# Secondary Impacts of Corrosion Control on Distribution System and Treatment Plant Equipment

Subject Area: Infrastructure

# Secondary Impacts of Corrosion Control on Distribution System and Treatment Plant Equipment

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# Secondary Impacts of Corrosion Control on Distribution System and Treatment Plant Equipment

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# FOREWORD

The Water Research Foundation is a nonprofit corporation that is dedicated to the implementation of a research effort to help utilities respond to regulatory requirements and traditional high-priority concerns of the industry. The research agenda is developed through a process of consultation with subscribers and drinking water professionals. Under the umbrella of a Strategic Research Plan, the Research Advisory Council prioritizes the suggested projects based upon current and future needs, applicability, and past work; the recommendations are forwarded to the Board of Trustees for final selection. The foundation also sponsors research projects through the unsolicited proposal process; the Collaborative Research, Research Applications, and Tailored Collaboration programs; and various joint research efforts with organizations such as the U.S. Environmental Protection Agency, the U.S. Bureau of Reclamation, and the Association of California Water Agencies.

This publication is a result of one of these sponsored studies, and it is hoped that its findings will be applied in communities throughout the world. The following report serves not only as a means of communicating the results of the water industry's centralized research program but also as a tool to enlist the further support of the nonmember utilities and individuals.

Projects are managed closely from their inception to the final report by the foundation's staff and large cadre of volunteers who willingly contribute their time and expertise. The foundation serves a planning and management function and awards contracts to other institutions such as water utilities, universities, and engineering firms. The funding for this research effort comes primarily from the Subscription Program, through which water utilities subscribe to the research program and make an annual payment proportionate to the volume of water they deliver and consultants and manufacturers subscribe based on their annual billings. The program offers a cost-effective and fair method for funding research in the public interest.

A broad spectrum of water supply issues is addressed by the foundation's research agenda: resources, treatment and operations, distribution and storage, water quality and analysis, toxicology, economics, and management. The ultimate purpose of the coordinated effort is to assist water suppliers to provide the highest quality of water economically and reliably. The true benefits are realized when the results are implemented at the utility level. The foundation's trustees are pleased to offer this publication as a contribution toward that end.

David E. Rager
Chair, Board of Trustees
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Robert C. Renner, P.E.
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# EXECUTIVE SUMMARY

## OBJECTIVES

The objective of the project was to assess distribution system and treatment plant equipment failures or problems that occur from water quality adjustments made for corrosion control. The study focused on distribution systems and plant infrastructure including valves, meters, impellers, and pumps. In addition to corrosion control treatment, related treatment processes that affect metal loss, scaling, and precipitation were studied. After assessing the extent of the problems, the project recommended guidance for how utilities should address the secondary effects.

## BACKGROUND

The primary objective of corrosion control treatment is to suppress the release of metals from the distribution system, in particular to ensure that lead and copper levels do not exceed permissible levels. After the Lead and Copper Rule (LCR) was passed, corrosion control treatment has been used much more frequently and with a regulatory emphasis. Whereas in the past, utilities could adopt corrosion control and monitor its progress on their own schedules, now they may be faced with implementation of the LCR and the need to manage secondary effects on shorter timetables.

Secondary impacts that occur from this treatment process are effects other than those intended by the primary objective, which is corrosion control. Secondary effects could relate to water quality as well as distribution system infrastructure, but the focus of this project is on the processes of metal release, scaling, and precipitation. For example, drinking water utilities in the Midwestern United States have reported pump failures and hot water system problems attributed to scaling after a water quality adjustment was made at the plant to control internal corrosion in the distribution system. These reports of pump failures and hot water system problems were thought to be indicators of more widespread problems. Therefore, utilities need to determine the extent to which corrosion control affects equipment failure and how widespread this problem is.

## APPROACH

The team included specialists in water supply infrastructure, aquatic chemistry, and hydraulic equipment. Its research approach was to interview and survey knowledgeable and experienced people, to interpret the water chemistry that caused secondary effects, to analyze system management issues that affected the secondary effects, and to explain solutions to the problems that were found.

An in-depth reconnaissance was made to assess the extent of the potential secondary effects, evaluate and report them, and explain how they were mitigated. The team cast a wide net to locate utilities and individuals with knowledge of scaling and deposition episodes. They interviewed or surveyed a range of regulators and utility experts as well as a number of researchers. This effort showed that non-regulatory operational issues involving water chemistry are poorly documented for utilities, regulators, and researchers. Without a regulatory driver,



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there may be poor characterization of water chemistry and conditions that cause distribution system problems, with the result that prediction and mitigation are seriously hindered.

The sequence of research tasks included organizing the advisory panel, studying the background literature, developing a technical guide to the secondary effects, preparing surveys and interviews, performing equipment analysis, reviewing utility corrosion control histories, interpreting survey and interview results, and preparing the final report. In addition to the initial screening processes, surveys, and interviews, a final survey was performed to verify the results.

## RESULTS/CONCLUSIONS

While corrosion, scaling, and precipitation occur on a widespread basis, most utilities do not focus on them until problems occur. It is difficult to find experts in a utility with knowledge of these effects and the responsible managers are likely to be treatment and water quality staff or operations managers for both treatment and distribution systems.

Of the 50 state governments surveyed, 21 replies were received and some included reports from several regions. When earlier contacts are included, this increased the number of states from which the team received some information to 30. The final survey added another 22 state regulator contacts, in some cases from the same states. Responses from state regulators were mostly "we have not heard of those problems" or "we will get the word around, and if we find anything, we will be in touch." In a few cases, regulators led the team to utilities with significant scaling problems.

Methods to assess utility problems included questions to AWWA committees and utility representatives, utilities with experience with the LCR, experts in internal corrosion, and utility representatives at conferences. Of about 150 utility surveys, some 60 replies were received. When all utility contacts and information sources are combined, the project results sampled some 250 to 300 utility experiences.

Utilities are concerned with their ability to meet demands and are aware of clogging and the need to flush and renew pipes. However, limited knowledge of scaling problems seems to exist, especially among smaller utilities. Utilities seem to assume that problems are inevitable and they can do little other than maintenance and renewal. One exception comprises the utilities that use pH control to create calcium scales to passivate pipe surfaces.

The secondary effects clustered around the dominating metal species involved, or calcium, aluminum, iron, and manganese. Calcium effects are most common in corrosion control treatment, but aluminum effects can also occur from changes in pH and from use of inhibitors. While iron and manganese effects do not always result directly from corrosion control treatment, they are interrelated with other effects on corrosion and deposition.

Calcium effects create the main fast-developing problems. Although these effects are widely-recognized, project surveys turned up little awareness of the specific nature of problems from calcium scaling. Significant effects were only reported by 9 of some 60 utility replies. In some cases, the calcium effects were reported in association with iron and/or manganese, showing how problems can be mixed in nature. This long-standing problem seems to be accepted among utilities and considered as part of the "aging infrastructure" issue unless it has reached a critical stage.

The ability of calcium compounds to remain in solution is very sensitive to pH changes and the few serious calcium problems that were identified occurred suddenly due to pH shifts. Even if such episodes result from corrosion control treatment, they may not look different from

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those that occur from other treatments, such as softening, that have been in use for many years. Utilities where calcium scaling is an ongoing problem have usually recognized it and already dealt with problems such as lower C factors and the need for pipe renewal.

Aluminum scaling can also occur from water quality adjustments used in corrosion control programs and can cause significant loss of capacity in water pipes. A number of historical reports about capacity losses from aluminum scaling are in the literature and are usually identified with reduced flow coefficients that caught utilities by surprise because the capacity loss seemed out of proportion to the thickness of the scale. The aluminum effects identified during the project were similar to those reported historically. While several utilities reported that aluminum scales were found, the most useful reports came from either published literature or information supplied to the project team from utilities that had studied the problem themselves. Utilities that had experienced significant problems had usually studied them and made their own adjustments.

Iron corrosion is the best-known of internal corrosion problems in pipes because it was recognized many years ago. It is not a direct effect of corrosion control treatment, but it might be related to the scaling and precipitation of other compounds that occur. Manganese scales and precipitates are also of concern to water distribution systems, but they are not generally associated with corrosion control. Manganese is normally in source waters and is affected by oxidation. It can be removed before entering distribution systems, but once it is there, it can be entrained and discharged with treated water supplies.

The potential consequences from secondary effects resulting from water quality adjustments for corrosion control are pipe scaling and clogging; inoperable valves, pumps, and meters; water quality changes causing red, yellow, or black water; and release of constituents and transport of released materials.

## APPLICATIONS/RECOMMENDATIONS

Internal corrosion, scaling, and precipitation in pipes and hydraulic systems are significant problems for water supply utilities, but the extent of their impact is not known in general. Detecting and remediating them presents a challenge to utilities because they are not easy to detect and measure, much less solve. It is important to respond to long-term as well as sudden problems.

Long-term issues require effective condition assessment programs as part of utility asset management systems. The utility should designate a single manager to be in charge and evaluate scaling problems because unless the cause of problems can be determined, remediation programs cannot be effective. A study may be required to evaluate corrosion effects, pipe coupons, loss of pipe capacity, valve problems, pump seizures, hydrants, colored water, hot water problems, plugged injectors, and other symptoms. It may be necessary to mount pilot- or full-scale studies of treatment changes and pipe responses. Remediation can also involve treatment changes for softening, coagulation, and changes in chemicals. Remediation will typically involve case-by-case analyses of the causes and remedies.

The utilities highlighted in the report found solutions through multiple approaches that involved uni-directional flushing, pH adjustment, change in chemical additives, re-plumbing of systems, cleaning and lining, and pipe replacement. Selecting among these options involves careful consideration by utilities of the benefits and costs of each in terms of all utility objectives, including water quality, hydraulics, customer service, and utilization of workforce.

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On a long-term basis, control of internal corrosion and scaling requires continual monitoring, adjustment, and assessment of results. Internal corrosion and scaling are as much water quality issues as they are infrastructure issues and their analysis and control are an organization-wide concern.

Where utilities experience unexpected calcium scaling and/or precipitation problems, they must perform studies to determine the relationships among pH and other treatment parameters and rates of scaling and/or precipitation. Then they can make the proper adjustments, keeping in mind the need for lead and copper control. As with calcium problems, remediation of aluminum problems normally involves pH control or change in inhibitors. No single solution will work in every case and utilities must conduct site-specific studies, possibly including pipe loop experiments, to probe the causes of problems and their solutions.

## RESEARCH PARTNER

U.S. Environmental Protection Agency

## PARTICIPANTS

Thirteen utilities from throughout the United States participated in this project.

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# CHAPTER 1
# INTRODUCTION, BACKGROUND, AND SCOPE

## SECONDARY IMPACTS OF CORROSION CONTROL TREATMENT

Corrosion control treatment is an established voluntary utility strategy to suppress corrosion on the walls of distribution pipes. After the Lead and Copper Rule (LCR) was passed, corrosion control treatment has been used much more frequently and with a regulatory emphasis. Whereas in the past, utilities could adopt it and monitor its progress on their own schedules, now they may be faced with implementation of the LCR and the need to manage secondary effects on shorter timetables.

Corrosion control treatment deals mostly with inorganic substances in distribution systems, and these were summarized in a recent White Paper for USEPA's review of the Total Coliform Rule (HDR Engineering, Inc. et. al., 2006). The substances addressed in that report were termed contaminants, but inorganics can include other substances as well. The connection between research on secondary effects and that on inorganic contaminants is important to recognize, however, because the same processes that influence inorganics as contaminants govern scaling and secondary effects that affect hydraulic systems.

The work summarized in this report is from a study of "Secondary Impacts of Corrosion Control on Distribution System and Treatment Plant Equipment." These secondary impacts refer to corrosion, scaling, and precipitation of materials that affect the capacity and performance of water distribution pipes, treatment plant equipment, and controls and meters in water supply systems.

The primary objective of corrosion control treatment is to suppress the release of metals from the distribution system, in particular to ensure that lead and copper levels do not exceed permissible levels. The "secondary impacts" (or effects) means impacts other than those intended by the primary objectives. In the case of corrosion control under the LCR, a secondary effect might be excessive scaling that clogged a pipe or prevented a valve from operating. Other secondary effects may involve changes in water quality.

The need to investigate these possible effects is explained by this statement from the Request for Proposals (RFP): "Drinking water utilities in the mid-west United States have reported pump failures and hot water system problems attributed to scaling after a water quality adjustment was made at the plant to control internal corrosion in the distribution system" (AwwaRF, 2006).

These reports of pump failures and hot water system problems were thought to be indicators of more widespread problems, and the RFP stated: "There is a need to determine the extent to which corrosion control affects equipment failure and how widespread this problem is." This requirement addresses the issue that the extent of the problem was unknown and research was needed to find out how widespread the hydraulic failures might be.

The RFP also stated: "If this assessment project demonstrates that this is a common occurrence for drinking water utilities, further research efforts would be necessary to provide guidance to utilities on how to mitigate these secondary effects of corrosion control." This part of the project addresses the need to formulate and transfer lessons learned to enable other utilities to avoid the problems that some experienced.



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Based on these problem statements, the RFP provided the following project objective: "This project would conduct an assessment of distribution system and treatment plant equipment failures or problems that occur as a result of water quality adjustments made for corrosion control." Also, "The research should focus on distribution systems and plant infrastructure to include valves, meters, impellers, and pumps."

This report presents the project findings and offers guidance for application of methods to reduce secondary impacts.

## EXAMPLES OF SECONDARY EFFECTS

The corrosion control treatment that is the focus of the study arises from the 1991 Lead and Copper Rule. Therefore, the experience base to be assessed is nominally the period after the rule was implemented. However, the research showed that a number of utilities experienced similar effects prior to 1991, and these are also explained in the report.

One Water Research Foundation study concluded that secondary effects from the LCR were relatively minor (Reiber, et. al., 1997). However, the secondary effects it referred to were water quality phenomena like taste and odor, regrowth of microbial organisms, nitrification, changes in DBPs and HAAs, and composition of sludge. The objective of the project was to use utility experiences to compile strategies to mitigate lead and copper corrosion by-products. The work involved surveys to over 2,000 utilities and follow-up interviews. The work did confirm the importance of finding the optimum point of high pH and low alkalinity to mitigate lead corrosion and it provided information on the effectiveness of some inhibitor strategies. It illustrated how, although corrosion control is more art than science, utilities can use experiences of others as guides to action. The report did not concentrate on scaling effects such as were studied in this project.

Corrosion control treatment focuses on use of pH control and use of additives to suppress corrosion of metals and their release. Utilities and experts view corrosion control treatment as part of a mix of treatment strategies meant to accomplish both regulatory and distribution system goals. Therefore, it is necessary to consider treatment strategies other than pure corrosion control to have a clear picture of the general issues of corrosion and scaling. For example, water softening can involve pH control, which is also a corrosion control treatment strategy, and softening was used for many years before the LCR.

Another example of treatment actions, in this case with the goal of passivating pipe surfaces to inhibit corrosion, is the deliberate use of scaling films. This has been practiced for many years, particularly to protect bare surfaces of unlined cast iron pipe. These passivation strategies are, for all practical purposes, the same as those used in more recent corrosion control treatment.

As a result of these realizations, the team determined early in the project that it had to consider a range of treatment methods that cause effects similar to those of corrosion control treatment rather than only study utilities that implemented corrosion control since the 1991 LCR. This range of treatment methods and historical experiences offers a rich base of knowledge to augment the more recent data. Thus, the secondary effects to be studied included any corrosive or erosive experiences and any deposition that occurs, whether from scaling or precipitation. These points will be explained further in Chapter 2.

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In addition to a range of treatment processes, the project considered all types of pipe and components in treatment plants and distribution systems with problems from corrosion and scaling (examples include valves, meters, pumps, and measurement devices).

The team learned early in the project that presenting a clear picture of secondary effects was important in explaining the project to utilities. This is illustrated by Figure 1-1, which shows the three sets of issues studied. One set is the secondary effects themselves, represented by scaling, precipitation, and impacts on hydraulic infrastructure. The second set is the corrosion and erosion effects that may occur sequentially with deposition processes. These can include scaling and precipitation by different mechanisms. The last set of issues is the driving forces, the treatment changes, the sources of metals, the source water issues, and the materials that interact with water during the course of secondary impacts. These three sets of issues define the scope of the project.

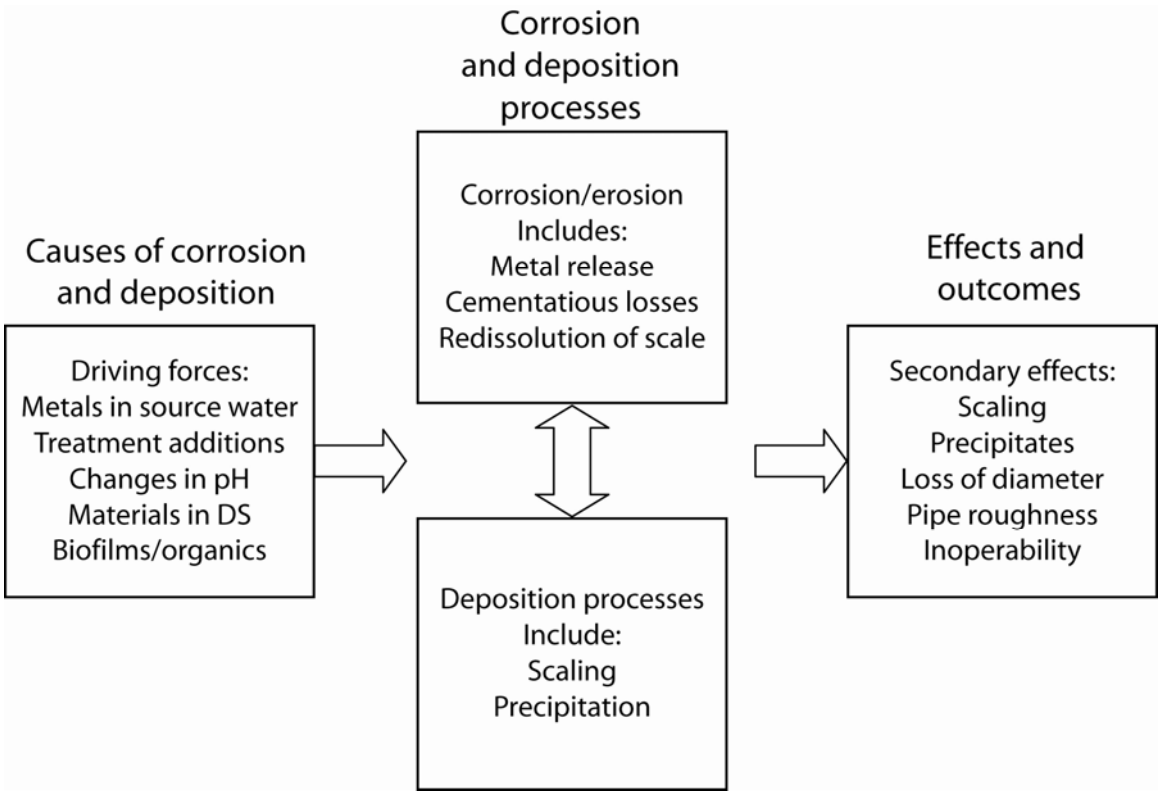


**Figure 1-1. Issues to define the project scope**

In addition to the causes, processes, and effects, the project reports on remediation strategies. Rather than a generalized approach to these, it reports on successes that were obtained by utilities that faced and overcame the secondary effects.

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## HOW SECONDARY EFFECTS OCCUR

### Why an Explanatory Model?

The research in this project showed that secondary effects occur on a widespread basis, but most utilities do not give major attention to them because they represent an insidious threat, and can be ignored without serious consequences unless something sudden happens, such as failure of a pump or complete loss of water service. Because it is difficult to explain the wide range of secondary effects, an explanatory model of how they occur will help.

This is the same issue that led the authors of the inorganics paper for EPA to create a diagram to explain their pathways as contaminants (HDR, Inc. et. al., 2006). Their conceptualization of these pathways and reservoirs is shown in Figure 1-2. The diagram is relevant to this project because it shows scaling agents, such as calcium, along with other contaminants, and it illustrates that materials balance within a pipe system includes contaminants and non-contaminants alike.

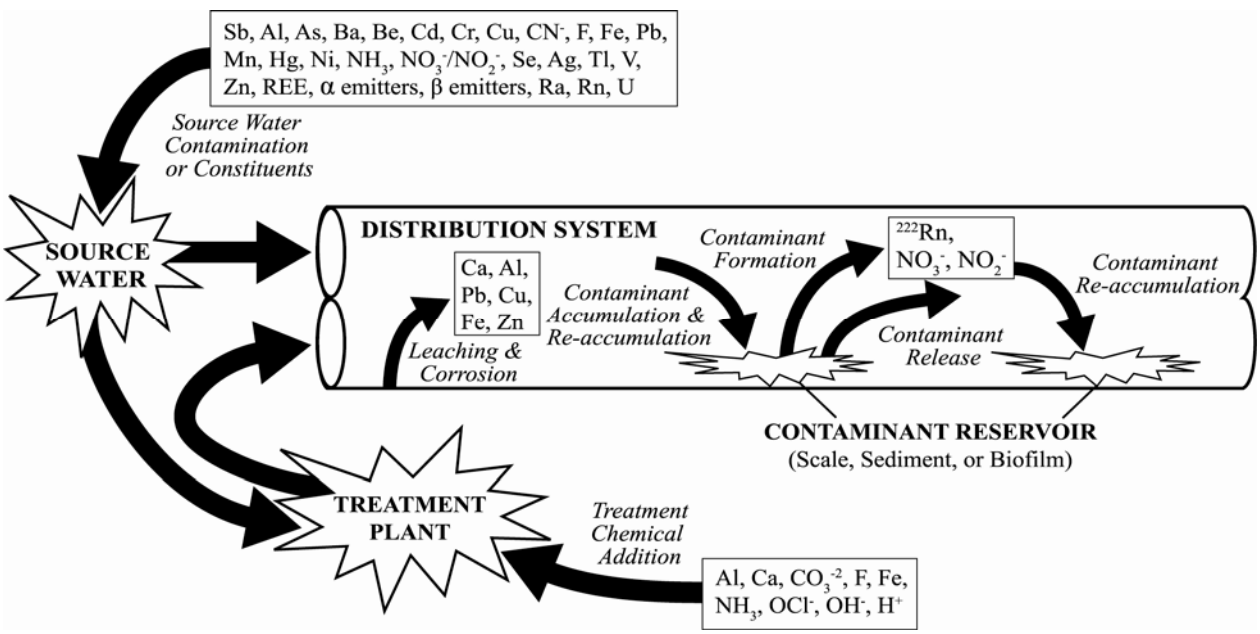


**Figure 1-2. Conceptual overview of inorganic contaminant pathways and reservoirs (Source: HDR Engineering, et. al., 2006).**

Secondary effects are impacts on hydraulic components caused by water treatment processes that have other primary objectives. For example, if corrosion control treatment is to prevent release of lead, then secondary effects will be any deposition from unwanted scaling or precipitation. To explain the secondary effects, three sets of variables are required: the secondary effects themselves, the corrosion and/or deposition processes, and the driving forces in the form of treatment changes and/or other hydraulic conditions. This systems problem shows that a treatment plant determines the quality of water that enters a distribution system, but the water quality has secondary effects on the distribution system infrastructure. In turn, the secondary effects have impacts on the water quality such as to alter water chemistry or change mineral content from adsorption and/or release of metals to the water.

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## Materials Balance in Source, Treatment, and Distribution Systems

Secondary effects involve physical, chemical, and biological changes in the distribution system or in water-handling equipment. Solid or dissolved materials move through the source water–treatment–distribution system and into premise plumbing systems with complex changes in the balance of chemical and sometimes organic constituents. The materials are metals and compounds that precipitate or deposit scale materials on the surfaces of pipes, components, or hydraulic machinery within distribution systems, treatment plants, or equipment.

Figure 1-3 shows the sequence of how these effects occur. Source water may contain metals such as aluminum or iron. Compounds such as aluminum or calcium may be added during treatment. In the distribution system, metal compounds may be leached and re-deposited, as for example, lead leached from fittings and deposited as lead scales. Scale may change through re-equilibration, a chemical change that might make metal compounds more soluble.

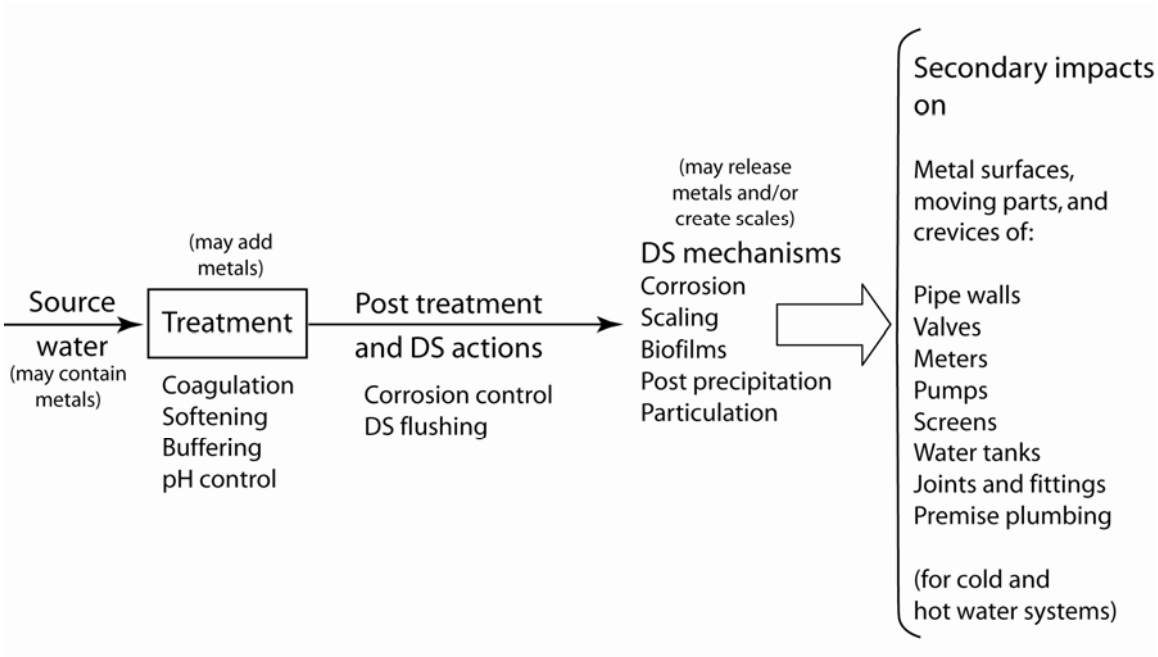


**Figure 1-3. Materials balance through a drinking water system**

In the USEPA White Paper, the authors drew from Schock (2005) and explains how contaminants enter the water: in dissolved state; attached to particulate matter; added by treatment chemicals; by-products of corrosion; or cross-connections or compromise of the distribution system (HDR, Inc. et. al., 2006).

While water supply systems all involve the conceptual source-treatment-distribution phases, they differ greatly in complexity and configuration. Imagine the difference in conditions in a large city system, perhaps with multiple water sources, and a small system consisting of a well, a chlorinator, and a few pipes. As we explain later, some of the problems that were found were in these small and simple systems, whereas some of the insidious and slow-developing problems seemed to be in the larger systems.

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## Classification System of Secondary Effects

In our data collection, surveys, and interviews (see Chapter 3) the reports formed patterns clustering around the dominating metal species involved. Thus, we developed a classification system of secondary effects related to calcium, to aluminum, and to iron and manganese. Of course, scale can contain combinations of these, as well as other metals and compounds. In any case, by classifying the effects, we are able to explain them to interviewees and experts and receive more organized review and feedback. Thus, the conceptual model can be applied to the separate elements and to their combinations.

## Source Water

Source water chemistry is a starting point to explain changes in mineral content as water passes from source to treatment to distribution. Water quality attributes of source water, such as pH, calcium, alkalinity, iron, aluminum, manganese, and total dissolved solids (TDS) are important to the onset of scaling. The knowledge base on source water and scaling is discussed in Chapter 2.

## Water Treatment and Secondary Effects

The primary treatment processes that affect corrosion control are those that raise or lower pH or are aimed at passivating or sequestering corrosion products. Water treatment technologies involve many complex physical, chemical, and biological phenomena and are explained in textbooks such as (Hendricks, 2006). The processes that seem most implicated in secondary effects are coagulation, softening, pH control, and passivation and sequestration.

Coagulation usually involves addition of aluminum salts, which can lead to aluminum precipitates and scales. Softening uses precipitation of calcium and magnesium, which can lead to post precipitation and scaling problems, so recarbonation is often used for pH control to stabilize the precipitates. The process of pH adjustment can occur through addition of various chemicals, and passivation and sequestration can be done through various means as well (Baruth, 2005).

## Distribution Systems and Secondary Effects

Although water treatment actions take place upstream, the distribution system is actually a water quality reactor where physical, chemical, and biological effects go on continually.

Examples of distribution system mechanisms include:

- Physical mechanisms: scour and direct impacts and impingement on surfaces
- Chemical mechanisms: oxidation, temperature changes, chemical reactions
- Biological: formulation and dissolution of biofilms

The actual effects that occur in the distribution system include corrosion and scaling, any formation of biofilms, and any related metal or material loss or deposition. These are discussed in Chapter 2. These effects occur on metal surfaces, moving parts, and crevices of all infrastructure components used in water treatment and conveyance including both hot and cold water. They may occur in on pipe walls; valves, meters, pumps, screens, and fittings, including

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all surfaces where water and metals come into contact; and in water tanks. These effects occur within the distribution system, in service lines, and within premise plumbing systems.

Flushing is a special kind of distribution system mechanism in that it creates higher velocities within pipes and can lead to changes in physical, chemical, and biological conditions.

## RESEARCH TASKS

Given the project objectives to "determine the extent to which corrosion control affects equipment failure and how widespread this problem is," as well as to "…provide guidance to utilities on how to mitigate these secondary effects of corrosion control," the project team developed tasks that included:

- Background studies to learn about secondary effects already reported
- Equipment analysis to study components that are vulnerable to secondary effects
- Assembly of an expert advisory panel
- Identification of interviewees and survey respondents
- Technical guide to explain project scope and issues
- Development of utility corrosion control histories to build a file of case studies
- Development of survey instrument
- Conduct survey and interviews
- Compile and interpret survey and interview results
- Reporting

Pursuing these objectives led to a four-phase research project:

- Phase 1: Creating the advisory panel, clarifying the survey respondents, examining background studies, performing hydraulic equipment analysis and developing a technical guide.
- Phase 2: Reviewing utility corrosion control histories, developing the survey instrument, performing the survey and interviews, and conducting further hydraulic infrastructure analysis.
- Phase 3: Compiling and interpreting surveys and interview results.
- Phase 4: Preparing the final report.

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# CHAPTER 2
# KNOWLEDGE BASE OF SECONDARY EFFECTS FROM CONTROL OF INTERNAL CORROSION

## SECONDARY EFFECTS KNOWLEDGE BASE

This chapter summarizes the knowledge base of secondary effects and is organized by the driving forces, corrosion and scaling process, and secondary effects in water supply. Driving forces include treatment changes, sources of metals, source water issues, and materials that interact with water. The corrosion, erosion, and deposition processes are those that lead to scaling and precipitation, and their impacts on hydraulic infrastructure.

In addition, remediation strategies to overcome secondary effects are introduced in this chapter, and described in more detail in Chapters 4 and 5.

Because knowledge about secondary effects is scattered, several knowledge bases must be assessed to characterize it. In this report, the secondary effects focus on scaling, which received little if any attention at the Water Industry Technical Action Fund (WITAF) workshop on secondary effects (AWWA, 2005).

The model of secondary effects presented by Figure 1-2 serves to organize the background information. The figure illustrates a systems model that includes source water, treatment, post-treatment actions, distribution system mechanisms, and secondary effects themselves. Variables reported in the literature and by utilities range across all of these categories.

The model leads to a set of research questions that were used to frame the project interviews and survey. These are shown on Figure 2-1 and illustrate how the knowledge about secondary effects resides among different functional groups in utilities, including treatment, engineering, and laboratory staff.

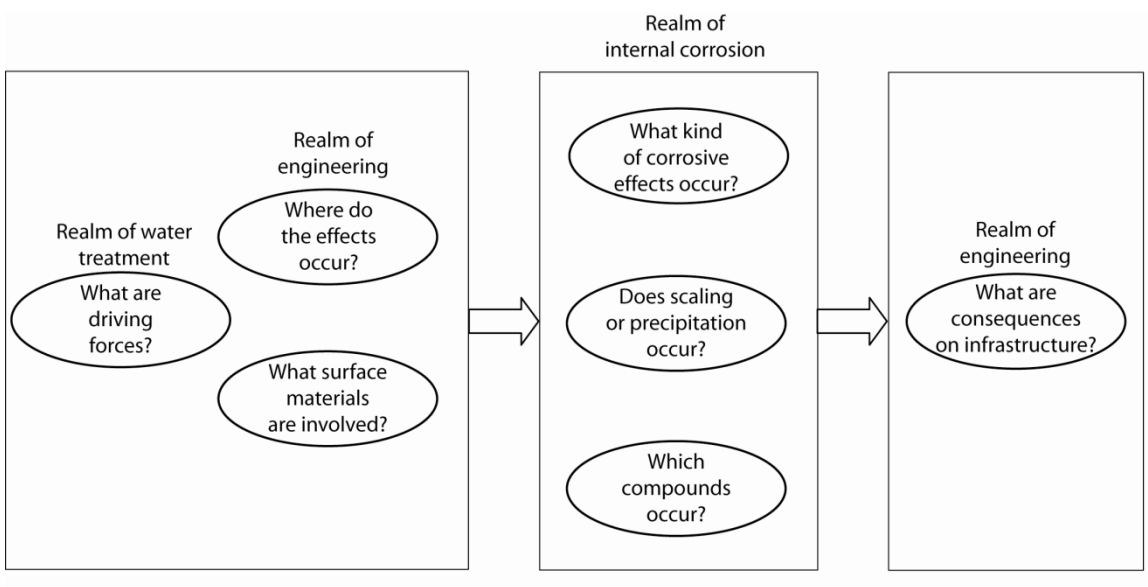


**Figure 2-1. Categories of questions about causes and nature of secondary effects**



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The set of research questions is:

- What driving forces cause secondary effects? (Source water and treatment processes)
- Where do the effects occur (pipe, valve, meter, pump, etc.)? (Engineering and O&M literature)
- What surface materials are involved and what is their condition? (Surface science, surface chemistry)
- What is the nature of the corrosive effects? (Internal corrosion)
- How do the scaling and/or precipitation occur? (Inorganic chemistry)
- Which chemical and/or organic compounds are involved? (Aquatic chemistry, water quality)
- What are the consequences of the effects (pipe roughness, change in diameter, inoperability, etc.)? (Engineering and O&M literature)

Each research question involves a separate knowledge base and together they show the systems nature of the problem.

## Consequences of Secondary Effects

The LCR was implemented in the early 1990s, and a WITAF workshop signaled its consequences with this statement: "Actions intended to improve water quality produce serious unintended consequences – especially in the areas of corrosion, stability of existing pipe scales, and aesthetics" (AWWA, 2005). Also, the report explained how: "Optimum corrosion control treatment requires utilities to strike a careful balance among challenging and often conflicting water quality goals for lead and copper solubility, coagulation and softening, disinfection, disinfection byproducts, aesthetic quality, phosphorus, and other water quality parameters."

The WITAF workshop report focused on general effects, rather than, specific examples. It's recognition of the need a careful balance helps explain why in our research we found it necessary to cover possible effects from treatments other than CCT, including coagulation, softening and interactive effects.

The secondary effects we noted from the literature review focus on scaling on the walls of pipes, which exacerbates pipe clogging. Clogging of pipes with precipitated material that is more voluminous than the scale that adheres to walls and surfaces also occurs. Increased energy use is evident from pipe scaling, clogging, and from impaired pumps. Also, inoperable components result from scaling, such as valves that will not shut or open, meters that are seized up, and pumps that will not work. Water quality changes can include red and black water or release of other constituents related to internal corrosion, erosion, scaling, deposition, and transport of released materials.

## Source Water, Treatment, and Distribution System Conditions

The driving forces of secondary effects include source water chemistry, treatment changes, where the effects occur in water systems, conditions in distribution systems, and corrosive effects of water on materials. Schock (2005) explained how the usual assumption that the inorganics are conservative as they move through systems may not be valid. The USEPA inorganics report (HDR, Inc., et. al., 2006) explained how reservoirs of inorganics accumulate,

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including scales, biofilms, and sediment. A number of Water Research Foundation reports about internal corrosioin explained control variables that determine the degree of accumulation and how scales and precipitates can involve corrosion products and other deposits.

## Source Water Influence on Scaling

The RFP's focus on drinking water utilities in the Midwest suggests that source water chemistry by region might be a significant factor in scaling problems. Source water chemistry can help explain changes in mineral content as water passes from source to treatment to distribution. Source water often contains significant quantities of calcium compounds, and the calcium system is perhaps the dominant cause of secondary effects. It is used to express chemical equivalents causing hardness and alkalinity, two widely-reported parameters that come into play in secondary effects.

Two widely-reported parameters that come into play in secondary effects are hardness and alkalinity. The pH level is also very important. Water hardness is defined in terms of ion concentrations that will react with a sodium soap to precipitate in an insoluble residue, and mainly measures calcium and magnesium constituents. Alkalinity measures the water's capacity to neutralize strong acid and is defined in terms of the quantity of base type compounds in the water (Snoeyink and Jenkins, 1980). Total dissolved solids (TDS) also come into play. TDS is a measure of all dissolved chemical and organic solids, including calcium and magnesium. Both surface and groundwater contain dissolved solids in varying amounts.

Given the dependence of surface waters on local springs and tributaries, surface water chemistry can be similar to that of local tributary aquifers. When groundwater is pumped from deeper aquifers, its chemistry will probably be different and depend on the geology of the strata from which it comes.

Groundwater is generally harder than surface water because it remains in contact longer with soluble minerals such as limestone or dolomite. Underground $CO_2$ causes more $CaCO_3$ to be dissolved than in surface water, which is constantly exposed to air. Groundwater is also more amenable to dissolution of iron and manganese. Upon sudden exposure to air, groundwater may precipitate a white $CaCO_3$ and/or a rusty manganese or iron compounds.

USGS collects data and publishes summary reports on water chemistry. One report, Public Water Supplies of 100 Largest Cities in the United States (1962), is a comprehensive explanation of water chemistry around the nation (Durfor and Becker, 1964). Although it is over 45-years old, the information remains relevant.

USGS reports that the softest surface waters are in parts of the New England, South Atlantic-Gulf, Pacific Northwest, and Hawaii regions and the hardest surface waters (greater than 1,000 mg/L) are in Texas, New Mexico, Kansas, Arizona, and southern California. However, hard and very hard waters are found in some streams in most regions (Briggs and Ficke, 1977). Given that water chemistry depends greatly on geology, and while some regional generalizations are valid, there is too much intra-regional variation among ground and surface waters to categorize them definitively.

Groundwater chemistry is more difficult to classify than surface water because it varies so specifically with local geology. Geology varies greatly from place to place and within geological layers and it is impossible to generalize about local source water chemistry.

Surface waters tend to integrate the influences of different geological condition as flows are mixed by successive inflows, diversions, and effluents. Given this localized nature of

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groundwater chemistry, the team was unable to provide a general classification for source water by location and hardness. However, it is known from USGS that carbonate rock aquifers that are associated with hard water are most prominent in the central and southeastern US, but also occur in small areas as far west as southeastern California and as far east as northeastern Maine and in Puerto Rico (Miller, 1999).

The Midwest is characterized by many small towns that rely on groundwater. Therefore association of this region with possible secondary effects might relate to percentage of groundwater versus surface water use. This would be a good research hypothesis to test, but our results did not yield the data needed to test it.

The following information is summarized from the USGS publication (Durfor and Becker, 1964). The most common chemical constituents of water are silica, iron, manganese, calcium, magnesium, sodium, potassium, carbonate, bicarbonate, sulfate, chloride, fluoride, nitrate and other dissolved solids. In some areas, aluminum, boron and strontium are present in appreciable amounts.

Most natural water contains the alkaline earths of calcium and magnesium, which are the chief cations found in many waters. Carbonate and bicarbonate are found in most natural waters because of the abundance of limestone (mainly calcium carbonate) and dolomite (magnesium and calcium carbonates).

Several chemical constituents are known to cause scale and other secondary effects in water. For example, Table 2-1 reports effects that were summarized in the USGS reference (Durfor and Becker, 1964).

**Table 2-1. Constituents and effect on scales**

| Constituent | Effects |
|---|---|
| Silica ($SiO_2$) | Forms scales, especially in presence of calcium and magnesium in boilers and steam turbines |
| Iron (Fe) | Can precipitate on exposure to air causing stains |
| Manganese (Mn) | Can precipitate on oxidation. Affects taste, causes stains, and fosters growth in water systems. |
| Calcium (Ca); Magnesium (Mg) | Combines with bicarbonate, carbonate, sulfate, and silica to form scale in hot water systems. |
| Sodium (Na); Potassium (K) | In presence of suspended matter can cause foaming and accelerate scaling and corrosion in boilers. |
| Carbonate ($CO_3$); Bicarbonate ($HCO_3$) | Upon heating carbonate combines with calcium and magnesium to form a crustlike scale of $CaCO_3$. |

Water quality parameters that are widely reported do not measure chemical content directly, but instead use the measures of dissolved solids, hardness, and alkalinity, among others. Therefore, a study of scaling in a utility's system will require a look beyond these mainline parameters to the constituent compounds in its water. Gross parameters such as these, as well as indices of water stability, may not signal the nuances of water chemistry that cause scaling.

The conclusions from our inquiries about source water chemistry indicate that while there are regional trends, the diversity of ground and surface water sources is so great that it is not possible to make general statements about where source waters might favor secondary effects. The exceptions might be to identify similar trends in common aquifer areas and/or large surface water systems like the Great Lakes.

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## Treatment Systems

The main water treatment changes that influence secondary effects are coagulation, pH adjustment, addition of softening chemicals, and use of corrosion inhibitors. Other treatments, such as disinfection can be involved. Also, as is discussed later, chlorination affects the deposition of manganese.

Scaling that occurs today was signaled by earlier experiences that happened when treatment processes evolved and pipe scales and related effects started to occur. Observations about related effects such as tuberculation and pipe clogging date to before 1900. Treatment innovations in the late 19$^{th}$ Century focused on microbes and filtration, followed by introduction of chlorination in the early 1900s. By the 1960s, chemical contamination had increased and a survey in 1969 showed that only 60% of systems met standards of the day. This finding, along with other drinking water quality problems, led to the SDWA in 1974. Along the way, processes had been introduced for coagulation, softening, passivation of pipe surfaces, and treatment of problem waters (USEPA, 1999). Even early processes of coagulation, softening and pipe passivation created changes such as those that cause today's secondary effects. Therefore, the experience base with the effects we are studying really extends back to the earliest initiation of water treatment.

The modification to the SDWA that created most change was the 1991 Lead and Copper Rule. The LCR was implemented because high levels of lead availability in service lines and plumbing create the potential for lead release, and corrosive and hydraulic effects in pipes have the potential to mobilize the lead and release it to the drinking water. The chain of lead exposure begins when water with varying quality interacts with materials and components of distribution systems. Literature about the LCR includes many reports prepared during rule development. The underlying science has been summarized by Schock et. al. (1996) and Case (2007) presented a detailed review of Water Research Foundation research on corrosion and the LCR.

The strategy to control lead in drinking water is different from other rules because lead is derived more from corrosion of materials than it is from source water. Therefore, corrosion control treatment is usually implemented downstream of treatment plants. A lead "action level" of 0.015 mg/L (90$^{th}$ percentile), triggers a variable set of required responses, although the LCR goal is to reduce lead levels as far as possible. Treatment requirements are to make water as non-corrosive as possible as it leaves the plant. The sampling protocol for monitoring considers stagnation time, flushing, and installation conditions.

Implementation of the LCR is challenging because so many variables are involved. According to an EPA official, "Water chemistry is among the hardest to do. Water is the universal solvent, so everything is a contaminant, many of which then affect the physical properties of the water. How aggressive the water is in attaching the lead in pipes depends on the water composition" (Powell, 1999)

Results of any treatment strategy may conflict with other water quality goals, so operators must balance corrosion control with other goals. Secondary effects of the LCR were recognized early on. An AWWA (2005) publication on unintended consequences of the Lead and Copper Rule stated: "Actions intended to improve water quality produce serious unintended consequences – especially in the areas of corrosion, stability of existing pipe scales, and aesthetics." Also: "Optimum" corrosion control treatment requires utilities to strike a careful balance among challenging and often conflicting water quality goals for lead and copper

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solubility, coagulation and softening, disinfection, disinfection byproducts, aesthetic quality, phosphorus, and other water quality parameters."

Compliance with the LCR is generally high. As Table 2-2 shows, in 2007 the larger systems had few violations, and most violations are in smaller systems (data is for Community Water Systems and Non-Transient, Non-Community Water Systems).

**Table 2-2. Compliance data for Lead and Copper Rule in 2007 (USEPA, 2008)**

| | System size | | | | | Total |
|---|---|---|---|---|---|---|
| | Very small 25-500 | Small 501-3,300 | Medium 3,301-10,000 | Large 10,001-100,000 | Very large >100,000 | |
| Number violations | 1,220 | 292 | 54 | 21 | 1 | 1,588 |
| Number systems | 874 | 227 | 38 | 16 | 1 | 1,156 |
| Population affected | 127,063 | 294,819 | 215,428 | 429,139 | 271,853 | 1,340,302 |

In reviewing the literature on water treatment, we were struck with how little discussion there is about corrosion and scaling even though parameters such as pH, alkalinity, dissolved oxygen, and hardness can promote or inhibit corrosion. Dissolved materials such as phosphates, sulfates, and some trace metals also affect corrosion. Water softening affects metal solubility by changing pH and carbonate levels and forming hydroxide ions, which promote scales that passivate pipe surfaces.

Coagulation usually involves addition of aluminum salts, which can lead to aluminum precipitates and scales but the possibility that coagulation can cause scales is seldom mentioned, if at all, in textbooks. Softening uses precipitation of calcium and magnesium, which can lead to post precipitation and scaling problems, so recarbonation is often used for pH control to stabilize the precipitates. The process of pH adjustment can occur through addition of various chemicals, and passivation and sequestration can be done through various means as well (Baruth, 2005).

EPA began to conduct tests in 1979-81 to focus on orthophosphate and silicate effects in distribution systems (Schock, Wagner, and Oliphant, 1996). Later, McNeill and Edwards (2002) found that few utilities were using scientific tests to assess the best inhibitor and are relying on vendor data or tips from neighbor utilities.

Our conclusion from the literature on water treatment is that relatively little attention has been given to specific issues of scaling that may occur as secondary effects. Perhaps scaling in distribution systems is considered a less serious issue than health effects or it may be that the effects build up so slowly in most cases and/or are difficult to monitor and detect. In any event, it is difficult to find much guidance about them in the published literature.

## Where Secondary Effects Occur

While corrosion in cast iron pipe has been known longer than other problems, secondary effects related to corrosion control and other treatments can occur anywhere the water is in contact with surfaces of metal, cement, and plastic. These include pipes, valves, meters, pumps,

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screens, tanks, and any other components of water control infrastructure. They can occur in premise plumbing systems as well as distribution systems (USEPA, 1984; Neff, Schock, and Marden, 1987). Effects occur on metal surfaces, moving parts, and crevices of all components including those in both hot and cold water systems. Many types of plumbing systems are in place, varying from residential through commercial to large scale industrial systems. They involve changes in size, direction, materials, velocities, storage, water age, and temperature. These plumbing systems can be the sources of customer complaints, which is one way that utilities learn of scaling and related issues.

Secondary effects mainly occur in distribution systems. Although water treatment actions take place upstream, the distribution system is a water quality reactor where physical, chemical, and biological effects go on continually. Examples of distribution system mechanisms include physical (scour and direct impacts and impingement on surfaces); chemical (oxidation, temperature changes, chemical reactions); and biological (formation and dissolution of biofilms).

As this quote from EPA (2002) explains, hydraulic and chemical conditions within distribution systems are highly varied: "Many finished water quality problems result from interactions between water within the pipe and the pipe wall, and within the bulk water. Increasing water age increases the reaction time, allowing for additional formation of contaminants that can lead to adverse health effects. Increased residence time can allow for increased corrosion. Corrosion control methods involve phosphate inhibitors and pH management that can be adversely affected as residence time increases in poorly buffered waters. Corrosion of unlined cast iron can decrease chlorine residual levels."

The time of contact between water and pipe surfaces is important. As water travels to a tap, its trip begins with transmission and distribution mains, with exact routes not known. The general time of travel from source to customer is referred to as "water age," but exact age is not known, and actual water ages take on statistical distributions. How water quality varies in distribution systems is explained by Clark and Grayman (1996) and by Besner et. al. (2001, 2002). In spite of these studies, variation of metal concentrations in networks has not been studied much, if at all.

A few explanations of flow dynamics that might enhance dissolution or entrainment of particulate matter are available. These include a few model studies of particle transport in drinking water systems, notably at the University of Cincinnati (Lu, 1991; Sethi, et.al., 1993). One set of investigators tested pipe materials for resistance to cavitation erosion, and arrayed materials from most resistance to least resistance: stainless steel, brass, bronze, cast iron, and copper (Chan, Cheng, and Chow, 2002). They found that the synergistic effects of corrosion and erosion played an important role in materials used in cold water distribution systems.

## Surface Materials

The materials in water supply infrastructure systems range from the bare cast iron in early distribution systems to modern plastics, metal alloys, and coated materials. An estimate of the quantity of these materials is given in AWWA's 2002 Distribution System Survey, which showed the quantities of pipe in place that are indicated in Table 2-3 (AWWA, 2007):

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**Table 2-3. Pipe material in place**

| Pipe material | Miles in place (AWWA, 2002) | % of Total Miles of Pipe* |
|---|---|---|
| Ductile iron, CML | 35,118 | 19.7 |
| PVC | 29,835 | 16.6 |
| Asbestos cement | 30,484 | 15.2 |
| Cast iron, unlined | 37,433 | 14.4 |
| Cast iron, CML | 34,039 | 14.4 |
| Ductile iron, unlined | 9,886 | 4.3 |
| Steel | 7,821 | 3.8 |
| Concrete pressure | 4,774 | 1.9 |
| Polyethylene | 1,377 | 1.1 |
| Other | 11,391 | 3.0 |
| Misc/unknown | 6,000 | Unknown |
| Total | 202,158 | * |

* The statistics are from the surveyed utilities and are a sample, not including all pipe in the US. Data on % and miles in place were obtained separately and are not always consistent. Percentages do not add to 100 because of data inconsistencies.

As is evident from the table, the greatest exposure of pipe material to water is in cement lining, AC cement, and unlined cast or ductile iron pipe. The "other" categories can also represent significant sources of leachates. They included: galvanized iron, HDPE, wrought iron, black iron, copper, steel cylinder pipe, plastic, cement-stove, fiberglass (Permastrand), concrete lined steel cylinder, steel, arch concrete masonry, polybutylene, and unknown.

No definitive inventory of appurtenances exists. However, these include large numbers of control valves, storage tanks, hydrants, pumps, backflow preventers, joints and gaskets, distribution system and customer meters, and other types of valves, such as for blowoff, air release, etc. The valves include various metal alloys, plastics, and other materials.

Customer service lines reported in the survey were mostly copper (56.3%). Other materials were: Polyethylene (11.4%); Galvanized (8.0%); Polyvinyl chloride (5.8%); Lead (3.3%); Polybutylene (2.4 %); steel (1.5%); cast iron (1.2%); and other (2.3%). The other category included asbestos-cement, ductile iron, plastic, brass, wrought iron, Tubelog, cement lined wrought iron, KITEC (aluminum/PE composite), Tuballoy, and HDPE. No attempt has been made to identify all materials used in hot and cold water premise plumbing systems.

## INTERNAL CORROSION IN DRINKING WATER SYSTEMS

### Types of Corrosion

This discussion deals with internal corrosion where pipe and component surfaces are exposed to water. External corrosion occurs where the outside surfaces of buried pipes or other components are exposed to the soil or air environments and is a different issue.

Internal corrosion can be classified by:

Electrochemistry – Chemical or galvanic (dissimilar metals)
Location – External or internal

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| | | |
|---|---|---|
| Spatial characteristics | – | Uniform or pitting corrosion |
| Influence of microbes | – | Microbially-influenced corrosion (MIC) |
| Physical cause | – | Erosion corrosion, stress corrosion |

The basic corrosion mechanisms from metal surfaces are metal release and formation of corrosion products on the surfaces. Metals such as calcium and aluminum can be released from cement surfaces as well, and this can be also considered as corrosion or leaching.

Regardless of the mechanism (unless it only involves pure physical erosion) internal corrosion is caused by the chemical properties of the water coming into contact with surfaces. The resulting reactions create many complex combinations of metal compounds and biological constituents.

This list provides further detail on types of corrosion and their mechanisms:

- Galvanic corrosion occurs when dissimilar metals are connected and create components of an electrochemical cell. Galvanic reaction is caused by difference in potential, area and proximity of metals, and chemistry of the water. Galvanic potential for metals is ranked from less noble metals to more noble metals that tend to become cathodic. An example is a brass fitting connected to a galvanized iron pipe (MWH, 2005). This type of corrosion can occur internally along a pipe wall.
- Uniform and pitting corrosion depend on proximity and size of corrosion cells. In uniform corrosion, the surface corrodes over a uniform area. Small reaction areas are spaced uniformly.
- In pitting corrosion, localized holes form along pipe walls. Pits can be associated with scratches, surface deposits, or other imperfections. Pitting corrosion can be influenced by oxidizing potential of the solution, presence of aggressive ions, and the condition of the metal surface. Once a pit is formed, the area around it becomes cathodic and suppresses additional pit formation. Pits are usually widely spaced within the pipe (MWH, 2005).
- In microbially-influenced corrosion (MIC), organisms such as bacteria or algae influence the formation of corrosion products on pipe surfaces. Bacteria beneath tubercles or in crevices can resist chemical treatment (MWH, 2005). MIC appears to be an important factor in copper corrosion (Bremer, Webster, and Wells, 2001).
- Erosion corrosion is mechanical removal of protective layers through abrasive action of water and debris. It might occur among waves or grooves in pipe walls. Flow paths involve velocity changes, sharp edges, pressure fluctuations and other dynamic changes. Materials that are weakened by chemical action or subjected to stress may be released due to erosive forces.

Corrosion control methods vary with type of corrosion. Examples of strategies are (Hill, 2007):

- Uniform Corrosion—Carbonate passivation (formation of metal complexes on pipe surface) and orthophosphate inhibitor addition
- Pitting corrosion—pH and DIC control

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- Microbially-influenced corrosion—Limit nutrients, maintain adequate residual, and reduce stagnation/water age
- Galvanic corrosion—eliminate contact between dissimilar metals
- Erosion corrosion—hydraulic controls

Corrosion products can form through various oxidation mechanisms, and the type and location of precipitates from pH adjustment can vary widely depending on chemical dosages. Examples might be $KMnO_4$ or $ClO_2$ oxidation to transform dissolved Mn or Fe to solid forms or manganese dioxide or manganese oxyhydroxide precipitation. Ferric oxyhydroxide precipitate might also result from oxidation. The source can be oxygen, the secondary disinfectant, or a kinetic issue to generate precipitates. Timing is an issue. One report was of a Ca-Al-Fe-phosphate precipitate, which might have nucleated on undissolved lime particles. Another report was of Ca-Zn-phosphates from inhibitor-based corrosion control systems. The pH change could be the main influence or a chemical-specific effect of the dosed chemical could play a role[1].

Other corrosion-related mechanisms might include re-equilibration of scale. This can occur from change in water chemistry, such as a change from chlorine to chloramines, which could reduce water oxidation reduction potential and change solubility of metals and increase dissolved metals concentrations. Adsorption and release can be involved where a liquid solute accumulates on the metal surface and forms a molecular film, and is released later (Hill, 2007).

## Internal Corrosion as a Field of Study

The study of internal corrosion in water mains blends the fields of corrosion and aquatic chemistry. Theory development leads to assessment of water chemistry, solubility diagrams and models. Tests include laboratory studies with pipe loop investigations and field data that use coupon studies and scale analysis. The interdisciplinary field of internal corrosion involves organic chemistry and fields such as surface chemistry and surface science, which study how particles attach to surfaces through chemical bonding and physical adsorption and lead to scaling.

Strictly speaking, the field of corrosion addresses the process whereby materials are degraded and released and does not include scaling. As a practical matter, scaling and precipitation are closely related to corrosion, however. Nevertheless, scaling and precipitation are not addressed extensively in AwwaRF's (1996) basic report on internal corrosion research, although Schock (1999) addresses it in a chapter on "Internal Corrosion and Deposition Control."

Knowledge about internal corrosion dates back many years and is scattered among fields of knowledge. Examples of research findings about internal corrosion can be found from studies of different materials, including iron, lead, and cement linings, as well as other metals. Prior to the SDWA, the major focus was on iron corrosion, about which a great deal is known. EPA initiated studies of internal corrosion in the 1980s and released a manual to explain it (Singley, Beaudet, and Markey, 1984). AwwaRF's 1996 report in cooperation with the German water association DVGW provides an extensive overview of internal corrosion mechanisms and effects

1 Credit to Michael Schock of EPA for providing these examples.

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(AwwaRF and DVGW-Technologiezentrum, 1996)[2]. It explains principles of corrosion, corrosion of different materials, mitigation, and assessments. Materials covered include iron, steel, galvanized, lead, copper, alloys, solders, and cements. This report is the most comprehensive reference that is available on internal corrosion in drinking water systems. Water Research Foundation has completed a number of additional projects about internal corrosion, which were summarized by Case (2007).

In addition to Water Research Foundation studies and related technical papers, some agencies, such as the National Drinking Water Clearinghouse, have published technical briefs on corrosion. However, these are synthesis documents and normally do not introduce new knowledge.

AWWA plans to issue Manual M58 entitled: "Assessment and Control of Internal Corrosion and Increased Metals Concentrations in Drinking Water Distribution Systems" (Hill, 2007). It will provide guidance to utility managers and operators on how to deal with internal corrosion issues from an operational standpoint.

Concern with iron corrosion predates the SDWA and concern about lead and utilities have long sought to suppress it by use of scales. While iron corrosion is normally not a target of corrosion control treatment under the LCR, it might be involved with scaling and precipitation of other compounds. Iron corrosion is an oxidation mechanism that occurs through electro-chemical processes at water-metal interfaces (Snoeyink et. al., 1996; Benjamin, et. al., 1996). McNeill and Edwards (2001) reviewed almost 300 peer-reviewed articles about iron pipe corrosion and they noted that the resulting scale is composed of many compounds and involves complex reactions. Lytle and Snoeyink (2002) studied the effects of ortho- and polyphosphate properties on iron particles and suspensions. Sarin, Clement, Snoeyink, and Kriven (2003) also studied iron release from corroded, unlined cast iron pipe. A utility might be suffering loss of capacity and not know if it is from iron corrosion or secondary effects of corrosion control. Later in the chapter, the effects of iron corrosion on pipe capacity are explained and compared to those caused by calcium and aluminum scaling and/or precipitation.

The causes of lead corrosion has also been studied extensively, and EPA studies of lead dissolution (plumbosolvency) started in 1977 as the agency was implementing the SDWA. Computer programs for lead solvency are now available and researchers have studied possible destabilization of passivation films by changed treatment regimes (Schock, Wagner, and Oliphant, 1996; Edwards, Reiber, and Schecher, 1997). Additional research has been published on experiences with LCR control and lead concentrations in water (see Case, 2007). While a good bit of knowledge about lead release is available, utilities may not know how much lead in distribution systems is exposed to corrosion.

Corrosion can also refer to leaching from cement-based materials. Also, see (Schock, 1999; Douglas and Merrill, 1991). Release of constituents from cement based materials might affect scale formation in pipes and hydraulic equipment. Water Research Foundation has a current project on "Impact of Phosphate Corrosion Inhibitors on Cement-Based Pipes and Linings" (Project 4033) and its results may shed additional light on corrosion of cement linings. The project summary states that it will determine impact of phosphate chemicals on formation of scales, lime leaching, and water quality for cement-based pipes and linings and that it will help utilities make decisions about use of inhibitors for cement-based pipes and linings. Highlights of

2 AwwaRF is the Awwa Research Foundation and DVGW-TZW is the Water Technology Center of the German Gas and Waterworks Association (Deutscher Verein des Gas- und Wasserfaches, Technologiezentrum Wasser, Karlsruhe). As of January 1, 2009, AwwaRF changed its name to the Water Research Foundation.

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this study will include experimental studies with test rigs and use of water that is similar in quality to that in participating utilities, at least some of which have experienced problems with aluminum scaling. They intend to learn the extent to which aluminum dissolves from cement-based materials in the presence of different water qualities and use of inhibitors.

Corrosion coupons offer a basic method to monitor corrosion. Two ASTM standards related to coupons are ASTM G4-01 (Standard Guide for Conducting Corrosion Tests in Field Applications) and ASTM G1-03 (Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens).

### Relationships Among Hydraulics and Corrosion

Corrosion in pipelines does not occur from static but from dynamic conditions, including those that occur during flushing. Due to velocity fluctuations, chemical conditions such as pH and potential for $CaCO_3$ precipitation near pipe walls can vary greatly from average or bulk conditions (Snoeyink and Wagner, 1996). Formation of scale can thus occur on a wall, even when the bulk parameters do not demonstrate the potential for it.

As mentioned earlier, a few studies of particle, chemical, and microbial transport in water distribution systems have been conducted. Lu (1991) studied the modeling of particulate transport in pipes, chlorine concentration decay, and simultaneous transport of substrate, biomass, and disinfectants in pipes. He studied lead transport and presented a model to predict lead levels at the tap. Problem areas in pipes were listed as cavities, bends, obstacles, bifurcations, and tees. Sethi (1993, 1996) also studied transport of dissolved and suspended contaminants in drinking water systems, including effects of multiple sources and consumption patterns on exposure to dissolved lead. He developed a model of mean and instantaneous lead concentrations at the end of plumbing systems, and he conducted bench-scale experiments to study lead leaching rates.

## SCALING AND PRECIPITATION IN WATER PIPES

Scaling is a different phenomenon than corrosion and involves the processes of precipitation and adherence. It is a general term meaning or the formation of scales on a surface. In practice, scaling is predicted from analysis of the potential for precipitation to occur, but the process of adherence may or may not occur at the same time. As Cowan and Weintritt (1976) wrote: "Data on scale-forming compounds have been gathered have been gathered by many investigators over the years… These data, however, only describe conditions under which *precipitation* will occur. They do not describe whether or not the precipitate will *adhere* to form a scale deposit." This explanation provides a useful distinction between precipitation, which can be analyzed using chemical parameters, and the complex issue of whether a scale will actually form.

A great deal of knowledge about scaling exists, but it is scattered across different fields. In their study of water-formed scale deposits for the petroleum industry, Cowan and Weintritt (1976) reviewed many chemical abstracts, original references and books, patents, internal sources, and samples. They wrote: "We found that while the scale problem has been recognized for many years, the concentration of training and effort actually applied in this area has been surprisingly scattered, not only in the petroleum industry but in all areas where deposits cause problems."

Scaling is an old problem. The authors traced the discovery of scale back to Roman times and their discussion carried through to today's problems with water treatment, cooling waters,

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boiler water, saline water conversion, product pipelines, marine fouling, and petroleum operations. Their explanation of the range of problems helps us to assess the difficulties encountered in drinking water and industrial systems. The authors listed a number of publications from the US Office of Saline Water, which operated during the 1970s. Some of these now hard-to-find publications shed light on today's scaling issues of importance to drinking water.

They began by summarizing the occurrence of diverse water-formed scales in pipes handling produced or disposal water in petroleum operations. The scales ranged across calcium sulfate, calcium carbonate, silicate, gypsum, and barium sulfate. They cited an ASTM handbook that classifies water-formed deposits on the basis of temperature, evaporation, and occurrence of steam. Given the authors' focus on brines, they were able to assess more severe conditions than in potable water systems and we can learn about scaling science from these conditions.

Scaling and precipitation involve a number of chemical equilibrium phenomena. The authors identified the essential conditions for scaling to occur as supersaturation, nucleation, and adequate contact time. The contact time is a logical variable to explain whether precipitation actually causes scaling or not, but is not something that can be analyzed easily in water distribution systems. Given our state of knowledge, it seems reasonable to summarize by saying that scaling and/or precipitation will occur when the depositing compound reaches supersaturation in water, conditions are favorable for nucleation to occur, and there is adequate contact time with surfaces of components for the scaling to happen.

Scaling can have favorable effects in water pipes and has been used for many years to protect pipes. As Schock (1999) explained, protection against corrosion can occur by the metal surface being immune or passive. The surface is immune if it is stable on an electrochemical basis. Protection by passivation can occur if the metal surface is made passive by covering with a stable film. Although scaling has been used as a pipe protection measure for a long time (Cowan and Weintritt, 1976, recent researchers have called into question whether scaling is effective in protecting pipe surfaces (Kvech and Edwards, 2001). In fact, Snoeyink and Jenkins (1980) pointed out "The coating of pipes with scales such as $CaCO_{3(s)}$ can lead to corrosion problems if the scale accumulation is excessive or uneven….scale may be washed off by the flowing water in the pipe and leave exposed metal areas where corrosion can proceed."

A number of forms of scaling can occur. When conditions are right, scaling can occur directly on the surfaces of components. Precipitation potential is not the same in bulk water and near surfaces. The hydraulic actions of pumps and other hydraulic equipment such as screens might induce calcium carbonate or other materials to deposit scale on surfaces or in machinery as a result of precipitation. Corrosion control inhibitors can induce scaling. These types of scaling episodes involve numerous chemical compounds and situations.

When scaling or precipitation is called post precipitation, it is taken to mean any precipitation that takes place after (or post-) treatment or downstream from the treatment plant. Scaling involves adherence of particles to surfaces, whereas post precipitation means any precipitation after the particles were dissolved, and might occur without actual attachment of particles to surfaces.

Treatment strategies to promote immunity or passivation can have direct or indirect effects on hydraulic equipment. A metal surface might become passive with a stable and harmless film on it, but this effect might deposit too much film on a moving surface of a piece of equipment and impair its operation.

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Several types of scales can cause secondary effects of treatment processes (not only corrosion control treatment). Calcium scaling is the most common and will be discussed first.

## Calcium Precipitation and Scaling

Most calcium effects in water are well-known to chemists, but may cause surprises to operators and engineers when sudden changes occur in water systems. Basic explanations of calcium chemistry are found in articles and textbooks on water chemistry (Cowan and Weintritt, 1976; Snoeyink and Jenkins, 1980; Langmuir, 1997; Kehew, 2001). They also appear in popular science writing about water quality, such as (Behrman, 1968) and in operation guides such as (Gebbie, 2000).

Calcium can be made available for scaling or precipitation from source water that varies in hardness and alkalinity, treatment processes, and leaching from pipes themselves. Source waters that are considered "hard" are those that have a high concentration of alkaline salts, mainly calcium and magnesium. Calcium is an abundant earth metal, and naturally enters source waters from surface or ground origins. Calcium is especially available from dissolution of limestone, where the dissolved product is a water high in $CaCO_3$.

Controlled calcium carbonate scaling has been used to protect pipe walls from corrosion, and utilities are aware that care must be taken to avoid excessive scaling and reduced hydraulic efficiency of pipes. We found literature in the Journal, AWWA on use of $CaCO_3$ to protect pipes going back at least to the 1930s, as for example the work by Langlier (1936) that led to his index. By the 1950s the strategy seems to have been broadly accepted (Larson and Skold, 1957). According to Snoeyink and Jenkins (1980), the most effective $CaCO_3$ layers seem to be those associated with iron hydroxide and iron carbonate precipitates.

The general understanding of water stability is that water can be undersaturated, in equilibrium, or oversaturated. If it is undersaturated, it will considered to be corrosive and if it is oversaturated, it will tend to precipitate $CaCO_3$. The management question for water distribution operators is to determine whether corrosion control through deposition of a film is required, whether a water in equilibrium (saturation) is desired, or whether to avoid any scaling by leaving the water at a slightly corrosive level (see Snoeyink and Jenkins, 1980).

The method to assess water stability has been to use indices to calculate the potential for precipitation of calcium carbonate. While the applicability of these indices varies, they are often cited as the tools of choice to compute the stability of water. Even if they are not all equally useful, and regardless of their applicability, the indices are closely related to the pH of the water. They are guides and not the final word on whether scaling will occur. Rossum and Merrill (1983) compared six indices and concluded that the only one that is valid over a range of pH is the calcium carbonate precipitation potential (CCPP).

The CCPP (or other indices) is not adequate by itself to tell a utility whether it will have a problem, but it can be used to guide operations. As the CCPP is complex to calculate, several authors have presented methods to calculate it. For example, Holm and Schock (1998) presented a spreadsheet method. Also, commercial software programs are available.

Calculations of water stability consider the carbonate–driven pH system, the calcium present, and other conditions, including temperature and presence of other compounds and ions. Other things being equal, the carbonate and pH system illustrates how conditions in water can change quickly from under-saturation to over-saturation.

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How the carbonate system controls the pH of aqueous solutions can be explained by a pC– pH diagram such as shown in Figure 2-2. In the acid-base reactions that occur in aqueous solutions, the carbonate anions usually combine with calcium cations and tend toward precipitation as supersaturation occurs (Kehew, 2001). The steep curves in the set of relationships hint that the chemistry of an aqueous solution changes rapidly with pH levels.

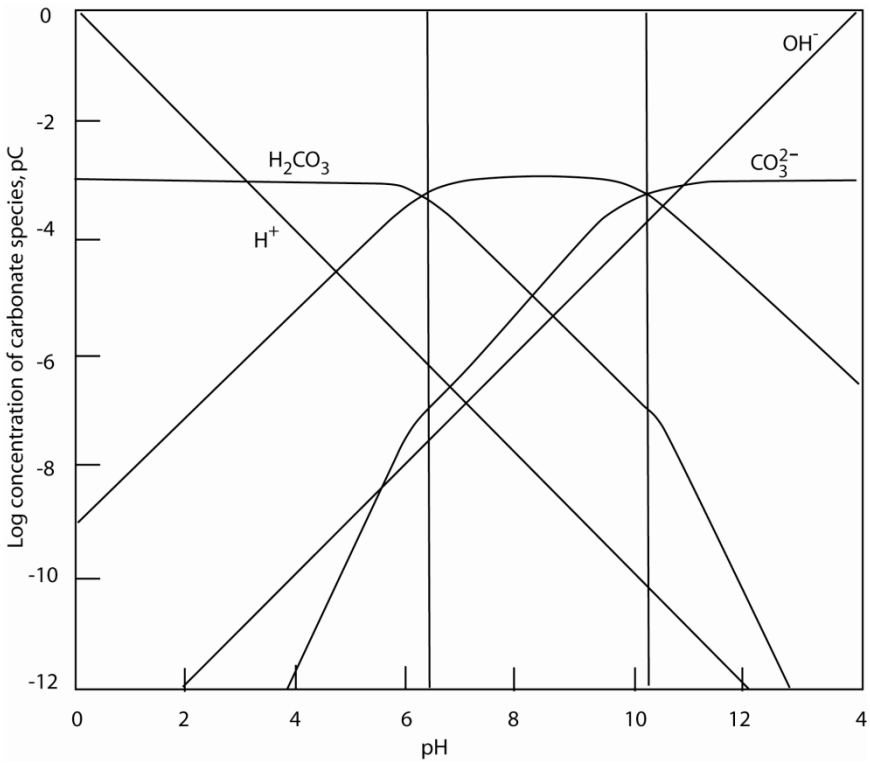


**Figure 2-2: Concentration Versus pH for the Carbonate System**

The phases on Figure 2-2 show that as pH increases, initial concentrations of carbonic acid ($H_2CO_3$), the free hydrogen ion ($H^+$), and the bicarbonate ion ($HCO_3^-$) change to create the hydroxide ion ($OH^-$) and the carbonate ion ($CO_3^{2-}$).

The basic equation to explain the diagram shows how carbon dioxide gas is dissolved in water to form carbonic acid ($H_2CO_3$), which dissociates into the free hydrogen ion ($H^+$) and the bicarbonate ion ($HCO_3$). In the next step, further conversion occurs and the carbonate ion ($CO_3^2$) is formed with the rate constant $K_2$. Values for the rate constants $K_1$ and $K_2$ are based on temperature.

On Figure 2-2, system points corresponding to $K_1$ and $K_2$ are located at values of pH at 6.37 and 10.33 which represent values at room temperature. These illustrate by dashed lines the crossover points where values of carbonic acid and bicarbonate are equal (pH = 6.37) and where bicarbonate and carbonate are equal (pH = 10.33). Notice also that hydrogen and hydroxide concentrations are equal at pH = 7.

At pH below $K_1$, carbonic acid is more prevalent. As the pH is raised above 6.37, the concentration of carbonic acid declines and the concentration of bicarbonate increases, thus reducing the potential for acidic attacks on pipe surfaces. Most natural water systems have pH values between 7 and 10, and the carbonic acid is mildly acidic.

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When the pH is near either system point of 6.37 or 10.33, there is a strong resistance to further changes in pH. A significant amount of effort is needed to increase or decrease the pH beyond these points because the hydrogen in solution goes toward changing species rather than to changing pH.

The useful information on Figure 2-2 for this discussion is to show how at different pH levels different types and levels of carbon compounds and ions are prevalent and how chemical forces may promote corrosive or super-saturated conditions in water. It is known that pH control is the major factor in causing $CaCO_3$ scaling and/or precipitation. Studies showed that even small changes in pH may generate large effects. The phase diagram for pH and the carbonate system shows steep slopes on concentration–pH curves for the compounds and ions. Thus, lack of precision and wide variability in the pH of a system can cause unexpected levels of scaling and precipitation.

There are no direct regulatory controls on calcium levels, and many systems have learned to keep pH in certain ranges without experiencing problems. For many, the Lead and Copper Rule was an impetus to change pH levels and in some cases to cause secondary effects. While water chemists understand the influence of pH on calcium scaling and precipitation, problems must be diagnosed on a case-by-case basis. Conditions vary so much among and within systems that actual measurements and tests must be undertaken to supplement theoretical studies.

Type and location of precipitates from pH adjustment can vary widely depending on chemical dosages. One utility noted a Ca-Al-Fe-phosphate precipitate which might have even nucleated on undissolved lime particles. Anecdotes have also been received of Ca-Zn-phosphates from inhibitor-based corrosion control systems. It is possible that pH could be the main influence or another chemical-specific effect of the dosed chemical could play a role. Also, calcium phosphate precipitates are more likely in hot water conditions than in cold water conditions[3].

Industrial water treatment specialists are aware of a mechanism to suppress calcium carbonate precipitation that involves "crystal growth poisoning" or "threshold treatment." An early AWWA reference for this is (Corsaro et. al., 1956). Additional suggested references for phosphate inhabitation of $CaCO_3$ formation include: (Giannimaras and Koutsoukos, 1987) and (Lin and Singer, 2005, 2006).

Turbulence seems to be a factor in inhibiting scale formation. This factor can be important in explaining the difference between precipitation and formation of the scales. As Snoeyink and Jenkins (1980) point out, "… the pH immediately adjacent to a metal surface may be different from that in the bulk solution. Thus a water that has a tendency to precipitate … may not actually precipitate on the metal surface because of localized conditions…" In one of the utilities that contributed to the project, Austin, Texas, the influence of turbulence was identified and requires further study (Morabbi and Clark, 1999).

3 Information from Michael Schock.

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## Aluminum Effects

Aluminum scaling is also a significant concern to water pipes, especially because it can cause significant loss of capacity. While recent water industry literature contains only a few papers about aluminum scaling, our research showed that capacity losses in pipes were observed as far back as when alum began to be used as a coagulant in water treatment. This suggests that aluminum scaling and precipitation are long-standing issues which, like calcium issues, may afflict water many transmission and distribution systems in minor ways but occasionally become major issues requiring immediate attention.

Aluminum was described as an unregulated inorganic contaminant in the USEPA White Paper (HDR, Inc. et. al., 2006). The authors explained how aluminum exists in solution in a trivalent form as a free ion ($Al^{3+}$) or as a hydrated complex and may form precipitates as oxide, hydroxide, or phosphate. Solubility is highly pH-dependent, and aluminum may partition to hydrous metal oxide substrates, clay, and organic matter.

The status of knowledge about aluminum scaling was summarized by Schock (1999): "Aluminum may be widespread as a component of films on distribution system piping that can act as diffusion barriers to reduce corrosion or metal release. Even though it has not been systematically studied, several investigations have found aluminum films to significantly reduce lead leaching … and to adversely affect the hydraulic efficiency of distribution mains… Aluminum was found on copper pipes … suggesting also that it can be widespread… In natural aquatic systems … aluminum readily combines to form aluminosilicate minerals of low solubility, also suggesting that they may be common in distribution systems."

The implication of aluminum as a seemingly minor issue was explained by Kriewall et. al. (1996) this way: "Attributes of Rochester's upland gravity flow transmission system afford an excellent opportunity to detect minor changes in pipeline capacity. Similar capacity deterioration might well go unrecognized in a more typical transmission system … It is likely that even visual evidence of a thin film on pipe walls will not convince the uninitiated that this could be the cause of much frictional resistance to flow."

Aluminum chemistry is complex and can take on several forms. A recent comprehensive paper reviewed the background on aluminum scaling and is summarized in the next section.

Snoeyink et. al. (2003) conducted a recon¬naissance of whether significant Al-containing solids were found in distribution systems and premise plumbing. Like calcium, aluminum deposits can increase energy loss but there is also the possibility that they can have a protective effect on pipe surfaces. Al-containing solids on walls of distribution pipes have been reported for several decades. There is also a suggestion that Al solids in distribution systems can protect against corrosion or metal ion release to water.

Al in distribution systems can originate from source water, coagulants, and leachates from distribution materials. More than 90% of Al in most natural waters is in particulate form, with Al bound to colloidal particles or NOM.

Al varies with water composition (including turbidity, silica, fluoride and phosphate) and temperature. Observations in stream flows also show the solubility of aluminum and relation to pH, see (Kimball, et. al. 2001), for example.

The main treatment processes that affect aluminum are disinfection, coagulation, pH adjustment, and use of corrosion control inhibitors. Leachates can be from aluminous deposits, cement or asbestos-cement pipes, and cement-mortar linings. Aluminum leaching from cement-based materials in low-alkalinity waters can be mitigated by silica in water.

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Aluminum compounds such as hydroxides, silicates, and phosphates can deposit in distribution pipes when solutions become super-saturated from not achieving equilibrium in the treatment plant, lowered transport temperatures, and decreasing pH.

Solubility and precipitation of aluminum will depend on the metal species and water conditions. Some studies have observed reductions in soluble aluminum by controlling the pH during coagulation, flocculation, sedimentation and filtration. Water temperature also affects aluminum concentrations in treated water. Some anions, particularly fluoride when applied before or during coagulation, can increase soluble aluminum levels. The solubility and speciation of inorganic aluminum hydroxide depend on pH.

Aluminum–phosphate interactions are widely reported and are important in scaling because phosphate corrosion inhibitors may supersaturate water with Al-phosphate solids. Aluminum scales may function as sinks for corrosion inhibitor chemicals.

The aluminum hydroxide solid can incorporate phosphorus via co-precipitation or adsorption of orthophosphate onto its surface. This phenomenon needs more study. Dissolved silica can affect coagulation with alum, depending on pH. Silica can affect the rate of floc formation and potential for precipitation.

A Water Research Foundation project (4133) is currently studying phosphate inhibitors and their effects on cement lined pipes. Inhibitors have the possibility to exacerbate aluminum phosphate scales, and the project is undertaking pipe rig tests to evaluate alternative outcomes. The report is due in 2010.

As it deposits on pipe surfaces, aluminum may mix with other solids such as iron or lead corrosion products, calcium carbonate and manganese dioxide. Scale composition data showed large amounts of Al, Si and P on lead pipes, as well as lead itself. Reductions in lead during pipe rig testing in Rochester appeared to be a function of aluminum deposition on lead piping materials. This accompanied a decrease in transmission main hydraulic capacity due to aluminum hydroxide. The original carrying capacity was restored by coagulating at pH of about 7.6 and increasing pH after filtration to about 8.7 during the summer when Al solubility was a maximum.

In one study, it was shown that use of polyphosphate might inhibit Al particles from attaching to pipe walls. Polyphosphates may increase Al leaching from a cement-mortar liner by attacking and softening it.

As many types of aluminum effects can occur, little general guidance can be given on treatment changes without study of specific cases.

Snoeyink et. al. (2003) collected scale from 10 water utilities to assess if aluminum-containing solids were prevalent in water distribution systems and premise plumbing. They asked plant managers if hydraulic properties had been observed and if they were aware of aluminum-based deposits. Their priority was to study lead pipes, deposits on cement, concrete or plastic pipes, and to a lesser extent, copper and unlined cast iron pipes.

They found substantial Al, Si, P, and Pb in the scale on lead pipes. Aluminum was usually present as a large percentage whenever aluminum-based coagulants were used. There were some exceptions to this finding. In one case, scale showed a large magnesium concentration and a high amount of zinc with hard, apparently zinc silicate deposits on cement pipes. Data they reported is summarized in the following list:

**(Baylis, 1953).** Rapid buildup of soft gelatinous coating covering old tubercles after the South (Chicago) District Filtration Plant was put in operation. Piping in many systems was

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covered with a white gelatinous coating that was not calcium carbonate. Chemical analysis showed mainly aluminum hydroxide with considerable silica.

**(Hudson, 1966).** Aluminum hydroxide can be deposited from treatment imbalance, regardless of the type of pipe or lining. Very thin aluminum deposits can reduce carrying capacity a lot. Aluminum deposits substantially decreased C-factors in Chicago.

**(Cooper & Knowles 1975).** Within 5 years of installation, they found more than 40% C-factor reduction for a 42-inch main in the London, Ontario, system within 5 years of installation. This was caused by a thin whitish-grey substance on the internal pipe surface. Conclusion was that the material was mostly amorphous (no defined structure) interspersed with fine silica, probably from filter media. Chemical analyses of samples ranged over $Al_2O_3$, $SiO_2$, CaO, MgO, $Fe_2O_3$.

**(McGinn & Briggs 1979).** Excess headloss occurred in a main caused by a slimy deposit less than 2 mm thick. Analysis showed 80–90% aluminum, with small amounts of iron, magnesium, silica and organic carbon. Precipitate was stabilized by polymer replacement and stopping the lime feed. Pigging increased the C-factor from 113 to 139.

**(Costello, 1984).** The author explained postprecipitation mechanisms in Chicago and other water distribution systems, including turbidity levels in the Manatee County, Florida, distribution system caused by aluminum coagulation and postprecipitation.

**(Qureshi and Malmberg, 1985).** Postprecipitation of Al was reported in distribution mains from Fridley Filtration Plant, Minneapolis.

**(Pigging cuts power costs in large-diameter water pipe, 1985. Wat. Engng Managmt, March 20.).** Onandaga, NY. Thin buildup of aluminum hydroxide in 54-inch main with filtered water from Metropolitan Water Board plant to Syracuse area. Deposit was rippled and gritty, could be removed with a rag. Loss of carrying capacity observed. C factor raised from 90 to 135 by cleaning.

**(Water Main Cleanout Restores Efficient Service. 1985. Public Works. August. 76-77).** Lexington, KY. Reduction of C-factor from 130 to 100 from 3 mm deposit on 24-inch and 30-inch pre-stressed concrete transmission main. Analysis indicated that 15% of the material was aluminum and 1.3% calcium. Other metals less in concentration. Soft pigging restored original flow and decreased rate of deposition.

**(Fitch and McCollum, 1986).** Alum was linked to rapid loss in transmission capacity and drop in pump discharge. A 10 mm maximum thickness gelatinous precipitate was found, composed predominantly of aluminum and silicon oxides.

**(Zimmerman, 1986).** Monitoring showed interrelationships with pH, coagulation and filtration, and Al postprecipitation. When finished water pH was increased, Al dissolution apparently increased in the distribution system. More optimal coagulation also helped. Pigging and changing coagulants restored transmission capacity from thin aluminum deposits in Grand Rapids, Minneapolis, Toronto and Syracuse.

**(Goold et al. 1991).** Pipe coupons from cement and iron pipe and a section of unlined pipe showed common iron and calcium carbonate minerals. Treatment was lime-softening and polyphosphates. In some soft scales considerable organic material was found and traces of other metals (Cr, Ba, Ni, Sr, Ti, Zn, Mg, Al, P, S and Si).

**(Fuge et al. 1992).** Aluminum remobilization in two Wales communities resulted from reduction in finished water Al caused by changes in water sources and treatment. Particulates from aluminum deposits sometimes concentrated Pb, Sb, Sn, Cu and Zn.

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**(Shea, 1993).** Green Bay, Wisconsin experienced lower pressures and C-factors in 36-inch pipelines. A white powder buildup of aluminum silicate was the cause. An orthophosphate addition did not improve the problem, but cleaning increased the C-factor from 90–100 to the 150 range.

**(Lauer and Lohman, 1994).** Aluminum deposition occurred in test pipe rigs, and samples from the Denver distribution system indicated 36–42% $Al_2O_3$, 24–29% $SiO_2$, 1–3% CaO.

**(Kirmeyer et al. 1999).** There was a reduction of Pb levels in a control loop of a pipe rig fed by the water. Deposit was reddish or reddish-grey and about 6 mm thick. Analysis showed 15% Al and 50% organic matter. Deposit dissolved and C-factor restored by controlling coagulation and pH.

**(Havics, 2001).** White precipitates in drinking water in a city in Georgia showed concentrations of aluminum and phosphorus, sometimes associated with Si, Fe and other compounds.

Additional experiences reported by Kvech and Edwards (2001) included:

**(Schoeler, Frensch, and Schoenen, 1990).** Alumino-silicates were found in a German utility.

**(Shea, 1993).** Green Bay WI, Lexington, KY, Onondaga County, NY, and Rochester, NY.

A previous study in the Denver system assumed that low hardness water would be corrosive, with a negative Langelier index (Kvech and Edwards, 2001). The fact that few problems with lead and copper release occurred led to a theory that the aluminosilicates were beneficial. The researchers studied finished water from Denver's Moffat Treatment Plant and samples of distribution system deposits. They considered that the most likely source of effluent aluminum was alum carryover and of the silica was the raw water. Deposits from a 96 inch water main showed a uniform brown color of pasty consistency with small sandy granules. The sample was mostly aluminum, with significant levels of silicon and a trace of calcium. The researchers thought that high concentrations of aluminum hydroxide suggested precipitation of aluminum and co-precipitation of silica in the distribution system. They thought the trace calcium was from added lime prior to filtration.

The researchers thought that a problem with this analysis was caused by the lack of validity of the Langelier Index approach to predict corrosivity of water. They theorized that the behavior of the water was typical for its level of alkalinity and pH and concluded that the deposited aluminosilicate solids were not beneficial.

## Manganese Deposition in Distribution Systems

Deposition of manganese in distribution systems is widespread but not well-understood, either for its causes, mechanisms or effects. It is not a direct result of secondary effects of corrosion control, but it is another scaling phenomenon requiring attention by utilities. For example, Sly et. al. (1990) found that particulate deposits in their pipes normally contained manganese, iron, calcium, and silica.

Manganese in drinking water is considered an aesthetic problem leading to "black water." It is normally not considered a health threat, but has a current standard as a secondary MCL of 0.05 mg/L (Casale, LeChavallier, and Pontius, 2002).

Manganese oxides will form coatings on many materials, including pipe walls. Kohl and Medlar (2006) found that the more manganese in the treated water effluent, the more would be

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found in the distribution system. The amount of manganese normally decreases with distance from the treatment plant.

The main source of manganese in drinking water systems is source water. Manganese is abundant in nature, and it occurs widely in surface and groundwater systems. In the past, groundwater systems seemed more vulnerable to manganese problems, but with changes in treatment requirements, surface water systems have also become vulnerable.

Control of manganese is made complex because of its variable chemical forms and solubility levels. It takes on different oxidation forms and may precipitate as manganese oxide (MnO2). Also, hydrous manganese oxides have been shown to serve as scavenging agents for some trace organics, such as lead, arsenic, and radium (HDR., Inc., et. al., 2006). Manganese chemistry involves several oxidation levels and compounds, and the element is usually found in combination with other metals. Simply stated, Mn(II) is the most common valence state and is soluble in water. It is oxidized to Mn(IV) by chlorine. Mn(IV) is less soluble and precipitates.

Kohl and Medlar (2006) found that utilities with the most manganese in source water had fewer problems than those where it was more variable. This happened because utilities with a large amount of manganese had usually developed control methods that worked, whereas those with variable amounts might be more likely to be caught by surprise.

Post-precipitation on the pipe surface seems to be a more common occurrence of Mn accumulation than adsorption. Sorption of dissolved Mn onto pipe surface material may be favored in materials like cements or iron pipe corrosion deposits. Accumulation of amorphous precipitates of Mn(IV) oxide (likely a type of MnO2 or MnOOH) is to be expected. Analytical techniques such as X-ray diffraction do not normally yield good identification. The texture of these precipitate may be gelatinous but may form as little nodules. These textures probably affect pipe roughness[4].

Manganese can be deposited by chemical processes or microbial activity. Chemical deposition is the greater problem. Sly et. al. (1990) found that microbial manganese deposits formed when chlorine levels were zero, and when biofilms were controlled with chlorination, manganese deposition diminished. On the other hand, chemical deposition of manganese increased with greater chlorine levels.

After Manganese is deposited in the distribution system, it can be re-entrained. Once the capacity of the pipe surface to adsorb manganese is reached, it will be transported through the pipes rather than adhere to the pipe walls. Hydraulic events in the distribution system can entrain manganese and cause customer complaints.

Sloughing of manganese oxide deposits causes brown-black water and taste problems and stains laundry, fixtures, and equipment (Sly, Hodgkinson, and Arunpairojana, 1990).

## EFFECTS OF INHIBITORS

Corrosion inhibitors are a widely-used method to promote formation of protective coatings on pipe surfaces and suppress corrosion, but their effectiveness varies. Examples of inhibitors are inorganic phosphates, sodium silicates, and mixtures of phosphates and silicates. Examples of inorganic phosphate inhibitors are polyphosphates, orthophosphates, glassy phosphates, and bimetallic phosphates. Zinc may be added along with polyphosphates, orthophosphates, or glassy phosphates to help inhibit corrosion. Sodium silicates have advantages for certain flow conditions and for hot-water systems.

4 Credit to Michael Schock for these observations.

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This list presents a survey of studies on inhibitors:

| | |
|---|---|
| Reed, Robinson, and Tucker, 1988 | Studied lab scale corrosion monitors in a treatment plant and monitors in distribution system. Investigated effectiveness of inhibitors relative to distance from the treatment plant. They found that some compounds had higher reversion rates and lower effectiveness than others. |
| Schock, Wagner, and Oliphant, 1996 | Description of EPA studies of orthophosphate and silicate effects in 1979-81. |
| Reiber et. al. (1997) | Water Research Foundation study evaluated utility experiences with inhibitors and offered lessons learned. |
| Kvech and Edwards, 2001 | Found that aluminosilicate deposits did not always protect lead and copper from corrosion. |
| Edwards, McNeill, Holm, and Lawrence, 2002 | Studied roles of phosphate inhibitors in mitigating lead and copper corrosion. They found that hydrocerrusite scale was associated with lead release, both soluble and particulate. |
| Lytle and Snoeyink, 2002 | Reported on effects of ortho- and polyphosphates on the properties of iron particles and suspensions. |
| McNeill and Edwards, 2002 | Reported on surveys in 1994 and 2001 of phosphate inhibitor use. They found that few utilities are using scientific tests to assess the best inhibitor for their use and are relying on vendor data or tips from neighbor utilities. |
| Holm and Edwards, 2003 | Studied metaphosphate reversion in laboratory and pipe-rig experiments. |

## INTERNAL CORROSION AND TUBERCULATION

In our inquiries, we found more concern about the internal condition of water mains than about other secondary effects and this led us to investigate the historical links between internal corrosion and pipe condition. We found that today's concerns are the logical result of decades of experience with changed water quality in distribution pipes.

Evidence of the problem was cited by a committee of AWWA in 1962: "In the operation of water transmission and distribution systems, no problem has caused more concern or occasioned greater expenditure of manpower and maintenance funds than the problem of loss in carrying capacity of water mains" (California Section of AWWA, 1962).

This concern had been building for decades. In 1900, cast iron pipe was in service and tuberculation had already been recognized. After that, water treatment and discoveries about rough pipe hydraulics increased. By the 1960s, new pipe materials were being introduced and research was on hand about loss of pipe capacity. The configuration of distribution systems has not changed much, but new materials and methods have been introduced. The main problems (but not the only problems) have been with unlined cast iron pipe, which corroded and caused red water. Tar lining was sometimes used to inhibit corrosion, and cement lining was introduced later for new pipe and re-lining. The tar lining was said not to last (Baylis, 1953), and the longevity and effectiveness of cement lining needed study.

Steel pipe has also been used for a long time. It has high strength and ductility but is more expensive than cast iron (American Water Works Service Co, 2002). Asbestos-Cement

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Pipe has been used in the United States since the 1930's as an alternative to cast iron, but it was only introduced in large quantities in the 1950s. It is made by mixing asbestos fibers with cement, which results in a hard pipe wall when heated. Concrete pipes had been introduced for water transmission lines, and are occasionally found in distribution systems. Ductile iron pipe was introduced in large quantities beginning in the 1960s. It is made by adding magnesium to the iron, which increases ductility and strength. Today, it comes with cement lining, an asphalt coat, and a poly wrap. The effectiveness of these should be evaluated in different service conditions. Polyvinyl chloride pipe (PVC) in large quantities dates back to about the 1970s. It is resistant to corrosion and is light in weight. Due to its limited strength, it is used more at small diameters. The newer high-density polyethylene (HDPE) pipe is a stronger plastic pipe and can be used at larger diameters.

The literature on pipe capacity shows that earlier scientists and engineers had understanding about the basic causes of pipe deterioration. By about 1900 they had noted causes of internal pipe deterioration from chemical and biological forces. They had discovered that tuberculation imparted a foul taste and red color to water, and they developed a tar-like lining to inhibit it (APWA, 1976). Bell (1882) had written "Hard water has but little effect on cast-iron pipe, due to the carbonates; but soft water attacks it so vigorously, that it not only gives a turbid appearance to the water but seriously weakens the pipe by corrosion, and the consequent formation of concretions that reduce the capacity of the pipe. Hard water also (causes) the formation of lime deposits, that offer great impediments to the flow of water."[5] Organic material in pipes was also recognized. This quote from 1897 illustrates: "Whipple reported decreases in organism densities during distribution. He examined tubercles as well as well as a large, thick brownish mat removed from a section of water main (in Boston) removed from service. The brownish mat was identified as the sponge, *Polyzoa*" (O'Connor and O'Connor, 2008; Whipple 1897). This organic matter is related to the problems that 1950s engineers referred to as "slimes."

Waterworks engineers reported in 1925: "...growth in mains of fairly soft nodules of rusty appearance, composed of hydrated ferric oxide and vegetable matter…" and that "… a 5-inch pipe was rendered impenetrable to water under pressure of 75 pounds. Surfaces completely covered with nodules 1 to 1 1/2 inch in thickness are frequently encountered. The supply is unfiltered" (AWWA, 1925, page 353). In Wales, the waterworks reported (page 497) that "...action of soft moorland water has reduced carrying capacity from about 11 1/2 to 7 m.g.d."

Knowledge about pipe flow developed rapidly during the 19$^{th}$ century, when researchers discovered principles of velocity distributions, boundary layers, and energy losses in pipes. The Hazen-Williams formula, which is an empirical version of the 19$^{th}$ Century formulas, has its origin in 1908 (Haestad Methods, 2003). Aging water mains are "rough pipes," and definitive hydraulics research about them began to appear in the 1930s (Nikuradse, 1933). Schlicting (1960) described 1950s German water transmission pipes where roughness increased much more from rib-like corrugations than it did from sand roughness of the same dimensions.

By the 1950s US waterworks engineers and operators were keenly aware of the problems of corrosion in water mains. Baylis (1953) presented an in-depth analysis of the causes and nature of corrosion and tuberculation and waterworks engineers were actively discussing loss of

5 Thanks to David Hendricks, Emeritus Professor at Colorado State, for this information. Bell was listed as Assistant Superintendent of the Cincinnati Water Works. The fact that he does not use the term tuberculation suggests that it had not become widely used among waterworks engineers by that time.

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water main capacity from corrosion[6]. Important 1950s work on pipe losses and tuberculation was also published by Larson and Sollo (1967).

The committee of the California Section of AWWA (1962) explained how even thin layers of deposits cause big roughness increases, such as bacterial slimes of 1/16 – 3/8-inches and more; that the slimes are soft, uneven, and slimy, and can be removed with a finger, although flowing water does not remove them. They explained how the remedy for slimes is chlorine treatment, but it might cause taste and odor problems. These slimes can afflict plastic pipes and lined metal pipes, as well as metal itself.

In the 1960s a comprehensive paper was published by Hudson (1966), with Pitometer Associates, a firm that had been gaging water mains since about 1900. In his report on observed capacity losses in several cities, Hudson attributed the losses to internal corrosion, tuberculation, deposits, and the attachment of growths to the inside of pipes. He showed how C factors decline with age and how the initiation of water treatment sometimes accelerates the declines. This paper is one of the earliest that considers with- and without-treatment cases of pipe aging.

In 1988, Walski et. al. (1988) published a comprehensive review of research on predicting internal roughness in water mains. They noted that roughness changes only slowly in plastic and cement-lined pipes, but old bare metal pipes continue to deteriorate. The exception they noted was when aluminum hydroxide flocs are poorly removed in any type of pipe.

Tuberculation is initiated by *internal corrosion*[7] of unlined metal pipe such as cast iron, steel, or copper. The corrosion takes different forms, but in the case of iron pipes, it can lead to formation of spikes and other protrusions, as explained long ago by Baylis (1953), for example. Figure 2-3 illustrates Baylis' (1953) basic explanation of the process of iron pipe tuberculation, with further information from more recent research (Gerke, et. al., 2007). Baylis also described tubercles with cone shape and spicule shapes (like small needles or spikes) and compared his drawings with photographs of tubercles.

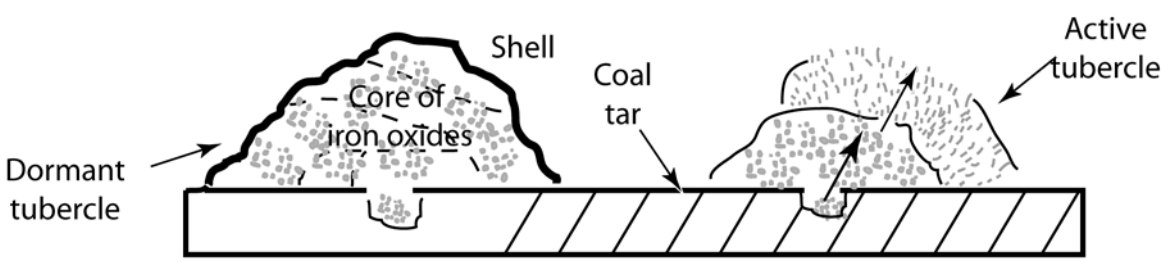


**Figure 2-3. Formation of tubercles (Adapted from Baylis, 1953)**

Chemical or biological deposits may cause tubercles, which restrict the access of oxygen to the metal surface, thus establishing differential aeration cells. The metal under a tubercle undergoes a pitting attack, while the surrounding metal serves as the cathode of a corrosion cell. Anerobic conditions within tubercles favor a sulfate-splitting type of bacteria and these can utilize cathodic hydrogen and cause microbiological depolarization.

6 This 1953 paper by Baylis is comprehensive and includes many useful photos and diagrams.

7 Internal corrosion is distinguished from external corrosion of pipes, which occurs from exposure of external pipe surfaces to environmental media such as soil, water, and air. Internal corrosion is caused by exposure to fluids and the internal environments of the pipes.

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Each case of tuberculation has its own unique history because it occurs over time and under varying structural, chemical and biological conditions. Researchers at EPA's Cincinnati Lab studied the morphology and mineralogy of three iron tubercules (Gerke, et. al., 2007). They removed three tubercles from a cast iron pipe and found that each tubercle had regions that started with a core overlain by shell and surface layers. The core was composed of iron oxy-hydroxides with magnetite-rich vein-like features. Magnetite is an iron oxide. They used X-ray diffraction to examine the scale, and found ten different metals. Only lead, copper, and chromium differed among the tubercles. They concluded that the variable composition of the tubercles meant that they were exposed to different water quality regimes. They concluded that the variability of metal type and concentration, even in a short length of pipe, meant that composition of pipe scale would not be a reliable predictor of future water quality effects on that scale.

The composition of scale was also illustrated by Benjamin et. al. (1996), who described the compounds normally found in different layers of scale (Figure 2-4):

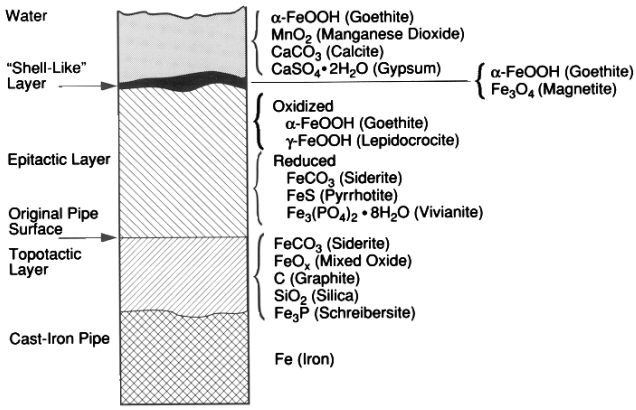


**Figure 2-4. Schematic of scale on a cast iron pipe (Source: Benjamin et. al., 1996)**

The scale and tuberculation materials on pipe walls vary in thickness and geometry. They normally include some metal compounds and some organic materials. Analysis of the materials in a tuberculation layer is not an exact science. Solids characterization involves numerous possibilities and is highly variable in costs. Some analysis techniques are specific only to certain compounds or elements, whereas others can give information on chemical bonding and structure at the surface of the corrosion deposits. In a report of a study of the San Antonio water system, Rodriguez et. al. (2005) wrote "…analysis is relatively crude…" and "…because of the amorphous nature of the corrosion scales, it is not possible to identify the precise mineralogy of the scale constituents (even using X-ray diffraction)."

As an example of how scales can take on variable compositions, the researchers studying red water episodes in the San Antonio system analyzed iron scales and wrote "Unlike some voluminous iron-based scales, there was little organic matter or microbial organisms contained in the typical scale from the various service areas. The lack of organic content indicates that the scales are not heavily populated with microorganisms, reducing the possibility of release of organic taste- and odor-causing substances should the scales be destabilized."

Figure 2-5 shows the general causes of loss of capacity.

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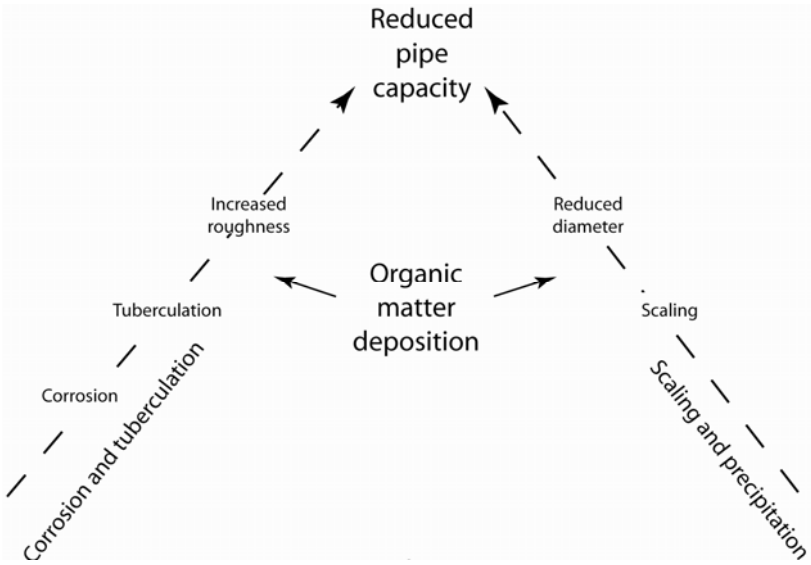


**Figure 2-5. Causes of pipe deterioration**

## TREATMENT GUIDANCE

The literature gives little attention to water treatment guidance for prevention of scaling. In Baruth (2005), for example, the main discussion of calcium scaling is in the chapter about membrane processes, where guidance is given on pH and use of anti-scalants to inhibit calcium scaling. There are no chapters on corrosion control treatment, perhaps because this topic is considered of more concern to distribution systems.

Guidance on treatment changes is provided in Chapter 4 as a result of the utility experiences reported in the project.

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# CHAPTER 3
# RESEARCH PROGRAM

## PHASES OF THE RESEARCH PROGRAM

This chapter describes the research program, which had four phases:

- Initiation phase (create advisory panel, identify survey respondents, review background studies, analyze hydraulic equipment, and develop a technical guide);
- Study phase (assess utility corrosion control histories and perform the survey and interviews);
- Compilation and interpretation phase (compile and interpret results of surveys and interviews);
- Reporting phase.

## ADVISORY PANEL

The Advisory Panel members were representatives of the participating utilities. In addition, the team received advice from other experts from industry and government. Collectively, the group that provided advice had broad experience in secondary effects of corrosion control on hydraulic equipment.

The following list shows membership on the Advisory Panel. On some occasions, when they could not advise on particular issues, they would consult with others in their organizations to provide advice.

| | **Participating utilities** |
|---|---|
| Mehrdad Morabbi | Austin Water Utility |
| Timothy W.D. MacDonald | Cambridge: City of Cambridge |
| Jeff Swertfeger | Cincinnati: Greater Cincinnati Water Works |
| Andrea Flores | Contra Costa Water District |
| John Kingsbury | Fairfax County Water Authority |
| Kevin Gertig | Fort Collins: City of Fort Collins Water Utility |
| Cal Van Zee | Laramie: City of Laramie Utility Division |
| Mark Johnson | Massachusetts Water Resources Authority |
| William T. Wanberg | Needham Water Division |
| Dale Kriewall | Rochester Water & Lighting |
| John J. Galleher Jr. | San Diego County Water Authority |
| Doug Borgatti | Springfield Water & Sewer Commission |

Early in the project, we discussed with Advisory Panel members how to explain the secondary effects. These discussions, together with preliminary telephone interviews with other utilities, confirmed the range of issues. As there are different kinds of secondary effects, we learned that it was important to be able to explain to them what we were looking for. This created the need for a Technical Guide for use with surveys and interviews. The Advisory Panel reviewed the technical guide and advised on how to make it clearer.



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Michael Schock of the Environmental Protection Agency helped with suggestions all during the project. He also contributed photos and papers to assist us in understanding and defining the issues. Carol Rego of CDM Inc. helped locate utilities with problems and in defining the issues. The PI visited two of the utilities in the Boston area that Ms. Rego identified. We also reviewed papers and presentations that she provided.

In addition, we contacted experts Vern Snoeyink of the University of Illinois, Marc Edwards of Virginia Tech, and Amrou Atassi of CDM, who was conducting a related project. Each person made useful suggestions and helped clarify the state of knowledge about the issues. We also obtained advice from utilities and state regulators during phone interviews. In addition, we discussed the project with experts and utility personnel at AWWA conferences. Chris Hill of Malcolm Pirnie, for example, was very helpful in providing advance information on AWWA's forthcoming internal corrosion manual. Other persons we contacted via interviews also provided helpful technical information.

Members of the Project Advisory Committee also assisted us with reviews and suggestions for the project. These included: Andrea Putz, City of Chicago; Ahmad Samadhi, Philadelphia Water Department; and John Wierenga, Grand Rapids Water System, MI.

Other than the utility visits, most of our work with the Project Advisory Panel and other experts was by phone and email. Early in the project we had planned to organize conference calls, but Panel members had such varied schedules and experiences that the issues lent themselves more to individual discussions than to group discussions.

## IDENTIFYING INTERVIEWEES AND SURVEY RESPONDENTS

The data collection program was the central part of the project. It turned out to be difficult to find the right people to ask about issues and to being specific about the issues. In this sense, the project had two phases: one where open-ended questions were directed to utilities, and a later phase where we were able to ask more specific questions to utility staff and regulators who were better prepared to answer the questions.

As secondary effects turned out to be such a specialized issue, it was apparent that blanket questionnaires to utilities without identifying the right contacts would not be successful. As a result, we conducted telephone and email prospecting activities in 2007 to find utilities and experts who could inform us of secondary effect episodes. This was time-consuming because there were no organized databases or systematic ways to search.

At this point, our questions were open-ended and were directed at finding the secondary effects from corrosion control treatment, and the questions elicited many responses from utilities that said: "We do not have those problems." However, further inquiry might turn up a problem in the past, but due to employee turnover, no one would remember the details. This was an example of the loss of institutional memory within utilities in that current staff might not have a recollection of past episodes and we also concluded from this that if problems were present, they were not serious enough to be on the radar screens of the people we contacted. This is one of the factors that led us to conclude that the published literature from the past might contain rich lodes of information.

Data from compliance with the Lead and Copper Rule would have been useful in identifying potential respondents, but no centralized data base of utilities with experience in corrosion control was available. Therefore, we contacted state drinking water primacy agencies to identify candidate utilities. This led to additional useful contacts but was also time intensive

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and led to many dead ends. Again, identification of the most knowledgeable personnel among regulators was difficult. For example, a state regulator might know about the LCR treatment methods in use within a state, but lack knowledge about effects in distribution systems.

In our initial contacts with state regulators, we sought to identify utilities doing LCR control. We contacted around 20 states in the interview phase and the typical responses were, "we have not heard of those problems" or "we will get the word around, and if we find anything, we will be in touch." Of the 20, five provided useful contacts to utilities that have experienced problems.

A few state regulators directed us to utilities with interesting stories to tell. This was helpful and led us to focus our studies on categories of problems: calcium issues, aluminum issues, manganese issues, iron issues, and all other problems with metals. Utility reports also fell into these categories, and it helped to give examples of problems in our interviews. This had the downside that a utility might indicate that they had a problem, but not have much information about it.

## TECHNICAL GUIDE

The Technical Guide was intended to explain to utility staff how corrosion and scaling in hydraulic equipment might occur from corrosion control and related treatment actions. It was intended to be clear and well-illustrated, and to be integrated into the project final report. Advice was sought from the Advisory Panel, and they helped identify a range of issues, causes, and effects.

Once we reached the interview and survey phases, we realized that the busy people we contacted, such as operators or operational managers, did not really want to wade through a detailed Technical Guide, so we used its concepts to explain to them the data sought and to prepare the surveys. A copy of the Technical Guide is included in the Appendix.

## ATTENDANCE AT AWWA MEETINGS

Attendance at AWWA meetings turned out to be a good way to identify experts and ask for experiences and opinions about secondary effects. The sessions organized on water quality and internal corrosion were particularly relevant.

The PI attended a special session on internal corrosion at the AWWA Research Symposium in Reno. Next, the PI and graduate assistant (Paul Sclafani) attended the 2007 ACE in Toronto and discussed corrosion and scaling issues with a wide range of vendors at the Exposition and experts in the technical and poster sessions.

The PI also attended the 2008 ACE in Atlanta and discussed secondary effects with utility personnel. These ongoing discussions with managers, treatment personnel, and distribution staff made it clear that in-depth knowledge about corrosion and scaling in distribution systems is restricted to a few experts. While many utility personnel know about them in general and are aware of the need to flush, clean, and renew distribution systems, the people who have given attention to the mechanisms of corrosion and deposition are only a small subset.

The PI presented a paper about the project at the 2008 Distribution Systems Symposium in Austin. Attendance at the session was on the order of 50 people. He asked the group about experience with secondary effects and only one person reported an experience, and it was some years back in an industrial setting. Two operators came forward after the session to report an

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incident of manganese precipitation near a chlorine dosing unit. The PI also asked others at the meeting, including vendors and national research experts, about their experiences.

The general conclusion from these inquires at AWWA meetings was that secondary effects are rare, but when they do occur, they can be significant. These interviews, covering two ACE meetings and two specialty conferences, are consistent with our other findings in the project that it is difficult to identify incidents of secondary effects but those that do occur usually require remedial action.

## SURVEYS AND INTERVIEWS

Our experiences with searching for utilities with problems led us to a survey strategy to contact about 150 medium sized utilities and all 50 state regulators. This strategy also turned up additional utilities for further interviews.

We prepared separate survey forms for utilities and for regulators. To inform them about the project, we included a fact sheet about the project. Copies of the survey forms and letters are included in the Appendix.

In both the interviews and surveys, the plan was to collect data on corrosion control experiences by asking about utility histories, their results and adjustments, and lessons learned. We learned early on that this information is mostly anecdotal, and we had to collect and analyze the data on a case-by-case basis.

The initial interview phase preceded the survey and was conducted by the PI and the Graduate Assistant. Initially, these interviews were of members of the Advisory Panel and other known experts and experienced persons. These interviews were for reconnaissance and led to identification of other experts to contact.

Of about 150 utility surveys, we received about 60 replies. In previous interviews, we had contacted about 40 utilities, so in that phase of the project, we had information from around 100 utilities. While this does not sound like a large number, given the time-intensive requirement of interviewing and surveying them, we considered that this was a good dataset.

We sent email queries to state government regulatory agencies, and in our initial survey we received 21 replies. We had previously contacted about 15 states, so we had information from about 35 of the states. We considered this a good data base for the project because, although most utilities and states reported few problems, a fraction reported serious incidents with scaling and precipitation, and we were able to follow up with them and produce an analysis based on our classification system.

At the end of the project, we decided to contact all 50 states again to see if additional information could be gleaned. This resulted in another 22 replies, which included two from EPA regional offices. It also identified a few more utilities, which we contacted for individual interviews. All of this information at the end of the project confirmed the findings that are summarized in Chapter 4.

## UTILITY VISITS AND DATA

In 2007, the PI was able to visit five of the participating utilities. This included: Fairfax Water; Needham MA; Cambridge MA; Massachusetts Water Resources Authority (MWRA); and Springfield MA. Two of these (Needham and Cambridge) had recent significant experiences, which are discussed in Chapter 4. MWRA is a large utility and has had scaling issues over the years, but no current urgent problems. The same is true of Fairfax Water, which is located in the

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DC Metro area. Springfield did not have urgent issues, and was engaged in a main cleaning program during the visit.

## INTERPRETATION, ANALYSIS, AND REPORTING

We analyzed hydraulic equipment in treatment plants and distribution systems to explain the nature of the metal surfaces, operating components and other elements that might be subject to chemical-induced failures and sensitivities to corrosion control programs. This analysis was facilitated by the PI's previous work with water industry data on infrastructure inventories and by the availability of university experts in hydraulic engineering with many years of hydraulic engineering experience. During our interviews we also asked pump manufacturers and designers if they knew of secondary effects. We also surveyed a community of practice devoted to meters. Chapter 4 includes a report on the inventory of components and what we learned about secondary effects on them.

As explained in Chapter 4, the research team compiled the data from utilities so it could be synthesized into a cause and effect presentation. By this time, we also had begun to focus on the calcium and aluminum incidents as the main effects to study. This led us to re-examine historical literature and to re-contact some experts to confirm our findings about these episodes. As mentioned earlier, we also conducted an additional survey of state regulators to check our earlier findings. The draft final report was due in February 2009, so Phase 3 extended into report preparation as we compiled, checked, and revised our major explanations and findings.

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# CHAPTER 4
# PROJECT FINDINGS

## SCOPE OF THE CHAPTER

This chapter outlines the project findings, which are organized by the effects of calcium, aluminum, iron, and manganese. It includes observations made by others about these effects, as well as observations that are reported for the first time through this project. In all cases, the sources of the observations are noted.

Calcium effects were noted more than others, but aluminum effects were also significant. Iron and manganese effects are not primarily due to secondary effects of corrosion control, but can be inter-related with other scaling effects and utilities do not always know what type of scales they are experiencing. For those reasons, iron and manganese effects are discussed briefly in this chapter, along with calcium and aluminum effects. In any case, as many scales are composites of different compounds, it is not always possible to separate the effects cleanly into distinct categories.

## CALCIUM EFFECTS

As noted in Chapter 2, calcium effects go back many years and are a central issue in aquatic chemistry. The experience base with them includes many episodes of scaling and precipitation under different conditions. Discovery of calcium problems in some utilities was an important driver that led to this project. However, the prospecting and surveys of the project did not turn up many instances where calcium scaling was considered a serious problem. Our assumption is that, because calcium scaling is an old and widespread issue, most utilities are aware of it and have already taken corrective steps where required. However, some serious problems with unexpected calcium precipitation were identified, and these are explained in this section. Also, we believe that many insidious problems with calcium scaling are building up and are part of the general problem of "pipe aging" in the country. The extent to which this is occurring was not identified in the project.

In the initial round of contacts and in the first survey, we were alerted to only a few incidents of calcium scaling by state government regulators. Again, in our final survey of regulators, only a few problems were reported. This seemed to confirm the rather low incidence of serious problems discerned from the first survey.

While in the initial utility survey, calcium problems were reported more than any other problem, only nine reports of significant effects were received in 63 utility replies. In some cases, the calcium effects were reported in association with iron and/or manganese, showing how problems can be mixed in nature.

### Specific Episodes of Calcium Effects

The water utility in Needham MA experienced pH–induced calcium precipitation of a groundwater supply. Rego (2006) had reported this case earlier, and it was one of the problems that led to this research project. Needham was also a participating utility for the project, and the Principal Investigator visited them to learn more about their experiences.



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Needham's base supply is local groundwater, but they also receive treated water from the Massachusetts Water Resources Authority (MWRA). This makes analysis of their situation more complex because of the mixture of the waters. The problem in Needham occurred when the utility was implementing corrosion control by carbonate passivation using NaOH for pH control. The calcium precipitation that resulted caused excessive pipe scaling and a range of customer complaints.

Needham's initial water supply parameters were (Rego, 2006):

| | |
|---|---|
| pH | 9.1 |
| Hardness (mg/L) | 75-90 |
| Calcium (mg/L as Ca++) | 25 |
| Alkalinity (mg/L as CaC03) | 100 |

The adjustment of pH began in January 2000. By late winter, customer complaints were of "sandy material," which tested as $Ca^{2+}$.

Needham's studies indicated that pH 8.2 was about the right level to avoid precipitation, but they needed to balance risk of lead release and calcium precipitation. The pH level of 8.2 was determined to be the point that would stop calcium from precipitating in hot water systems and to deal with aesthetic issues, but it would result in a significant increase in lead solubility. They reported that the solution was to keep the pH higher but to use orthophosphate and blended polyphosphate sequestering agents to control $CaCO_3$ precipitation. They used a feed system with a 75/25 orthopolyphosphate blend, and very few calcium precipitation complaints occurred afterwards[1]. This indicated that the phosphate addition was helping to inhibit calcium precipitation.

The lessons from Needham's experience were that high pH in their water led to excessive calcium precipitation and that they were able to maintain a pH high enough to suppress lead release by using the correct feed of a blended polyphosphate. The source waters receiving this treatment were a mixture, and a trial and error approach was required.

Cambridge MA is also located in the Boston area, but it uses a surface water source, along with some treated water from MWRA. Cambridge also experienced problems with calcium precipitation, but in a different way than Needham (Rego, 2006). Needham's problems were in the distribution system, whereas Cambridge had problems in the treatment plant. The utility joined the project as a participating utility and the PI visited them to discuss their problems and solutions.

In October 2004, Cambridge started experiencing pump failures. The utility had made a minor change to their finished water pH control strategy, with a 0.1 to 0.2 upward shift in pH. This created calcium carbonate deposits in their high-lift pump wells and on the exterior and interior surfaces of the pumps.

Investigation showed hard coating and gritty material on the wetted parts. The build up started after the KOH injection point, which was used for pH adjustment. X-ray diffraction showed substantial $CaCO_3$ (Rego, 2006; MacDonald, 2007). In addition to the pH increase from about 9.0 to 9.3, the source water had increased in $Ca^{2+}$ over the last 10 years (13 to 25 mg/L), possibly as a result of an increase in road salting.

The solution used by Cambridge was to go to a more precise pH adjustment and to move the KOH injection point downstream of the pumps. This has apparently solved the problem. This

1 Personal communication with Bill Wanberg, December 13, 2007.

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solution was implemented by utility managers as a result of inspection and study of their unique experiences. This solution has been reported to the PI by other utilities as well, indicating that the dispersion of the high-concentration chemical is a factor in causing precipitation near injector points.

Cambridge's problems point to calcium precipitation in mixing zones and during chemical feed. These problems also occurred in smaller utilities described later who were using chemical dosing to raise pH.

Figure 4-1 is a view inside the pump housing of a high lift pump in the Cambridge Water Department's treatment plant. It illustrates the extensive scaling that caused the problems described above.

**Figure 4-1. Calcium scaling in pump housing (Credit: Cambridge MA Water Department)**

The project team learned from the state regulator that the City of Lorain, Ohio was having calcium problems and we discussed the problem with utility management. We contacted them a year later as well to learn of any useful follow up experiences.

Lorain uses source water from Lake Erie, and lime is added to raise pH for LCR control. This caused a substantial buildup of calcium in the distribution system. The calcium problem was spread across the distribution system, and a number of pipes were completely clogged up. A 6" pipe might be clogged down to 1", for example. This is an old system, and pipe is mostly cast iron, even some wood. It was also necessary to replace some customer service lines due to the clogging. The scales and precipitates contain calcium compounds, some silicates, and some magnesium salts.

Lorain did unidirectional flushing and got rid of a lot of the sludge, but not all of the calcium problems. The flushing program also helped to identify valve locations and condition and to get information on the system.

For remediation of the calcium problem, Lorain has replaced pipes and they got permission from Ohio EPA to lower pH from 7.8 to 7.5. At the time of our first contact, they

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were working on interim approval, which was about to expire. Therefore, a period of adjustment and monitoring was required.

A year after the initial contact, Lorain indicated that their interim permission to hold pH down was contingent on a program of orthophosphate dosing, which they ramped up from a level of 0.5 mg/l to 1 mg/l. They are in compliance on lead and copper and the flushing program has been continued, with only a little indication of excessive scales and precipitates being flushed out. There have been some high orthophosphate concentrations in dead ends, and turbidity was an issue with the orthophosphate. However, calcium clogging seems under control after a replacement program[2].

Lorain's experiences point to pH problems with their source waters and control by use of pH control and pipe replacement.

In Pennsylvania, the team was directed by state regulators to a small utility, the Shrewsbury Water Company. The utility had discovered a problem a few years ago with the pipeline that discharges from a well house clogged with solids. Shrewsbury thought the problem was caused by sodium hydroxide that was injected to raise raw water pH. Their samples showed that most of the material was calcium (Sweitzer, 2007). A photograph of the pipe clogging illustrates this problem clearly (Figure 4-2).

**Figure 4-2. Calcium scaling in piping (Credit: Shrewsbury Water Company)**

In our final survey, conducted in fall, 2008, the team was directed by the Wisconsin state regulator to two small utilities with problems similar to those experienced by Shrewsbury. In one utility that used a groundwater source, calcium precipitated downstream of a caustic soda injection point, plugging a pipe. The problem had built up over a period of years and was solved by pipe replacement, and there is no evidence of serious problems further downstream. The operators indicated that they knew of one other local utility with similar issues.

The lessons from these episodes of small utilities using groundwater sources is that a high chemical concentration may cause severe localized calcium precipitation, and the solution

2 Information about Lorain, Ohio is from personal communications with Jim Miller, City of Lorain.

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depends on local configuration and methods of injection. As in Cambridge, the solution might be relocation of dosing points and in some cases, pipe replacement.

Austin, Texas is an example of a water utility with scaling problems from lime-soda softening. Their scaling problems did not involve corrosion control treatment, but were similar to utilities that did practice it. The utility participated in our project, and shared valuable details of their experiences with us.

Austin applies softening to its relatively hard water from the Lower Colorado River (hardness and alkalinity of 200 and 160 mg/L as $CaCO_3$). The city carried out an extensive investigation of causes of scaling, and the results are reported in (Morabbi and Clark, 1999). Because of the published research paper, details of Austin's experience can be summarized here.

Austin produces water that is relatively high in pH. To minimize scaling and prepare for disinfection regulations, they initiated re-carbonation in 1994 at two of its three plants and sought to lower the pH from 10.1 to 9.2 in small increments. During 1996, maintenance crews noticed that scale in the south system was softer and more fragile than in the north system. Their data suggested a relationship between pH and scale integrity in the distribution system.

They calculated recommended values for the Langelier Saturation Index and the Calcium Carbonate Precipitation Potential (CCPP) and although results varied, they suggested that even the lowest observed pH of 9.5 indicated that the tap water was supersaturated with $CaCO_3$. However, their previous analysis showed that very little $CaCO_3$ was in the scale, and suggested that sodium hexametaphosphate was inhibiting formation of $CaCO_3$. The phosphates inhibit the deposition of $CaCO_3$ but have no effect on deposition of magnesium and silicates.

Austin performed coupon and pipe loop studies including a hot water pipe loop. They noticed significant corrosion and scaling on some steel coupons after 73 days. After 820 days, all steel coupons showed higher scale buildup than copper coupons. They attributed this to the reaction of iron and creation of tubercles. They concluded that there was an important role of pH in scale accumulation. They found that the coupons removed from an inlet showed lower scale accumulation rate than those removed from an outlet. This is due to higher turbulence in the inlet versus the outlet.

Austin performed analysis of scale from clearwells, the distribution system, and pipe loops. Very little calcium was identified in the scale. The chemical model MINEQL+ predicted different scales than the XRD showed, and scale from the south system seemed to be different than scale removed from the north and central distribution systems.

A slight reduction in pH had a dramatic effect on the deposition rate and composition of scale (looking at accumulation rates on copper pipes. Scale in the hot water loop was not affected by the pH reduction. The majority of the scale retrieved from steel pipes and coupons consisted of iron minerals. Magnetite and goethite were in the scale from the steel pipe sections at two plants, and calcium, magnesium, and silicate minerals were found at different locations.

Overall, Austin believes that even small (0.2) reductions in pH dramatically affect the stability of scale. They believe that polyphosphate addition inhibits formation of calcite, even though the calcium carbonate precipitation potential (CCPP) values show supersaturation. Their studies suggest that turbulence, pH, and temperature have the greatest effects on scaling rates. Iron materials experience more scaling than other materials due to the initial reaction of unprotected steel with the water before protective scale is formed. Temperature is an important variable in scaling and raising temperature of water by about 20$^{o}$C increased the scaling rate by a factor of four in one case.

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Austin's experiences were not directly from corrosion control treatment but they involved water with high pH levels. Their experiences show how a utility must consider multiple factors and types of scales, and how in complex systems a utility must conduct careful studies before drawing conclusions about courses of action. Austin considered that the corrosion rates determined from the study demonstrate the beneficial protective effects of the scale. Austin anticipates that disinfection and disinfection by-product rules will place more focus on pH in disinfection practices.

The Tampa Water Department experienced pump failures from scaling that occurred after treatment for iron corrosion. They were responding to severe red water and scale build-up that were associated with drought conditions. A study showed that pH stabilization and higher CCPP values should be used to correct red water from iron releases. After implementation of this control program for iron corrosion, the problem shifted to scale build up that seized pumps. Later, in addition to numerous pump failures, there were indications of reduced metered account sales attributed to excess calcium carbonate scale. Pump failures were correlated to high CCPP and pH levels. Solution included control of scale production within a tighter CCPP range while maintaining a target pH, and this eliminated the pump failures, reduced meter failures, and reduced red water complaints (Brodeur, 2007; Tampa Water and Boyle, 2006).

This set of experiences indicates that pH control is the key issue in calcium scaling, and that such scaling can occur when a utility responds to a corrosion problem such as red water. Solutions in this case focused on target pH control.

In the initial survey of state regulators, only a few other problems were reported. For example, in Iowa, a mid-western state with a large percentage of groundwater use, the state regulatory agency reported that significant problems had occurred in only a few situations as a result of treatment. Some small water systems did have scaling problems from use of galvanized steel pipe installed 50 or more years ago. One small utility in particular was described as having highly–precipitating water, but no recent scaling problems have been reported and the problems are not state wide.

In Colorado, the regulators had tracked LCR issues for 14 years but there was no database of experiences and the data trail on experiences was described as weak. A number of utilities controlled pH and alkalinity for LCR and most were successful. Where there were problems, they tended to be small utilities with operator turnover. One small utility with a contract operator had tried a number of approaches (sodium silicate, caustic soda, pH, alkalinity, etc.) but had problems and frozen meters. The regulator thought that problems like this were caused by not controlling feed rates well. This seems to be the same type of problem experienced in other smaller utilities, as described above.

A Northwest Florida regulator reported that most water comes from two aquifers, one sand and gravel and the other in the Floridan formation. The sand and gravel aquifer is low in calcium and while the Floridan contains limestone, no precipitation problems have been noted. A medium utility in the Florida panhandle reported no problems with plugging or pump failures caused by precipitation products. However, precipitation in the distribution system did occur when the pH exceeded 8.0. The resulting "white water" is controlled by flushing. They use orthophosphate and pH control to form a passivating film on distribution piping and house lines and have had compliance with the LCR since 1996.

A state regulator in Minnesota knew of one issue with $CaCO_3$ scale when pH adjustment using caustic soda was applied. The report was of problems with $CaCO_3$ precipitation and the

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need to replace water meters and respond to complaints about low water pressure and clogging of hot water lines in high-rise buildings.

A large utility in Southern California responded: "… our corrosion control strategy is pH adjustment of our finished water prior to entering any clearwell. The only problem we have is the localized softening causing $CaCO_3$ precipitation on the walls of concrete structures. Other then nuisance rodding out of chemical diffusers, we don't have any real impacts to hydraulic equipment."

From Missouri, a regulator reported a small utility with red water problems and the operator was afraid of scale-forming water coating the mains and plugging them with calcium deposits, so he went too far in the opposite direction and created corrosion issues.

A report from Connecticut was of a small private water company that used lime for corrosion control. About ten years ago they experienced severe $CaCO_3$ buildup in pipes and valves and changed to sodium hydroxide for corrosion control treatment. The operator has left.

In our survey of the meter community, we found almost no reports of general scaling issues. One quote was: "In my 50 years of experience … there has never been an operational problem as long as the $CaCO_3$ is in solution. I have seen cases where slight deposits did build up on bronze internal measuring chamber surfaces, but being soft they actually made the meters more accurate by reducing the normal slight leakage clearances, and otherwise had no ill effects. If the inside of the meter is ever allowed to dry out the deposits will become hard and this may cause operation problems. Of course this drying never happens while the meter is in service."

Another quote about meters was: "In round numbers, there are something like 80 million water meters in service in the USA. These meters have an average useful life of something like 15 to 17 years. Yes, there are some recorded instances of scale fouling in water meters but the sheer numbers of successful lives unencumbered by all causes suggests that this might not be a worthwhile project (meaning to look for scaling problems). … Our Returned Material records show relatively little instances of stuck or "frozen" meters from any and all causes considering the large numbers shipped to our customers. There would be an even more miniscule number of returned meters where the cause of stopped meters was identified as precipitation of $CaCO_3$." Also, the meter managers in two large East Coast utilities wrote: "I have not seen any scaling problems in the meters we have removed for whatever reason," and "To my knowledge, we have never had an incident of a frozen "non-registering" or "seized" meter that could be attributed to water chemicals or any associated scaling."

One meter specialist did report some past problems: "… in many cases, stuck meters are directly related to scale. Twenty years ago, my experience was in testing large water meters for many different utilities around the county. I remember one particular utility… most of the meters were in very poor condition due to $CaCO_3$ build up on the internal parts. Most had stopped running. Since it was a long time ago, they may have resolved the issue."

## Conclusions About Calcium Scaling

Given the widespread occurrence of hard water, the results showed that utilities where calcium is a problem have usually recognized it and dealt with problems caused by calcium scaling. This has normally required them to implement local solutions that work. When we did find problems, they seemed to surprise the utility due to a change or underlying condition that had not been recognized before.

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For a long time, the use of controlled calcium carbonate scaling has been considered desirable to protect pipe walls from corrosion. This strategy assumes that if scales are deposited on pipe walls, they will protect the pipe from corrosion. The strategy depends on the operator's knowledge as to whether CaCO3 will stay in solution, precipitate, or be in equilibrium. The accepted method to assess if water is saturated has been to use saturation indices as guides. However, this method has been called into question due to the rapid changes in CaCO3 scaling that can occur. The conclusion is that the indices provide rough guidance but are not precise enough for all decisions.

Lack of precision and wide variability in the pH of a system can cause unexpected levels of scaling and precipitation. The reasons for this were explained in Chapter 2 where the ability of the calcium compounds to remain in solution was shown to be very sensitive to pH changes. In some waters, calcium precipitation can occur suddenly due to pH shifts. When CCT is added to established treatment regimes, such upsets can occur when they had not been experienced before. Even if these episodes result from corrosion control treatment, they may not look different from those that occur from other treatments, such as softening.

Hard water that contains calcium compounds is subject to saturation. The carbonate system controls pH, and water solutions can change quickly from stable to saturated. Thus, water might experience sudden precipitation if pH increases beyond a threshold. This can be exacerbated in hot water systems because calcium carbonate precipitates more readily in them.

Another factor is the difference in bulk and wall conditions. The indices may indicate bulk conditions, but near the wall velocities can be slower and precipitation might occur there but not in the faster-moving zones. Turbulence as well as velocity itself seems to be a factor in inhibiting scale formation.

While water chemists generally understand the influence of pH on calcium scaling and precipitation, problems must be diagnosed on a case-by-case basis. The problems identified in this project were episodic and not systemic. When the problems were found, they were generally solved by system-specific studies that usually focused on pH control. The use of inhibitors together with pH control was also a common factor, both because inhibitors might compensate for a low pH (as in Lorain, OH) and serve to inhibit calcium scaling at higher pH values (as in Needham, MA).

Where calcium problems occur near points of injection, remedies may be more local in nature. That is, moving the point of injection, using diluted feedwater, or changing velocities through re-configuration of piping may help to solve localized problems.

On a final note about calcium scaling, it should be noted that it often occurs in association with other compounds. Figure 4-3 illustrates the inner parts of a meter from a utility's pump station discharge line. The scale is mostly calcium carbonate, but it has a brown veneer, which suggests iron deposits. The lower layer is rich in copper, which may have occurred from leaching of the base metals in the meter.

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**Figure 4-3. Scaling on pump station meter**

## ALUMINUM SCALING

The aluminum effects identified during the project were signaled by historical reports of loss of pipe capacity. While several utilities in our surveys and/or interviews reported that some aluminum scales were found, the most useful reports about aluminum came from either published literature or information supplied to the project team from utilities that had studied the problem themselves, such as Chicago.

Rochester, NY had encountered serious problems with aluminum scaling and reported them in (Kriewall, et. al., 1996). Their issues related to raw water, coagulation, and pH control. The utility also participated in this study and supplied updated information about their experiences.

In 1993, Rochester began filtering its drinking water from Hemlock Lake in the Finger Lakes Region. After pilot studies in 1988-89, an aluminum effluent residual of 0.3 mg/l was considered the upper limit. The majority of pilot runs with polyaluminum chloride as a coagulant resulted in residuals between 0.05 and 0.2 mg/1.

Raw water pH was an important factor. In the pilot runs, the lowest aluminum residuals occurred after the fall lake turnover when lower raw water pH conditions were more conducive to aluminum coagulation. It was concluded from the pilot studies that a combination of polyaluminum chloride and cationic polymer coupled with dual media filters were best.

Soon after startup, the capacity of the transmission gravity system decreased. In 1995 a five-mile section of one conduit was isolated and drained. Inspection showed a very thin and reddish, slimy coating on the cement mortar lining. This was a fairly uniform but rippled layer less than 6 millimeters thick along the entire circumference and length of the pipe.

Analysis of the coating showed 15% aluminum content and 50% organic component by dry weight. The source of the organic material was not determined. The analysts found the aluminum content was similar to data from Lexington, Kentucky, which also had an experience with precipitate buildup.

The slime deposit did not seem thick enough to cause the flow reduction, but investigators concluded that it probably did explain the loss in capacity. This report is similar to

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historical reports we found where utilities were surprised that thin layer of rippled scale could cause large losses in capacity.

Rochester made a concerted effort to reduce the aluminum residual. They installed a $C0_2$ system to reduce raw water pH to about 7.5 during the summer months when it tended to increase. After the $C0_2$ installation, they found that aluminum chlorhydrate (ACH) was an effective summer coagulant and they could generally keep residual down to 0.05 mg/L or less without $C0_2$. They used ACH as the warm water coagulant for a few years and only turned on $C0_2$ if treatment was difficult.

Al residual was not a problem in the colder months because raw water pH dropped back to around 8 or less when lake algae were not thriving. Since ACH tends to form a weak floc in cold water, they switched back to polyaluminum chloride from about Oct through May.

An adjustment of pH was effective to dissolve the precipitate and full capacity was restored within four months. Initiation of pH adjustment was by adding potassium. hydroxide at the clear well. The target effluent pH was 8.7. In a test, aluminum residuals increased almost immediately, indicating that some precipitate was dissolving.

Later, polyaluminum chloride was re-introduced as a coagulant to remove blue green algae from the raw water. Also, the pH adjustment was stopped in anticipation of lead and copper control. This caused loss of capacity again, despite aluminum residuals of less than 0.1 mg/l. It was unknown if this low level of residual aluminum could have impacted flow capacity in such a short test period.

Sodium silicate was introduced to raise pH for lead and copper control. This was apparently not sufficient to re-dissolve the residue but was adequate to prevent further aluminum precipitation. After remediation, their gravity feed conduit system retained a capacity of about 45 MGD, compared to about 37 MGD when the problem occurred.

Rochester's experience shows that a thin layer of aluminum scale can cause significant capacity losses. It illustrates that a utility must consider seasonal changes and experiment with treatment processes that work on its water, as opposed to off-the-shelf remedies. Their remedies had to work in the presence of the particular aluminum species involved and might not apply to other utilities.

Figure 4-4 is a photo taken inside of Rochester's pipeline. It illustrates the "slime" that can occur from certain types of aluminum deposits on pipe walls. While the photo is not as graphic as some iron tuberculation photos, it illustrates the "wavy" corrugations that lead to high head loss in pipes.

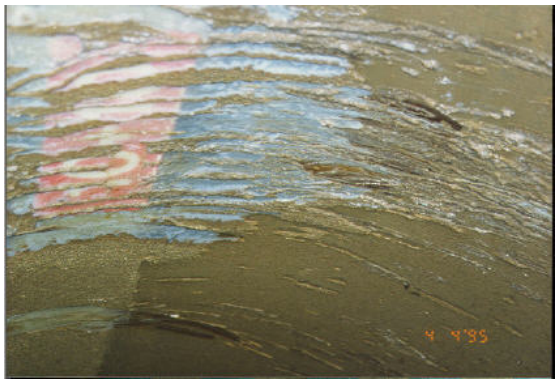

**Figure 4-4. Aluminum scaling in Rochester pipeline (Credit: City of Rochester Water Department)**

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The Chicago Water Management Department has extensive experience with aluminum-phosphate scales. Chicago's system serves 5.4 million people in the City and another 125 suburbs as wholesale customers. Chicago utilizes Lake Michigan as its source water with two conventional water treatment plants, one to serve the northern areas and suburbs and the other to serve the southern areas and suburbs. Finished water is distributed to the districts through three finished water tunnels and twelve pumping stations[3].

Chicago's experiences with water treatment and pipe effects have been noted before. As noted in Chapter 2, Hudson (1966) reported different pipe aging experiences downstream of Chicago's two treatment plants as a result of treatment. Costello (1984) reported on some of the city's post-precipitation experiences.

Chicago's distribution system contains 73.4% cast iron (very little with concrete lining); 23.3% ductile iron with concrete lining; 3.1 % concrete mains; and 0.2% steel mains. The total size is 4,230 miles of drinking water distribution pipes

At plant start-up in the 1947-64 period, Chicago used pH adjustment for corrosion control. The pH was increased via lime feeding and the Langelier Saturation Index was maintained at greater than 0.1 to minimize lead leaching by scale in pipe. In 1986 to 1990, Chicago conducted lead surveys and found that concentrations were above today's action level but below the MCL of the time at 50 µg/l. After that, blended phosphates were used from the 1993 to 1994 period to reduce lead levels.

In 1995 to 1996 the DWM stopped feeding lime for pH control because the pH was too high for optimum phosphate-based corrosion control. In late 1997, a wholesale customer in the suburbs reported hydraulic losses, possibly due to deposition from phosphate addition. Dr. Vernon Snoeyink characterized the deposition as aluminum-phosphate.

Chicago initiated pilot plant studies to investigate the problem. They found that adding orthophosphate during coagulation could reduce aluminum concentrations without degrading finished water quality.

Chicago's efforts to study and manage scaling and water quality have involved extensive in-house research, consulting studies, and participation in research projects. The utility continues to evaluate data and make adjustments to optimize treatment and distribution system effects. Given the size and complexity of their networks, their research programs must continue and be linked to periodic treatment adjustments.

Figure 4-5 illustrates white aluminum phosphate and brown lead phosphate scales obtained in City of Chicago pilot studies.

3 Andrea Putz, a member of the Project Advisory Committee, contributed materials to explain Chicago's ongoing experiences with pipe scaling and water treatment. See (Putz, et. al., 2005).

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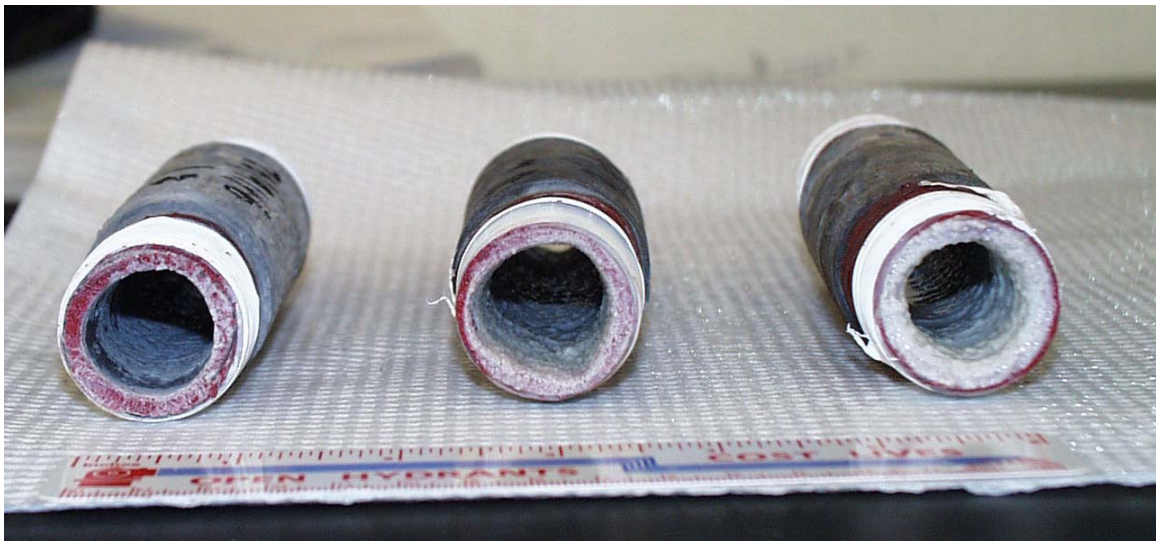

**Figure 4-5. Phosphate scales from City of Chicago pilot studies (Credit: Chicago Water Department).**

Grand Rapids has experienced significant mechanical failures and maintenance needs due to feed of blended phosphate. They treat water from Lake Michigan and pump it approximately 25 miles to the City. The most serious problem is a reduction in pumping capacity since phosphate feed for lead corrosion control started. Inspection showed a rough but soft buildup 1/16 to 1/8 inch in depth on the walls of a smooth concrete pipe. The coating is mostly P, Ca, and Al[4].

The service life of the high pressure pumps has been reduced. Their bearings and shaft surfaces show a white buildup of phosphate. Also, the treatment plant has plugged strainers. The utility also has increased maintenance requirements on preventers and pressure regulators from phosphate buildup. The treatment plant is altering the feed water to overcome problems.

Samples in 2003 from the transmission main showed aluminum at 11-17%; calcium at 20-40%; P (as total P) from 9-16%. Prior to initiation of the phosphate feed the coating was thinner. It included 22% aluminum, 22% silicon, 10% calcium and 39% iron, which may have been from $FECL_3$ feed at that time. Earlier, they fed lime ahead of the filters, thus dissolving more aluminum and creating problems with AlOH . The pH leaving the plant was about 8.2, and it has been lowered to about 7.5 (John Wierenga, personal communication).

## Data From Surveys

While we expected to hear about aluminum scaling in our surveys and interviews, we received very little comment about it. A few utilities reported that the scale contained some aluminum, but we did not identify utilities with the kinds of problems reported in Snoeyink et. al. (2003), which are summarized in Chapter 2. This does not mean that the problems are not widespread, but it seems to indicate that serious problems have been attended to by utilities such as Rochester and Chicago and that the other problems are building slowly and/or are

4 John Wierenga, also a member of the Project Advisory Committee, contributed materials to explain Grand Rapids' experiences with scaling and remedial actions.

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manageable. Chapter 2 contains more extensive information on aluminum scaling from historical accounts.

### Conclusions About Aluminum Scaling And Precipitation

The fact that this project turned up few reports of aluminum problems is consistent with the observation by Snoeyink et. al. (2003) that aluminum scaling has received little attention. However, the anecdotal reports of capacity losses from decades past indicate that aluminum scaling is a long-standing issue, most likely attributable to coagulation effects.

The complex chemistry of aluminum scaling and precipitation is manifest by the different forms they can take, indicating that problems can occur from different source waters, different treatments, and even from conditions that occur within distribution systems. Given these many possibilities, it is not possible to prescribe a universal solution, other than to recommend monitoring, analysis, and pilot studies. Aluminum problems, like other incidents of scaling and precipitation, will require case-by-case studies.

The most significant effect of aluminum scales seems to be that they can cause large capacity losses. Other effects have not been demonstrated, but appear as research needs, such as those identified by Snoeyink et. al. (2003). These research needs include to learn the extent to which treatment changes can destabilize aluminum deposits and how this would occur. Given the possibility that aluminum coatings are protective of metal surfaces, research is needed to determine how to retain the protection while reducing the capacity loss. This will include showing the roles of the origins of aluminum, so that proper treatment strategies can be designed.

Coagulation and corrosion control seem to be jointly implicated in aluminum changes in pipes, and it is unknown whether treatment changes, and the different forms of aluminum chemistry, affect concentrations of lead and copper at the tap. In particular, it is important to study the role of inhibitors in forming aluminum deposits because utilities need information on which to base their choices of inhibitors.

## IRON AND MANGANESE EFFECTS

In our surveys and interviews, we encountered utilities with corrosion and scaling problems associated with cast iron and ductile iron pipe, but the problems were chronic and generally known to the utilities. These pipes and their fittings provide sources of iron that can become part of scales in distribution systems. The iron available to become part of scales comes from multiple sources because natural waters also contain iron.

In our interviews and visits, we were shown photographs and examples of scale that had been removed from pipe. These seemed to be a combination of iron tubercles and scale or precipitates that has collected in pipes. Each of these would have a different composition, but most seemed to be combinations of iron compounds and organic material, similar to those reported in the literature (see Chapter 2).

There does not appear to be any result of corrosion control treatment that affects iron scales or precipitates in a significant way, although pH control and other forms of corrosion control treatment will affect iron corrosion, metal release, and scaling. The literature review on these effects is in Chapter 2.

Figure 4-6 illustrates a common form of iron corrosion. In fact, this sample is displayed in the lobby of the AWWA in Denver.

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**Figure 4-6. Iron pipe corrosion (from lobby of AWWA in Denver)**

In a similar way to iron effects, we heard of manganese problems during our interviews and surveys, but they did not seem to be related to corrosion control treatment. Chapter 2 provides background on manganese effects and research.

Figure 4-7 illustrates an episode of manganese deposition from a pump in a treatment plant.

**Figure 4-7. Manganese deposition from pump.**

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## HYDRAULIC EQUIPMENT ANALYSIS

Part of the project was a study of hydraulic equipment to learn which components were most vulnerable to failures due to secondary effects. The utilities surveyed manage thousand miles of distribution systems and their components. From the relatively few utilities that reported problems, we were able to ascertain the relative vulnerability of pipes, pumps, valves, meters, injectors to scaling. While no general patterns emerged and while the incidence of problems was relatively low, we were able to see vulnerabilities of components as follows:

| | |
|---|---|
| Pipes | Beginning with tuberculation in unlined cast iron pipes, all raw and treated water supply pipes are subject to some form of corrosion and/or scaling. Calcium and aluminum scales can form on any pipe surface, and water supply pipes must be managed to minimize negative effects of these scales. |
| Pumps | Pumps are vulnerable to failure due to excessive scaling. The scales can be of different metals and compounds, but as shown by the project, they can cause problems ranging from lower efficiency to outright failures. |
| Valves | Valves are similar to pumps in that they involve moving parts whose function is inhibited or blocked by scales. While utilities are aware of many inoperable valves in their systems, the degree to which the inoperability does not seem to be understood very well. |
| Meters | Meters have moving parts and can lose accuracy and functionality from scaling in the same way as pumps. While the project reports did not turn up an epidemic of meter failure, loss of accuracy and periodic meter replacement are caused by corrosion and scaling. |
| Injectors | Injectors are directly involved with scaling issues because they may create precipitates directly downstream due to incomplete mixing and high chemical concentrations. |

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# CHAPTER 5
# PROJECT CONCLUSIONS

## GENERAL RESULTS

The project goal was achieved in that the study resulted in an assessment of distribution system and treatment plant equipment problems that occur as a result of water quality adjustments made for corrosion control. This assessment included a scan of the literature, surveys and interviews of utilities, regulators, and experts, and analysis of a large amount of written and anecdotal data.

In addition to recent implementation of corrosion control under the LCR, the project also studied older corrosion control methods and other treatment processes, such as water softening, which have similar effects. In effect, it provided an overview of historical as well as current problems with secondary effects based on scaling, precipitation, and failure of pipes and hydraulic equipment.

The project did not turn up any unexpected severe problems, so there is no "smoking gun" for the general problem of secondary effects from corrosion control or related treatments. Problems can occur suddenly, but more often they occur gradually and are part of the larger problem of aging infrastructure, somewhat like the gradual buildup of plaque in human vascular systems that cause hardening of the arteries.

The report can be useful for operators and utility managers who must diagnose the health of their systems and implement improved management practices, as well as to solve sudden problems that require emergency action and special studies.

Outside of a small community of scientists, operators, and engineers who are expert in internal corrosion, collecting data on secondary effects is not easy for several reasons. It is not always clear whether the water quality manager, the distribution manager, or the customer service manager will be the source of information. In the absence of direct knowledge, a response from a utility will be "we do not have those problems," or the utility will report routine tuberculation, encrustations, and loss of pipe capacity. Also, most regulators normally lack direct knowledge of effects in utilities. There is no central database for utilities with experience in corrosion control. This is logical as there is no database for compliance with other regulated parameters either.

## SPECIFIC RESULTS

The scaling and precipitation problems that occur are usually from imbalances among chemical content, pH, water temperature, and other constituents and parameters. Problems manifest themselves mainly as calcium or aluminum-based scales, and to a lesser extent as other metal compounds, including iron, manganese, and others that contribute to mixed scales. Sudden problems are rare but can be serious. Chronic problems are widespread but are not given much attention because they build up slowly and seem to have been accepted by utilities as inevitable issues requiring maintenance and renewal.

Calcium problems are more common than aluminum problems, but seem to be mostly under control or occurring gradually in distribution systems. Use of calcium carbonate scaling to protect pipe walls from corrosion has been practiced for a long time, but can get out of balance.



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Use of saturation indices as guides to chemical dosing is in practice by many utilities, but the precision of these indices in predicting problems has been called into question by researchers.

The aluminum effects identified during the project seemed to continue a historical pattern of loss of pipe capacity. The compounds involved in aluminum scaling and precipitation take on different forms and universal solutions will not work. Aluminum effects identified during the project, such as corrugated or rippled precipitates, were similar to those reported historically about loss of pipe capacity. As with calcium scaling, no single solution works in every case and utilities normally must conduct site-specific studies.

## REMEDIATION STRATEGIES

Generally speaking, remediation of secondary effects involves water treatment changes, system re-plumbing, and replacement of components. Water treatment changes focus on pH adjustment, use of inhibitors, and adjustment of other treatment processes, such as coagulation, that might be implicated in excessive scaling.

While it would be desirable to offer general solutions, calcium scaling and precipitation problems are dependent on local and highly-variable water chemistries, and must be diagnosed on a case-by-case basis. Diagnosis should involve problem identification, learning the cause of the problem, and taking corrective actions.

## OVERALL OBSERVATIONS

It is difficult to predict where effects will occur because hydraulic and chemical conditions within distribution and plumbing systems are so varied. While regional trends in water quality exist, the diversity of water sources is too great to make general statements about links between source waters and secondary effects. Combining this localized nature of source water chemistry with the variation among treatment and distribution system characteristics leads to the site-specific nature of scaling problems.

While the project did not uncover an epidemic or generalized pattern of secondary effects, it noted that corrosion, scaling and precipitation are important, long-standing issues for utilities. However, there seems to be a low level of concern with this problem, probably reflecting the fact that it is a creeping problem rather than a sudden one. However, sudden problems can occur and a utility can lose capacity quickly and be forced into action. Distribution system scaling is like heart disease, where routine concern about build up of plaque in arteries may not be enough to lead to change of habits, but eventually remedial action is required and in some cases, a young person can suffer a sudden heart attack.

Managing internal corrosion and scaling requires high-levels of skill and understanding and some utilities may suffer from workforce losses that impair their institutional memory of the buildup of problems. The remedy for this will be to include internal corrosion and scaling in the knowledge management programs of utilities, and to connect these to condition assessment and the utility asset management program. The need to integrate treatment and distribution system knowledge this way so that secondary effects can be monitored presents an organizational challenge for coordinated work among treatment, distribution, and laboratory staff.

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## GAPS AND RESEARCH NEEDS

The main gap observed in the project is that internal corrosion and secondary effects of treatment that impact pipes and hydraulic equipment are insidious problems without a current long term solution. Using a heart disease analogy, it is not possible to stop aging but performance and life can be improved and prolonged by appropriate action.

While medicine has specialists in heart disease, the water industry lacks a concentrated effort to deal with internal corrosion and deposition effects. It is noteworthy that AWWA does not have a separate technical committee devoted to these issues and the Corrosion Committee's mission explicitly excludes internal corrosion. However, a subcommittee in the Division is preparing an AWWA manual on internal corrosion.

The research exposed that non-regulatory operational issues involving water chemistry are poorly documented and disseminated in the water industry. Without a regulatory driver, there may be poor characterization of water chemistry and materials conditions that cause problems. Thus, prediction and mitigation are both seriously hindered.

Specific research needs that were identified in the project are:

- Basic studies to characterize the formation of biofilms and different scales;
- Studies to probe the nature of scale formation in different flow conditions, on different materials, and with different water chemistries;
- Studies of water treatment effects on corrosion and deposition in distribution systems and on re-equilibration and destabilization of scales;
- Studies of flow under both steady and unsteady state conditions and in different pipe configurations to determine effects on biofilms and scales;
- Studies of roles of inhibitors in passivating pipes and inhibiting formation of precipitates and scales;
- Optimization studies issues to understand systems effects of galvanic actions, microbial actions, electrical potentials, lead leaching, and responses of components to different water chemistries;
- Economic studies of the insidious build up of scale and precipitates;
- Infrastructure studies of pipe aging and the extent to which equipment failures are due to slow build up of scale.

## GUIDANCE FOR UTILITIES

### General

Utilities require a dedicated program to manage internal corrosion, scaling, and precipitation in pipes and hydraulic systems. These are large and expensive problems for water supply utilities, and they are an important, but hidden part of the problem of aging infrastructure. Most utilities do not know the extent of these problems, but given the close connection between these effects and pipe aging and water quality, utilities should give close attention to monitoring and studying them.

Managing internal corrosion, scaling, and precipitation in water distribution systems is an operational optimization problem that poses challenges for detection and measurement, as well as finding solutions. Detecting and remediating these problems presents an organizational

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management challenge to utilities and utilities should recognize that this is a case of what is everybody's problem may not be anybody's problem. Internal corrosion and scaling can involve source water, treatment, and distribution systems. Therefore, utilities should consider management of internal corrosion and scaling as a utility-wide issue.

### Link to Asset Management

While responding to a sudden problem will require immediate and urgent action, the more important long term issue is to link analysis of scaling with condition assessment of pipes and hydraulic systems. Condition assessment is a complex challenge, and utilities should like it to their asset management system. As long as internal corrosion and scaling problems are relatively minor, they can go untreated with the risk being accelerated pipe aging and infrastructure problems. If scaling is found to be an important utility issue, then the next step would be monitoring and diagnosis.

### Monitoring and Diagnosis

Given their long term and sometimes subtle nature, internal corrosion and scaling problems are difficult to monitor. Therefore, they require dedicated utility programs to monitor and analyze them. Therefore, the first required action is for the utility to make the decision to study scaling and deposition issues to determine if a problem does in fact exist.

This requires a program that is similar to corrosion monitoring because scaling will be detectable on metal coupons or on pipe section walls in much the same way as metal loss. However, utilities normally lack systematic guidance for conducting such monitoring programs and must design their information collection programs. This requires someone to be in charge and to make a special study of scaling problems. Unless the cause of problems can be determined, remediation programs cannot be designed accurately. However, pipe cleaning and replacement can proceed, even in the absence of exact knowledge of the causes of scaling and precipitation. The risk in programs like this is that it attacks the symptom but not the cause.

### Studies

Utilities should study their systems to detect the presence of internal corrosion and scaling problems. The study should consider the following factors at a minimum:

- Corrosion effects
- Pipe coupons
- Loss of pipe capacity
- Valve problems
- Pump seizures
- Hydrant problems
- Colored water
- Hot water problems
- Plugged injectors

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Scale can be scraped off and analyzed for chemical composition, and the residues from pipe flushing and cleaning can be analyzed. A typical finding might be that scale and deposits are present but their nature is not known exactly. Given that scale composition may be mixed in character, this can present a challenge to learn what is happening in the distribution system. There can be seasonal or annual changes in composition and some scales look like tree rings with different characteristics and quantities over time. Others seem to be mixed with galvanic type corrosion to create mélanges of precipitate and deposits.

Pilot or full scale studies of treatment changes and pipe responses may be needed to learn the nature of problems and to test possible remedies. This can be done in experimental pipe segments located in places where they will respond to treatment changes, and data can be collected over long periods of time to ascertain the effects of the changes. In some cases it may be good to organize special research studies with in-house staff or consultants to study to water chemistry and scaling that occurs from various modifications of water quality parameters.

Utilities may find their study programs overlapping with capacity and energy studies, which may indicate the presence of scaling problems. In those cases, treatment personnel must be involved to learn the possible treatment-related causes of pipe aging.

### Remediation Actions

Remediation can also involve treatment changes for softening, coagulation, and changes in chemicals. In some cases, remediation may require re-configuration of systems and/or renewal of piping systems, either in treatment plants or distribution systems.

Remediation of scaling and precipitation problems will typically involve case-by-case analyses of the causes and remedies. The main tools of corrosion control, pH adjustment and use of inhibitors, will normally be involved in remediation programs, but knowing the correct levels and doses will require data collection, analysis, and follow-on monitoring.

The utilities highlighted in the report found solutions through multiple approaches that involved uni-directional flushing, pH adjustment, change in chemical additives, re-plumbing of systems, cleaning and lining, and pipe replacement. It is apparent that selecting among these options involves careful consideration by utilities of the benefits and costs of each in terms of all utility objectives, including water quality, hydraulics, customer service, and utilization of workforce.

### Monitoring, Adjustment, Assessment

On a long term basis, control of internal corrosion and scaling requires continual monitoring, adjustment, and assessment of results. Internal corrosion and scaling are as much water quality issues as they are infrastructure issues and their analysis and control are of organization-wide concern to utilities. Currently, the main requirements for monitoring water quality in distribution systems come via the Total Coliform Rule. As Schock (2005) has pointed out, the old assumptions of conservative behavior of inorganics in distribution systems may not be valid and when the issue of secondary effects is added to the list of concerns, new approaches to monitoring may be required.

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# APPENDIX A
# SURVEY FORMS AND RESULTS

## SURVEY PURPOSE AND METHODS

In the initial phase of the project, we interviewed utilities to learn of their issues with corrosion and scaling. Results were scattered among types of problems, but the team learned enough to prepare a definitive survey. The survey targeted water supply utilities and state regulators who oversee water supply utilities. The goals were to learn or verify the extent of utility experience with corrosion/scaling problems; to discover any other treatment-related problems that cause corrosion or scaling; and to identify utility experts who can be interviewed.

As we had limited success with email contacts and cold phone calls, we thought our chance of reaching a representative audience seemed better with a mail survey. This would limit the number of people we could reach, but give us a better chance of getting quality information and returns.

We decided to mail a first class business letter with a one page survey form and stamped return envelope to utilities and state regulators. Rather than the lengthy Technical Guide, our experience suggested that it would be better to include in our letters a clear but brief explanation of what we had learned so far. The mailing would go to both groups, but the letter and survey forms would be different.

The letter to utilities stated: "We would appreciate your help with a Water Research Foundation project about impacts of treatment practices on distribution systems and hydraulic equipment. The research question is whether and how treatment practices may cause significant internal corrosion and/or scaling problems."

Our letter to regulators added this information: "We are interested in whether you as the drinking water regulatory agency are aware of problems with corrosion and/or scaling caused by treatment practices. We are surveying utilities separately, and we seek your opinion because we believe you are in the best position to know the general situation in your state, particularly about issues with the Lead and Copper Rule."

The utility survey was sent during several mailings to about 150 key persons. This utility list was compiled from our own records and additional utilities that we thought likely to have problems and to reply to our survey. To find these utility contacts, we used AWWA's water industry database and additional information we had from other Water Research Foundation projects. We used EPA's list of state programs to find names and addresses for regulators in all 50 states (See http://www.epa.gov/safewater/links.html.) As California is such a large state, we sent three different surveys to their regulators.

## RESPONSES FROM UTILITIES

We logged 63 responses from utilities. In some cases, the responses came via returned survey forms and in other cases the replies were by email and/or through phone followup.

**Were corrosion and scaling:**

| | |
|---|---|
| Insignificant | 41 |
| Significant | 17 |



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| | |
|---|---|
| Very significant | 2 |
| Unknown or other | 3 |

**Of those that were significant or very significant:**

| | |
|---|---|
| Involving calcium ( in some cases with iron and/or manganese) | 9 |
| Involving iron scaling or corrosion | 6 |
| Involving aluminum (in one case also calcium, iron, manganese | 2 |
| Involving copper corrosion | 1 |
| Involving lead and copper problems | 1 |

**Who manages these problems:**

| | |
|---|---|
| Distribution system operations and maintenance staff | 19 |
| Treatment staff | 17 |
| Treatment and distribution (includes customer service, engineering, lab) | 9 |
| Water quality staff | 2 |
| Engineering staff | 1 |
| Utility staff | 1 |
| Homeowner | 1 |

**Treatment**

Have CCT?
No—19
Yes—40

**Have softening?**

No—35
Yes—11
Other treatments: desalination, coagulation, manganese removal, pH control (all mentioned only once or twice).

**COMMENTS**

Corrosion is more of an issue in low flow /velocity older cast iron mains

Problems are insignificant—some scaling may be due to hardness (Ca++)

Don't use groundwater and we have mortar lined pipes, survey not applicable

Calcium scaling is due to NaOH and ammonia addition and manganese is resulting from source water quality.

Treatment staff handles initial observation by mechanics and operators, followed up by joint engineering and operations inspection.

Much of distribution system is cast iron pipe over 100 years old. In addition to iron scaling, biological problem related to tuberculation.

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KMnO4 addition to oxidize Fe and Mn; Greensand effect on filters for Mn Control

Cost and maintenance of corrosion control feed systems is an issue, open to interview but not having any problems

Flushing of problem areas requested and carried out as part of distributions

We did experience significant lime scale build-up on our filter media until 1999 when we began feeding 0.10 ppm of sodium hexametaphosphate. This has stopped lime scale build up on filter media as well as pipe walls

Treatment staff controls corrosion with pH adjustment. There is a corrosion control section within operations.

## REGULATORS

We received 21 replies to the initial regulator survey. In an additional survey of regulators, we received another 22 replies.

**Problems in your state?**
Are you aware of scaling problems?
Yes—5
No—1
Unknown—5

**Might problems occur, but you do not know about them?**
Yes—13
No—6

**Is more attention to scaling problems needed?**
Yes—8
No—5
Unknown—8

## COMMENTS FROM REGULATORS

In Iowa we have had significant problems in a few situations as a result of treatment.

Some small water systems do have scaling problems from use of galvanized steel pipe installed 50 or more years ago. There are no recent scaling problems reported.

The problems are not state wide.

One system that we are aware of: Needham in 1999

Calcium Carbonate can damage pipe material, especially home spigots (chrome plated) and adhere to toilet shower etc.

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Problems are only in a few utilities.

Scaling is probably not as severe in NH as in some states as NH waters are generally low in hardness, alkalinity and pH.

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## LETTER TO REGULATORS

Re: "Secondary Impacts of Corrosion Control on Distribution System and Treatment Plant Equipment" (Water Research Foundation 4029)

Dear Mr. (Ms.) xxxx :

We would appreciate your help with a Water Research Foundation project about impacts of drinking water treatment practices on distribution systems and hydraulic equipment. It is important to have 100% responses from the states, and we will value your response very much.

The research question is whether and how treatment practices may cause significant internal corrosion and/or scaling problems. Our research team studying drinking water issues at Colorado State University includes me, two research scientists from our hydraulics laboratory, and a registered engineer working toward a graduate degree. Prior to this project on secondary impacts, I completed Water Research Foundation projects on surviving disasters, infrastructure integrity, and main breaks.

We are interested in whether you as the drinking water regulatory agency are aware of problems with corrosion and/or scaling caused by treatment practices. We are surveying utilities separately, and we seek your opinion because we believe you are in the best position to know the general situation in your state, particularly about issues with the Lead and Copper Rule.

Our survey form will require only a few minutes from you or a staff member. In return, we will be glad to provide you with a brief report on our findings. We have made the survey as short as possible. Please return it in the stamped, self-addressed envelope. Thank you very much for contributing to the project.

Yours very truly,

Neil S. Grigg

Professor

Encl: survey response form; fact sheet; return envelope

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# STATE DRINKING WATER PROGRAM SURVEY (REGULATORS)

SECONDARY IMPACTS OF CORROSION CONTROL ON DISTRIBUTION SYSTEM AND TREATMENT PLANT EQUIPMENT (WATER RESEARCH FOUNDATION PROJECT 4029)

*The purpose of this survey is to document the extent of corrosion and scaling problems that may occur in your state. It does not focus on the details of treatment practices or water chemistry. Please circle responses that apply and/or fill in the blanks.*

**Have drinking water utilities in your state experienced significant problems with internal corrosion or pipe scaling due to treatment practices?**

Yes No Unknown

**If "yes," please identify the causes of the problems (circle all that apply):**

Source water chemistry

Drinking water regulations

Treatment practices

Other (please explain) _____

**Has treatment under the Lead and Copper Rule caused significant corrosion or scaling problems in distribution systems within your state?**

Yes No Unknown

**Do you think scaling and/or corrosion issues could occur and you would not know about them?**

Yes No Unknown

**Do you believe that internal corrosion and pipe scaling from treatment practices are significant issues that require more attention from drinking water utilities?**

Yes No Unknown

**If of interest to you, we would like to interview you about issues in your state. If you would be interested, please provide your name and contact information:**

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Name: _____

Utility:_____

Phone: _____

Email: _____

Thank you for your help! Please mail the form in the stamped envelope to:

Paul Sclafani

Engineering Research Center

Colorado State University

Fort Collins CO 80523

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## LETTER TO UTILITIES

Addressed individually to utilities

Re: "Secondary Impacts of Corrosion Control on Distribution System and Treatment Plant Equipment" (Water Research Foundation 4029)

Dear Mr.(Ms) xxxx :

We would appreciate your help with a Water Research Foundation project about impacts of treatment practices on distribution systems and hydraulic equipment. The research question is whether and how treatment practices may cause significant internal corrosion and/or scaling problems.

Our research team studying drinking water issues at Colorado State University includes me, two research scientists from our hydraulics laboratory, and a registered engineer working toward a graduate degree. Prior to this project on secondary impacts, I completed Water Research Foundation projects on surviving disasters, infrastructure integrity, and main breaks.

Our survey form will require only a few minutes from you or a staff member in treatment, distribution, or operations. In return, we will be glad to provide you with a brief report on our findings. We have made the survey as short as possible. Please return it in the stamped, self-addressed envelope. Thank you very much for contributing to the project.

Yours very truly,

Neil S. Grigg
Professor

Encl: survey response form; fact sheet; return envelope

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# UTILITY SURVEY RESPONSE FORM (UTILITIES)

SECONDARY IMPACTS OF CORROSION CONTROL ON DISTRIBUTION SYSTEM AND TREATMENT PLANT EQUIPMENT (WATER RESEARCH FOUNDATION PROJECT 4029)

*The purpose of this survey is to document the extent of corrosion and scaling problems. It does not focus on the details of treatment practices or water chemistry. Please circle responses that apply and/or fill in the blanks.*

**Treatment practices used by your utility that might cause corrosion or scaling:**

Lead and copper control Yes No

Softening Yes No

Other (please indicate)_____

**In your utility, you would rate problems with internal corrosion or scaling as:**

Very significant Significant Insignificant Unknown

**If your problems are significant, please indicate if they involved primarily:**

Calcium scaling or precipitation

Aluminum scaling or precipitation

Iron scaling or corrosion

Manganese scaling or deposition

Other (please explain) _____

**In your utility, would problems with internal corrosion or scaling be detected and managed <u>primarily</u> by:**

Treatment staff?

Distribution system operations and maintenance staff?

Customer service staff or other _____(please indicate)

**If you have corrosion/scaling problems, we would like to interview you about them. If you would be interested, please provide your name and contact information:**

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Name: _____

Utility:_____

Phone: _____

Email: _____

Thank you for your help! Please mail the form in the stamped envelope to:

Paul Sclafani

1320 Campus Delivery

Colorado State University

Fort Collins CO 80523

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# APPENDIX B
# TECHNICAL GUIDE TO PROBLEMS

## PURPOSE

The Water Research Foundation is sponsoring a project to study Secondary Impacts of Corrosion Control on Distribution System and Treatment Plant Equipment (Project 4029) and the research team is seeking to identify and explain instances where secondary effects have occurred.

Unintended consequences caused by corrosion, erosion, scaling, deposition, and transport of released materials may produce serious effects on distribution system and treatment plant equipment.

The primary effect of corrosion control in water treatment is to suppress corrosion of metal surfaces within the distribution system. "Secondary effects" can occur on water quality or on the distribution system itself. These distribution system effects are the subject of this study.

We have learned in initial interviews that these effects may occur from coagulation and other treatment processes that might interact with corrosion control. Therefore, the scope of the investigation has been expanded to consider a range of treatments, with emphasis on secondary impacts on distribution systems and treatment plant equipment.

The purpose of this technical guide is to explain the secondary effects to enable utilities to identify the problems and explain them to the research team.

## SECONDARY EFFECTS OF WATER TREATMENT ON DISTRIBUTION SYSTEM EQUIPMENT

Secondary problems may occur because drinking water utilities make water quality adjustments at treatment plants to control internal corrosion in distribution systems. These were summarized in an AWWA (2005) publication on unintended consequences of the Lead and Copper Rule, which stated: "Actions intended to improve water quality produce serious unintended consequences – especially in the areas of corrosion, stability of existing pipe scales, and aesthetics."

Also, the report explained how: "Optimum corrosion control treatment requires utilities to strike a careful balance among challenging and often conflicting water quality goals for lead and copper solubility, coagulation and softening, disinfection, disinfection byproducts, aesthetic quality, phosphorus, and other water quality parameters." This is why the research team is also studying possible secondary effects from other treatments, including coagulation, softening and interactive effects.

## TYPES OF EQUIPMENT IN TREATMENT PLANTS AND DISTRIBUTION SYSTEMS

We are studying all types of equipment and infrastructure in treatment plants and distribution systems that may have problems from corrosion and scaling that occur from treatment interventions. Examples of infrastructure components to be studied are pipe surfaces, valves, meters, pumps, screens and other hydraulic equipment.



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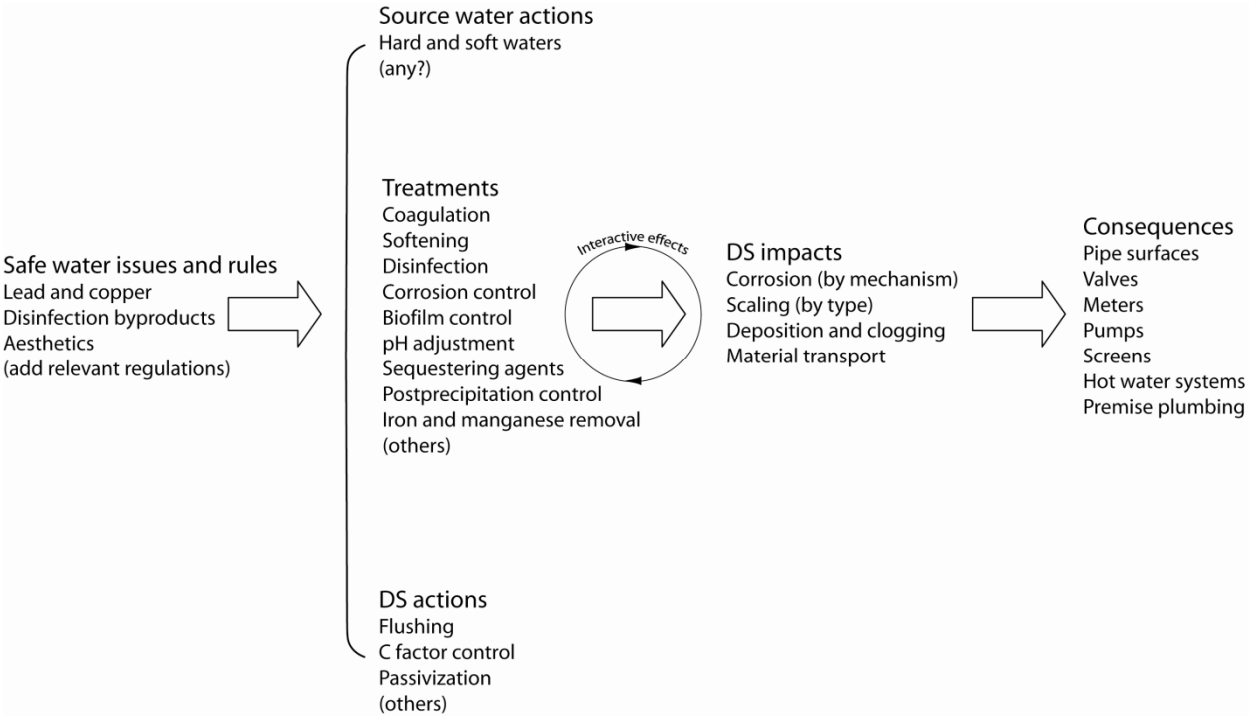
## HOW SECONDARY EFFECTS MIGHT OCCUR

The figure shows a chain of events to explain secondary effects. The chain begins with water treatment regulations such as the Lead and Copper Rule, which is the primary rule governing corrosion control. Other rules that affect water treatment actions may also affect the water chemistry that creates secondary effects.




Safe water rules might require actions on source water and distribution system management, but they are implemented primarily through water treatment. Treatment strategies may have direct, intended effects, or they might have unintended and/or interactive effects.

In the distribution system, an intended effect of corrosion control is protection of metal surfaces. As Schock (1999) explained, protection can occur by the metal surface being "immune" or "passive." The surface is immune if it is stable on an electrochemical basis. That is, the electrochemical potential between the metal and the water is such that no corrosion occurs.

Protection can occur if the metal surface is made passive by covering with a stable film. This process is called "passivation."

Treatment strategies to promote immunity or passivation can have direct or indirect effects on hydraulic equipment. A direct effect might be to make a metal surface passive by depositing a stable and harmless film on it. Whereas this effect might be positive for one metal surface and prevent corrosion, it might deposit too much film on a moving surface of a piece of equipment and impair its operation.

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## SYMPTOMS AND EVIDENCE OF PROBLEMS.

Classes of cause and effect can relate to source waters (hard water), to treatments (softening, coagulation, corrosion control), or to distribution system operations (poor flushing). Also, there are different mechanisms of corrosion and different causes of scaling.

Connections between equipment failures and corrosion control or other treatments are anecdotal.

Some utilities have reported pump failures and water system problems that may be caused by scaling.

An initial inquiry among participating utilities and recent literature resulted in these reports (Rego, 2006; Bureau of Water and Lighting, 1996; Kriewall, 2006; Public Works, 1985; O'Brien and Gere, undated; Kirmeyer, et. al., 2004).

| |
|---|
| Small pH adjustment for lead and copper control apparently caused sudden clogging of treated water pumps by $CaCO_3$. The problem was alleviated by more precise pH control and other measures. |
| A new treatment plant came on line to apply iron and manganese removal and corrosion control to a groundwater source water. The pH adjustments led to complaints about customer plumbing, including clogging of hot water heating systems. Utility used coupled pH control and use of sequestering agents to control lead release and calcium precipitation. |
| Utility experienced loss of capacity in a treated water line due to excessive aluminum coagulant residual and post precipitation. The pH adjustment was effective to dissolve the precipitate. |
| Utility had excessive scaling 6-7 years ago. Problems with meters and backflow preventers. Plastic, metal, rubber. Were using high pH to suppress nitrification. 1/8 inch thick scale. Used lemon juice to reduce in components. Now pH 8.2 range, problems gone. |
| Utility's LCR has not caused problems. Disassembly of pumps, control valves, etc., shows coatings by corrosion inhibitor, but did not adversely impact operations or maintenance. Material handling is an issue in bulk storage. |
| Utility experienced mechanical failures and increased maintenance due to feed of blended phosphate. Includes reduction in pumping capacity and buildup 1/16 to 1/8 inch in depth on the walls of concrete main. In-plant issues include plugged strainers, maintenance on back flow preventers, differential pressure cells, and pressure regulators etc. Increased maintenance on pressure regulator valves |
| After increase in pH to control lead some valves scaled up to point to be inoperable. Lost major pump station for a day. Scale issues in some altitude valves and pressure regulators and other valves. |
| AwwaRF 2004 study effects summarized as: initial increases in color, turbidity, iron, and/or HPC as scales stabilize and system re-equilibrates; upsets due to multiple WQ changes in short time (incl red water); localized changes with unlined CIP and/or stagnant conditions; film may reduce HPC by reducing sloughing of corrosion byproducts. |

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## ISSUES TO BE STUDIED FURTHER

Comments in this section are based on (Schock, M. and Carlson, K., personal communications).

In searching for other phenomena that might cause problems with hydraulic equipment, one that was mentioned was that oxidative processes can affect the solubility of some metals.

Oxidation can create precipitates from soluble material entering the distribution system. Examples might be KMnO4 or ClO2 oxidation to transform dissolved Mn or Fe to a solid form, or manganese dioxide or manganese oxyhydroxide precipitation. Ferric oxyhydroxide precipitate also might result from oxidation. The source can be oxygen, the secondary disinfectant, or a kinetic issue could generate precipitates. For example, chlorine or chloramines may not oxidize the Mn(II) to Mn(IV) in the timeframe the water is in the DS. Oxygen will almost certainly not if a residual is low or not present.

Also, before treatment, the physical action of pumps (cavitation, degassing), well screens, and other pressure-drop situations might induce calcium carbonate, strontium carbonate, or other insoluble materials to deposit scale on surfaces or in machinery as a result of precipitation due to mixing.

Calcium and aluminum, among other metals, can readily be released from cement linings. These metal releases can be considered as corrosion or leaching.

Type and location of precipitates from pH adjustment can vary widely depending on chemical dosages. WASA noted a Ca-Al-Fe-phosphate precipitate which, based on Mike Schock's experience, might have even nucleated on undissolved lime particles. Schock also heard anecdotes of Ca-Zn-phosphates from inhibitor-based corrosion control systems. It is possible that pH could be the main influence or another chemical-specific effect of the dosed chemical could play a role. Also, calcium phosphate precipitates are more likely in hot water conditions than in cold water conditions.

## SUMMARY

Our focus is on any distribution system mechanisms that lead to secondary effects on equipment. The main ones seem to be:

- Corrosion - to release metal
- Scaling - to create scale that might be released later or form on equipment parts
- Biofilm growth - that might be released or have effects on pipe walls leading to corrosion and/or release
- Post precipitation - that will create solid matter to be released to clog hydraulic equipment
- Particulation - any other mechanism (such as hydraulic erosion) that creates particles that might affect hydraulic equipment.

Of the issues we have found so far, several were $CaCO_3$ precipitate and several were deposits of aluminum residual from coagulation processes. Investigation continues to learn of more incidents.

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# APPENDIX C
# FACT SHEET ON PROJECT

# SECONDARY IMPACTS OF CORROSION CONTROL ON DISTRIBUTION SYSTEM AND TREATMENT PLANT EQUIPMENT (WATER RESEARCH FOUNDATION 4029)

## PROJECT OBJECTIVES

The project objective is to assess equipment failures or problems in distribution systems and treatment plants that result from water quality adjustments for corrosion control or other objectives such as coagulation and softening. We are evaluating pipes, valves, meters, pumps, and related equipment.

## WHAT WE HAVE LEARNED SO FAR

The eleven participating utilities have supplied us with information on their experiences. Also, we have advice from several national experts, and we have reviewed the literature on problems with internal corrosion control and scaling. We have interviewed other utility experts and state regulators, and we have contacted vendors to learn of their experiences. All in all, we have quite a bit of information as of July, 2007.

As a result of this work, we believe that serious corrosion and scaling problems are not widespread but that they can become serious quickly under some conditions. They cause reduced C factors, damaged equipment, pipe blockages, water quality changes, colored water, etc.

We think the problems fall into one of the following four categories:

- **Calcium issues**: post precipitation and scaling of calcium. These problems can build up quickly and lead to malfunctioning of equipment as well as lost capacity.
- **Aluminum scaling and deposition**: these problems are not as well known as calcium problems, but they have caused serious loss of pipe capacity and malfunctioning of equipment.
- **Manganese problems**: scaling and release of manganese is thought to be a widespread issue, but is not widely reported. Some utilities think this problem is more serious than many people think.
- **Iron problems and scaling/corrosion of other metals**: this miscellaneous category includes colored water, scaling of metals such as iron, magnesium, and others, and any other issues not included in the calcium, aluminum, and manganese categories.



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## WHAT WE NEED TO LEARN

When these problems occur, they are handled within individual utilities and do not get much publicity. Our tasks in this survey are to learn how widespread these problems are, whether other problems occur, the conditions that lead to them, their impacts, and their solutions. The result will be a comprehensive report to Water Research Foundation and papers for AWWA as well.

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# ABBREVIATIONS

| | |
|---|---|
| APWA | American Public Works Association |
| ASTM | American Society for Testing of Materials |
| AWWA | American Water Works Association |
| AwwaRF | Awwa Research Foundation |
| CCPP | Calcium carbonate precipitation potential |
| CML | Cement mortar lined |
| DBP | Disinfection by-products |
| DIC | Dissolved organic carbon |
| HAA | Haloacetic acid |
| HDPE | High density polyethylene |
| LCR | Lead and Copper Rule |
| NOM | Natural organic matter |
| O&M | Operations and maintenance |
| PVC | Polyvinyl chloride |
| RFP | Request for proposals |
| SDWA | Safe Drinking Water Act |
| TDS | Total dissolved solids |
| USEPA | U.S. Environmental Protection Agency |
| USGS | U.S. Geological Survey |
| WITAF | Water Industry Technical Action Fund |



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