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IDENTIFYING RESEARCH-NEEDS RELATED TO IMPACTS OF WATER QUALITY ON THE INTEGRITY OF DISTRIBUTION INFRASTRUCTURE

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Abstract: Drinking water systems can experience frequent changes in their water-sources, treatment processes and/ or practices to maintain safe and aesthetically acceptable water quality. In addition, as new water quality regulations are implemented, further changes in water quality are anticipated. Evaluation of the impacts of such changes on the structural integrity of the distribution infrastructure is a daunting undertaking due to numerous inter-related processes occurring within the distribution system. A change in water quality may impact the structural integrity of the distribution infrastructure in many ways.

The National Research Council Canada (NRC) and the American Water Works Association Research Foundation (AwwaRF) recently concluded a partnership project to identify key research needs related to the impacts of water quality changes on the integrity of the distribution infrastructure. This paper provides a synopsis of available knowledge and challenges in the protection of drinking water distribution infrastructure against water quality changes.

Keywords: water quality, distribution system, infrastructure integrity, AwwaRF-NRC.

Introduction

The deterioration of drinking water distribution infrastructure is among the main causes for the loss of quality and quantity of drinking water at the consumers tap. However, since a major portion of the distribution infrastructure is underground, its deterioration does not present the same visual urgency as other visible infrastructure. Since deterioration of the distribution infrastructure adversely impacts the water quality, public water systems cannot justify the costs and efforts of treating water to potable levels and then transmitting them through deteriorating distribution systems.

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Components of distribution infrastructure deteriorate due to internal and external corrosion, wear and tear, and fatigue. Deterioration rate and extent is a function of stresses to which the pipe is exposed, and the duration of exposure. The failure of water distribution infrastructure can cause an array of economic and social costs including direct damage to transmission and distribution infrastructure, adjacent property and business, traffic delays, and inconvenience to public (Cromwell III *et al.* 2002).

The interaction of interior pipe surfaces with treated water is by no means the only (or even the most significant) process that leads to the overall deterioration of the infrastructure components. Other processes including, structural loading, external corrosion, inadequate operation and maintenance and human errors are significant contributors to infrastructure failure. However, water quality-induced deterioration may exacerbate the condition of pipes, and make them more susceptible to other failure mechanisms.

For the purpose of evaluating the impact of water quality on the distribution infrastructure, the lowest common denominator is the type of material of which a component is constructed. Though the distribution infrastructure is composed of different components fulfilling different functions, they are constructed using a limited number of materials. The choice of materials in drinking water applications is determined by health and aesthetic concerns as well as manufacturing, performance and economic considerations.

In this paper the impact of water quality on deterioration of distribution infrastructure is mainly related to the interaction of the component's surface in contact with the water.

Deterioration Mechanisms

Distribution infrastructure components can be categorized into three broad material groups - metallic, polymeric and/or cement-based. In the context of this paper, the distinction between these three is based on the dominant deterioration processes, which can be either internal corrosion, microbiologically induced corrosion (MIC) or leaching of material. Though a specific material may have a predominant mechanism of deterioration, all three processes may play some role towards its overall deterioration (Table 1).

Physico-chemical based internal corrosion

Physico-chemical based internal corrosion (referred to as 'corrosion'), can be regarded as 'metallurgy in reverse', where a purified metal or its alloy interacts with the environment to return to a more stable state. Three conditions are required in order for corrosion to proceed; a metallic surface that corrodes, an oxidant that oxidizes (corrodes) the metal to a more stable state and lastly, a medium that will transport the oxidant to the metal and facilitate further corrosion by moving the corrosion byproducts away from the corrosion site. All these conditions are present in many water distribution systems. A water distribution system may corrode both internally and externally. However, the external corrosion is related to the water quality only in an indirect way (increases the likelihood of contaminant intrusion) and is not discussed here.

Microbiologically induced corrosion

Microbiologically induced corrosion (MIC) is different from other deterioration processes because it is caused by the biological activities of microorganisms. While some researchers suspect that biofilms (colonies of native microorganisms on the water/ metal interface) inhibit deterioration by providing a protective coating, others have reported biofilm as exacerbating deterioration. The presence and structure of these biofilms is related to hydraulic conditions, nutrient availability, type and concentration of residual disinfectant and the roughness of pipe surfaces. Many researchers have reported that pipe material seems to have a significant effect on microbial inactivation by different disinfectants (Gagnon *et al.* 2005).

Leaching

Leaching is typically defined as the release of material to water without involving corrosion processes. It can take the form of dissolution of the metal-bearing corrosion scales, monomers from plastics, or calcium from the cement-matrix.

Deterioration of Metallic Components

Deterioration of metallic components, almost always, occurs due to corrosion. Corrosion of metallic components can cause three distinct but interconnected problems. First the metal is lost through oxidation to soluble metallic species or metallic corrosion scales leading to loss of structural strength and subsequent leaks and breaks (Boulos *et al.* 2005). Second, the scale can accumulate as large tubercles that increase head loss and decrease hydraulic capacity. Finally, the release of soluble or particulate metallic corrosion byproducts to the water bulk decreases its acceptability for potable use (Imran *et al.* 2005).

Biofilms on metal surfaces produce an environment at the biofilm/ metal interface that is radically different from that of the bulk medium in terms of pH, dissolved oxygen, organic and inorganic species. Microorganisms can accelerate rates of partial reactions in the corrosion process or alter corrosion mechanisms. The physical presence of biofilm causes variable conditions on the metal surface resulting in differential aeration and the formation of consequent anodic and cathodic regions that can accelerate corrosion. Uniform biofilms can decrease corrosion by providing protective film, whereas the products of biological activity can either enhance or reduce corrosion.

Surface film and scale are naturally occurring deposits or growths that occur on the interior pipe surfaces as a result of corrosion, biological growth or residue deposition. The composition and structure of the surface film depends on the type and composition of the pipe and the aqueous phase. The formation of surface film is governed by several factors that include pH, alkalinity, buffer intensity, natural organic matter (NOM) and dissolved oxygen (DO). Sarin *et al.* (2001) studied the effects of water quality parameters on metal release from corrosion scale to the modification of the properties of the corrosion scale; namely porosity and solubility of scale phases.

Iron

Starting in the late 1800s iron has been the material of choice for the construction of distribution piping. Currently, nearly 70% of the water distribution mains in North America are iron based. Some of the most persistent water quality problems are due to the corrosion of unlined cast iron pipes and lined iron pipes that have lost their interior linings. These often manifest themselves in the colored water (or red water) phenomenon.

Table 1. Significance of impact of water quality deterioration mechanisms on different distribution materials

		Internal Corrosion	Microbiologically Induced Corrosion	Leaching
Water Distribution Infrastructure Material	**Metallic Components** (Iron, copper and lead)	Major	Unknown	Minor
	Polymeric Components (PVC, PE and PAH)	None	Unknown	Major
	Cement-based Components (AC and CC)	Major	Unknown	Major

AC – Asbestos cement, CC – Concrete, PE – Polyethylene, PAH – Polyaromatic hydrocarbons (bituminous or coal-tar), PVC – Polyvinylchloride

The problems associated with colored water conditions are mainly aesthetic. However, a more serious consequence could be the loss of disinfectant residual and subsequent biofilm formation in the distribution systems. Corrosion byproducts attached to pipe surfaces or accumulated as sediments in the distribution systems can shield microorganisms from disinfectants. Release of corrosion byproducts in the form of turbidity may provide safe havens for pathogens (Torvinen *et al.* 2004).

Copper

Copper pipes are commonly used in household plumbing due to their flexibility, ease of installation in plumbing spaces and resistance to thermal stresses. However, copper pipes can corrode and leach unacceptable levels of copper to the drinking water. Copper corrosion is a complex process driven by at least three chemical sub-processes:

metal oxidation, fixation of dissolved copper in the corrosion scale and solubility equilibrium. Pitting has often been the main failure mechanism identified in copper pipes used for household plumbing (Boulay and Edwards 2001).

Copper corrosion in distribution infrastructure can also cause problems downstream at the wastewater treatment plants. Isaac *et al.* (1997) reported that the increased corrosion in water supply systems can contribute to the violation of the maximum allowable concentrations in discharges to receiving waters.

Lead

Lead in drinking water principally arises from contact between municipally supplied water and lead service pipes. Boyd *et al.* (2001) reported that an estimated 3.3 million lead service lines are located throughout the United States, especially in the older section of major cities. Schock (1999) observed that permissible lead concentrations in drinking water of many countries were so low that the rate of lead corrosion was of no practical concern. Even slightly aggressive water in contact with lead or lead containing material will pick up lead after a brief period of stagnation. Therefore, the deterioration of lead pipes is not a major concern when compared to the deterioration of water quality. Most utilities are engaged in an aggressive lead pipe replacement policy, wherever lead levels in drinking water are a concern. However, till the time that all the lead plumbing is replaced, utilities need to maintain conditions that mitigate lead release to water.

Edwards and Dudi (2004) reported a case in Washington, D.C., where a switch of disinfectants from chlorine to chloramines increased the release of lead from lead service lines, lead solder and brass plumbing material into the bulk water. Bench-scale testing by the authors found that chlorine reacted with soluble lead to rapidly precipitate a stable lead solid that did not form in the presence of chloramine.

Deterioration of Polymeric (Plastic) and Bituminous Components

The long-term deterioration mechanisms in polymeric pipes are not documented as well as those of metallic pipes, mainly because these mechanisms are typically slower and because polymeric pipes have been used commercially only in the last 35-40 years. These deterioration mechanisms include chemical and mechanical degradation, oxidation and biodegradation of plasticizers and solvents (Dorn *et al.* 1996).

The problems associated with polymeric material is that they leach contaminants (monomers, anti-oxidants and other organics) and are susceptible to the permeation of organic contaminants from the exterior pipe surfaces. These two processes (leaching and permeation) are the major cause of water quality deterioration in the polymeric components of distribution infrastructure.

Polymer

Age and manufacturing processes can also play a role in polymer degradation. For instance, 'early-era' PVC, manufactured prior to 1977, can leach excessive vinyl chloride monomer into the drinking water (Beardsley and Adams 2003).

Polymeric material contains a variety of organic and inorganic additives to improve material durability, manufacturing and handling, as well as to modify the color (Brocca *et al.* 2002). The absorption of water into the polymer matrix may cause swelling or softening. Water can also serve as an extraction agent for stabilizers and inhibitors, leading to the depletion of these substances by leaching. This causes a concentration gradient that lowers the activation energy for degradation of the polymeric material (Fischer *et al.* 1993).

Bonds (2004) evaluated the effects of chloramines degradation on various elastomers used in distribution system fittings. The year-long study concluded that joint gaskets and fittings (with lower exposed surface area) exhibited negligible deterioration compared to sheets of the same material exposed to similar environments.

Polyaromatic Hydrocarbons (PAHs)

Bituminous (coal-tar) linings have been used in the past to limit internal corrosion of iron and ductile iron pipes, and have been implicated in water quality deterioration due to leaching of polyaromatic hydrocarbons (PAHs) (Maier *et al.* 2000).

Deterioration of Cement-based Components

Cementitious materials in the presence of acidic or aggressive waters can degrade in several ways (Leroy *et al.* 1996). First, reactions involving hydrolysis and leaching of the components of the hardened cement matrix can increase the porosity and permeability of the component allowing aggressive ions to infiltrate the cement matrix. Second, exchange reactions take place between aggressive fluid and components of the cement matrix, resulting in leaching of calcium ions. Substitution reactions can replace the calcium in the calcium-silicate-hydroxide (C-S-H) complex resulting in loss of strength and rigidity (softening). Third, reactions involving the formation of expansive products can lead to cracking and spalling (Mehta 2003).

The extent of leaching increases with water aggressiveness and residence time in the pipe, and is inversely proportional to pipe diameter. Aggressive waters can dissolve the cement in asbestos-cement (AC) pipes causing the release of asbestos fibers into the water (Leland 2002) or turbidity from cement pipes and linings.

Research Needs Workshop

A workshop was conducted at the NRC campus in Ottawa, Canada in March 2006. More than 20 experts, including municipal engineers (managers), consultants, researchers and academicians were invited to identify research needs based on a draft synthesis document that had been distributed ahead of time. Inputs from experts were also solicited in the form of a questionnaire survey. The experts were asked to rank the ‘state of knowledge’ related to different distribution system materials and their rates of deterioration. A ranking of ‘0’ indicated a state of *no knowledge* while a ranking of ‘10’ indicated a state of *high knowledge*.

Figure 1 illustrates the experts' opinion about the 'state of knowledge' related to different materials and different modes of deterioration. The figure indicates that materials regulated under either aesthetic or health based guidelines have a high awareness associated with them.

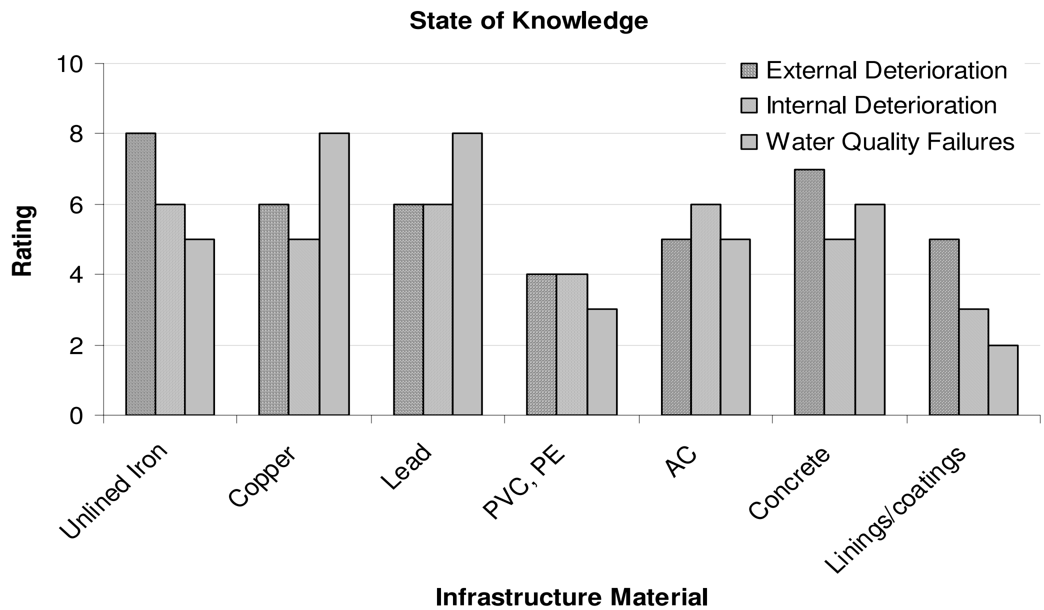

Figure 1: Current state of knowledge on different materials based on consensus of participating experts.

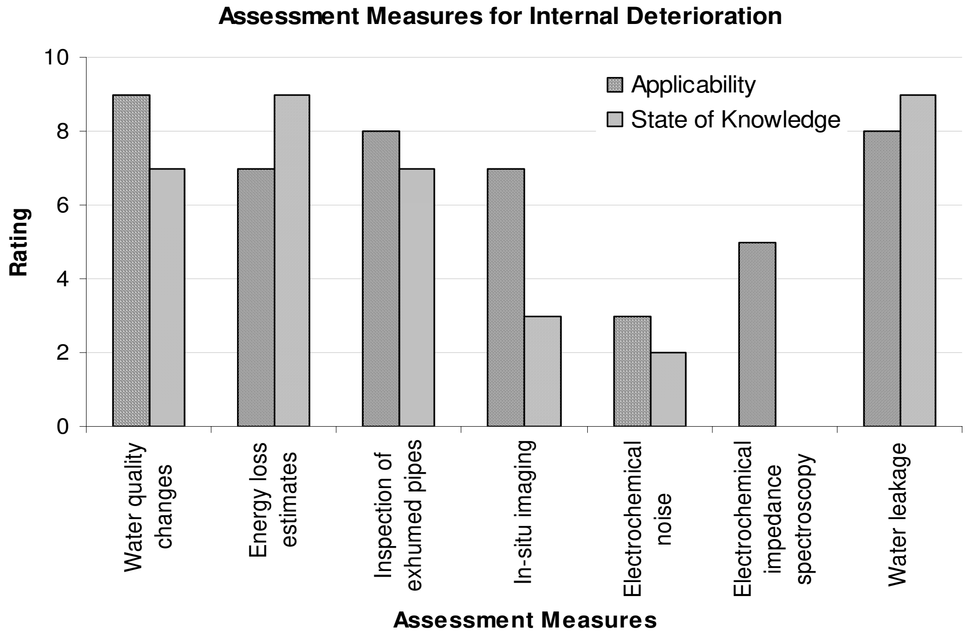

Figure 2: Rating of assessment measures for integrity of distribution infrastructure

Assessing the internal condition of a pipe would be a first step in determining the rate of deterioration as well as impact of water quality changes. However, this is not an easy task due to limited accessibility to buried pipes. Also the common methods of condition assessment are aimed at determining the structural strength and remaining life of the pipe, rather than an internal condition assessment for changes due to water quality. The experts were asked to rate different methods that could be used to assess the extent of deterioration of pipe surfaces in contact with drinking water. The results, as shown in Figure 2, indicate that though methods such as in-situ imaging or electrochemical impedance measurements could potentially provide a snapshot of the internal condition of pipes, reliable interpretation of the results would require considerable research.

Summary of Recommendations

Maintaining a compatible physico-chemical composition of the finished waters in contact with distribution components can provide better control over the rate and magnitude of deterioration. While this chemical compatibility is relatively easy to achieve for any single material, different components of a distribution infrastructure can have varying responses to change in water quality. Often a change in practice can trigger conflicting results, i.e. a positive influence on one component and a negative influence on another (Imran *et al*. 2006).

In an experts workshop a number of knowledge gaps and research needs were identified and prioritized. The detailed research findings and recommendations will be published as an AwwaRF report in the near future. Insights gained from this project will help in defining future research projects to address identified gaps in knowledge and understanding, while considering water quality as well as impact on the deterioration of distribution infrastructure.

General recommendations for future research are summarized below:

1. The evaluation of how changes in water sources, which trigger changes in the water chemistry, can affect different components of the distribution network. For instance, some surface waters can corrode unlined iron pipes faster than groundwater;
2. The reconciliation of conflicting impacts of physico-chemical properties of water on different pipe materials. For instance, water composition compatible with iron pipes may not be incompatible with copper pipes. Therefore, the addition of chemicals to protect iron pipes may cause failure of copper pipes;
3. The evaluation of unintended effects of change in water treatment processes. For instance, increasing the amount of chlorine to kill pathogenic microorganisms can increase deterioration rate in some pipe materials;
4. The evaluation of the effects of frequent changes in water quality on the distribution pipes. For example, evaluating the impact of the frequency and duration of alternating conditions on distribution pipes when a utility regularly switches between different sources, e.g., surface water and groundwater to meet seasonal demand; and
5. The development of a decision-support system to help water utilities evaluate the effect of changing water treatment technologies (practices) on the deterioration of different pipe materials.

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Literature Cited

Beardsley M, and Adams CD. 2003. Modeling and Control of Vinyl Chloride in Drinking Water Distribution Systems. *Journal of Environmental Engineering* 129 (9): 844-848.

Bonds RW. 2004. Effect of chloramine on ductile-iron pipe gaskets of various elastomer compounds. *Journal of the American Water Works Association* 96 (4): 153-158.

Boulay N, and Edwards M. 2001. Role of temperature, chlorine, and organic matter in copper corrosion by-product release in soft water. *Water Research* 35 (3): 683-688.

Boulos PF, Karney BW, Wood DJ, and Lingireddy S. 2005. Hydraulic transient guidelines for protecting water distribution systems. *Journal of the American Water Works Association* 97 (5): 111-114.

Boyd GR, Tarbet NK, Kirmeyer G, Murpby BM, Serpente RE, and Zammit M. 2001. Selecting lead pipe rehabilitation and replacement technologies. *American Water Works Association Journal* 93 (7): 74-14.

Brocca D, Arvin E, and Mosbaek H. 2002. Identification of organic compounds migrating from polyethylene pipelines into drinking water. *Water Research* 36 (15): 3675-3676.

Cromwell III JE, Reynolds H, Pearson J, and Grant M. 2002. *Costs of Infrastructure Failure*. Denver, CO: AwwaRF.

Dorn, R., Houseman, P., Hyde, R. A., and Jarvis, M. G. 1996. *Water Mains: Guidance on Assessment and Inspection Techniques*. London, UK. Construction Industry Research and Information Association.

Edwards M, and Dudi A. 2004. Role of chlorine and chloramine in corrosion of lead-bearing plumbing materials. *Journal of the American Water Works Association* 96 (10): 69-14.

Fischer WR, Wagner D, Siedlarek H, and Sequeira JAGC. 1993. Perforations of polypropylene pipes in potable water caused by cracking - A case study. 8 1992, at Great Britain.

Gagnon GA, Rand JL, leary KC, Rygel AC, Chauret C, and Andrews RC. 2005. Disinfectant efficacy of chlorite and chlorine dioxide in drinking water biofilms. *Water Research* 39 (9): 1809.

Imran SA, Dietz JD, Mutoti G, Xiao W, Taylor JS, and Desai V. 2006. Optimizing source water blends for corrosion and residual control in distribution systems. *American Water Works Association Journal* 98 (5): 107-115.

Imran SA, Dietz JD, Mutoti G, Taylor JS, Randall AA, and Cooper CD. 2005. Red water release in drinking water distribution systems. *Journal of the American Water Works Association* 97 (9): 93-10.

Isaac RA, Gil L, Cooperman AN, Hulme K, Eddy B, Ruiz M, Jacobson K, Larson C, and Pancorbo OC. 1997. Corrosion in Drinking Water Distribution Systems: A Major Contributor of Copper and Lead to Wastewaters and Effluents. *Environmental Science and Technology - Columbus* 31 (11): 3198-6.

Leroy, P., Schock, M. R., Wagner, I., and Holtschulte, H. 1996. *Cement-based materials*.Denver, CO. American Water Works Association Research Foundation/ American Water Works Association.

Maier M, Maier D, and Lloyd BJ. 2000. Factors influencing the mobilisation of polycyclic aromatic hydrocarbons (PAHs) from the coal-tar lining of water mains. *Water Research* 34 (3): 773-14.

Mehta PK. 2003. *Concrete in the marine environment*. Essex, England: Elsevier Science Publishers Ltd.

Sarin P, Snoeyink VL, Bebee J, Kriven WM, and Clement JA. 2001. Physico-chemical characteristics of corrosion scales in old iron pipes. *Water Research* 35 (12): 2961-2969.

Schock MR. 1999. Internal corrosion and deposition control. ed RD Letterman New York: McGraw Hill.

Torvinen E, Suomalainen S, Lehtola MJ, Miettinen IT, Zacheus O, Paulin L, Katila ML, and Martikainen PJ. 2004. Mycobacteria in Water and Loose Deposits of Drinking Water Distribution Systems in Finland. *Applied and Environmental Microbiology* 70 (4): 1973-1979.