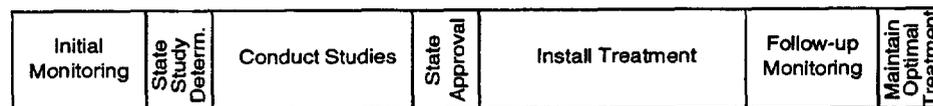


Figure 1-5. Regulatory schedules for large, medium-sized, and small systems.

The assessment also examined lead service line replacement. In the early 1980s, a federal regulation required that systems conduct a distribution system materials survey and submit the results to the state, as well as perform service line corrosion control testing. These material surveys indicated that lead service lines were not a significant problem in Maryland. Lead service lines were used to a significant degree only in the city of Baltimore, which 10 years ago began to replace service lines on a standard rate basis every year. Only 250 service lines are left to replace, and the city eventually would have replaced these lines regardless of the lead and copper rule.

The total annual costs for small system capital and O&M compliance were estimated to be \$3,000 to \$4,000 per year. To this amount must be added the additional costs for coliform monitoring, the surface water treatment rule, Phase II monitoring, radon, and Phase V. The costs to comply with these regulations continue to increase, and some small systems eventually will be unable to achieve compliance.

Another impact of the lead and copper rule, particularly for Maryland, is the effect of phosphorus- and zinc-based corrosion inhibitors on wastewater treatment. Maryland, Virginia,

the District of Columbia, and Pennsylvania have spent considerable energy and funds over the past few years trying to clean up the Chesapeake Bay. Part of that effort is included under the nutrient control strategy to reduce nitrogen and phosphorus by 40 percent. One initiative implemented to reach that goal is a ban on phosphate detergents. As a result of that ban, phosphorus levels in rural wastewaters going to plants in Maryland have dropped significantly. In addition, controls on most of the wastewater plants that discharge directly to the bay are very stringent, with a NPDES phosphorus limit of 0.3 mg/L and stringent toxicity standards for zinc.

For planning purposes, it was estimated that about 30 percent of Maryland's systems would not comply with the monitoring requirement after the first round. Approximately two-thirds of the systems not in compliance would require treatment or optimization of existing treatment. It was estimated that the remaining one-third, or about 230, would require some kind of enforcement action to ensure compliance with the regulation.

Current enforcement procedures have two levels. One level involves issuing a public notice of violation and, in many cases, providing technical assistance to identify the nature of the compliance problem and to reach compliance. This level of enforcement is usually 80 to 90 percent effective in getting systems back into compliance, but it is very resource-intensive. For those systems that do not comply after the first step, the standard process is to issue an administrative order. An estimated 110 administrative orders might have to be issued for the 230 systems. A significant number of these will be referred to the attorney general's office or to the court. Court action can result if the system does not comply with the order. These situations frequently end up in some kind of civil action or appeal, which becomes a long and convoluted process and is very resource intensive. This year, a proposal will be submitted to the Maryland legislature for a bill that would give the state the authority to levy administrative penalties against noncompliant systems. In so doing, the state could avoid bringing these situations to court. This proposal is not a panacea, but it is one of a number of tools available to bring systems into compliance. One positive aspect is the creation of a fund that will use fines for research, technical assistance, and training.

Another key to implementing the lead and copper rule is an effective training program for water suppliers, engineers, and state agencies. Training is especially critical to meeting monitoring and recording requirements, selecting the optimum treatment, and safely operating and maintaining treatment systems. In addition, chemical dosage control can be critical in controlling corrosion in systems, and proper operation of facilities will be very important.

Operator certification might be affected by the rule. In Maryland, a system that provides simple chlorination is a Class 1 facility, but a system providing any other treatment such as corrosion control would increase its classification level to Class 2. Training programs would enable operators to upgrade their certification. In addition, training in analytical methods for

monitoring lead, copper, and water quality parameters should be provided. Water quality parameters such as pH and alkalinity should be monitored at least once a day, especially in smaller systems, and more frequently in larger systems. (EPA requires such monitoring only every 2 weeks.)

Maryland is developing some interesting approaches to training. The state training center initially was developed under the Safe Drinking Water Act. This center was set up to provide water and wastewater training for operators and managers. The training is conducted by engineers, scientists, and operating specialists. The center receives local, state, and some federal funds, and the training is provided at a network of community colleges across the state. The center offers 25 different courses per year that are developed with assistance from the Water Supply Program. Last fall, the center conducted training on the total coliform rule in 12 different locations, reaching 250 people. The state anticipates that it will need to train as many as 2,000 people regarding the lead and copper rule.

In addition, a number of agencies are setting up state training coalitions. The agencies involved include EPA, AWWA, the Association of State Drinking Water Administrators, the National Environmental Training Association, the National Rural Water Association, and the Rural Community Assistance Programs. These agencies are working together at the national level to encourage state drinking water programs to coordinate and direct the available training resources. Maryland is one of two states where this approach will be tested. At the first meeting, these agencies will identify the types of training needed; then they will develop a specific plan to perform the training. Training for the lead and copper rule will receive priority.

The staff of the Water Supply Program and eight large water utilities are expected to review the rules and requirements, the progress each utility has made, and the problems they have identified. Ideally, issues raised and lessons learned by larger systems will be applied to smaller systems. All state-certified laboratories will meet to discuss the rule and to analyze the required samples.

State staff training is critical. The lead and copper rule places substantial responsibility on state agency personnel who review treatment plans, identify optimum corrosion control, and deal with many other issues. State staffs frequently are short of personnel and expertise, and training for those who are available is necessary to counter the deficit.

Finally, the matter of state resources is probably the most critical issue facing state programs. States will have to develop some sources of funding, such as fees, operating permits, and taxes. Maryland requires an additional \$1.3 million to implement all of the federal regulations through the radionuclide rule and \$0.3 million to fund the six and a half positions needed to implement the lead and copper rule. A proposal will be submitted to the legislature for a water-use tax assessed from water suppliers (\$1 per year per household), state property taxes, or income taxes. (This also could benefit private well protection programs.)

For additional information on how to comply with the technical requirements of the lead and copper rule see the *Lead and Copper Rule Guidance Manual, Volume 1 (Monitoring)* and *Volume 2 (Corrosion Control Treatment)* developed by the U.S. Environmental Protection Agency. The manual can be ordered from:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
(800) 533-NTIS

Ask for PB92112101 (Volume 1) and PB93101533 (Volume 2).

Chapter 2

Corrosion Characteristics of Materials

This chapter presents an overview of the corrosion characteristics of materials. It describes the corrosion cell, uniform corrosion and pitting, passivation, galvanic corrosion, and corrosion rate vs. metal uptake. Corrosion occurs only when there is a corrosion cell, consisting of an anode, a cathode, metal to conduct electrons from the anode to the cathode, and a conducting solution that transports excess positive or negative ions produced during corrosion. Some corrosion products deteriorate water quality, and others react with chemicals in solution to produce scales on the corroding surface that significantly reduce the rate of corrosion. Changes in water quality that cause dissolution might cause periodic high concentrations of corrosion products in solution.

In addition, corrosion rates sometimes increase when dissimilar metals are connected. Examples are copper pipe joined with solder and brass fittings in contact with galvanized pipe.

A thorough understanding of corrosion-related reactions will enable water systems to make scientifically valid judgments in order to minimize corrosion problems.

2.1 The Corrosion Cell

Corrosion essentially consists of four components: an anode, a cathode, a conducting solution, and a conducting metal. The anode is the point at which corrosion takes place and electrons are released (Figure 2-1). The released electrons travel through the conducting metal to the cathode. The cathode can be referred to as an electron acceptor. Once the cathode has

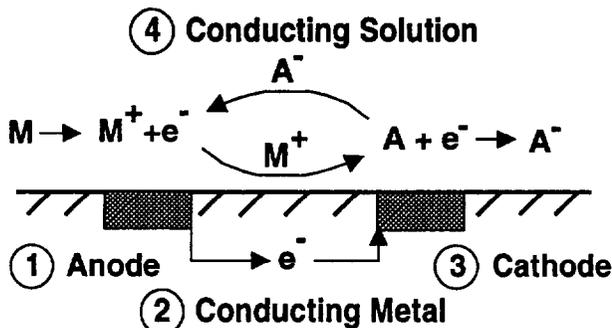


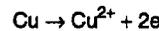
Figure 2-1. A diagram of the corrosion cell.

received these electrons, ions move from the cathode through the conducting solution back to the anode. If the anode is a different type of metal from the cathode, such as in the case of pipe and an attached fitting, a gasket between the fitting and the pipe will prevent the flow of electrons and stop the corrosion current. Equally important is the conducting solution—in this case, water. At the anode, positive ions are produced and at the cathode, negative ions are produced. A flow of positive ions toward the cathode and a flow of negative ions toward the anode must exist to maintain corrosion. If water is eliminated from this cell, corrosion stops because metal ions and anions can no longer be conducted.

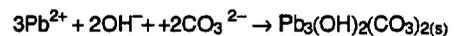
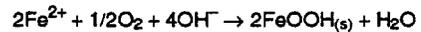
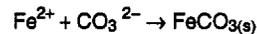
Examples of typical anodic reactions (Figure 2-2) are elemental copper converting to cupric ions (Cu^{2+}), lead converting to lead ions (Pb^{2+}), and iron converting to ferrous ions (Fe^{2+}). Once the ionic form of the metal is released into the solution, it can undergo secondary reactions (Figure 2-2). Under the appropriate conditions, ferrous iron (Fe^{2+}) can precipitate to

Typical Anodic Reactions (a)

Primary

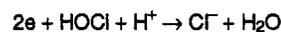
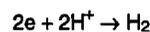
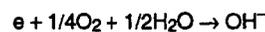


Secondary



Typical Cathodic Reactions (b)

Primary



Secondary

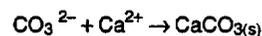
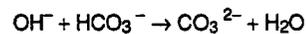


Figure 2-2. Typical anodic (a) and cathodic (b) reactions.

form FeCO_3 . When iron scales on pipes are analyzed, FeCO_3 commonly is found, indicating a deposit or a corrosion scale. Fe^{+2} can be oxidized to the ferric ion (Fe^{+3}), which then can form precipitates such as FeOOH . During these reactions, hydroxide ions are consumed; as a result, the pH drops in the region where these reactions take place. Secondary reactions with lead can result in the formation of lead precipitate, which includes hydroxide ions (OH^-) and carbonate ions (CO_3^{2-}) (lead hydroxycarbonate). The species that deposit, the manner in which they deposit, and the amount of the deposit are very important; they affect subsequent corrosion reactions. It is important to know whether they attach to the pipe, forming an adhering layer, or whether they become a particulate and do not adhere to the pipe.

The factors that determine whether an adhering scale or particulate is formed are not well understood. Oxygen plays an important role in cathodic reactions because it accepts electrons. The corrosion rate would be reduced by eliminating oxygen, but oxygen is also a component essential to scaling, which helps reduce the corrosion rate. When the pH drops below 4.5, hydrogen ions can accept electrons, but this is unlikely to occur in most water systems. Disinfectants such as chlorine also can serve as electron acceptors, sustaining the corrosion reaction. When oxygen accepts electrons, it also reacts with hydrogen to form hydroxide ions. These hydroxide ions can convert bicarbonate (HCO_3^-) to carbonate (CO_3^{2-}). Calcium carbonate and ferrous carbonate then can be formed in the presence of carbonates. At the point where these reactions take place (e.g., on the pipe wall), localized high pH can occur, causing metal carbonates to precipitate. This pH might be significantly different than the pH of the water away from the pipe surface (bulk solution). Since the pH is localized, the high pH values will not be detected by collecting samples from the bulk solution.

2.2 Uniform Corrosion and Pitting

For a single metal to corrode, there must be an anode and a cathode and a difference in the electrical potential between them. The difference in potential must come either from within the material, perhaps from a difference in the crystalline structure, in the way the atoms are put together to make the metal, or in the concentration of the electron acceptor. For corrosion to occur uniformly, the anode and cathode must be moving rapidly across the surface of the pipe. Pitting corrosion results if the anode is fixed, causing metal loss at one point.

A local differential in oxygen concentration can support corrosion of a metal (Figure 2-3a). Low dissolved-oxygen conditions can prevail under sludge or a suspended solid that has attached to the surface of the pipe. In the area surrounding the attached particle, higher concentrations of dissolved oxygen will exist. Corrosion taking place at the anode, underneath the particle, will produce electrons that will be transmitted to the surrounding area. Corrosion does not occur in the region with high dissolved oxygen because it functions as the cathode.

Pitting and tuberculation (Figure 2-3b) are particular problems with iron. The point at which corrosion takes place becomes fixed for an extended period of time, resulting in pitting corrosion. The electrons produced from this reaction are con-

sumed by the surrounding dissolved oxygen. Ferric ions produced will react with hydroxide ions or oxygen to form precipitates that attach to the pipe. As these precipitates attach themselves to the pipe, a porous tubercle is formed. The result of this corrosion is the formation of pits and tubercles, giving the pipe a rough surface.

2.3 Passivation

Passivation involves the development of a layer of material resistant to corrosion on the surface of the metal. Initially, the corrosion rate of a fresh bare metal is relatively rapid, but over time the corrosion rate slows because of the accumulation of deposits (Figure 2-4). The corrosion rate of lead/tin solder can be reduced by 90 percent in a period of 2 weeks. The purpose of changing water chemistry through chemical additions is to promote the formation of these deposits or scales.

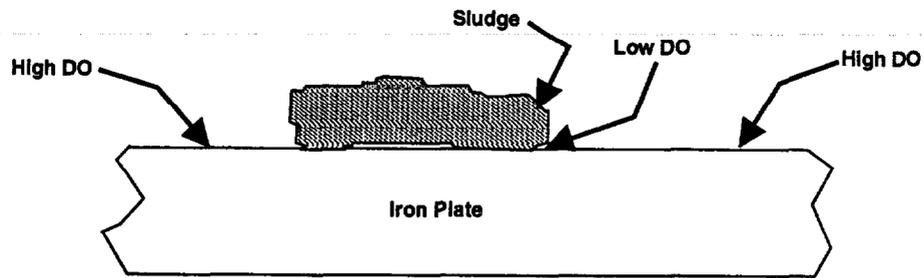
Earlier literature suggested that corrosiveness could be reduced by an eggshell-thin layer of calcium carbonate; if it is not possible to form such a layer, the water is corrosive. The occurrence of eggshell-thin layers of calcium carbonate in piping systems is very rare. Data from Hanover, Germany, indicate that several distinct layers of scale exist, which form over a period of time (Figure 2-5). The outermost layer of scale, the layer in contact with water, consists of a mixture of Fe^{+3} , Mn^{+4} (the oxidized forms of iron and manganese), and some calcium carbonate. Thus, this outer layer consists of a mixture of different compounds and elements. Residing underneath this layer is a dense, shell-like layer of Fe^{+3} . Beneath these two layers, the conditions are more reduced (low dissolved-oxygen concentration) and the iron is in the Fe^{+2} or iron solid [$\text{Fe}(\text{s})$] state. This layer is particularly dense, and inhibits the passing of different constituents of the corrosion reaction. The presence of this dense layer might, in part, explain the relatively low corrosion rate associated with iron pipe. In contrast to this dense film is the formation elsewhere in the pipe of loosely packed, localized scale produced by microbial action. Iron bacteria derive energy by converting Fe^{+2} to Fe^{+3} . The iron, released from the water in the Fe^{+3} state, is arranged in a nonordered, porous array. As a result, constituents necessary for sustaining corrosion can pass through this type of scale. Equivalent data for copper and lead pipe are lacking, but the possibility of similar reactions must be recognized.

2.4 Galvanic Corrosion

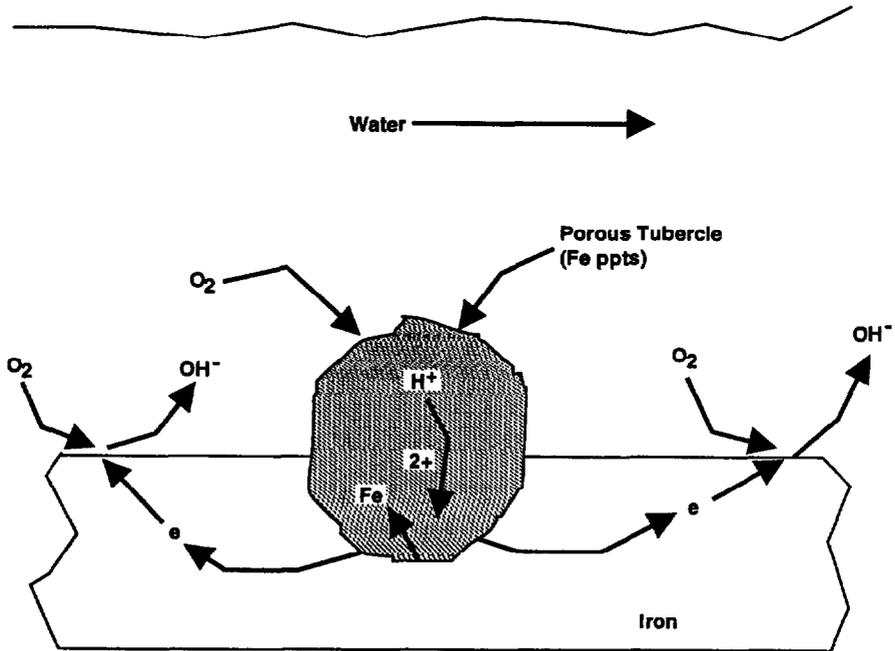
In galvanic corrosion, two different kinds of metals are in contact with each other: the anode, with a higher potential, and the cathode, with a lower potential (Table 2-1). In this respect, potential is a measure of a metal's capacity to give electrons:

Table 2-1. Examples of Galvanic Corrosion

| Anode (corrosion) | Cathode |
|-------------------|-----------|
| Galvanized (Zn) | Copper |
| Lead/tin solder | Copper |
| Lead | Brass |
| Zinc | Cast iron |



(a) Oxygen Concentration Cell



(b) Pitting and Tuberculation

Figure 2-3. The oxygen concentration cell (a) and pitting and tuberculation for iron pipe (b).

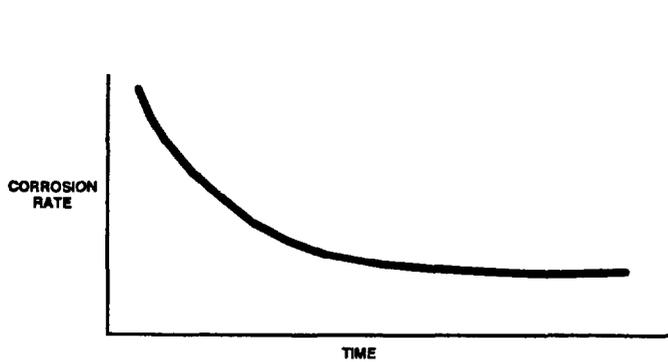


Figure 2-4. Corrosion rate as a function of time.

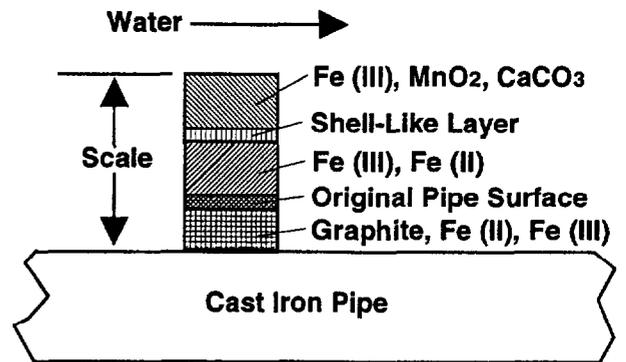


Figure 2-5. Scale composition on the surface of iron pipe.

the higher the potential, the higher the tendency to lose electrons. In a situation where galvanized pipe is attached to copper pipe, the difference in the potential of these metals causes the galvanized pipe to serve as anode and the copper to serve as cathode. Lead has the potential to undergo galvanic corrosion when it is in contact with brass. Brass fittings can contain up to 8 percent lead (by weight). Brass is a mixture of copper and zinc with lead added to make the brass more machinable. The lead contained in brass is not spread uniformly but in pockets along the grain boundaries (Figure 2-6). In these circumstances, the lead (anode) corrodes, discharging its electrons to the adjacent brass. This can be one way in which lead is corroded from brass. Another way in which lead held within the brass can be corroded is by the action of dezincification of brass. As brass

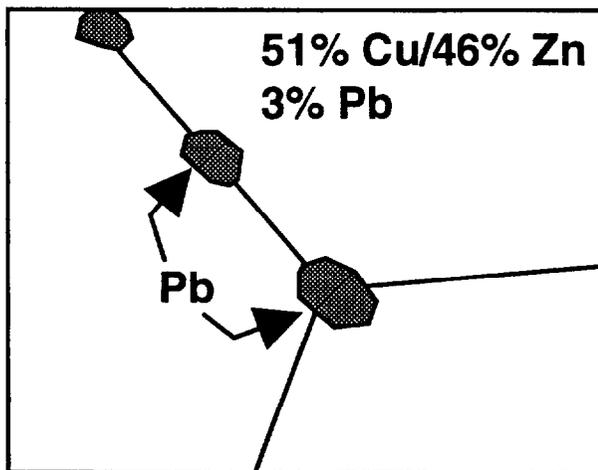


Figure 2-6. A micrograph of a cross-section of brass (x100).

dezincifies, the underlying pockets of lead can be exposed to water passing by.

2.5 Corrosion Rate vs. Metal Uptake

As pipe material corrodes, metal will be lost at the anode. This metal can pass into the bulk solution, leading to water quality problems. It is possible, however, to find corrosion without any noticeable impact on water quality, because the metal released is retained as scale at another point on the surface of the pipe. Scale often is formed by the combination of iron and oxygen. As the oxygen combines with the iron, the dissolved oxygen in the vicinity of the pipe is depleted. Reducing conditions occur with the low dissolved oxygen and, by accepting electrons, the Fe^{+3} is converted to Fe^{+2} . Low dissolved oxygen in water distribution systems can be caused, for example, by dead ends or heterotrophic bacteria that consume oxygen. In the absence of dissolved oxygen, another element, in this case iron, serves as the electron acceptor. After the Fe^{+3} is converted to Fe^{+2} , Fe^{+2} is free to migrate into the bulk solution because of the low dissolved-oxygen concentration. Once in the bulk solution, away from the surface of the pipe, the dissolved-oxygen concentration is higher, and the Fe^{+2} is converted back to Fe^{+3} . Suspended in the bulk solution, the Fe^{+3} reacts with hydroxide ions to form ferric hydroxide, which causes red water problems.

The reactions described above also can apply to the corrosion of copper. As with iron pipe, it is possible for oxygen to be depleted on the surface of copper pipe and for Cu^{+2} to be converted to Cu^{+1} or $Cu(s)$ by accepting electrons. Studies have shown that the copper concentration in water sitting motionless in contact with copper pipe increases and then decreases. The decrease has been attributed to the formation of a layer of cuprous oxide, which prevents loss of copper.

Chapter 3

Monitoring Design and Implementation

EPA's lead and copper rule contains requirements for tap water monitoring for lead and copper, monitoring for water quality parameters, source water monitoring for lead and copper, and studies for evaluating corrosion control treatment.

This chapter describes the part of the rule that pertains to analysis, reviews the analytical procedures, and discusses the criteria for selecting a laboratory. It discusses baseline monitoring to characterize the system, drawing on the experience of the District of Columbia. It also presents three case studies illustrating issues related to sampling and analysis:

- "At the tap" monitoring: Greater Vancouver Water District.
- Monitoring program design using utility employees and customers: Cincinnati Water Works.
- Integrating water testing and occupancy certification: Durham, North Carolina.

3.1 Characterizing the System: Baseline Monitoring

3.1.1 Introduction

The recent lead and copper regulations set requirements for monitoring lead levels at high-risk residences connected to community water systems. This baseline monitoring will be used to determine regulatory compliance for the water system and also can be used to evaluate the effectiveness of any corrosion control treatment required by the regulations. The methodology for developing the sampling pool is specified as part of the rule. The appropriate selection of monitoring locations will be extremely important in helping both water utilities and regulatory agencies meet the baseline monitoring requirements.

To assist in the sampling pool selection, the regulation also requires a characterization of the water system by a materials survey. This characterization benefits utilities beyond providing the basis for the selection of sampling locations. By identifying pipe materials within the traditional water distribution system, in the customers' service lines, and as much as possible, in the customers' indoor plumbing, the utility can better understand its own system and the extent of lead materials in the system. Knowledge of lead and copper materials and their location helps the utility optimize corrosion control. In addition, if a water utility falls under the requirement to replace lead service lines, the materials survey used to characterize its system

should be invaluable in locating these lead service lines for replacement.

The baseline monitoring program for compliance with the lead rule is unique, with a completely different philosophy from the standard practice of trying to obtain samples representative of the water distribution system. The monitoring program attempts to identify the level of lead exposure for individuals who drink water when the lead level is likely to be highest (first draw for water standing in interior plumbing or services for 6 to 10 hours) in residences where the risk for lead sources is high. In essence, the monitoring program seeks to obtain representative samples from a nonrepresentative portion of the system, the high-risk homes with lead service lines and other lead sources the location of which probably is not well known. For many systems, this is not an easy task.

3.1.2 Characterizing the Water System

The lead and copper rule identifies the method for characterizing the water system as a materials survey. The rule states that the level of effort put into this survey needs to be only what is necessary to select the sampling pool from which baseline monitoring is required, as long as the highest category of sampling pool is achieved. Several categories exist, based on the availability for sampling of single-family residences that have interior plumbing with lead solder installed after 1982 or lead service lines. The highest category of sampling pool consists entirely of single-family homes and is made up of equal numbers of homes with lead service lines and post-1982 lead solder. This category is designated as Tier One—Category A (Figure 3-1).

If a water system cannot obtain 50 percent of its sampling sites from lead service lines and 50 percent from homes with post-1982 lead solder, it should try to meet the next highest category, which consists entirely of single-family residences with an unequal mix of lead service line sites and post-1982 lead solder sites. Tier One—Category B (Figure 3-1) must stay as close to the 50 percent/50 percent mix as possible. If a system can get enough sampling locations from single-family homes, but only with either all lead service lines or all post-1982 solder (but not both) the sampling pool is Tier One—Category C (Figure 3-1).

A sampling pool becomes Tier Two only if it needs to include multiple-family residences to obtain enough lead ser-

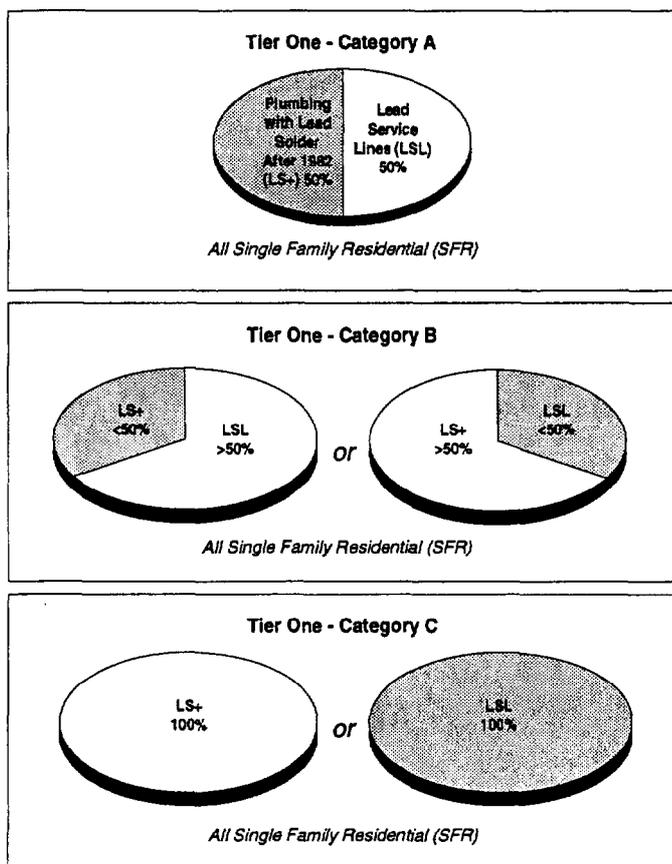


Figure 3-1. Tier One sampling site requirements.

vice lines and post-1982 solder locations to meet monitoring requirements (Figure 3-2). Presumably, the preference for the even mix that differentiated classes A and B in Tier One would also apply to Tier Two, but all Tier Two sampling pools are classified as Category D. Finally, any system that cannot meet Tier Two is allowed to include homes with lead solder from before 1982 and will be classified Tier Three—Category E (Figure 3-3). It is presumed that every system in the United States will fall into one of these categories.

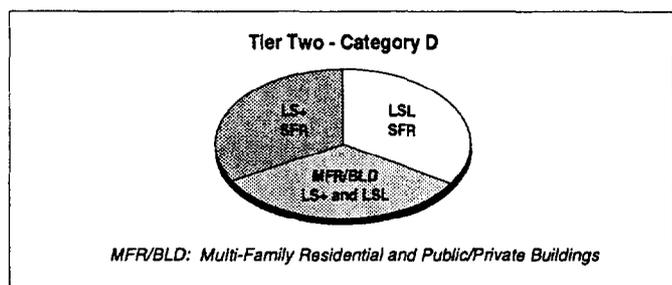


Figure 3-2. Tier Two sampling site requirements.

3.1.3 The Materials Survey

Any water system that cannot obtain a sampling pool of Tier One—Category A will have to document why it cannot do so, and will have to document that its sampling pool category is as high as possible. The materials survey can be used to

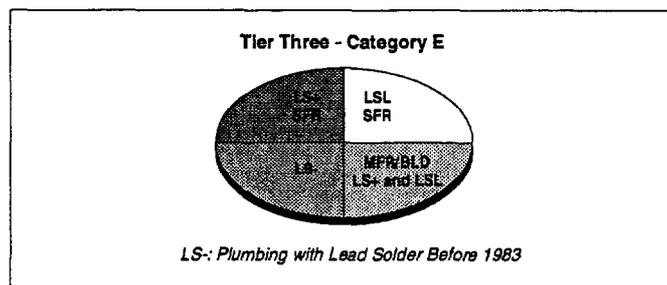


Figure 3-3. Tier Three sampling site requirements.

provide this documentation. The survey should attempt to determine the location and material of water mains, service lines, service line connections, and interior plumbing throughout the utility's distribution system. These should be categorized by building type to help with sampling site selection. For large systems, the survey should have been completed before finalizing site selection and beginning the baseline monitoring, and should have been submitted along with the first monitoring results. Systems of medium size should have completed the materials survey by June 1992. Small systems should complete the survey by June 1993.

If it is available, additional information can be included in the survey such as estimates of the age of lead solder in interior plumbing and a breakdown of portions or numbers of lead service lines under the control of the water system. (The rule defines "control" as any one of the following: ownership of service lines; authority to replace, repair, or maintain service lines; or authority to set standards for construction, repair, or maintenance of service lines.) Based on plumbing practices within a utility's customer service area, the water system might want to characterize plumbing with solder used before and after implementation of the lead-solder ban. Or it might prefer to abide by the rule's assumption that 1982 is a reasonable date demarcating the use of lead and nonleaded solder.

3.1.4 Information Sources

If a water system needs to go beyond the minimum effort for a materials survey (meaning that it cannot meet the Tier One—Category A sampling pool criteria and must document why), the effort that it must put into the survey could be considerable. For the characterization of materials within the distribution system, most of the data should be available from the water utility's own records. These could include permit or tap files, distribution maps or drawings, maintenance records, meter records, information from senior and retired staff, contract documents and dates, and water quality data.

The need to determine materials used on customer property presents a greater challenge. Except for information on customer service lines, probably little or no information on residential materials is available from the water system's own recordkeeping systems. Thus, numerous external information sources will need to be researched. These might include plumbing codes, building/plumbing permits, water quality data, dates of construction, interviews with plumbers and/or building inspectors, and community surveys.

In larger systems, several information sources usually will be available from a number of different agencies that can contribute to the materials survey. Many of these sources are computerized data bases. The development of a master data base can be very useful in accumulating, compiling, and analyzing these data. Frequently such a data base also will provide additional advantages and applications unrelated to the materials survey.

3.1.5 Conclusions

To develop a sampling pool for baseline monitoring, and to document the type of sampling pool within the various sampling categories, the lead and copper rule requires that water utilities characterize their distribution system and their customers' plumbing systems by conducting a materials survey. The survey need be only of sufficient effort to select a sampling pool for monitoring. If the water system cannot meet the highest sampling category (50 percent lead service lines, 50 percent interior plumbing with post-1982 solder in single-family homes), then it must extend its materials survey effort to document why it could not meet this category and that its sampling pool is at the highest category possible. The water system then would carry out a search of its own and other agency records to determine the materials of construction of its own and of customers' piping and plumbing. The schedule for completion would be to conduct the materials survey prior to the required dates for carrying out the baseline monitoring sampling.

3.2 Selection of an Analytical Laboratory

3.2.1 Introduction

The part of the lead and copper rule that regulates the analysis of the parameters contained in the rule is a very small part of a complex regulation. The results obtained from these analyses could play a very large role, however, in the ways in which a utility must respond to the regulation. Selecting a laboratory to conduct the analysis, therefore, becomes very important.

The regulated concentration of lead, for example, is being reduced from 50 $\mu\text{g/L}$ to 15 $\mu\text{g/L}$. It is well known in the analytical community that the smaller the concentration of an element to be measured, the larger the chance of missing the true value. So, as the regulated maximum contaminant level becomes smaller and more difficult to analyze accurately, it becomes more important that laboratories provide accurate compliance monitoring data. Many utilities' responses to portions of this rule will depend on the analytical results obtained from the monitoring.

3.2.2 The Regulation

Section 141.89 of the lead and copper rule addresses the methods required by the regulations and presents a list of methods that may be used to analyze the requisite parameters. There are three methods and five references to the methods listed for lead (Table 3-1). The methods are the Atomic Absorption (AA) Furnace, Inductively Coupled Plasma Mass Spectrometry

(ICPMS), and AA Platform Furnace. There are three EPA references and one each for American Society of Testing and Materials (ASTM) and Standard Methods. For copper, five methods are listed along with 10 references to the methods. Methods for copper are the AA Furnace, AA Direct Aspiration, ICP, ICPMS, and AA Platform Furnace. Five EPA references are listed along with two ASTM references and three Standard Methods.

The next paragraphs in the regulation address laboratory certification. Paragraph 1 states that "analyses under this section shall only be conducted by laboratories that have been certified by EPA or the State." It further says that, to obtain certification, these laboratories must have analyzed performance samples containing lead and copper and must meet the quantitative acceptance limits.

A major portion of this rule is the regulation requiring monitoring for water quality parameters. Large utilities and the small and medium-sized utilities that exceed the action levels must monitor for pH, conductivity, calcium, alkalinity, orthophosphate, silica, and temperature. The regulation specifies the approved methodology for the analyses for these parameters, but it does not require laboratory certification for the analyses and reporting of these data.

3.2.3 Decision Time

A utility must make some important decisions about data analysis: should it become certified and conduct all the analyses in-house; should it go to an outside laboratory for lead and copper testing only and conduct the analyses of water quality parameters in house; or should it go to an outside laboratory for all analyses, including field sampling and field analyses for the water quality parameters?

At the Water Quality Technology Conference in 1988, a paper was presented on "A Utilities' Perspective of Laboratory Certification." It was reported that most large utilities preferred to be certified, for both chemical and microbiological analyses, and preferred to conduct their own analyses. Most medium-sized utilities are certified for bacteriological analyses only and most cannot afford the personnel and equipment needed to be certified for chemistry parameters. The report also noted that small utilities depend on outside laboratories to provide their compliance monitoring data. Since 1988, more medium-sized utilities, specifically those on the upper end of the "population-served" scale, have been considering in-house capabilities.

Numerous scenarios show that a medium-sized utility could enter the analytical field. For example, two utilities in Colorado, which fit the picture of midsized utilities, are both certified for bacteriological parameters and want to obtain certification for organic analyses. They currently have qualified personnel in charge of their laboratory operations and are producing (unofficial) in-house data. Both have adequate space in which to expand. Both need to purchase atomic absorption instrumentation, which costs between \$30,000 and \$60,000, a high price if dedicated to analyzing lead and copper only. A utility probably should consider obtaining an instrument that

Table 3-1. Analytical Methods

| Contaminant | Methodology | Reference (Method Number) | | AWWA Standard Method (SM) | USGS Procedure |
|--|---|---------------------------|------------|---------------------------|----------------|
| | | EPA | ASTM | | |
| Lead | Atomic absorption; furnace technique | 239.2 | D3559-85D | 3113 | |
| | Inductively coupled plasma; mass spectrometry | 200.8 | | | |
| | Atomic absorption; platform furnace technique | 200.9 | | | |
| Copper | Atomic absorption; furnace technique | 220.2 | D-1688-90C | 3113 | |
| | Atomic absorption; direct aspiration | 220.1 | D-1688-90A | 3111-B | |
| | Inductively coupled plasma | 200.7 | 3120 | | |
| | Inductively coupled plasma; mass spectrometry | 200.8 | | | |
| | Atomic absorption, platform furnace | 200.9 | | | |
| pH | Electrometric | 150.1 | D1293-84B | 4500-H | |
| | | 150.2 | | | |
| Conductivity | Conductance | 120.1 | D1125-82B | 2510 | |
| Calcium | EDTA titrimetric | 215.2 | D511-88A | 3500-Ca-D | |
| | Atomic absorption, direct aspiration | 215.1 | D511-88B | 3111-B | |
| | Inductively coupled plasma | 200.7 | 3120 | | |
| Alkalinity | Titrimetric | 310.1 | D1067-88B | 2320 | 1-030-85 |
| | Electrometric titration | | | | |
| Orthophosphate, unfiltered, no digestion or hydrolysis | Colorimetric, automated, ascorbic acid | 365.1 | | 4500-P-F | |
| | Colorimetric, ascorbic acid, two reagent | 365.3 | | 4500-P-F | |
| | Colorimetric, ascorbic acid, two reagent | 365.2 | D515-88A | | |
| | Colorimetric, phosphomolybdate; automated-segmented flow; automated discrete ion chromatography | 300.0 | D4327-88 | 4110 | |
| Silica | Colorimetric, molybdate blue; automated-segmented flow | | | | 1-1700-85 |
| | Colorimetric | 370.1 | D859-88 | | 1-270-85 |
| | Molybdosilicate | | | 4500-Si-D | |
| | Heteropoly blue | | | 4500-Si-E | |
| | Automated method for molybdate-reactive silica | | | 4500-Si-F | |
| Inductively coupled plasma | 200.7 | 3120 | | | |
| Temperature | Thermometric | | | 2550 | |

can, at a minimum, analyze all the inorganic metal MCLs, and that is capable of both flame and furnace procedures.

Personnel, space, and major instrumentation purchase are the three main factors to be considered when establishing an analytical laboratory. Capital outlay and annual O&M costs will be the major stumbling blocks to obtaining management approval. On the positive side are the utility's ability to be flexible and control monitoring and analytical programs, including ensuring that data and reports are produced in a timely manner. Over the long term, in-house laboratory capability will pay for itself. There is no way of telling how the lead and copper rule and other rules will affect analytical capacity nationally, but it is strongly recommended that utilities take a comprehensive look at establishing in-house capability.

Small systems serving a population of fewer than 3,300, including many nontransient, noncommunity systems, depend

on commercial or outside laboratories to conduct analyses for lead and copper. Some of these, however, could and should consider conducting their own analyses for the required water quality parameters if they exceed the lead and copper limits. Laboratory certification will not be required for those parameters to be reportable, but specific analytical procedures are required. EPA has specified the electrometric method as the approved method for testing pH and the conductance method as the approved method for testing conductivity (formerly known as specific conductance) (Table 3-1). Portable field instruments are available on the market for both of these analyses. Titrimetric methods are specified for alkalinity measurement. A well-trained technician could conduct these analyses and provide valid, accurate data. In some instances, therefore, conducting these analysis in house will be beneficial.

On the other hand, many small and medium-sized systems will choose not to enter the analytical laboratory business and will select outside assistance. The following section presents

criteria to help systems select an appropriate analytical laboratory.

3.2.4 Selection Criteria

The first consideration is whether to choose a state- or EPA-certified laboratory. Most state health departments and all regional EPA offices can provide a list of certified laboratories. It is important to make sure that the laboratory is certified to analyze all of the parameters desired, especially for lead and copper.

The instrumentation and methodology must be investigated when a system is selecting a laboratory. Familiarity with the rule is important because the rule contains information on the methods that the laboratory must use to analyze the parameters. The laboratories should be asked what instruments and which of the three approved methods for lead and the five approved methods for copper they will use to analyze the samples. For example, an ICP method is approved for copper; an ICPMS, however, is required for lead. If a laboratory has only ICP capabilities, it cannot provide valid lead data.

A discussion should be held with the laboratory manager about detection limits. The various methods have various sensitivities; ICPMS, for example, is more sensitive than AA Furnace. If necessary, a laboratory can provide lower detection limits than is its usual practice, but such testing might cost more than usual. Conversely, acceptable detection limits can be reported through the use of less sensitive instrumentation than is the laboratory's norm and can be less expensive.

Along with discussing detection limits, an agreement should be reached about the procedures that the laboratory will use in reporting the quality assurance/quality control (QA/QC) data. The system must have documentation that QA/QC procedures were carried out and that the sample data are verifiable.

Analysis time is important and must be guaranteed. Section 141.91 of the lead and copper rule reporting requirements states that utilities must report data to the primacy agencies within 10 days of the end of the monitoring period. Sampling must be timed so that the analysis can be conducted and a report prepared within the required time frame. Most commercial laboratories can improve analysis time at additional cost.

Prices and costs must be checked, compared, and verified. Some laboratories have minimum costs, for example \$50 for a single parameter; as already mentioned, lower detection limit reporting and quicker turnaround times can increase the costs. Supply and demand will probably play an important role in future analytical costs.

If necessary, a small utility might desire to contract with an outside laboratory to conduct the analyses for the water quality parameters. If this is the case, then further investigation and discussion must be conducted with the laboratory. Since certification is not required, laboratory personnel qualifications must be ascertained. The type of field equipment and methodology to be used must be verified. A monitoring plan, including

sample locations, must be developed between the commercial entity and the utility.

3.2.5 Conclusions

Only time will tell if all of the rules being promulgated, including the lead and copper rule, will make it difficult to produce reliable compliance data. For now, utilities can only do their best under the prevailing conditions to comply with the rules and submit timely reports to their primacy agencies.

It might be prudent for many utilities to attempt to conduct in-house analyses. If, however, outside laboratory services are required, a utility should be selective in hiring this service. Criteria to be considered include certification status, instrumentation available and methods to be used, the laboratory's QA/QC program and reportable detection limits, turnaround time, and costs for analyses.

Concerns have been raised about whether adequate analytical services will be available to meet the requirements of all the rules. Supply and demand usually dictate availability and cost, however, and experience indicates that sufficient services will be available for utilities to exercise their selection expertise.

3.3 "At the Tap" Monitoring

Another requirement of EPA's lead and copper rule is "at the tap" monitoring at high-risk locations, which are homes with newer lead solder, lead pipes, or lead service lines.

3.3.1 Materials Surveys and Site Selections

A materials survey is required to establish areas with high-risk sites. Information on expected plumbing materials can be obtained from area plumbing codes, building department files for plumbing age and materials, utility records for age and materials of service lines, and water quality data for potentially corrosive water. The materials survey will identify potential high-risk sites with site-selection priority as required by the EPA regulations (lead service lines and lead solder plumbing for single-family homes). Highest priority site selections will be single-family home subdivisions constructed after 1982 and before 1987 and older areas where lead service lines connect the street water main to the house.

When the highest risk priority areas have been chosen and sufficient sample sites selected, questionnaires should be sent to each potential site owner to confirm information such as the age of plumbing, type of plumbing and joints, type of service line, plumbing modification, and fixture staining, and to obtain an agreement to allow sampling. An adequate number of suitable sites should be obtained to provide an excess (10 to 20 percent) of the statutory number to allow for attrition through homeowners' moving, plumbing changes, lack of interest in further sampling, and incorrect sampling.

3.3.2 Sample Collection

The most practical sampling of the first draw of overnight standing water is performed by the resident rather than a utility employee. To ensure proper sampling, clear and simple instructions must be provided to residents who take their own samples. It must be made clear that it is better to report poor sampling procedures and repeat them if necessary than to provide a sample that is not properly taken (e.g., water flushed during the minimum 6-hour standing period). Lead service lines might require special sampling procedures as outlined in the EPA regulations. Monitoring frequency is dependent on system population and is outlined in the regulations.

3.3.3 Other Water Quality Parameters

All large water systems (serving more than 50,000 people) and smaller systems exceeding the copper and lead action levels must carry out monitoring for other water quality parameters, including pH, alkalinity, calcium, conductivity and temperature, as well as orthophosphate or silica if such inhibitors are used. These samples must be taken from the distribution system and from each water source entering the distribution system (they can be taken from coliform sampling sites). It might be easiest to take these samples from home water taps when the copper and lead monitoring samples are taken.

3.3.4 Case Study One—Greater Vancouver Water District Experience

The Greater Vancouver Water District (GVWD) wholesales water to 1.5 million people through 17 municipalities. The water supply comes from three lake impoundments sited in the mountains north of the city. The lake watersheds are closed to the public and are unfiltered sources with chlorination as the only treatment process. The sources provide very soft, low-pH water with corrosive characteristics.

The GVWD has undertaken an intensive water quality improvement investigation in recent years. Initiatives included primary disinfection, secondary disinfection, and corrosion control. As part of the corrosion control investigation, a number of programs monitoring metals corrosion and leaching were undertaken. Plumbing water samples were tested in schools, homes, apartments, office buildings, and hotel rooms as well as in simulated plumbing systems in a corrosion control pilot plant.

In a 1988 monitoring program, 36 homes in the GVWD service area were tested for lead and copper. First-draw 1-L samples were taken; 21 percent exceeded a lead concentration of 20 µg/L, and 52 percent had copper levels exceeding 1.3 mg/L.

A monitoring program of 60 single-family homes and 72 apartment suites was carried out in 1990. It was found that 46 and 50 percent of first-draw 1-L samples in apartments and homes, respectively, exceeded 1.3 mg/L of copper; 32 and 35 percent of samples in apartments and homes, respectively, exceeded 15 µg/L of lead. Tukey box plots of lead and copper levels in newer (less than about 10 years) and older single-family homes in the same study clearly showed higher lead and

copper concentrations in the newer home samples (Figures 3-4 and 3-5).

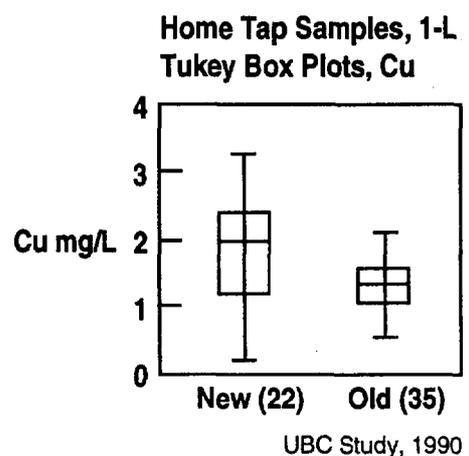


Figure 3-4. Copper levels from the Greater Vancouver Water District monitoring program.

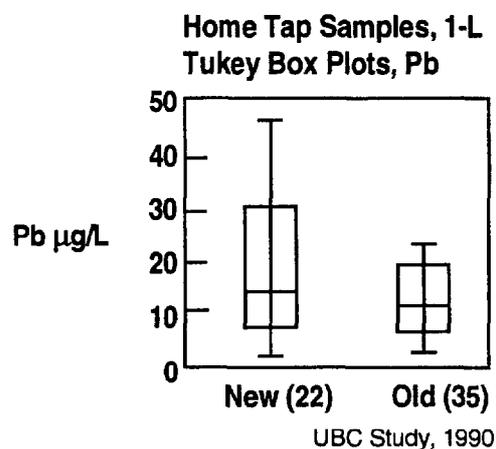


Figure 3-5. Lead levels from the Greater Vancouver Water District monitoring program.

3.4 Monitoring Program Design Using Utility Employees and Customers

3.4.1 Introduction

During the regulatory activities carried out in the past few years regarding corrosion by-products (CBPs), the most controversial issues, from the utility viewpoint, have centered around first-draw samples at the customer's tap. The requirement of ensuring compliance with action levels or providing

optimal treatment related to CBPs presents a major challenge to utility managers. One of the major reasons for concern is that in most instances the major CBP, lead, occurs beyond the point where utilities have direct control regarding the materials used, methods of construction, and factors required to collect appropriate samples that describe the problem. Unlike microbiological problems generally caused by inappropriate treatment or distribution cross connections, the major cause of CBPs lies in the building owners' piping and plumbing fixtures. Utilities do have control, however, over the corrosivity of the water that comes in contact with the homeowner's plumbing. Realizing their important role, many utilities collected data in advance of the January 1992 date for implementing the monitoring regulations.

3.4.2 Case Study Two—The Cincinnati Water Works System

The Cincinnati Water Works (CWW) consists of a surface and ground water treatment plant to provide water to a common distribution system. The surface water treatment plant (Figure 3-6a) processes water from the Ohio River water by coagulation, settling, and rapid sand filtration. Alum, polymers, and sometimes ferric sulphate are used for solids removal. Chlorine is used for disinfection, and fluoride is added for prevention of tooth decay. The raw water pH of about 7.5 is raised to a finished water pH of about 8.5 by lime addition. About 88 percent of the distributed water is produced by this surface water treatment plant, which is located in the southeastern part of the system. The remaining 12 percent of the distributed water is ground water processed by a lime softening treatment plant located at the northwest portion of the distribution system (Figure 3-6b). Raw water is pumped from 10 wells located along the bank of the Great Miami River. The conventional lime softening treatment facilities include primary and secondary basins and dual media filters. Chlorine is added for disinfection, and sodium hexametaphosphate is used as a sequestering agent. Fluoride also is added under state mandate. The raw water pH of about 7.5 is raised to about 9.5 in the finished water.

The piping network under CWW's direct control (Table 3-2) comprises a variety of distribution system materials. Iron pipe constitutes the majority of the water mains, because iron pipe was used during the largest part of the expansion, with the most popular size installed being 6 and 8 inches.¹ In 1975, ductile iron pipe was installed to replace cast iron pipe. Prestressed concrete and steel pipe are used for larger diameter pipe installations; steel pipe is used where special conditions warrant the added expense. About 8 miles of asbestos-cement pipe are still in use. Small copper mains were put into service as a means of minimizing stagnant water quality concerns at dead-end locations. Prior to 1947, all pipe was unlined. Cement-lined grey and ductile iron pipe have prevailed as the largest part of the system since that time.

Tables 3-3 and 3-4 list representative joint and service branch materials used in the distribution system. Lead and leadite joints were discontinued for new main use in the late

¹English units (inches and miles) are used in this publication to facilitate its use by the intended audience. Appendix B contains a table for conversion to metric units.

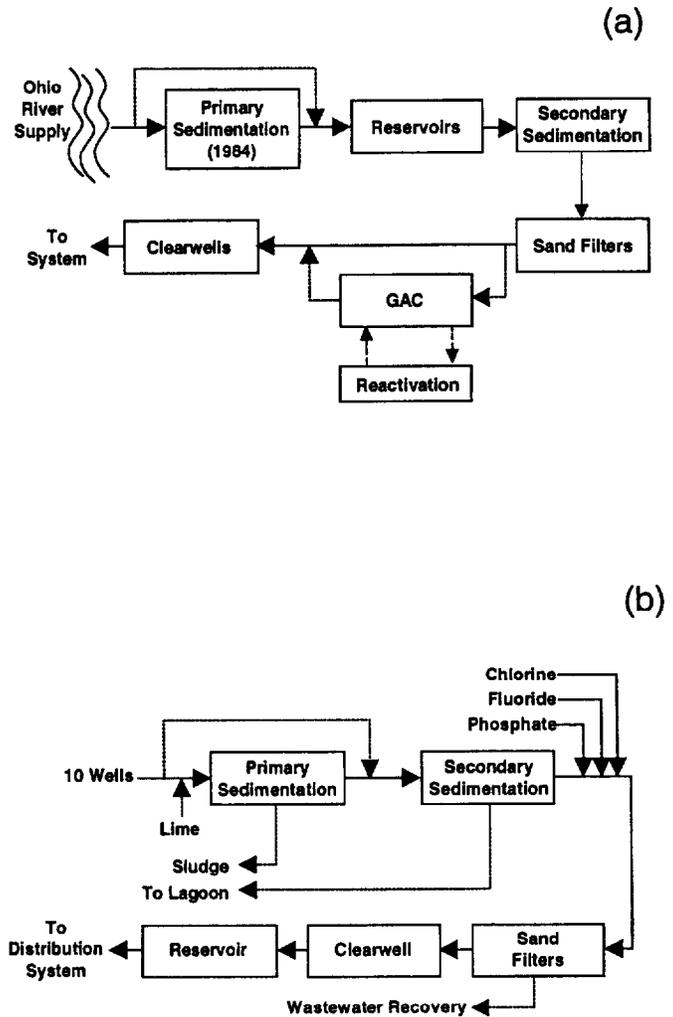


Figure 3-6. Cincinnati Water Works: Schematic of treatment system for the Ohio River supply (a) and lime softening treatment system for the ground water supply (b).

Table 3-2. Water Main Materials

| Type | Period of Major Use | Miles in Use | Predominant Size |
|--------------|---------------------|--------------|----------------------|
| Grey Iron | 1850–1975 | 2203 | 6", 8", (10"–60") |
| Ductile Iron | 1975–present | 288 | 8", 12", (16") |
| Concrete | 1956–present | 104 | 24", 36", 48", (54") |
| Steel | 1920–1953 | 15 | (36"), 42", 48" |
| Transite | 1940–1952 | 8 | 6", 8" |
| Copper | 1975–1985 | 4 | 2" |

1950s. Rubber gaskets, both mechanical and compression joints, have been used in new main construction since 1958. Table 3-4 shows that lead service branches have not been installed in Cincinnati since 1927. CWW records indicate that about 31,000 lead service branches are still in active service among the 212,000 customer taps in the system.

Table 3-3. Joint Materials

| Water Mains | Period of Major Use |
|----------------|---------------------|
| Lead Joints | 1860–1958 |
| Leadite Joints | 1931–1958 |
| Rubber Gaskets | 1958–present |

Table 3-4. Service Branch Materials

| Types | Period of Major Use |
|--------|---------------------|
| Lead | 1837–1927 |
| Brass | 1923–1927 |
| Copper | 1927–present |

3.4.2.1 The Awakening

A coupon study was performed to evaluate the corrosivity of the finished water. The past state and federal MCL of 50 µg/L for lead never posed any problems, primarily because of the required sampling methods. Water was sampled from the water distribution system, rather than from water standing in residential plumbing. In September 1985, EPA performed a short-term monitoring study of employee homes in the Greater Cincinnati area. Of the 81 homes monitored, 50 were supplied from the CWW distribution system. First-draw 125-mL and 1,000-mL samples were collected and analyzed for eight metals: lead, copper, cadmium, chromium, zinc, iron, sodium, and calcium. Thirty-eight of the 50 samples did not show detectable lead levels in either sample (Table 3-5). Only two of the 50

Table 3-5. Lead Levels in First-Draw Samples as Part of Employee Monitoring Program

| Sample | Percentile | 1-Liter Sample (µg/L) |
|--------|------------|-----------------------|
| 1–38 | 2–76 | BDL* |
| 39 | 78 | BDL |
| 40 | 80 | BDL |
| 41 | 82 | BDL |
| 42 | 84 | BDL |
| 43 | 86 | BDL |
| 44 | 88 | 7 |
| 45 | 90 | 8 |
| 46 | 92 | 16 |
| 47 | 94 | 21 |
| 48 | 96 | 34 |
| 49 | 98 | 72 |
| 50 | 100 | 94 |

*Below detection limit.

residences had standing sample results that exceeded the 50 µg/L regulation for flowing water (94 µg/L and 72 µg/L). Five of the 50 samples exceeded the current 15 µg/L action level. These nontargeted locations, selected at random, would have had a 90th percentile concentration of 8 µg/L. The concentration corresponding to the 92nd percentile was 16 µg/L. Although CWW was concerned about the few sporadic high lead levels, there was no sense of urgency in addressing these “worst-case” results because they were well below the regulations in effect at that time.

Nevertheless, in 1985, CWW started to conduct monitoring studies to determine the extent of lead contamination. Sampling taps were installed at a residence served with a lead pipe and containing plumbing with lead solder. The results from this initial study indicated that the plumbing presented a larger problem than the lead service branch, with temperature effects especially evident. The results of this initial study prompted further investigation into the problems with lead.

In June 1987, a pipe loop was constructed with 50/50 lead solder to determine the length of time required for lead levels to stabilize. Lead concentrations in the first-draw samples taken through mid-1991 typically exceeded 15 µg/L. The lead levels in samples collected from service lines and water mains seldom contained lead but still exceeded 15 µg/L concentrations on occasion.

A one-time sampling of 25 drinking water locations was conducted within the various CWW facilities: detectable lead concentrations were discovered at 12 of the sites, and 3 locations contained lead levels greater than 15 µg/L. Another survey performed by the Cincinnati Health Department found that 86 of 656 samples from electric water coolers at various sources had lead concentrations at or above 15 µg/L.

The 2-year CWW monitoring program of about a dozen employee homes resulted in data on first-draw and service line standing water. None of the locations tested consistently had lead levels in excess of 15 µg/L. This was true even of the three locations with lead service lines, both the first-draw and service branch samples. CWW also began a 1-year monitoring program of a home with a lead service line. Lead concentrations were consistently detected in the first liter and in samples collected during each 1-minute interval for 5 minutes after the first-draw sample. Concentrations appeared to follow seasonal water temperature variations. A number of lead service branches might be added to the study in the area being monitored.

Other random samplings of routine bacterial sample locations and storage tanks showed sporadic lead levels. Most recently, a program has been developed to collect and analyze tap water samples before and after replacement of city-owned portions of leaking lead service branches. It appears that replacing a portion of a lead service branch will improve the quality of water at the consumer’s tap. No efforts have been made to control the standing time before sampling. A more structured study might be attempted at a later time.

The results of the studies have demonstrated that elevated concentrations of lead are present in water that has remained motionless while in contact with residential plumbing and distribution piping. Thus, it is important for CWW to initiate the structured monitoring required by U.S. EPA and the Ohio EPA for compliance with the lead and copper rule. Table 3-6 is a simple outline of the plan for implementation. CWW’s review of draft rules and the final rule resulted in a series of questions from the utility (Table 3-7). The Ohio EPA answered these questions as of September 1991 and CWW proceeded with its overall plan. The first phase of work for the plan consisted of establishing representative Tier 1 locations, efficiently solicit-

Table 3-6. Outline for Implementation

1. Review Final Rule for Monitoring Implementation Plan
2. Obtain Federal and State Answers to Questions, Pose Own Answers Based on Rule Review
3. Establish Representative Sample Locations for Tier 1
4. Prepare Monitoring Plan Packet for Ohio EPA Approval
5. Solicit Volunteers from Questionnaire
6. Screen Volunteers and Resolicit as Needed
7. Train Dispatchers, Valvemen, and Homeowners
8. Perform Materials Evaluation
9. Begin Monitoring After Ohio EPA Approval Is Received
10. Collect All Locations Within One Month and Repeat in Six Months

Table 3-7. Lead and Copper List of Monitoring Questions for Ohio EPA

1. Are the Bolton & California plants two different systems?
2. How do we determine the number of people served by each plant?
3. Is an estimate of population served, based on pumpage acceptable? i.e.,
Bolton service area population 96,360 based on 12% total CWW pumpage
WTP service area population 706,640 based on 88% total CWW pumpage
Total CWW service area population 803,000
4. What are OEPA/USEPA criteria for selection of targeted sites?
5. Will OEPA allow CWW employees to sample their own residences?
6. Are commercial sites considered single-family structures?
7. Can monitoring be spread over 6 months or must it be done all at the same time?
If at 6 months frequency, must the repeat samples be precisely 6 months apart?
8. How should the materials survey be conducted?
9. What is the purpose of each of the two samples at each of the 25 sites and the distribution system entry points?
10. Do WQ parameter samples have to be collected at official bacteriological sites?
11. Will OEPA accept homeowner sampling?
12. How can one guarantee 6-hour static time prior to first draw sampling?
13. Do we need to survey for water-using appliances or leaky plumbing?
14. How do we guarantee that the solder in the 1982 and newer sampling sites is 50/50?
15. Will sites need to be approved prior to sampling?

ing and screening volunteers from questionnaires, and training samplers.

Since CWW has a separate Public Water Supply Identification (PWSID) number for each of its water treatment plants, the total number of sites would be 160. The U.S. EPA appears to consider such situations to be one distribution system, but the Ohio EPA considers the CWW to be two separate distribution systems. CWW shows a fair distribution of copper branches, but the lead service branches only occur in clusters

in the northern half of the distribution system and hardly at all in the northwestern part of the system, which is supplied by the Bolton plant. If there are two distribution systems, how does CWW delineate the two? Are there any additional requirements in the mixing zone (wherever it might be on a given day)? These questions had to be resolved to the best of CWW's ability.

CWW determined that it would need to collect 100 samples from its California Ohio River treatment plant service area and 60 samples from its Bolton service area. These numbers were based on the population served by each system. Each of the systems includes lead service lines and copper service branches that were installed after 1983. Therefore, CWW assumed that Tier 1 sampling was required and that half of the samples in each system had to be lead and the other half fairly new copper installations with 50/50 solder. Obtaining a representative sampling of lead services in the Bolton system would be possible only in a cluster area. The other requirement of pipe installed after 1982, however, would easily yield a group of sites scattered evenly throughout the distribution system. Current and former CWW employees, as well as employees of U.S. EPA's Drinking Water Research Division and the Ohio EPA who reside in the area served by the distribution system, would be asked to perform sampling, as long as representative sampling could be achieved. This approach could provide the most credible set of samples possible, given the knowledge base of these potential sample-location homeowners. Private citizens who wished to participate would not be excluded if they could meet the requirements. Obviously, locations with automatic ice-makers, humidifiers, and leaks would not provide adequate samples without precautions. A questionnaire identified potential problem areas for follow-up discussions. All of the first 6-month monitoring was planned for January or February 1992 and samples would be analyzed the following month, thus establishing the cold weather conditions; a repeat 6 months later would establish the warm weather conditions. Also, this method would provide a finished program in time to evaluate any necessary follow-up prior to January 1993.

CWW put its lead and copper program together using experts from each of the pertinent divisions involved with water distribution. The Water Quality and Research Division has responsibility for adding the proper chemicals and ensuring optimum treatment and the distribution of quality water to the customer. The Distribution Division has responsibility for ensuring that water pipes are properly selected and laid to deliver potable water with proper pressure. These representatives know precisely where the water from each plant goes and the location of various types of mains and service branches. The Commercial Division determined when various materials were installed and provided target lists for representative sampling. The Engineering Division has design and contracting responsibility for pipe installed in the system. This team provided a CWW response to a monitoring program that appears to satisfy the intent of the federal law. From the studies that CWW has conducted, it is apparent that lead can be present when water is allowed to stand in contact with plumbing and piping materials for extended periods of time. The challenge now is to understand the magnitude of the problem in CWW's distribution system and implement a program that will minimize the presence of harm-

ful corrosion by-products while keeping other health-threatening constituents under control.

3.5 Integrating Water Testing and Occupancy Certification

One way to ensure high-quality water at the consumer's tap is to integrate water testing with occupancy certification for facilities. The experience of Durham, North Carolina, demonstrates the usefulness of such a program in ensuring that drinking water meets standards for lead as well as other parameters.

3.5.1 Case Study Three—Durham, North Carolina

The City of Durham, North Carolina, has a new facility water testing program that has improved the quality of water at the customer's tap. The water is tested for standing and running lead, standing and running copper, and heterotrophic plate count (HPC) and coliform bacteria. The water at the facility must meet minimum standards before an occupancy permit is allowed.

3.5.1.1 Background for Developing the Program

In 1985, a survey was conducted in Durham to determine the presence of elevated lead levels. Sampling was conducted at 582 buildings and elevated lead levels were discovered, especially in samples collected from new facilities. Lead levels in excess of 15,000 µg/L were observed in a few unoccupied new homes in which water had been standing in the line for an undetermined period of time (Table 3-8). Sixty-two of the 582

Table 3-8. Lead Concentrations in Samples Collected as Part of Durham Lead Survey

| Location | Sample Date | Lead Concentration, µg/L | |
|--|-------------|--------------------------|---------|
| | | Standing | Running |
| #34 Clearwater Place | 09/16/85 | 17,000 | 20 |
| #34 Clearwater Place (1st Resample) | 09/18/85 | 76 | 10 |
| #34 Clearwater Place (2nd Resample) | 09/23/85 | 10 | <10 |
| 3414 Shady Creek Dr. | 09/16/85 | 11,000 | 20 |
| 3414 Shady Creek Dr. (1st Resample) | 09/18/85 | 950 | 10 |
| 3414 Shady Creek Dr. (2nd Resample) | 09/23/85 | 20 | <10 |

samples exceeded 50 µg/L (the city lead limit prior to August 1991). All 62 sites in violation were less than 2 years old. Even new facilities soldered with 95-5, tin/antimony solder were found to be in violation of the 50 µg/L lead standard (due to lead impurity in the solder and lead in fixtures).

Of the 62 locations that exceeded 50 µg/L lead in the standing water sample in 1985, 58 were resampled in January 1988. No standing sample exceeded 50 µg/L lead and only 2 exceeded 20 µg/L of lead. Only 8 standing samples exceeded 5 µg/L and no running sample exceeded 5 µg/L.

To further demonstrate that Durham's lead problem existed primarily with new facilities, approximately 100 new facilities were sampled in cooperation with the Inspections Department. Using the standards finally adopted into the program, more than 30 percent of the facilities failed one of the three parameters tested (lead, copper, and bacteria). In addition to lead, bacteria and copper were found to be major contaminants of these new facilities during this survey.

3.5.1.2 Implementation of the Program

Since it was demonstrated that Durham had a problem with lead, copper, and bacteriological contamination in new facilities, the new facility water testing program was developed and presented to the City Council for approval. The City Council approved the program effective July 1, 1987. The program was initiated in June 1988. The implementation of this program was slow because of the coordination needed among various city departments. The city water distribution system also serves areas of Durham County beyond the city limits. Therefore, both city and county Plumbing Inspections Divisions had to be involved for sample collection. The Engineering Department, which controls the distribution and collection system, was involved whenever flushing of the distribution system was needed to improve water quality. In addition, sampling and testing procedures had to be established and local organizations representing real estate agents, building contractors, and plumbing contractors had to be notified about the new procedures. As a result of making these contacts, the implementation went relatively smoothly. There were some problems with real estate agents and owners, especially when "closing" deadline dates were being postponed by test failure. But with extra efforts by all parties involved, most of these problems were resolved.

3.5.1.3 Sampling and Analysis

A 100-mL sample is taken for standing and running lead and copper. The standing sample is taken after a minimum of 8 hours standing time. The running metal and bacteriological samples are taken after running the water for at least 2 minutes. The samples are collected by the plumbing inspectors during final inspection. If resamples are required, they are taken by Water Resources personnel.

The standards established by the city are:

1. Lead: standing and running 15 µg/L (August 1, 1991)
2. Copper: standing and running 1.3 mg/L (August 1, 1991)
3. Heterotrophic Plate Count Bacteria: 100 colonies/mL
4. Coliform Bacteria: 0 colonies/100 mL

If these standards are not met, the occupancy permit is withheld.

This testing program requires access to a free-flowing outlet for sample collection with no question of access authority. There have been no problems with authority to gain access to free-flowing outlets with other programs, such as cross-connection control, and Durham definitely has control over facilities that have not been approved for connection to the water system. Once facilities, especially private homes, are occupied, it is

much more difficult to arrange for sampling. Standing samples are almost impossible to obtain.

The city maintains a certified laboratory equipped with three atomic absorption (AA) spectrophotometers; two are equipped with a graphite furnace, used for lead analysis. Although it is possible to analyze lead at a lower level, 5 µg/L has been established as the analytical detection limit. Copper is analyzed with standard flame AA.

For the standard plate count bacteriological test, a 24-hour incubation period is used instead of the 48 hours usually used by the city. This shorter time is used to expedite the testing procedure. The coliform analysis is by membrane filter procedure.

Since the occupancy permit is withheld until the water meets the water quality criteria, it is important to complete the analyses as soon as possible. Samples are received from the Inspections Department at about 5:00 p.m. Bacteriological analyses are initiated immediately, and lead and copper are analyzed within 24 hours. This system produces final results in less than 24 hours.

If the facility fails any of the parameters, the company that requested the test, usually the builder, is notified and requested to flush the system thoroughly. Each outlet, hot and cold, is to be flushed for a minimum of 30 minutes at maximum velocity. The facility is resampled 24 hours after flushing is completed. The resample is analyzed on the day it is collected. If the sample fails the resample, further investigation is made to determine the reason for failure before refilling and resampling.

The program is partially financed by a \$40 fee collected with the meter fee. There is a \$30 resample fee for the first resample. Any additional resamples are without charge.

3.5.1.4 Results of the Program

This program has improved the water quality at residential plumbing taps. From June 1988 through December 1990, 4,826 facilities were sampled and tested (Figure 3-7). Some 1,521, or 27 percent, failed one or more of the three tested parameters. Without this program, the occupants of 1,500 facilities would have consumed water that failed to meet the city standards. If five people in each facility consumed the water, then 3.8 percent of the 130,000 people served by the water system would have consumed water that failed to meet water standards. In the same period, 297 facilities, or 5 percent, failed coliform

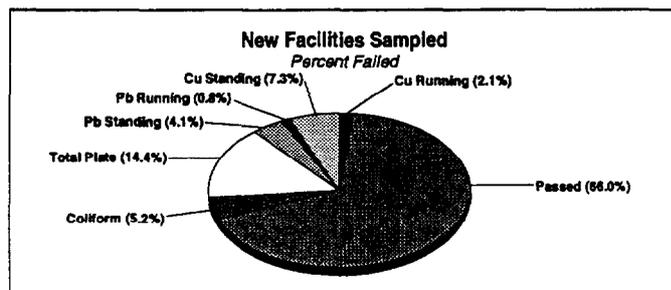


Figure 3-7. Percent of samples failing lead, copper, coliform, and standard plate count tests.

bacteria testing, and 820, or 15 percent, failed the standard plate count for bacteria. Also, 234, or 4 percent, failed the standing lead standard of 50 µg/L. Even 47, or 1 percent, would have failed the running lead test. Without the program, the occupants of 412 facilities would have consumed water with a copper content in excess of 1 mg/L (the city copper limit prior to August 1991). Some copper levels were found in excess of 100 mg/L.

Failures to meet the standing lead standard decreased from 15 percent, when the program started, to less than 1 percent in December 1990. The failures because of standing copper have decreased from 11 percent to 5 percent from June 1988 to December 1990. These results probably are because of better workmanship by the builders (Figure 3-8).

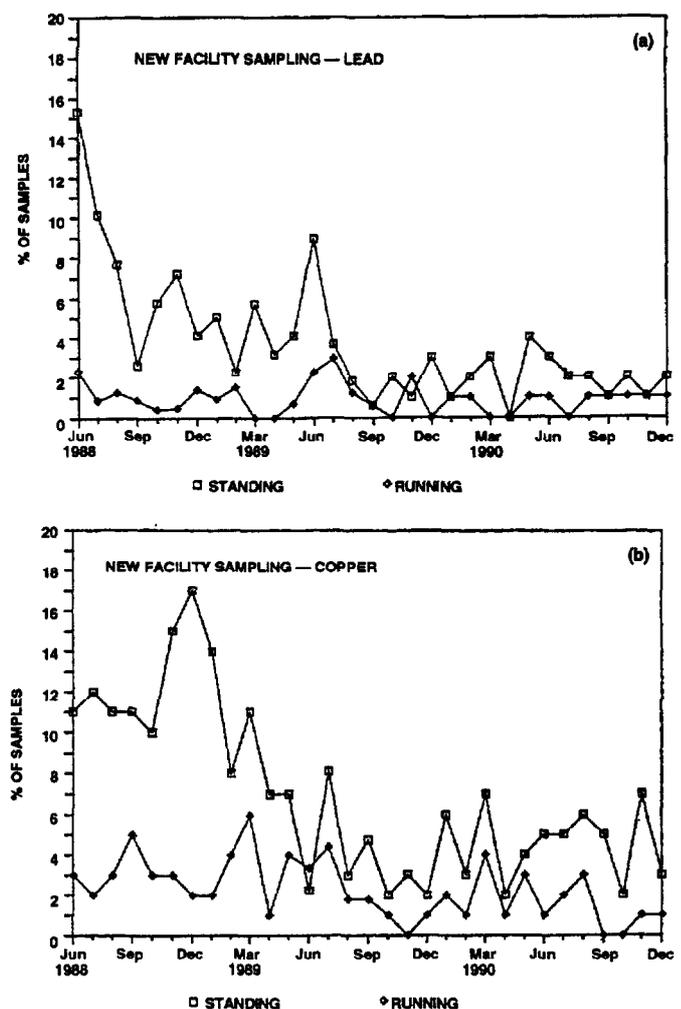


Figure 3-8. Percent of samples failed for lead (a) and copper test (b).

Figure 3-9 illustrates that bacteria and copper contamination are also water quality problems for new facilities. It is important to correct for these parameters as well as for lead.

No new facility testing program is responsible for meeting any water standard. The testing program only indicates whether

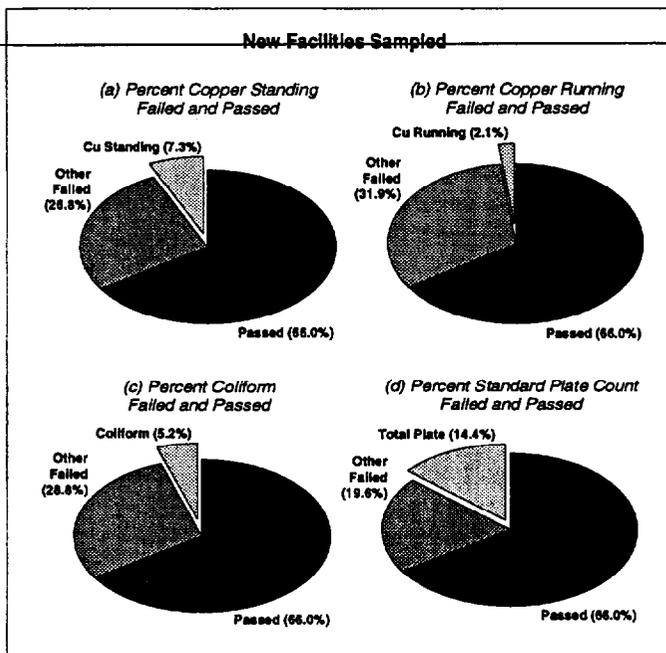


Figure 3-9. Percent samples failed and passed for copper, coliform, and standard plate count tests.

standards are being met. Action to correct the water problem must accompany the testing program. No system with corrosive water such as Durham's should expect to meet a lead or copper limit without a correctly applied corrosion control program. The City of Durham has used zinc-orthophosphate for corrosion control since 1976. This phosphate-based compound was tested extensively from 1974 through 1976 and found to be very effective in drinking water for controlling both iron and copper corrosion. Although lead corrosion was not tested, the compound also has been proven effective for lead control in other systems. Some products tested, such as metaphosphates, a form of polyphosphate, increased copper corrosion and thus possibly lead corrosion.

A flushing program also is essential to ensure high-quality water within the distribution system. This program must include flushing all water lines on a regular basis. All new facilities must be adequately flushed. No water line should be constructed without a way to flush the line. Hydrants or blow-offs must be installed on the ends of all lines. A sampling program is of limited value without mechanisms in place for correcting potential problems.

A cross-connection control program is essential if water quality standards are to be met at the residential taps. No new facility sampling program is adequate without a cross-connection control program.

A new facility sampling program is valuable in policing the illegal use of lead solder, but an education and training program to forestall the use of lead in water systems is probably even more effective. A new facility sampling program also will identify high levels of copper. Good workmanship and proper use of solder flux will help prevent high levels of copper in drinking water.

The practice of grounding electrical systems, both AC and DC, to the water system should cease. Although it was not identified as a problem in Durham, electrical grounding has been implicated in causing copper corrosion. If lead corrosion is controlled by isolation of the copper cell in a dissimilar metal cell consisting of lead and copper, then electrical grounding also could cause lead corrosion.

3.5.1.5 Acceptance of the Program

Reaction to and acceptance of the program was varied. The Inspections Department's initial reactions were all negative. Such comments as the following were common:

- There is no way we can handle the extra workload.
- The program is just too much trouble. Our people are not trained to collect samples.
- The delay in occupancy will make the program unworkable.
- The public will never stand for the delay.

Although the Water Resources Department accepted this program, the overtime requirements caused difficulty. As a result, the requirements have been reduced by allowing the laboratory staff to work "flex time."

Appreciation and support for the program, as well as complaints, have been received from builders and contractors. A frequent complaint is "no one else is doing it." Many have complained about the extra expense. "I can't close and will miss the sale" is probably the most frequent comment in opposition to the program from the builders and contractors. A few cases of illegal use of lead solder were discovered. Of course, builders objected to having to re-plumb the facility. Individuals are now aware that inspections are being performed, and therefore little if any lead solder presently is being used. When problems that are not directly attributable to the builder—usually bacteria in Durham's water system—cause the facility to fail, extensive complaints result. On the other hand, many builders have recognized the value of the program for assuring their customers that the water meets quality standards, especially in regard to lead.

Most opposition from consumers has been because of a delayed move. A few commercial establishments have had to delay opening after widely advertising an opening date. Although some individuals concluded that the problem must be with the water system, many have expressed support for the program. Lead in drinking water has received significant attention in the Durham area. It has helped to have facts to share with the public and to have a positive program to deal with the lead contamination problem.

The State Division of Health Service Water Supply Branch, which has primacy in North Carolina, has been complimentary but noncommittal about the new facility water testing program. Other water systems representatives have commented that the Durham testing program is making matters difficult for them. An investigator from the University of North Carolina who

conducted a survey by actual lead analysis of water throughout North Carolina has stated that Durham has the least serious problem with lead in the entire state. Of the 120 homes with copper plumbing tested, only 4, or 3.3 percent, exceeded a first-draw lead level of 15 $\mu\text{g/L}$. The highest lead level found was only 31 $\mu\text{g/L}$, probably as a result of the new facility sampling program and the corrosion control program.

3.5.1.6 Effect of Lowering the Lead Standard

The lead limit has been lowered to 15 $\mu\text{g/L}$ in drinking water. Although the lower limit results in a larger number of failures, additional flushing by the builder still meets the lower lead standard (Figure 3-10).

3.5.1.7 Summary

The new facility sampling program has resulted in improved water quality at the consumer's tap. The program has proven to be economical and without jurisdictional problems concerning the purveyor's authority on private property. The new facility sampling program is recommended to all water purveyors.

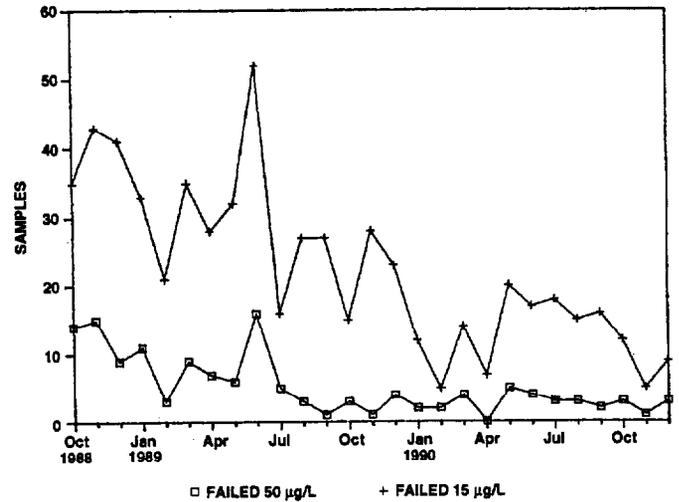


Figure 3-10. Number of samples exceeding 50 vs. 15 $\mu\text{g/L}$.

Chapter 4

Corrosion Control Assessment

Large public water systems (PWSs) will be required to conduct corrosion control studies, and medium-sized and small systems might need to conduct studies if required by the state. This chapter provides guidance on how utilities should conduct corrosion control studies to meet the requirements of the lead and copper rule.

Several methodologies, including coupon tests, electrochemical testing devices, and pipe loops, can be used to assess the effectiveness of various corrosion control strategies. Coupon tests are based on weight loss measurements. Electrochemical measurements use devices that sense the flow of electrons, providing a direct measurement of corrosion. Of particular interest to utilities are pipe loop systems that simulate residential plumbing systems and whose key measurements consist of metal levels. This chapter provides an overview of each of these corrosion control assessment methodologies.

4.1 Basics of a Corrosion Control Study

The lead and copper rule requires corrosion control studies to be performed by large PWSs and those small and medium-sized PWSs required to do so by the state because they exceed the lead or copper action level (AL). The lead and copper rule defines certain conditions that must be met by these studies, but it does not specify (1) the investigative components necessary to accomplish the study, (2) the testing protocols to be used, (3) the procedures for evaluating data, or (4) the basis for identifying "optimal" corrosion control treatment. This section discusses these issues and provides recommendations for states and utilities for performing and evaluating corrosion control studies. It also presents examples of corrosion control studies to illustrate alternative approaches and rationales used in the design, implementation, and interpretation of findings generated by these studies.

4.1.1 Regulatory Requirements

The lead and copper rule (141.82(c), 56 FR 26550) specifies six conditions that must be met when performing a corrosion control study:

- (1) **Evaluate** the effectiveness of each of the following treatments and, if appropriate, any combinations of these approaches:
 - (a) pH/alkalinity adjustment (carbonate system passivation)

- (b) Calcium hardness adjustment (calcium carbonate precipitation)

- (c) Phosphate- or silicate-based inhibitors (phosphate or silicate passivation)

- (2) **Protocols** should include the use of pipe rig/loop tests, metal coupon tests, partial-system tests (full-scale), or analyses based on documented analogous treatments with other systems of similar size, water chemistry, and distribution system configuration.

- (3) **Analytes** are to include the following water quality parameters in the course of testing: lead, copper, pH, alkalinity, calcium, conductivity, water temperature, and orthophosphate or silicate when an inhibitor containing the respective compound is used.

- (4) **Constraints** (chemical or physical) that can limit the application of a particular treatment option are to be identified and the existence of one of the following conditions should be documented:

- (a) A particular corrosion control treatment has adversely affected other water treatment processes when used by another PWS with comparable water quality characteristics.

- (b) From the experience of the PWS, a particular corrosion control treatment has been demonstrated to be ineffective and/or to adversely affect other water treatment processes.

- (5) **Secondary impacts** due to the effect of corrosion control treatment on other water treatment processes are to be evaluated.

- (6) **Recommendation** of the optimal corrosion control treatment, as identified by the PWS based on an analysis of the data generated, is to be provided to the state with supporting documentation and rationale.

While these elements present important pieces of a corrosion control study, they do not clearly delineate how to organize and execute a study.

4.1.2 Study Components

Three major elements are available to PWSs in defining optimal treatment through a corrosion control study:

- **Desktop evaluations** to determine the range of treatment alternatives.

- **Demonstration testing** to define the performance of alternative corrosion control treatment approaches.

- **Source water evaluations** to assess whether removal of lead and copper is necessary through the treatment facilities prior to distribution.

The full scope of corrosion studies will vary from system to system, and the methods and procedures used to reach a recommendation necessarily will reflect this level of site specificity. During the state review of these studies, the following criteria can provide a framework for evaluating PWS findings and recommendations for optimal treatment:

- Reasonableness of the study design and findings.
- Technical integrity of the data handling and analysis procedures.
- Best professional judgment of the state regarding the decision-making criteria used by the PWS in determining the recommended optimal corrosion control treatment.

The following sections describe the scope of the testing and evaluations that PWSs might be required to perform.

4.1.2.1 Scope of Corrosion Control Testing Activities

By requiring all systems conducting studies to evaluate specific treatment alternatives, EPA did not intend for all PWSs to construct pipe rigs or conduct bench-scale tests to accommodate any and all treatment options. It is anticipated that desktop evaluations will be used as a preliminary step in the study. Alternatives are to be screened on the basis of the available findings from: (1) other corrosion control studies for systems with comparable water quality, (2) theoretical and applied research efforts, and (3) the potential adverse impacts associated with treatment modifications. As a result of this desktop evaluation, primary alternatives are to be selected (at most, two

or three treatment options) for additional evaluation via demonstration testing.

Beyond the desktop evaluation, the specific components, or steps, included in performing corrosion control studies depend in part on the extent of testing required. EPA believes that, in certain cases, the results of the desktop evaluation would suffice in the selection of optimal treatment and additional testing would not be required.

Small and medium-sized systems must recommend optimal corrosion control treatment to the state within 6 months of exceeding an AL. EPA envisioned the use of a desktop evaluation to be a sufficient level of effort for these systems to identify optimal treatment. The state retains the discretion to require additional testing should the supporting documentation and rationale provide insufficient justification.

Some large PWSs might not need to perform demonstration testing to identify optimal treatment. Table 4-1 presents a recommended matrix of the degree of testing to be performed by large PWSs based on the results of initial monitoring for lead. The rule classifies the existing treatment of large PWSs as optimized for corrosion control only when the difference between the 90th percentile tap water lead level (Pb-TAP) and the highest source water lead concentration (point of entry [Pb-POE]) is less than the practical quantitation level (PQL) of 5 µg/L for each 6-month period of the initial monitoring program. If this condition is met, then no study or testing is required and the monitoring results for copper are irrelevant. It is recommended, however, that states give some consideration to the presence of copper in tap samples when determining whether the treatment in place is optimized.

Large PWSs not experiencing problems with lead corrosion might find elevated levels of copper for which corrosion control treatment would be warranted. The recommended level of effort for corrosion control studies by large PWSs based on copper is as follows:

Table 4-1. Recommended Corrosion Control Study Components for Large PWSs Based on Lead Levels

| Tap Lead Level as the 90th Percentile, µg/L | Source Water (POE) Lead Level, µg/L | | |
|---|--|--|---|
| | Pb-POE < PQL | PQL < Pb-POE < 10 | Pb-POE > 10 |
| Pb-TAP < PQL | None required | — | — |
| PQL < Pb-TAP < 10 | None required | None required | — |
| 10 < Pb-TAP < 15 | Desktop evaluation | If (Pb-POE - Pb-TAP) < PQL, then none; otherwise, desktop evaluation | No corrosion control testing Source water treatment recommended or required |
| Pb-TAP > 15 | Desktop evaluation and demonstration testing | Desktop evaluation and demonstration testing | If (Pb-POE - Pb-TAP) < PQL, then only source water treatment required. Otherwise, desktop evaluation and demonstration testing and source water treatment recommended or required. |

- Copper AL exceeded and source water copper is low (Cu-POE \leq 0.2 mg/L): Desktop Evaluation + Corrosion Testing.
- Copper AL exceeded and source water copper is high (Cu-POE $>$ 0.2 mg/L): Desktop Evaluation + Corrosion Testing + Source Water Treatment.
- Cu-TAP (90th percentile) contribution is $>$ 0.5 mg/L: Desktop Evaluation + Corrosion Testing.
- Cu-TAP (90th percentile) contribution is $<$ 0.5 mg/L: Desktop Evaluation.

4.1.2.2 Evaluating Source Water Contribution

PWSs are required to monitor lead and copper at the points of entry (Pb/Cu-POE) only if either AL is exceeded on the basis of first-flush tap samples. Some systems might choose to monitor the source water contribution of these metals simultaneously with first-flush tap sampling to determine whether the existing treatment is optimal with regard to corrosion control (90% Pb - Pb-POE $<$ PQL). Otherwise, this monitoring must be completed within 6 months of exceeding the lead or copper AL.

All systems must submit source water treatment recommendations to the state within 6 months of exceeding an AL. While the lead and copper rule is silent with respect to the levels of lead or copper that mandate treatment, Table 4-2 provides a guideline for source water treatment needs. If the source water is contributing more than the AL for either lead or copper, then source water treatment is required. In cases where a significant amount of lead or copper is present, treatment is recommended to reduce the overall lead or copper exposure and to assist PWSs in meeting the ALs in future monitoring events. Table 4-2 also shows that source water treatment is optional when moderate levels of metals are found and is unnecessary when very low levels of either lead or copper are present.

Table 4-2. Source Water Treatment Guidelines

| Source Water Treatment Guidelines | Point of Entry Monitoring Results | |
|-----------------------------------|-----------------------------------|-----------------------|
| | Lead, $\mu\text{g/L}$ | Copper, mg/L |
| Not Necessary | ≤ 5 | ≤ 0.2 |
| Optional | 5–10 | 0.2–0.8 |
| Recommended | 10–15 | 0.8–1.3 |
| Required | > 15 | > 1.3 |

In cases where systems find elevated levels of lead or copper, the sources of supply (raw water) should be monitored prior to treatment and at various stages within the existing treatment facility (if currently treating the supply) to determine the source of the metals. This monitoring also will help the system assess the performance of the existing treatment in removing lead and copper.

Several types of treatment might be appropriate for removal of lead and copper. EPA specified the following techniques in the lead and copper rule:

- Ion exchange
- Reverse osmosis
- Lime softening
- Coagulation/filtration

If a PWS currently is providing conventional treatment (whether alum or ferric coagulation, iron/manganese removal, or lime softening), modifying these processes might produce the desired results. If treatment is not available, package treatment units for any of the above technologies can be installed at individual wellheads (especially when the elevated metals are contributed by a small number of individual wells) or at a centralized treatment location. In the case of elevated copper, eliminating copper sulfate applications might reduce the background level of copper for some surface water facilities.

States must respond to the recommendations for source water treatment within 6 months. If required, PWSs have 24 months to install source water treatment once that treatment is approved by the state. For large PWSs, the installation of source water treatment could precede corrosion control treatment by as much as 18 months. Followup monitoring for Pb/Cu-POE and first-flush lead and copper tap samples will occur simultaneously, however, after corrosion control treatment has been installed.

4.1.3 Desktop Evaluations

The logic diagram shown in Figure 4-1 presents the process involved in performing desktop evaluations for selecting alternative treatments for further investigation or the optimal treatment for systems not required to perform demonstration testing. This procedure allows systems to eliminate any treatment approaches that are not feasible and then to determine the water quality conditions defining the best corrosion control treatment approaches. Among the remaining alternatives, the system should select the optimal treatment on the basis of the following criteria:

- Corrosion control **performance** based on either the reductions in metal solubility or the likelihood of forming a protective scale.
- The **feasibility** of implementing the treatment alternative on the basis of the constraints identified.
- The **reliability** of the alternative in terms of operational consistency and continuous corrosion control protection.
- The estimated **costs** associated with implementing the alternative treatments.

The first step is to describe the existing conditions of the PWS in terms of its water quality parameters and the theoretical estimation of lead and copper solubility as well as the potential for calcium carbonate precipitation. Changes in water quality conditions for alternative treatments should be compared to the

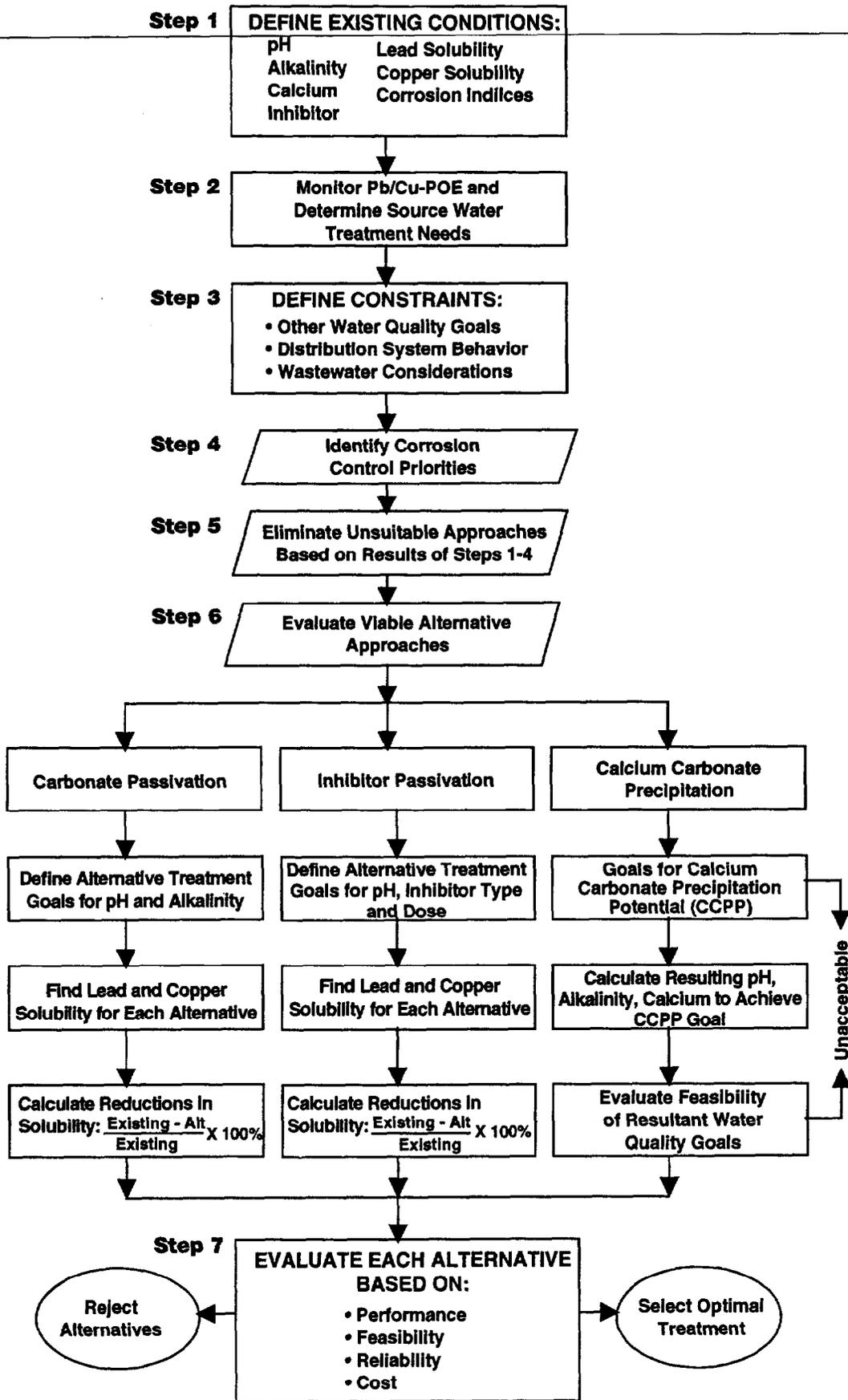


Figure 4-1. Logic diagram for evaluating alternative corrosion control approaches.

existing conditions to determine relative performance and potential to reduce corrosion.

Each PWS operates within certain constraints—such as conflicting water quality goals, existing coatings in distribution system piping, multiple sources of supply of varying water quality, and wastewater permit limits on metals or nutrient levels—that can be improved or compromised by corrosion control treatment. The PWS should identify and document any constraint that could affect the feasibility of implementing an alternative treatment. This information will be important in the selection of those treatment options that are viable alternatives for the PWS to consider further.

Based on the water quality characteristics of the supply and site-specific constraints, the PWS can eliminate corrosion control treatment approaches that would be infeasible to implement successfully. The remaining options should be evaluated on the basis of each PWS's corrosion control treatment priorities. For example, a system that experiences lead levels greater than the AL in first-flush tap samples should set lead control as its primary goal. A second system that finds low lead levels, but has elevated copper levels in first-flush tap samples, should set copper as the primary objective of corrosion control treatment. In the latter case, however, optimal treatment should not worsen lead corrosion behavior, and the control of lead can be considered a constraint on the decision-making process for selecting optimal treatment for copper control.

Each of the corrosion control treatment approaches that are viable options should be evaluated to determine the water quality characteristics that describe optimal treatment within each option. For the passivation methods (pH/alkalinity adjustment and corrosion inhibitors), alternative treatments are evaluated by comparing their ability to reduce the solubility of each targeted metal (lead and/or copper). The calcium carbonate precipitation method is evaluated by comparing the ability of alternative treatments to produce sufficient potential for scale-forming conditions to exist in the distribution system. The "rule of thumb" guidelines presented in Appendix A of EPA's *Lead and Copper Rule Guidance Manual, Volume 2* (see Chapter One for ordering information) can be used to rank the alternatives within this treatment approach.

The final selection of optimal treatment will rest on the four factors discussed above: performance, feasibility, reliability, and costs. Direct comparison of corrosion control performance for alternative treatment approaches might not be possible. Professional judgment and experience will be necessary to provide a basis for ranking alternatives.

The following sections provide more detailed descriptions of the steps involved in performing a desktop evaluation of alternative treatments and developing final recommendations for optimal treatment.

4.1.3.1 Documenting Historical Evidence

The first step of the desktop evaluation is to identify and document any existing information pertinent to the evaluation of corrosion control for the system. Four categories of data

should be compiled: (1) water quality data, (2) evidence of corrosion activity, (3) results of corrosion studies performed by other PWSs as reported in the literature, and (4) results from prior corrosion studies or testing performed by the PWS. The most pertinent information is the results of any prior corrosion control testing performed by the system. Beyond the direct testing results, the PWS should conduct a comprehensive review of the other sources of information.

Water Quality Data. The PWS should compile and analyze current and historical water quality data. The key parameters of interest include pH, alkalinity, hardness, total dissolved solids or conductivity, temperature, dissolved oxygen, and metals (e.g., aluminum, manganese, iron, lead, and copper). These basic water quality parameters only represent those most commonly required. The system should consider site-specific requirements when selecting water quality parameters for review. The data collected should pertain to raw and finished water conditions as well as to the water quality in the distribution system, if available. Additionally, the results of the initial monitoring program should be considered when available.

Understanding the treatment processes at a PWS facility and their effects on water quality is an important aspect of interpreting the water quality data and evaluating the appropriateness of alternative corrosion control treatment techniques (1). Figure 4-2 illustrates the relationship between water quality and alternative corrosion control treatment approaches. In many cases, site-specific water quality conditions will reduce the feasibility of an alternative treatment approach. For example, it would be reasonable to eliminate the calcium carbonate precipitation option as a viable treatment approach for PWSs exhibiting low pH, alkalinity, and hardness in the treated water. Conversely, a PWS exhibiting high pH conditions with moderate to high alkalinity and calcium content might concentrate its efforts on calcium carbonate precipitation, for the following reasons:

- Although high pH conditions might be optimal for lead control, these water quality conditions are very aggressive towards iron corrosion and most likely would cause severe degradation in distribution system water quality if calcium carbonate precipitation is not pursued.
- High dosages of corrosion inhibitors might be necessary to maintain an effective residual throughout the distribution system due to the presence of calcium. Also, some inhibitors can cause existing corrosion by-products to be released in the distribution system, resulting in water quality degradation (2).

Figure 4-2 is intended to provide general guidelines on water quality conditions vs. alternative treatment approaches; it is not intended to serve as the sole basis for selection or elimination of the available alternatives. Furthermore, a PWS must use caution any time a corrosion control approach requires a severe modification of the existing water quality entering the distribution system. Disruptions and upset of existing corrosion by-products will affect the overall performance of any corrosion control treatment approach.

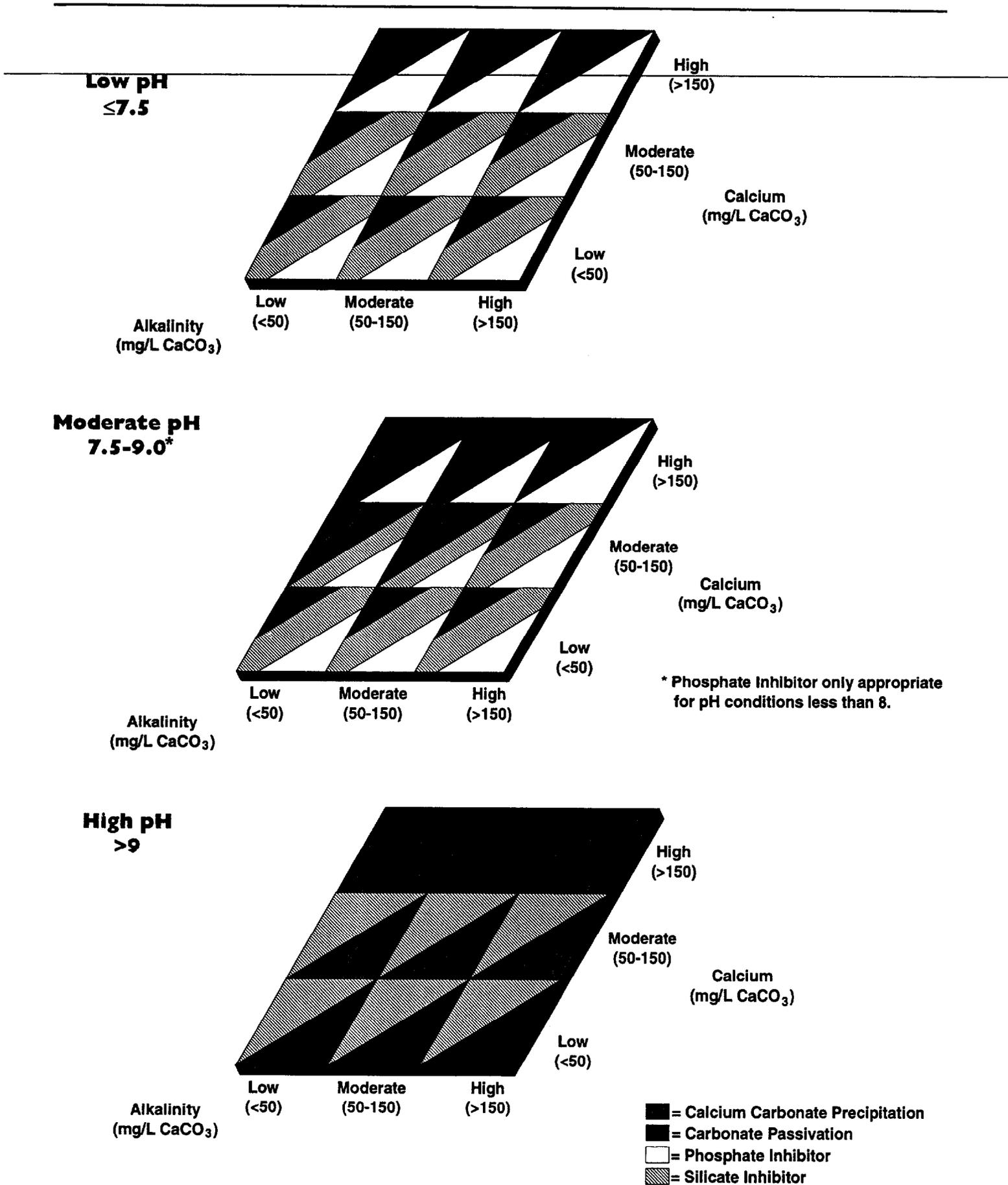


Figure 4-2. Suggested corrosion control approaches based on water quality characteristics.

Corrosion Activity. The PWS should identify and analyze existing records indicating corrosion activity within the distribution and home plumbing systems to obtain information about the nature and extent of corrosion activity anticipated within the service area. Evidence of corrosion activity can be obtained by: (1) reviewing customer complaint records for dirty water or metallic taste and odor events, (2) performing an informal survey of area plumbers regarding the frequency and nature of plumbing repairs (especially, for example, hot water heater replacements), (3) reviewing records citing the inspection of distribution system mains and service lines when they are being replaced or repaired, and (4) water quality monitoring for metals or other corrosion by-products within the distribution system or home plumbing environments.

Several factors should be considered in evaluating the usefulness of this information: (1) the frequency of data collection, (2) the number of coupons, if used, and their locations within the distribution system, (3) the analytical methods and their respective detection limits, (4) the temporal and spatial consistency of the data, and (5) the reliability of the incidence reports. The results of the initial monitoring program required by the lead and copper rule, if available, should be included in this pool of information.

This information can be used to set priorities among the corrosion control program elements by identifying the key materials for protection and to assess the general effectiveness of the existing treatment approach.

Review of the Literature. The PWS should review the available literature to ascertain the findings of similar systems when performing corrosion control testing and the theoretical basis for alternative corrosion control approaches.

Several water suppliers in the United States have performed corrosion control studies and published the results (3,4,5,6). Each study has site-specific goals and objectives, as well as water treatment and quality conditions, relevant to the testing protocols. The experiences of these systems provide a useful resource to other PWSs investigating corrosion control in terms of study design and execution, data handling and interpretation, and recommended treatment given the goals and constraints acting on the system. EPA's *Lead and Copper Rule Guidance Manual, Volume 2* contains a summary of the available literature on corrosion control studies.

Prior Experience and Studies. Corrosion control treatment is not a new concern for water suppliers, and many systems have performed studies in the past to assist in the design and implementation of corrosion control treatment. These past experiences and studies should be revisited by PWSs to incorporate their findings and results in the present evaluation of corrosion control for lead and copper. In some cases, the prior testing targeted lead and copper control. These findings would be directly applicable to the corrosion control study objectives for the lead and copper rule. Therefore, additional testing might not be necessary to formulate recommendations for optimal corrosion control treatment (if not already considered to be in place).

Example:

The Town of Allywad, a small PWS operating a ground water well, found lead levels above the action level during initial monitoring. To prepare recommendations for optimal treatment, the PWS operator began collecting information about the condition of distribution system materials and the experiences of nearby towns and communities. From previous pipe replacement activities, the PWS operator had noticed a thin, buff-colored deposit on the walls of the distribution system piping. Since the ground water source is well buffered, with an average pH of 7.4, alkalinity of 160 mg CaCO₃/L, and calcium hardness of 140 mg CaCO₃/L, this deposit was assumed to be calcium carbonate.

A nearby township with wells located in the same aquifer as Allywad had installed orthophosphate inhibitor feed facilities for corrosion control. The township's experience was not altogether positive. It had a significant number of turbid and dirty water complaints after the addition of the orthophosphate. The township gave up the use of the corrosion inhibitor to restore the aesthetic quality of the delivered water supply.

After learning of these experiences, the Town of Allywad decided to eliminate the use of orthophosphates from its list of alternative corrosion control treatment approaches.

4.1.3.2 Identifying Constraints

The lead and copper rule provides two conditions by which a water system may identify constraints that limit or prohibit the use of corrosion control treatments: (1) the treatment has been shown to adversely impact other water treatment processes and cause a violation of a National Primary Drinking Water Regulation, or (2) the treatment has been shown to be otherwise ineffective for the PWS.

PWSs should evaluate the impact of alternative corrosion control treatment options on compliance with existing federal and state drinking water standards, and with regulations anticipated to be finalized within the timeframe for corrosion control installation by small and medium-sized PWSs. Table 4-3 presents the schedule for regulatory actions during the next decade in conjunction with the compliance timeline for medium-sized and small system implementation steps for the lead and copper rule. The key regulatory actions that small and medium-sized PWSs should fully evaluate to select optimal corrosion control treatment are discussed below.

- Under the **Surface and Ground Water Treatment Rules (SWTR/GWTR)**, PWSs will be required to meet disinfection performance criteria. These criteria are pH-dependent for free chlorine, where less effective disinfection results under higher pH conditions.
- The **Total Coliform Rule (TCR)** requires all PWSs to meet minimum occurrence standards for total and fecal coliforms in distribution system samples. Some PWSs have noted increases in microbiological growth within the distribution system after installing corrosion control treatment. In most cases, however, corrosion control treatment has been found to have little or no effect on heterotrophic plate counts.

Table 4-3. Schedule of Drinking Water Regulatory Activity: 1990–2000

| Regulatory Action | Proposal Date | Final Date | Effective Date |
|--|---------------|-------------|----------------|
| Phase I Volatile Organic Chemicals | 11/85 | 07/87 | 01/89–01/91 |
| Phase II Synthetic Organic Chemicals and Inorganic Chemicals | 05/89 | 01/91–07/91 | 07/92–01/93 |
| Phase V Synthetic Organic Chemicals and Inorganic Chemicals | 07/90 | 03/92 | 09/93 |
| Phase IIb Arsenic | 11/92 | 01/95 | 07/96 |
| Surface Water Treatment Rule | 11/87 | 06/89 | 07/93 |
| Total Coliform Rule | 11/87 | 06/89 | 01/91 |
| Radionuclides Rule | 07/91 | 04/93 | 10/94 |
| Ground Water Disinfection Rule | 06/93 | 06/95 | 01/97 |
| Disinfectants/Disinfection By-Products | 06/93 | 06/95 | 01/97 |
| Lead and Copper Rule | 08/88 | 05/91 | 07/91-01/99* |

*Dates reflect effective date of the lead and copper rule through small PWS installation of optimal treatment after the system exceeds ALs during first round of initial monitoring and is required to perform a corrosion study.

- The **Disinfectants/Disinfection By-Products Rule (D/DBPR)**, currently under development, will be finalized when PWSs are installing corrosion control treatment as a result of the lead and copper rule. Adjusting pH conditions can affect the level of certain DBPs, especially total trihalomethanes (TTHMs) and total haloacetic acids (THAAs). These two contaminant groups are likely to be included in the future DBPR, and they exhibit opposite relationships to pH adjustment; that is, TTHM formation increases with increasing pH, and THAA formation increases with decreasing pH. An additional consideration is the point of pH adjustment within treatment plants, since lower pH conditions favor increased removal of DBP precursors during coagulation by alum. Compliance with the DBPR could be compromised by increasing the pH of coagulation as part of the corrosion control treatment approach, because this might reduce the efficiency of conventional treatment in removing precursor material.

Additional constraints that PWSs should consider beyond those required by the rule include:

- Compatibility of a treatment approach with multiple sources of supply.
- Compatibility of a treatment approach for consecutive systems.
- Reliability features for the particular treatment approach, including: (1) process control, (2) operational redundancy requirements, and (3) chemical supply integrity and availability.

- Adverse impacts on the service community, including: (1) commercial users' water quality criteria, (2) health-care facility water quality criteria, and (3) wastewater operations (permit requirements for discharges and solids handling programs).

The particular conditions that define the constraints for each system will be site-specific. The PWS should investigate these conditions thoroughly as part of the desktop evaluation aspect of the corrosion study. Small and medium-sized systems that exceed the ALs but are not required to perform testing should consider each of these items when selecting the optimal treatment for recommendation to the state. Large PWSs required to perform only a desktop evaluation must present rigorous documentation of any constraints to support the recommended treatment approach for the system. For any PWS performing corrosion testing, the availability of information regarding system constraints will assist in limiting the optional treatment approaches that must be evaluated through the testing program.

It is recommended that all constraints acting on the PWS be identified and considered in the selection of treatment approaches either for additional testing or as the recommended treatment process. Worksheets are provided in Tables 4-4(a) and 4-4(b) for each of the three treatment alternatives (pH/alkalinity adjustment, calcium adjustment, and corrosion inhibitors) to assist PWSs in evaluating the constraints on their systems.

Example:

After exceeding the lead AL during initial monitoring, the City of Dannyport began investigating alternative corrosion control treatment measures to provide the state with recommendations for optimal treatment. The city had concerns about the medium-sized surface water facility's compliance with the SWTR and selection of optimal treatment for corrosion control. The existing treatment provided by Dannyport is conventional coagulation/flocculation with rapid sand filtration. Under the SWTR, at least 0.5 logs of inactivation of *Giardia* and 2.0 logs of virus inactivation were required. For the *Giardia* requirements, the plant's performance is adequate to meet the C^*t required, i.e., the $C^*_{\text{lact}}:C^*_{\text{req}}$ is 1.2 at present. Virus inactivation performance is satisfactory and is not affected by pH changes. *Giardia* inactivation performance, however, is a function of pH, and at the higher pH levels under consideration for corrosion control, the resulting $C^*_{\text{lact}}:C^*_{\text{req}}$ ratios are 0.99 and 0.83, respectively. Neither case would provide adequate disinfection performance.

An additional concern is continued compliance with the total trihalomethane (TTHM) standard. Currently, an average of 60 $\mu\text{g/L}$ TTHM is found in the distribution system with seasonal peaks of nearly 100 $\mu\text{g/L}$ TTHM. Increasing the pH of the finished water supply could only increase the probability of Dannyport exceeding the future TTHM standard, which is expected to be finalized at the same time that the city initiates corrosion control treatment.

Given the above regulatory concerns, the City of Dannyport determined that pH adjustment would not be a feasible option.

Table 4-4(a). Constraints Worksheet for pH/Alkalinity or Calcium Adjustment Treatment Alternatives

Adjusting pH/alkalinity and/or calcium for corrosion control typically consists of augmenting their levels to generate favorable conditions for lead and copper passivation or calcium carbonate precipitation.

A. National Primary Drinking Water Regulations Constraints

| Rule | Constraint |
|------------------------------|--|
| Surface Water Treatment Rule | Reduces inactivation effectiveness of free chlorine. Potential for interference with dissolved ozone measurements. Might increase turbidity from post-filtration precipitation of lime, aluminum, iron, or manganese. |
| Ground Water Disinfection | Reduces inactivation effectiveness of free chlorine. Potential for interference with dissolved ozone measurements. |
| Disinfection By-Products | Higher THM concentrations from chlorination. Reduced effectiveness of some coagulants for precursor removal. |
| Coliform Rule | Potential for higher total plate counts, confluent growth, or presence of total coliforms when chlorination is practiced. |
| Radionuclides | In-plant adjustments can affect removal of radioactive particles if precipitation techniques are used for coagulation or softening. Removal of radionuclides during softening might be linked to the degree of softening. Modifying softening practices to achieve corrosion control could interfere with removals. |

B. Functional Constraints

Increased potential for post-filter precipitation can give undesirable levels of aluminum, iron, or manganese.

Process optimization is essential. Additional controls, chemical feed equipment, and operator attention might be required.

Multiple entry points will require pH/alkalinity adjustment at each entry location. Differing water qualities from multiple sources will require adjusting chemical doses to match the source.

The use of sodium-based chemicals for alkalinity or pH adjustments should be evaluated with regard to the total sodium levels acceptable in the finished water.

Users with specific water quality needs, such as health care facilities, should be advised of any changes in treatment.

Excessive calcium carbonate precipitation can produce "white water" problems in portions of the distribution system.

It might be difficult to produce an acceptable coating of calcium carbonate on interior piping for large distribution systems. High calcium carbonate precipitation potential (CCPP) levels eventually might lead to reduced hydraulic capacities in transmission lines near the treatment facility, while low CCPP values might not provide adequate corrosion protection in the extremities of the distribution system.

Table 4-4(b). Constraints Worksheet for Inhibitor Treatment Alternative

Corrosion inhibitors can cause passivation of lead and copper by the interaction of the inhibitor and metal components of the piping system.

A. National Primary Drinking Water Regulations Constraints

| Rule | Constraint |
|------------------------------|--|
| Surface Water Treatment Rule | The application of phosphate-based inhibitors to systems with existing corrosion by-products can result in the depletion of disinfectant residuals within the distribution system. Additionally, under certain conditions phosphate-based inhibitors can stimulate biological growths which can result in high heterotrophic plate counts. |
| Ground Water Disinfection | Same as above. |
| Disinfection By-products | No apparent effects. |
| Coliform Rule | If corrosion by-products are released after the application of inhibitors, coliforms might be detected more frequently and confluent growth is more likely. |
| Radionuclides | No apparent effects. |

B. Functional Constraints

Potential post-filtration precipitation of aluminum.

Consumer complaints regarding red water, dirty water, color, and sediment might result from the action of the inhibitor on existing corrosion by-products within the distribution system.

Multiple entry points will require multiple chemical feed systems.

The use of sodium-based inhibitors should be evaluated with regard to the total sodium levels acceptable in the finished water.

The use of zinc orthophosphate might present problems for wastewater facilities with zinc or phosphorus limits in their NPDES permits.

Users with specific water quality needs, such as health care facilities, should be advised of any treatment changes.

4.1.4 Corrosion Study Organization

The suggested framework for the performance of a corrosion study is shown in Table 4-5, presenting a logical sequence of steps organized to satisfy the requirements and recommendations described in this section. For completing steps 1 through 3, a logic diagram was presented in Figure 4-1, referring to desktop evaluations. The result of the desktop evaluation for those systems performing corrosion control studies is the selection of alternative treatments to be evaluated in the demonstration testing step of the study. (Small and medium-sized

Table 4-5. Organization of the Major Components in Corrosion Control Studies

Step 1. DOCUMENT HISTORICAL EVIDENCE

- Review PWS water quality and distribution system characteristics
- Review PWS evidence of corrosion activity
- Identify prior corrosion control experiences and studies performed by PWS
- Identify prior corrosion control experiences and studies performed by other PWSs with similar characteristics

Step 2. IDENTIFY CONSTRAINTS

- Interferences with other water treatment processes
- Compatibility of multiple sources of supply
- Compatibility for consecutive PWSs
- Reliability features for particular treatment approach, including (1) process control, (2) operational redundancy requirements, and (3) chemical supply integrity and availability
- Adverse impacts on the community: commercial users, wastewater operations, health-care facilities

Step 3. DECISION

For any PWSs NOT Required to Perform Testing to Evaluate Alternative Treatments:

- Formulate decision criteria
- Select primary treatment alternatives.
- Go to Step 5

For any PWS required to perform testing to evaluate alternative treatments:

- Formulate minimum feasibility criteria for alternative treatments
- Select the alternative treatments to be included in the testing program
- Establish overall decision criteria for selection of optimal corrosion control treatment

Step 4. ASSESS CORROSION CONTROL PERFORMANCE BY TESTING

- Develop testing protocols and procedures
- Perform testing program and collect data
- Analyze data generating corrosion control performance results
- Rank performance results by priority of corrosion control program goals

Step 5. PRELIMINARY COST ESTIMATES AND FACILITY MODIFICATIONS

- Prepare preliminary facility design
- Prepare preliminary cost estimate

Step 6. DECISION:

- Based on the decision criteria established at the outset, formulate recommended corrosion control treatment and submit to the state

PWSs not required to perform testing otherwise would select the recommended treatment on the basis of the desktop evaluation as shown in Figure 4-1.)

When the alternative treatments have been selected for evaluation, a testing program is formulated and implemented. This includes such steps as:

- Developing testing protocols, procedures, and frequency for data collection and evaluation.
- Analyzing the resultant data to generate performance measurements.
- Determining the performance ranking of the alternative treatment approaches on the basis of corrosion control, secondary treatment impacts, and process operations and control.

The PWS should prepare preliminary design and cost estimates for the alternative treatment approaches selected from the desktop evaluation. Although cost is not directly a factor in assigning optimal treatment, instances will occur where comparable treatment performance is observed among two or more treatment approaches. Holding all else constant, cost might be the deciding factor in selecting optimal treatment. Additionally, preliminary design will be required for the state review process.

The PWS can base the final recommendation of optimal corrosion control treatment on the results of a decision criteria matrix and the ranking of the alternative processes. The system must fully document and present to the state the rationale for the selection.

4.1.5 Demonstration Testing

A PWS can use a variety of approaches and mechanisms to evaluate corrosion control treatment through demonstration testing. Although flexibility exists for the actual design of a testing program, all such endeavors should clearly define and document the following elements of the study:

- *Measures of corrosion activity*, such as weight loss, metal leaching, corrosion rates, and surface condition.
- *Sampling program design*, including sampling frequency, locations, volume, parameters, and analytical methods.
- *Materials used to simulate the targeted piping environment*, such as lead, copper, iron, lead soldered joints, and brass.
- Protocols for material exposure, specifically, flow-through or static environments under predetermined operating conditions.
- *Data handling and analysis techniques*, including statistical testing and identifiable approaches to the interpretation of the findings.
- *Secondary testing requirements* to determine the potential impacts of alternative corrosion control treatment on existing PWS operations and on compliance with other drinking water standards.

- *Quality assurance/quality control program* elements for each aspect of the testing program.

The remainder of this section discusses each aspect of corrosion control testing program design as identified above in general terms. Each PWS, however, is responsible for the design and execution of a testing program that meets its own overall goals and objectives.

The premise underlying corrosion control testing is that alternative treatment approaches should be evaluated in terms of their relative reductions (or increases) in corrosion activity for specific materials of concern. Quite often, testing efforts are used to predict the behavior of various treatment components. In this respect, corrosion studies differ. It is NOT the intended purpose of these studies to either: (1) predict the levels of lead or copper in first-flush tap samples from targeted consumers' homes or (2) predict the actual reductions in corrosion activity within the distribution or home plumbing systems. Instead, the purpose of corrosion control testing is to **demonstrate** the relative performance of alternative treatment approaches.

4.1.5.1 Flow-Through Testing Protocols

The use of flow-through testing methods to evaluate corrosion control performance is preferred, because these methods more accurately simulate the home plumbing environment, where the majority of lead and copper corrosion originates. The protocols and methods described below are suggestions that PWSs undertaking flow-through testing can consider in the design and execution of their demonstration study.

Flow-through testing refers to continuous or cycled flow-through conditions through a testing apparatus where the solution is not recirculated. Typically, flow-through testing is used to describe pipe rig operations where pipe loops or coupon/insert apparatus are attached to a central pipe which distributes the test water to one or more corrosion testing units. Figure 4-3 illustrates conceptually a flow-through pipe rig.¹

¹For a more detailed description of standardized pipe rig construction and implementation, see the American Water Works Association Research Foundation (AWWARF), *Lead Control Strategies* (Denver, CO: AWWARF, 1990) or P. Temkar et al., *Treatment Evaluation for Reducing Lead Dissolution from Plumbing Systems Using CERL Pipe Loop System* (Champaign, IL: U.S. Army Construction Engineering Research Laboratory, 1989).

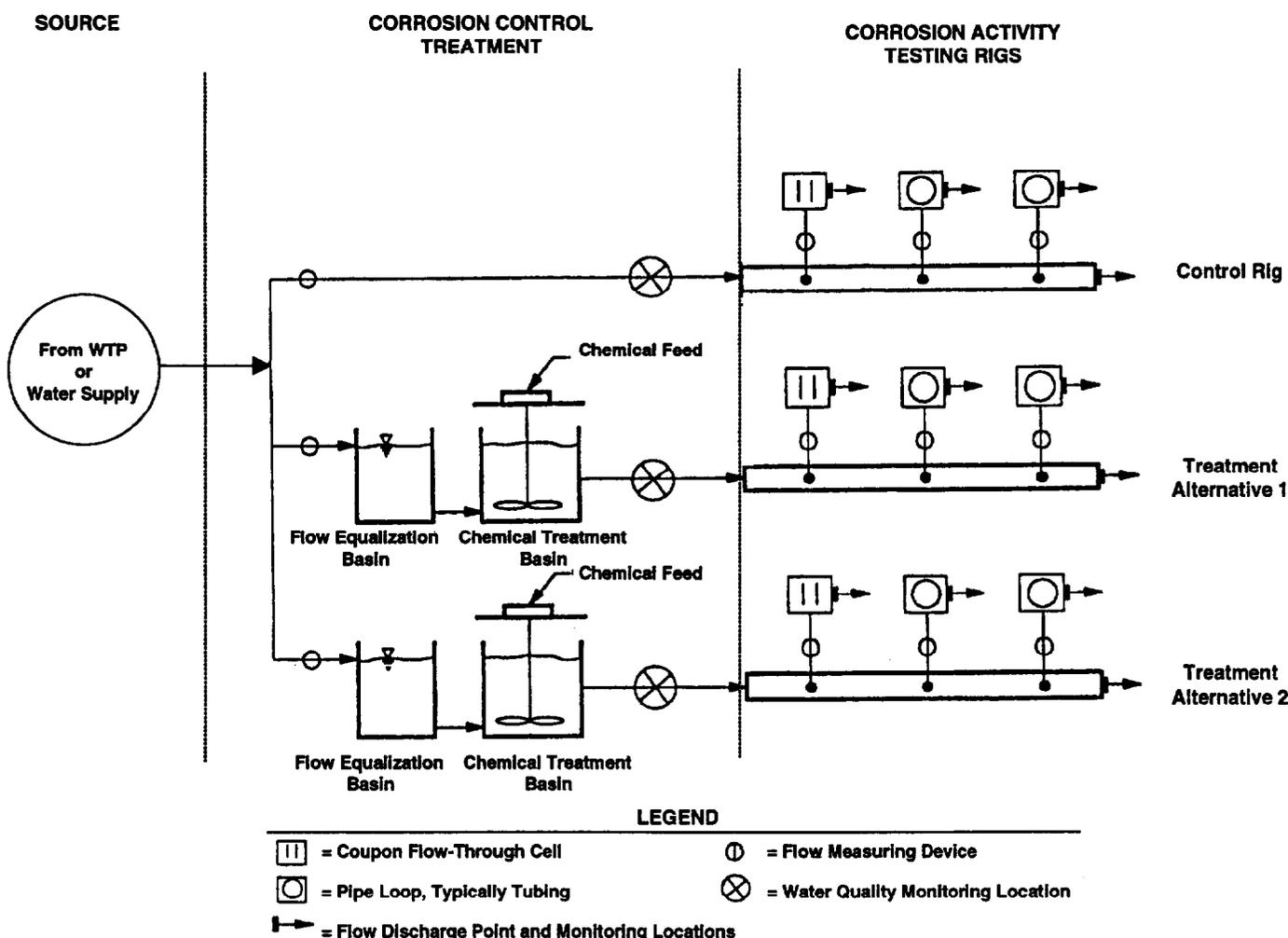


Figure 4-3. Conceptual layout of flow-through testing schemes.

Flow-through testing methods provide the following advantages for determining corrosion control treatment:

- Evaluation of a limited number of alternative treatment approaches with more rigor than static tests provide.
- Refinement of the chemical feed and water quality conditions that best describe the selected corrosion control treatment option.
- Improved simulation of the real-world conditions present in the distribution system that the selected corrosion control treatment will need to address.

PWSs and others conducting such studies should consider the following general recommendations regarding the design and implementation of a flow-through testing program:

- Duration of testing should be 9 to 12 months to capture seasonal effects. The longer the testing period, the more confidence a PWS can have in distinguishing treatment performance.
- A standardized sampling program should be established before initiating the testing period to enhance the analysis of results.
- Alternative locations for siting the testing apparatus should be considered: (1) laboratory or water treatment plant, (2) remote within the distribution system, or (3) distribution system in situ apparatus. Sites experiencing significant amounts of vibrations or humidity should be avoided. These conditions can interfere with the performance of the testing apparatus.
- The test material surfaces should be evaluated at the conclusion of each test run for each material in order to assess the corrosion behavior of the treatment alternative more completely.
- When first-flush samples are being collected, the samples should be drawn slowly so as not to induce high-velocity events within the test apparatus.
- For each sample withdrawn, water quality parameters and inhibitor residuals (if appropriate) should be analyzed in addition to the metal content of the sample.
- To the extent practical, the test conditions evaluated should simulate the chemical feed application points and finished water quality conditions expected during full-scale operations.

An important feature of this testing method is the in-line corrosion control treatment that must be performed to generate the test solutions. This treatment requires some pretreatment appurtenances, such as chemical feed pumps, constant head tanks, flow meters, and water quality sampling stations. In some cases, the operation and control of the corrosion control treatment component of the test rig can be as complicated as the pipe rig itself, if not more so. The PWS should pay careful

attention to the feasibility of creating a "continuous" supply of treated water prior to any final testing decisions.

PWSs might be able to use the flow-through testing system on a long-term basis to assist in understanding the corrosion response of the distribution system on the full-scale level. In many cases, relationships between the flow-through testing system and the metal levels found in first-flush tap samples can be developed in terms of trends in responses to treatment conditions. Calibration of the flow-through testing system to first-flush tap samples would be required for this use, necessitating concurrent flow-through testing and first-flush sampling activity beyond the initial monitoring period. Continued use of the flow-through testing systems could provide PWSs with an additional mechanism to determine the potential effects of treatment changes on the full-scale level.

4.1.5.2 Testing Program Elements

The design and operation of a flow-through testing program requires special consideration of several study components. These components are briefly discussed below.

Pipe Rig Operation and Fabrication. The required flow rate through a pipe rig depends on the number of connections it is supplying. Typically, between 0.5 and 2 gallons per minute (gpm) of flow through a pipe loop is adequate. If a pipe rig consists of two or three loops, then at least 1.5 to 6 gpm of flow is required. Operating a rig at much higher flow rates could compromise its feasibility, depending on the complexity of the pretreatment component. For example, a system feeding soda ash for alkalinity and pH modification at an average rate of 20 mg/L and operating the testing rig for 16 hours of continuous flow with 8 hours of standing time each day would require 29 gallons of stock solution (20 mg/mL) for a 6 gpm pipe rig. Daily stock solution requirements beyond 30 gallons become difficult to handle, especially when extremely concentrated solutions are used.

Additional attention must be given to the limitations of the pretreatment component when a slurry chemical feed condition exists, such as lime. Stock solution strengths of hydrated lime become problematic when solutions more concentrated than 10 mg/mL are used, depending on the pump head and tubing sizes used. (The use of quick lime for testing rigs is not very practical because of the large amount of impurities and the inability to properly slake the lime.) These solutions also require continuous, rigorous mixing during application to ensure a consistent suspension of the slurry solids.

When a system uses a corrosion inhibitor, typically requiring much lower dosages and therefore much lower feed rates, the pretreatment step is less limiting on the design and operation of the pipe rig system. Systems exploring corrosion inhibitors might have more flexibility in terms of the number of loops and/or coupon/insert apparatus that a single pipe rig can accommodate.

The pipe loops attached to the rig should be of sufficient length to permit a 1-L sample to be collected without introduction of water from the central pipe. Table 4-6 presents the

Table 4-6. Pipe Volumes by Tubing Length and Diameter

| Pipe Volume Table (Volumes Listed in Liters) | | | | | | |
|---|---------------------|------|------|------|------|-------|
| Pipe Length (ft) | Pipe Diameter (in.) | | | | | |
| | 3/8 | 1/2 | 5/8 | 3/4 | 1 | 1 1/4 |
| 1 | .03 | .04 | .07 | .09 | .16 | .25 |
| 2 | .06 | .09 | .14 | .19 | .32 | .50 |
| 3 | .09 | .14 | .21 | .29 | .49 | .74 |
| 4 | .11 | .18 | .27 | .38 | .65 | .99 |
| 5 | .14 | .23 | .34 | .48 | .81 | 1.24 |
| 6 | .17 | .27 | .41 | .57 | .97 | 1.48 |
| 7 | .20 | .32 | .48 | .67 | 1.14 | 1.73 |
| 8 | .23 | .36 | .55 | .76 | 1.30 | 1.98 |
| 9 | .26 | .41 | .62 | .86 | 1.46 | 2.22 |
| 10 | .28 | .45 | .69 | .95 | 1.62 | 2.47 |
| 11 | .31 | .50 | .75 | 1.05 | 1.78 | 2.72 |
| 12 | .34 | .55 | .82 | 1.14 | 1.95 | 2.96 |
| 13 | .37 | .59 | .89 | 1.24 | 2.11 | 3.21 |
| 14 | .40 | .64 | .96 | 1.33 | 2.27 | 3.46 |
| 15 | .43 | .68 | 1.03 | 1.43 | 2.43 | 3.71 |
| 16 | .46 | .73 | 1.10 | 1.52 | 2.60 | 3.95 |
| 17 | .49 | .78 | 1.16 | 1.62 | 2.76 | 4.20 |
| 18 | .51 | .82 | 1.23 | 1.71 | 2.92 | 4.45 |
| 19 | .54 | .86 | 1.30 | 1.81 | 3.08 | 4.70 |
| 20 | .57 | .91 | 1.37 | 1.90 | 3.24 | 4.94 |
| 25 | .71 | 1.14 | 1.71 | 2.38 | 4.06 | 6.18 |
| 30 | .86 | 1.36 | 2.06 | 2.85 | 4.87 | 7.41 |
| 35 | 1.00 | 1.59 | 2.40 | 3.33 | 5.68 | 8.65 |
| 40 | 1.14 | 1.82 | 2.74 | 3.80 | 6.49 | 9.88 |
| 60 | 1.43 | 2.27 | 3.43 | 4.76 | 8.11 | 12.36 |

Notes:

1. Volumes can be added together for pipe lengths not listed.
2. Liters can be converted to gallons by dividing by 3.785.

volume of water contained in various lengths of piping by interior diameter dimension. Standard plumbing materials should be used for the pipe loop tubing. All materials used for each rig should be obtained from the same lot of piping. For example, if copper piping loops are to be used in three different pipe rigs, evaluating three different treatments, then all of the copper used in each rig should be purchased at the same time from the same lot. This minimizes variability in the testing results due to differences in materials.

For copper loops with lead-tin soldered joints, fabrication of all of the loops should be done by the same person and at the same time (do not fabricate one set of loops and then wait several weeks or months before fabricating the next set). In addition, the solder should come from the same spool. After soldering, the piping should be flushed prior to starting the testing program to remove any excess debris.

Test Monitoring Programs. The sampling program for testing rigs should include: (1) the metals being investigated, (2) water quality parameters defining the treatment process, (3)

chemical feed rates and stock solution strengths, (4) water flow rate through each testing apparatus, and (5) sample identification criteria such as test run, date, analyst, time of sampling, sample handling steps, and location of sample.

Prior to initiating the testing program, the system should define the frequency of monitoring for specific parameters and the method of sample collection. For example, first-flush samples can be collected every 2 weeks over a 12-month period for metals and for water quality parameters representative of tap samples. Daily water quality parameter sampling and notation of the appropriate chemical feed and flow rate measurements can be performed when operating the pipe rig, even though tap samples are not collected, to document the water quality conditions to which the test loops are exposed during the study.

4.1.5.3 Static Testing Protocols

Static tests can be performed to ascertain the corrosion behavior of alternative treatments toward different piping materials. Static testing by definition refers to “no flow-through” conditions or batch testing (for example, the jar testing many PWSs perform to evaluate coagulant dosages represents a batch testing protocol). The most common form of static testing is immersion testing, where a pipe material, typically a flat coupon, is immersed in a test solution for a specified period of time. The corrosion behavior then can be described by weight loss, metal leaching, or electrochemical measurement techniques. Other static testing methods include: (1) using a pipe segment of the desired material, filling it with test water and measuring the metal pickup obtained at the conclusion of a specified holding time, and (2) recirculation testing, where a reservoir of test water is circulated through pipe segments or pipe inserts over a period of time. (Although water is flowing through the piping segments, the same “batch” of water is being recirculated during the holding time; in this sense, it represents a static test.)

The general methods described above are not exhaustive. Testing design will be a function of the overall goals and objectives of the testing program.

In many cases, static tests can be used to evaluate more quickly the numerous alternative treatments that might be appropriate for a PWS. This procedure would allow a PWS to narrow the treatment approaches to a more limited number for additional testing, if required. Since flow-through testing programs tend to be more complex and costly, eliminating inappropriate treatment alternatives prior to performing flow-through testing is advantageous. To the extent that static testing can provide such capabilities, it should be included in the comprehensive testing program.

For many systems, however, static testing can be sufficient to identify optimal corrosion control treatment. Small and medium-sized PWSs required to perform corrosion studies should consider static testing programs to verify the appropriate treatment process. Large PWSs also should consider using static tests for developing recommendations on optimal treatment when only a limited number of treatment alternatives are available and flow-through testing is difficult to perform adequately.

Drawbacks associated with using the static testing protocols as the basis for selecting optimal corrosion control treatment include the following:

- Static testing conditions do not represent the conditions to which piping systems are subject during normal operations. Household plumbing environments experience on-and-off cycles of flow, and the distribution system piping network experiences continuous flow-through conditions.
- The variability found in testing results might confound a PWS's ability to differentiate treatment performance among the alternatives tested. Replicate testing and measurements are important components of the testing design, providing additional precision and accuracy assessment capability.
- Comparability of the test results with full-scale performance is uncertain based on existing information. It might be useful for PWSs to place coupons or pipe inserts within the service area and at water treatment plant effluent lines during the testing program. This would provide a basis of comparison between the static tests (control conditions only) and the full-scale system.

4.1.6 Data Handling and Analysis

Data needs are an important consideration in the design of the testing program (7,8). Analytical procedures should be defined clearly prior to developing the testing program. These procedures should: (1) describe the behavior of the testing data, and (2) generate performance rankings for the alternative treatments. The most useful approach to statistically evaluating corrosion control data involves the application of nonparametric statistics.

Underlying all statistical measures are certain fundamental assumptions regarding the "true" behavior of the data or its universe. The most commonly applied statistical tests (such as the student's t test, chi-square distribution, difference of means, and analysis of variance) are preconditioned to describing universes that exhibit a normal distribution of their values. Corrosion control testing data, however, tend to be non-normal, and therefore conventional statistical measures would not describe the behavior of the data accurately, or would not reliably generate results that could be used to rank alternative treatments. Nonparametric analyses accommodate non-normal conditions and can be applied to develop relative performance measures for numerous treatments.

The nonparametric tests of importance are: (1) the Wilcoxon test, or U-test, which can compare the results of two conditions to determine whether they behave similarly (i.e., no difference in corrosion performance can be ascertained) or whether they behave differently (i.e., one treatment method produces better corrosion protection), and (2) the Kruskal-Wallis test, or H-test, which is the more general case and can evaluate more than two test conditions.

The information to be collected for each testing run includes descriptions of: (1) test conditions (run number, treatment dosages of applied chemicals, water quality parameters,

and date), (2) sampling event (control vs. test apparatus, location of sampling point, time, and type of material), and (3) analytical results (water quality parameters such as pH, temperature, alkalinity, hardness, inhibitor residual, disinfectant residual, lead, copper, iron, etc., and/or coupon weight conditions).

Data base management capabilities for microcomputer applications are satisfactory for evaluating most corrosion study data. The use of spreadsheets or data base management software in conjunction with statistical analysis programs is essential when large amounts of data are collected.

4.1.7 Secondary Testing Programs

Secondary testing programs are vital to the overall study design because this corollary information will be incorporated into the selection process for defining optimal treatment. A major area of concern for secondary treatment is how the alternative corrosion control treatment can be installed successfully and operated to meet future state-mandated operating conditions that define compliance with the lead and copper rule. When pH, alkalinity, or calcium adjustment are components of a treatment alternative, the stability of these parameters between the point of adjustment and finished water entry to the distribution system should be ascertained. The likelihood of inhibitors and key water quality parameters remaining within acceptable limits in the distribution system also should be investigated.

The PWS must achieve compliance with existing and future drinking water standards after the installation of corrosion control treatment. Testing to evaluate these conditions should be included in the design of the corrosion control study. Of particular concern might be changes in: (1) the levels and types of disinfection by-products that might occur, (2) the occurrence of positive total coliform events, including those induced through increases in the presence of heterotrophic plate count bacteria, or (3) disinfectant residual concentrations.

4.1.8 Quality Assurance/Quality Control Programs

Critical to the interpretation of the data and findings is ensuring that proper quality assurance and quality control (QA/QC) procedures were followed during the testing program. A well-designed QA/QC program permits the investigator to describe more accurately the variability introduced into the data by the response of testing materials to the corrosion control treatment processes being evaluated. Elements to be included in a QA/QC program include:

- Sufficient sampling frequency for water quality parameters during the period of time when water is flowing. Sufficient sampling frequency is necessary to adequately describe the test conditions to which the materials were subject between first-draw samples. For example, if standing samples are collected each week, then at least daily sampling for water quality parameters should be performed for the treated water supplied to the pipe rig.

- Split samples for metal analyses, especially when metal test kits are used. It is recommended that at least 5 percent of the samples collected be split samples.
- Preparation of sample blanks and spikes by someone other than the chemical analyst to verify routine measurements. A sample blank and spike should be performed during each testing period for metals.
- Proper calibration of all analytical instruments at the beginning of each testing period. Chemical feed and flow rate meters should be fully calibrated prior to the initiation of testing and checked periodically during the testing program.
- Sample handling procedures that follow those required in the lead and copper rule for metals and water quality parameters. Special care should be given to the cleaning procedures used for metals analysis containers to minimize cross-contamination of sampling events.

Each testing program will have specific QA/QC requirements. The PWS should delineate these elements at the beginning to prevent the collection of data that cannot be adequately verified.

4.1.9 Example of Selecting Optimal Treatment

A large PWS performed a desktop evaluation of its system and identified two alternative treatments for further study by corrosion testing. Flow-through testing was performed using pipe rigs with: (1) iron tubing and copper tubing with lead solder, and (2) copper, lead, and iron coupon flow-through cells. Figures 4-4a and 4-4b present the results of the corrosion testing in terms of the percent reductions in metal solubility for standing samples and average weight loss for treatment alternatives A and B as compared to the existing treatment results.

The first step in developing the final treatment selection decision matrix is defining the performance ranking of each treatment evaluated. The score for the best treatment option used in this analysis is 7, for the second, 4, and for the worst option, 0. Given the priorities of the PWS, the weighting factors to each metal were 0.45, 0.40, and 0.15 for lead, copper, and iron, respectively. Because of the increased importance of controlling lead and copper solubility, the measurement weighting factors were 0.7 and 0.3 for solubility and weight loss results, respectively, for lead and copper. For iron, however, the measurement weighting factor was 0.3 and 0.7 for solubility and weight loss results, respectively, because of more concerns about maintenance and repair of iron piping.

Table 4-7 presents the corrosion control performance matrix with the appropriate weighting factors shown. The resulting score indicates that treatment A provided the best corrosion control protection, while treatment B provided the second best, and the existing treatment provided the worst performance. These results are used in the final treatment selection matrix.

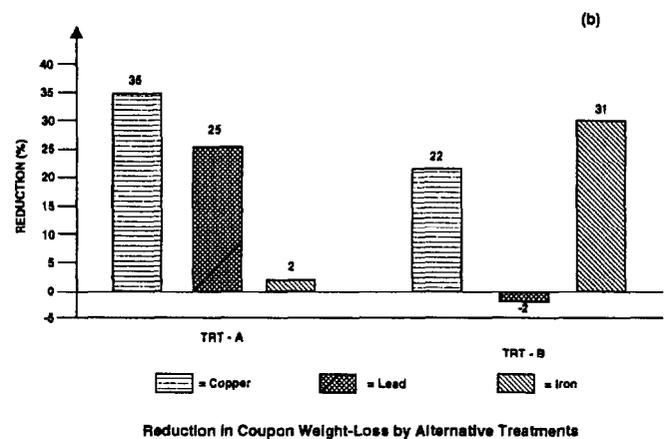
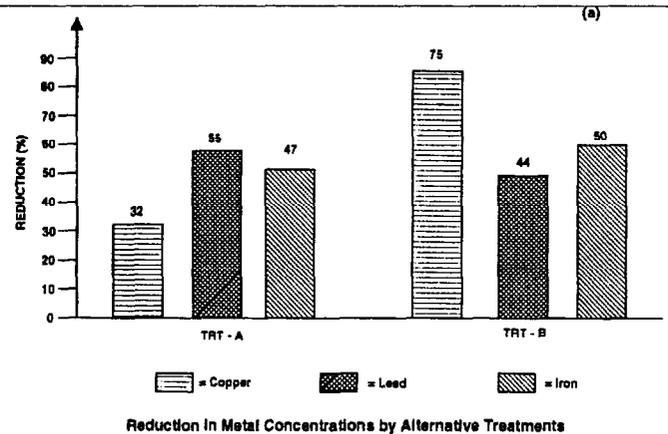


Figure 4-4. Reduction in metal concentrations (a) and coupon weight-loss (b) by alternative treatments.

Table 4-8 presents the final treatment selection matrix for the PWS. Because a desktop evaluation was performed prior to the selection of treatments A and B for further testing, it was determined that all treatment options were equally feasible, eliminating this parameter from the decision matrix. By far, the most important consideration for identifying optimal treatment in this case is treatment performance, shown by setting its weighting factor at 0.75. The reliability and cost weighting factors were set at 0.20 and 0.05, respectively. The reliability of the treatment options is considered more important than the costs, because compliance eventually will be determined by the ability of the PWS to consistently produce finished water that meets its optimal treatment objectives.

Based on the results of the final treatment selection decision matrix, Treatment A would be recommended as optimal corrosion control treatment.

4.1.10 Example of a Flow-Through Demonstration Testing Program

Utility A exceeded the action level for lead during its first 6-month period of diagnostic monitoring and initiated a corrosion control study. The utility treats water from a surface supply

grams, therefore, are used to select treatment techniques; final action levels after installation of full-scale treatment can only be estimated. In the testing program discussed here, finished water from the treatment facility was pumped continuously through all three loops for 4 weeks to partially acclimate the pipe rig before the initiation of the weekly sampling program.

Parametric statistics were used to compare the two treatments with the control. Recognizing that water quality data frequently is skewed, the data were investigated for skewness (as the moment coefficient of skewness approaches zero, the data approach a more normal distribution). If the distribution is normal, or can be made more normal by a transformation, the statistical techniques based on a normal distribution are appropriate; otherwise, they are only approximations and the use of nonparametric statistics might be more appropriate. As indicated in the example, calculating the skewness coefficient, γ , showed that a logarithmic transformation gave smaller skewness coefficients, so the data were evaluated in the log normal mode.

The skewness coefficient is defined as:

$$\gamma = \frac{m_3}{m_2^{1.5}}$$

where:

$$m_2 = \frac{1}{n} \sum x_i^2 - \bar{x}^2$$

$$m_3 = \frac{1}{n} \sum x_i^3 - \frac{3}{n} \bar{x} \sum x_i^2 + 2\bar{x}^3$$

x_i = individual samples, $i = 1$ to n
 \bar{x} = mean

Table 4-10 gives the calculated skewness coefficients for the lead data in Table 4-9 for both normal distributed samples and the log normal mode. The smaller coefficients for the log normal distribution were used as indicators that the data would adapt more appropriately to parametric statistics using a logarithmic transformation.

Table 4-10. Skewness Coefficients for Lead Data

| Mode of Distribution | Skewness Coefficient | | |
|----------------------|----------------------|--------|--------|
| | Loop 1 | Loop 2 | Loop 3 |
| Normal | 1.21 | 0.47 | 0.60 |
| Log Normal | 0.53 | -0.04 | -0.32 |

The student's t statistic was used to compare paired data among the three loops. These results are presented in Table 4-11. The student's t can be defined as:

$$t = \frac{\bar{d}}{s_d}$$

where the numerator represents the mean difference between paired sample data and the denominator represents the standard deviation appropriate to the difference between the sample means. These values then are compared to standard statistical tables to determine if any statistical difference in treatments exists.

Table 4-11. Calculated Student's t Values

| Comparison | t |
|-------------------|---------|
| Loop 1 and Loop 2 | 5.46*** |
| Loop 1 and Loop 3 | 6.98*** |
| Loop 2 and Loop 3 | 2.87** |

Notes: All test data transformed to logarithmic values

**Highly significant difference at the 0.01 level

***Extremely significant difference at the 0.001 level

Results from the testing program indicate that either treatment would be beneficial when considering the entire 35 weeks of data. Any statistical evaluation of data must be tempered with good judgment, however, and reviewing the data seems to indicate fewer fluctuations in all the data during the final weeks of testing. This is a reasonable result, because one would expect the pipes to become more acclimated as the testing program proceeded. Using a data set from week 25 on, the data were examined once again. These results showed that there was still a significant difference when each treatment was compared to the control, but there was no apparent statistical difference between treatments. Thus, the utility needs to examine other factors such as initial cost, operating costs, and operating philosophy before deciding which treatment to implement for full-scale treatment.

4.2 Design Considerations and Procedures for Coupon Tests

4.2.1 Summary of Method

This section presents guidelines for monitoring the corrosivity of water by coupon weight loss methods. The information is based on the ASTM Standard Test Method D 2688-90, Corrosivity of Water in the Absence of Heat Transfer (Weight Loss Methods) (9). Two types of corrosion specimens are described by the ASTM method: flat, rectangular coupons and cylindrical pipe inserts. The cylindrical Illinois State Water Survey (ISWS) and Construction Engineering Research Laboratory (CERL) pipe inserts were developed by the ISWS and were adopted later as an ASTM standard. Coupons have had a long history of use in industrial and research applications. Both coupons and pipe inserts are used routinely in the ISWS laboratory to measure corrosion rates in potable and industrial water systems. Several publications by ASTM, the National Association of Corrosion Engineers (NACE), and others are available that provide additional insight on the application and use of corrosion specimens to measure corrosion rates by the weight loss method (10,11,12,13,14).

The weight loss method simply measures the mass of a metal coupon that has been transformed by corrosion into sol-

uble and insoluble corrosion by-products. A clean metal specimen is weighed and exposed to water for a specified time. The specimen is removed from the water and is cleaned chemically or mechanically to remove all deposits above the underlying metal. The specimen then is reweighed and the weight loss is converted into the desired corrosion terms. Although this premise is simple, many factors must be considered to obtain reliable data when using corrosion specimens in field studies. Some of these factors are addressed in this section, but the section focuses primarily on the laboratory procedures employed to prepare, process, and evaluate both coupon and pipe insert types of corrosion specimens.

The procedures require a laboratory setting. An analytical balance, microscope, fume hood, oven, desiccator, hot plate, and other common laboratory equipment are used to process corrosion specimens. The capability to store, handle, and dispose of chemicals safely is an essential requirement of the procedure. Staff members responsible for carrying out the procedures should have technical training and laboratory experience. In the absence of an in-house laboratory, independent laboratories and consultants might be needed to perform the corrosion studies and conduct corrosion rate measurements.

4.2.2 Basic Corrosion Measurement Considerations

The objectives for determining corrosion rates in potable water systems should be well defined. Typical objectives include determining the water corrosivity, life of materials, and treatment effects. Corrosion specimens have been used in laboratory, pilot-scale, and field experiments to meet these objectives. Laboratory studies generally are used to evaluate the factors that influence the corrosion of metals under closely controlled conditions. The laboratory studies also are useful for accelerated testing and screening.

Corrosion studies conducted in the laboratory, however, do not represent actual service conditions, and pilot-scale and full-scale field studies should be used to complement the laboratory data. In field studies, the corrosion specimens encounter the actual environmental conditions of the system and consequently reflect the variability in corrosion because of water chemistry, temperature, and flow. Since the surface of a corrosion specimen is bare metal, it is not representative of a material in equilibrium with the system. The effects of chemical treatment and water quality on corroded materials will not be reproduced by the clean specimens. Corrosion specimens nevertheless are effective tools for studying or monitoring corrosion, as long as proper procedures are applied and results are interpreted correctly.

Early in the design of a corrosion study, a decision must be made about the type of corrosion specimen to use, the metal alloy or alloys to be tested, and the quantity of specimens needed to complete the study. Both the coupon and the pipe insert type of corrosion specimen have been widely used in potable water systems. The coupon type is the least expensive and the most readily available in a variety of alloys. It also requires less preparation than pipe inserts. The pipe insert type of specimen, however, offers some characteristics that might offset the advantages offered by coupons. Pipe inserts are de-

signed to simulate the environment on the surface of a pipe wall. This environment is usually more representative of the corrosion that occurs in the plumbing system than the disturbed flow environment surrounding coupon installations. Pipe inserts, which are produced from genuine pipe available from local plumbing suppliers, help ensure that the exposed surface and material of a specimen are representative of real piping systems. The inserts also have three to four times the exposed surface area of coupons, which produces more weight loss and sensitivity to surface attack.

Corrosion specimens can be purchased directly from suppliers or they can be prepared in house when adequate laboratory and machine shop support is present. The choice depends on the capabilities, expertise, and desire of staff to assume complete control of a corrosion study. The cost associated with purchasing specimens is relatively low when compared with the total cost of a study. There can be a vast difference, however, in the cost of specimens, depending on the alloy and type of specimen required. The metals of most concern in public water supplies are cast iron, steel, galvanized steel, copper, brass, lead, and solder. Coupons of these materials are readily available from various suppliers. A list of suppliers of coupons and representative costs is shown in Tables 4-12 and 4-13. Suppliers of the ASTM pipe insert specimens are not readily available, and only one has been licensed to distribute the CERL pipe loop and corrosion test assemblies. The ISWS laboratory has always constructed the pipe inserts in house or in local machine shops. The ASTM D 2688-90 method provides the specifications needed to prepare the inserts and test assemblies in house.

Table 4-12. Suppliers of Corrosion Specimens and Pipe Loops (ASTM Method D 2688-90)

Flat Rectangular Coupons, Coupon Holders, and Pipe Loop Assemblies:

INSS, Inc.

2082 Michelson Drive, Suite 100, Irvine, California 92715,
714-250-3033

Metal Samples Company

Route 1, Box 152, Munford, Alabama 36268, 205-358-4202

METASPEC Company

P.O. Box 22707, San Antonio, Texas 78227-0707, 512-923-5999

Cylindrical Pipe Inserts, Supporting Assemblies, and Pipe Loops:

Evans Machine Company (licensed USA-CERL Pipe Loop supplier)

410 Summit Avenue, Perth Amboy, New Jersey 08861,
908-442-1144

4.2.3 Purchasing and Preparation of Corrosion Specimens

Whether corrosion specimens are purchased or prepared in house, the specimens must be machined from a metal of known composition and made of a material equivalent to the piping material to be studied. A mill report should be requested when coupons are purchased to certify the alloy number, composition, and other metallurgical information. The pipe used for the fab-

Table 4-13. Typical Coupon and Pipe Loop Costs

Flat, Rectangular Specimens (1/16" x 1/2" x 3"), preweighed:

| Material | Price range, July 91 (\$ per coupon) |
|------------------------|---|
| Mild Steel, C1010 | 1.60 to 2.65 |
| Copper, CDA 110 | 1.80 |
| Copper, CDA 122 DHP | 3.15 to 4.10 |
| Zinc, 99.9% pure | |
| Lead, 99.9% pure | 1.90 to 6.00 |
| Lead/Tin Solder, 60/40 | 2.00 to 10.00 |

Pipe Plug Assemblies, 3/4" plug, 3" nylon stem:

Price range \$7.25 to \$10.00 per unit

Pipe Loop, PVC, 3/4" Sch. 80, for four (4) plug assemblies:

Price range \$71.00 to \$140.00 per unit

Cylindrical, Pipe Specimens, USA-CERL type, 3/4' x 4", preweighed:

Estimated Price \$20 to \$35 per specimen, depending on material (does not include lab fees). A complete CERL Pipe Loop, with meter, pump, etc., can cost \$1,200 to \$2,000.

rication of pipe inserts should be inspected for metallurgical defects, physical damage, and surface films. All pipe that does not meet high quality standards should be rejected. A sufficient number of specimens should be purchased, or sufficient material should be in stock, to provide an ample number of identical specimens to meet the demand of current and anticipated corrosion studies.

Coupons of the same alloy must be identical, if possible. Each must be machined and treated in the same manner. They must have the same size, shape, and surface finish. Steel, copper, and galvanized zinc coupons are impacted with glass beads for a final finish, whereas lead and solders are scoured with a fine abrasive powder. During the finishing process, extreme care must be taken to prevent contamination from being carried over to the coupon surface by other metals. The surface of pipe inserts is inspected to ensure that they are metallurgically sound and free of mill scale, and defective inserts are discarded.

A distinctive identification number is assigned to each corrosion specimen. This number should be stamped prominently on the surface of the specimen and also should identify the metal alloy used to produce the specimen. All specimens must be degreased and scoured with a fine abrasive to remove lubricants and debris from machining operations. After degreasing, the specimens must be handled with gloves or plastic-coated tongs to prevent further contamination.

The clean, dry specimens are weighed on an analytical balance to the nearest 0.1 mg. The weight of each specimen is recorded along with its identification number on a customized report form (Figure 4-5). The report becomes part of a permanent file for documenting future weight loss and evaluation data concerning the specimen. Specimens are stored in a desiccator or similar noncorrosive atmosphere until needed. Steel specimens are especially susceptible to corrosion during handling and storage and should be kept in envelopes impregnated with a vapor-phase inhibitor. Sealed plastic envelopes should be used

to protect all corrosion specimens when they are removed from the moisture-free environment of a laboratory.

Corrosion specimens can be installed in a test loop designed to investigate specific corrosion problems, or they can be inserted into a conventional plumbing system for routine monitoring. The specimens must be electrically insulated from any associated piping during exposure to water to eliminate galvanic and stray current influences. Coupon-type specimens are attached to a rod threaded into a pipe plug. The threaded rod, pipe plug, and associated nuts, screws, and washers are constructed from PVC, nylon, phenolic, or other nonconducting materials. The pipe plug and mounted coupon are inserted into a pipe tee with the coupon protruding into the flowing water. Coupons also can be inserted in the reverse direction to check for a flow effect on the corrosion results. Pipe inserts are installed in a holder assembly consisting of standard PVC pipe unions, nipples, and fittings. Multiple pipe inserts can be inserted into a single PVC assembly if separated by PVC spacers. The complete test assembly containing the pipe inserts can be installed in a standard pipe loop or can become an integral part of a building plumbing system.

All relevant information concerning the installation of corrosion coupons is recorded on the report form assigned to each specimen: date of installation, site location, water supply, orientation of specimens, and similar details. This report is filed for future reference until the specimens are removed and returned to the laboratory for processing.

4.2.4 Duration Guidelines for Corrosion Studies

The optimum length of time that specimens need to be exposed to obtain reliable corrosion rates depends on the surface area exposed, the metal corrodibility, and the water corrosivity. The physical size of specimens is limited by the weighing constraints of the analytical balance, although the exposed surface area is designed to maximize weight loss during installation. A significant weight loss must be obtained to assess the corrosion resistance of pipe materials accurately or to evaluate the effect of water treatment. Because the corrodibility of piping materials is very low by design, long-term corrosion studies are needed in public water supplies to obtain the needed weight loss. Table 4-14 lists the typical corrosion rates for plumbing materials exposed to a variety of Illinois water supplies.

Table 4-14. Typical Corrosion Rates for Pipe Inserts in Illinois Waters

| Pipe Material | Corrosion Rates (range in mpy) |
|------------------|-----------------------------------|
| Copper | 0.05-0.60 |
| Galvanized Steel | 0.10-2.00 |
| Mild Steel | 0.50-10.00 |

As a general guideline, the ISWS has found that corrosion specimens require at least 6 months exposure for meaningful corrosion rates, but under some conditions, these specimens can require up to 24 months exposure (15). Copper and galvanized steel pipe inserts are installed for 12 months for routine monitoring purposes. The duration for a corrosion study is a variable

that should be determined for each water source. Corrosion specimens must be installed and removed at regular intervals to determine the effect of time on corrosion. The accuracy and quality of the corrosion data are improved significantly by the use of replicate specimens.

Wachter and Treseder's (16) planned-interval test procedure is recommended for corrosion studies designed to develop treatment strategies in public water supplies. This is an excellent procedure for evaluating the effect of time on the corrosion of metals and also for monitoring changes in corrosivity of the water during a corrosion study.

4.2.5 Processing of Corroded Specimens

After a specified interval, the coupon holders and/or pipe insert test assemblies are removed from the piping system to terminate exposure of the specimen(s). Each specimen is separated carefully from the corrosion test assembly. Specimens are air-dried immediately and are kept in a 105°C oven, desiccator, or similar low-humidity atmosphere until processed in the laboratory. The appearance and condition of each specimen should be evaluated visually. Any degradation in appearance of the specimen is recorded on the report form: i.e., localized attack; physical damage; and color, porosity, and abundance of surface deposits. When required, the appearance of specimens can be documented with color photographs for future reference. Specimens then are grouped and processed in sets of like metal alloys.

Any coating applied to the specimen to confine corrosion damage to a defined surface area is removed. Pipe inserts usually are painted to limit corrosion to the internal surface of the specimen. Paint must be removed carefully to prevent solvents and water from contacting the corroded surface area and degrading the oxide or mineral deposits on the specimen. The specimens are rinsed with water and acetone before being re-dried in a 105°C oven. In the ISWS, the specimens are removed from the oven, allowed to cool, and weighed with the deposition products intact. Although some deposit might be lost in handling, the difference in specimen weight before and after chemical cleaning is an indication of the mass of corrosion and mineral deposits occurring in the system. The specimens then are cleaned by chemical and mechanical procedures to remove all surface deposits above the base metal.

4.2.6 Chemical Cleaning Procedures

Bulky deposits are removed from the corrosion specimens prior to chemical cleaning to minimize the time that specimens are exposed to the aggressive chemical solutions. A plastic spatula or similar tool is used to scrape the deposits off the specimens without damaging the underlying metal. These surface deposits often are saved for chemical analyses and evaluation by x-ray diffraction to identify the mineral components.

An ideal cleaning procedure will remove all the corrosion products and mineral deposition from the surface of a coupon without any loss of base metal. Some base metal is lost by all cleaning procedures, however, and this weight loss must be determined by the use of uncorroded specimens (blanks). Rep-

licate blanks are subjected to the same cleaning procedure and solutions that are used to process corroded specimens. To obtain the net weight loss because of corrosion, the mean weight loss of the replicate blanks resulting from the cleaning process is deducted from the gross weight loss of specimens. This net weight loss is used to calculate the corrosion rate.

Various chemical cleaning procedures are cited in the literature for each type of alloy (10,13,17). The ISWS laboratory has found that the ASTM D 2688-90 cleaning procedures are quick, simple, and efficient for processing large numbers of specimens. An ultrasonic cleaning bath also is used to improve the chemical cleaning efficiency for removing adherent deposits. The cleaning procedures used by the ISWS for copper, zinc, iron, and lead alloys (both pipe inserts and coupons) are summarized in Sections 4.2.6.1 through 4.2.6.4. The procedures are based on the ASTM 2688 method, but other acceptable cleaning procedures are documented in the literature (10,13,17). Note that the procedure for cleaning lead specimens has been modified because the weight loss of lead blanks was high using the ASTM cleaning solution. The cleaning procedures for lead and lead-solder require further study.

Chemical cleaning solutions employ acids, alkalis, and solvents that can be hazardous to personnel. The handling, use, and disposal of chemical solutions should comply with current laboratory safety regulations. Cleaning procedures should be carried out in a fume hood and personnel should wear protective clothing and goggles.

4.2.6.1 Iron and Steel Specimens

Specimens are immersed in freshly prepared hydrochloric acid (10 percent HCl) for 5 minutes at ambient temperature. Alternately, scour, brush, and acid clean to remove stubborn deposits. Specimens should not be immersed in cleaning solution for more than 30 minutes. Specimens are rinsed thoroughly in order with tap water, deionized water, and a dilute passivating solution. The specimens are placed immediately in a 105°C oven to dry for 1 hour. They are removed from the oven, allowed to cool, and are reweighed to the nearest 0.1 mg on an analytical balance. This final weight is recorded on the report form to complete the data needed for the corrosion rate calculation.

4.2.6.2 Copper and Copper Alloys

The copper specimens are immersed in hydrochloric acid (10 percent HCl) for 1 to 2 minutes at ambient temperature. The specimens are rinsed thoroughly with tap water, deionized water, and acetone. They are allowed to dry for 5 to 10 minutes in a fume hood to remove acetone and are stored in a desiccator for 24 hours before weighing in the same manner as steel specimens. Acid solutions used to clean copper specimens must not be used to clean other metals.

4.2.6.3 Zinc and Galvanized Steel

Zinc and zinc-coated specimens are immersed in sulfamic acid solution (10 percent) for 5 minutes at ambient temperature. Beakers containing the cleaning solution are placed in an ultrasonic bath to improve cleaning efficiency. Specimens are alter-

nately scoured, brushed, and acid cleaned until the surface deposits are removed. The specimens then are rinsed thoroughly with tap water, deionized water, and acetone. They are immediately placed in a 105°C oven to dry for 1 hour before weighing.

4.2.6.4 Lead and Lead Solder

Lead specimens are immersed in a 1 percent acetic acid solution for 2 minutes and held at a temperature of 60 to 70°C. The specimens are brushed very lightly and rinsed thoroughly with deionized water and dry acetone. They are placed in 105°C oven to dry for 1 hour before weighing. Lead specimens must be handled very carefully to minimize unintentional metal loss.

4.2.7 Evaluation of Localized Corrosion

After the corrosion specimens have been cleaned and weighed for the final time, the surface of each specimen is examined for evidence of localized corrosion. A low-powered microscope (5x to 50x) is a useful tool for examining coupons and pipe inserts. The degree of attack, pit shape, pit density (pits/sq in.), and pit depth (mils) are routinely recorded. Byars & Gallop (18) published photos and terminology that are an excellent guideline for describing the attack on coupons. Pipe inserts are evaluated in the same manner as coupons but need to be split lengthwise to permit visual and instrumental inspection of the specimen. A dial depth gauge is employed to measure the pit depth. The visual appearance and pitting measurements are recorded on the specimen data form.

The pitting data can be equated with the results from other studies by calculating the Pitting Rate Equivalent (PRE), which is expressed as mils penetration per year (mpy) and is calculated by the following equation:

$$PRE (mpy) = \frac{365 * d}{t}$$

where

d = maximum pit depth, thousandths of an inch

t = specimen exposure time, days

The Pitting Factor (PF), which also is used for this purpose, is the ratio of deepest metal penetration by a single pit to the average metal penetration as determined by the weight loss measurement. A value of 1 represents uniform corrosion with no pitting, whereas higher values indicate an increased pitting tendency.

4.2.8 The Corrosion Rate Calculation

The corrosion rate is calculated from the recorded net weight loss of a specimen and is reported in terms of average surface penetration per specified time interval. This implies that the metallic corrosion is linear with time, which is seldom true with potable water. In most instances, the corrosion rate decreases with time as oxide films develop or as minerals deposit on the metal. Reporting of corrosion rates also implies that the weight loss is due to uniform corrosion and not to pitting,

dealloying, crevice corrosion, or other forms of localized corrosion. This might or might not be true. It is important, therefore, that the specimens be inspected carefully before and after cleaning to identify the presence of localized corrosion.

Corrosion data can be calculated and expressed as weight loss per unit area per unit time or the equivalent rate of penetration. The generally accepted units are grams per square meter per day (g/m²/d) and millimeters penetration per year (mmpy). The ISWS traditionally has used mils per year (mpy) for reporting corrosion rates.

The Corrosion Rate (CR) is calculated by the following equation:

$$CR(mpy) = \frac{W * F}{A * T * D}$$

where

W = weight loss of coupon during exposure, grams

A = exposed surface area of coupon, square inches

T = time coupon was exposed to water, days

D = density of metal coupon, grams per cubic centimeter (from Table 4-15 and various handbooks)

F = factor for converting units of measurement into mpy, use 22,250 for units listed above

To convert units from mpy to mmpy, multiply the mpy value by 0.0254.

Table 4-15. Density of Selected Metals

| Metal | Density, g/cm ³ |
|--------------------------|----------------------------|
| Brass, Red | 8.75 |
| Carbon Steel | 7.86 |
| Copper | 8.94 |
| Galvanized Steel or Zinc | 7.13 |
| Grey Cast Iron | 7.20 |
| Lead | 11.33 |
| Solder, 50Pb/50Sn | 9.32 |
| Stainless Steel, 316 | 7.98 |

Source: NACE Corrosion Engineer's Reference Book

4.2.9 Interpretation of the Corrosion Data

A planned-interval corrosion study conducted by the ISWS (15) serves as an example of the interpretation of data. Copper and galvanized steel corrosion specimens were installed for various intervals over a 2-year period in different water supplies. The corrosion specimens, identified by the letters A through G, were exposed for the time span shown in Figure 4-6. Changes in water corrosivity and metal corrodibility were evaluated for each water supply by examining the relationships in the weight loss data using the Wachter and Treseder technique. Multiple relationships may be drawn from the differences between the various combinations of specimen weight loss measurements. Table 4-16 summarizes some of these relationships and their significance.

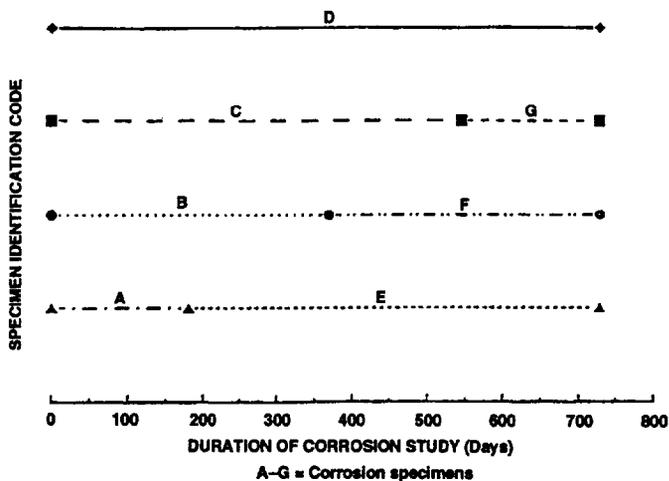


Figure 4-6. Planned-interval pipe insert exposure during EPA/ISWS corrosion study.

Table 4-16. Significance of Coupon Weight Loss Measurements

| Coupon Weight Loss Results | Significance |
|----------------------------|----------------------------------|
| A = G or B = F | No change in water corrosivity |
| G < A or F < B | Decreased corrosivity |
| A < G or B < F | Increased corrosivity |
| D-C = G or D-B = F | No change in metal corrodibility |
| D-C < G or D-B < F | Decreased corrodibility |
| G < D-C or F < D-B | Increased corrodibility |

A change in corrosivity and its effect on the weight loss of galvanized steel specimens were observed at Site 302 during the aforementioned study. Figure 4-7 shows the weight loss data for the specimens. The change in corrosivity occurred because the water utility was not satisfied with its corrosion control program. The difference was most obvious between specimens A and G. Specimen A was installed during the period when a phosphate/zinc product (0.7 mg/L) was being applied. At approximately the same time, specimen A was removed, the phosphate/zinc treatment was discontinued, and caustic soda (19 mg/L) was applied for the remainder of the study to main-

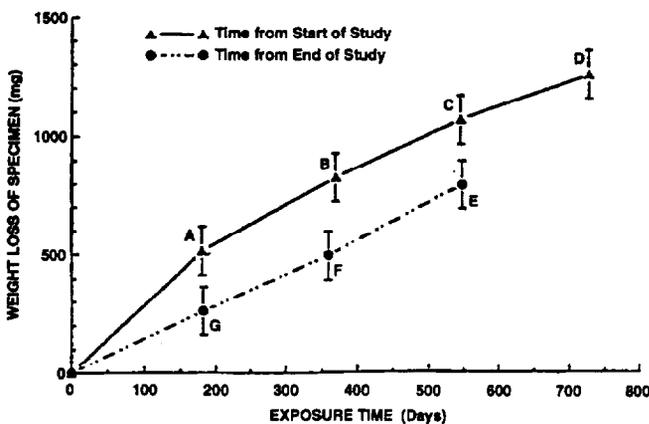


Figure 4-7. Corrosion of galvanized steel specimens at Site 302.

tain a pH of 8.5. This treatment strategy proved to be effective in controlling a red water problem in the distribution system, and the corrosion data indicate it was effective in reducing the corrosion of galvanized pipe. The weight losses of specimens F and E also were significantly less than the corresponding weight losses of specimens B and C, which provide additional confirmation that the water corrosivity changed during the study.

The corrosivity of another water supply was found to be relatively consistent throughout the same corrosion study. The weight losses of copper specimens at Site 307 were nearly linear (see Figure 4-8). There was no significant difference in

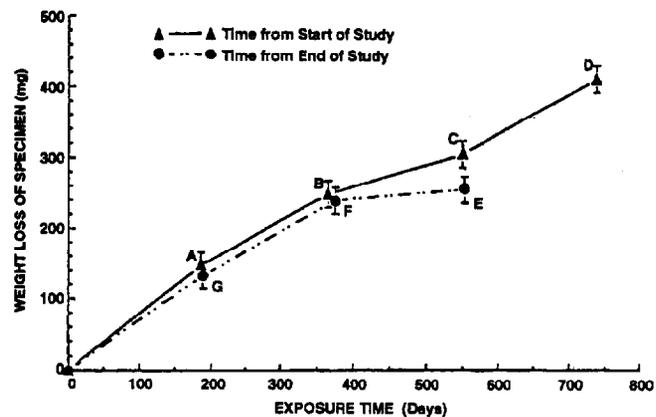


Figure 4-8. Corrosion of copper specimens at Site 307.

the weight losses of specimens A and G (or B and F), although the specimens were exposed at different time spans during the study. The lower weight loss found for specimen E might be because of processing or metallurgical factors, since the other six specimens provided consistent results. The use of replicate specimens is recommended to reduce the uncertainties of a single weight loss measurement.

In the previous example, the corrodibility of copper was examined by the weight loss relationships outlined in Table 4-16. The weight loss of specimen G was greater than the calculated difference between specimens D and C. The weight loss of specimen F also was greater than the calculated D - B value. Both comparisons indicate that the corrodibility of copper decreased during the study. This is an anticipated result since the corrosion or mineral deposition that occurs gradually on the surface of coupons will tend to protect the underlying metal and reduce the apparent corrosion rate.

Coupon test results can be used to compare the corrosivity of various water sources or differences in the corrosivity within a distribution system. Figure 4-9 illustrates the effect of time on the corrosion rate for galvanized steel pipe specimens. The corrosion rates at the two sites located in water supply A both declined with time, although the corrosion rates were significantly different. Site 302 was located at the water treatment plant, whereas Site 304 was situated at a remote location in the distribution system. Site 302 is the example cited previously as

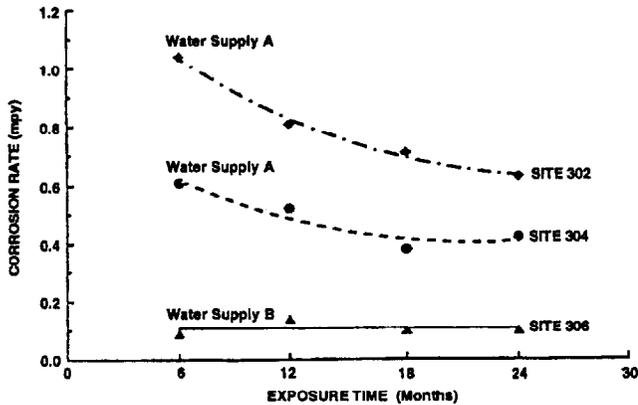


Figure 4-9. Effect of water corrosivity on galvanized steel.

experiencing a change in corrosivity because of a change in water treatment. The data underscore the importance of conducting corrosion studies at different locations when evaluating the effects of water treatment in a distribution system. The data likely reflect the difference in the chemical equilibria of the two sites.

Figure 4-9 also illustrates the corrosivity of two water supplies and how they compare. Water supply B is a lime-softened ground water source using the calcium carbonate saturation indices for corrosion control. Water supply A is a clarified and filtered surface water source that tried both a zinc/phosphate and a caustic soda treatment to control corrosion. The corrosion of galvanized steel attained equilibrium and a very low corrosion rate within 6 months in water supply B. A much longer interval was required in water supply A to reach equilibrium, which will be at a higher corrosion rate than water supply B.

4.2.10 Summary

The preceding examples demonstrate various techniques for interpretation of the corrosion data obtained from coupon weight loss measurements. Corrosion specimens can be very effective tools for accessing the corrosivity of water or the corrodibility of metals. Because many factors influence the corrosion of plumbing materials in potable water, the variability due to the preparation and processing of specimens must be minimized. Pipe insert and/or coupon type specimens can produce valuable data for evaluating the effects of water treatment on plumbing materials. The advantages and limitations of the coupon weight loss procedure, however, must be considered carefully in designing a corrosion study to meet this objective.

4.3 Design Considerations for Pipe Loop Testing

4.3.1 Introduction

Traditionally, corrosion pilot plants have consisted of either static bench-scale immersion tests or flow-through loops containing metal coupons for weight loss evaluations. Flow-through pipe loops designed to evaluate the leaching charac-

teristics of a particular metal have not been as prevalent as these other methods for evaluating corrosion in a system. With the recent lead and copper rule comes a need to evaluate corrosion control with respect to the leaching of these metals. Since weight loss and metals concentrations have not been correlated sufficiently, a pilot system that assesses the leaching potential of the system might be most appropriate when evaluating optimum corrosion control treatment. Pipe loops can be used in corrosion optimization studies in the following ways:

- To compare the impacts of various water qualities on metal levels.
- To compare the ability of various treatments to reduce metals levels.
- To evaluate the side effects of various treatments.

The following section provides a brief discussion of the design, construction, operation, and data evaluation issues related to conducting pipe loop evaluations for determining optimal corrosion control.

4.3.2 Pipe Loop Design and Construction Considerations

Several operating conditions should be considered when designing a pipe loop system, including operating pressure, flow, velocity, pipe diameter, length of loops, total through-put volume, and on-off cycling. These factors should be controlled to reduce the amount of variability in the test results. The American Water Works Association Research Foundation (AWWARF) pipe rack model was designed by the Illinois State Water Survey as part of the *Lead Control Strategies* manual (4). The model was designed to enable the metal leaching characteristics of various pipe materials to be evaluated under equivalent operating conditions. (The *Lead Control Strategies* manual contains a complete description of the pipe loop model.) AWWARF is in the process of revising that initial protocol. The following discussion lists several key issues that should be incorporated in the design of the AWWARF pipe loop model or other models designed to evaluate the leaching potential of a particular system.

The lead source to be evaluated in the pipe loop should reflect the sources of lead in the system. If lead service lines are a major source of lead in a system, lead pipe of a similar diameter should be incorporated into the pipe loop; a similar process should be followed for soldered copper pipe. Brass faucets also have been shown to contribute significantly to lead levels measured in a standing 1-L sample from the tap. Incorporating brass faucets into the pipe loop system might be considered; the vast number of existing faucets and their varying lead content, however, make the choice problematic. PVC should be used for the remainder of the pipe loop to prevent metals contamination from non-test loop piping sections. Teflon[®] tape, rather than pipe-joint sealing compounds, should be used to connect the PVC sections in the manifold.

The variability of lead levels measured both at the tap and from controlled pipe loop studies indicates that multiple loops of the same material exposed to the same water quality conditions should be incorporated. The AWWARF pipe rack design includes three replicate loops of the same material. In a corrosion optimization study, several of these pipe racks with replicate test loops must be run side-by-side to obtain a comparison of the various treated water qualities.

Another factor in design of the pipe loop system is the location of the apparatus. The facility where these loops are constructed must have adequate space, heat, power, water supply, and wastewater drain to accommodate several pipe racks with replicate test loops of the materials of interest. It also is important to recognize water quality changes when siting the apparatus. The quality of water leaving the treatment plant might be significantly different from that of the water that reaches the residential units. Construction of the pipe rack can be accomplished either by in-house or contract staff. The quality of workmanship should be similar to local plumbing contractors. With soldered copper loops, the amount of solder used for each loop should be recorded.

4.3.3 Pipe Loop Operational Considerations

4.3.3.1 Startup Issues

Prior to initiating pipe loop operations, several data collection and operations issues should be considered. Decisions must be made about:

- What metals levels to evaluate
- The need for corrosion rate information
- Corrosion mechanism evaluations
- Collection of auxiliary water quality parameters

Metals from corrosion reactions might be present as dissolved aqueous species, minute colloidal or freshly precipitated particles that are suspended in the water, or as fragments of corrosion by-product films that have been eroded or removed from the pipe by water flow. Knowledge of the form of the metal and the relative fraction that is dissolved might be important for developing the optimum treatment. For lead or copper corrosion control, the solubility must be decreased, and the passivating film must adhere to the pipe.

From a regulatory standpoint, all of the metal is assumed to be bioavailable, so differentiation between dissolved and other forms is not necessarily critical for a pipe loop experimental study. Modeling and predictions of metal solubility, however, are based on establishment of equilibrium with the dissolved species. For comparison to modeling predictions, therefore, some type of isolation of the dissolved metal fraction is necessary. This isolation can be done by complicated analytical techniques such as anodic stripping voltammetry or by ultrafiltration. More often, however, simple membrane filtration is used, and the cutoff for what size particle is considered "dissolved" is set at some level, such as 0.4 μm . Since filtering

of samples removes particulate metals, it reduces the variability, allowing improved comparisons between loops.

Filtration appears to be simple, but it can create additional problems if not done carefully. All materials in contact with the water should be of plastic or Teflon[®] and the membranes themselves should be of polycarbonate. Filters should be rinsed with sample water to satiate adsorption sites, with that volume of water being discarded before the sample is collected. The filtration apparatus should be cleaned thoroughly and acid-rinsed between filtrations of different samples. In-line filtration during sample collection generally is more desirable than vacuum filtration.

Another decision to be made when planning a pipe loop study is whether the corrosion rates are important. Clearly, from a materials performance perspective, lower corrosion rates are desirable. Lead corrosion rates are relatively low compared to other metals. Although these low corrosion rates produce trace quantities of lead solution, they generally are significant enough to produce health problems. Often, coupons or inserts that are sections of pipe are used for weight loss determinations. Soft materials, such as lead, might be extremely difficult to process accurately for this purpose. Galvanically stimulated corrosion processes, such as solder joint corrosion, are not easily amenable to evaluation by weight loss, although some procedures to do this have been developed (see Section 4.4). Various electrochemical instruments provide instantaneous (or nearly instantaneous) readings of corrosion rate. The data frequently can be captured by computers for integration and plotting.

Finally, the water quality characteristics of the source water both before and after it is treated should be identified, as should the accuracy of the chemical feed system. Depending on the treatment, the chemical feed system can be monitored by evaluating pH, alkalinity, concentration of inhibitor, calcium, and disinfectant residual. Thorough records of the mechanical operating conditions also should be maintained. These conditions include flow, pressure, and through-put volume. It is advisable to record the quantity of chemicals used so that comparison can be made with measured quantities.

4.3.3.2 Sampling Issues

Prior to initiating normal sampling, it might be advisable to characterize the usable sample volume in each loop, since mixing fresh influent water with the stagnant water in the loops might dilute the metals concentrations. This characterization can be accomplished by collecting a series of small volume samples (25 to 50 mL) from the loop after a designated standing time and measuring each sample for metals levels. A "profile" of lead levels can be obtained, and the usable volume in the loop can be determined. The sampling protocol for standing samples in the pipe loop study then can be organized to fit the total usable volume contained in each loop.

Utilities or researchers with a more scientific orientation might be interested in trying to understand the mechanisms of corrosion and inhibitor performance to better predict treatment goals. The sampling and analysis program must be configured

to include special procedures for sampling and chemical analyses when this information is desired. Measurements of depletion of dissolved oxygen or chlorine, reduction in inhibitor concentration, increases in pH caused by corrosion reaction, and changes in metal speciation (i.e., $\text{Cu}^{+1}/\text{Cu}^{+2}$, Fe^{+3}) are examples of analyses that could give insight into corrosion and treatment mechanisms.

Obtaining accurate information on initiation of stagnation conditions is important in determining the rate and extent of metal leaching from the plumbing materials. Whenever the water source for the pipe rack system is inconsistent, the background samples should be taken during the flow period immediately before the standing time and as close to the shutoff time as is practical. Valuable information also is obtained if a sample is taken of the metal or metals of interest from the loop sampling tap during the flowing period. This shows how much metal is picked up when water travels through the pipe.

Several special precautions must be taken when certain sensitive analyses are to be performed on samples in the corrosion study. For example, samples collected for pH analysis should be taken in closed containers with no air space. The pH will change, sometimes radically, if the samples come into contact with air. The amount of the change will depend on the characteristic of the individual water and its buffer intensity. Waters particularly susceptible to pH drift are low-alkalinity water with a pH greater than 8, moderate-alkalinity waters of high pH, and very high-alkalinity waters of low pH where oxygen and carbon dioxide degassing occur. During analysis, pH measurements should be made directly on water in the original container with minimal air contact. Using 25- to 40-mL glass sample vials with caps having conical polyethylene inserts has been found to be quite useful. A rubber stopper around the electrode will enable the samples to be protected from the air. Sealed containers such as these might enable the preservation of pH for hours or days. The stability of pH, however, must be determined for each water supply to be tested. It is possible that the sensitivity to pH change from atmospheric contact will differ among waters representing one treatment or another.

Similar to analyses of pH, direct analyses of dissolved inorganic carbonate (DIC) require that samples be taken with little disturbance and sealed in bottles with no air space. Dissolved oxygen also requires special collection precautions. Special preservation requirements for other analytes should be determined by consulting the laboratory and standard analytical procedure references for the test of interest.

When metal speciation analysis such as sample filtration is to be performed, the samples must not be acidified until after the separation has been done.

Finally, when determining the frequency of sampling and length of study period, the following interrelated factors should be considered:

- The analytical precision of the results
- The natural variability of the parameters to be measured

- The length of the test
- The availability of staff and laboratory resources

The length of time to operate a pipe loop system to obtain stable data for making comparisons will depend on the material used and the influent water chemistry to each loop.

4.3.4 Characteristics of Pipe Loop Data

Leaching data collected from actual pipe loop studies displays an intrinsic variability in lead and copper levels. This variability limits the certainty with which extrapolation of results from the pipe loop to distribution system standing samples can be made. The use of new materials and the operating conditions with which these materials are exposed in a pipe loop system can create film characteristics that rarely represent conditions in the field. These issues place significant constraints on estimating "optimum" corrosion treatment.

4.3.5 Data Evaluation Considerations

Statistical evaluation of data has commonly been performed using parametric statistics, with which there is widespread familiarity and for which software is readily available. With parametric statistics, there is a strong assumption that the probability density function of the data is normal or bell-shaped (nonskewed). For data distributions that are non-normal (skewed) or for which there are so few data points that the distribution cannot be determined, nonparametric statistical techniques are more statistically efficient. These techniques are not as widely recognized as parametric or normal distribution techniques, and until recently, few software packages incorporated these methods. The simple comparison between parametric and nonparametric statistics is as follows:

| <i>Parametric</i> | <i>Nonparametric</i> |
|---------------------------------|---------------------------|
| Interested in levels | Interested in location |
| Use mean and standard deviation | Use median and percentile |
| T-test | Ranked Sign Test |

Lead levels from both pipe loop data and standing samples collected at the tap typically display non-normal (skewed) distributions that, in many cases, appear to be log-normal. In addition, pipe loop studies can provide a limited number of data points with which to evaluate treatments because of the length of time needed to obtain relatively stable metals levels. Either of these circumstances suggests that nonparametric techniques should be used when evaluating the data from a pipe loop study.

4.4 Electrochemical Methodologies for Corrosion Measurement in the Distribution System

Electrochemical corrosion assessment techniques have been sufficiently developed to provide a useful tool for corrosion control optimization programs. Electrochemical corrosion assessment is a direct assessment methodology, the type emphasized in the lead and copper rule. Calcium carbonate-based saturation indices, in contrast, are indirect assessment methodologies and are inadequate to characterize corrosion processes.

The obvious reason for using electrochemical techniques is that they provide a nearly instantaneous measure of the underlying corrosion process. They provide a snapshot of what is taking place on the surface of the corrosion specimen at a particular time. They are not a cumulative measure, so they are particularly useful for many process control operations or screening programs. Once the instrumentation is in place, performing an electrochemical screening program is a rather inexpensive process.

Electrochemical techniques can be used with a variety of different analyses. Assessing corrosion rate could certainly be high on any system operator's list, but these techniques also can be used for analyzing passivity phenomena, coating effectiveness, pitting susceptibility, galvanic interactions, and inhibitor evaluations. Electrochemical techniques, however, cannot measure directly the underlying corrosion current between the oxidized and the reductant couple, because both the oxidation and the reduction are taking place on the same sample, perhaps within a few micrometers or microns of each other. The reductant couple cannot be isolated; hence, it is not possible to measure the corrosion current directly. The assessment of the actual surface potential of the corrosion specimen also is not adequate to define the corrosion process.

The goal in performing an electrochemical evaluation of a particular specimen is to obtain an Evans diagram or a Koppel plot. In effect, a current is applied to a specimen, a piece of metal that is presumably at equilibrium. The current is applied in both the anodic and cathodic direction. The piece of metal is perturbed by this current, and the offset in potential, brought about by those respective anodic and cathodic currents, is measured. The Koppel plot, which can be developed from these measurements, graphically demonstrates that the intersection of the anodic Koppel slopes and the cathodic Koppel slopes should yield the underlying corrosion current.

Coupon testing is the definitive measure of the actual corrosion rate. Other analytical techniques, including electrochemical methodologies, must be compared to some reference, and a suggested reference is coupon testing using either the flat coupon technique and the Illinois State Water Survey (ISWS) technique, or modifications to the ISWS technique using actual pipe. Making an assessment of a corrosion rate based on a single specimen or even two or three specimens simply is not adequate. The variation in corrosion, most importantly on steels, is so large that multiple coupon exposures are required. This definitive technique for corrosion assessment requires 3 to 6 months to carry out.

4.4.1 Polarization Techniques

A potentiostat is required for electrochemical testing. This device is capable of measuring the surface potential of the corrosion specimen to an accuracy in the millivolt range and simultaneously controlling the impressed current applied to a specimen in the micro range. The cost for a potentiostat is several thousand dollars. The polarization cell is the device used to hold the corrosion specimen, consisting of three different elements: the test specimen, reference electrode, and counter electrode. The reference electrode is used to compare

the shifting potential of the corrosion specimen. Because the reference electrode has a stable electrochemical potential, all changes are measured relative to that potential.

Some initial work has been performed at the University of Washington and subsequently at the University of North Carolina at Charlotte to develop polarization cells that are specific for the distribution network. The goal of this work was to develop a simple system that uses plumbing materials as the actual electrode surface and that has a cell geometry that can reflect the hydrodynamics of pipe flow. The polarization cell developed consists of two pieces of plastic that hold a test specimen between them. The auxiliary electrode penetrates the test specimen axially, and the reference electrode is directly above. It is relatively inexpensive to produce, because all that is required is some plastic machining, a reference electrode, and auxiliary electrodes. Potentiostats and corrosion monitoring equipment essentially can be compressed into a single circuit board, or a single board that fits inside a laptop computer. The cost to purchase them as a package varies between \$8,000 and \$15,000. No unusual laboratory facilities are required. Most laboratories probably are doing part of their own electrochemical analyses already. The metal specimens can be fabricated easily or purchased from one of several different companies that produce fabricated metal specimens.

Rather than performing a full-blown potentiodynamics scan of a surface, a linear polarization can be performed. Linear polarization relies on only a single offset, which shifts surface potential of the corrosion specimen by 10 or 20 millivolts; a reading of the impressed current is produced at that point. If Koppel slopes are known for a corroding specimen, then an interpretation of the corrosion rates can be made from a single measurement. There are two-electrode and three-electrode variations on that theme, both of which have worked fairly well.

Linear polarization instrumentation has the advantages of speed, simplicity, relative low cost, and relative accuracy. In this context, relative accuracy means that an assessment can be made to determine whether there are increases or decreases in the corrosion rate; however, it has low absolute accuracy. A potentiodynamic scan must be performed if a highly accurate electrochemical assessment is needed in terms of absolute terminology.

There is a developing polarization technique that is referred to as alternating current (AC) impedance. The AC impedance technique is just now beginning to be applied in distribution networks. The technique actually has been available for about a decade and has been used extensively in other industries.

AC impedance does not use direct current; it applies an alternating current to the corrosion specimen. The alternating current and the subsequent perturbation of the corrosion specimen produce a variety of information, including the corrosion rate. An electrical model of the corrosion surface is constructed, taking into account the different resistances on that surface. Most importantly, there is very little distortion of the surface chemistry when AC impedance techniques are used. This is important in water distribution networks because the other polarization techniques often apply or create a potential shift of

50 or 100 millibles. This is a substantial change in the nature of the corrosion surface and alters the underlying electrochemistry of the surface. AC impedance gets around this problem by applying an alternating current that has an offset no greater, generally, than 5 millibles. The disadvantages of the system of AC impedance is that it is still an emerging technology, at least for water distribution systems, and requires fairly extensive instrumentation. The instrumentation is being reduced to a single computer control system, however, and prices are becoming more affordable. Today an AC impedance system can be purchased for around \$20,000 to \$25,000.

4.4.2 Electrical Resistance and Electrochemical Noise

In addition to polarization techniques, other forms of electrochemical methodologies include electrical resistance and electrochemical noise. Electrical resistance measures the change in the resistance of an element that is exposed to the flow stream. As that element corrodes, its cross-sectional area changes; hence, its resistivity changes, and that resistivity is related to a corrosion rate. Advantages of electrical resistance measurement are that it is very simple, well suited to on-line measurements, and somewhat sensitive to long-term changes. A disadvantage is that it is limited to rapidly corroding systems. Although many systems might believe that they have a serious corrosion control problem, most water distribution networks have minimal corrosion rates, at least compared to other industries, such as the petrochemical industry, where many of these techniques were developed. The electrochemical resistance instrumentation is relatively straightforward.

The electrochemical noise technique uses sensitive information to measure the static electricity generated on the corrosion surface. On a molecular level, it is possible to interpret a corrosion rate by the rate of individual molecular events occurring on the surface.

4.4.3 Summary

Electrochemical techniques should be used only when supplemented by other investigative techniques, specifically, the definitive corrosion assessment techniques of gravimetric coupons and weight loss techniques. Because of their speed, electrochemical techniques can be ideal for screening programs. Correlation of the electrochemical results with field results can yield fast and realistic predictive procedures, but only after electrochemical techniques have been properly calibrated.

Electrochemical measures generally are limited to uniformly corroding surfaces. Many attempts have been made to perform these measurements on pitting surfaces such as galvanized steel. The success with such surfaces has been much more limited than with the uniformly corroding surfaces of copper, copper alloys, and other materials. Linear polarization might be a particularly appropriate technique for on-line continuous measures of finished water corrosivity, specifically for screening programs and process control. Potentiodynamic techniques will remain necessary for measurement of absolute corrosion rates.

Electrochemical techniques are best restricted to copper and its alloys, including brass and bronze. Electrochemical techniques also work well on lead and lead-tin solders and tin-antimony and tin-silver solders. The absolute accuracy can be low unless a rather involved potentiodynamic scan is performed. The data interpretation used to be difficult, but the reduction is automated by the statistical software available with the package units. Improved electrochemical techniques are pending. AC impedance soon will be available for water distribution systems, and widespread application will improve assessment technology overall for the distribution system.

4.5 References

1. Wysock, B.M. et al. (1991). A Study of the Effect of Municipal Ion Exchange Softening on the Corrosion of Lead, Copper and Iron in Water Systems. *Proc. Annual Conf. American Water Works Association*, Denver, CO.
2. AWWA Research Foundation (1987). *Deterioration of Water Quality in Distribution Systems*. American Water Works Association, Denver, CO.
3. AWWA Research Foundation (1990a). *Chemistry of Corrosion Inhibitors in Potable Water*. American Water Works Association, Denver, CO.
4. AWWA Research Foundation (1990b). *Lead Control Strategies*. AWWA Research Foundation and American Water Works Association, Denver, CO.
5. Holm, T.R. and S.H. Smothers. (1990). Characterizing the Lead-Complexing Properties of Polyphosphate Water Treatment Products by Competing-Ligand Spectrophotometry Using 4-(2-Pyridylazo)Resorcinol. *Intern. J. Environ. Anal. Chem.* 41:71.
6. Ilges, A. (1991). Control of Lead and Copper in Drinking Water Champlain Water District Presentation Outline. *Trans. EPA/AWWA National Workshop on Corrosion Control*. American Water Works Association, Denver, CO.
7. Rohlf, F.J. and R.R. Sokal (1981). *Biometry: The Principles and Practice of Statistics in Biological Research*, 2nd Edition. W.H. Freeman and Co., New York, NY.
8. Schock, M.R. (1990). Causes of Temporal Variability of Lead in Domestic Plumbing Systems. *Environmental Monitoring and Assessment*. 15:59.
9. ASTM (1991a). *Standard Test Methods for Corrosivity of Water in the Absence of Heat Transfer (Weight Loss Methods)*. American Society of Testing and Materials, Designation D 2688. Annual Book of ASTM Standards, Vol. 11.01. Philadelphia, PA.
10. ASTM (1991b). *Standard Recommended Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens*. American Society of Testing and Materials, Designation G1. Annual Book of ASTM Standards, Vol. 3.01. Philadelphia, PA.

-
11. NACE (1976). *Laboratory Corrosion Testing of Metals for the Process Industries*. National Association of Corrosion Engineers, Standard TM0169. Houston, TX.
 12. ASTM (1991c). *Standard Recommended Practice for Examination and Evaluation of Pitting Corrosion*. American Society of Testing and Materials, Designation G46. Annual Book of ASTM Standards, Vol. 3.01. Philadelphia, PA.
 13. Ailor, W.H., ed. (1971). *Handbook of Corrosion Testing and Evaluation*. The Electrochemical Society and John Wiley & Sons, New York, NY.
 14. Haynes and Baboian, eds. (1985). *Laboratory Corrosion Tests and Standards*. American Society of Testing and Materials, Standard Technical Presentation 866. Philadelphia, PA.
 15. Neff, Schock, and Marden (1987). *Relationships Between Water Quality and Corrosion of Plumbing Materials in Buildings, Vol. I: Galvanized Steel and Copper Plumbing Systems*. EPA/600/S2-87/036.
 16. Wachter, A. and R.S. Treseder (1947). Corrosion Testing Evaluation of Metals for Process Equipment. *Chemical Engineering Progress* 43:316-326.
 17. Fontana, M.G. and N.D. Greene (1967). *Corrosion Engineering*. McGraw-Hill Book Company, New York, NY.
 18. Byars, H.G. and B.R. Gallop (1975). An Approach to the Reporting and Evaluation of Corrosion Coupon Results. *Materials Performance*, pp. 9-16 (Nov.).

Chapter 5

Control Strategies

This chapter provides an overview of control strategies for lead and copper in drinking water. Control strategies can consist of any combination of materials selection, materials removal, point-of-use devices, and chemical water treatment. Chemical water treatment programs consist of either manipulating the general water chemistry (such as pH, hardness, and inorganic carbonate) or adding a chemical or chemicals (silicates, orthophosphates, or blended phosphates) to the water to produce a less corrosive water quality.

Usually, chemical treatment employs one of two strategies: the formation of a coating on the pipe that slows the corrosion of the underlying pipe or the formation of a relatively insoluble “passivating” film with the pipe metal itself. Frequently, both approaches must be used simultaneously. The treatment program must consider the nature of the lead or copper contamination source, the initial water chemistry, and the chemistry of the treatment chemical when dissolved in the water.

This chapter also examines the secondary effects of controlling corrosion through carbonate stability or the use of inhibitors. For example, adjusting the pH can benefit oxidation and coagulation, but it also can hinder a utility in its effort to comply with the Surface Water Treatment Rule (SWTR) and can enhance the formation of disinfection by-products. Inhibitor usage can promote algal growth and might create waste discharge problems due to zinc. Use of unleaded plumbing materials can introduce other undesirable contaminants, such as antimony, into the water.

Finally, this chapter presents five case studies in corrosion control:

- Sodium silicate for the simultaneous control of lead-, copper-, and iron-based corrosion: York, Maine.
- Assessing zinc orthophosphate vs. pH adjustment: Champlain, Vermont.
- Reducing corrosion products in municipal water supplies: Chippewa Falls, Wisconsin.
- Evaluating chemical treatment to reduce lead in a building.
- Iowa’s lead in schools’ drinking water program.

5.1 Overview of Control Strategies for Lead in Drinking Water

Control strategies for lead in drinking water generally fall into three categories: physical, point-of-use, and chemical treatment control. *Physical* control is the removal of lead-containing materials or the limiting of lead content in materials. *Point-of-use* (POU) control is the use of devices attached to water taps or in lines near water outlets. These devices include filter units, ion-exchangers, reverse-osmosis units, or adsorber cartridges. POU control is effective only when the source of lead is located prior to the device. Many POU devices have terminal brass faucets or soldered joints and therefore are not effective for lead removal. In some cases, the devices reintroduce the problem in a more aggressive (corrosive) water. *Chemical treatment* means either that the water has been treated as it comes from the plant, or that chemical treatment has been used in a building. This chapter looks only at chemical treatment strategies and the major treatment chemicals used to apply them to distribution systems.

5.1.1 Chemical Treatment Strategies

Two modes of effective chemical treatment can be used to limit lead contamination. The use of *surficial coatings* seals the surface from interaction with water to prevent either migration of solubilizing agents into lead-containing materials or migration of lead out of materials. Alternatively, the creation of *passivating films* relies on altering the chemical properties of the water to form relatively insoluble compounds with lead from the plumbing material to render the lead relatively immobile.

5.1.1.1 Surficial Coatings

Three categories of surficial coatings can be created, either naturally or by central chemical water treatment. These are natural diffusion barriers, calcium carbonate deposition, and silicate addition.

Natural Diffusion Barriers. Natural diffusion barriers can consist of a variety of insoluble materials that coat the pipe surface by means of precipitation reactions within the distribution system, caused by some chemical imbalance in the source water or after treatment processes. These solids may be aluminum hydroxides or silicates, coming from residual aluminum present from coagulation. Solids also include magnesium ammonium phosphate, magnesium silicate, or manganese dioxide,

which result from other aspects of water treatment. Natural diffusion barriers also can be made up of adsorbed organic material, ferric oxyhydroxides, or a combination of these materials in colloidal form, which adhere to the interior pipe walls. The iron can either occur naturally in the water or from the corrosion of iron mains in the distribution system.

A "stagnation curve" describes diffusion of lead from the corroding or dissolving surface into the water contained in pipe when the water is not flowing (2,8,11). Figure 5-1 shows two ideal stagnation curves computed for a water with an alkalinity of 30 mg/L calcium carbonate (CaCO_3) and a pH of 8 at a temperature of 25°C. The diffusion barriers function by changing the shape of the stagnation curve, making the slope of the initial limb of the curve much shallower. Because of these diffusion barriers, it takes much longer for the water to attain equilibrium levels. The standing time represented in most sampling programs is insufficient to allow equilibrium to be attained. Therefore, the amount of lead often tends to be lower than would even be predicted by the unadjusted stagnation curve equations.

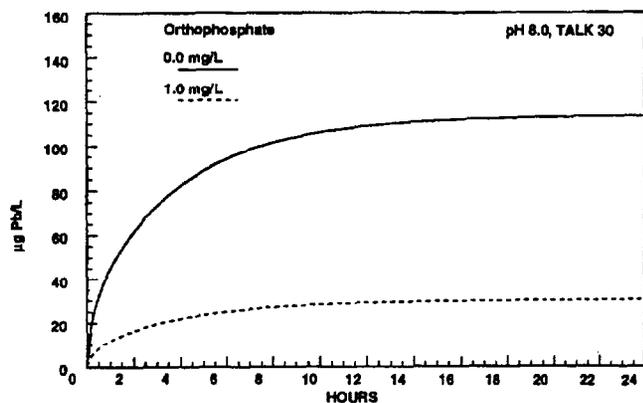


Figure 5-1. Stagnation lead levels.

Calcium Carbonate Saturation Considerations. Attempting to coat pipes with CaCO_3 to seal them from corrosion is historically the most common approach used by utilities. Unfortunately, little evidence exists to show that it works. An underlying (incorrect) assumption in the water treatment field states that corrosion rates and metal release into the water is somehow proportional to the amount of oversaturation or undersaturation with CaCO_3 in the water. In some cases, particularly in lime-soda softened waters of high pH, uniform thick CaCO_3 films are observed on pipes. These coatings also can have a small component of silica and lead corrosion product solid. In the absence of true CaCO_3 supersaturation, no chemical link exists between CaCO_3 , as measured by a variety of indices, and corrosivity towards lead.

To actually form CaCO_3 barriers, several optimum water conditioning issues must be satisfied. The first issue is that, when a water is sampled for analysis, the water conditions do not necessarily represent the conditions at the surface of the pipe where corrosion actually occurs. At the pipe surface, the pH is somewhat higher than in the bulk solution, resulting from

hydroxide ion generation originating in the corrosion. The degree to which that is the case is a function of the buffering intensity of the water. Further, the distribution of corrosion cells is not uniform across the surface of the pipe, so localized spots of precipitation might exist.

It is important to understand that pH, alkalinity, and dissolved inorganic carbonate (DIC) are interrelated (2,11,13). That is, as you change pH, you change alkalinity, and vice versa. The variables actually needed to define the conditions of a water system are pH and DIC, which are linearly related. In other words, for any given pH, total alkalinity represents a unique concentration of DIC. Similarly, for the same DIC, the corresponding total alkalinity changes with pH. Figure 5-2 illustrates the relationship for a hypothetical situation of a total alkalinity of 25 mg/L CaCO_3 at an ionic strength of 0.005 and a temperature of 25°C. At pH 10, this represents a DIC of 3.4 mg/L carbon, while at pH 6 the same alkalinity is generated by a DIC of 18.5 mg/L carbon.

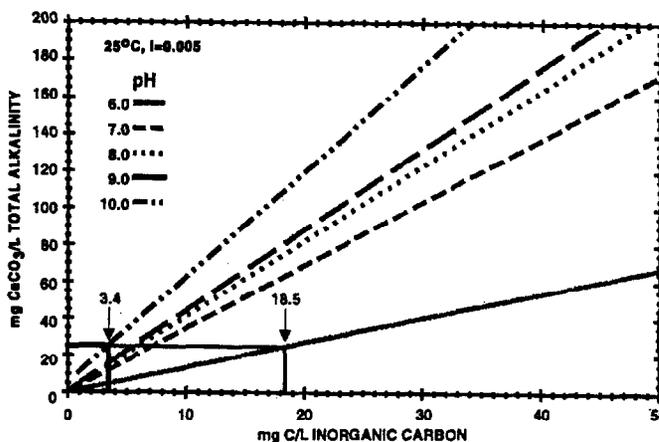


Figure 5-2. Alkalinity/DIC relationships.

An important implication of these relationships is that waters of low pH and low alkalinity might not necessarily also have low DIC. Thus, pH adjustment for lead and copper control might be adequate, without additional carbonate supplementation through the addition of sodium carbonate or bicarbonate chemicals. The central question to be determined before treatment is whether a given water has enough DIC to provide adequate buffer intensity at the targeted pH after adjustment.

To form a protective CaCO_3 pipe coating, a water must have sufficient available mass of calcium and carbonate species for precipitation. Enough calcium and carbonate ion must be delivered to the surface to create the necessary bulk of a good coating. It follows that good coatings are likely to be found only in relatively hard waters, in appropriate total alkalinity and pH ranges.

A second issue to be considered is what physical or operational steps must be taken to achieve optimum water conditions for lead control. A key is to quantify achievable conditions in the most reliable manner, traditionally by some CaCO_3 corrosion index or empirical test.

Saturation Index Determination. Historically, the most commonly used index is the Langelier Index (1,2). Basically, the Langelier Index is an estimate of the thermodynamic driving force for either precipitation or dissolution of calcium carbonate (2). Generally, three forms of the Langelier Index are found in the literature: approximation, quadratic, and "saturation index" forms. The Langelier Index is defined by the simple relationship:

$$LI = \text{pH}_{\text{sat}} - \text{pH}_{\text{act}}$$

where pH_{sat} represents the theoretical pH at saturation equilibrium with calcium carbonate (calcite form), and pH_{act} is the actual measured pH of the water. Most reported values for a Langelier Index have been computed using one of the numerous simplified expressions. Many approximation forms make compromises in assuming temperature, ionic strength, and the absence of significant side reactions with calcium carbonate, calcium bicarbonate, magnesium carbonate, calcium sulfate, and other soluble ion pairs. Frequently, these assumptions are based on numerically outdated or erroneous values for CaCO_3 solubility constants (1,2).

The quadratic form (1,2,3) is more precise. It avoids problems in some mathematical configurations of the Langelier Index where there is a sign change at high pH and the positive index then represents undersaturated conditions.

The "Saturation Index" (sometimes called a "Disequilibrium Index") approach has its origins mainly in the geochemical literature (2). It is a generalized formulation that compares ion activity products to thermodynamic equilibrium solubility constants for the given water chemical conditions. It allows for correction for ion pairs and complexes in a general way, and is particularly amenable to calculation on personal computers using a variety of chemical modeling programs that are widely available (1). The saturation index expression for CaCO_3 is shown in the equation below. The curved braces $\{ \}$ represent the activity of the ions in solution.

$$\text{CaCO}_3(\text{s}) = \text{Ca}^{2+} + \text{CO}_3^{2-}$$

$$SI_{\text{calcite}} = \log_{10} \left\{ \frac{\{\text{Ca}^{2+}\} \{\text{CO}_3^{2-}\}}{K_{\text{sp}}} \right\}$$

The major problem with the Langelier Index and the Saturation Index for estimating the potential for developing surficial coatings is that they do not clearly quantify the mass available for precipitation. To overcome this problem, the calcium carbonate precipitation potential (CCPP) (1,2,3) was developed. It is mathematically more complicated than the Langelier Index and Saturation Index, but with the widespread availability of programmable calculators and computers, this is not a significant problem.

Table 5-1 presents the advantage of CCPP over the Langelier Index. Comparing the example of a relatively soft water at high pH with a hard water at low pH shows that the Langelier Index is the same for both waters. The CCPP is much higher

Table 5-1. Langelier Index (LI) vs Calcium Carbonate Precipitation Potential (CCPP)

| Parameter | Same Langelier Index | |
|-------------------|----------------------|---------------------|
| | Soft Water (high pH) | Hard Water (low pH) |
| Temperature (°C) | 15 | 15 |
| Alkalinity (mg/L) | 25 | 350 |
| Calcium (mg/L) | 17 | 130 |
| TDS (mg/L) | 75 | 750 |
| pH (units) | 8.90 | 7.03 |
| LI (units) | 0.10 | 0.10 |
| CCPP (mg/L) | 0.40 | 15 |

for the hard water with the higher alkalinity. In this example, a factor of almost 40 times more CaCO_3 is predicted to be precipitated from the hard water than from the soft water.

Like the Langelier Index, the CCPP also assumes formation of pure CaCO_3 (calcite form) and no kinetic barriers to deposition. A problem arises in cases where some cations, such as magnesium, copper, or zinc, might inhibit the formation of well-ordered calcite (CaCO_3). Similarly, certain anions, such as ortho- or polyphosphates, might inhibit the formation of calcite. These "natural inhibitors" reduce coatings through interaction with growth of crystal nuclei, possibly by creating distortions of the crystal lattice formation. Other likely inhibitive mechanisms are by complexation or sequestration of calcium.

None of the published forms of the Langelier Index or CCPP can take into account these inhibitory factors, particularly the presence of polyphosphates. Therefore, in systems containing polyphosphate either for corrosion control or for prevention of unwanted calcium carbonate deposition, calculation of any of the widely published indices of calcium carbonate saturation or precipitation is invalid.

The third control method is the old empirical test, commonly referred to as the "marble" test (1). This test can be done in several different ways. *Empirical tests* such as the marble test are the *only valid ways to assess calcium carbonate dissolution or solubility potential in the presence of polyphosphates or some other inhibiting ions.*

Silicate Addition. Another chemical approach to creating surficial coatings is silicate addition. Silicate species, when present in sufficient concentration under the appropriate water chemistry conditions, can adsorb to pipe surfaces to create a film. Sometimes, the silicate operates in conjunction with other metals present in the water, forming colloidal species that can adhere to pipe surfaces. Silicate can also react slowly with existing carbonate, basic carbonate, or oxyhydroxide corrosion products, either to form fewer soluble reaction products on the pipe surface or to bind existing corrosion products into more uniform surface deposits. In this mode of action, the silicate might act more like a grout or cementing agent.

A second way silicate might function to reduce corrosion is to buffer against hydroxide production at high pH, because it can produce increased buffering intensity for the typical soft water. The role of silicate in augmenting buffer intensity has been described by Snoeyink and Jenkins (13). Hydroxide ion production is a normal by-product of most metal corrosion oxidation reactions in potable waters, so that limiting its production would tend to stifle corrosion.

Relatively little quantitative information exists to predict the effect of silicate addition. It is clear, however, that its effectiveness depends on pH, silicate concentration, and hardness. Silicate treatment chemicals are added in polymeric form as a highly viscous, basic chemical. In water, soluble monomeric silica acts as a diprotic acid, having a negatively charged species at high pH. Silicate reaction can be relatively slow. Silicate addition also might need the presence of existing corrosion by-product films to work. This becomes a complicating issue when evaluating corrosion treatments in pipe loop systems or through coupon tests. Because experimental systems are ordinarily made with new materials, silicates might not give the same results in actual distribution system use relative to other experimentally tested treatments that react more readily with fresh metal surfaces.

5.1.1.2 Passivating Film Formation

Conceptual Approach. The driving concept in the formation of passivating films is to adjust water quality to form the most thermodynamically stable phase possible. Even in pure water with only carbonate species, such as HCO_3^- and CO_3^{2-} ions, lead chemistry is very complicated. Lead forms soluble complexes such as PbCO_3^0 and $\text{Pb}(\text{CO}_3)_2^{2-}$, in addition to hydroxide complexes, depending on pH and carbonate concentration. Figures 5-3 and 5-4 show lead species distribution in equilibrium with normal and basic lead carbonate for waters with relatively low and high DIC concentrations. The figures show that in neutral to slightly basic systems, as in most treated drinking water systems, lead exists in complexed forms as PbCO_3^0 and $\text{Pb}(\text{OH})_2^0$. The ultimate significance of these complexes can be illustrated by looking at a three-dimensional solu-

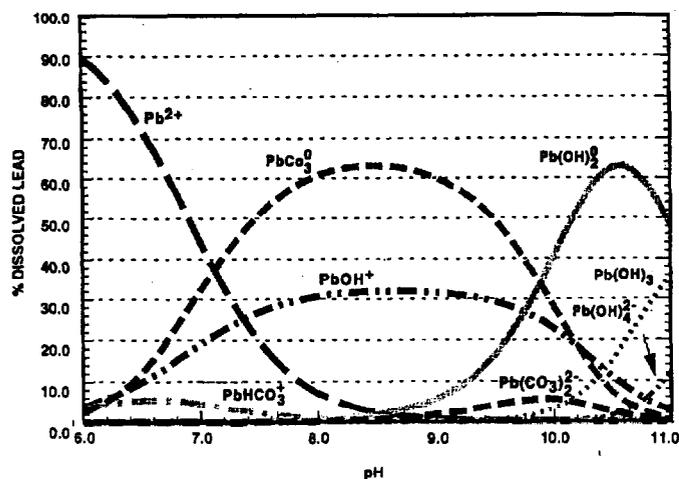


Figure 5-3. Lead speciation for 25°C, ionic strength (I) = 0.01, dissolved inorganic carbonate (DIC) = 3 mg/L.

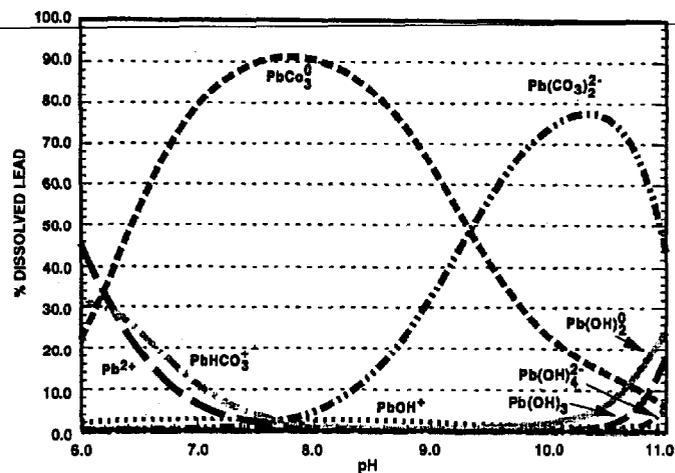


Figure 5-4. Lead speciation for 25°C, I = 0.01, DIC = 50 mg/L.

bility diagram for lead (Figure 5-5). The figure shows that, at very low lead concentrations, lead is very soluble. However, the addition of small amounts of carbonate drastically reduces lead solubility, particularly above pH 8.5 to 9. Further increases in carbonate levels, however, cause resolubilization of lead because of the formation of PbHCO_3^+ , PbCO_3^0 , and $\text{Pb}(\text{CO}_3)_2^{2-}$ complexes.

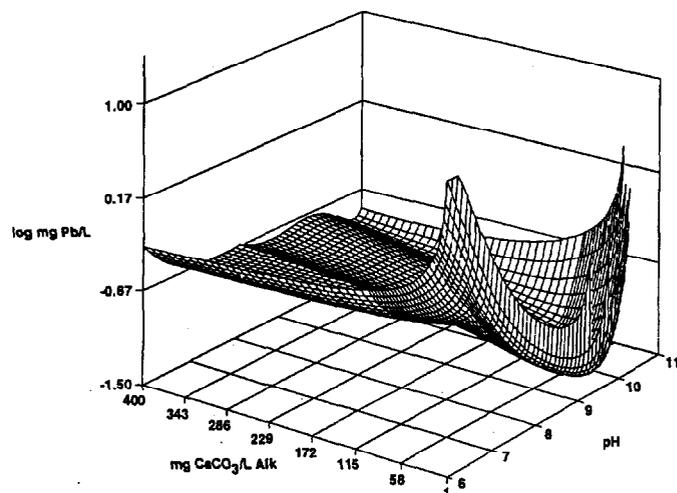


Figure 5-5. Lead solubility (I = 0.01, 25°C).

Lead also can form very insoluble orthophosphate compounds, particularly $\text{Pb}_5(\text{PO}_4)_3\text{OH}(s)$ and $\text{Pb}_3(\text{PO}_4)_2(s)$ (2,10,11). These orthophosphate solids are less soluble than $\text{Pb}_3(\text{CO}_3)_2(\text{OH})_2(s)$ (basic lead carbonate, hydrocerussite) or $\text{PbCO}_3(s)$ below a pH of about 8. Figures 5-6 to 5-8 show solubility diagrams for the addition of 0 to 5 mg/L PO_4 of orthophosphate to waters of different total alkalinities, at pHs of 7.0, 7.5, and 8.0. For these figures, all alkalinity is assumed to be contributed by a carbonate species or a hydroxide ion, through the relationship:

$$\text{TALK} = 2[\text{CO}_3^{2-}] + [\text{HCO}_3^-] + [\text{OH}^-] - [\text{H}^+]$$

in which the brackets [] represent concentrations in mol/L. These figures are explained further in the section on orthophosphate addition.

Control of lead by solubility considerations follows one of four approaches.

pH Adjustment. For many waters, merely adjusting the pH is adequate. This adjustment might succeed by decreasing equilibrium lead solubility to an acceptable level or by reducing the diffusion rate of lead into solution so that lead levels are lowered under the usage patterns of most consumers. The use of pH adjustment also might be adequate to reduce the lead leaching from soldered joints or brass materials to acceptable levels.

pH/Alkalinity/DIC Adjustment. In some waters, both pH and DIC need to be adjusted. One reason DIC adjustment is useful is to decrease lead solubility in conjunction with pH. The other equally important reason is to provide enough carbonate concentration to give the water a higher buffering intensity to help maintain desired pH throughout the distribution system. Many treatments fail because the pH of water in the distribution system drops substantially below the pH at which the water left the plant, rendering conditions unsuitable for the formation of passivating films on the pipe.

Orthophosphate Addition. Orthophosphate addition has been shown to be extremely effective in 10 years of application in Great Britain and Scotland (4,5,12). Published literature from the United States is more ambiguous, but the utilities reporting poor results in reducing lead levels almost always use improper control conditions. The utilities usually are operating in an incorrect pH range or at an insufficient orthophosphate dosage to maintain an adequate level for keeping lead solubility low in all parts of the distribution system.

Several important factors govern the effectiveness of orthophosphate addition. Effectiveness strongly depends on pH, DIC, and orthophosphate dosage; it probably also is influenced by temperature, but this factor has not been quantified precisely. Figures 5-6 through 5-8 show, for example, that for treatment at pH 7.5, the lead level is reduced significantly by the addition of the first 0.5 to 1.0 mg/L of orthophosphate as PO_4 . Additional dosage has relatively less effect, particularly above approximately 3 mg/L PO_4 .

The optimum pH for solubility reduction by orthophosphate also depends on the background DIC/alkalinity of the water (2,10,11). Figures 5-6, 5-7, and 5-8 also show that for higher alkalinities, the level of lead achievable (in terms of equilibrium solubility) is not as low. For waters with high alkalinity, however, orthophosphate dosage provides much greater reduction in lead concentration than is possible with pH and alkalinity adjustment alone.

The dosages of orthophosphate possible might be limited by the calcium hardness of the water. Depending on the pH, hardness, and orthophosphate dosage, a solid such as octacalcium phosphate or other orthophosphate solid can form and consume phosphate, creating turbidity in the water (10). It is important to note that precise and accurate predictions of this

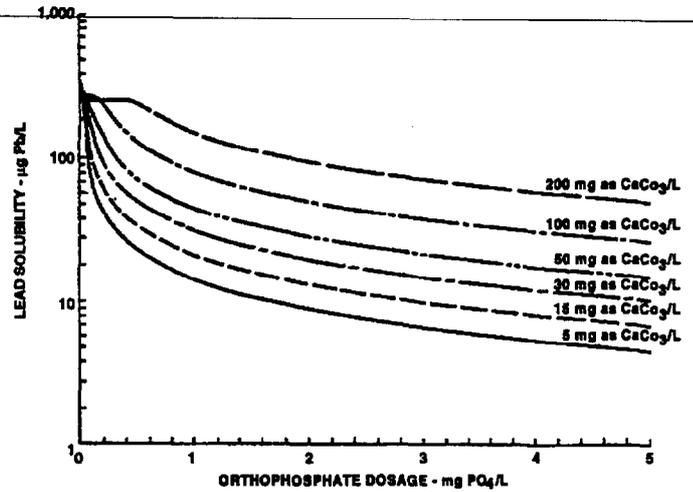


Figure 5-6. Variation in lead solubility (pH 7.0) as a function of orthophosphate dosage for different alkalinities.

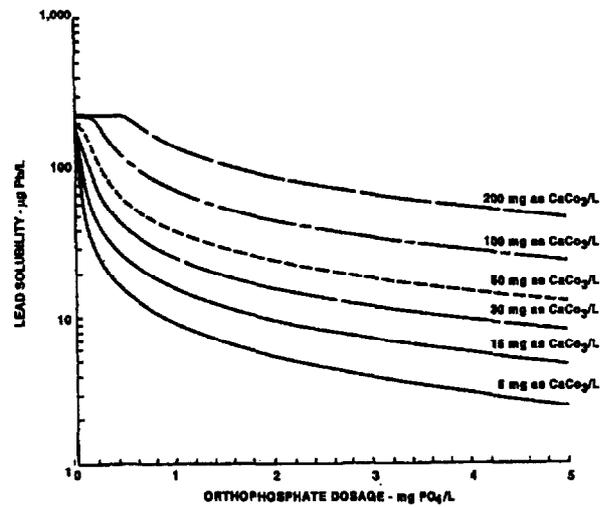


Figure 5-7. Variation in lead solubility (pH 7.5) as a function of orthophosphate dosage for different alkalinities.

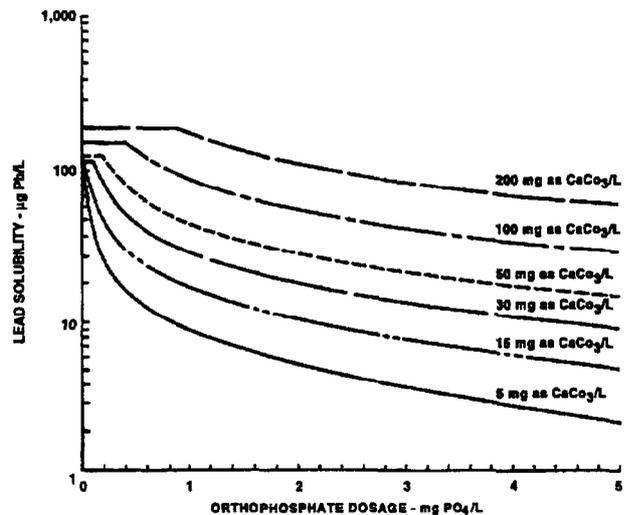


Figure 5-8. Variation in lead solubility (pH 8.0) as a function of orthophosphate dosage for different alkalinities.

limitation have not been established. In many cases, CaCO_3 might be more likely to precipitate first before orthophosphate solids.

A very important, but little recognized, limitation to orthophosphate addition is the interaction of zinc with pH, DIC, and orthophosphate. Most commercial orthophosphate treatment chemicals contain zinc in some proportion. Contrary to many manufacturers' literature and assertions, the orthophosphate effectively reacts with lead in plumbing materials and does not function by depositing a zinc orthophosphate coating (2,10,11). The solubility of zinc depends on both pH and DIC, as is shown in Figure 5-9. Zinc can precipitate as basic zinc carbonate $\text{Zn}_5\text{OH}_6(\text{CO}_3)_2(\text{s})$, thus causing turbid water, if the DIC or pH is too high to maintain its solubility.

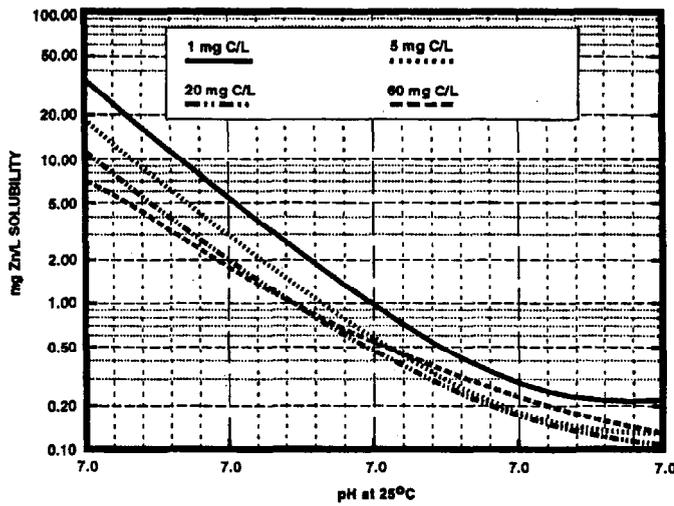


Figure 5-9. Zinc solubility ($I=0.01$).

Similarly, given certain pH, DIC, and orthophosphate concentration combinations, the precipitation of actual zinc orthophosphate (e.g., α -hopeite, $\text{Zn}_3(\text{PO}_4)_2 \cdot 4\text{H}_2\text{O}$) could take place (Figure 5-10). This also would cause turbid water, and it would reduce the concentration of orthophosphate available to react with the lead elsewhere in the distribution system. For example, if a zinc orthophosphate formulation were used that had a 1:1 ratio of $\text{Zn}:\text{PO}_4$, the maximum dosage of orthophosphate that could be achieved without danger of zinc orthophosphate precipitation at pH 7.5 would be approximately 1.6 mg/L for a DIC of 80 mg/L C, or approximately 1.4 mg/L for a DIC of 20 mg/L carbon. The limits would be different at different pHs.

One further issue with orthophosphate addition is the necessity for zinc in the formulation. For the control of lead pipe corrosion, it is unlikely to be useful (10). For brass or soldered joint corrosion control, there is a scarcity of real data. What data exist suggest that zinc might be helpful (2,6,10,11), possibly by providing a counter to dezincification in brass by the addition of the zinc in the water. In the case of brass, the deposition of zinc orthophosphate solid might also be advantageous. Arguments also are made, with similarly little published data, that the zinc is somehow useful in providing more effective

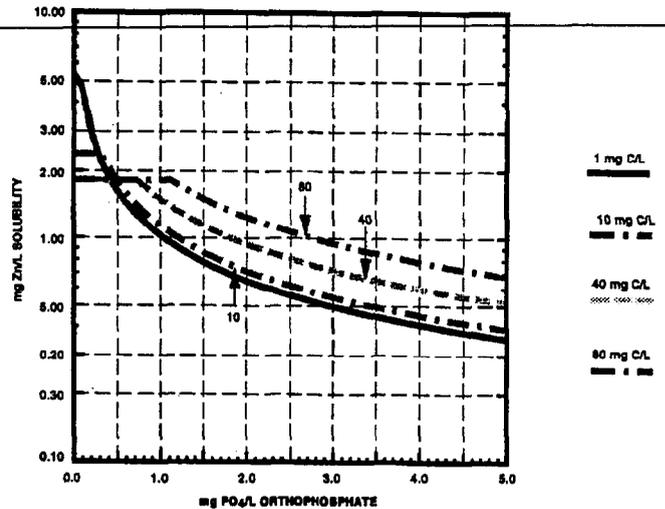


Figure 5-10. Zinc solubility (pH 7.5, $I=0.01$, 25°C).

control of iron corrosion, possibly by forming a mixed Zn-Fe-Ca phosphate film.

Clearly, much more research needs to be done in this area. Current experiments at EPA show that orthophosphate alone can be effective in slowing lead leaching from brass, given correct pH and sufficient orthophosphate dosage. The considerations of zinc orthophosphate solubility discussed above show that, if zinc is not necessary in the formulations or if a much lower concentration of zinc than phosphate is useful, then high $\text{PO}_4:\text{Zn}$ ratios would be advantageous for dosing.

Blended Orthophosphate Addition. The remaining viable approach to formation of passivating films is addition of "blended" phosphates. These chemicals are mixtures of orthophosphate (often 40 percent) with some combination of linear polyphosphates. The blended phosphates are used to provide the necessary sequestration or crystal growth-poisoning properties for such problems as "red water," CaCO_3 precipitation, or manganese precipitation, without having excess polyphosphate to solubilize lead and copper. The orthophosphate component is present to form a passivating lead orthophosphate film on the pipe, as is the case with direct orthophosphate addition alone. From the standpoint of lead and copper control, the use of blended phosphates is a "balancing act" between the *solubility enhancing* properties of the polyphosphate with the *solubility decreasing* (for lead) properties of the orthophosphate.

As with orthophosphate addition, the effect of blended phosphate addition will depend on at least the combination of pH, DIC, and chemical dosage. Temperature is also almost sure to play an important role by affecting the solubility of the passivating solid, the aqueous speciation of the metal, and the aqueous speciation of the phosphate species. The effectiveness also will depend on the ratio of polyphosphates to orthophosphates in the chemical, although what that dependence is cannot be readily predicted at present. The effect also will depend on the specific identity of the polyphosphate components and their speciation under the water quality condition in the distribution system. Polyphosphates have an intrinsic ability to complex and

solubilize lead (and copper) and different affinities for calcium, magnesium, manganese, ferrous iron, ferric iron, and other substances (7).

Colloidal and Particulate Metal Forms. Another important factor in the formation of passivating films is the possible existence of colloidal and undissolved metal forms. This problem manifests itself in several ways. If treatment chemicals form an insoluble colloid with lead and that colloid does not adhere to the pipe wall, erratic lead levels can be observed in water samples and treatment will not produce substantial improvement in lead levels at the tap.

The chemical treatment also might not be effective in preventing the physical creation of particles of lead, such as from solder or brass, in turbulent water conditions.

5.1.2 Selection Criteria

Several factors need to be taken into account when deciding what strategy to pursue for the control of lead and copper.

5.1.2.1 Mix of Materials in the Distribution System

Distribution systems are not homogeneous. They are made up of a variety of materials, such as lead pipes; soldered joints; brass, copper, or galvanized pipe; iron mains; asbestos-cement pipe; or cement mortar-lined mains.

The source of lead and copper in the water passing through the system usually is found at the end of the distribution system, in domestic and commercial plumbing installations. However, even though the regulatory target is the control of lead and copper, the utility must devise a control method that is compatible with all of its distribution system materials. Water chemistry conditions that effectively control lead and copper corrosion might not be optimum for controlling cast iron corrosion, for instance, and could even cause an increase in corrosion rates (9).

5.1.2.2 Initial Water Quality

Initial water quality not only dictates the success of a particular control strategy but also governs the efficiency of employing a particular strategy. For instance, it would not be cost-effective to use a CaCO_3 saturation control strategy when the source water has a very low hardness and pH. Similarly, employing pH adjustment to achieve a good pH for lead control—approximately 9.0—would be very difficult in a hard water. As discussed previously, the critical initial water quality factors that should be considered during the control method selection process are, at minimum, pH, alkalinity/DIC, hardness, and CaCO_3 saturation. Depending on the exact initial chemical characteristics of a water supply, additional factors also might be of considerable importance in defining treatment options and their limitations.

Another critical water quality concern is whether a shift in treatment strategy could result in the destabilization of existing corrosion films and a significant increase in exposure to lead or copper for some time. As an example, consider a utility currently employing pH adjustment to approximately pH 9.0 to

limit lead leaching. Further, assume that because the utility is concerned about disinfection effectiveness and trihalomethane formation potential, it would prefer to switch to the use of orthophosphate dosage to enable operation at a considerably lower pH. Such a pH change could jeopardize the integrity of the lead films on the surface of the pipe, potentially resulting in increased lead levels.

5.1.2.3 Source Water Problems

Source water problems can cause severe conflicts when a particular strategy is used to control copper and lead. Examples of source water problems include the presence of iron, manganese, volatile organic compounds, humic or fulvic substances, and high trihalomethane formation potential.

A utility has to judge to what extent it should attempt to solve the source water conflicts by physical means, or whether to rely solely on chemical treatment to provide an effective general treatment.

Chlorine dosage can adversely affect lead and copper control because chlorine is frequently added as an acidic gas. Consequently, pH in a poorly buffered water is decreased, requiring additional pH adjustment to balance the corrosivity toward copper and lead. Furthermore, evidence exists that chlorine can accelerate the rate of copper corrosion. Fluoride dosage, when added as hydrofluosilicic acid, also causes a pH decrease in poorly buffered waters.

Section 5.2 discusses some of these conflicts in greater detail.

5.1.2.4 Related Requirements

Different locations must comply with different regulatory requirements. The considerations of the lead and copper rule itself, as well as other water treatment objectives dictated by other primary and secondary drinking water regulations, must be balanced. Further, each primacy agency has the latitude to impose other constraints that are thought to be effective in the region or state. Certain treatment processes might be favored over others. Additional water quality objectives also might exist.

Major industrial/commercial water users provide a significant economic base to a community. These users can be seriously affected by major changes in water treatment and water quality. Therefore, a utility might be constrained by, or at least must take into serious consideration, the compatibility of a water treatment with current users. The utility might select a method to which the users can adjust, given equivalent health-based performance.

It is a regulatory requirement that optimal lead and copper control, once in place, must be properly maintained, as demonstrated by meeting specified treatment goals. There is more than one way to achieve a water quality objective. Since the utility has to meet goals agreed to with the primacy agency, it is in the utility's best interest to choose the most mechanically reliable, safest, and most operationally consistent method.

A utility is best served by choosing the least costly among otherwise equivalent treatment approaches. It is sometimes difficult to obtain accurate cost projections for a fully implemented treatment from bench and pilot-plant scale studies. A significant difference is that, when full-scale treatment is implemented, large quantities of bulk chemicals can be obtained through a bidding process. This can give the utility the ability to get a large quantity of a chemical much more cheaply than most tabulated price estimates. For example, a single barrel of silicate might appear very expensive, but when vendors begin competing with other vendors for a long-term supply of bulk chemical (e.g., railroad car scale), relative prices are often much lower.

5.1.3 Treatment Chemicals

For each chemical control strategy, a variety of specific chemicals is available. The chemicals can be obtained from water treatment chemical specialists, often having proprietary formulations for inhibitors. They also can be obtained from industrial chemical manufacturers and their distributors. A useful source for chemical suppliers and available products is Standard 61 from the National Sanitation Foundation.¹ It is a tabulation of water treatment chemicals tested by a standardized procedure for contamination by elements or compounds that are regulated in drinking water for health concerns.

5.1.3.1 pH Adjustment

For pH adjustment, the most useful chemicals are lime (CaO), slaked lime (Ca(OH)₂), caustic (NaOH, KOH), and sodium silicate. Lime, slaked lime, and caustics have been discussed widely in the literature and historically have been the major ways to adjust pH. Many utilities, however, particularly smaller ones, continue to have consistent problems with pH control using these chemicals. Historically, sodium silicate has not been used for the specific purpose of pH adjustment. However, its properties easily lend it to this application. Sodium silicate might have several advantages over the other four chemicals. It is easy to feed consistently, using relatively simple pumps. It is at least as safe to use as any of the other chemicals and possibly safer for the operators to handle. Its desirable properties for source water iron and manganese control might make it possible to accomplish more than one treatment objective simultaneously.

Type N[®] has been the most commonly used silicate, because it has one of the highest SiO₂:Na₂O ratios. For pH adjustment, however, a formulation having a lower SiO₂:Na₂O ratio would be advantageous.

5.1.3.2 Alkalinity Adjustment

For alkalinity adjustment, appropriate chemicals are lime, slaked lime (CaO, CaOH), caustic (NaOH, KOH), sodium silicate, sodium bicarbonate, sodium carbonate (soda ash), and sodium silicate.

These chemicals can work as pH adjusters (indirectly increasing alkalinity), alkalinity adjusters (indirectly increasing pH), or both.

5.1.3.3 Inorganic Carbon Adjustment

Only two chemicals are widely used for the supplementation of inorganic carbon (DIC): sodium bicarbonate (NaHCO₃) and soda ash (sodium carbonate, Na₂CO₃). Both will provide some increase in pH, with soda ash having a greater effect than sodium bicarbonate. The magnitude of the pH effect will depend on the original water chemical characteristics.

5.1.3.4 Hardness Adjustment

Only two chemicals are ordinarily used to provide hardness (calcium) addition: lime (CaO) and slaked lime (Ca(OH)₂). Both also increase the pH. Frequently, the effects are confused.

These chemicals, at the proper dosages, can create conditions that provide supersaturation of calcium carbonate in the bulk water solution or at the pipe surface. By increasing pH, the chemicals can increase buffering intensity in some pH regions. Sometimes the buffering intensity increase can inhibit hydroxide ion production by heterogeneous (calcite saturation) buffering (2). Except under these conditions, little evidence exists that calcium content has a direct role in reducing lead or copper leaching.

5.1.3.5 Corrosion Inhibitors

Four classes of chemical inhibitor formulations are useful for lead control:

- Sodium silicate (maximizes SiO₂:Na₂O ratio)
- Zinc orthophosphates
- Generic orthophosphates
- Blends of ortho- and polyphosphates

When selecting the sodium silicate formulation for use as an inhibitor (instead of as a pH adjuster), the key basis for selection is to obtain the *maximum* SiO₂:Na₂O ratio. For this purpose, the silica concentration is the active agent. Dosages of sodium silicate for lead and copper control can be perhaps 18 to 30 mg/L SiO₂, which is much greater than the dosage usually suggested in the literature. The extent to which the dosage can be lowered to provide an adequate "maintenance" dosage has not been studied extensively. Experiments by EPA suggest that high sodium silicate dosage might be more useful than orthophosphate dosage to reduce copper leaching from copper pipe, but pH effects cannot be totally ruled out.

The effectiveness of the use of orthophosphate and blended phosphates for the control of copper leaching is less clear. Some researchers report a decrease in the corrosion rate for copper when orthophosphate is used; few studies, however, have been conducted thus far that show orthophosphate addition at realistic concentrations (0 to 5 mg/L PO₄) to reduce copper dissolution conclusively beyond that attributable to pH adjustment

¹National Sanitation Foundation, 3475 Plymouth Road, Ann Arbor, MI 48113-0140, 313-769-8010.

alone. Experiments by EPA have shown 3 mg/L PO₄ orthophosphate to be effective in reducing the leaching of lead from brass at pH 7.5 in a moderately hard water with a DIC concentration of approximately 10-12 mg/L C.

The family name "zinc orthophosphate" applies to a wide range of commercial formulations. The chemicals are usually acidic blends of zinc sulfate or zinc chloride, with phosphoric acid or a dihydrogen salt of sodium or potassium (e.g., NaH₂PO₄). Sometimes, a deoxygenating or dechlorination agent, such as sodium bisulfite, is added to decrease water aggressivity. The formulations characteristically have different ratios (as mg/L) of Zn:PO₄, ranging from 1:10 to 1:1 in the most common commercial products. The ratio selection depends on the necessity for zinc in the system (for example, to protect asbestos-cement pipe), the orthophosphate level desired for lead control, and the solubility of zinc in the background water chemistry conditions (pH, orthophosphate concentration, and DIC concentration).

The second family of orthophosphate chemicals are the "generic orthophosphates," including industrial chemicals such as:

- H₃PO₄
- NaH₂PO₄ (or K)
- Na₂HPO₄ (or K₂)
- Na₃PO₄ (or K₃)

From the standpoint of lead control, there should be essentially no significance to whether the salt is based on sodium or potassium. Mixtures of the chemicals are also possible. The use of orthophosphoric acid (H₃PO₄) in conjunction with pH adjustment has been widely used in Britain (4,5,11,12).

The family of "blended" phosphates is highly diverse. In general terms, the family includes:

- Orthophosphate salt plus Na- or K-pyrophosphate (P₂O₇⁴⁻)
- Orthophosphate salt plus Na- or K-tripolyphosphate (P₃O₁₀⁵⁻)
- Orthophosphate salt(s), plus mixture of linear polyphosphates

Each possible polyphosphate chain has slightly differing properties of affinity for different metals and resistance to breaking down into a molecule of shorter length and an orthophosphate group. Commercial products usually are formulated to control a background water problem, such as iron or manganese oxidation or calcium carbonate encrustation. The orthophosphate component helps in film formation on metals that form relatively insoluble surface films, such as lead and zinc.

Little objective data have been published on lead and copper control using blended phosphates in different water chemistries. In principle, however, depending on the exact nature of

the formulation, blended phosphates should be a viable treatment alternative, especially for lead.

When pH effects and reversion to orthophosphate are accounted for, no evidence exists that straight polyphosphate addition is a desirable strategy for the control of lead and copper. In fact, considerable data exist to show detrimental effects (7), especially under the low pH conditions (pH 6-7) that are often optimal for source water iron sequestration.

5.1.4 Summary

Many approaches are available for lead and copper corrosion control. The selection of the best choice might be limited by several factors, particularly:

- Source water characteristics
- Secondary impacts
 - On other drinking water parameters
 - On wastewater treatment efficiency
 - On discharged waters
- Need to control corrosion of other materials (e.g., asbestos-cement, iron, cement mortar-lined pipe)
- Relative cost of equivalently performing treatments

A source of confusion in selecting a control strategy to optimize corrosion control for a distribution system is that copper and lead might not respond equivalently to each strategy. Additionally, except for new construction areas with fresh copper and brass plumbing pipes and materials, distribution systems have had scales and corrosion product buildups for many years. Therefore, implementation of new corrosion control strategies might cause short-term problems. This problem is illustrated by the scenario given in Figure 5-11.

In Figure 5-11, point A represents the starting point on a lead solubility diagram for a system currently applying pH

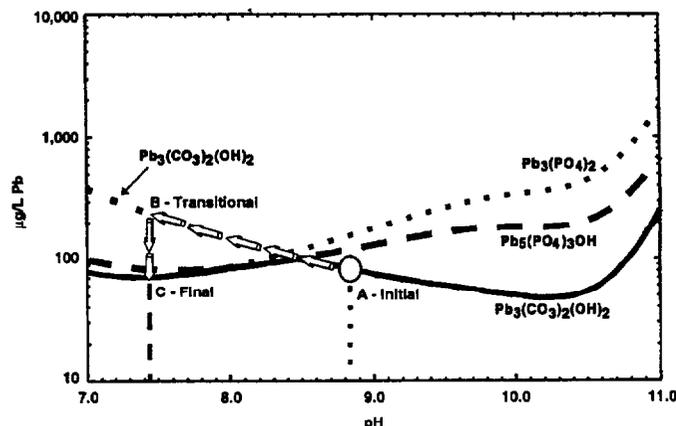


Figure 5-11. Path of lead response to treatment changes.

adjustment to approximately 8.8 as its control strategy. At this point, the lead leaching is being controlled by a mixed surface coating including basic lead carbonate (hydrocerussite). Consider the case in which the same utility decides to change its corrosion control approach to the addition of 1 mg/L PO₄ orthophosphate at a pH of approximately 7.5, to improve disinfection effectiveness and to reduce the rate of trihalomethane formation. Because the basic lead carbonate film is reversible, and because the lead orthophosphate film formation rate on an old pipe surface is possibly somewhat slower than the dissolution rate of the existing basic lead carbonate, the stability of the system might follow the arrows along the solubility curve for Pb₃(CO₃)₂(OH)₂ to the solubility for pH 7.5 (point B). The solubility at this pH is much greater than at the original pH of 8.8, causing a transitional period in which the existing film is destabilized. Until there is adequate contact time with the orthophosphate to reestablish a stable new lead orthophosphate film (point C), lead levels might be higher and more erratic than they were originally.

Very little published information exists on the stability of lead corrosion films, as well as their formation and dissolution rates under realistic distribution system conditions. Until these gaps in the research are filled, utilities and their advisors must carefully consider unintended risks to public health, while working to optimize corrosion control and simultaneously meet other regulatory needs.

Although treatment strategies exist that make it possible for utilities to comply with the action levels in the new lead and copper rule, additional optimization might soon be necessary. This problem might be caused by the increasingly stringent wastewater effluent guidelines. Ambient, normal domestic and commercial plumbing corrosion might ultimately contribute enough lead and copper to the wastewater to cause difficulty in meeting those regulations. The problem will be even more likely to occur as industrial discharge becomes a smaller fraction of the contaminant load into the wastewater system. Utilities will come under more pressure to minimize both lead and copper levels beyond those required from the drinking water regulatory standpoint.

At this time, inadequate systematic research exists to provide specific guidance for dosages and water chemistry adjustments to guarantee the best selection of chemicals and water chemistry conditions to ensure the minimization of lead and copper levels in drinking water. The information in this chapter and Chapter Four, however, should provide a starting point from which to begin the evaluation process and choose among the numerous alternatives available to best fit the overall needs of a water utility.

5.2 Secondary Effects and Conflicts with Lead Corrosion Control Strategies

The American Water Works Service Company (AWWSC) is a large, private water company that has approximately 121 individual operating water systems merged into 21 companies located throughout the country. The AWWSC has had the benefit of dealing with a variety of waters and has been controlling

corrosion in these waters for many years; the need to control corrosion is not something new that arose because of the lead rule. There are basically three ways to control lead: controlling mineral stability, using an inhibitor, and not using any lead-based materials in plumbing or distribution systems.

5.2.1 Carbonate Passivation

Most waters have some dissolved inorganic carbonate (DIC), and by raising the pH, the amount of bicarbonate (HCO₃⁻) and carbonate (CO₃⁻²) can be increased. The CO₃⁻² reacts with lead to form stable insoluble carbonate films. When the pH is raised, a decision must be made about where pH will be adjusted within a treatment plant. Using lime presents quite a problem if alum is used as a coagulant, because the solubility of aluminum is very dependent on pH. If the pH is above 7, a large fraction of aluminum will carry over through the treatment plant to the clearwell. Another option is to add lime just prior to filtration, after coagulation with alum, but the lime deposition that can occur in the filter is potentially a serious problem. Injection of lime ahead of granular activated carbon should be avoided. The safest way to avoid deposition in the clearwell is to use caustic soda or caustic potash.

Careless raising of the pH can cause excess metal carbonates to accumulate, particularly at the high-service pumps where there is high velocity and high pressure and immediately downstream of the high-service pumps.

Many industrial customers cannot tolerate elevated levels of minerals, a high pH, or high concentrations of carbonates. Proposed water quality modifications should be discussed with large industrial customers.

The effect of pH on chlorine's ability to disinfect is very important (Figure 5-12a), particularly now as many water systems are trying to meet the requirements of the Surface Water Treatment Rule (SWTR). As the pH is raised, the stronger oxidizer hypochlorous acid is converted to the weaker hypochlorite ion. The higher the pH, the less effective the chlorine

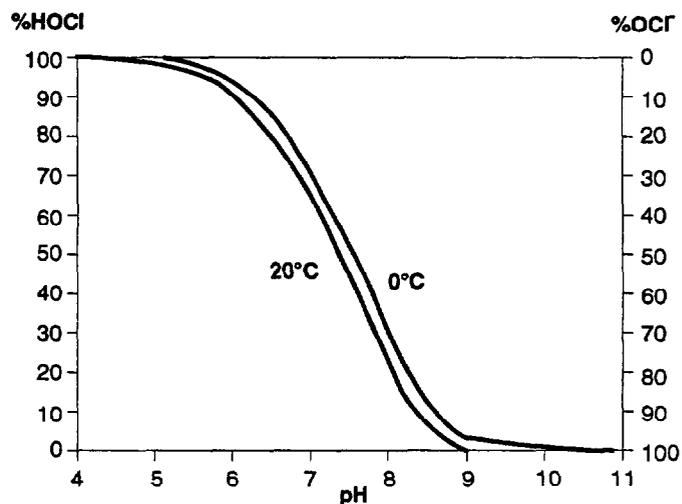


Figure 5-12a. Distribution of HOCl and OCl⁻ in water as a function of pH.

will be. By raising the pH, the disinfection process might not be able to meet the contact times (CTs) that are required by the SWTR. The CT required by EPA increases by 50 percent when the pH is increased from 7 to 8. To compensate for a pH increase in the disinfection process, the free chlorine, CT, or both will need to be increased.

Another potentially major problem of corrosion control is the effect on disinfection by-products. The trihalomethane formation potential (THMFP) increases as pH increases (Figure 5-12b). In one study, a 40 percent increase in trihalomethanes was observed as a result of raising the pH from 7 to 8. That is bad news regarding THMs; it is not the case, however, with every disinfection by-product. All of them are pH dependent, but some have the reverse trend and actually decrease with increasing pH. EPA will be regulating many disinfection by-products, and any changes in pH levels might affect future

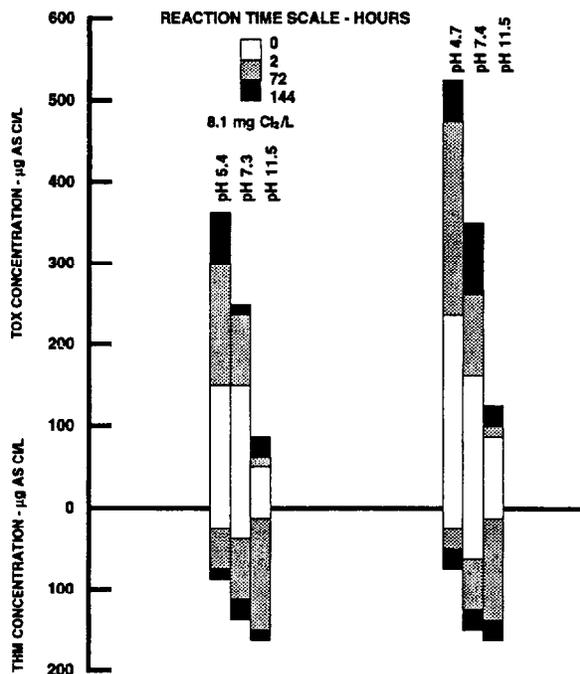


Figure 5-12b. Effects of pH and oxidant dosage on the formation of TOX and THMs (CHCl₃) at 20°C in distilled water solutions of 5 mg humic acid/L.

compliance.

There are other difficulties with trying to attain carbonate passivation. All systems have trouble feeding lime, but options exist for feeding lime that are virtually problem-free. Liquid chemicals such as sodium hydroxide have very few feed problems. Soda ash works well in 15°C water, but trying to dissolve soda ash in 5°C water will result in most of the carbonate accumulating in the bottom of the feeder.

The addition of sodium itself also can present a problem. Many years ago, EPA suggested a possible standard for sodium and some of the states attempted to meet this standard. Some of the New England states have a primary maximum contami-

nant level (MCL) for sodium (Massachusetts, for example, has an MCL of 20 mg/L). Because of sensitivity in those states about adding any sodium, problems can occur with the addition of soda ash or caustic. It is preferable to raise pH with potassium hydroxide rather than sodium hydroxide.

5.2.2 Corrosion Inhibitors

Zinc orthophosphate has performed best in AWWSC's distribution system. However, wastewater treatment plants might object because there is a limit on zinc in land application of sludge for composting. Another problem of this method involves phosphates. Phosphates have been controlled for many years in this country, and wastewater treatment plants have a limit on phosphates. Therefore, these plants might have a problem meeting their own discharge limits with phosphate addition. Phosphates are nutrients essential for sustaining growth of algae. If the system has any open reservoirs, particularly in a warm climate, a summertime water problem of algal growths will occur. Many corrosion inhibitors have a narrow pH range in which they are effective. The pH range in which to use phosphates to maximize their effectiveness is 7.0 to 8.0. Many systems will need to either increase or decrease their pH to stay within that range. For example, a lime-softening plant that operates at a pH of 9.0 would need to lower its pH for phosphate to be effective.

Compatibility with other chemicals is also important. In some cases, a metal-phosphate precipitate forms. That can occur with aluminum when more than 0.1 mg/L of aluminum is carried through the treatment plant and clearwell. The phosphate can combine with the aluminum, and aluminum phosphate compounds will precipitate in the clearwell and in the distribution system. The amount of precipitate depends on how much aluminum is present.

Figure 5-13 shows the corrosion rate as a function of pH; increasing the pH above 7.5 can in some cases increase the corrosion rate. Figure 5-14 shows the potential impact of calcium hardness on phosphate addition. Above the curve, precipi-

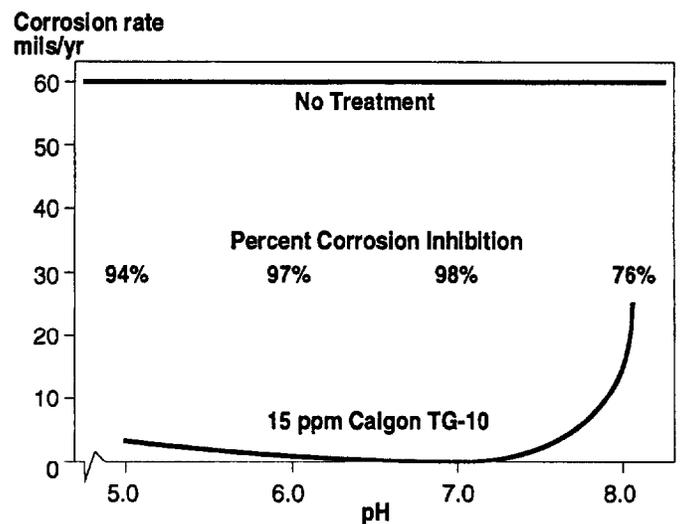


Figure 5-13. Corrosion rate vs. pH, 114-hour laboratory test with aerated tap water.

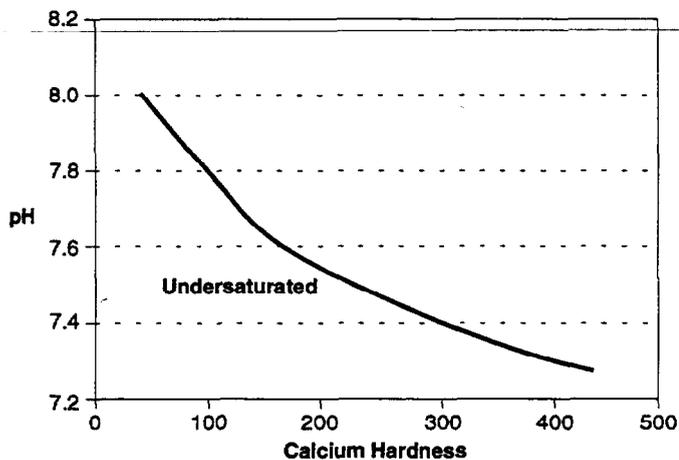


Figure 5-14. Tricalcium phosphate saturation.

tation of tricalcium phosphate will occur. For example, if the calcium hardness is at 300 and the pH is at 7.4, tricalcium phosphate will precipitate.

In addition, the sequestration properties associated with phosphates should be considered. Polyphosphates under the appropriate chemical conditions sequester iron and manganese. One danger is that polyphosphate might sequester lead, which will actually make the lead concentration increase. Iron and manganese might consume the phosphate or polyphosphate that is added, so the residual at the end of the system would be very low.

5.2.3 Materials

A ban on lead solder now exists, and alternative materials (antimony and silver solder and plastic pipes) must be used. Some lead solder, however, is still in use. The substitutes—antimony and silver solder—also might have problems. On July 25, 1990, EPA proposed a maximum contaminant level goal (MCLG) and an MCL for antimony. EPA proposed a MCLG for antimony of 3 mg/L, with a possible MCL of 5 mg/L. Studies need to be performed to determine the quantity of antimony that can be leached into water from antimony-based materials.

Plastic pipe, plastic faucets, and other items made from plastics, such as PVC and polyethylene, can be used in lieu of lead, brass, or copper pipe. All of these also have some inherent problems. Some plastic pipes are made with lead, and although these are not approved in this country, imported pipe often is made with a large amount of plasticizers, phelate being the most frequently used. Plasticizers can release vapors that permeate the pipe and enter the water column. Solvents can penetrate through all plastic pipe and enter the water column while it is under pressure.

5.2.4 Conclusions

All systems are going to be faced with looking at treatment options and with trying to optimize lead control. While the new regulation minimizes lead in water systems, every system needs

to consider secondary effects. The lead control strategy that a water system selects and presents to the state as the optimal solution might be one that creates problems regarding secondary effects. These possible secondary effects must be brought to the state's attention.

5.3 Full-Scale Performance Testing of Sodium Silicate to Control the Corrosion of Lead, Copper, and Iron: York, Maine

5.3.1 Introduction

In Summer 1991, the York Water District (YWD) in Maine placed a 4 million gallons per day (mgd) water treatment facility into service to provide coagulation, clarification, filtration, and disinfection of its surface water supply. The plant was designed to meet the requirements of the SWTR. In common with other surface water treatment plants in New England, the water produced by the plant is soft ($\text{Ca} < 1 \text{ mg/L}$), low in alkalinity ($< 10 \text{ mg/L as CaCO}_3$), and has a moderately high pH (8.3 to 8.8). As this generally corrosive water passed through the distribution system, it picked up significant quantities of iron from unlined cast iron pipe. Consumers served from cast iron water mains complained of a red water problem. Samples were collected from these sites to verify the presence of iron, and the iron concentration in these samples ranged from 0.4 to 1.9 mg/L.

Although the plant was designed with the ability to feed polyphosphate to control the red water problems, the appropriateness of this and other treatment chemicals was reviewed to address the anticipated requirements of the lead and copper rule. Zinc orthophosphate and silicate addition also were evaluated as treatment strategies. Calcium carbonate saturation was not considered a feasible or practical option, because it would involve the construction of additional feed systems to introduce both calcium and carbonate into the water.

Polyphosphates, although well-known for their ability to control red water problems by sequestering iron, were deemed inappropriate as a method to control lead- and copper-based corrosion. To control iron, polyphosphates generally require a pH in the 7.2 to 7.6 range, which is not optimal for control of lead or copper. Furthermore, polyphosphates have the ability to complex with lead and copper, potentially causing the concentration of these metals to increase (7). Zinc orthophosphate was considered for its ability to control lead by forming sparingly soluble lead orthophosphate films (14), but it is unable to provide a mechanism for control of iron corrosion. Also, there was concern that the zinc would be concentrated in the sludge generated by the community wastewater treatment facility. The use of sodium silicate reportedly has been a common strategy for low-hardness waters and has been favored for its potential to form a surficial coating on piping systems (15). In addition, silicate has a large capacity to disperse iron colloids, thus masking the red water problems (16). Several utilities in Maine with low alkalinity ($< 15 \text{ mg/L as CaCO}_3$) and low hardness ($< 5 \text{ mg/L as CaCO}_3$) have reported that sodium silicate was extremely effective in eliminating red water complaints. An advantage of silicates over polyphosphates is the pH range in

which each inhibitor is effective for control of red water problems. Polyphosphates can sequester iron at a pH generally <7.5, whereas silicates are effective in controlling red water problems at a higher pH (>8). The higher pH that can be used with silicate treatment is also more appropriate for controlling the dissolution of lead and copper. A well-known advantage associated with sodium silicate is that it does not contain zinc. Based on these considerations and system constraints, sodium silicate was recommended for full-scale performance testing.

With assistance from an engineering firm, the YWD designed a water quality monitoring program to track metal concentrations in response to the addition of sodium silicate over an extended period of time (18 months). Twelve sampling sites were identified throughout the distribution system to account for spatial variations in water quality. All sampling sites were cold water faucets located within buildings. First- and second-draw samples were collected from all 12 sites on the same day every 2 months. The first- and second-draw samples were analyzed for lead, copper, iron, calcium, and silica. A third sample was collected immediately after the second and analyzed for pH and alkalinity. The monitoring data collected over the course of 1991 are discussed in the following sections.

5.3.2 Findings

- The finished water produced from the YWD filtration plant without the application of sodium silicate has low alkalinity (8 to 10 mg/L as CaCO₃), moderately high pH (8.3 to 8.8), low turbidity (<0.10 NTU), low color (<10 CU) and is very soft (Ca <1 mg/L; Fe <0.05 mg/L). The water was corrosive toward lead and iron, as it produced an average lead level of 83 ± 145 µg/L in first-draw samples and iron levels in the range of 0.33 ± 0.55 mg/L from first- and second-draw samples. The finished water was less corrosive toward copper; the average copper level from first-draw samples was 0.15 ± 0.13 mg/L.
- Periods of 2 to 3 years might be required before the impacts of silicate addition can be determined, due to annual cycles in temperature and flow rate.
- The low buffering capacity of the plant water and variations in the coagulation process resulted in large pH fluctuations in the water exiting the filters. Sodium silicate fed into the filtered water served essentially two functions: to adjust the pH and to add silica to the finished water. As a result, it was extremely difficult for the operator to maintain a constant finished water pH and silica dosage.
- The alkalinity and pH were significantly lower at dead ends of the distribution system, especially when the dead-end lines were unlined cast iron. These areas consistently had lower silica concentrations and higher concentrations of corrosion products.
- Lead levels averaged 83 ± 145 µg/L during the initial sampling event when sodium hydroxide was being applied to finish the water during December and the first week of January 1991. After feeding sodium silicate in lieu of sodium hydroxide, the average lead levels in first-draw samples decreased and stabilized to 26 ± 22 µg/L during the period of May to December 1991.
- Red water complaints received by the YWD when sodium hydroxide was being fed were eliminated completely with the application of sodium silicate. Iron concentrations in the samples collected throughout the distribution system ranged from 0.10 to 1.9 mg/L before silicate treatment, and from 0.10 to 1.37 mg/L after treatment. It is likely, therefore, that silicate was sequestering iron.
- Iron concentrations showed only a slight reduction over time in response to treatment with silicate.
- Copper levels in the first-draw samples before application of silicate were relatively low, averaging 0.15 ± 0.13 mg/L and ranging from 0.06 to 0.48 mg/L. Application of sodium silicate reduced these levels slightly.
- Silica concentrations decreased as the water passed through the distribution system, suggesting that silica was coating the surface of pipes. Also, the average silica concentration in the first-draw samples was lower during each sampling event than the average silica concentration in the second-draw samples, suggesting that forms of dissolved silica were coating the internal surfaces of plumbing.
- With the average maintenance silica dosage of 11 mg/L used in this evaluation (startup period excluded), the chemical cost to the YWD is \$8.12 per million liters.

5.3.3 Recommendations

- If silicates are used to control corrosion in soft, low-alkalinity waters, careful consideration must be given to the design of feed systems to ensure that a constant dosage of silica is provided. Therefore, it might be necessary in certain situations to adjust pH separately by the addition of another chemical, such as potassium or sodium hydroxide.
- In water with low alkalinity (<10 mg/L as CaCO₃), the use of silicates in conjunction with carbonate (alkalinity increase) adjustment should be investigated. Alkalinity could be supplied by silicates as long as the pH is raised into the 9.0 to 10.0 range. Increasing the alkalinity would minimize the pH reductions that occurred at the ends of the system.
- Studies should be conducted under controlled conditions to determine relationships among hardness, DIC, pH, existing films, silica dosage, and effectiveness of treatment.
- Full-scale water quality monitoring programs aimed at determining the effectiveness of silicate addition should be performed over a period of several years.
- When silicates are used as a means of corrosion control, pH, alkalinity, and silica levels should be monitored at the extremities of the distribution system.

5.3.4 Methodology

5.3.4.1 Description of the Facilities

The source of water for the YWD is a shallow (<10 m) pond. The facilities that process the water are an intake facility at the shore of the pond and a filtration facility. Water flows by gravity from the intake facility to the filtration facility. Although the intake facility contains equipment to permit addition of chlorine and potassium permanganate, these chemicals are not routinely added.

Water entering the filtration facility is injected with aluminum sulfate and sodium hydroxide for coagulation. After being coagulated, the water enters an upflow clarifier, consisting of plastic media retained by a stainless steel screen. The media retain a portion of the coagulated material, and the remaining residual particulate matter is retained on a mixed-media filter. Water exiting the mixed-media filter is chlorinated for disinfection before it enters a 300,000-gallon contact basin/clearwell. The pH of the disinfected water exiting the clearwell is raised to between 8.3 and 8.8, prior to the addition of ammonia gas, to maximize the formation potential of monochloramine. When the trial application of sodium silicate was initiated, it was fed through the sodium hydroxide feed system.

The distribution system consists of approximately 40 percent unlined cast iron pipe and 60 percent cement-lined cast and ductile iron pipe. The unlined cast iron pipe is approximately 50 to 100 years old. There are no known lead service lines or asbestos-cement pipe in the system. York is a coastal tourist community with the population served by the YWD ranging from 5,000 in the winter to approximately 10,000 in the summer. The large population fluctuation causes the average daily flow rate to range from approximately 1.3 mgd in the winter to 3 mgd in the summer.

5.3.4.2 Study Objective

The objective of the evaluation was to determine the effectiveness of sodium silicate in controlling iron, lead, and copper corrosion in the YWD's distribution system and within residential home plumbing systems. Effectiveness, in this case, means noticeable reductions in the concentrations of the referenced corrosion products over a period of 18 months. This report covers data collected over the first 12 months of monitoring.

5.3.4.3 Treatment Scheme

The sodium silicate solution used in the evaluation was Type N[®] (PQ Corporation, Philadelphia, PA), which has a silica (SiO₂) to sodium oxide (Na₂O) ratio of 3.22:1. It was selected because it was the least expensive available silicate solution in the region and because it has a relatively high SiO₂:Na₂O ratio.

The silicate dosages used in this evaluation were based on recommendations from the manufacturer and on information available in the literature (15,17). The goal was to follow the present practice of applying silica to control corrosion in water distribution systems. Over the first 2 months of the monitoring program, a silica dosage of 16 to 20 mg/L as SiO₂ was used. For the remainder of the monitoring program, the silica dosage was lowered to 8 to 12 mg/L as SiO₂.

5.3.4.4 Monitoring Program Design

The main objective of the monitoring program was to generate sufficient data to determine the effectiveness of sodium silicate in reducing levels of principal corrosion products, including lead, copper, and iron. Another goal was to gain an understanding of the potential mechanism of silicate corrosion inhibition (e.g., surficial coating) by monitoring silica concentrations throughout the distribution system. To meet these objectives effectively, a monitoring program was designed to track pH, alkalinity, calcium, lead, copper, and iron levels at 12 points throughout the distribution system over an 18-month period. Sampling events consisted of collecting three samples from each monitoring location on the same day.

Because water system personnel could gain regular entrance to only a limited number of buildings, a survey was conducted to identify and select individual homeowners to participate in the monitoring program. The selection of sites was based on the ability of the participating residents to understand and perform the prescribed sampling procedures effectively for the period of the monitoring program. In addition, the locations were apportioned throughout the distribution system, covering both the center and the ends of the distribution system (Figure 5-15). An extensive materials survey to identify specific sampling locations based on sources of lead and copper was not performed prior to the monitoring program.

In York, annual cycles in water flow through the distribution system and in temperature represent important temporal variations. It was necessary, therefore, to monitor water quality changes over a period of 18 months. Sampling was conducted every 2 months to account for changes in flow and temperature.

5.3.4.5 Sampling and Analytical Procedures

Sampling Procedures. First-draw and second-draw samples were collected from taps from 12 buildings throughout the distribution system (Figure 5-15). First-draw samples were collected after the water was allowed to stand motionless for 6 to 12 hours. Second-draw samples were collected after the tap had been flushed for a period of 5 minutes. The first- and second-draw samples were collected in 250 mL bottles, and each was analyzed for lead, copper, iron, calcium, and silica. A third 250-mL sample was collected immediately after the second-draw sample and was analyzed for pH and alkalinity. The three samples were collected on the same day from each of the 12 sites to relate metal concentrations to the referenced water quality parameters.

pH and Alkalinity. Samples for pH and alkalinity were measured in the laboratory within 24 hours of the time of collection. The pH was measured with an ORION SA250 pH meter. The meter was calibrated with pH buffer standards at pH 4, 7, and 10. The meter was recalibrated at the end of a group of analyses to check for instrumental drift. Alkalinity was determined by EPA (1983) Method No. 310.1 using 0.02 N H₂SO₄.

Lead, Iron, Calcium, and Copper. Upon arrival at the laboratory, samples for lead were acidified to pH <2 with concentrated nitric acid. Lead samples were analyzed on a Perkin

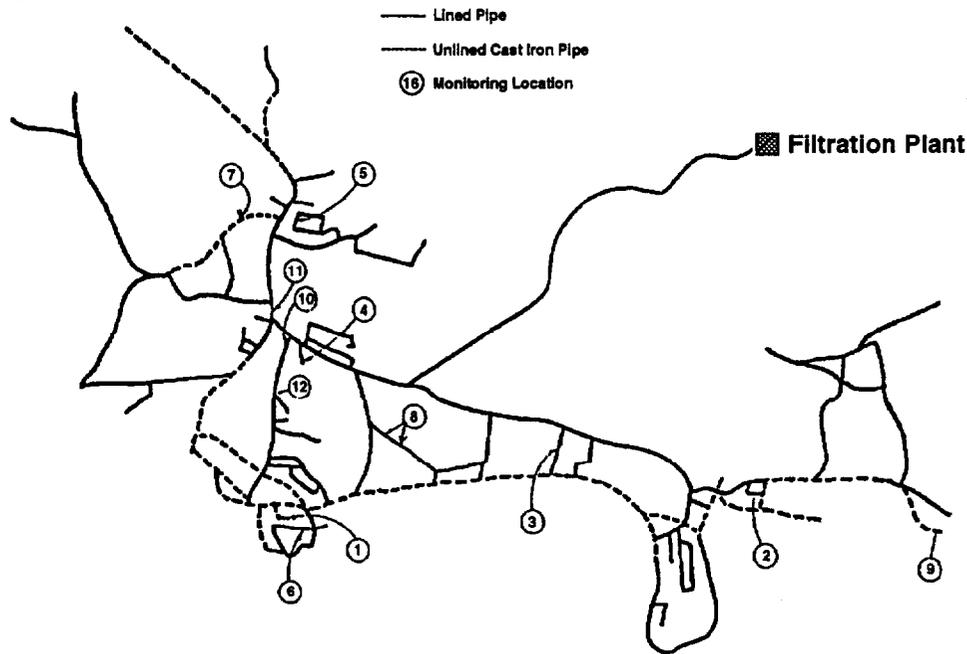


Figure 5-15. Map of the York Water District distribution system.

Elmer 5100 PC Atomic Absorption Graphite Furnace according to Standard Methods (1989) No. 3113 B. Samples for iron, calcium, and copper were analyzed on a Perkin Elmer Model No. 460 Flame Atomic Absorption Spectrophotometer, according to Standard Methods No. 3500 B. Field spikes and blanks were performed during each analysis to determine the accuracy of the method.

Silica. Silica analyses were conducted using Inductively Coupled Plasma (ICP) according to EPA (1983) Method No. 200.7.

Data Analysis. In the case of small sets of data, including outliers can result in a bias in the calculated mean. Therefore, sets of lead data from every sampling event were subjected to the Dixon Test to eliminate outliers.

5.3.5 Results and Discussion

The data collected for the evaluation of silicates are presented in the following two sections. First, treatment plant operating data over the 12-month period are discussed. Second, the results of the distribution system monitoring program are presented.

5.3.5.1 Plant Operating Data

Finished Water Quality Data. Table 5-2 summarizes the average annual finished water characteristics at the YWD filtration facility during the monitoring period. In general, the water is corrosive toward lead and iron due to its low alkalinity. With the exception of temperature, the finished water quality parameters do not vary significantly on a weekly or annual basis.

Table 5-2. Average Finished Water Quality Summary

| Parameter | Mean | Standard Deviation |
|---|------|--------------------|
| pH | 8.5 | ±0.29 |
| Alkalinity (mg/L as CaCO ₃) | 8.0 | ±1.65 |
| Turbidity (NTU) | 0.06 | ±0.01 |
| Temperature (°C) | 13.0 | ±3.0 |
| Iron (mg/L) | 0.03 | ±0.01 |
| Manganese (mg/L) | 0.06 | ±0.02 |
| Aluminum (mg/L) | 0.05 | ±0.04 |

Temperature. Temperature can have a pronounced effect on the rate of corrosion. In general, as the temperature increases, so does the corrosion rate of most materials. As illustrated in Figure 5-16a, the temperature in the finished water increased from 4°C during the winter to 24°C in the summer months. Therefore, the rate of corrosion due to temperature effects would be highest in the summer months.

Flow Rate. The average velocity of the water carried through a distribution system should increase, in general, as plant flow rate (output) increases. Velocity is an important physical factor that affects the rate of corrosion. Slow velocities within a distribution system cause water to be stagnant; often a marked decrease or increase in pH is observed. Velocity, as it relates to inhibitor-based corrosion control, is important in sustaining a passivating film on a pipe surface. As velocity increases, so does the rate at which a given mass of inhibitor comes in contact with a given unit surface area of pipe.

The quantity of water produced varied significantly from winter to summer (Figure 5-16b), due to seasonal population patterns. This variation had a tendency to cause stagnant areas during the winter months, which resulted in lower pH values at dead-end monitoring locations.

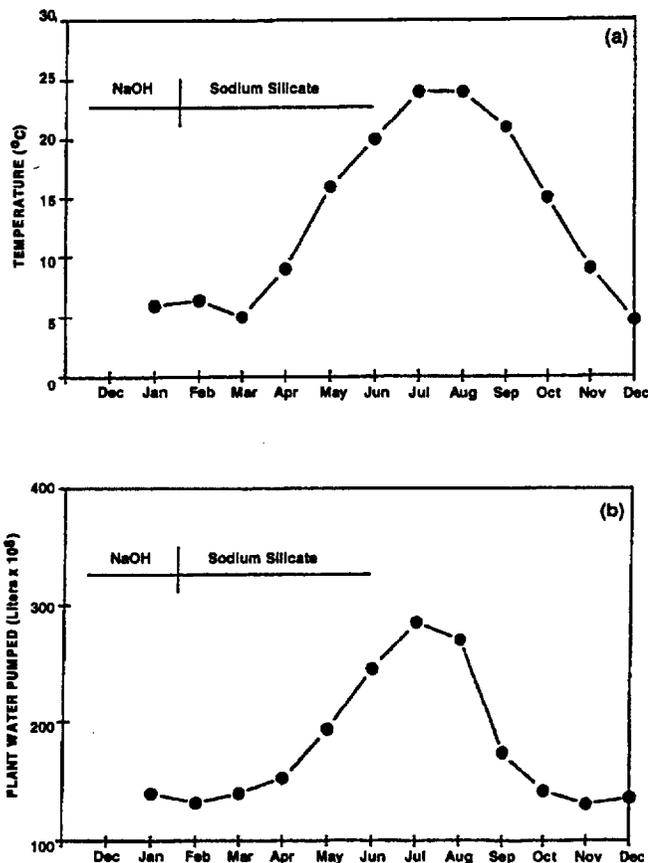


Figure 5-16. Temperature of the filtration plant finished water (a) and monthly water production (b).

Silica Dosage. The monthly average silica dosage and raw water silica concentrations over the course of a 12-month monitoring period are presented in Figure 5-17. The average silica dosages were determined by dividing the total volume of silica

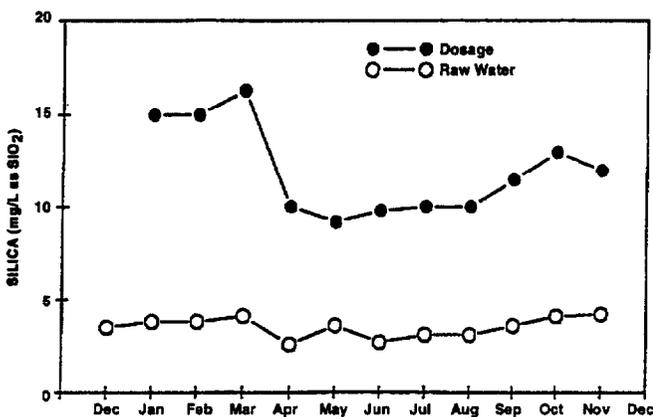


Figure 5-17. Average monthly silica dosages and raw water silica concentrations.

applied by the volume of finished water pumped. The silica dosages used in this evaluation (9 to 16 mg/L) were similar to dosages (12 to 20 mg/L) at a nearby utility with similar water quality conditions.

After reviewing the distribution system data in August, it was noted that the pH at remote points in the distribution system was low (<7.2). To raise the pH at these locations, the feed rate of sodium silicate was increased in September and October. As a result, the silica dosage increased (Figure 5-17) over the same time period. The sodium silicate solution, therefore, was performing two functions: to raise the pH of, and to add silica to, the plant finished water. The operating data suggest that the feasibility of feeding a more alkaline sodium silicate solution (lower SiO₂:Na₂O ratio) or accomplishing pH adjustment separately with another chemical, such as sodium or potassium hydroxide, should be investigated.

5.3.5.2 Distribution System Monitoring Data

pH. During the period when the finished water was adjusted with sodium hydroxide, prior to application of sodium silicate, the average pH from the monitoring points was 8.34 ± 0.26 . When the average startup dosage of approximately 16 to 20 mg/L as SiO₂ was being administered, the pH from the sites averaged 8.38 ± 0.14 . After the initial startup dosage was lowered to a maintenance dosage of 10 mg/L as SiO₂ during late March, the pH dropped to an average of 7.75 ± 0.10 for the remainder of the monitoring program (Figure 5-18).

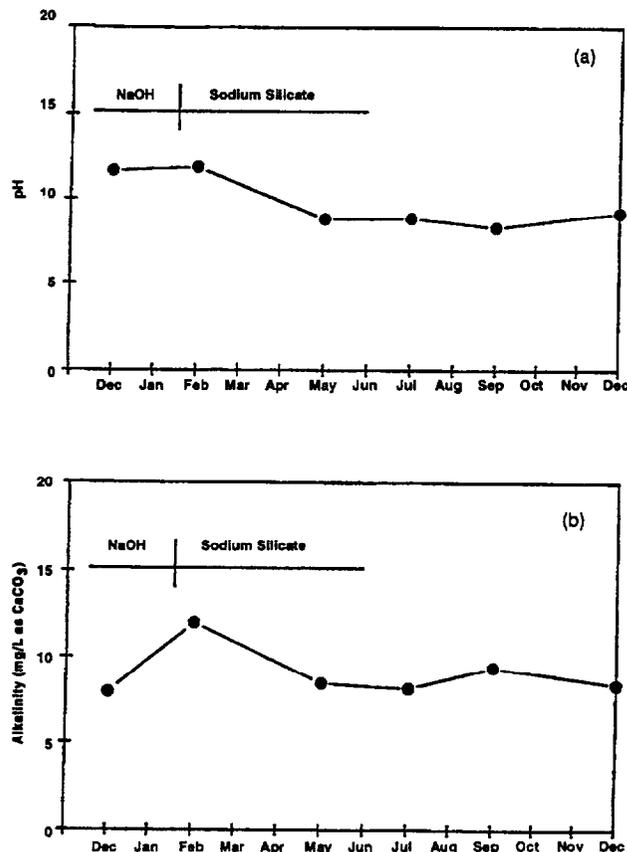


Figure 5-18. Average pH (a) and alkalinity (b) from the distribution sampling events.

At the dead ends of the system, the pH (7.52 ± 0.38 ; $n = 3$) was lower than the pH (8.17 ± 0.05 ; $n = 8$) at central points within the distribution system. Lower pH values observed are likely due to the release of metals such as iron, and subsequent hydroxide-ion uptake, which frequently occur in stagnant areas. The lower pH values are generally consistent with lower silica concentrations found in the same regions (see the following discussion on silica).

Alkalinity. The alkalinity typically ranged from approximately 5 mg/L as CaCO_3 at dead-end locations to 10 mg/L at most other points within the system. The average alkalinity remained relatively constant throughout the monitoring period, with the exception of a slight rise during February when the startup dosage of silica was being administered (Figure 5-18b). The increase in alkalinity was probably due to the presence of the anionic silica species, H_3SiO_4 .

Silica. From the distribution system monitoring data, it can be seen that the silica concentrations in the center of the system were higher (17.8 ± 0.53 mg/L as SiO_2) than at the ends of the system (16.0 ± 1.2 mg/L) (Figure 5-19a). These data suggest that silica was being adsorbed onto pipe surfaces as the water moved through the system. Silica has the ability to adsorb onto metal-oxide surfaces (18,19). Potential evidence of this type of

adsorption was observed in this study as the average silica concentration was lower (15.6 ± 1.5 mg/L; $n = 3$) at sampling sites located on unlined cast iron mains than at sites located on other types of pipe (17.5 ± 0.71 ; $n = 9$) (Figure 5-19a).

The calculated means of the first- and second-draw samples were compared; they displayed evidence of silica adsorption onto the surfaces of home plumbing systems (Figure 5-19b). Although these data suggest adsorption of silica was occurring, it cannot be confirmed without X-ray diffraction analyses.

Lead. Figure 5-20 shows the variation in lead concentration of first-draw samples over the monitoring period. Prior to application of sodium silicate, the lead levels ranged from 6 to 488 $\mu\text{g/L}$ and averaged 84 ± 145 $\mu\text{g/L}$. Over the period of May through December, when the lead levels were relatively stable, the lead concentrations ranged from 5 to 166 $\mu\text{g/L}$ and averaged 26 ± 22 $\mu\text{g/L}$ (Figure 5-20a). These lead levels are relatively high, considering that 11 of the 12 buildings were constructed before 1981. The other building was constructed in 1990 and, as a result, contained pipes with lead-free solder. Since the first-draw sample volume was 250 mL, it is likely that the major source of lead is from brass fittings.

The average lead concentrations were consistently lower during the time when the sodium silicate was being fed. When

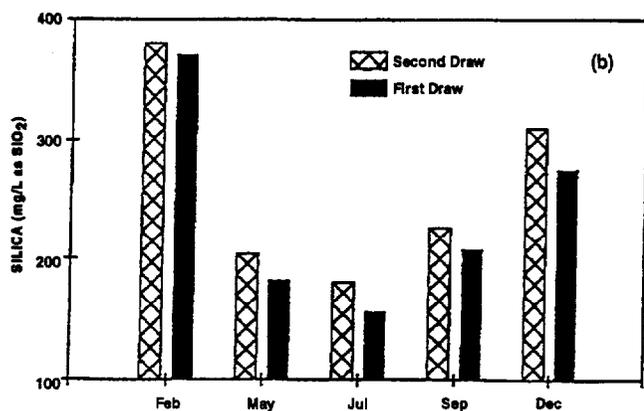
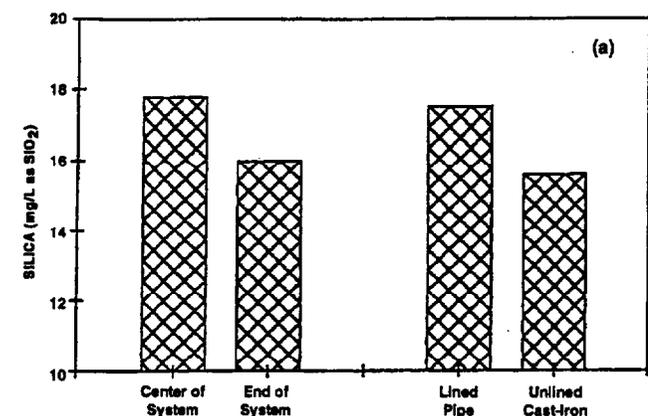


Figure 5-19. Silica concentrations from selected sites within the distribution system (a) and in first- and second-draw samples (b).

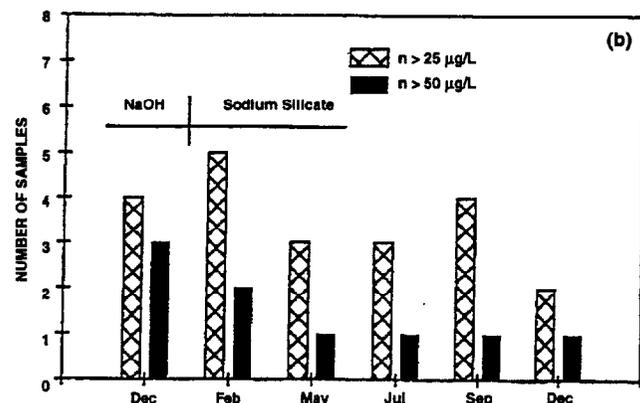
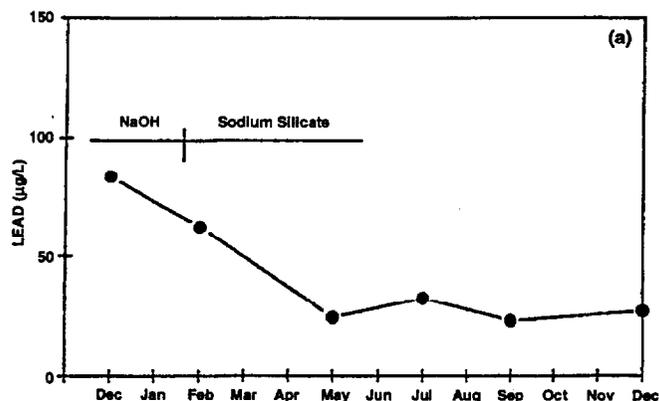


Figure 5-20. Average lead concentrations in the first-draw samples (a) and the number of samples exceeding specified concentrations in first-draw samples (b).

the number of samples exceeding $>50 \mu\text{g/L}$ as lead and $>25 \mu\text{g/L}$ as lead (Figure 5-20b) were compared before and after treatment, however, only a slight improvement was observed with the addition of sodium silicate. Second-draw samples, collected after flushing for a minimum of 3 minutes, were typically below the detection limit.

The highest lead concentrations were consistently found in samples collected at monitoring points on dead-end unlined cast iron mains, probably because of the lower pH values witnessed at these locations. Typically, the pH at these locations ranged from 6.6 to 7.2 compared to other sampling locations, where the pH was 7.6 to 8.5.

In general, some sites showed a consistent reduction in lead concentration; at other sites, the concentrations either remained relatively constant or increased. This result is to be expected since the source of lead (e.g., dezincification of brass, or dissolution of lead-tin solder) and types of films present will vary significantly depending on the specific location of the site. In particular, the dezincification of brass fittings, which was probably the major source of lead at most of the sites, can respond erratically to silicate treatment (20).

Iron. As shown in Figure 5-21, the iron concentration over time, after silicate addition, gradually decreased, and then increased, probably in response to low flow rates during the following fall and winter months. Each point on the figure represents the average iron concentration of 12 first-draw and 12 second-draw samples.

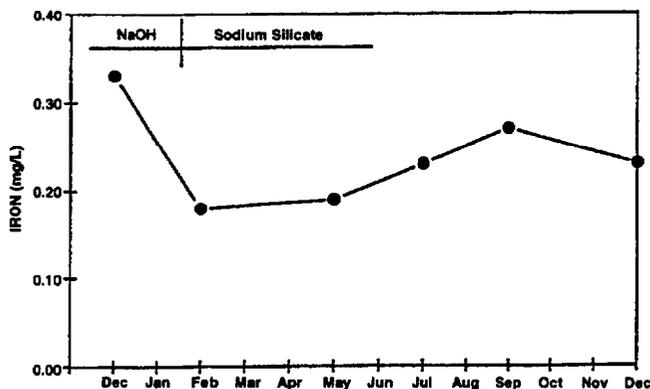


Figure 5-21. Average iron concentrations in the first- and second-draw samples.

During the last 6 months of 1990, the York Water District received approximately 15 red water complaints. Silicate treatment eliminated these complaints over the 12-month trial application. Iron concentrations ranged from <0.10 to 1.87 mg/L before treatment, and <0.10 to 1.37 mg/L after treatment; therefore, it is likely that the particulate iron was being sequestered by dissolved silica. The ability of sodium silicate to sequester oxidized forms of iron in soft, low-alkalinity water has been well documented (16).

Copper. Average first-draw copper concentrations from the six sampling events were especially low (Figure 5-22), as has

been observed in other corrosion monitoring programs under similar water quality conditions (21). A possible reason for the low copper levels is that the first-draw sample volume was 250 mL; as a result, a large portion of the sample volume was contained within brass fittings and was not in contact with copper pipe.

The copper levels decreased during the initial sampling events but later increased during the winter (Figure 5-22). The increase was primarily due to a drop in pH at two monitoring stations located on dead ends. At dead-end monitoring stations located on unlined iron pipe, the copper concentration averaged $0.39 \pm 0.04 \text{ mg/L}$, and at all other locations averaged $0.05 \pm 0.02 \text{ mg/L}$. When the average copper concentrations are determined excluding dead-end monitoring points, there appears to be a slight reduction in copper levels from the application of silicate over time (Figure 5-22).

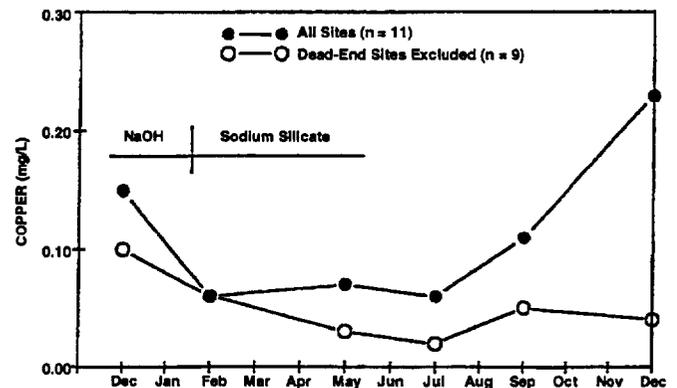


Figure 5-22. Average copper concentrations in the first-draw samples.

5.3.5.3 Treatment Costs

Given the average maintenance silica dosage of 11 mg/L administered between April and December, the cost of sodium silicate is $\$8.12$ per million liters. This figure is based on bulk deliveries ($\geq 15,142 \text{ L}$) of Type N[®] liquid sodium silicate and a bulk chemical cost of $\$21.30/100 \text{ kg}$ ($\$73.70/100 \text{ kg}$ as SiO_2).

5.4 Assessing Zinc Orthophosphate vs. pH Adjustment: Champlain, Vermont

5.4.1 Introduction

Champlain Water District (CWD) is a regional water supplier in northwestern Vermont chartered by legislative action in 1971. As a municipal district, its primary purpose is the supply of potable water. At the time the CWD was chartered, communities in the greater Burlington area were using a variety of water sources. These existing sources were deficient in quality and/or quantity and demand was being increased by a fast-growing economy and population. CWD presently is composed of eight member communities: South Burlington, Shelburne, Williston, Essex, Colchester, Winooski, Milton, and the Village of Jericho. Because of political divisions within member com-

munities, the CWD presently serves water to the following 12 water systems: South Burlington, Shelburne, Williston, Essex Junction, Essex Town, Colchester Town, Colchester Fire District #1, Colchester Fire District #3, Winooski, Milton, Jericho Village, and the Mallets Bay Water Company. The total population served is 50,000 to 55,000 and the average daily flow in 1990 was 8.3 mgd, with a peak day of approximately 12 million gallons.

The CWD's treatment and supply system went on line in March 1973 and consists of three major components: (1) raw water intake and pump station, (2) water treatment facility and plant storage, and (3) the finished water pumping and transmission network of CWD-owned lines and storage facilities. The distribution network encompasses both a low-pressure and a high-pressure component. The CWD's transmission and storage network was interconnected with existing distribution systems of its member towns. The raw water source for the CWD is Lake Champlain. The intake is located in the northern channel of Shelburne Bay as it passes into the broad lake, and is located at a depth of 75 feet, 2,480 feet from the Red Rocks Park shoreline. Lake Champlain is characteristic of many New England surface waters. CWD finished water has a moderate alkalinity (approximately 50 mg/L as CaCO₃), moderate hardness (approximately 75 mg/L as CaCO₃), and a pH of approximately 7.2. These properties, combined with typically saturated O₂ levels, are conducive to forming an aggressive water. Calculations indicate a Langelier Saturation Index (LSI) of -1.39 to -0.96 (0 to 20°C), indicating a significant CaCO₃ undersaturation. The Aggressiveness Index (AI) also was used to evaluate corrosion potential and resulted in a value of 10.3. This falls into the moderate to high range (≥12 is considered nonaggressive, 10 to 11.9 moderately aggressive, and <10 highly aggressive).

Further verification of corrosivity was evidenced by the visual inspection of the diatomaceous earth (DE) filtration piping dismantled during a plant expansion in 1982. This construction replaced the high service pumping units and required removal and replacement of suction and discharge piping installed in 1972. The older piping was examined, and tuberculation and pitting measuring 1/4 to 3/8 inches throughout the interior diameter of the pipe wall were observed. The piping material was bare, unprotected steel. Although this type of pipe was used in the CWD plant facility, it is very uncommon in the distribution systems of CWD and its member towns. Assessment of these findings warranted further investigation, based on economics, health, and expectation of stricter federal regulation of corrosion by-products. A corrosive water would be costly to the CWD because of its large investment in water storage tanks and distribution and transmission piping. Consumers also would be affected economically through deterioration of domestic plumbing and water-related appliances. Additionally, consumer health could be at risk as a result of corrosion by-products leaching into drinking water.

Initial data at the CWD indicated that corrosion, with its potential ramifications, needed to be studied further. To this end, a pilot study was designed to establish corrosion rates of metal coupons using CWD finished water and to help predict the effectiveness of different treatment techniques. This initial

16-month study, begun in April 1984, used mild steel coupons to establish the corrosion rate of the CWD finished water vs. finished water treated with zinc orthophosphate (ZOP). A corrosion rate of 9.61 mils per year (mpy) was obtained and is considered to be in the moderate to severe range. This was based on 10 tests conducted for an average of 24.3 days each. The result of adding ZOP at a dose of 1 mg/L as zinc (product has a 1:1 ratio of zinc to orthophosphate) was an average 78.8 percent reduction (range, 67.9 to 86.6 percent) in the corrosion rate to 2.04 mpy (range, 1.15 to 3.71 mpy). This initial research was expanded to include lead coupons, coupons in the distribution system, and a bench-scale comparison of elevated pH treatment technique to the use of ZOP. Expansion of the bench-scale research also permitted the assessment of combining ZOP addition with pH elevation. Analysis of the resulting data indicated that implementation of a corrosion control treatment program would be beneficial to CWD and its consumers on both an economic and a health basis. The CWD Board of Commissioners approved the expenditure to design and implement the use of ZOP as a corrosion inhibitor on May 27, 1986, and the process was on line April 28, 1987.

5.4.2 Materials and Methods

5.4.2.1 Materials

Metal coupons (1/2 inch x 3 inches x 1/16 inch) based on the ASTM Standard D 2688-70 and NACE standard TM-01-69 were used to study corrosion rates and potential reduction in corrosion due to (1) ZOP addition (pH = 7.0-7.2), (2) pH elevation (to approximately 8.0), and (3) a combination of these two treatments. The methods established the corrosivity of water by measuring the weight loss of various metal coupons. The rate of corrosion of a metal immersed in water is a function of the tendency for that metal to corrode and the tendency of the water and the materials it contains to promote (or inhibit) corrosion. The relative corrosivity of water can be determined by comparing the corrosion rate of a material in water with a corrosion rate of the same material in another water. Mild steel (SAE Steel [1010]) coupons were used from April 1984 to the present. Use of lead coupons was incorporated into the study in December 1988.

Technical Products Corporation (TPC) (formerly Virginia Chemical Inc.) supplied the metal coupons and the 2902 and 2900 Corrosion Test Units used in the bench-scale studies. The 2902 unit consists of three connected plexiglass cylinders on a base. A plexiglass rod extends down from the cover that allows for coupon attachment using a nylon nut and bolt. Cylinders are approximately 9 inches high and 2 3/4 inches in diameter. Water enters at the base of the first cylinder housing the pre-weighed control coupons, then flows over the coupons into the center cylinder. Here a Diaz AccuPlus[®] peristaltic metering pump adds the ZOP corrosion inhibitor (Virchem[®] 932) from a 5-gallon polycarbonate bottle. The ZOP-treated water then flows into the bottom of the last cylinder over a second set of pre-weighed coupons and exits at the top of this cylinder to waste. The water flow was regulated (approximately 0.5 gallon/minute) as was the rate of Virchem[®] 932 feed solution (approximately 26 to 28 mL/hr) to maintain the desired 1 mg/L (ppm) zinc concentration. Adjustments to the flow rate and feed

solution concentration were made as required to maintain the desired 1 mg/L zinc level. The Virchem[®] 932 feed solution was prepared by mixing 900 mL of concentrated Virchem[®] 932 with 5 gallons of effluent water from the direct filtration process. The prepared, weighed (to 0.1 mg) metal coupons were placed in contact with flowing water for a period of 24 days. Upon removal, coupons were submerged in acetone for 1 to 2 minutes, removed, and allowed to air dry before mailing to TPC. TPC reweighed the coupons after processing and computed corrosion rates based on weight loss and exposure time. Corrosion rates expressed as mils per year (mpy), equivalent to 0.001 inch, were determined. TPC supplied all coupons, preparation of coupons, Virchem[®] 932, and weight loss and corrosion rate analysis.

Virchem[®] 932 is a liquid synergistic corrosion inhibitor developed for use in potable water and designed to control corrosion of contacted metal surfaces. It also has demonstrated corrosion protection of asbestos-cement pipe in studies conducted by EPA. Dissociated zinc and phosphate ions (at a 1:1 ratio) are provided by Virchem[®] 932 with the zinc concentration being analyzed to control the desired amount of ZOP addition. TPC reports Virchem[®] 932 to have the following characteristics: color—clear, odor—none, density—10.6 lb/gal, specific gravity (@70°F)—1.273, solution pH—0.8, and zinc content—0.83 lb/gal.

The 2900 Single Cell Corrosion Test Unit has the same dimensions and shape as the cylinders of the 2902 unit but consists of only one cylinder with an inlet at its base and an outlet near the top. Two of these units were used in the bench-

scale study to establish corrosion rates of the finished high service water (HS) and nontreated effluent water from the direct filtration filters (DFs). DF water has been prechlorinated (0.60 to 0.80 mg/L) and filtered after the addition of coagulants (alum and a polymer).

Coupons were inserted into water main distribution lines using Corrosion Coupon Probe Assembly 2901 supplied by Technical Products. The coupons were left in place for a period of 83 to 142 days. The assembly fits onto a standard 1-inch corporation stop (outside diameter = 1.25 inch). The insertion rod is adjustable so that the faces of the coupons are parallel to the water flow and near the center of the distribution line. The probe assembly consists of three main parts: insertion rod, bonnet, and body. The insertion rod is constructed of stainless steel with a molded nylon tip, nut, and bolt that holds the coupons and a movable stainless steel collar held in place by a set screw. The bonnet is bronze and contains a brass packing gland with asbestos packing. The packing gland prevents leakage and holds the rod in place after insertion. The body is made up of a short nipple and a 1.25-inch inside diameter. NPT coupling that screws onto the corporation stop.

5.4.2.2 Methods

Coupon Studies. The original 2902 triple cell unit (station #2) in the pilot bench study used HS water (finished water being supplied to the distribution system), mild steel coupons, and a 1 mg/L zinc concentration added via the Diaz pump (Figure 5-23). After the plant began using Virchem[®] 932 and ZOP in the distribution system, two 2900 single cell units with

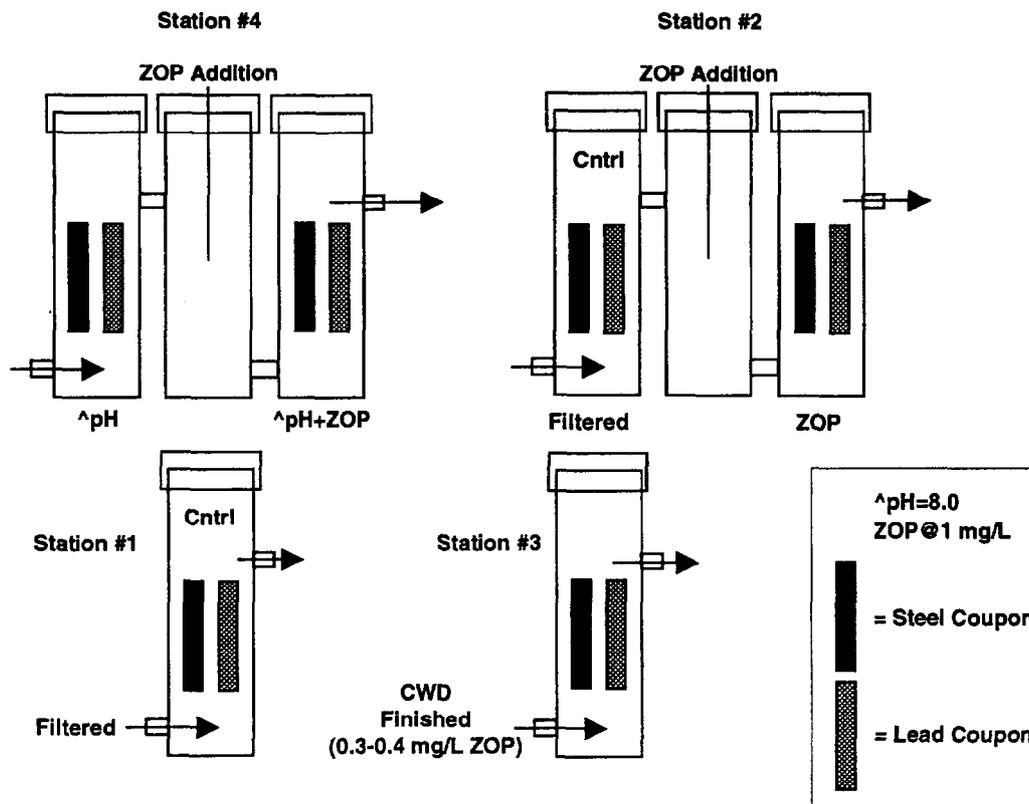


Figure 5-23. Coupon studies on corrosion rates in four cell units.

mild steel coupons were set up in the laboratory. Station #1 was supplied by DF water (no ZOP) and the other 2900 cell was supplied with HS water (station #3), which now contained Virchem® 932 at a 0.3 to 0.4 mg/L as zinc concentration. To monitor and evaluate the effects of Virchem® 932 in the distribution system, 2901 probes were installed with mild steel coupons in three distribution mains. By comparing the corrosion rate of these coupons to the corrosion rate of the DF station #1 coupons in the laboratory (pre-ZOP addition), a percent reduction in the coupon corrosion rate was calculated.

The construction of an interconnection between the CWD and the neighboring city of Burlington (which had elevated its water's pH for corrosion control) offered an opportunity for a comparison study in the CWD's laboratory (Figure 5-24). The CWD and Burlington Water Resources (BWR) both use Lake Champlain as their source water; therefore, raw water characteristics show only minimal differences. The test cells were set up to allow a comparison of ZOP treatment against BWR's technique of raising the pH (to 8.0) to precipitate a CaCO₃ film. The design allowed the use of CWD DF water (post pre-chlorination, coagulation, and filtration, yet prior to hydrofluosilicic

acid, final chlorination, and plant ZOP addition) as the base control unit at station #1 (Figure 5-25). The corrosion rate in this DF control unit allowed for calculated reductions in corrosion rates using three techniques: (1) adding ZOP, (2) raising the pH (to 7.9-8.2) to precipitate CaCO₃ (ΔpH), and (3) adding ZOP after elevated pH (7.9-8.2) adjustment (ΔpH + ZOP). Once these rates were established, a comparison analysis was possible among any combination of these three different corrosion reduction techniques.

A single cell 2900 unit at station #1 was used for the base control coupons using CWD DF water. At station #3, ZOP was added to CWD DF water and at station #4, to BWR water, using triple cell units. The inlet cylinder to station #4 contained the elevated pH coupons, and the outlet cylinder contained the ΔpH + ZOP treated coupons. The inlet cylinder to station #2 used DF water, which contained base control coupons (duplicating the 2900 DF coupons), and the outlet cylinder (after ZOP addition) contained the ZOP-only treated coupons. Therefore, much of the time, duplicate coupons were being exposed to DF water. During this time the corrosion rate from station #1 was used as the base rate in calculating the rate reduction for the

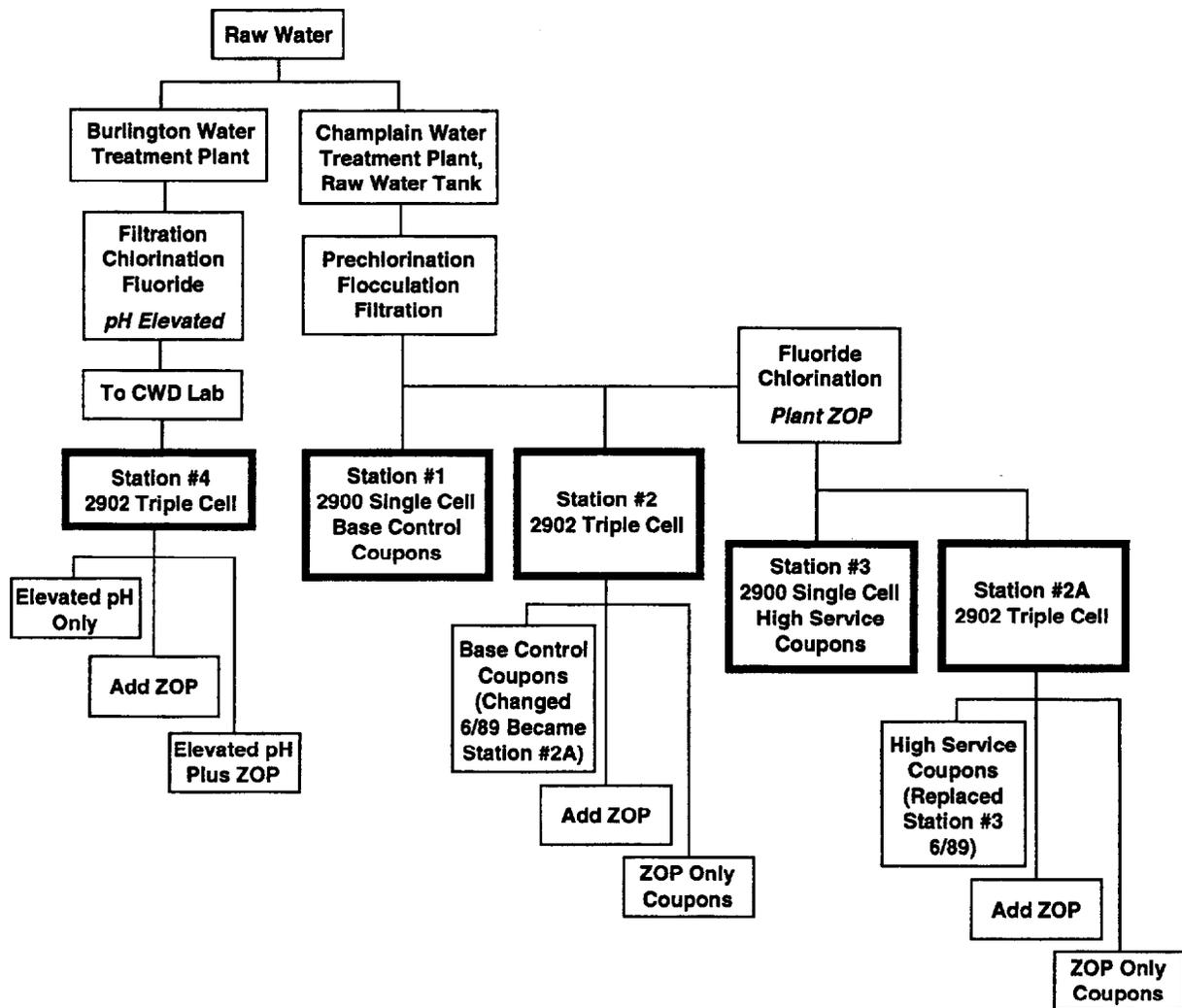


Figure 5-24. Comparison of municipal and regional water treatment using the same source waters (Lake Champlain, Vermont).

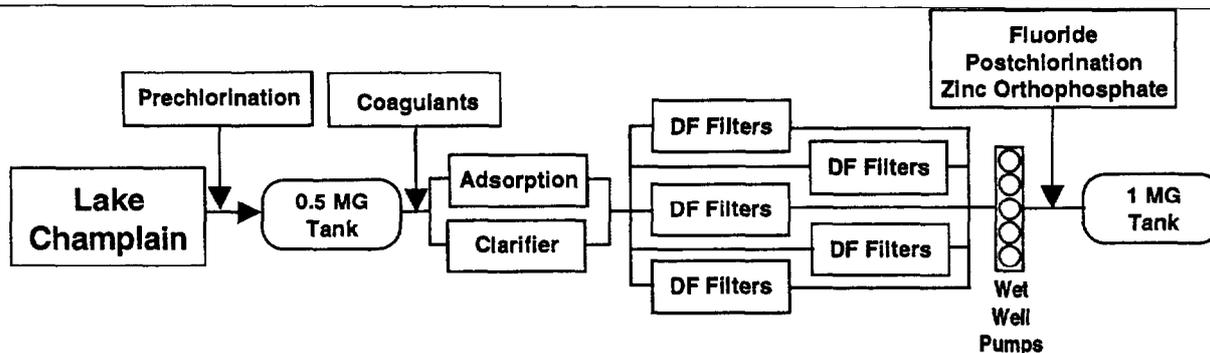


Figure 5-25. Schematic of Champlain Water District water treatment process.

distribution coupons (2901 units). The corrosion rate from the inlet cylinder of station #2, using identical DF water, was used as the base rate for comparing corrosion rate reductions in both triple cell units (stations #2 and #4). A change in procedure was made on June 1, 1989, to better reflect differences in corrosion rates between CWD and BWR waters due to pH. The DF water going to station #2 (ZOP only treatment) was changed to finished CWD water (post-chlorine, fluoride, and plant ZOP addition). These additions drop the pH of CWD DF water from approximately 7.5 to approximately 7.2. Also, station #3 (a single cell) coupons now were represented by the inlet cell of station #2 using CWD finished (HS) water. (See Figure 5-26 for the laboratory coupon procedure change.)

Consumer Tap Sampling. The second approach used to assess corrosion was sampling at consumer taps for specific corrosion by-products. Over the course of approximately 2

To better reflect the actual differences in corrosion rates between BWR and CWD waters, the source water going into the CWD triple cylinder has been changed. Previously, DF water (postfiltration but pre-plant ZOP and C12 addition) has been used. Finished distribution water (postchlorination and plant ZOP addition) will now feed to this triple cylinder, which will represent the reduced pH caused by these additions (typically pH 7.71 vs. pH 7.28).

The inlet cell will be used as the HS coupon value and the ZOP solution being added will be adjusted to continue to yield a 1 ppm zinc concentration. The required number of test coupons will be reduced as the single cylinder used for the HS can now be eliminated. The "basic rate" will be the single cylinder "DF Lab" unit.

Historical data of the single cylinder and the first cylinder of the triple cell (both DF water) show no variation in corrosion rates. This change will more accurately reflect CWD's distribution water and the comparison of BWR's pH adjustment technique to CWD's ZOP treatment for corrosion control.

Figure 5-26. Champlain Water District laboratory coupon procedure change (06/01/89).

years, 16 different locations were sampled, with a total of 154 samples collected as of January 1990. Initial sampling included first-draw samples (initial water from a tap after an extended period of non-use, collected typically in the morning); a 2-minute flush sample; and a 6-minute flush sample. Originally, the length of non-use or stand time was not recorded. Collection of the 6-minute flush sample was discontinued after the third sampling (July 1988), because samples showed no reduction in metal concentrations compared to the 2-minute flush samples. Higher lead level sites were sampled more frequently. The metals originally tested for were iron, zinc, copper, and lead. The iron, zinc, and copper tests were performed in the CWD laboratory using a Hach DR/3000 Spectrophotometer (Hach Co., Loveland, Colorado). Copper was analyzed using Procedure Code C.12, Bicinchoninate Method; total iron using Procedure Code 1.4, Ferrozine Method; and zinc using Procedure Code Z.1, Zincon Method. Iron testing was discontinued after the August 1988 sampling because extremely low levels were found in all samples. The Vermont Department of Health Laboratory in Burlington, Vermont, conducted the lead analysis. The CWD laboratory performed all pH measurements using an Al-tex Model 71 pH meter and a Hach Model 44300 combination electrode.

Most sample volumes were 1 liter, but samples collected in May 1989 were 250 mL, and samples collected in October 1989 were 1-L samples except at three locations. The first-draw sample was broken down into two fractions, a 125-mL portion followed by a 875-mL portion. The reported 1-L first-draw lead concentration was calculated from the first two samples. Only the 875-mL sample was used in testing for other metals, because of the volumes required. This sampling protocol was followed to determine the lead contribution by faucet fixtures, because these three locations had shown elevated lead levels. The 125-mL sample primarily represented the water contained in the faucet fixture.

Samples were collected in December 1989 from these same three locations. To further identify the source of lead, five samples were collected without flushing between sample collection. Again, a 125-mL sample was taken followed by a 875-mL sample. Then, a series of three 1-L samples were collected without flushing between samples. Each liter represents approximately 25 feet of 1/2-inch copper pipe.

5.4.3 Results

5.4.3.1 Deviations

Certain inherent and operational deviations occurred:

1. Flow rates, and therefore ZOP concentrations, to the triple cells at stations #3 and #4 fluctuated and were adjusted periodically to maintain a 1 mg/L concentration as zinc. Flow variations were always as reduced flows (increased ZOP concentration).
2. Water temperature of the laboratory coupons was higher than the water temperature of the distribution coupons. This would be expected to yield a higher corrosion rate in the laboratory coupons, resulting in a positive error in the percent of corrosion rate reduction for the field coupons.
3. The pH of the DF filtered water supplied to the base control coupons at station #1 (single-cell unit) was 0.3 to 0.4 (7.5 to 7.6) units higher than the distribution water. The lower pH in the distribution water is because of the addition of fluoride (1 mg/L), postchlorination (approximately 1.8 mg/L as free chlorine) and plant ZOP addition (0.3 to 0.4 mg/L) to DF water. This higher pH water also was fed to the 2902 triple cell representing ZOP-only treatment until the procedure change of June 1, 1989.
4. Coupons in the distribution system were exposed to much higher water velocities than were the laboratory coupons.
5. Lead coupons are extremely soft and were subject to abrasion during insertion into distribution mains.

5.4.3.2 Laboratory Coupon Analysis

Steel coupons in the laboratory study treated only with ZOP showed the most consistent and highest average percent reduction in corrosion rate (Table 5-3). Elevated pH plus ZOP addition also showed good reductions in corrosion rates, although not as high as the ZOP-only treatment. Elevated-pH treatment only increased the corrosion rate in four of the five runs with an average corrosion rate increase of 8 percent.

Table 5-3. Corrosion Rate Reductions of Laboratory Steel Coupons 84 days exposure time

| Treatment | % Reduction* | Range | Avg. Mpy | Avg. pH | Range |
|-----------|--------------|------------|----------|---------|--------------|
| ZOP only | 84% | 62% - 95% | 1.25 | 7.1 | 44 - 3.45 |
| ZOP + ^pH | 76% | 20% - 92% | 1.94 | 8.0 | 0.47 - 7.20 |
| ^pH only | (8%) | (16%) - 5% | 7.62 | 8.0 | 5.04 - 10.46 |

*Based on comparison to raw water (pH = 7.0 - 7.2)

The base control coupons in the DF filtered water averaged a corrosion rate of 7.00 mpy, with a range of 4.81 to 9.00 mpy, over 84 days of exposure.

All treatment techniques for lead coupons in the laboratory showed a lower percent reduction and mpy rate than the steel coupons. ZOP-only and elevated-pH-plus-ZOP additions were

equally effective and averaged a 44 percent reduction in corrosion rates (Table 5-4). Elevated pH alone reduced corrosion rates in only two of the five runs and increased corrosion rates in three runs. The lead base-control coupons in the DF filtered water averaged a corrosion rate of 1.25 mpy with a range of 0.76 to 1.69 mpy.

Table 5-4. Corrosion Rate Reductions of Laboratory Lead Coupons 84 days exposure time

| Treatment | % Reduction* | Range | Mpy | Avg. pH | Mpy Range |
|-----------|--------------|-------------|------|---------|-------------|
| ZOP only | 44% | 17% - 63% | 0.70 | 7.1 | 0.46 - 1.30 |
| ZOP + ^pH | 44% | 3% - 71% | 0.67 | 8.0 | 0.49 - 1.23 |
| ^pH only | 2% | (39%) - 25% | 1.20 | 8.0 | 0.85 - 1.87 |

*Based on comparison to raw water (pH = 7.0 - 7.2)

5.4.3.3 Distribution Coupon Analysis

Coupons placed at the four distribution sites (station #3 single-cell laboratory location is included here, because the water used was finished water as supplied to the distribution system) yielded the results shown in Tables 5-5 and 5-6.

Table 5-5. Corrosion Rate Reductions for the Distribution System Steel Coupons

| Location | % Reduction* | Range | Mpy | Mpy Range |
|--------------|--------------|------------|------|-------------|
| High Service | 53% | 8% - 86% | 3.09 | 1.02 - 6.92 |
| Essex West | 64% | (2%) - 90% | 2.75 | 0.49 - 7.64 |
| Kellog Rd. | 47% | 20% - 67% | 4.26 | 1.55 - 6.38 |
| DE Header | 78% | 64% - 91% | 1.62 | 0.98 - 3.45 |
| Overall Avg. | 61% | 23% - 84% | 2.93 | 1.01 - 3.45 |

*Based on comparison to raw water (pH = 7.0 - 7.2)

Table 5-6. Corrosion Rate Reductions for the Distribution System Lead Coupons

| Location | % Reduction* | Range | Mpy | Mpy Range |
|--------------|--------------|-------------|------|-------------|
| High Service | 39% | 10% - 67% | 0.74 | 0.42 - 1.21 |
| Essex West | 31% | (8%) - 51% | 0.76 | 0.30 - 1.20 |
| Kellog Rd. | 30% | (26%) - 59% | 0.78 | 0.25 - 1.28 |
| DE Header | 43% | 24% - 56% | 0.63 | 0.27 - 0.86 |
| Overall Avg. | 36% | 0% - 58% | 0.73 | 0.31 - 1.14 |

*Based on comparison to raw water (pH = 7.0 - 7.2)

The average control coupon corrosion rate for the DF filtered water was 7.08 mpy, with a range of 4.55 to 9.51 mpy, over 84 days of exposure.

The average lead control coupon corrosion rate for the DF filtered water was 1.11 with a range of 0.84 to 1.29 mpy.

5.4.3.4 Consumer Tap Analysis

A total of 154 samples over a 2-year period were collected from 16 different locations. Sampling was conducted with the following three frequencies per location: three locations were

sampled once, one location was sampled three times, two locations were sampled four times, three locations were sampled five times, three locations were sampled six times, and one location was sampled seven times.

First-Draw and 2- and 6-Minute Sampling. Thirty-five first-draw and 2-minute flush samples were analyzed for total iron and averaged 0.037 mg/L and 0.047 mg/L, respectively. The 24 6-minute flush samples averaged 0.025 mg/L iron. Forty-four first-draw and 2-minute flush samples from ZOP-treated water were analyzed for zinc and averaged 0.422 mg/L and 0.317 mg/L, respectively. The 18 6-minute flush samples averaged 0.280 mg/L zinc. Fifty-seven first-draw and 56 2-minute flush samples were analyzed for copper and averaged 0.343 mg/L and 0.079 mg/L. The 25 6-minute flush samples averaged 0.055 mg/L.

Fifty-seven first-draw and 2-minute flush samples were analyzed for lead and averaged 37 µg/L and 2 µg/L. The average for the 25 6-minute flush samples was 1 µg/L.

Sequential Tap Sampling. To identify lead sources in locations showing the highest lead levels, samples were collected without flushing between samples. To represent water standing in faucet fixtures, 125-mL samples were collected, followed immediately by successive samples, representing water standing in the plumbing. The highest lead levels were from the 125 mL samples (Table 5-7).

Table 5-7. Lead Concentrations in Sequential Samples, µg/L

| Location # | 125 mL | 875 mL | 1L | 1L | 1L |
|------------|--------|--------|----|----|----|
| #10 | 49 | 08 | — | — | — |
| #12 | 190 | 92 | — | — | — |
| | 211 | 55 | 52 | 12 | 10 |
| #13 | 55 | 35 | 40 | 15 | 11 |
| #16 | 73 | 33 | — | — | — |
| | 21 | 14 | 32 | 16 | — |

5.4.4 Discussion

The pathways and causes of corrosion, and the influence of various factors on the corrosion process, are enormously complex. Taking information from controlled research conditions to applied field applications, where several parameters continuously react and can vary regionally along with treatment processes, sources, and season, is extremely difficult. EPA's extended efforts to promulgate the lead and copper rule are evidence of the complexities of addressing corrosion and its by-products. In addition, several different materials typically make up a distribution system and household plumbing, each with its own dissolution characteristics.

One portion of this study, using controlled laboratory conditions, measured the weight loss of coupons to determine corrosion rates. Weight loss of lead and steel coupons (reported as a mpy corrosion rate) compared three treatment techniques (ZOP, elevated pH, and ZOP plus elevated pH). Baseline rates were determined by coupon weight loss in water exiting the direct filtration process (prior to any corrosion treatment). The

laboratory bench-scale results also were compared to weight loss of coupons placed in the distribution system. The distribution coupons assessed ZOP's effectiveness under actual field conditions.

The second stage of this study involved measuring certain corrosion by-product levels at consumer taps. Unfortunately, these levels were not measured at the consumer taps prior to the CWD implementing its corrosion control program (ZOP). Thus, a comparison of these values is not available. The resulting information, however, has been valuable in identifying lead sources and in educating consumers on how to minimize their exposure to lead.

5.4.4.1 Steel Coupons, Laboratory

In a similar laboratory study by Mullen and Ritter (22) using mild steel coupons, corrosion rates of three different treatment techniques were analyzed. Raising pH with caustic soda to reach the pH of saturation reduced corrosion by approximately 13 percent, addition of sodium zinc glass phosphate at 2.0 mg/L reduced corrosion by 13 percent, and addition of ZOP at 2.5 mg/L (0.5 mg/L as zinc) reduced corrosion by 55 percent. Below 16°C, pH elevation increased the corrosion rate by 22 percent and, above 16°C, pH adjustment with caustic soda reduced the rate by 5 to 32 percent. The combination of ZOP plus pH adjustment reduced corrosion by 79 percent. Below 13°C, when pH was increasing corrosion, ZOP without pH adjustment was reported more effective than ZOP plus pH adjustment. This might be because pH adjustment with ZOP brought the pH (7.8 - 8.0) outside the optimal range for ZOP. The filtered effluent pH used for ZOP addition was 6.8, with plant effluent after pH treatment being 7.8. A 63 percent reduction in corrosion rates was reported for distribution coupons for a comparable time and temperature period.

It is possible that the additional reduction in corrosion rate reported in Mullen and Ritter's study by raising pH plus ZOP addition was because the relatively low pH (6.8) was below the optimal range for ZOP. The CWD's study showed no additional reduction by raising the pH from 7.5 to 8.0.

These two studies, and others, make it obvious that any corrosion control treatment program that does not account for other water quality characteristics might not result in successful corrosion control. Pisigan, Jr. and Singley (23) noted that the composite effects of pH and alkalinity combined into one parameter, buffer capacity, might be more useful in assessing the corrosive behaviors of water. Significant differences in corrosivity of two waters having similar qualities have been attributed by Loewenthal and Marais to higher buffer capacity of one water compared to that of the other (24).

Conductivity also has been found to have a positive relationship to corrosion rates (23). As more ions (Na⁺ and HCO₃⁻) are introduced into aqueous systems (to raise alkalinity and/or pH) the ionic conductivity increases and enhances the corrosive attack on metal. Other research also has shown that in some circumstances the dominant effect of adding alkalinity might be to increase corrosion by increasing conductivity (25). Different materials show different corrosion rate responses to a

change in the water's chemistry. Stone et al. (25) found that an increase in pH from 6.0 to 8.0 decreased new copper corrosion by 50 percent and aged copper even more, while no change in the corrosion rate of a zinc electrode occurred over a pH range of 5.0 to 9.0.

While the use of mild steel (or other) coupons might be helpful in the general assessment of a water's corrosivity, a comprehensive analysis must consider the response of all distribution materials (none of which include mild steel) as well as that of home plumbing materials. In the case of the latter, corrosion by-products of components containing lead (brass fixtures, leaded solder, and pipe) might be the dominant factor that dictates a particular corrosion control treatment. It is critical, however, to consider additional factors when changes in a water's chemistry are made.

5.4.4.2 Lead Coupons, Laboratory

The solubility of Pb^{+2} can be greatly reduced by increasing pH into the range of 9.0 to 10.0 (26). Often, even in a low alkalinity, enough DIC is present for protective film formation. The lack of significant reductions in corrosion rates for CWD coupons exposed to the 8.0 pH adjusted water would indicate that factors other than pH are the dominant rate-controlling factors.

Substantial reductions in the theoretical solubility of Pb^{+2} were computed for a system containing several levels of orthophosphate at a DIC concentration of 32 mg $CaCO_3/L$ (28). The results indicated that a substantial reduction of lead solubility could take place when the pH is increased from 7.0 to 9.0 with an orthophosphate concentration of only 0.5 mg/L. (The theory that zinc in a ZOP formulation combines with lead to form a protective film has not been proved.) The passivating action of orthophosphate depends, at least, on the pH, DIC concentration, phosphate concentration, and temperature (10). The CWD results showed significant reductions in lead coupon corrosion rates in the pH range of 7.2 to 7.5 with no further reduction when the pH was raised to 8.0. This shows that the optimal range for ZOP in this system was 7.2 to 7.5. A major advantage to corrosion control methods that do not substantially raise the pH is lower organic halogen formation rates (THMs). Also, the increased disinfection efficiency of free chlorine at lower pH values has been well documented (26).

5.4.4.3 Distribution Coupons

At least three important variables—ZOP concentration, temperature, and flow rate—make it difficult to identify the cause of lower corrosion rate reductions of both steel and lead coupons in the distribution system. The laboratory coupons were exposed to higher temperatures and ZOP concentrations (1 mg/L as zinc) but to greatly reduced flow rates as compared to distribution coupons. Increased corrosion rates of mild steel and copper due to high flow rates have been noted in other studies (23). Low flow rates, typical of home plumbing, were found not to affect corrosion rates (25). The flow rate in the laboratory cylinders was less than that found in home plumbing. The expected net result, because of flow differences, would be for the distribution coupon rate to be higher. Based on lead solubility, the higher ZOP concentration dosed to the laboratory

coupons would be expected to reduce corrosion rates to a greater degree. The higher laboratory water temperature should increase corrosion rates compared to the colder distribution water. The degree to which two of these factors, flow rate and temperature, affected the corrosion rates is not possible to determine. Some insight, however, might be gained as to the effect of ZOP concentration by comparing the distribution location designated as HS at station #3 and the laboratory location designated ZOP-only station #2. During the four test periods over a 7-month span, the 1 mg/L dosed steel coupons averaged 1.46 mpy and lead coupons averaged 0.72 mpy. This compares with 3.35 mpy for steel coupons and 0.74 mpy for lead coupons at the 0.3-0.4 mg/L concentration. (All time periods were the same.) Comparison of the two laboratory test cylinders, both using water exiting the direct filtration plant, showed equivalent corrosion rates. Station #1 steel averaged 7.00 mpy (range 4.81 to 9.00) to station #2 at 7.08 mpy (range 4.55 to 9.51); station #1 lead averaged 1.11 mpy (range 0.84 to 1.29) to station #2's 1.25 average (range 0.76 to 1.69). The higher ZOP concentration used in the laboratory was based on the recommendation of the chemical supplier, whose previous experience indicated that this adjustment yielded laboratory results that corresponded to distribution environments.

Although these studies are helpful in designing and monitoring a corrosion control strategy, one should be aware that because of lead's toxicity, corrosion control in systems incorporating lead-containing materials must target only the lead levels in the water rather than a reduction in corrosion rates. Therefore, lead control programs are somewhat different from corrosion control programs normally designed for other metals such as copper, iron, or galvanized steel, where there is more concern about the lifetime of the plumbing materials.

5.4.4.4 Consumer Tap Analysis

Iron. Minimal amounts of exposed iron are in the CWD distribution system and most CWD households. The CWD rarely experiences any iron-related consumer complaints, as evidenced by the extremely low iron concentrations reported. The iron analysis was dropped after consistently low levels were established. Iron, currently classified as a secondary contaminant, has a Secondary Maximum Contaminant Level (SMCL) of 0.3 mg/L. This SMCL currently is being met, with an average iron concentration of 0.04 mg/L for all first-draw samples.

Zinc. The 44 first-draw samples from ZOP-treated water had an average zinc concentration of 0.404 mg/L. This value is higher than the amount attributable to ZOP addition. The additional zinc probably was introduced from galvanized piping and brass fixtures. The 0.266 mg/L average of the 18 6-minute flush samples best represents the residual zinc concentration in the distribution system. The corresponding 18 first-draw samples had an average zinc concentration of 0.429 mg/L.

Zinc is listed as a secondary contaminant with a SMCL of 5 mg/L. Even at substantially higher ZOP addition rates, the total zinc concentration due to ZOP and corrosion by-products would be well below the 5 mg/L SMCL.

One concern about ZOP application is the possible zinc buildup in municipal wastewater sludge. Sludges used in land application or disposed of in landfills typically are regulated as to maximum allowable metals concentration. The increase in sludge zinc at one of the largest area facilities has not adversely affected sludge disposal or usability. This plant has noted a reduction in sludge copper levels. Other smaller wastewater treatment plants also have not experienced any detrimental zinc increases. One facility reported a reduction in sludge per acre that could be applied due to maximum metal concentrations in one sludge application. This case is the only one reported since ZOP addition began in 1987. Given the requirements of the lead and copper rule, the likelihood of the state approving a less effective treatment technique because of a reduction of sludge application seems remote. The additional phosphorus loading at wastewater treatment plants due to ZOP application has not resulted in any known adverse effects. Phosphorus is considered beneficial in sludge used in land application, but it might pose a problem because of strict effluent phosphorus limitations.

Copper. The average copper level in the 57 first-draw samples was 0.34 mg/L. Only two samples exceeded the new MCLG for copper of 1.3 mg/L. The CWD foresees no problem meeting the copper MCLG.

Lead. Site selection for the consumer tap analysis was made before the lead and copper rule guidelines were established. Sites selected are more representative of the CWD consumer base and are not necessarily "high-risk" sites as specified in the final rule. Sites consistently showing low lead levels were sampled less often than sites having higher levels, which resulted in a higher overall average for all sites.

Sample sites that showed low lead levels were relatively consistent and concentrations did not vary greatly (Table 5-8). Sites with levels >20 µg/L often showed a wide range of concentrations. The variability in stand times and one sampling

Table 5-8. Average Lead Concentrations at Consumer Taps
Conc. µg/L (number of samples)

| Location # | 1st Draw | 2 Min. Flush | 6 Min. Flush |
|------------|----------|--------------|--------------|
| 1 | <5 (1) | <5 (1) | — |
| 2 | 17 (1) | 24 (1) | — |
| 3 | 3 (4) | <5 (4) | 2 (3) |
| 4 | <5 (4) | <5 (4) | <5 (3) |
| 5 | 4 (5) | <5 (5) | 3 (2) |
| 6 | <5 (3) | <5 (3) | <5 (2) |
| 7 | 10 (5) | 3 (5) | 3 (2) |
| 8 | 7 (2) | <5 (2) | — |
| 9 | 3 (2) | <5 (2) | — |
| 10 | 36 (6) | <5 (6) | <5 (3) |
| 11 | <5 (1) | <5 (1) | <5 (1) |
| 12 | 116 (5) | 5 (5) | <5 (2) |
| 13 | 76 (6) | 6 (6) | <5 (3) |
| 14 | 108 (2) | 9 (2) | — |
| 15 | 1 (5) | <5 (5) | <5 (2) |
| 16 | 102 (5) | 1 (5) | 7 (2) |

using a 250-mL volume is not believed to be the cause of these fluctuations. In other studies, particulates containing lead were believed to be the source of similar variations. Large concentration variations appear in many reported studies. The other metal concentrations monitored in this study showed much smaller fluctuations. Small changes in water chemistry that significantly affect lead solubility compared to other metals, or the mechanism by which lead corrosion by-products are introduced, might be unique. Sites #12 and #16 had both high lead levels and the highest copper levels. First-draw copper levels at these sites were several times higher than all other sites sampled. Site-specific factors are thought to be influencing corrosion rates at these two sites. Electrical grounding to water lines is known to affect corrosion rates, as is the joining of dissimilar metals. Site #12 also showed the highest lead levels in 125-mL samples (190 and 211 µg/L). The faucet fixture has a "goose neck" style of spigot. Sample sites #9 through #16 are commercial locations and account for all of the highest lead level sites. No identifiable cause for differences in lead levels between residential and commercial locations is apparent.

Ten of 16 sites (63 percent) had average first-draw lead concentrations of <15 µg/L. An average value of 31 µg/L was obtained when each location's average was used to calculate the overall average (based on 57 first-draw samples and using 2.5 µg/L for samples below the practical quantitation level [PQL] of 5 µg/L). Seventy-seven percent of all 2-minute flush samples were below the PQL of 5 µg/L. Only three samples (5 percent) were above 15 µg/L, with respective values of 16, 18, and 24 µg/L. The average lead concentration for all 2-minute samples was 4 µg/L (using 2.5 µg/L for results reported as <5 µg/L).

In light of the variability commonly reported in first-draw concentrations, a ±30 percent accuracy factor in analysis, and the action level having to be met each monitoring period (as compared to the THM regulation, which uses a rolling 12-month average), a majority of PWSs are likely to exceed the action level eventually.

5.4.4.5 Asbestos-Cement Pipe

A substantial portion of the CWD and/or town distribution mains contain asbestos-cement (A-C) pipe. This study did not address the response of A-C pipe to the different treatment techniques. Other studies, however, have analyzed ZOP effects on A-C pipe. Mah and Boatman (27) reported that a mixture of lime and ZOP was the only inhibitor of six tested that was believed to be beneficial in protecting A-C pipe. This mixture consisted of lime and orthophosphate (5.0 mg/L) plus zinc (0.3 mg/L). In contrast to materials containing lead, zinc deposits (not phosphorous) were found on the surface of the A-C pipe after 218 days of exposure. This finding was contrary to the belief that ZOP deposited a film containing zinc and phosphorus such as $Zn_3(PO_4)_2$ or $Zn_3(PO_4)_2 \cdot 4H_2O$. Subsequent computations of chemical equilibria showed these results to be reasonable and predictable. Schock and Buelow (28) reported that orthophosphate salts of zinc provided substantial protection to A-C pipe when added at proper concentrations and pH ranges. Zinc was found to be the active agent in coating the

pipe and protecting against asbestos fiber release and water attack.

Tests at pH 8.2 by EPA's Drinking Water Research Division (DWRD) using lead and A-C pipe in the same recirculation system showed that ZOP provided corrosion inhibition for both types of piping material due to the action of the orthophosphate ion. The lead solubility in these systems was found to be governed by the formation of lead orthophosphate compounds rather than ZOP. Protection of distribution materials also would depend, at the least, on pH and dissolved carbonate concentrations.

5.4.5 Conclusions

- A review of corrosion studies shows that a successful corrosion control treatment for a particular water might be ineffective in another water, or might even increase corrosion of certain materials in contact with that water.
 - Each distribution and residential plumbing material has its own dissolution characteristics.
 - Each contacted material might be affected differently by water quality constituents (chemical and physical), external factors (electrical grounding), and dissimilar materials contacting each other.
 - Past corrosion control studies and treatments by utilities probably have been broader in scope than future studies designed to comply with the lead and copper rule might be. Future studies required by the lead and copper rule might mistakenly be narrowly targeted at reducing lead corrosion from sources identified in a specific water system.
 - Identical materials of different ages can respond differently to identical water chemistries.
 - Lead pipe and/or lead coupons respond differently to a water than does leaded solder in copper plumbing. If use of lead coupons is anticipated, corrosion rates correlated with consumer tap lead levels might be beneficial.
 - The use of steel coupons in bench-scale or distribution lines probably has little or no benefit in assessing lead corrosion responses. Correlating corrosion rate reductions in steel coupons to corrosion by-product levels at consumer taps currently is not possible. Steel coupons might be useful in helping to assess the general corrosivity of a water.
 - Some of the factors that should be considered in choosing the best lead control treatment strategy include distribution materials; type of storage facilities; commercial customer uses and needs; potential impacts on wastewater treatment plants; disinfection by-product levels; and EPA, state, and local regulatory requirements.
 - To date, no lead service lines or interior lead plumbing have been identified in CWD households.
- The primary source of lead is leaded solder and faucet fixtures in consumer plumbing.
 - Sequential sampling at locations with elevated lead levels showed that faucet fixtures at these locations contributed significantly to the high lead levels.
 - Selected sample sites represented a broad cross section and included residential and commercial structures. Included in the 16 sites were eight commercial locations, one mobile home, one residence with lead-free solder, one residence built after 1982 with lead solder, and five residences built prior to 1982 with lead solder. Only one of these sites met the requirements of the lead and copper rule.
 - The absence of lead service lines and interior plumbing in CWD households limits all sample sites to homes that were built, or that replaced interior plumbing, between 1983 and 1986.
 - All the highest average lead levels were at commercial locations.
 - Sites showed either consistently low (<10 µg/L) lead levels or significant variations.

5.4.6 Recommendations

- Initiate the materials survey and establish monitoring sites as specified in the lead and copper rule as soon as possible.
- Set up an accelerated sampling program from the identified sample base.
- Assess the probability of the action level being exceeded in any one monitoring period.
- Review literature further as to zinc concentrations effective in A-C pipe corrosion control.
- Establish asbestos fiber levels from A-C pipe.
- Based on literature review, asbestos fiber levels, and documentation of lead levels at lead and copper rule sample sites, test on a full-scale basis a ZOP formulation that maintains the needed zinc concentration for A-C pipe protection and that provides a higher orthophosphate concentration (approximately 0.5 to 1.0 mg/L).
- Determine the effectiveness of the new ZOP formula and propose a corrosion control treatment program to the state.

5.5 Reducing Corrosion Products in Municipal Water Supplies: Chippewa Falls, Wisconsin

5.5.1 Background

The ground water from the Chippewa River Valley in west-central Wisconsin is naturally soft (hardness = 80 mg CaCO₃/L) and generally of good quality, both chemically and bacterially.

The low pH (6.5) of the water makes it aggressive to metal plumbing.

In July 1984, during routine testing of its water supply, the City of Eau Claire found lead concentrations at South Junior High averaging 285 µg/L with some 100-mL samples containing lead concentrations as high as 1,000 µg/L. At that time, the applicable federal drinking water standard for lead was 50 µg/L.

The discovery of elevated lead levels at the junior high school began a chain of events that resulted in a detailed sampling program throughout the area by the Wisconsin Department of Natural Resources (WDNR) and the subsequent request to the City of Chippewa Falls to centrally treat its water source to reduce corrosion products. The situation quickly became a heated local issue. Chippewa Falls was displeased more than the other area communities, not only because additional expense would be necessary to provide water treatment, but also because the city's slogan is "Home of the World's Purest Water." The local residents did not want corrosion control chemicals added to their water supply under any circumstances.

5.5.2 Water System

Water is supplied to the City of Chippewa Falls from seven wells. Five wells are located on the east side and two wells are on the west side of the city (see Figure 5-27). Water is distributed to residential, commercial, and industrial customers through a pipe network of approximately 73 miles. Water pressure is provided by three elevated storage tanks with a total capacity of 2.25 million gallons.

5.5.3 Regulations

As an operator of a municipal water supply system, the city is regulated by the Wisconsin Administrative Code, Rules of the Department of Natural Resources, Environmental Protection (cited as NR Code). Specific regulations (prior to the promulgation of EPA's new lead and copper rule) included the following:

- NR 109.11 establishes a maximum lead concentration of 50 µg/L.
- NR 102.12 specifies that samples taken for compliance be collected at the customers' tap.
- NR 109.14 allows the WDNR to require the water supplier to implement corrosion control measures.
- NR 109.60 specifies a secondary standard (aesthetic limit) of 1.0 mg/L for copper.

Sampling in Fall 1984 indicated that some buildings in the service area were exceeding the 50 µg/L standard for lead content at the water tap when the first 250 mL was withdrawn in the morning. Measured levels within the distribution system did not reveal elevated lead concentrations prior to entering service lines, indicating corrosion occurring within the service piping.

The Langelier Index is based on a chemical analysis of the water supply and is an indication of the water's tendency to precipitate or dissolve calcium carbonate (see Section 5.1.1). A negative value indicates a tendency for the water to dissolve calcium carbonate, whereas a positive value indicates a tendency to precipitate calcium carbonate. Chippewa Falls has an index value of -2.2.

Many water samples collected at the customer's taps (250 mL) also have exceeded both the state's 1 mg/L limit and the new federal MCLG of 1.3 mg/L for copper.

The WDNR contacted city officials in December 1984 and requested that corrosion control methods be implemented. In a letter dated January 1985, WDNR clarified its earlier position and required the City of Chippewa Falls to "centrally treat its water source to reduce corrosion products."

Chippewa Falls hired a consultant to study the lead problem and evaluate alternative treatment methods. Work was begun in late March 1985 to develop information and present technical solutions. Six areas that were studied and that are described briefly in the following sections include:

- Hot water flushing of service lines
- Aging study on corrosion activity
- Centralized treatment
- Pilot test area
- Implementation
- Operating results

5.5.4 Hot Water Flushing

Research indicates that lead levels at the water tap tend to decrease over a period of years. Two theories offer a possible explanation for this reduction. One idea is that the tinning flux used by plumbers during construction dissolves over a period of time and slowly leaches into the water supply. A second idea is that the piping system tends to become coated with metallic oxidation products that prevent rapid dissolution of the lead solder used in copper piping systems.

To test the first theory, three newly constructed homes were chosen for testing. Early laboratory work revealed that flux rapidly dissolves at a water temperature above 140°F. To see if dissolving the flux would reduce lead levels, a series of four hot water flushes was made on each of the test homes at approximately 3-week intervals. A portable hot water heater was connected to the cold water system in each house. A hot alkaline soap solution was circulated through the plumbing system for several hours to dissolve residual flux. With the cooperation of the homeowner, a first-draw tap water sample was collected on the day preceding and the day following each flushing. A followup sample also was collected 3 weeks after the fourth flushing. The water samples were sent to a commercial testing lab for lead analysis. The results are presented in Table 5-9.

CHIPPEWA FALLS

POSTAL ZIP CODE 54729

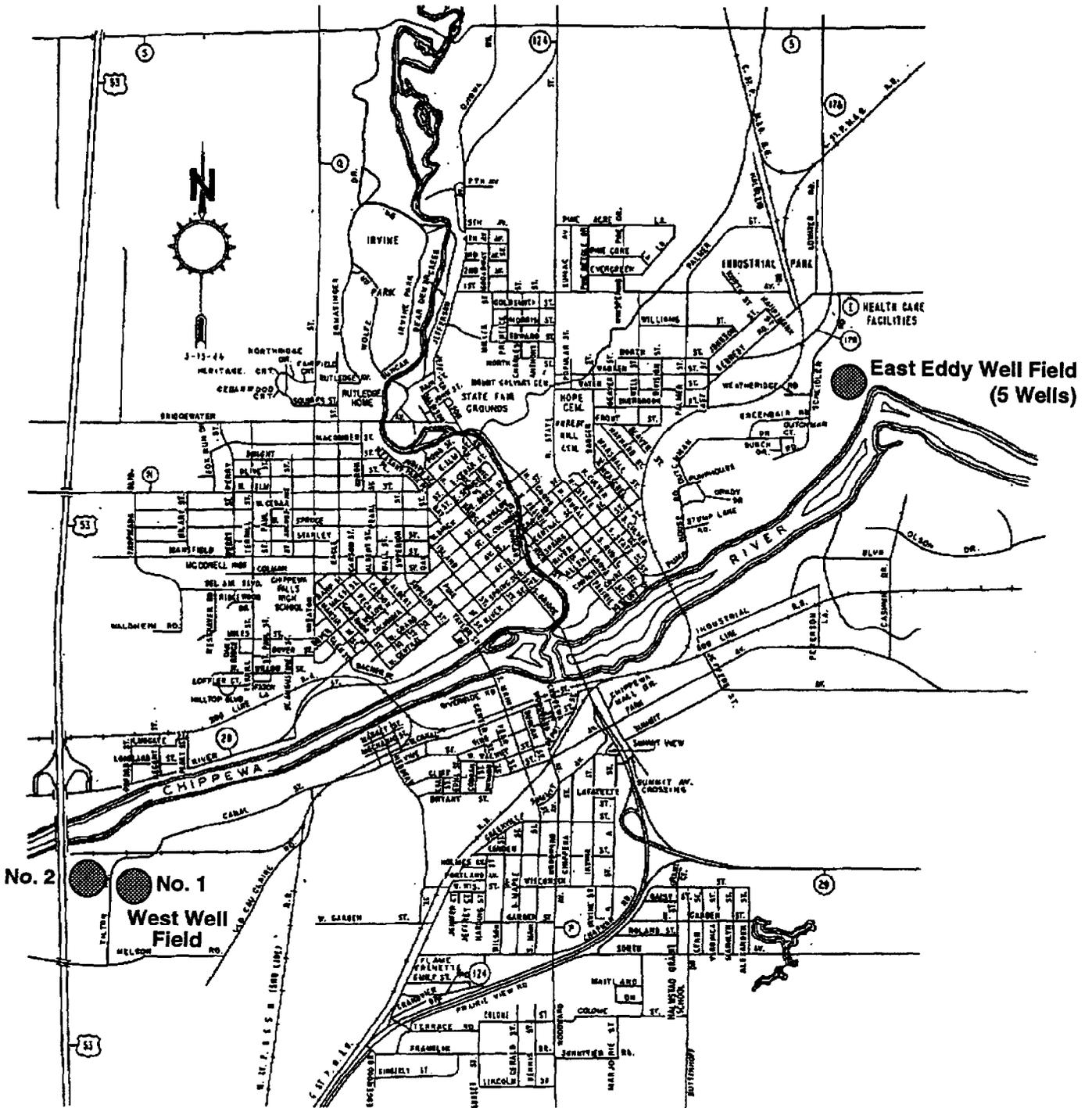


Figure 5-27. Well locations, Chippewa Falls, Wisconsin.

Table 5-9. Hot Water (140°F) Flushing Results* (lead in µg/L)

| Cycle No. | Home A | Home B | Home C |
|--------------|--------|--------|--------|
| Before one | 660 | 400 | 730 |
| After one | 330 | 200 | 820 |
| Before two | 610 | 230 | 760 |
| After two | 140 | 96 | 177 |
| Before three | 22 | 180 | 850 |
| After three | 12 | 540 | 590 |
| Before four | 120 | 150 | 510 |
| After four | 52 | 230 | 230 |
| Followup | 60 | 110 | 610 |

*250-mL sample size.

Test results show a lower lead level in the final samples than originally measured. Consistent results were not obtained, however, and only general trends can be evaluated. It is evident that levels below 50 µg/L were not obtained through the hot water flushing program. Further work in this area was not done.

5.5.5 Aging of Service Pipe

To determine if lead and copper concentrations decrease with time, city residential customer taps were sampled. Six sampling groups were developed based on the age of the home. The ages and sample size by group were:

- Less than 1 year—9 homes
- 1 to 2 years—10 homes
- 3 to 5 years—10 homes
- 5 to 10 years—10 homes
- 10 to 20 years—12 homes
- Greater than 20 years—12 homes

A minimum of nine homes in each age group was sampled for first morning water drawn from the kitchen tap. Samples (250 mL) were sent to a commercial testing laboratory.

A total of 63 samples was collected. Ten of the samples exceeded the state's 50 µg/L standard for lead. All but one of these homes with elevated lead levels were less than 2 years old. The tenth sample was from a home more than 20 years of age, which had been replumbed recently. Based on the sampling, it appears that the elevated lead levels diminish over a 2-year period.

Copper levels also were measured in 63 samples. Only 11 of the 61 samples collected were below 1.3 mg/L. Six of these low levels occurred in homes more than 20 years old. The other 5 samples testing at low levels were distributed among the remaining sample groupings. Copper concentrations did not appear to decrease with time.

5.5.6 Chemical Stabilization

After the failure of the hot water flushing to give consistently low lead tap water readings, an estimate of the cost to chemically stabilize the water was developed. A second benefit of stabilization is lower copper concentrations at the customers' tap.

Reviewing the characteristics of the chemicals available for stabilization (lime, polyphosphate, and sodium hydroxide) resulted in a decision to use sodium hydroxide (caustic soda) in a 50 percent by weight concentration. The multiple locations and the relative ease and safety of handling the materials were the major factors in the decision. Each well pump will be interlocked with a small chemical feed pump to raise the water pH prior to entry into the distribution system.

The Langelier Saturation Index would indicate an optimum pH of approximately 8.5 to provide a water that is neither corrosive nor depositing in reference to calcium carbonate. It must be remembered that the Langelier Index was developed for use on waters subject to softening via the lime-soda ash method. The application in Chippewa Falls is different. To raise the pH too high would result in inefficient use of chemicals; too low a pH level would not adequately reduce the corrosion products.

A review of the technical literature revealed a wide range of operating pH limits. No credible experimental data applicable to the Chippewa Falls water were found. It was decided to estimate the cost for chemical stabilization based on a pH of 7.9. The pH of 7.9 was not based on any scientific rationale but rather on experience by other local water utilities. Cost estimates for caustic soda stabilization for the seven wells are \$91,000 for capital costs and an annual operation and maintenance cost of \$52,600 at the pH 7.9 level.

5.5.7 Administrative Order

Because the city had not taken action voluntarily to correct the corrosive water problem in the city water supply system, WDNR issued an Administrative Order. On August 16, 1985, the city received this order from the WDNR, Division of Enforcement, which required the city to select a plan that would reduce corrosion products to levels within the drinking water standards on a systemwide basis. In response to this order, the City Council initiated the following actions:

- Scheduled a special Election for a Referendum Question.
- Retained special legal counsel to fight the WDNR order.
- Hired a consultant to prepare plans and specifications for chemical treatment.

5.5.8 Referendum

To support the city's legal position and to verify that the Mayor and Council were supporting the feelings of the majority of the citizens regarding chemical treatment, a special election

was scheduled. At this election, the voters considered the following referendum question:

Shall the city of Chippewa Falls centrally treat its water with chemicals to lower its corrosivity in order to meet state drinking water health standards as to lead and taste and color standards as to copper?

On October 8, 1985, the citizens of Chippewa Falls showed that they were in agreement with the Mayor and Council, with 343 voting "Yes" and 1,508 voting "No" to chemical addition to control corrosion in the water system.

5.5.9 Legal Action

The legal channels were explored because the Mayor and Council were not convinced that systemwide treatment was the proper course of action. The Wisconsin Department of Industry, Labor, and Human Relations (DILHR) had issued an emergency order (9/25/84 to 2/22/85) that banned the use of lead solder. DILHR reasoned that if the sources of the elevated lead were in fact the 50/50 lead solder and the flux used in the soldering process and this source was removed, the lead levels should drop within a few years. Only a small percentage of homes experienced elevated lead levels, and the majority of the citizens were not in favor of chemical treatment. Furthermore, the city was willing to test anyone's water, and if elevated lead levels were detected, to furnish bottled water for drinking.

In addition, raising the pH by chemical addition to the water would result in economic burdens. First, there would be a capital investment for the chemical treatment facilities and annual operation and maintenance costs. Second, two major industries, Leinenkugel Brewery and Cray Research, were concerned when the discussion of treatment of the city water supply began. If the pH had been increased to 8.5 to 9.0 as originally thought, both industries would need to lower the pH for some of their applications.

The city requested a contested case hearing and on October 1, 1985, a "Notice of Prehearing Conference" was issued by the Division of Hearings and Appeals. On October 22, 1985, a prehearing conference was to be held for the purpose of identifying all parties to the proceeding, to simplify the issues that would ultimately be contested at the hearing, and to establish appropriate schedules for the presubmission of documentary evidence and for prehearing discovery. No testimony would be heard at the prehearing conference; however, a date would be set for the hearing on the merits at the conference.

On October 14, 1985, the city met with its special legal counsel and its expert on corrosion, Vernon L. Snoeyink, Ph.D., of the Department of Civil Engineering, University of Illinois at Urbana-Champaign. During this meeting with Dr. Snoeyink, the problem and potential solutions were discussed. This discussion led to the idea of proposing a "pilot study" to the WDNR.

On October 21, 1985, a meeting between WDNR and the city was held at the Governor's request in his office in the state capitol. During this meeting, it was agreed to implement a pilot

study. It also was agreed that, during the pilot study, the contested case hearing would be held in abeyance. Also, during the pilot study, the city would continue to supply bottled water on request to those homes where tests indicated lead levels in excess of the health standard.

5.5.10 Pilot Study

With water supplied from seven wells through four pump houses on two sides of the city, central treatment, in fact, would require treatment at multiple locations.

Since any treatment method would involve construction to house the needed equipment, it was necessary to know what the space requirements would be. The total treatment required had to be determined before construction and equipment purchases began. A pilot study was desirable to verify whether the addition of caustic soda would sufficiently reduce the lead and copper to comply with the current standard and the proposed standards. The pilot system would determine the levels of lead and copper that could be reached with caustic soda alone. If additional treatment was needed, an orthophosphate could be added and its effects determined.

Dr. Snoeyink believed that the pilot system also was desirable to see what the effects would be on homes with galvanized (pipe) services. With the change in water quality, the corrosion of galvanized services should be less than without any treatment, but that had to be verified. Also, a possibility existed that the treated water might release the scale built up in galvanized services and actually cause a poorer water quality as the pipes were cleaned.

The size of the pilot project was reviewed and the first plan considered was to select and treat buildings known to show high lead levels. This plan was not believed to be a feasible alternative, because it would not accurately simulate what was being done with the whole system. If individual homes were treated, it would not be very easy to control the feed rate.

A map of the city was studied and an area on the south end of the city was selected (see Figure 5-28). By closing one valve on a 20-inch water main, the total flow from the well would be directed to the test area. This area is controlled with only three small water main outlets, all near the northeast corner of the area. The plan was to feed caustic soda with equipment that ultimately would be used at this well when treatment was installed.

5.5.11 Goals of the Pilot Study

If the addition of caustic soda resulted in meeting the drinking water standards for lead and copper, the city agreed to implement systemwide treatment. If caustic soda was not effective in meeting standards for lead and copper, the city would add an orthophosphate with the caustic soda (probably at reduced concentrations) for up to 3 additional months with monitoring. If the WDNR or the use of orthophosphates required the addition of other chemicals (such as chlorine) or if the orthophosphate caused adverse operational effects, then the city was not obligated to perform systemwide treatment. If either of the

CHIPPEWA FALLS

POSTAL ZIP CODE 54729

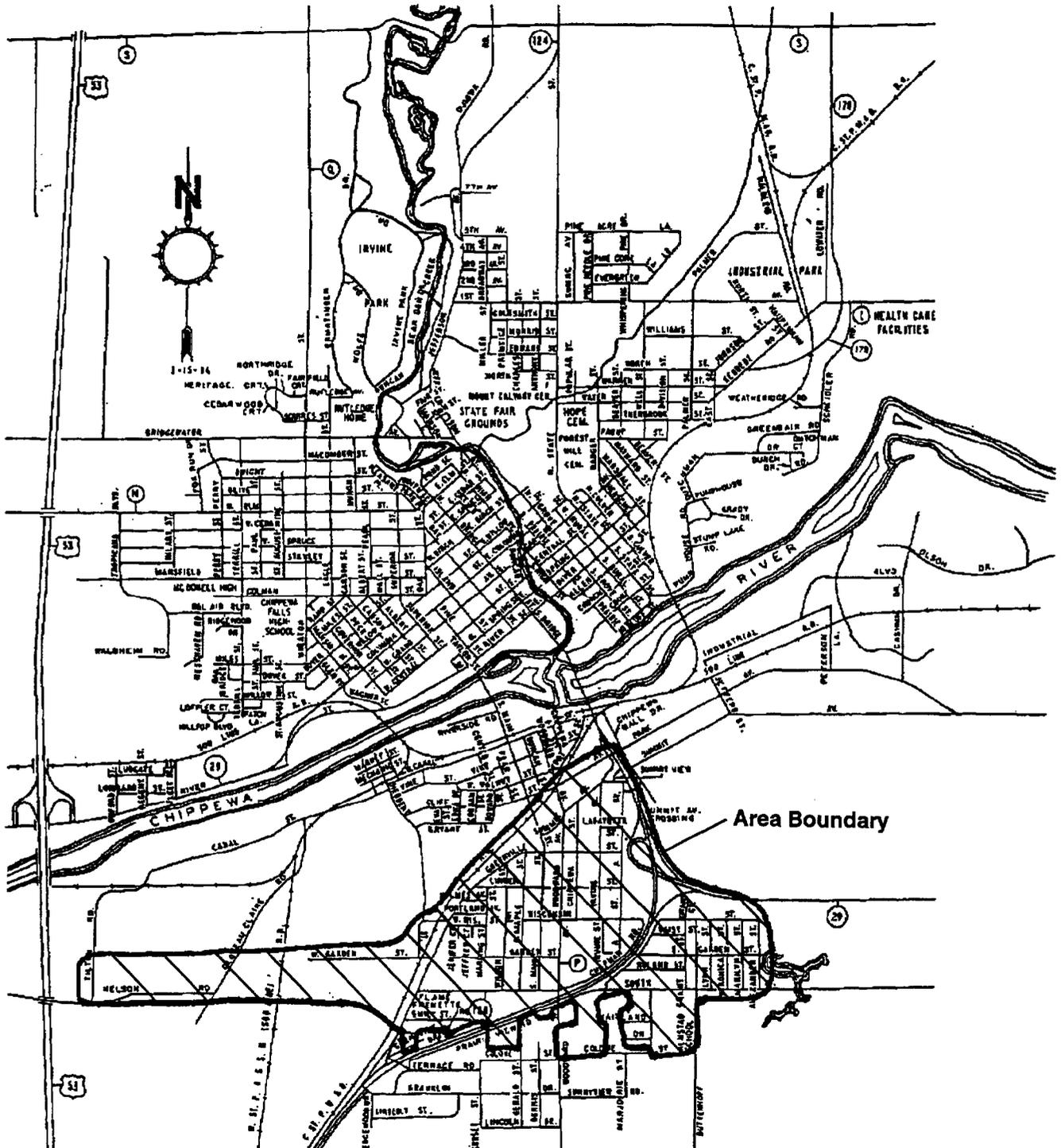


Figure 5-28. Pilot test area, Chippewa Falls, Wisconsin.

above situations occurred or if the health limits were not attained, both parties agreed to resume negotiations.

5.5.12 Implementation of the Pilot Study

Prior to starting the chemical addition, a test program would be started to get baseline results to help determine the effects of the pH adjustment. Samples would be collected on a weekly basis for 1 month prior to starting chemical addition. WDNR and the city jointly selected 10 sites with copper plumbing and 4 sites with galvanized plumbing. These homes had all shown elevated levels of lead and/or copper.

During the month that baseline data were being gathered, the chemical feed equipment and a day tank were purchased and installed. After starting chemical feed and closing the valve to restrict the flow from the test well into the test area, problems developed with trying to control the pumps to maintain equal water levels in all elevated tanks. By partially closing the discharge valve of the test well to reduce the volume of water delivered to the test area, the water levels in the tanks could be controlled. This action increased the operating pressure, and the feed pump selected did not feed accurately at the increased pressure. A different feed pump had to be installed. It took about 2 weeks to get an even pH and work out mechanical problems. Because of these difficulties, the pH was not raised to the desired 8.5 level. By mid-December, however, weekly test results were showing that lead levels and copper levels were meeting drinking water standards without reaching a pH of 8.5.

On December 19, 1985, the city and WDNR personnel met to review test results. Test results showed that in the test homes where the pH had been raised from 6.5 to 7.8, lead and copper levels were below health standards.

Figure 5-29 shows the results from the tests at 461 A Street. This site had a copper water service and copper plumbing and had shown elevated lead and copper levels before the pilot study. In May and September 1985, the lead had been at 310 and 490 µg/L, respectively. This figure shows that with the pH below 7.0, the health standards were being met. The other test sites showed similar results. In fact, after November only three sites had any samples that exceeded 15 µg/L.

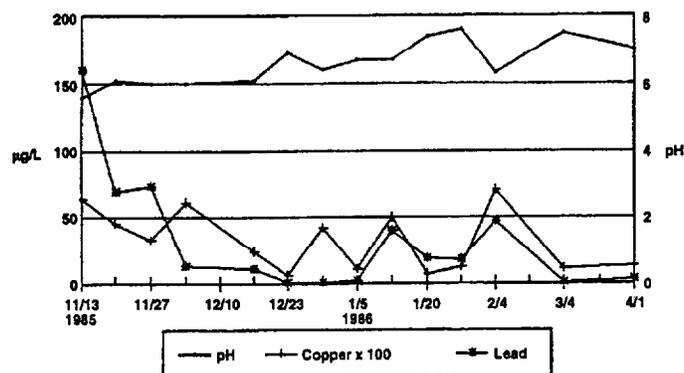


Figure 5-29. pH, copper, and lead at the 461 A Street copper services during pilot study.

Figure 5-30 shows the results from the tests at 467 Chippewa Street. This site is one of four with a galvanized water service and galvanized plumbing. It appears that the addition of caustic soda had no noticeable effect on the levels of iron or zinc in the water.

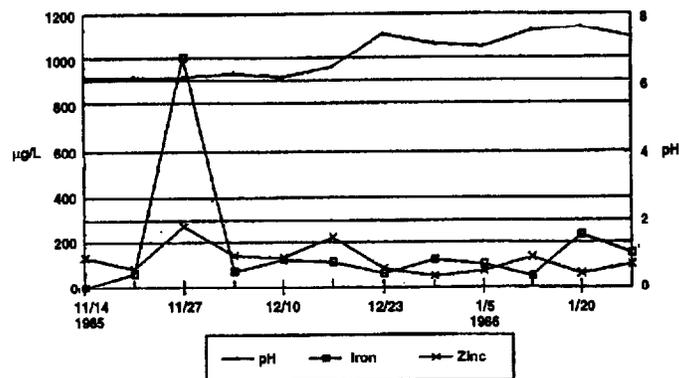


Figure 5-30. pH, iron, and zinc at the 467 Chippewa Street galvanized service.

Based on the lower lead and copper results at a lower pH, the WDNR agreed to allow chemical feed to continue at reduced feed rates and to study the effects. If needed, the feed rates could be raised until allowable lead and copper levels were attained.

5.5.13 Decision to Treat

The following factors prompted the city to proceed with chemical addition on a systemwide basis:

1. The use of 95/5 solder in new homes was not successful in attaining lead levels meeting the primary (health) drinking water standards.
2. Indications were that the state's secondary (aesthetic) drinking water standard of 1.0 mg/L for copper would soon be changed to a primary (health) standard of 1.3 mg/L.
3. It was proposed to reduce the state's primary standard for lead from 50 µg/L to 20 µg/L.
4. Meeting the standards for lead and copper were attainable with the pH at 7.0 and no chlorination, producing no noticeable change to the water.

On March 4, 1986, the City Council adopted a resolution stating that because the pilot project for addition of caustic soda had been successful, systemwide treatment (50% NaOH) should be implemented.

5.5.14 Implementation of Central Treatment

On April 19, 1986, a letter from the city to WDNR advised the department that the schedule below had been approved by the Chippewa Falls Common Council on March 18, 1986, and that the city should proceed on this schedule:

- Open bids on April 17, 1986.
- Board of Public Works reviews and makes recommendation on April 21, 1986.
- City Council awards contract on May 6, 1986.
- Construction begins on May 15, 1986.
- Contractor completes work; city begins equipment installation on July 15, 1986.
- City completes equipment installation on August 15, 1986.

The Council authorized the preparation of plans and specifications as well as advertising for bids for the building additions to the pumphouses to accommodate water treatment equipment. The initial schematic plans submitted to WDNR were approved. Public Utilities staff prepared bid plans and specifications for the building additions. Bids were opened on April 17, 1985, and an award was made on May 6, 1986. Construction began in late May and was completed in early August 1986. Public Utilities staff sought quotations on the needed equipment and tanks. All equipment was purchased and installation, with the exception of electrical work, was completed by Public Utilities staff.

5.5.15 Facilities Constructed

At the East Well Field, where five pumps are located, a 20 ft x 22 ft addition was built onto the existing pumphouse. Inside are housed two 1,600-gallon storage containers for bulk caustic soda. A separate chemical feed and day tank are provided for each well pump. The chemical feed pumps are electrically interlocked to the matching well pump.

At each West Well Field pumphouse, a 10 ft x 22 ft addition was constructed. Each of these buildings contains a 1,000-gallon storage tank along with a chemical feed pump and day tank. At each of the installations, the main storage tanks are within a containment area of sufficient size to hold the contents of the tanks.

All installations also have:

- A transfer pump to move the chemical from the storage tanks to the day tanks.
- Connections for transfer of caustic from transport to the storage tank.
- Water supply for flushing and safety eye wash stations.
- A stand-by chlorine feed system including a day tank and pump interlocked to each well.

As part of the central control system, a temperature alarm was added (because of the high freezing temperature of caustic soda) along with a flooding alarm. If the liquid level on the floor rises 1/8 inch above the floor, an alarm will be sounded. All alarms are transmitted back to the wastewater treatment

plant, where there is 24-hour coverage. The estimated costs compared to actual costs are listed in Table 5-10.

Table 5-10. Construction Costs

| | Estimated | Actual |
|---------------------------------|-----------|----------|
| Building Additions | \$38,300 | \$44,127 |
| Equipment, Tanks, Piping, Misc. | 31,100 | 33,172 |
| Installation Costs | 8,800 | 2,821 |
| TOTAL | \$78,200 | \$80,220 |

The engineering report also estimated \$11,900 for design costs. With the utility staff doing this work, these costs were included in the normal operating budget and not included above. Installation costs also are distorted because staff labor costs are not included above.

5.5.16 Monitoring

The WDNR required monitoring of the treatment, and in September 1986, the city proposed a monitoring program to WDNR. The proposal was based on input from the WDNR district engineer on the frequency of sampling and on the analysis of several parameters. The city's proposal was as follows:

- In conjunction with sampling for bacteria, collect pH samples at the 15 sites sampled each month.
- On a daily basis, monitor the pH at the wastewater treatment plant laboratory.
- Three times per week, monitor the pH at the individual wells.
- Select 10 sites for the monitoring of copper, lead, and pH of first-draw water to evaluate the effects of treatment in reducing corrosion products.
- Implement a sampling schedule as follows:
 - For the first 3 months, sample and analyze on a monthly basis.
 - For the next 9 months, sample and analyze on a quarterly basis.
 - Thereafter, sample and analyze on an annual basis.
- Continue to use the same laboratory for the copper and lead analysis, thus avoiding the need to split samples with the state laboratory to verify accuracy.

In October 1986, the WDNR Area, District, and Central offices reviewed and approved this monitoring program without change. They indicated that modifications to the monitoring program might be necessary based on monitoring results and the evaluation of treatment effectiveness.

5.5.17 Sampling Protocol

The sampling protocol up to this stage was to collect three 250-mL samples in the morning after the water had been in the pipes overnight. The first sample was taken in the morning before any water was used. The second sample was taken after the water was run for approximately 2 minutes or until the water felt cool. The third sample was taken after the water was run for approximately 5 minutes after the first sample. The first sample reflected the water in the faucet assembly, the second sample reflected the water in the house plumbing, and the third sample reflected the water in the distribution system.

The sample from 1301 Waldheim Road taken on October 25, 1984, shown in Table 5-11, is typical of most results. It shows that as the water was run, the lead levels dropped. This finding indicated that the elevated lead seemed to come from the faucet assembly, and a lesser amount of lead from the house plumbing.

Table 5-11. Lead Levels in the Samples Collected at 1301 Waldheim Road ($\mu\text{g/L}$)

| | Lead |
|-------------|------|
| First Draw | 400 |
| Second Draw | 8 |
| Third Draw | 4 |

During early sampling, there was some discussion about whether the first-draw sample should be used for determining compliance with the health standard, or if an average of the three samples should be used. With an average, a first-draw sample could be well in excess of the 50 $\mu\text{g/L}$ limit and the average would still be less than the limit.

In July 1987, WDNR tried to compare the three 250-mL sampling procedure with a two 1,000-mL sample routine. The 250-mL and 1,000-mL samples were taken at a home on successive days in the morning before any water had been used.

Table 5-12 shows a comparison at the same home as above. These results also are compared in Figure 5-31 for the lead results and Figure 5-32 for the copper results. The 1,000-mL sample appears to be about an average of the first-and second-draw of the 250-mL.

Table 5-12. Lead and Copper Levels in the Samples Collected at 1301 Waldheim Road

| | 250 mL | | 1,000 mL | |
|-------------|--------------------------|---------------|--------------------------|---------------|
| | Lead ($\mu\text{g/L}$) | Copper (mg/L) | Lead ($\mu\text{g/L}$) | Copper (mg/L) |
| First Draw | 18 | 3.3 | 6 | 5.2 |
| Second Draw | <3 | 3.8 | <3 | 4.0 |
| Third Draw | <3 | 0.32 | | |

On the same days, the same sampling procedures were used in another home (at 47 Stump Lake Road), shown in Table 5-13. In that case, the first-draw had a lower lead level than the second-draw using the 250-mL sample. However, the first-draw

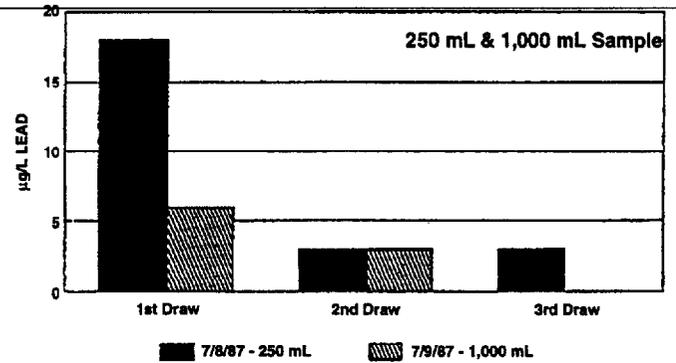


Figure 5-31. Lead levels in samples collected at 1301 Waldheim Road.

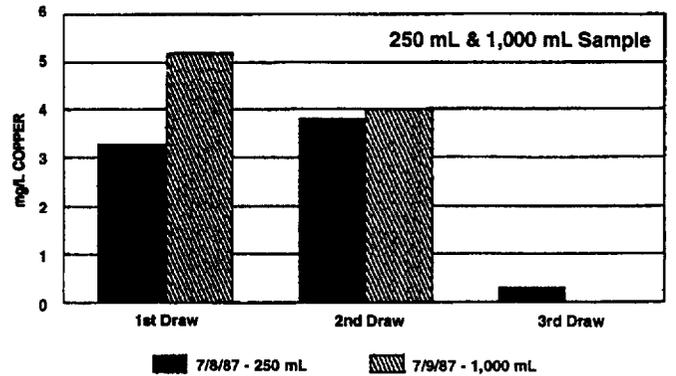


Figure 5-32. Copper levels in samples collected at 1301 Waldheim Road.

Table 5-13. Lead and Copper Levels in Samples Collected at 47 Stump Lake Road

| | 250 mL | | 1,000 mL | |
|-------------|--------------------------|---------------|--------------------------|---------------|
| | Lead ($\mu\text{g/L}$) | Copper (mg/L) | Lead ($\mu\text{g/L}$) | Copper (mg/L) |
| First Draw | 17 | 0.67 | 20 | 0.82 |
| Second Draw | 31 | 1.50 | 8 | 0.56 |
| Third Draw | 4 | 0.93 | | |

with a 1,000-mL sample still appeared to be an average of the first-and second-draw lead levels with the 250-mL samples.

At a third location where this procedure was used, 1100 West River Street (Table 5-14), the lead results were different. The results indicated elevated lead levels in all samples, with

Table 5-14. Lead and Copper Levels in Samples Collected at 1100 West River Street

| | 250 mL | | 1,000 mL | |
|-------------|--------------------------|---------------|--------------------------|---------------|
| | Lead ($\mu\text{g/L}$) | Copper (mg/L) | Lead ($\mu\text{g/L}$) | Copper (mg/L) |
| First Draw | 81 | .86 | 62 | .82 |
| Second Draw | 28 | 1.9 | 63 | .51 |
| Third Draw | 16 | .29 | | |

some exceeding the health standard. The high lead levels at this location should be considered differently, because this location is not a residence. It is the Water Department Maintenance Building, which has a large plumbing system with little water usage except when water meters are being tested.

In all three of the above cases, the data indicated that the copper levels were elevated for all water sitting in the house plumbing. These levels varied depending on time as well as on water chemistry.

Based on these data, although the existing standards were not violated at every location, corrosion products were clearly present at elevated levels. As a result, WDNR asked that the city:

- Raise the pH in the system to 8.0 or above. This was still not at the saturation point but would be closer. WDNR was willing to allow the city to operate at a lower pH provided that the treatment was effective.
- If it should wish to attempt some other method to reduce the level of corrosion products, submit that proposal to WDNR by October 1, 1987.
- Begin monthly sampling for lead, copper, and pH at the 10 selected locations once the treatment scheme was implemented.

Figures 5-33 and 5-34 show the past 2 1/2 years' results from 1301 Waldheim Road and 43 to 45 Stump Lake Road. At 1301 Waldheim Road, the last exceedance of the 50 µg/L limit was in October 1988. The last time this site exceeded the new 15 µg/L limit was May 1990. At Stump Lake Road, which is an eight-unit condominium, the last exceedance of the 50 µg/L limit was in April 1989. The last time it exceeded the 15 µg/L limit was in May 1990. The third site, 1100 West River Street, has not exceeded the 50 µg/L limit since February 1989 and has not exceeded the 15 µg/L limit since August 1990.

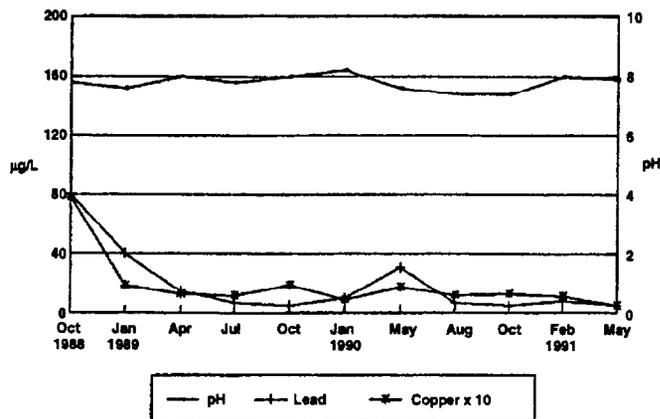


Figure 5-33. pH, lead, and copper at 1301 Waldheim Road.

On December 15, 1987, the city proposed that data from the 10 selected locations were not providing significant information to warrant continuing. A proposal was made to monitor

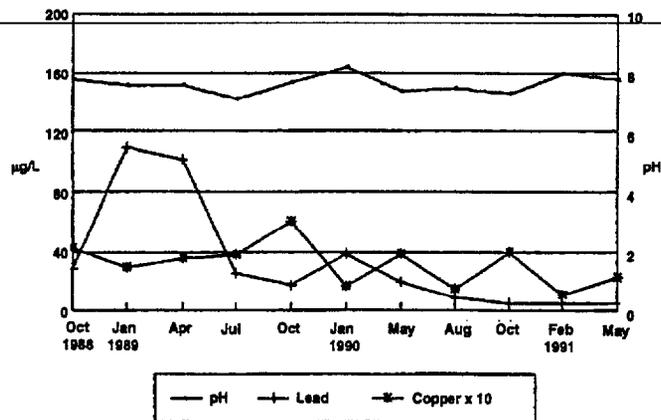


Figure 5-34. pH, lead, and copper at 43-45 Stump Lake Road.

at only the two locations that showed some significant levels of lead and copper: 1301 Waldheim Road and 43 Stump Lake Road. If these samples indicated that the treatment could attain the desired results, then the city would require pH monitoring only.

On January 20, 1988, the city and WDNR met to discuss the corrosion product monitoring. The WDNR District Engineer summarized the meeting as follows:

- **Monitoring Frequency and Location.** Most of the sites that are being monitored show lead levels well below the standard. The city believed that these additional data serve no purpose because little has changed over the past year. Copper levels also were down significantly from where they were prior to treatment. The city believed that since the standard for copper at that time was not a health-based standard, any reduction was an indication that the treatment was working. The recommendation was that the city continue to monitor at Stump Lake Road, 1301 Waldheim Road, and the Water Department shop (1100 West River Street) on a quarterly basis for lead and copper.
- **Optimum pH.** The industries in the city were reporting problems from the higher pH and customer complaints had increased. These issues, coupled with the cost of treatment, prompted the city to look for an optimum pH level to maintain. Using copper levels as an indicator and choosing an arbitrary level of 1.0 to 1.3 mg/L as appropriate, it appeared that a maximum pH of about 7.8 would be effective. Realizing that the pH tends to vary within the system, the city proposed to aim for a pH of 7.5 to 7.8 throughout the system. The recommendation was an operating pH of 7.5 to 7.8.
- **pH Variations.** Sampling data often showed a wide variation of pH within the system on any given day. The city would initiate some bench testing to determine a cause for this variation.
- **Summary.** It appears that the caustic addition was having a measurable effect on the level of corrosion products. It was suggested that the pH be maintained between 7.5 to 7.8 and monitored at three locations quarterly. If significant levels

were still noted within a year, another evaluation could be performed.

On February 8, 1988, the city was notified that monitoring at the three locations for lead, copper, and pH should continue and that the pH should be maintained at a minimum of 7.7 in the system.

During 1987, only one site had a lead level that exceeded 50 µg/L. This was 1100 West River Street, the Water Department Maintenance Building. Two of the 10 sites had exceeded the new 15 µg/L limit but were under the 50 µg/L limit at that time.

5.5.18 Feed Rates

Based on the results observed during the pilot study, the feed rates were set to attain a pH of 7.0 rather than the design pH of 7.9 or the calculated pH of 8.5 to reach the Langelier Saturation Index.

The feed rate at startup, based on the pilot study, was about 20 to 21 gallons of caustic soda per million gallons of water. When the systemwide treatment was started, the feed rates were up to 24 to 26 gallons per million gallons. When WDNR required that the pH be raised to 7.7, the feed rates had to be raised to average about 28 to 30 gallons per million gallons. The average feed rates and average daily pumpage are listed in Table 5-15 by year.

Table 5-15. Chemical Feed Rates of Caustic Soda

| Year | Avg. MGD | Caustic Soda Gal/MG |
|------|----------|---------------------|
| 1986 | 3,504 | 24.5 |
| 1987 | 4,058 | 24.0 |
| 1988 | 4,156 | 26.5 |
| 1989 | 3,951 | 30.8 |
| 1990 | 3,854 | 28.0 |

5.5.19 Operation and Maintenance Costs

The annual operation, maintenance, and chemical costs for the past 5 years are listed in Table 5-16 and displayed in Figure 5-35.

The operation costs have decreased as the system problems are worked out and as less monitoring and testing is conducted. The caustic soda costs have increased drastically. This increase was due to the higher feed rates and was also due to rising costs for caustic soda.

Table 5-16. Annual Operation and Maintenance Costs

| Year | Operation | Maintenance | Caustic Soda |
|------|-------------|-------------|--------------|
| 1986 | \$ 8,133.24 | \$1,678.81 | \$10,910.00 |
| 1987 | 21,422.80 | 1,678.81 | 20,990.00 |
| 1988 | 14,579.74 | 236.33 | 38,325.00 |
| 1989 | 14,597.68 | 687.77 | 57,345.00 |
| 1990 | 7,814.17 | 2,089.53 | 51,080.00 |

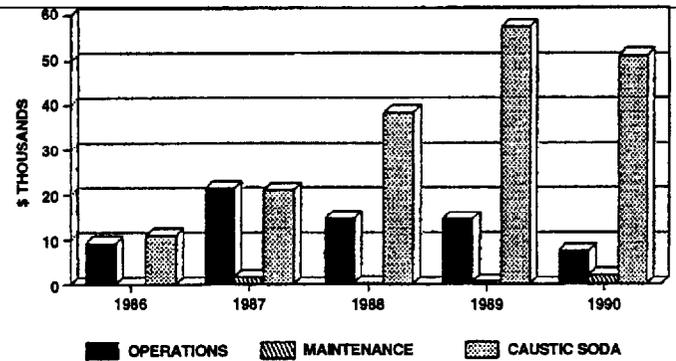


Figure 5-35. Annual operation and maintenance costs for the chemical feed system.

Originally, in late 1986, the price for caustic soda (sodium hydroxide) was \$155 per anhydrous ton. Since then, the cost has increased as shown in Table 5-17. This increase is shown graphically in Figure 5-36. In 1989, there was a shortage of caustic soda and suppliers established quotas for existing customers and would not take any new customers. As a result of the monthly quotas, shortages existed in some of the wells, which caused pH adjustment to cease.

Table 5-17. Caustic Soda Costs

| Month/Year of Increase | Cost Per Anhydrous Ton |
|------------------------|------------------------|
| 1986 | \$155.00 |
| September 1987 | 195.00 |
| December 1987 | 215.00 |
| May 1988 | 245.00 |
| August 1988 | 300.00 |
| October 1988 | 330.00 |
| January 1989 | 350.00 |
| April 1989 | 420.00 |
| July 1989 | 410.00 |
| September 1989 | 375.00 |
| May 1990 | 400.00 |
| October 1990 | 420.00 |

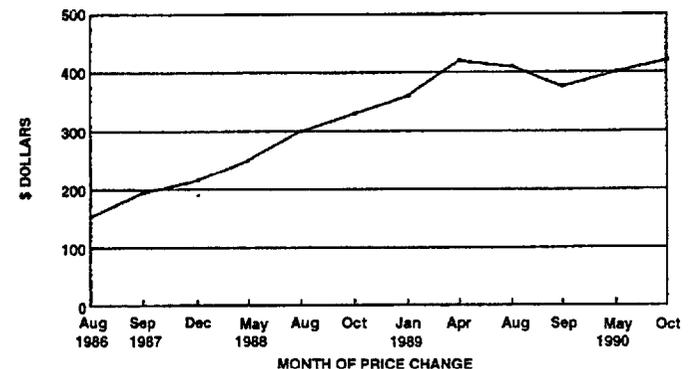


Figure 5-36. Cost of caustic soda per anhydrous ton.

5.6 Evaluating a Chemical Treatment Program to Reduce Lead in a Building: A Case Study

For many people, a significant fraction of total daily water intake comes from the workplace, such as an office building, a factory, or a school. Most people spend about one-third of their work days in the building environment, which is being scrutinized for health and safety factors by employees and employers. Buildings have the same types of plumbing materials as residences and are subject to the same types of potential problems. Corrosion of the distribution system components results in the leaching of lead and copper into the drinking water. Buildings also have unique situations and problems. A large building might have hundreds or even thousands of water taps and might serve a population larger than a small community. Because of concerns about the quality of drinking water in buildings, more and more tenants are getting their drinking water from water coolers, drinking water fountains, and water taps that have been analyzed for levels of lead and copper. If these levels are high, solutions are being investigated and implemented at the site.

A building that EPA has studied is a research facility constructed 5 or 6 years ago in the Washington, DC, area. Because of a variety of construction problems, several years and \$10 to \$15 million were spent correcting structural and other defects in the building. When the drinking water was sampled, however, elevated lead levels were found throughout the building. The water had the characteristics shown in Table 5-18. The pH was in the mid-7s, the alkalinity was 37, and hardness was at about 50. As Table 5-19 shows, the flush samples ranged from less than 5 to about 81. Sixty to 70 locations were sampled. A 4-day static test was made and the lead levels ranged from 63 to more than 100 $\mu\text{g/L}$.

Table 5-18. Water Quality Characteristics

| | |
|----------------|-------------------------------|
| pH | 7.53 |
| Alkalinity | 37 mg/L (as CaCO_3) |
| Total Hardness | 46.9 mg/L |
| Calcium | 14 mg/L |
| Magnesium | 2.9 mg/L |
| Iron | 0.11 mg/L |
| Manganese | <0.05 mg/L |
| Chloride | 14 mg/L |
| Sulfate | 13 mg/L |
| Fluoride | 0.62 mg/L |
| Silica | 1.3 mg/L |

It was decided that a possible solution might be to flush the water system, putting 7 million gallons through the building in 4 to 5 days. Presumably, the flushing would remove some of the lead and perhaps age the system. But flushing 7 million gallons of water through a system (requiring 6 months under normal circumstances) does not necessarily age the system. After flushing, two sequential samples showed lead levels ranging from 11 to more than 200 $\mu\text{g/L}$.

Table 5-19. Lead Levels in Samples of Flushed and Static Water from Various Locations

| | Pb ($\mu\text{g/L}$) Sample Locations | | | |
|---------------------------------|--|----------|----------------|------------------|
| | Fountain | Lab Sink | Utility Closet | Locker Room Sink |
| Flushed (15 min.) (12-14-90) | 81 | >5 | >5 | >5 |
| 4-Day Static (12-26-90) | 63 | 183 | 63 | 101 |
| Flushed (2-8-91) | | | | |
| 1 | 72 | 27 | 47 | 246 |
| 2 | 36 | 11 | 21 | 21 |
| Static (2-12-91) | | | | |
| 1 | 40 | 96 | 121 | 189 |
| 2 | 13 | 242 | 69 | 1,480 |

Several weeks later samples were collected again, and the lead levels were as high as 1,000 $\mu\text{g/L}$. According to the specifications, the building did not contain lead solder. As shown in Table 5-20, the percentage of lead from about 20 different locations varied from very low to approximately 50 percent, indicating 50/50 lead solder. It was apparent that the contractor had not followed specifications and had used lead solder at least in part of the building.

Table 5-20. Percentage of Lead in Solder Samples

| Sample | Percentage of Lead |
|--------|--------------------|
| 1 | 51.2 |
| 2 | 0.17 |
| 3 | 58.0 |
| 4 | 0.13 |
| 5 | 34.1 |
| 6 | 0.15 |
| 7 | 39.3 |
| 8 | 49.1 |
| 9 | 46.4 |
| 10 | 42.0 |

EPA's Drinking Water Research Division in Cincinnati, Ohio, was contacted at this point, and the division explained some potential problems: lead solder joints, brass valves, and brass fittings. The building had more than 600 outlets and thousands of lead-soldered joints. Usually, three or four soldered joints are associated with each fixture. The main lines might have seven or eight additional soldered joints. Several large brass valves located on the incoming water lines could cause potential problems at the water coolers, which now carry warnings.

The primary question was: "What are the main sources of lead?" EPA believed that the main sources would be the brass fixtures and the lead solder. The second question was: "Can you determine the amount of lead from each source?" The

intent was to go back to the contractor and recover some funds to help pay for a solution or to be compensated for the lead problems. Facility personnel had not been fully aware of the lead levels that could result from brass fixtures. EPA sampled about 40 taps and found the same elevated lead levels. EPA collected 250-mL samples of 24-hour standing water and the lead levels varied extensively. The values EPA obtained were different from the initial samples, even though the same sites were sampled. A total of 12 sequential samples were collected at about six locations that were likely to produce high values. The first 2 samples were 60-mL samples and the remaining 3 to 12 samples were 125-mL samples. The samples were ana-

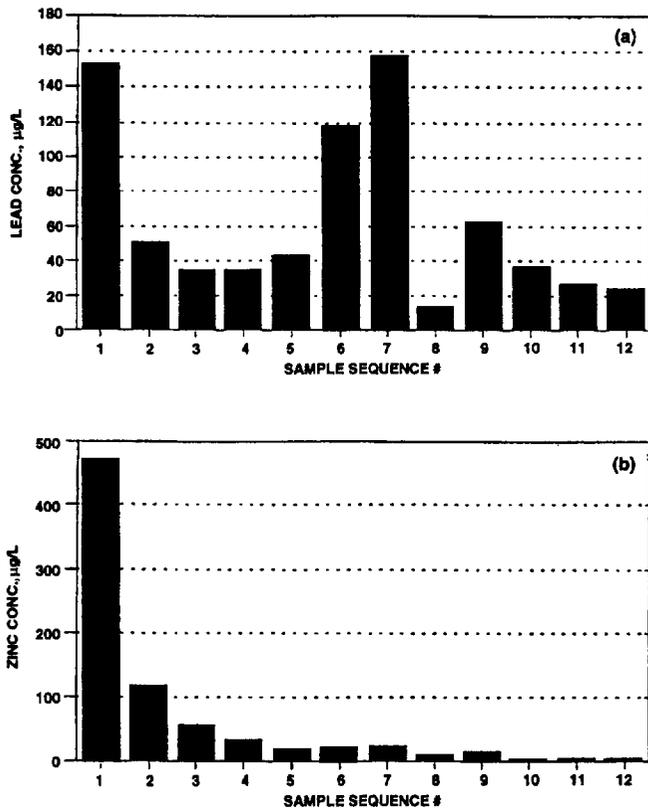


Figure 5-37. Lead (a) and zinc (b) concentrations in samples collected sequentially (Room 3329).

lyzed for lead, zinc, and copper. Figures 5-37 and 5-38 show the results of the data for zinc (part of the brass in the brass fixture) and lead. High levels of zinc were noticed in the first two samples at 60 mL each and represent the water contact with the fixture. If the only source of lead was the brass fixture (brass generally contains about 7 or 8 percent lead) then the concentration pattern of lead would be similar to that of zinc. As shown in Figure 5-37, higher lead levels were found at the 6th and 7th sample and at around the 9th through 12th samples, indicating that lead was coming from the solder. On the other hand, if no lead was found in the brass and the only source of lead was the solder, the first few samples would have had low lead levels and the following samples would have had high lead levels. With these data, it was apparent that the fixtures, solder, and some brass valves were contributing to the high lead levels.

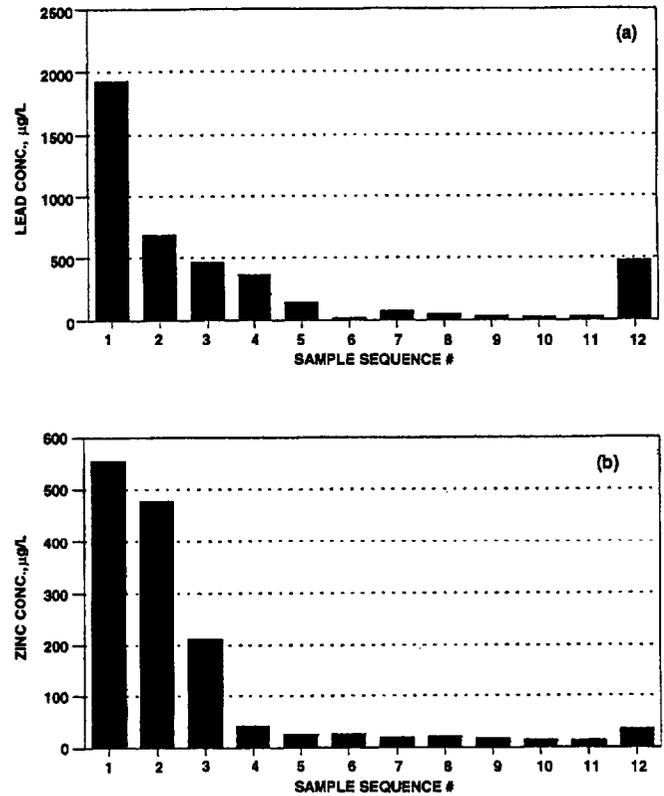


Figure 5-38. Lead (a) and zinc (b) concentrations in samples collected sequentially (Room 1618).

Potential solutions were presented to the building management. The people who worked in the building were well aware of the problem and were urging management to replace all of the plumbing. Management estimated that this would cost \$2 million to \$4 million and probably would take 6 months to 1 year. Although new plumbing was a potential solution, it was ruled out because of the time it would take to implement this solution. A point-of-use (POU) manufacturer was contacted and there was some discussion about installing POU systems at each tap. It was impractical, however, to place POU devices at each of more than 600 taps. POU devices could be placed within the lines, taking out the lead from the solder, but the problem with the brass valve would still exist. As a result, POU devices were not considered a practical solution.

The third potential solution, chemical treatment (such as using corrosion inhibitors) was selected. A research plan was developed to determine which chemical treatment scenario would be most effective for the system. The research plan had two phases. First, the effect of water usage on lead leaching was evaluated. This new building had not been used and EPA was convinced that, with water usage, the lead levels would decrease. Second, the effect of adding a corrosion inhibitor was evaluated. Three inhibitors were selected for evaluation: zinc orthophosphate, "calcium" orthophosphate (manufacturer designation), and sodium silicate. In discussing these, some of the management people, particularly the technical people, objected to all three. They continued to favor having all the plumbing replaced. Some were concerned about the potential for high

sodium and others were concerned about zinc. Eventually, the building personnel were convinced that action should be taken and that it was likely that the water utility would add a corrosion inhibitor in the future.

Half of the building is devoted to laboratories, and as a result, a total of eight sections of the building could be isolated. A program was set up in which water would be run 5 days a week for 30 minutes at a time, four times a day, with an hour and a half between each time. Standing samples (16 hours) were collected twice a week. All of these samples were 250-mL samples. A meter was placed on the line leading into each isolated section. Tap water from nine laboratories was sampled in each wing.

Baseline data, produced by collecting flushed water samples, are shown in Table 5-21. On the ground floor, the lead in

Table 5-21. Lead Baseline Data Collected at the Ground Floor and at the Third Floor

| Results - Initial (Pb (µg/L) Tests | | | | |
|------------------------------------|--------------|----------|-------------|----------|
| Tap | Ground Floor | | Third Floor | |
| | Flush | Standing | Flush | Standing |
| 1 | 11 | 131 | 11 | 46 |
| 2 | 8 | 112 | 5 | 583 |
| 3 | 3 | 50 | 5 | 79 |
| 4 | 5 | 291 | 14 | 101 |
| 5 | 4 | 117 | 6 | 167 |
| 6 | 6 | 330 | 3 | 118 |
| 7 | 2 | 99 | 102 | 135 |
| 8 | 6 | 125 | 7 | 309 |
| 9 | 2 | 109 | 4 | 75 |
| Avg. | 5 | 152 | 17 (6.9)* | 179 |

*6.9 is the average value excluding tap 7.

the samples averaged about 5 µg/L; on the third floor, the average was about 7 µg/L. Standing samples were collected on the ground floor and the third floor. The lead levels had a wide range, but the average produced at the taps on the ground floor was 152 µg/L, and on the third floor, 179 µg/L. During the operation of the system, the lead levels had varied (Figures 5-39 and 5-40). The chemists who performed the analysis at the laboratory in Cincinnati indicated that most of the samples with high lead levels had some particulate material in the sample, indicating that the system was still being flushed. There also might have been some particulate in the line from solder being broken off.

After about 80 days, there appeared to be a consistent reduction in lead levels. Figure 5-41 shows average values for the ground floor (nine taps). Until the 62nd day, the lead levels varied greatly. Then the lead levels declined, probably due to aging or film developing on the insides of the pipes. Figure 5-42 shows the average values for the third floor. The third floor is the top floor; those rooms have not been used. Some administrative and maintenance people had been using several

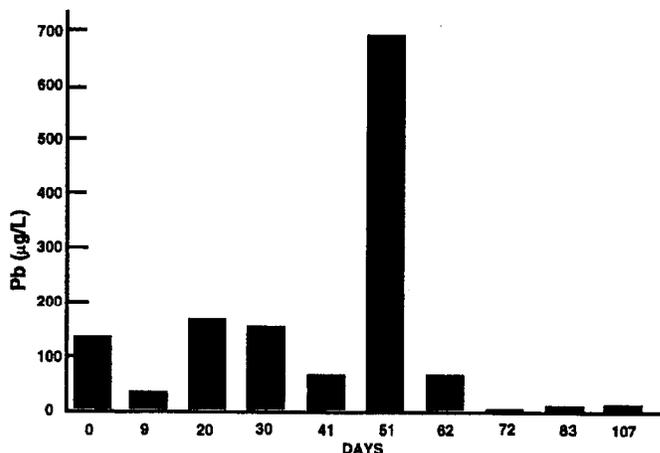


Figure 5-39. Water usage study—lead concentrations over time in Room G402.

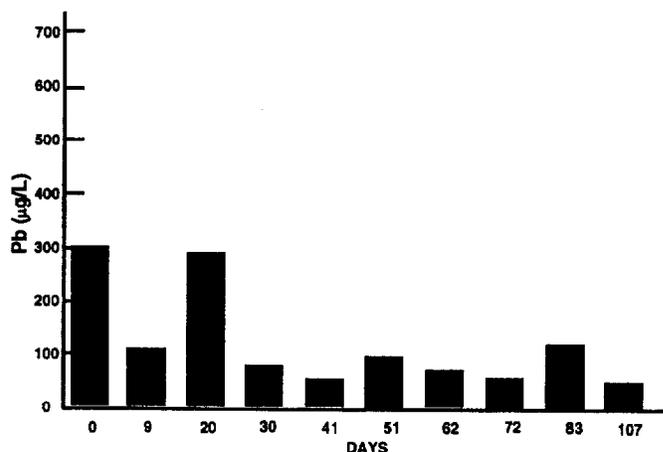


Figure 5-40. Water usage study—lead concentrations over time in Room 3325.

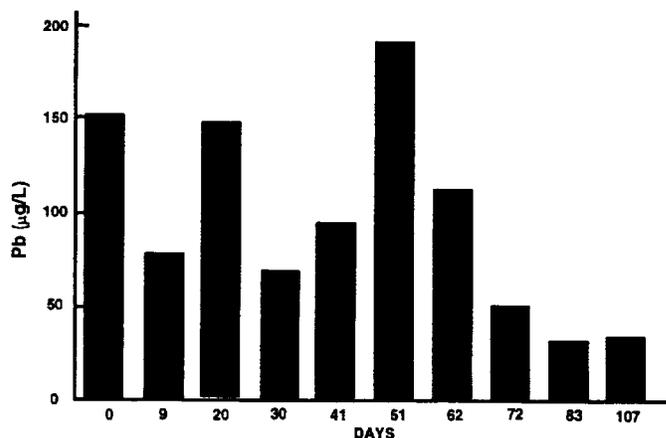


Figure 5-41. Water usage study—average lead concentrations from the ground floor.

laboratories on the ground floor. It was assumed that these individuals had used some of the taps in these laboratories, which might explain why the ground floor lead levels seem to be slightly lower than the third floor lead levels.

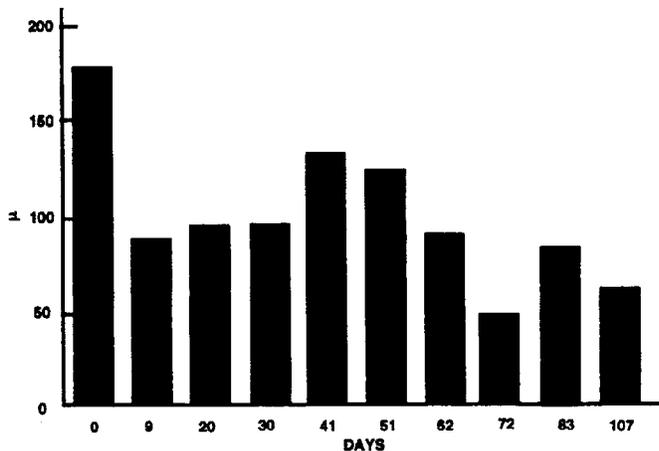


Figure 5-42. Water usage study—average lead concentrations from the third floor.

The number of samples collected at the taps that are below 50 µg/L is increasing (Figures 5-43 and 5-44). Building personnel must make a decision about when they believe the water is safe or potable. The third floor response to treatment is slightly slower than that of the ground floor. It is suspected that the slowdown results from the regular water usage on the

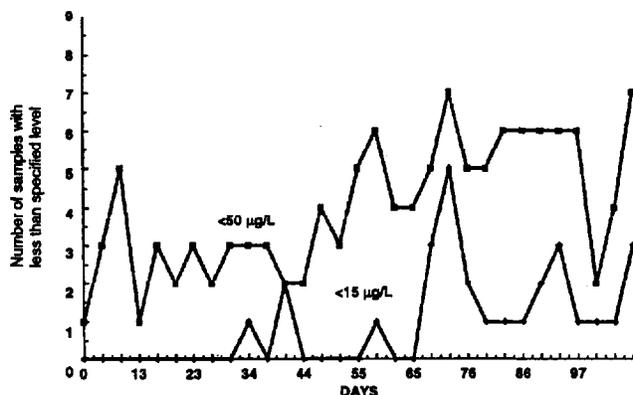


Figure 5-43. Water usage study—number of samples with less than 50 µg/l and 15 µg/L lead from the ground floor.

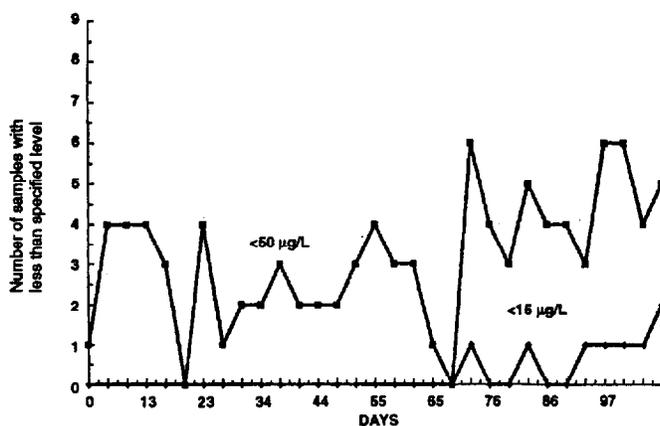


Figure 5-44. Water usage study—number of samples with less than 50 µg/l and 15 µg/L lead from the third floor.

ground floor. The goal is to have all taps eventually below 15 µg/L.

5.7 Iowa's Lead in Schools' Drinking Water Program: More Than Just a Monitoring Program

5.7.1 Introduction

The Lead Contamination Control Act of 1988 (LCCA) was enacted on October 31, 1988. The passage of this act was prompted by concerns that children were being exposed to excessive levels of lead in drinking water in schools, preschools, and daycare centers. The water at these locations was of particular concern for three reasons. First, several models of water coolers found in schools at this time were known to have lead-lined storage tanks that contributed high levels of lead to the water. Second, the pattern of water usage in these buildings meant that water could sit in contact with any lead in the plumbing for an extended period of time, leading to high lead levels in the drinking water. Finally, children are more likely than adults to suffer adverse health effects from exposure to lead.

5.7.2 Requirements of the LCCA

The LCCA placed requirements on EPA, the Consumer Product Safety Commission (CPSC), the states, the Centers for Disease Control (CDC), schools, preschools, and daycare centers. The law also prohibited the sale of water coolers that are not lead-free.

EPA was directed to distribute a list of water coolers that were not lead-free and a guidance document and water testing protocol to the states by February 1989. EPA also was directed to make grants to states for the purpose of helping schools, preschools, and daycare centers to test their water for lead and to solve problems. These grants were never funded by Congress.

The CPSC was directed to initiate a recall or other corrective action for water coolers with lead-lined tanks by October 31, 1989.

The states were directed to distribute the EPA guidance information, the list of certified laboratories, and the list of water coolers that were not lead-free. The states also were directed to establish programs by July 31, 1989, to assist schools, preschools, and daycare centers in testing their water. The state programs were directed to ensure that schools, preschools, and daycare centers would take steps to eliminate lead contamination from coolers that were not lead-free by January 31, 1990.

The law is somewhat unclear as to whether schools, preschools, and daycare centers are required to test their water for lead. The requirement actually is for the states to ensure that the testing is done rather than for the institutions to perform testing. If institutions do test their water, however, they are

required to notify the public that the test results are available for their inspection.

The CDC was directed to provide grants for prevention of childhood lead poisoning. These grants were funded by Congress.

5.7.3 More Than a Monitoring Program

Two years after implementation, Iowa's program was perceived to be simply a "monitoring" program, that is, a program to monitor the levels of lead that the schools found in water. The LCCA directed, however, that lead levels above the action level of 20 µg/L (250-mL sample size) be reduced to safe levels; if the monitoring showed problems, solutions were needed. The distinguishing feature of Iowa's program has been that it helps schools, preschools, and daycare centers with widespread contamination problems to find solutions.

5.7.4 Implementation in Iowa: Monitoring Results

In Iowa, this program was assigned by the Governor to the Iowa Department of Public Health (IDPH). IDPH assigned the program internally to the Health Engineering Section. This section provides technical assistance to the public and to local health officials in the areas of plumbing, health effects of drinking water contamination, well construction, and other related subjects. No money was allocated specifically for this program. An interagency effort and existing technical assistance programs were used, however, to overcome this lack of specific funding.

The program was initially implemented through three mailings made to all schools, preschools, and daycare centers. An initial informational mailing was sent in May 1989. A followup survey was sent in October 1989, and a second informational mailing was sent in July 1990. The Iowa Departments of Education and Human Services provided mailing lists for schools, preschools, and daycare centers and shared the printing and mailing costs for all mailings.

The first informational mailing (May 1989) contained a memo offering assistance from IDPH, a list of Iowa laboratories certified to test for lead in water, a list of coolers that were not lead-free, and the EPA booklet, *Lead in Schools' Drinking Water*, which contained the water testing protocol. The followup survey asked schools, preschools, and daycare centers to let IDPH know whether they were finding any coolers that were not lead-free, whether they were testing their water for lead, and if they were testing, what lead levels were found. The second informational mailing (July 1990) contained an updated list of coolers that were not lead-free, a question-and-answer sheet to help alleviate some of the confusion revealed by the responses to the followup survey, and a second followup survey to be filled out and returned to IDPH.

The responses to the initial followup survey (October 1989) revealed that schools, preschools, and daycare centers were confused about the requirements of the law and about the level of lead that was to trigger action on their part to lower the lead levels. Some thought that the law mandated water

testing, while others thought that it was a voluntary program. Some schools thought that it was sufficient to test only a few outlets rather than all drinking water outlets. In some cases, schools took no action to reduce the high levels of lead that were discovered. In addition, there was confusion about the 50 µg/L MCL as opposed to the 20 µg/L action level that the schools were directed to use. An effort was made to clear up this confusion with the question-and-answer sheet that was included in the second informational mailing. In addition, the University Hygienic Laboratory agreed to send out a special notice with test results to schools, preschools, and daycare centers to inform them of the 20 µg/L action level and to direct them to call IDPH with any questions.

In addition to indicating confusion, the responses to the followup surveys indicated that schools, preschools, and daycare centers were finding problems and needed help in solving them. Because the program was assigned to a section of the health department that already provided extensive technical assistance to the public, it was natural that the program would progress beyond a simple monitoring program to providing the needed technical assistance.

5.7.5 Implementation in Iowa: Technical Assistance Program

The technical assistance program consists of telephone consultations to answer questions and limited assistance and onsite investigations as needed to solve widespread contamination problems. The onsite investigation component of Iowa's program is unique among the states. Local health officials and water utilities are involved whenever possible. The investigations consist of a visit to the building to look at the plumbing, take metal samples from solder and fixtures to screen for lead, and determine where to take additional water samples to pinpoint the source of the problem and to provide a solution. Extensive water testing often is required to find the source(s) of lead and the solution. This water testing is provided free of charge to the school through the state laboratory as part of the investigation. To date, six investigations have been completed, six more are under way or pending, and many more are needed.

5.7.6 Test Results from Iowa's Program

Statistics have been compiled from the returned followup surveys to show the extent of lead contamination being found by schools, preschools, and daycare centers. Two items were considered when interpreting these results. First, these are results from 250-mL samples taken in the morning before any water is used. Second, not all institutions sampled all types of sources, such as coolers, bubblers, and faucets. Some sampled only coolers or only coolers and bubblers. The results of this sampling showed that an unexpected number of schools, preschools, and daycare centers found lead levels higher than the 20 µg/L action level.

There are 800 public school districts and private schools in Iowa and 1,300 licensed preschools and daycare centers. A followup survey was returned by 48 percent of the schools and 44 percent of the preschools, although many of these surveys

were not complete. Some 34 percent of the schools and 25 percent of the preschools and daycare centers sampled drinking water outlets for lead. A slightly smaller number (32 percent of the schools and 23 percent of the preschools) actually reported test results to IDPH. Of those reporting test results, 27 percent of the schools and 8 percent of the preschools had at least one source testing above the action level of 20 µg/L. Because it was anticipated that the standard for lead in water might be lowered, the number of institutions reporting levels between 10 µg/L and 20 µg/L was also recorded. Forty-one percent of the schools and 13 percent of the preschools/daycare centers had at least one source that tested in this range. A summary of the lead results is presented in Table 5-22.

Table 5-22. Summary of Lead Levels Found by Institutions

| Level Found (µg/L) | Facilities Reporting |
|--------------------|----------------------|
| 20 - 30 | 47 |
| 30 - 40 | 32 |
| 40 - 50 | 24 |
| 50 - 60 | 12 |
| 60 - 70 | 12 |
| 70 - 80 | 7 |
| 80 - 90 | 7 |
| 90 - 100 | 6 |
| >100 | 17 |

The points of water sampling where lead levels greater than 20 µg/L were reported and the highest lead level recorded for each type of sampling point are presented in Table 5-23. The highest level reported on a followup survey was 3,700 µg/L, and the highest level found by the University Hygienic Laboratory in a sample sent in by a school was 10,000 µg/L.

Table 5-23. Number of Facilities Reporting Lead Levels above 20 µg/L and the Highest Lead Levels Recorded from Those Facilities

| Point of Sampling* | Facilities Reporting >20 µg/L | Highest Levels |
|--------------------|-------------------------------|----------------|
| Cooler | 45 | 100 µg/L |
| Non-cooled bubbler | 28 | 3,700 µg/L |
| Faucet | 44 | 1,100 µg/L |
| Steam kettle | 4 | 300 µg/L |

*250-mL sample, overnight standing.

5.7.7 Example of a Solution: Finding a Solution for New Hampton High School

In Summer 1989, New Hampton High School began sampling for lead in water according to the EPA protocol. Officials flushed outlets the day before testing to simulate normal use during the school year. Three of 12 coolers tested higher than 20 µg/L. Eight of the 9 remaining coolers tested higher than 10 µg/L. All of the 8 faucets tested had levels higher than 20 µg/L.

Additional tests were taken in September 1989, shortly after school started. Nine out of 9 faucets tested higher than 20 µg/L. Eight of these were repeat samples. All of the lead levels were lower than those found in the summer samples, even though they were higher than 20 µg/L.

According to the EPA protocol, the next step was to take flushed samples. For coolers, this test involved a 15-minute flush. Two out of the three coolers tested had levels almost as high after flushing as they did on first-draw samples. This result indicated that the problem was likely to be in the upstream plumbing. Flushed samples also were taken from the faucets. Six out of 9 faucets tested lower than 10 µg/L after a 30-second flush. The remaining three faucets tested between 10 µg/L and 20 µg/L. This finding again indicates that the upstream plumbing is contributing to the high levels.

The service connection and water main samples were all low, indicating that the problem was within the building.

The school continued to follow the EPA protocol and attempted to test the upstream plumbing. They took these samples at shut-off valves upstream. The valve stem packings/seals were partially dismantled to collect the samples. These samples had lead levels 5 to 10 times higher than any first-draw or flushed samples taken at the sources. The EPA protocol gave little guidance for what should be done when the flushed samples came back much higher than the first-draw samples. At this point, the school contacted IDPH for assistance.

The IDPH onsite investigation revealed that the distribution system within the building was made primarily of galvanized pipe. The system was oversized in that it had 60 ft of 4-inch pipe for a school with approximately 400 students. Analysis of solder and brass with a lead-in-solder test kit indicated the likely presence of lead in some solder and brass at the school. It appeared from the test results to date that the high lead levels could be isolated largely to one part of the building. (The EPA protocol recommends trying to isolate the levels.) This line of reasoning was followed initially in the IDPH investigation, but it turned out that there was actually a different reason for high- and low-testing areas.

Additional samples were taken at Iowa's expense, but the results were confusing because there were large variations in lead levels for water samples taken from the same source. The results indicated that water corrosivity as measured by the Langelier Index should not be a problem. After all of the original and additional samples were listed together by source and analyzed, a pattern of high and low readings according to the time that the sample was taken appeared. The lead levels were high when taken during the summer or just after school started when water usage was low and stagnant water had not been completely flushed from the pipes. The lead levels were mostly lower than 20 µg/L during periods of high water usage during the school year. This result was confirmed by selected retesting. The high lead levels found in the upstream samples are believed to be due to contamination introduced from the valve bodies in the abrasive action of dismantling them prior to the water sampling. These valves are not believed to contribute to the high

lead levels at the points of initial sampling (coolers, bubblers, or faucets).

The major source of contamination is believed to be sediment in the galvanized pipe, compounded by the presence of oversized pipe (because a large amount of water must be used to completely empty the distribution system of stagnant water). Smaller amounts of lead are contributed by lead solder and brass faucets at the sources.

The solution developed for the school is to flush all water out of the building after more than a 2-day (weekend) vacation. This solves the problem in all but four sources (three sinks and one cooler.) Daily flushing, replacing brass faucets and/or lead solder in the immediate vicinity of the faucets, or disabling the outlets was recommended for these four sources.

5.7.8 General Observations from Investigations

The following observations have been summarized from the investigations:

- Galvanized pipe should be suspected as the lead source when contamination is widespread throughout a building and when lead levels in flushed samples are higher than those in first-draw samples.
- Brass in faucets should be suspected as a source when most of the faucets have high lead levels, most of the coolers have low lead levels, and the lead levels in the 30-second flushed samples from faucets are low.
- Lead solder should be suspected as a major source of lead contamination when it can be seen from the outside that a sloppy job of soldering was done and when the lead levels in the flushed samples are high, but lower than those in the first-draw samples.
- Schools can have high lead levels even if the water utility monitoring in homes shows no problems, if the water is not corrosive, or if the water utility uses corrosion inhibitors. This situation is due to different sources of lead in homes and school buildings, different water usage patterns in homes and schools buildings, and the different sampling protocols used by the schools and the water utility.

The future of Iowa's program is uncertain at this point. The state will continue to provide technical assistance as time permits. Additional followup with most schools, preschools, and daycare centers is needed, however, to remind them to test their drinking water and to ensure that any earlier testing was done properly. This requirement undoubtedly will increase the need for technical assistance to provide solutions for the lead contamination problems that will be found. It is unlikely that additional funding will come from the state of Iowa. One possible source of federal funding exists, however, which Iowa currently is pursuing.

5.8 References

1. APHA-AWWA-WPCF (1989). *Standard Methods for Examination of Water and Wastewater*. Washington, DC.
2. American Water Works Association (1990). *Water Quality and Treatment, Fourth Edition*. McGraw-Hill, Inc., New York, NY.
3. Amlie, R.F. and T.A. Berger (1972). Polarographic Analysis of Lead (IV) Species in Solutions Containing Sulfuric and Phosphoric Acids. *Journal of Electroanalytical Chemistry*. 36:427.
4. Breach, R., S. Crymble, and M.J. Porter (1991). Systematic Approach to Minimizing Lead Levels at Consumers Taps. *Proc. AWWA Annual Conf.* Philadelphia, PA.
5. Colling, J.H. et al. (1992). Plumbosolvency Effects and Control in Hard Waters. *Journal of the Institute of Water and Environmental Management*. 6(6):259.
6. Gregory, R. (1990). Galvanic Corrosion of Lead Solder in Copper Pipework. *Journal of the Institute of Water and Environmental Management*. 4:112.
7. Holm, T.R. and Schock, M.R. (1991). Potential Effects of Polyphosphate Products on Lead Solubility in Plumbing Systems. *Journal of the American Water Works Association*. 83(7):74.
8. Kuch, A. and I. Wagner (1983). A Mass Transfer Model to Describe Lead Concentrations in Drinking Water. *Water Research*. 17(10):1301.
9. Millette, L. and D.S. Mavinic (1988). The Effect of pH Adjustment on the Internal Corrosion Rate of Residential Cast-Iron and Copper Water Distribution Pipes. *Canadian Journal of Civil Engineering*. 15:79.
10. Schock, M.R. (1989). Understanding Corrosion Control Strategies for Lead. *Journal of the American Water Works Association*. 81(7):88.
11. Schock, M.R. and I. Wagner (1985). The Corrosion and Solubility of Lead in Drinking Water, Chapter 4 in *Internal Corrosion of Water Distribution Systems*. AWWA Research Foundation. Denver, CO.
12. Sheiham, I. and P.J. Jackson (1981). Scientific Basis for Control of Lead in Drinking Water by Water Treatment. *Journal of the Institute of Water Engineers and Scientists*. 35(6):491.
13. Snoeyink, V.L. and D. Jenkins (1980). *Water Chemistry*. John Wiley and Sons, New York, NY.
14. AWWA Research Foundation (1990). *Lead Control Strategies*. AWWA Research Foundation and American Water Works Association, Denver, CO.

-
15. Lane, R.W. et al. (1977). The Effect of pH on Silicate Treatment of Water in Galvanized Piping. *Journal of the American Water Works Association*. 69(8):457.
 16. Robinson, R.B. et al. (1990). *Sequestering Methods of Iron and Manganese Treatment*. AWWA Research Foundation.
 17. Kastanis, E.P. et al. (1986). Soluble Silicate Corrosion Inhibitors in Water Systems. *Materials Performance* 25:19-25.
 18. Oliphant, R. (1978). *Dezincification by Potable Water of Domestic Plumbing Fitting: Measurement and Control*. Water Research Centre Technical Report TR-88.
 19. Hingston, F.J. et al. (1987). Specific Adsorption of Anions. *Nature*. 215:1459.
 20. Huang, C.P. et al. (1975). The Removal of Aqueous Silica from Dilute Aqueous Solution. *Earth and Plant Letters*. 27:265-275.
 21. Karalekas, P. et al. (1983). Control of Lead, Copper, and Iron Pipe Corrosion Pipe in Boston. *Journal of the American Water Works Association*. 75(2):92-95.
 22. Mullen, E.D. and J.A. Ritter (1980). Monitoring and Controlling Corrosion by Potable Water. *Journal Health*. May.
 23. Pisigan, R.A., Jr. and J.E. Singley (1987). Influence of Buffer Capacity, Chlorine Residual, and Flow Rate on Corrosion of Mild Steel and Copper. *Journal of the American Water Works Association*. 79(2):62-70.
 24. Loewenthal, R.E. and G.V.R. Marais (1976). *Carbonate Chemistry of Aquatic Systems: Theory and Practice*. Ann Arbor Science Publications, Ann Arbor, MI.
 25. Stone, A., C. Spyriclakis, M. Benjamin, J. Ferguson, S. Reiber, and S. Osterhus (1987). The Effects of Short-Term Changes in Water Quality on Copper and Zinc Corrosion Rates. *Journal of the American Water Works Association*. 79(2):75-82.
 26. AWWA Research Foundation and DVGW Forschungsstelle (1985). *Internal Corrosion of Water Distribution Systems*. Denver, CO.
 27. Mah, M. and E.S. Boatman (1978). Scanning and Transmission Electron Microscopy of New and Used Asbestos-Cement Pipe Utilized in the Distribution of Water Supplies. *Scanning Electron Microscopy*. (1):85-92.
 28. Schock, M.R. and R.W. Buelow (1981). The Behavior of Asbestos-Cement Pipe Under Various Water Quality Considerations: Part 2, Theoretical Considerations. *Journal of the American Water Works Association*. 73(12):609.

Appendix A

EPA/AWWA National Workshop on Control of Lead and Copper in Drinking Water

Workshop Agenda

Monday, September 23, 1991

- 8:45 a.m. WELCOME
 Dale S. Bryson, Water Division, U.S. EPA Region 5
- 9:00 a.m. INTRODUCTION AND OBJECTIVE
 Jon DeBoer, AWWA
- 9:30 a.m. LEAD AND COPPER REGULATION
 Jeff Cohen, Office of Drinking Water, U.S. EPA
 Harry Pawlowski, Office of Drinking Water, U.S. EPA
- 10:00 a.m. LEAD AND COPPER MONITORING PROGRAM USING EMPLOYEES AND CUSTOMERS
 Jack DeMarco, Cincinnati Water Works
- 10:30 a.m. AT THE TAP MONITORING
 Doug Neden, Greater Vancouver Regional District
- 11:00 a.m. BREAK
- 11:30 a.m. SELECTION OF AN ANALYTICAL LABORATORY
 Jack C. Dice, Denver, Colorado Water Department
- Noon LUNCH
- 1:30 p.m. CHARACTERIZING THE SYSTEM—BASELINE MONITORING
 William G. Richards, Roy F. Weston, Inc.
- 2:15 p.m. IOWA'S LEAD IN SCHOOL'S DRINKING WATER PROGRAM: MORE THAN JUST A
MONITORING PROGRAM
 Rita M. Gergely, Iowa Department of Public Health
- 2:45 p.m. BREAK
- 3:15 p.m. INTEGRATING WATER TESTING AND OCCUPANCY CERTIFICATION
 Tom Bailey, Durham, North Carolina Department of Water Resources
- 3:45 p.m. EVALUATING CHEMICAL TREATMENT TO REDUCE LEAD IN A BUILDING:
A CASE STUDY
 Thomas J. Sorg, Risk Reduction Engineering Laboratory, U.S. EPA
- 4:15 p.m. CORROSION CHARACTERISTICS OF MATERIALS
 Vernon L. Snoeyink, University of Illinois
- 4:45 p.m. ADJOURN

Tuesday, September 24, 1991

- 8:00 a.m. OVERVIEW OF CONTROL STRATEGIES
Mike Schock, Risk Reduction Engineering Laboratory, U.S. EPA
- 8:45 a.m. SECONDARY EFFECTS—CONFLICTS WITH CONTROL STRATEGIES
Richard H. Moser, American Water Works Service Co., Inc.
- 9:30 a.m. BREAK
- 10:00 a.m. OVERVIEW OF DIAGNOSTIC TOOLS FOR CORROSION STUDIES
Michelle M. Frey, Black & Veatch
- 10:30 a.m. IMPLEMENTING THE LEAD AND COPPER RULE AT THE STATE LEVEL
Lou Allyn Byus, State of Illinois EPA
- 11:00 a.m. STATE PERSPECTIVE
William F. Parrish, Jr., Maryland Department of Environment
- 11:30 a.m. LUNCH
- 1:00 p.m. SODIUM SILICATE FOR THE SIMULTANEOUS CONTROL OF LEAD,
COPPER, AND IRON-BASED CORROSION
Jonathan A. Clement, Wright-Pierce Engineers & Surveyors
- 1:30 p.m. ZINC ORTHOPHOSPHATE VS. pH ADJUSTMENT, AN OVERVIEW OF TEST
Al Ilges, Champlain, VT Water District
- 2:00 p.m. BENCH-SCALE CORROSION STUDIES AT BOULDER, COLORADO —
RESULTS AND EXPERIMENTAL SETUP
Brad D. Segal, City of Boulder Water Department
- 2:30 p.m. BREAK
- 3:00 p.m. REDUCING CORROSION PRODUCTS IN MUNICIPAL WATER SUPPLIES
John W. Allen, Chippewa Falls, Wisconsin
William F. Barry, Ayres Associates
- 3:30 p.m. SMALL WATER SYSTEM SOLUTION TO LEAD AND COPPER REGULATION
Victor Ertman, Cass Rural Water Users, Inc.
- 4:00 p.m. ARLINGTON'S EXPERIENCE WITH pH ADJUSTMENT AS ITS CORROSION
CONTROL STRATEGY
Travis Andrews, Pierce-Birch Treatment Plant, Arlington, Texas
- 4:30 p.m. METHODOLOGIES FOR ELECTROCHEMICAL CORROSION MEASUREMENT
Steve H. Reiber, University of North Carolina at Charlotte
- 5:15 p.m. OPEN DISCUSSION

Wednesday, September 25, 1991

- 8:30 a.m. *TWO CONCURRENT WORKSHOPS*
DESIGN CONSIDERATIONS FOR PIPE LOOP TESTING
Anne Sandvig, Economic and Engineering Services, Inc.
S. Boris Prokop, Economic and Engineering Services, Inc.
Mike Schock, Risk Reduction Engineering Laboratory, U.S. EPA
DESIGN CONSIDERATIONS AND PROCEDURES FOR COUPON TESTS
Chester H. Neff, Illinois State Water Survey
John Ferguson, University of Washington
- 10:15 a.m. WORKSHOPS REPEATED
- Noon ADJOURN

Appendix B Units and Conversions

Metric to inch-pound units

LENGTH

1 millimeter (mm)=0.001 m=0.03937 in.

1 centimeter (cm)=0.01 m=0.3937 in.=0.0328 ft

1 meter (m)=39.37 in.=3.28 ft=1.09 yd

1 kilometer (km)=1,000 m=0.62 mi

AREA

1 cm²=0.155 in.²

1 m²=10.758 ft²=1.196 yd²

1 km²=247 acres=0.386 mi²

VOLUME

1 cm³=0.061 in.³

1 m³=1,000 L=264 U.S. gal=35.314 ft³

1 liter (L)=1,000 cm³=0.264 U.S. gal

MASS

1 microgram (μg)=0.000001 g

1 milligram (mg)=0.001 g

1 gram (g)=0.03527 oz=0.002205 lb

1 kilogram (kg)=1,000 g=2.205 lb

Inch-pound to metric units

LENGTH

1 inch (in.)=25.4 mm=2.54 cm=0.0254 m

1 foot (ft)=12 in.=30.48 cm=0.3048 m

1 yard (yd)=3ft=0.9144 m=0.0009144 km

1 mile (mi)=5,280 ft=1,609 m=1.609 km

AREA

1 in.²=6.4516 cm²

1 ft²=929 cm²=0.0929 m²

1 mi²=2.59 km²

VOLUME

1 in.³=0.00058 ft³=16.39 cm³

1 ft³=1728 in.³=0.02832 m³

1 gallon (gal)=231 in.³=0.13368 ft³=0.00379 m³

MASS

1 ounce (oz)=0.0625 lb=28.35 g

1 pound (lb)=16 oz=0.4536 kg

United States
Environmental Protection Agency
Center for Environmental Research Information
Cincinnati, OH 45268

Official Business
Penalty for Private Use
\$300

EPA/625/R-93/001

Please make all necessary changes on the below label,
detach or copy, and return to the address in the upper
left-hand corner.

If you do not wish to receive these reports CHECK HERE :
detach, or copy this cover, and return to the address in the
upper left-hand corner.

BULK RATE
POSTAGE & FEES PAID
EPA
PERMIT No. G-35