Drinking Water Research

Advancing the Science of Water®

January–March 2009 volume 19, number 1 strategic initiative chloramines biofilm regulatory requirements health effects lead and copper rule

Distribution System Water Quality

Foundation Research Provides Knowledge for Water Suppliers

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Drinking Water Research

Advancing the Science of Water®

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The Water Research Foundation is a member-supported, international, nonprofit organization that sponsors research to enable water utilities, public health agencies, and other professionals to provide safe and affordable drinking water to consumers.

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Helping Utilities Protect the Quality of Water in the Distribution System

The water distribution system is rightly called the "last frontier" in water quality protection. With some one million miles of buried water lines in the United States and another six million miles of premise plumbing, the distribution system is vast and complex. It is the last place finished water touches before it reaches consumers, and it is the least studied element of our water infrastructure.

While the general public takes safe, affordable drinking water for granted, for water industry professionals, this underground empire is hardly out of sight, out of mind. In recent years, utilities and regulators have renewed their interest in distribution system water quality (DSWQ). Concerns over waterborne disease, infrastructure security, leaks, metals leaching, and chloramine decay have spurred a new focus on the topic.

Since 1985, the Water Research Foundation has sponsored or co-sponsored a number of research studies addressing various aspects of DSWQ. These include research on chloramines, distribution system nitrification, real-time monitoring of contaminants, premise plumbing water quality changes, and biofilms. The body of existing and ongoing Foundation research, much of it done in collaboration with other national and international water utility research institutions, is highlighted in this special newsletter edition.

The Foundation has further strengthened its research efforts through the Strategic Research Initiative on DSWQ, established by the Board of Trustees in 2007. This multi-year, multi-project approach will sponsor $1 million worth of research each year into DSWQ. The outcome: valuable, practical information and tools. We will focus on understanding premise plumbing water quality changes; defining and measuring multiple barriers to ensure DSWQ; and filling in the gaps in our knowledge of chloramines.

In tandem, the Foundation and the U.S. Environmental Protection Agency (USEPA) have signed a memorandum of understanding to jointly undertake research and information collection in this important area. This partnership will serve as a source of research ideas as the Foundation proceeds with planning research, including that of the DSWQ strategic initiative.

We will keep you and your organization up to date on our ongoing DSWQ research through reports, Webcasts, the Web site, and newsletters.

Sincerely,

David E. Rager
Chair, Board of Trustees

Robert C. Renner, P.E., D.E.E.
Executive Director

Drinking Water: Protecting a Resource We All Take for Granted

Rachel Brand, Water Research Foundation writer

You turn on the tap and water comes out. Period.

While pouring a glass of water may seem simple, that drinking water has traveled several miles—possibly hundreds—to your tap. It passed from treatment facilities to underground pipes to the pipes in your home's basement and walls. This underground empire of pipes and valves, the distribution system of your utility, comprises a national aggregate of approximately one million miles of buried pipe and another six million miles of onsite plumbing.

Safe, affordable drinking water is one of our nation's most precious resources and something most of us take for granted. Yet the aging infrastructure that delivers this resource and water utilities that guarantee its purity and quality are facing increasing challenges.

The pipes can be made of 19th century cast iron or 1970s plastic. They can be brand-new or on the verge of collapse. In short, the variety, age, and size of the distribution system makes it one of the water infrastructure's least understood and most complex elements. Yet protecting our drinking water distribution system is vital to public health, our economy, and national security.

While clean and pure when it leaves the treatment facility, drinking water can degrade as it travels through miles of pipe. Exactly how that happens is complex. Chemicals used to safely treat water can change and become harmful. Pathogens can enter pipes through pinhole leaks. Lead can leach into water, exposing consumers to dangerous levels of metals. Worse, the distribution system is vulnerable to terrorist attacks.

For these reasons and others, the Water Research Foundation is sponsoring more than $1 million of research each year to help utilities better protect water in the distribution system. Findings from this work are crucial for water utilities so that they can implement proven, cost-effective techniques in this area. This special edition of *Drinking Water Research* outlines current and planned research.

Topics include:

- How water quality may change as it passes through residential plumbing, leading to poor odors, tastes, and potentially unsafe levels of contaminants
- Developing means to better quantify the benefits of multiple barriers used to maintain water quality in distribution systems
- Gaps in our knowledge of chloramines, otherwise a commonly used disinfectant, and how to address them
- The nature of biofilms—naturally occurring microbial communities—and how biofilms and pathogens interact
- The implications of real-time, online monitoring in the distribution system

For more than 40 years, the Water Research Foundation has sponsored research to empower water utilities and public health agencies to provide safe and affordable drinking water to the public. Our five-to-seven year distribution system research initiative proves the Foundation's pledge of ensuring safe drinking water and protecting public health.

Overview of the Distribution System Water Quality Strategic Initiative

Chris Rayburn, Water Research Foundation director of research management

Introduction

Significant water quality changes can occur within drinking water distribution systems. These changes can make it challenging for water utilities to provide expected levels of service and to comply with regulatory requirements. The mechanisms that can affect distribution system water quality (DSWQ) are both complex and dynamic. Water quality can be degraded due to chemical and biological transformations that take place within the distribution system, as well as loss of physical integrity (e.g., pipe breaks). Distribution system design, installation, operation, maintenance, and repair can all contribute to DSWQ challenges.

Distribution system design, installation, operation, maintenance, and repair can all contribute to distribution system water quality challenges.

Although drinking water utilities have effectively managed water quality in their distribution systems for years, drinking water professionals, public health officials, and regulatory agencies have paid more attention to DSWQ in recent years. The increased attention is due to factors including aging infrastructure, increased use of chloramines as a secondary disinfectant, and the recognition that premise plumbing (i.e., customer plumbing not owned or maintained by the water utility) is a key DSWQ variable.

In 2001 and 2002, the USEPA sponsored a series of white papers on DSWQ as part of the agency's revision of the Total Coliform Rule (TCR). USEPA then commissioned two National Academies of Science studies on the topic. These studies, published in 2005 and 2006, focused on identifying, prioritizing, and evaluating DSWQ issues from a public health risk perspective. The 2006 National Academies study, *Drinking Water Distribution Systems: Assessing and Reducing Risks*, states that, "The distribution system is the remaining component of public water supplies yet to be adequately addressed in national efforts to eradicate waterborne disease." This statement suggests that the distribution system is the "last frontier" in potable water operations. We have committed significant efforts over the years to source water quality and to the treatment of water. We now need to better understand protection of water quality in distribution systems.

In 2007, USEPA established a committee under the Federal Advisory Committee Act (FACA) to advise them on revisions to the TCR and to help identify information that was needed to better understand and address possible DSWQ-related public health impacts. This committee's recommendations, as well as results from ongoing research and information collection activities, will inform USEPA's revision of the TCR and help determine the need for future DSWQ-related regulations.

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The Strategic Initiatives Program

The Foundation's Strategic Initiatives Program focuses resources on critical drinking water issues through a sustained research effort that comprises multiple, coordinated projects. Projects within a strategic initiative serve as discrete steps toward a common objective or objectives. The program enables the Foundation to provide a more complete and timely research response to key issues, and ultimately to provide greater benefit to subscribers by solving specific problems.

Topics for strategic initiatives are selected by the Foundation's Board of Trustees with extensive input from Foundation subscribers and other drinking water community stakeholders. The Board of Trustees selects topics based on criteria that include their long-term importance to water utilities, their breadth of impact, and the potential to leverage subscriber funding through partnerships. Once a strategic initiative is approved, an expert panel develops a strategic research plan that identifies several specific objectives for the initiative. The objectives represent problems to be solved or opportunities to be attained. The panel then develops a multi-year research agenda that outlines discrete research projects to achieve these objectives. All projects funded under the strategic initiative must contribute to meeting one or more objectives.

The Expert Panel is not only responsible for developing the strategic research plan, but also for overseeing its execution. The panel reviews and refines the strategic research plan as new information becomes available, thereby ensuring that the plan remains current and appropriately focused.

For more information about the Strategic Initiative Program and other Water Research Foundation programs, see http://www.waterresearchfoundation.org/theFoundation/ourPrograms/ResearchPrograms.aspx

Distribution System Water Quality Strategic Initiative

In 2007, the Foundation chose DSWQ as one of the first two topics to address under the Strategic Initiatives Program. The Foundation commits up to $1 million annually for the DSWQ initiative. This funding is substantially leveraged with partner co-funding and researcher in-kind contributions.

DSWQ is not a new issue. The Foundation's earliest related projects date to the early 1980s. With the DSWQ Strategic Initiative, the Foundation is now enhancing its efforts to solve several specific DSWQ challenges through a sustained, multi-year, integrated research effort. The initiative will be sustained until the objectives outlined below are achieved. The target timeframe for the initiative is five to seven years. More detailed info about the DSWQ Strategic Initiative can be found at http://www.waterresearchfoundation.org/theFoundation/ourPrograms/ResearchProgramSIDSWQ.aspx

With the DSWQ Strategic Initiative, the Foundation is now enhancing its efforts to solve several specific DSWQ challenges through a sustained, multi-year, integrated research effort.

Expert Panel

As discussed above, an Expert Panel is formed to oversee and direct each of the Foundation's strategic initiatives. The members of the DSWQ initiative Expert Panel are:

- Gary Burlingame, Philadelphia Water Department
- Anne Camper, Montana State University
- Mark LeChevallier, American Water
- Gregory Kirmeyer, HDR Engineering
- Pankaj Parekh, Los Angeles Department of Water and Power (Chair)
- Charlotte Smith, Charlotte Smith & Associates, Inc.

Objectives

The Expert Panel has established the following three objectives for the DSWQ strategic initiative. All projects funded under the initiative will contribute to meeting one or more of these objectives, which themselves were established after reviewing research projects identified by more than 20 experts that attended a May 2007 workshop on this topic.

The DSWQ Strategic Initiative will achieve a substantial understanding of water quality changes caused by premise plumbing, and of methods to control the negative impacts of these changes.

Goal 1: Understand Premise Plumbing Water Quality Changes

Although drinking water utilities do not generally assume direct responsibility for water quality changes caused by premise plumbing, these changes can reflect negatively on customer perception of tap water quality and utility performance, and thus are an important issue for utilities. The DSWQ Strategic Initiative will achieve a substantial understanding of water quality changes caused by premise plumbing, and of methods to control the negative impacts of these changes. It will produce new and specific understanding of water quality impacts caused by premise plumbing, a new set of forensic tools to determine causes of premise plumbing water quality impacts, and an improved ability to positively impact water quality at the tap. This knowledge will enable drinking water utilities to take appropriate action in helping customers improve water quality at the tap.

Goal 2: Define and Measure Multiple Barriers to Ensure DSWQ

Secondary disinfection (providing a disinfectant residual in the distribution system) has been a key component of drinking water treatment and distribution in the United States. While this practice provides a barrier to microbial contamination of finished water, it may also contribute to disinfection by-product formation, off-flavors, and other undesirable water quality changes. In some other countries, utilities focus on supplying biologically stable water without disinfectant residual as an alternative approach to controlling microbial contamination. This practice avoids water quality issues associated with disinfectant residual but provides no protection against pathogen intrusion into the distribution system through pipe breaks or negative pressure transients. Periodic flushing of distribution systems is also used to help mitigate distribution system water quality changes, but the level of protection afforded by this practice has not been quantified. Finally, many questions remain about the value of total coliform measurements as an indicator of distribution system integrity, as stipulated in the United States under the Total Coliform Rule. The DSWQ strategic initiative will develop tools and approaches to thoroughly evaluate the benefits and costs of multiple barriers used to ensure distribution system water quality. New approaches for measuring distribution system integrity will be carefully evaluated. This work will enable water utilities to quantitatively evaluate the value of different barrier approaches, and institute measurement programs that will substantially increase the ability of utilities to measure the health of their system.

Goal 3: Chloramines—Filling in the Gaps

For a variety of reasons, the use of chloramines as a secondary disinfectant by U.S. drinking water utilities has been increasing, and this trend is expected to continue. Although the use of chloramines for secondary disinfection has already been studied extensively, considerable knowledge gaps remain. The DSWQ strategic initiative will develop additional guidance and understanding to help address these gaps.

Although the use of chloramines for secondary disinfection has already been studied extensively, considerable knowledge gaps remain.

While these three objectives may first appear to be separate and distinct, they are in fact closely related and complementary. Thus, a particular project funded under the strategic initiative may be relevant to one, two, or all three of these objectives.

Integration with Other Research Programs

While the DSWQ strategic initiative represents a commitment to solve several key DSWQ issues, it does not address the full breadth of utilities' DSWQ challenges. DSWQ-related research will continue under the Foundation's other research programs—Solicited, Unsolicited, Tailored Collaboration, and Partnership—to help utilities meet these challenges. Close coordination between the Expert Panel and the planning committees for the other programs ensures that the DSWQ initiative and other programs are well integrated. Where projects of direct value to the DSWQ SI are identified and funded by other Foundation research programs, the knowledge generated in these projects will be incorporated into the DSWQ SI.

As noted previously, USEPA undertook review and revision of the TCR at approximately the same time that the Foundation was starting the DSWQ SI. The TCR advisory committee discussions were supported by nine distribution system white papers, eleven TCR issue papers, and the two National Academies reports. (Foundation research was cited more than 240 times in these commissioned works, illustrating the strategic value of Foundation research in understanding distribution system issues.) The members of the FAC signed an agreement in principle (AIP) on September 18, 2008. The AIP is available at: http://www.epa.gov/safewater/disinfection/tcr/pdfs/tcrdsac/agreementinprinciple_tcrdsac_2008-09-18.pdf. This agreement, in addition to describing a revised TCR (RTCR), includes a priority list of seven issues that require further research and/or information collection, and sets forth provisions for a DSWQ-focused partnership between the Foundation, USEPA, and other potential stakeholders to pursue this research and information collection.

The Foundation and USEPA have recently signed a memorandum of understanding to undertake the research and information collection partnership set forth in the TCR AIP. The partnership will identify and prioritize research and information collection needs for the seven key DSWQ challenge areas identified in the AIP, including but not limited to areas relevant to the DSWQ strategic initiative. (These seven areas were discussed in more detail in the October–December 2008 [Volume 18, Number 6] edition of *Drinking Water Research*.) Research planning will involve a broad range of stakeholders and experts under the direction of a steering committee assembled by USEPA and the Foundation. In effect, the partnership will serve as a source of research ideas for the Foundation to consider through its existing research planning activities, including those of the DSWQ initiative and the Solicited Program.

Conclusion

Challenges associated with DSWQ are not new. Drinking water utilities have successfully managed water quality in their distribution systems for many years. A variety of factors, however, have brought increased attention in recent years to DSWQ issues. The Foundation has committed to solving several of these issues through a focused DSWQ strategic initiative, and continues to help utilities address the full range of DSWQ issues through targeted projects in its other research programs. Collaboration on DSWQ research with USEPA and other stakeholder organizations leverages subscriber funding and helps ensure that future rulemaking activities are underpinned by sound science.

The remainder of this *Drinking Water Research* special issue details the results of completed and ongoing Foundation projects in a number of specific DSWQ focus areas.

Premise Plumbing Water Quality Changes

Traci Case, Water Research Foundation project manager

Most people recognize that the 1.4 million kilometers of publicly-owned water distribution piping in the United States are a critical infrastructure asset. Lesser known, residential premise plumbing piping is estimated to be five to ten times that length (according to the ***Assessment of Non-Uniform Corrosion in Copper Piping***, 2008, order #91217). Providing safe, aesthetically pleasing and compliant potable water after it has traveled through customer-owned premise plumbing is a vexing challenge for utilities.

Although utilities do not typically control customer-owned premise plumbing, the customer uses finished water after it travels through premise plumbing—at the tap or faucet. Changes in water quality due to customer-owned premise plumbing can cause compliance challenges for the utility, can lead to plumbing failures in the form of leaks, and can lead to the release of metals and biological effects that can harm customers. These considerations led the DSWQ SI Expert Panel to identify premise plumbing as a program goal area (see sidebar).

Premise plumbing includes that portion of the potable water distribution system associated with industrial facilities, schools, hospitals, public and private housing and other buildings. Distribution systems are thought to represent the "last frontier" of ensuring safe drinking water, and the impacts of premise plumbing on water quality have only recently become an area of concern and are little-known. In addition, premise plumbing systems have unique characteristics. Premise plumbing systems typically have about ten times more surface area per unit length than a pipe in the distribution system. These systems have a wide range of materials present, such as lead lines or other materials not common in the utility distribution system. Premise plumbing can harbor increased levels of opportunistic pathogens such as *Legionella*.

Distribution System Water Quality Strategic Initiative Goal 1: Understand Premise Plumbing Water Quality Changes

Although drinking water utilities do not generally assume direct responsibility for water quality changes caused by premise plumbing, these changes can reflect negatively on customer perception of tap water quality and utility performance, and thus are an important issue for utilities. The DSWQ SI will achieve a substantial understanding of water quality changes caused by premise plumbing, and of methods to control the negative impacts of these changes. It will produce new and specific understanding of water quality impacts caused by premise plumbing, a new set of forensic tools to determine causes of premise plumbing water quality impacts, and an improved ability to positively impact water quality at the tap. This knowledge will enable drinking water utilities to take appropriate action in helping customers improve water quality at the tap. *From the Distribution System Water Quality Strategic Initiative Plan, October 19, 2007.*

Premise plumbing may also have a greater prevalence of cross connections, reduced levels of secondary disinfectants, increased development of biofilms (which can contribute to the loss of disinfectant residual) and high water age, when compared with the utility distribution system (NAS 2006).

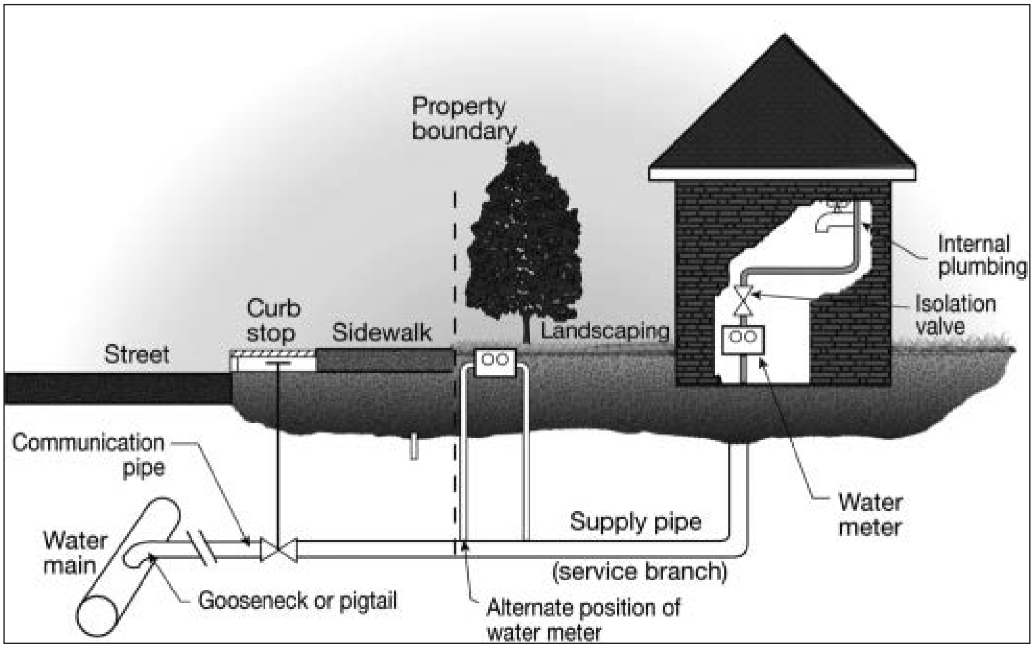

Figure 1. Schematic of premise plumbing from water main to tap. (Source: Contribution of Service Line and Plumbing Fixtures to Lead and Copper Rule Compliance Issues*, 2008, order #91229)*

In addition, as finished water travels from distribution line to a customer's tap, it may come in contact with a host of materials. Different materials may be used in the service line, the meter, shut-off valves, pressure regulators, piping, faucets, etc. (see Figure 1). While NSF 61 and ASTM standards now certify the materials that touch drinking water, there is no guarantee that your customers' materials were certified or installed correctly. Older homes often have full or partial lead service lines, leaded solder joints, and older brass materials with high lead content. Newer homes often have unpassivated piping such that raw materials come in direct contact with drinking water.

Therefore, customer-owned premise plumbing can present a three-fold challenge for utilities: in meeting regulations at the tap, in customer relations (plumbing failures attributed to utility actions), and in health implications or aesthetic issues for consumers.

Regulatory Compliance

Since the early 1990s, the Foundation has created a large body of knowledge about meeting the requirements of the USEPA's lead and copper rule (LCR) and corrosion control for lead and copper. This research focused on determining how treatment changes affect distribution system water quality and how those water quality changes affect corrosion and metal release in the distribution system and premise plumbing. A comprehensive summary of Foundation research related to corrosion and the LCR can be found on the Foundation Web site at http://www.WaterResearchFoundation.org/research/TopicsAndProjects/Resources/SpecialReports/Corrosion/index.aspx#Corrosion.

While many of the projects summarized below address utility-owned distribution system issues, quite a few focus on customer-owned premise plumbing and how it affects lead and copper levels at the tap.

Because the LCR is monitored at the tap, utilities are required to take first draw samples at cold water taps in homes and buildings that are at high risk of lead and/or copper contamination (as identified in 40 CFR 141.86[a]). For sampling sites with lead service lines, the service line typically contributes the greatest percentage of lead measured at the tap, followed by premise piping, faucets, and then brass meters. For sampling sites without lead service lines, premise piping contributes the greatest percentage of lead measured at the tap, followed by the faucet. (from ***Contribution of Service Line and Plumbing Fixtures to LCR Compliance Issues***, 2008, order #91229).

Two new projects will address premise plumbing and how it can affect LCR compliance. One project, funded by the DSWQ SI in 2008, will develop a guide for utilities that oversee or respond to plumbers, contractors, and construction managers who install new or rehabilitated plumbing construction. The guide will describe steps to minimize lead and copper corrosion problems. **"Lead and Copper Corrosion Control in New Construction"** (project #4164), will establish procedures for properly flushing new building plumbing, including the specific flushing velocity and duration necessary to remove ammonia, zinc, and high chloride from flux, as well as to remove metallic debris and solvents from plumbing lines. The project will address the extent to which residual PVC solvents and flux contribute to the initiation of nitrification. It will also describe premise plumbing chlorination procedures that will not damage plastic or copper plumbing components. Marc Edwards of Virginia Tech is the principal investigator.

While there has been a tremendous effort to get lead out of drinking water systems, some new distribution system and plumbing components still contain minute amounts that can leach into finished drinking water. Lead can leach from brass materials found in meters, valves, faucets, and leaded solder. To solve this problem, brass manufacturers are now offering non-leaded brass alloys. These new non-leaded brasses (0.1 to 0.25 percent lead by weight) contain much less lead than the older brass alloys referred to as "lead-free" (typically 1.0 to 6.0 percent lead by weight). Although uniform regulatory requirements have not been set, water utilities have begun to specify non-leaded brass materials for their systems. These new materials are often available at local hardware stores. **"The Performance of Non Leaded Brass Materials"** (project #4191) will identify and prioritize key water quality characteristics and changes that might adversely affect the performance and leaching of non-leaded brass materials in the distribution system and premise plumbing. Josef Klinger of TZW in Germany is the principal investigator.

Premise Plumbing Material Failures

Non-uniform corrosion—also known as copper pitting—that manifests as pinhole leaks can greatly shorten potable plumbing pipes' usable lifespans. The resulting leaks can damage customers' homes and possibly lead to the growth of mold. Copper pitting corrosion in residential plumbing is expensive to repair and stressful to customers. Further, the exact water quality and hydraulic factors that cause pitting remain difficult to discern. While many factors are proposed or suspected—including faulty or improper grounding, manufacturing defects of the copper pipe, microbial corrosion, and improper plumbing installation—none has yet been proven to cause pitting corrosion under scientifically reproducible conditions. Case studies done as a part of ***Assessment of Non-Uniform Corrosion in Copper Piping*** (2008, order #91217) pointed to three water chemistry and microbiological factors with strong links to pinhole leaks:

- High pH and high levels of disinfectant, exacerbated by aluminum and other particles
- Local production of hydrogen sulfide in and around pits by sulfate-reducing bacteria (SRB)
- Erosion corrosion in hot water circulation systems

Of course, other factors may influence copper pitting corrosion, and further research must be done to identify and confirm them.

Various corrosion monitoring techniques have been used to assess the likelihood that a given water quality could induce or allow copper pitting corrosion. **"Monitoring of Non-Uniform Corrosion in Copper Piping"** (project #3109) identified problems or inconsistencies with all of the electrochemical monitoring techniques tested in this study—E_{Corr} rise, electrochemical noise (ECN), and pit wires. Naturally-occurring water quality and hydraulic factors in the systems artificially affected the electrochemical data. The team found that the monitoring results always depended on the specific test and site conditions, that the orientation and placement of the electrodes controlled the monitoring output, that turning the pump on or off created spikes in the electrochemical indicators and that free chlorine or chloramines levels controlled the results. It is clear that electrochemical techniques have fundamental limitations and cannot be used as a sole tool for indicating the pitting propensity of an unknown water system. In some cases, these methods can be used along with other methods or after extensive experience with a given water system.

Potential Health Effects and Aesthetic Issues at the Tap

Consumers do not drink water immediately after treatment. Rather, they drink water that has traveled from the treatment plant to their taps via distribution system pipes and premise plumbing. That water may contain accumulated contaminants from the distribution system. The fate and transport of contaminants—and their subsequent accumulation and release within the distribution system—is a complex process controlled by a number of chemical, physical, and microbial mechanisms. The USEPA and industry place a high priority on investigating this issue because of the potential for elevated contaminant concentrations at the tap and associated public health ramifications. **"Inorganics Accumulation in Drinking Water Scales and Sediments"** (project #3118) is investigating the accumulation of regulated inorganic contaminants and naturally-occurring radionuclides in pipe scales and sediments. Contaminants being investigated include lead, arsenic, copper, uranium, selenium, and iron as well as corrosion scales. In addition, chemical species typically associated with scale and sediment are being analyzed, including calcium, iron, magnesium, manganese, and silicon. HDR Engineering is leading this research effort.

A unique form of corrosion can pose problems within some copper tubing premise plumbing systems. When sulfate-reducing bacteria (SRB) become active within residential premise plumbing, these bacteria can cause potable water discoloration, high copper levels, taste and odors, or property damage in the form of pinhole leaks. Relatively little is known about such bacterial growth in the unique physical-chemical environment of home plumbing systems. Certain bacteria that are not problematic in continuously flowing water mains become a problem in the stagnant, intermittent flow of premise plumbing. Warmer temperatures in the hot water system can enhance bacterial growth. Given the frequency of consumer complaints about black water and SRB-associated odors, as well as the likelihood that SRB contribute to corrosion problems, **"Premise Plumbing Water Quality Changes—Sulfate Reducing Bacteria"** (project #4219) will examine water quality factors that contribute to SRB growth in premise plumbing. In the process, it will establish some scientific guidelines that can help to control these organisms. Paolo Scardina of Virginia Tech will lead this research effort under the DSWQ SI program.

Recent Centers for Disease Control and Prevention studies have indicated concern about the regrowth of *Legionella* and other pathogens such as *Mycobacteria* in premise plumbing. Microbial communities are dependent on various organic substrates to survive and proliferate. However, some microorganisms grow in environments with low organic carbon levels, such as the conditions found in distribution systems and premise plumbing. Drinking water characterized as biologically stable should be less prone to supporting microbial activity. Biological treatment, a process that reduces the organic load to distribution systems, could be important for controlling distribution system microbial activity and may influence the water quality in premise plumbing. The Foundation released another DSWQ SI RFP in March 2009 to examine the impact of varying levels of biodegradable organic matter on the growth and persistence of opportunist pathogens in model distribution systems ("Relationship Between Biodegradable Organic Matter And Pathogen Concentration In Premise Plumbing Systems", RFP #4251). This project will help define biological stability of distributed water by assessing the correlation between the availability of BOM and the growth, decay, and activity of organisms in the distribution system and premise plumbing.

The Future of Premise Plumbing and Drinking Water

Although the issues of customer-owned premise plumbing pose challenges for utilities, the drinking water industry is now more aware of the need to educate customers about premise plumbing and its possible effects on their tap water. We are seeing better standards and the availability of less-harmful materials in premise plumbing components. We are also seeing new ideas for plumbing and building codes, novel insurance programs, and more customer relations activities, all designed to address premise plumbing problems. The premise plumbing-oriented projects undertaken by the Foundation will provide additional scientific data, context, and focus for these activities.

References

NAS (National Academy of Sciences), 2006. *Drinking Water Distribution Systems: Assessing and Reducing Risks*. National Academies Press, Washington, D.C.

Quantification of the Value of Multiple Barriers in the Distribution System

Frank J. Blaha, Water Research Foundation senior project manager
Gary Burlingame, Philadelphia Water Department

The drinking water distribution system has been described as the "last frontier" in the science of drinking water protection. This statement partly arises from the fact that the multiple barrier concept has not been as rigorously defined and applied in this system as in others. In source water and water treatment, for instance, the "multiple barrier" concept has existed for decades, and over the last twenty years has been highly fine-tuned such that regulations based on the concept were established (SWTR, ESWTR, LT2ESWTR, D/DBPR, Stage 2 D/DBPR) and water industry management practices developed (such as the Partnership for Safe Water). When it comes to the distribution system, the multiple barrier concept has been applied in a number of practical and common-sense ways. However, the research and public health data to provide the scientific basis for these practices and to quantify their value has not been well developed.

For these reasons, the DSWQ SI Expert Panel identified Goal 2: Implementing Multiple Barriers for Distribution System Integrity (see sidebar). Work under this goal will generate specific and quantifiable information to better inform decisions amongst multiple barriers and will help optimize the benefit of specific barriers used. Of the Strategic Initiative's three goals, this one most clearly links distribution system water quality impacts to public health impacts, since only by quantifying these impacts can the relative value of different multiple barriers be fully understood.

Just as work on this strategic initiative started, the Total Coliform Rule/Distribution System (TCRDS) Federal Advisory Committee (FAC) Act meetings were taking place. They reinforced the need for more work on distribution system multiple barriers. The FAC concluded with the signing of an Agreement in Principle (AIP)

Distribution System Water Quality Strategic Initiative Goal 2: Implementing Multiple Barriers for Distribution System Integrity.

The use of multiple barriers to prevent water quality degradation and contamination has been a key component of water system design and operational philosophy for decades. A multiple barrier approach is also typically used in distribution system design and operation, but measuring and quantifying the value of those different barriers in the distribution system, and the trade-offs between using different barrier approaches, are generally not explicitly identified and quantified. This goal will generate specific and quantifiable information to allow for more informed decisions amongst multiple barriers and approaches to ensuring distribution system integrity, and will help optimize the benefit of any specific barrier used.

SIDEBAR CONTINUED NEXT PAGE

Goal 2 Continued

The multiple barriers to ensure distribution system integrity to be considered in this goal will include, but not be limited to:

1. Use of secondary disinfection and its benefits and costs, especially the formation of disinfectant by-products (DBPs), off-flavors, etc.
2. Use of biologically stable water to minimize possible microbiological activity, but possibly resulting in carry-through of microbes from biologically active treatment processes if there is inadequate secondary disinfection
3. Management practices that prevent degradation of water quality in the distribution system including design, operation, and maintenance techniques such as flushing programs, booster disinfection, elimination of dead-ends, pipe lining programs, etc.
4. Use of indicators for changes in water quality related to health effects; this may include indicators beyond total coliforms such as other indictor organisms, specific pathogens, or other water quality/biological surrogates for loss of system integrity
5. Maintenance of a positive pressure in the distribution system, which should generally result in leakage out of the system rather than into the system, but which is also susceptible to short-term pressure transients in areas where practices or design are not optimal and which may go un-noticed

Given these concerns, by the end of this five year DSWQ SI the benefits and costs of different barriers to negative distribution system water quality changes will be thoroughly researched and measurement approaches identified, including consideration of new measurement systems. From this work water utilities will be able to more quantitatively evaluate the value of different barrier approaches and significantly enhance the ability to measure the "health" of their system. *From the Distribution System Water Quality Strategic Initiative Plan, October 19, 2007*.

on September 18, 2008. The AIP categorized research and information collection needs into seven prioritized technical areas. The FAC discussions will be followed up with further research and information collection activities under the auspices of a research partnership between the Foundation and USEPA. Each of these seven areas, to varying degrees, is relevant as possible multiple barriers.

While the Foundation is sponsoring projects in many of the possible multiple barrier areas identified in the AIP, we still lack a larger picture of the multiple barrier context for the distribution system. We need to integrate existing information, fill in gaps, and quantify the barriers with some form of measurement process. We expect to do this as part of Goal 2 of the Strategic Initiative. This paper offers a brief discussion of past work relevant to the issue of multiple barriers and previews work expected to be performed under this Strategic Initiative goal.

Water Research Foundation Topic Work Prior to the Strategic Initiative

The Foundation has done considerable work relevant to multiple barrier considerations prior to the strategic initiative or recent TCRDS-related discussions. Foundation reports were cited numerous times in the materials that fed into the TCRDS FAC discussions, making clear that the organization already provides considerable information in this topic area. There are more than 100 Water Research Foundation reports relevant to implementing multiple barriers against water quality degradation in the distribution system. Following the technical structure of the TCRDS AIP research partnership and augmenting that with a few additional areas of substantial technical work, this effort can be categorized into the following topic areas:

- Use and effectiveness of secondary disinfectants
- Storage facility design, operation, and maintenance
- General operational and maintenance practices as related to water age
- General operational and maintenance practices as related to pipe/valve maintenance
- General operational and maintenance practices as related to flushing practices
- General operational and maintenance practices as related to pressure maintenance including short-term pressure transients
- Contaminant control/sanitary practices associated with main installation, repair, and rehabilitation practices
- Cross connection and backflow control programs
- Biofilm control
- Understanding health risks associated with the distribution system

The first nine topics identified above are addressed in other articles in this issue of *Drinking Water Research*, or were addressed in previous issues, especially the October–December, 2008 issue (Volume 18, Number 6). This earlier issue of *Drinking Water Research* contains an article about the research follow-up to the revised Total Coliform Rule discussions, and it specifically addresses each of the seven areas of needed research/information collection. However, we address the tenth topic—understanding health risks associated with the distribution system—in greater detail below.

Understanding health risks may not appear relevant to the other, more technical and water utility-related topics identified above. However, a greater understanding of health risks provides a necessary context for the utility-oriented, technical topics and allows us to weigh the health risks associated with one multiple barrier over another. Again, utilities have implemented these multiple barrier practices for distribution systems to varying degrees, but the measurable value of these programs has not been quantified to date.

Some of the Foundation's past projects clearly anticipated the linkage of utility technical activities to the health risks, as evidenced by the titles of the studies. For example, ***Impacts of Cross-Connections in North American Water Supplies*** (2003, order #90928F) anticipated that understanding water quality impacts associated with cross connection and backflow events would inform an understanding of health risks and, in turn, advance the state of practice in cross-connection and backflow prevention. Although the report captured cost and other data regarding contamination events, it found these events highly variable and could draw few conclusions about national impact regarding the extent or type of impacts associated with cross-connection and backflow events.

Estimating Health Risks from Infrastructure Failure (2006, order #91125) provides background on waterborne disease outbreaks and their link to distribution systems, acknowledges flaws in the reporting of outbreaks, and points out that the data were insufficient to fully understand distribution system health risks. The study concluded that water utilities and public health agencies should communicate better. A number of articles in recent technical literature implicate the distribution system in an increasing percentage of waterborne disease outbreaks. Still, as described in the 2006 National Academy of Sciences (NAS) report, *Drinking Water Distribution Systems: Assessing and Reducing Risks*, the exact quantification of health impacts from distribution system operations is unknown, especially when the contribution from individual risks (such as, for instance, the cross-connection and backflow contributions) is needed.

Water Research Foundation Work Under the Strategic Initiative

Fully understanding distribution systems is a daunting task since U.S. distribution systems consist of approximately one million miles of utility-owned water lines and an estimated six million miles of privately-owned service lines and premise plumbing (NAS 2006). This quantity of pipe provides many opportunities for water quality degradation. In addition, most of the distribution system health risks noted to date, such as backflow events and *Legionella* outbreaks, were likely isolated to premise plumbing. By including these premise-plumbing-caused cases in our database of distribution system-associated outbreaks, we may have biased our understanding of the outbreak data and public health risks over time.

One challenge of analyzing the risk or incidence of distribution system-related illness is how to relate results from one point in time to a dynamic and complex network. For example, a positive lab result for an indicator organism tells us that the organism was present at that specific sampling location, at a given time. It does not indicate that the organism will be homogeneously distributed in either space or time. In the same way, the absence of indicator organisms in a discrete grab sample does not ensure absence of pathogens in a newly installed main or storage facility. Since the quality of water changes as it moves through a distribution system, exposure assessment is a complex task.

Another complication is that utilities can makes changes to water system operations that affect water quality and exposure on a daily basis. Further, researchers conducting health risk studies on drinking water exposure may not have much distribution system operations experience and might make assumptions and produce study designs that leave in question critical aspects of system operations and water quality. In addition, drinking water exposure estimates need to consider the use of different drinking water sources to supply a given individual. For instance, an individual may consume tap water from one utility at home, but water from a different utility on a different raw water source at the office. Utility systems vary in the level of data they maintain and the quality of the data that they can provide. Some data are available through regulatory compliance information (such as sanitary surveys) while other data are available depending on the system (such as whether the system uses a hydraulic model).

Given this situation, project #4166, **"Tools for Evaluating Distribution System Water Quality and the Risk of Waterborne Disease,"** will give public health professionals and epidemiologists tools to help them collect and interpret data from drinking water distribution systems in order to enhance public health studies. The project is expected to produce the Distribution System and Premise Plumbing (DSPP) water quality tool, which should standardize and improve information collected on distribution and premise plumbing systems. Specifically, the project will provide the following products:

- A glossary of terms and data attributes linked to checklists on distribution systems and premise plumbing.
- Data checklists for easy collection of standardized data on distribution systems and premise plumbing and related drinking water data.
- A reference guide to data sources for completing the checklists with an emphasis on how to access data and assess their quality.
- Standardized water exposure questions with recommended analytical and statistical approaches for using the data collected in the checklists.
- Best practices to guide environmental investigations including standardized water exposure questions and a list of best practices for environmental investigations.

These products will interface with non-Water Research Foundation activities such as electronic reporting of waterborne disease outbreaks, a project under development by the USEPA and the Centers for Disease Control (CDC) in collaboration with public health jurisdictions through the National Outbreak Reporting System (NORS). Also, due to the use of NORS and EHS-Net Water, we expect to improve the environmental investigation of waterborne disease outbreaks. EHS-Net Water involves the USEPA, CDC, and five state health departments, and it will improve waterborne disease outbreak identification, reporting, investigation, and response.

Conclusions

When it comes to protecting water quality and public health, utilities lack critical tools and information to maximize the benefits of the multiple barrier concept in the distribution system. Utilities also lack the background support necessary to make tough decisions. Cross-cutting factors, such as understanding the protective value of a chloramine residual (or other disinfectant residual), must be considered when integrating different technical concerns into an overall vision of distribution system operation. The strategic initiative should significantly improve our operational understanding by attempting to quantify the value of multiple barriers in a strategic and coordinated manner.

References

NAS (National Academy of Sciences), 2006. *Drinking Water Distribution Systems: Assessing and Reducing Risks*. National Academies Press, Washington, D.C.

Definition of "multiple barrier approach"

The concept of using more than one type of protection or treatment in series in a water treatment process to control contamination and provide overall process reliability, redundancy, and performance. For example, to ensure the safety of drinking water, multiple barriers may include wastewater collection and treatment, protection of water sources, adequate treatment (including disinfection), adequate maintenance, the protection of water quality during storage and distribution, aggressive management, and adequate utility personnel training. Definition from: Symons, J.M., et al. 2000. *The Drinking Water Dictionary*, American Water Works Association, Denver, Colorado.

Chloramines: Filling in the Knowledge Gaps

Kenan Ozekin and Frank Blaha, Water Research Foundation senior project managers

Chloramines have been used in drinking water treatment since the early 1900s, but their use has been low compared to that of chlorine. With the introduction of the Stage 2 Disinfection/Disinfection By-Products (D/DBP) Rule, chloramine use has increased. Chloramines provide an effective disinfectant residual while reducing the formation of regulated disinfection by-products such as trihalomethanes and haloacetic acids. Chloramines are also more stable than chlorine and therefore last longer in the distribution system. However, chloramine use has drawbacks, including nitrification, formation of nitrogenous by-products, and deleterious effects on some elastomeric materials used in the distribution system. Since chloramine use has been increasing, many utilities are seeking a more complete understanding of their behavior in distribution systems. These considerations led the DSWQ SI Expert Panel

Distribution System Water Quality Strategic Initiative Goal 3: Chloramines – Filling in the Gaps.

For a variety of reasons the use of chloramines as a secondary disinfectant in the United States has been increasing, and indications are that the use of chloramines will continue to increase for the foreseeable future. Although the use and management of chloramines has already been extensively researched, considerable gaps are still present in our knowledge for complete and appropriate management of chloramine systems. By the end of this five year DSWQ SI, we will have developed additional guidance and understanding on the total cost and use of chloramines. Some specific issues that will have been addressed include:

1. An understanding of lead and copper corrosion models useful for systems initially switching to chloramines from free chlorine, as well as predictive models
2. Additional technical insights into issues such as skin rashes that are leading to current customer acceptance problems
3. Further advancing the understanding of DBP formation from chloramines
4. Identifying, preventing, and controlling nitrification episodes (especially addressing how to recover from a nitrification episode without the use of free chlorine)
5. Understanding and quantifying the impacts of nitrification episodes including impacts on premise plumbing
6. Quantifying the relative pathogen disinfectant benefit of chloramines compared with free chlorine
7. Quantifying the relative biofilm control benefit of chloramines compared with free chlorine
8. Understanding the impacts of ammonia on finished water as well as on the environment when discharged

Water utilities will benefit from this work by having a much more comprehensive understanding of chloramines and how to monitor and manage chloraminated systems to maximize the benefit from this disinfectant. This work will also allow a better understanding of those situations and systems, if any, where chloramines may not be the secondary disinfectant of choice. *From the Distribution System Water Quality Strategic Initiative Plan, October 19, 2007.*

to identify improving our understanding of chloramine use and decay as a program goal (see sidebar).

Since the mid-1980s, the Water Research Foundation has funded more than 60 research projects that examine chloramine-related issues, such as making the switch to chloramines, nitrification events, formation of disinfection by-products, formation of nitrogenous disinfection by-products, and lead and copper release as related to chloramine use. What follows is a summary of this work as well as information on work expected to be completed under the Strategic Initiative.

Switching to Chloramines

Although the Economic Analysis for the Stage 2 D/DBP Rule produced by the USEPA estimated that more than 50 percent of the surface water systems would use chloramines as a secondary disinfectant, the switch to chloramination has been somewhat slower than expected. The 2004 AWWA secondary disinfection practices survey found that 29 percent of community water systems currently use chloramines for secondary disinfection and that another 3 percent are converting to chloramine use (Seidel et al. 2005).

Switching to chloramines is certainly not easy and requires advance planning. Utilities considering such a switch need to consider issues ranging from public perception to compatibility of chloramines with the distribution system. ***Optimizing Chloramine Treatment—Second Edition*** (2004, order #90993), an update to an earlier report, is a manual on the use of chloramines and the role they play in water quality improvements for drinking water utilities. Using documented information from 68 utilities that use chloramines, the report identifies critical parameters for controlling chloramination and spells out a chloramination optimization strategy. ***A Guide for the Implementation and Use of Chloramines*** (2004, order #91018F) summarizes the current state of knowledge regarding chloramine use and synthesizes the information into step-by-step procedures for using chloramines in a water system. Finally, ***Long-Term Effects of Disinfection Changes on Water Quality*** (2007, order #91169) documents the long-term effects of disinfectant changes on distribution system quality, including changes in microbial quality, chemical quality, and aesthetic quality. The report contains issue papers on microbial quality, chemical quality (DBPs), chemical quality (corrosion, metal release, color, and particle characteristics), and aesthetic quality impacts associated with disinfectant changes.

Nitrification

Two-thirds of medium and large systems in the United States that chloraminate experience nitrification to some degree. Nitrification can significantly diminish water quality and can cause violations of coliform, disinfectant residual, and nitrite limits, as well as overall increased microbial growth in the affected areas. Therefore, utilities using chloramines are concerned about nitrification events that occur when chloramines decay in the distribution system.

When chloramines decompose, ammonia is released and can be oxidized to nitrite. This process, known as nitrification, is believed to be facilitated by ammonia oxidizing bacteria (AOB), which use the ammonia as an energy source. These bacteria are commonly found in drinking water systems, and nitrification occurs when conditions allow their numbers to rise. Although AOB seem to be implicated in most nitrification events, new information from the Foundation and others indicates that other bacteria may also play a critical role.

Two groups of factors influence nitrification and methods of control: water quality factors (pH, temperature, chloramine residual, ammonia concentration, chlorine-to-ammonia ratio, and concentrations of organic compounds) and distribution system factors (detention time, reservoir design and operation, sediment, tuberculation in piping, biofilm, and absence of sunlight). Understanding chloramine decay and nitrification events is clearly a critical issue in the effective use of this disinfectant, and the Foundation has conducted considerable research on this topic and will continue this work under the strategic initiative.

In a Foundation study of chloramine decomposition, ***Chloramine Decomposition in Distribution System and Model Waters*** (1998, order #90721), researcher Richard Valentine of the University of Iowa and his colleagues described the influence of water quality parameters on chloramine decomposition rates, compared decay rates in actual distribution systems with rates in model systems, and characterized chloramine decomposition products. The research team found that the rate of monochloramine decay increased as pH and ammonia concentrations decreased. Valentine and his team also produced two models of chloramine loss in drinking water. The more sophisticated model elucidates the reactions monochloramine undergoes as it decays. The simplified model can be used to determine the theoretical stability of monochloramine in a given finished water supply.

In the report, ***Ammonia From Chloramine Decay: Effects on Distribution System Nitrification*** (2003, order #90949), Greg Harrington of the University of Wisconsin and his colleagues studied the influence of ammonia release on the growth of AOB and evaluated treatment methods to reduce the frequency of nitrification in distribution systems. Harrington and his team also produced a model that simulates the water quality effects associated with chloramine decay and nitrification.

Disinfection By-Products

One of the main advantages of using chloramines over free chlorine is the lower

Additional Information on Nitrification

Utilities interested in knowing more about nitrification may also want to review the following Water Research Foundation reports:

- ***Nitrification Occurrence and Control in Chloraminated Water Systems*** (1995, order #90669)
- ***Monitoring Ammonia-Oxidizing Bacteria in Chloraminated Distribution Systems*** (2007, order #91162)
- **"Organic Chloramine Formation in Water Distribution Systems and Influence on Disinfection Efficacy and Nitrification"** (project #4065)

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production rate of regulated chlorinated disinfection by-products. However, recent studies indicate that under certain conditions, the use of chloramines may enhance the production of nitrogenous disinfection by products (N-DBP) by introducing reactive nitrogen into the water. Although N-DBPs are currently not regulated, several species are on the USEPA's Unregulated Contaminant Monitoring Rule 2. In the last several years, the Foundation has funded a number of projects to understand N-DBP occurrence and formation. ***Strategies for Minimizing Nitrosamine Formation During Disinfection*** (2008, order #91209) outlined strategies that could be used by water utilities to minimize the formation of nitrosamines during disinfection of drinking water.

Lead and Copper Release

Recent literature indicates that when some water systems switch to chloramines, there is a concurring increase in lead in drinking water. Perhaps that is because chloramines cause lead to leach from pipes, fixtures, and solder. To investigate this phenomenon, the Foundation has funded several projects. **"Effect of Changing Disinfectants on Distribution System Lead and Copper Release"** (project #3107) examines the effect of changing disinfectants (from free chlorine to chloramines and vice versa) on metals leaching rates and leaching levels from lead, brass, and copper distribution system components. The first phase of the project is complete and published as ***Effect of Changing Disinfectants on Distribution System Lead and Copper Release Part 1—Literature Review*** (2006, order #91152). The second phase includes laboratory, pipe loop, and field studies and will be published and available in early 2009. **"The Role of Free Chlorine, Chloramines, and Natural Organic Matter in the Release of Lead into Drinking Water"** (project #3172) investigates whether natural organic matter, free chlorine, and chloramines can act synergistically to either inhibit or accelerate the release of lead into drinking water. This report improves our understanding of the causes of excessive lead release into drinking water and will be published in early 2009.

Further Chloramine Work Under the Strategic Initiative

Although the use of chloramines for secondary disinfection has been studied

Additional Foundation Research on Disinfection By-Products and Chloramines

The following list provides additional ongoing Water Research Foundation projects related to disinfection by-products and chloramines.

- **"Occurrence and Formation of Nitrogenous Disinfection By-Products"** (project #3014) (available in early 2009)
- **"Exploring Formation and Control of Emerging DBPs in Treatment Facilities: Halonitromethanes and Iodo-Trihalomethanes"** (project #4063)
- **"Development of a Protocol to Predict the Formation of Nitrosamines While Minimizing the Formation of Regulated DBPs"** (project #4180)
- **"Development and Application of a Total Nitrosamine Assay for Disinfected Waters"** (project #4209)

For more information about these projects and more, visit the "Research Center" on the Foundation's Web site at www.waterresearchfoundation.org/research/. You can also search by project number using the "Project Center" of the site at www.waterresearchfoundation.org/research/TopicsAndProjects/projectCenter.aspx extensively, knowledge gaps remain. Recognizing the need for more research, the DSWQ SI Expert Panel has identified this topic as one of the Strategic Initiative's goal areas. Relevant projects funded through DSWQ SI include:

- **"Characterizing the Components of the Microbial Community Responsible for Nitrification"** (project # 4165). We do not understand the diversity of organisms that nitrify and their activities in finished water. This study aims to identify and characterize the microorganisms in distribution systems that are responsible for nitrification. Determining which organisms are involved will allow for better detection and quantification methods and may also provide insights into monitoring and control methods to help prevent or minimize the impacts of a nitrification episode.
- **"An Integrated Field-Scale Assessment of Chloramine Dynamics, By-Product Formation, and Nitrification Modeling"** (project #4218). This project focuses on water quality modeling (chloramine loss, DBP formation, and occurrence of nitrification events) and further evaluates and adapts the MSX-EPANET computer model for this application.
- **"Controlling Chloramine Decay and Nitrification in Distribution Systems"** (project #4220). This project is also focused on water quality modeling (chloramine loss and nitrification) and the evaluation/calibration of the Comprehensive Disinfection and Water Quality (CDWQ) model for this application.

These three projects are expected to yield practical chloramine information for water utilities. The first project should help to further define which bacteria play critical roles in nitrification events. The latter two projects will further advance the application of computer modeling to understand chloramine use and nitrification events. While these projects—in combination with other Foundation work—should prove extremely valuable to those who manage distribution systems that use chloramines, further research will likely be needed. The Strategic Initiative will track new information developed in this area and identify and coordinate appropriate future projects on this topic.

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Biofilm and its Importance to Distribution System Water Quality

John Albert, Water Research Foundation project manager

Since 1985, the Water Research Foundation has funded more than 25 projects that focus primarily on biofilms and many more that touch on biofilm-related issues. We know that some microorganisms that inhabit drinking water distribution systems can proliferate and form what is known as a biofilm. The vast networks of distribution systems provide a large surface area for their formation. We are still learning what types of microorganisms grow and the extent that they persist in these environments. Of special concern are primary and opportunistic pathogens that enter the distribution system by means of inadequate primary disinfection or through compromised distribution system integrity. Once in the distribution system, these pathogens can join existing biofilms where they are protected from secondary disinfection and can persist and even proliferate.

Given biofilms' potential to harbor pathogens and support their proliferation, further understanding of biofilms is relevant to the strategic initiative's multiple barriers goal. In addition, since biofilms may play a role in nitrification events, and further understanding of nitrification events fills knowledge gaps on chloramine use, biofilms research is also relevant to the initiative's chloramine goal. Finally, since biofilms may play a role in premise plumbing corrosion through pitting or other processes, further understanding biofilms also relates to the goal of advancing our understanding of premise plumbing water quality changes. Given these multiple connections, the expert panel deemed that further research on biofilms is needed. The topics of biofilm interactions with pathogens, and biofilm influence on nitrification events, corrosion, taste and odor, and loss of residual will be addressed below in terms of relevant, new, ongoing and completed projects.

Biofilm and Pathogen Interactions

There are a number of completed, ongoing and planned biofilms-related projects that touch on biofilms' microbial makeup and potential pathogen interactions. The report ***Pathogen Intrusion into the Distribution System*** (2001, order #90835) was instrumental in identifying a new pathway for how pathogens may be introduced into the distribution system: intrusion due to pressure transients. The project described how microbial pathogens enter the distribution system, particularly when treatment appears to be providing adequate multiple-barrier protection, and the author estimates the extent of pathogen contamination by different sources of intrusion. The report evaluated the effectiveness of distribution system maintenance practices in protecting against pathogen intrusion. The report concludes by recommending monitoring programs that detect pathogenic distribution system contamination.

The ongoing project, **"The Role of Amoebae in the Protection and Proliferation of Pathogens in Distribution Systems"** (project #4092), will determine the extent to which amoebae shelter pathogenic organisms and enable the proliferation of pathogens such as *Legionella* and *Mycobacterium avium* complex in distribution systems. It should add considerably to our understanding of how pathogens and biofilms interact. In early 2009, the expert panel will launch a new project to further understand interactions of biofilms and pathogens. "Characterizing the Interactions Between Pathogens and Biofilms and Their Fate and Transport in Distribution Systems," advertised as RFP #4259 in March 2009, will focus on understanding the retention, fate, persistence, potential for release, and dispersion of pathogens with biofilms in potable water distribution systems. This biofilm/pathogen work aims to better understand and control exposure to introduced pathogens. Quantitative approaches to data generation and analysis are preferred.

The project, "Relationship Between Biodegradable Organic Matter and Pathogen Concentration in Premise Plumbing Systems," advertised as RFP #4251 in March 2009, will examine how varying levels of biodegradable organic matter influence the growth and persistence of opportunistic pathogens in model premise plumbing systems. This will be coordinated with another strategic initiative project, **"Microbial Ecology of Drinking Water Distribution Systems"** (project #4116). The microbial ecology project will develop a broad-range ecological assessment of the microbiota within distribution system and premise plumbing biofilms. By identifying normal/baseline community structures, we may gain insight into periods of system compromise. This project will be conducted in partnership with Singapore Public Utilities Board, which is engaging in related, coordinated work of similar scope and size. By integrating the results of two separate research efforts, we hope to considerably advance our understanding of the microbial ecology of biofilms and gain insights into biofilm pathogen management.

By integrating the results of two separate research efforts, we hope to considerably advance our understanding of the microbial ecology of biofilms and gain insights into biofilm pathogen management.

Biofilms and Nitrification Events

Nitrification can impact public health by increasing public exposure to nitrate and nitrite as well as reducing disinfectant residuals in the distribution system (therefore reducing the level of protection from intrusion events). Biofilms are expected to play a major role in the onset of nitrification events. The Foundation has two ongoing projects in this area:

"Characterizing the Components of the Microbial Community Responsible for Nitrification" (project #4165), funded as a Strategic Initiative project, will identify and characterize the distribution system microorganisms responsible for nitrification. This project will also document methods suitable for nitrite identification so that other utilities and researchers can conduct similar studies and further develop nitrification monitoring and control strategies.

"Organic Chloramine Formation in Water Distribution Systems and Influence on Disinfection Efficacy and Nitrification" (project #4065), will develop a new organic chloramine selective analytical method.

The project research team will attempt to quantify organic chloramine yields upon exposure of biofilms to free chlorine or monochloramine and to quantify the biocidal efficacy of organic chloramines. In addition, this project will assess formation, fate, and efficacy of organic chloramines and their influence on nitrification in laboratory pipe loops that simulate water distribution systems. Project results should provide tools to help quantify the formation of organic chloramines in the field during nitrification events, recommendations for monitoring organic chloramines, and strategies to minimize the onset of nitrification.

Biofilms and Corrosion: Focus on Premise Plumbing Corrosion

Biofilms, primarily communities of iron and sulfur bacteria, may be an important factor in pipe corrosion. These and other microorganisms can change the oxidation-reduction potential of piping materials, resulting in environments that accelerate corrosion. The Foundation has two ongoing projects in this area.

"Effect of Nitrification on Corrosion in the Distribution System" (project #4015), will identify the role of nitrification-induced water quality changes that may affect corrosion in the distribution system. The research team will investigate the factors that influence the activity of nitrifiers across various situations as well as the magnitude of their effect on water chemistry. This project will also examine the potential significance of nitrification on lead and copper release.

"Premise Plumbing Water Quality Changes—Sulfate Reducing Bacteria" (project #4219), is an ongoing project funded under the Strategic Initiative as a targeted unsolicited project. This project aims to improve our understanding of water quality factors that contribute to sulfur-reducing bacteria (SRB) growth in premise plumbing. In the process, the project will also establish some scientific guidelines that can help to control these organisms. Relatively little is known about bacterial growth in the unique physical-chemical environment of home plumbing systems (NAS 2006). Certain bacteria that do not pose problems in the continuously flowing water mains become a problem in the stagnant, intermittent flow of premise plumbing. In addition, warmer temperatures in the hot water system—or even in warming cold water lines within walls—can enhance bacterial growth. Given the frequency of consumer complaints about black water and SRB-related odors (FL Blackwater, 2001), as well as the likelihood that SRB contribute to corrosion problems, this research has a high reward value to the water industry. Further, this study could serve as a model for future investigations of bacteria colonization within residential systems.

Biofilm Contribution to Taste and Odor

Microbially-mediated processes have been implicated in finished drinking water aesthetic concerns, such as taste, odor, and discoloration. The USEPA white paper *Health Risks from Microbial Growth and Biofilms in Drinking Water Distribution Systems* reviewed several microorganisms associated with these aesthetic concerns. Some organisms produce sulfur compounds, which result in a foul odor. Other organisms produce compounds that result in earthy-musty odors. In other instances, when in high enough numbers, certain organisms produce color changes in finished water. Many of these organisms are associated with pipe biofilm. The Foundation has funded recent research on the impacts of disinfection on taste and odor complaints.

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In the report, ***Long-Term Effects of Disinfection Changes on Water Quality*** (2007, order #91169), researchers examined information from water utilities that have made changes to their disinfection strategy in order to document benefits and adverse consequences in water quality parameters. The final report provides guidance on how water utilities can evaluate potential changes in distribution system water quality due to changes in disinfection practices. In general, the data indicated that changes in disinfection practices led to better microbial quality, such as lower coliform levels and heterotrophic plate counts (HPC), and reduced levels of disinfection by-products such as trihalomethanes and haloacetic acids. Also, the data indicated that disinfection changes led to reduced numbers of customer complaints regarding red or discolored water and poor tastes and odors.

Loss of Residual

Biofilms are more resistant to disinfection than single microorganisms found in the water column. Therefore, increased amounts of distribution system biofilms may require more secondary disinfectant for biofilm control purposes as well as for maintaining minimal residual requirements. The following projects focus on assessing and controlling biofilm to prevent residual loss as well as other negative impacts:

Assessing and Controlling Bacterial Regrowth in Distribution Systems (1990, order #90567) provides guidance on assessing the extent and relative importance of biofilm and biological activities on water quality deterioration in distribution systems. The project describes methods and procedures that effectively evaluate the potential for biological problems and identifies specific practices to control such problems, including the loss of disinfectant residual.

The ongoing project **"Assessing and Managing Biofilm in Distribution Systems"** (project #4087), will develop utility-friendly guidance on assessing and managing distribution system biofilms, including the management of disinfectant residual. In addition, this project will present the current state-of-the-science knowledge on biofilms in a practical format.

Conclusion

While the Foundation and others have conducted considerable research on biofilms and their impact on distribution systems and water quality, some knowledge gaps remain. The DSWQ Strategic Initiative is focusing some additional strategic effort on developing a higher-level understanding of biofilms, and some of the projects already underway are likely to yield considerable value. The Strategic Initiative will closely follow the biofilm-related projects already underway—or those that may start in the future—and adjust the focus of any further Strategic Initiative projects as appropriate to maximize the value of this biofilm work to water utilities.

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Online Monitoring of Distribution System Water Quality for Security and Protection of Water Quality

Hsiao-wen Chen project manager and Frank J. Blaha senior project manager, Water Research Foundation

In the wake of the Sept. 11 terrorist attacks, water professionals became painfully aware of the distribution system's vulnerability to purposeful, malevolent contamination. As a result, there is a growing interest in online, real-time distribution system monitoring. Yet while the related technologies have been applied to treatment process and source water monitoring, their application in the distribution system is relatively new.

The concept of online real-time monitoring of distribution systems is appealing and simple, but effectively using these technologies in an operating distribution system is complicated and difficult. While the Foundation and others have devoted considerable resources to this topic since 2001, we still lack a comprehensive understanding of these technologies' applications to water community distribution systems as a whole. In fact, while more and more utilities are deploying these units in the distribution system, the generation and analysis of a near-continuous stream of distribution system data is a new frontier of knowledge. While online real-time monitoring of distribution systems is not a specific goal of the DSWQ SI, this technology has many theoretical advantages that could support the goals of water quality protection and active management of distribution systems. However, the technology must be improved in order to realize its full potential. Key findings from some of the more relevant projects are presented below.

In the wake of the Sept. 11 terrorist attacks, water professionals became painfully aware of the distribution system's vulnerability to purposeful, malevolent contamination.

State of the Science in 2001

The comprehensive report, ***Online Monitoring for Drinking Water Utilities*** (2002, order #90829), the result of collaboration between the Foundation and CRS PROAQUA, Italy, elucidates several aspects of online monitoring:

- Rationale for online monitoring
- Specification and testing of online monitors
- Selecting online monitoring equipment
- Specific types of online monitoring instrumentation
- Data handling and validation
- Advanced process control using online monitors

While most of the report addresses using these technologies for treatment and source water monitoring, several case studies address distribution systems. At the time this report was completed, little had been done to use online technologies in the distribution system. This report is aimed at a broad audience: operators, laboratory technicians, instrument engineers, equipment selecting and purchasing personnel, managers, and regulators.

More recent Foundation reports and projects on distribution system water quality monitoring have more specific goals. They can be categorized into sensor technology and data analysis.

Current State of the Science in Online Sensor Technology for Distribution Systems

Deploying online sensors is not as straightforward and easy as simply determining where one wants to take samples. Instead, you must consider access to the sensors, access to the distribution system, the need for electrical power, the possible need to provide chemicals or other consumables, as well as the parameters you will actually monitor.

"Real-Time Online Monitoring of Contaminants in Water" (project #4025) reviews the literature about state-of-the-art online sensor technology for chemical, microbial, and radiological contaminants. For the distribution system, conventional sensors for water temperature, dissolved oxygen, pH, turbidity, conductivity, and particle count are reliable, robust, and well-established. Equally trustworthy are ultraviolet (UV) probes for turbidity, total suspended solids, UV absorption at 254 nm (UV_{254}), chemical oxygen demand, total organic carbon (TOC), biological oxygen demand, assimilable organic carbon, nitrate, nitrite, ammonium, hydrogen sulfide, benzene–toluene–xylene, oxygen, and ozone.

In addition to the literature review, **"Real-Time Online Monitoring of Contaminants in Water"** (project #4025) reports the results of a survey of real-time online monitoring practices and experiences in the United States, the United Kingdom, Australia, Belgium, and the Netherlands. The results gave an indication of the scope and reliability of monitoring data. The majority of the 52 U.S. respondents measured four to six parameters online. The four parameters most frequently monitored were flow rate, turbidity, pH, and water temperature. The majority of respondents deemed the measurements of these four parameters, as well those of fluoride, chlorine, and UV_{254}, reliable.

Based on experiments using pipe loop systems, ***Distribution System Security and Water Quality Improvement Through Data Mining*** (2008, order #3086) concluded that a conventional sensor suite consisting of pH, conductivity, chlorine residual, and either TOC or UV_{254} could detect contaminants such as synthetic organics, arsenic, and cyanide salts at sub-lethal concentrations. For optimal detection of organic contaminants, TOC would be preferred to UV_{254}. Unfortunately, the authors did not find the current TOC technology dependable for field application. This finding corresponded to the survey results reported in **"Real-Time Online Monitoring of Contaminants in Water"** (project #4025). Only 21 percent of U.S. respondents that monitored TOC online considered the data accurate.

"Cross-Connection and Backflow Vulnerability: Monitoring and Detection" (project #3022), to be completed in 2009, compiled information about commercially available single-parameter sensors and multi-parameter sensors, including panel systems, probe systems, and sonde systems for distribution system monitoring. The pilot testing conducted for this project demonstrated that

- free chlorine and oxidation–reduction potential showed responses to a number of different contaminants spiked into the water,
- higher contaminant concentrations were required for turbidity and conductivity to respond, and
- online TOC analyzers were very sensitive to a relatively small quantity of organic matter.

While water quality analysis conducted in a laboratory is generally reliable, it is more challenging to apply analytical methods to monitoring water quality in the distribution system online. The two most critical factors identified in ***Distribution System Security and Water Quality Improvement Through Data Mining*** (2008, order #3086) are the location of sensor suites and the design of sensor data collection schemes. A suitable location needs to provide all electrical and supervisory control and data acquisition (SCADA) connections and a proper design should avoid pressure transients, which can disrupt sensor performance. At times these different requirements may suggest locations suitable for one set of criteria but totally unsuitable for the other set of criteria. For instance, in this project, a number of months of data generation were lost due to unreliable distribution system sensors. These sensors, located at an optimal site based on electrical, SCADA, and access considerations, were unsuitable due to pressure fluctuations that ultimately caused probe failure. The project recommends the use of a calibrated water quality and hydraulic model for identifying optimal sensor locations from the perspective of generating representative data and being aware of pressure fluctuations.

Distribution System Security and Water Quality Improvement Through Data Mining (2008, order #3086) also advises that before purchasing online monitoring equipment, utilities should conduct a thorough inquiry into the equipment's full-scale application. Even well-established manufacturers can have both very reliable and very unreliable equipment for in-field application. Utilities should seek examples from equipment suppliers of existing successful installations.

Current State of the Science in Data Processing and Analysis

Much of the recent work on the application of online sensors and the reduction of the generated data has been driven by security concerns and not routine operational concerns. But while some of the parameters monitored may be different, the purpose of monitoring in either case is to identify out-of-tolerance water quality conditions. Whereas data generated from composite samples collected over a long period of time or from occasional grab samples can be more

Types of Monitoring Sensors

- **panel systems:** an online stand alone system of sensors that monitor a side stream of water
- **probe systems:** an online system of sensors using a single head and data/power cable that monitors a side stream of water and operates at atmospheric pressure
- **sonde systems:** an online sensor that is inserted into the water flow under distribution system pressure

straightforward, online monitoring can produce a near real-time data stream. A number of questions arise on how to optimize the monitoring system. How frequently should data be taken—every second, every minute, every ten minutes, once per day? How frequently should the data be analyzed in order to identify out-of-tolerance conditions, and how are out-of-tolerance conditions identified? For instance, if data is generated every minute, is one data point more than three standard deviations above the mean of the previous 1,440 data points out-of-tolerance? Should there be one or two samples confirming such a high number before an alarm sounds, or should there be corresponding elevated data at nearby sensors, or other approaches to determining out-of-tolerance conditions? Answers to these data processing questions must balance the need to ensure adequate sensitivity in collection and analysis without creating too many false positive alarms. If too many false positives sound, the data stream may be judged useless or simply ignored. A number of Foundation reports have attempted to address these issues.

Armed with this information, operators can make necessary process and operational adjustments, justifying the cost of online monitoring.

Data Processing and Analysis for Online Distribution System Monitoring (2008, order #91226) offers a thorough literature review of existing data processing techniques and commercially available software packages for online distribution system monitoring. This review focuses on a method's strengths, limitations, and ability to indicate water quality impairment based on expected normal conditions. The most promising data processing techniques were the control chart, time series analysis, and Kriging and Kalman filter techniques.

Distribution System Security and Water Quality Improvement Through Data Mining (2008, order #3086) evaluated the reliability and cost-effectiveness of an early warning decision support system for processing and analyzing data from conventional sensor technology. The evaluation was performed via a full-scale trial of the decision support system. Distribution system water quality data included turbidity, pH, chlorine residual, conductivity, and water temperature. The authors employed proven multivariate geometric algorithms for clustering and classification. They employed univariate filtering to monitor water quality and identify outlying data that could indicate a contamination incident. They proved that various types of water quality behavior, including responses to contaminant injection, could be distinguished from baseline behaviors.

In addition to monitoring for public health and security purposes, the authors of ***Distribution System Security and Water Quality Improvement Through Data Mining*** (2008, order #3086) identified auxiliary advantages of distribution system online monitoring. These include the ability to detect trends characteristic of nitrification events, diminished chlorine residual, and the formation of disinfection byproducts. Armed with this information, operators can make necessary process and operational adjustments, justifying the cost of online monitoring. The authors also found that correlating the analytical data stream with other metadata was critical to accurately interpreting the data stream.

Data Processing and Analysis for Online Distribution System Monitoring (2008, order #91226) provides the following practical recommendations for online distribution system monitoring:

- An overall description of the distribution system is essential.
- Metadata, defined as necessary background information, should be recorded in a standard format for each measured variable.
- Off-line sensor should be set to read a known error state or a specific value that is not a credible reading.
- Strong quality control procedures should be implemented.
- A copy of the original recorded data should be used for pre-processing. The original recorded data should not be altered.
- A table of monitored variables should be produced using standard abbreviated names for variables and include the methods, units, and mode of measurement.
- For each variable, the acceptable values should be determined.
- Pre-processing of the data should aim to have time-order variables.
- An exploration of past data and the identification of typical problems and events are important.
- Variables should be measured and recorded to the greatest number of significant figures possible.
- Control charts applied to first differences of each variable can be used to provide a useful start to identify changes worthy of attention.
- Individual water utilities should determine alarm levels suitable for their own particular circumstances.

Individual water utilities should determine alarm levels suitable for their own particular circumstances.

As illustrated in ***Data Processing and Analysis for Online Distribution System Monitoring*** (2008, order #91226), metadata are necessary to enable sensible interpretation of the sensor data. A new Foundation project titled, **"Interpreting Real-Time Online Monitoring Data for Water Quality Event Detection"** (project #4182), aims to integrate water quality sensor data with subsets of metadata, namely hydraulic data and operation information, so that operators can effectively identify water quality abnormalities while minimizing false alarms. This project will utilize the pattern matching, outlier detection, and case-based reasoning algorithms developed for ***Distribution System Security and Water Quality Improvement Through Data Mining*** (2008, order #3086) to build an automated real-time monitoring and decision aide (ARTMADA). A demonstration version of ARTMADA is expected to be available along with the published final report.

Summary

Effective online monitoring of distribution system water quality involves a number of factors:

- Reliable monitoring sensors. Currently, the measurements of flow rate, turbidity, pH, water temperature, fluoride, chlorine, and UV_{254} are generally considered reliable. More reliable TOC analyzers are needed.

- Suitable sensor locations in the distribution systems that can provide all electrical and SCADA connections.
- Suitable sensor locations or proper design of those sensor locations to avoid pressure transients, which can disrupt sensor performance.
- For optimal locations, a calibrated water quality and hydraulic model is recommended.
- An early warning decision support system for processing and analyzing data stream from sensors. Promising data processing techniques include control chart techniques, time series analysis, Kriging techniques, and Kalman filter techniques.
- Multivariate geometric algorithms for clustering and classification and univariate filtering to monitor water quality and identify outlying water quality.
- Metadata that are supplied and updated on a regular basis
- Strong quality control procedures

In addition to protecting public health, online monitoring of distribution system water quality provides auxiliary information that can be used to optimize your operation. This advantage can help justify the cost of online monitoring. Water utilities are advised to inquire into the full-scale application performance of online monitoring equipment before purchasing and deploying these units.

Estimating Health Risks From Infrastructure Failures

(order #91125, project #2773)

Karen M.E. Emde, Daniel W. Smith, James A. Talbot, Les Gammie, Susan Ancel, Nelson Fok, and Janet Mainiero

Health risks from infrastructure failures are not well understood, despite the potential widespread introduction of chemical, microbial, and physical contaminants, as well as service disruptions. While the water utility is responsible for safe water, including the operation and maintenance of distribution infrastructure, other agencies such as public health regulators, medical practitioners, and first responders (e.g., police, firefighters, and others) also play a pivotal and active role when dealing with the impacts of infrastructure failures on the community.

The project consisted of two components. First, an international workshop was held that brought together experts from the various disciplines and agencies involved with some aspect of community health protection, safe drinking water, and water infrastructure failures.

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Strategies for Minimizing Nitrosamine Formation During Disinfection

(order# 91209, project #2979)

Frank Sacher, Carsten K. Schmidt, Changha Lee, and Urs von Gunten

Recently, N-nitrosodimethylamine (NDMA) has been identified as a possible disinfection by-product and has been detected in United States and Canadian water treatment plants that use chloramine as a disinfectant. Nitrosamines are known to be both toxic and carcinogenic, and carcinogenic effects have been observed at low parts per billion concentration levels. In addition to NDMA, the USEPA has identified eight other aliphatic nitrosamines as significant health concerns. Therefore, the objective of this project was to identify strategies that could be used by water utilities to minimize the formation of NDMA as well as other nitrosamines during disinfection of drinking water.

The research team performed an extensive literature search to collect information on mechanisms of nitrosamine formation, to identify or at least

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Assessment of Non-Uniform Corrosion in Copper Piping

(order #91217, project #3015)

Marc Edwards, Paolo Scardina, G.V. Loganathan, Darrell Bosch, and Sharon Dwyer

Premature pipe failures and pinhole leaks have become problematic and worrisome to homeowners in communities where outbreaks of leaks have occurred. These failures and leaks are sometimes caused by non-uniform corrosion. In contrast to uniform corrosion, in which all parts of the internal pipe surface are attacked at roughly the same rate, non-uniform or pitting corrosion is localized, leading to rapid loss of pipe wall at a particular location. In copper piping, pitting that manifests into a pinhole leak greatly shortens the usable lifespan of potable plumbing pipes. The resulting leak can damage housing infrastructure and other valuables or potentially lead to mold growth. Unfortunately, factors that cause pinhole leaks and corresponding mitigation strategies are not well understood.

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Contribution of Service Line and Plumbing Fixtures to Lead and Copper Rule Compliance Issues

(order #91229, project #3018)

Anne Sandvig, Pierre Kwan, Gregory Kirmeyer, Barry Maynard, David Mast, R. Rhodes Trussell, Shane Trussell, Abigail Cantor, and Annette Prescott

Implementation of the Lead and Copper Rule (LCR) has resulted in significant reductions in first liter standing lead levels measured at the tap in the United States. However, there are utilities that have implemented optimal treatment but may still experience lead concentrations at or near the action level for lead. There are also utilities that would like to go a step further in reducing lead levels measured in their system by proactively replacing lead source materials. For these utilities, and the drinking water and regulatory communities as a whole, an understanding of the contributions that various lead-based materials may have on lead levels measured at the tap is needed and was the focus of this project.

The researchers also addressed the broader long-term goals of moving

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Estimating Health Risks From Infrastructure Failures

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Participants included water utilities, public health and environmental regulators, consulting engineers, water quality scientists, physicians, and police. The workshop participants explored the needs and capabilities of detecting, preventing, and correcting adverse health outcomes caused by infrastructure failures. The second component was to consolidate the considerable knowledge gained from the workshop into this report.

All the agencies acknowledged that the true extent of health effects, while not yet well known or characterized, required a collaborative, interagency approach. The study identified methods to develop future collaborative efforts, which included improved understanding of the relationships and outcomes between infrastructure failure events and measured health outcomes, as well as the need to develop improved tools for the detection and monitoring of these events and community effects. This included the need to develop and refine collaboration for interagency surveillance, response, and mitigation efforts for infrastructure failures.

Community impacts from water infrastructure failures may include canceling public events, closing public places, or providing alternative sources of water, in addition to any water quality issues that may arise. Successful resolution of these issues requires timely interagency collaboration and communication. The relationships required are neither intuitive nor commonplace; ongoing efforts are needed well before the infrastructure failure emergency event occurs.

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Strategies for Minimizing Nitrosamine Formation During Disinfection

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characterize possible precursors for nitrosamine formation, and to identify tools for removal of precursor compounds prior to disinfection. The possibilities for nitrosamine removal were evaluated. Laboratory-scale tests to characterize water samples for nitrosamine formation potential were performed in order to fill in knowledge gaps identified during the literature search. The conclusions from the literature search and the laboratory-scale experiments were verified by full-scale tests in water utilities in the United States, Australia, and Germany.

Several options for minimizing nitrosamine formation became apparent from the outcome of the research. Effective options for removal of nitrosamine precursors were biodegradation, oxidation with either ozone or chlorine, and granular activated carbon filtration. Aeration, lime softening, and coagulation/flocculation turned out to be rather ineffective for precursor removal. Besides precursor removal, optimization of operational parameters was a promising option for minimizing nitrosamine formation during chloramination. Effective options included reduction of disinfectant dose, lowering of pH, use of chlorine instead of chloramine, and minimizing dichloramine levels during disinfection (e.g., by addition of free chlorine before ammonia). Pre-oxidation steps were very effective in reducing NDMA formation during chloramination if carefully optimized with respect to location, dose of oxidant, contact time, and pH. The researchers also discovered that the formation of many other nitrosamines during chloramination is almost negligible compared to the formation of NDMA.

This project provides information on the identity of a relevant precursor compound for NDMA formation that can act as a first step towards the elimination of this unwanted compound. This precursor compound along with the other strategies described in the report will enable water utilities that use chloramination for disinfection purposes to minimize the nitrosamine levels in their drinking water and thus comply with existing or future drinking water standards and minimize consumers' exposure.

Assessment of Non-Uniform Corrosion in Copper Piping

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The purpose of this project was to assess the extent and implications of copper pitting and pinhole leaks for residential potable water plumbing systems. The research team conducted national surveys targeting plumbers, homeowners, businesses, and corrosion experts. The team also reviewed the Copper Development Association's database of copper failures, which spans 30 years. The mechanistic causes of pinhole leaks were investigated via intensive case studies at participating communities, where hydrological, biological, and aqueous chemical factors were considered.

Pinhole leaks were confirmed in all states and most major urban areas. Approximately 8.1 percent of homeowners nationally have experienced at least one pinhole leak, and between 21–60 percent of homes in certain communities have observed pinhole leaks. The total cost of pinhole leaks and pinhole leak prevention in the United States is estimated at $967 million annually, with the largest proportion of cost ($564 million) in single family homes particularly devoted to repairs (44 percent). About 58 percent of responding water utilities reported using corrosion inhibitors, and annual costs of dosing corrosion inhibitors ranged from $0.10 to $5.72 per customer with an average of $1.16 per customer.

Case studies at communities experiencing pinhole leaks were designed to confirm suspected mechanisms and identify new mechanisms causing pinhole leaks. In terms of internal copper corrosion problems caused by unfavorable water chemistry and microbiology, three factors emerged with strong links to pinhole leaks: high pH and high levels of disinfectant exacerbated by aluminum and other particles, local production of H2S in and around pits by sulfate reducing bacteria, and erosion corrosion in hot-water recirculation systems. Other factors are believed to influence pitting corrosion and pinhole leaks.

The results of the various surveys demonstrated that copper pitting is a nationwide concern, particularly where certain unfavorable water chemistry and microbiological factors are present in the distribution system. Based upon the experiences of working with communities and water utilities for this project, a protocol was developed to help assess the extent of pinhole leaks in a community. The protocol involves periodic surveys of local plumbers, cultivating relationships with homeowners, and a proactive effort when leaks are encountered. If no serious problems are detected, the process still generates baseline data for future reference if a problem were to occur.

Contribution of Service Line and Plumbing Fixtures to Lead and Copper Rule Compliance Issues

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the industry toward a new "lead free" future and providing information that can be directly applied to future regulatory reviews of the LCR.

The researchers also addressed the broader long-term goals of moving the industry toward a new "lead free" future and providing information that can be directly applied to future regulatory reviews of the LCR.

During the course of the project, the research team discovered that lead source contributions will be influenced by the physical characteristics of the source (i.e., length, diameter, surface area), water quality conditions, water use and hydraulic patterns, and mixing and dilution effects as the water flows during sampling. In addition, it was hypothesized that the presence of a lead service line at an individual site may elevate the contribution of individual sources by providing an additional source of lead, either by seeding the premise system with lead or introducing lead derived from the service at the start of the stagnation period.

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

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

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