

Challenges in addressing variability of lead in domestic plumbing

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ABSTRACT

Current data indicates that lead exposure is of concern even at low concentrations. Corrosion is an important problem in drinking water because it can affect public health due to leaching of lead or other metals into the drinking water. For this reason, a corrosion control program is an important measure to help mitigate exposure to lead in drinking water. The biggest challenge that remains in assessing corrosion control through monitoring programs is the variability of the concentrations of metals such as lead in drinking water, and the interpretation of the results when using different approaches for monitoring. This is due to the many factors that contribute to the leaching of metals from drinking water distribution system materials. Balancing the challenges of stagnation time, sample volume and sampling frequency to assess corrosion control with their practicality and the need to ensure optimal corrosion control treatment are important considerations for regulators and decision-makers to ensure that potential exposure to lead through drinking water is minimized.

Key words | corrosion control, lead in drinking water, stagnation, water sampling

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INTRODUCTION

Lead has no known biological function and exposure to lead can affect a variety of tissues, organs and systems including the cardiovascular; reproductive; blood; and immune systems as well as the kidneys. The adverse health impacts of lead exposure are well documented in the literature in both experimental (animal) and epidemiological studies (ATSDR 2007). Of note, recent studies indicate that lead exposure, even at low concentrations, is of concern with respect to cognitive impacts in children (Lanphear *et al.* 2005) and cardiovascular effects in adults (US ATSDR 2007). The US Centers for Disease Control has stated that ‘No safe blood lead level has been identified.’ (CDC 2010).

In 1991, the US Environmental Protection Agency’s (USEPA) promulgated the Lead and Copper Rule (LCR) (US EPA 1991a,b, 1992). This rule resulted in the implementation of monitoring programs for assessing the effectiveness of corrosion control programs to help reduce exposure

to lead and copper through optimal corrosion control treatment (OCCT). Under the LCR, first draw water samples are taken at defined sites following at least 6h of stagnant contact with the plumbing materials. Other countries, notably Canada (Health Canada 2009) and many countries in the European Union (EU) (European Commission 1999) have developed guidelines or regulations on lead sampling and corrosion control, as a way to reduce exposure to lead from drinking water.

Health Canada (2009) provides guidance for both municipalities and water suppliers on assessing corrosion and implementing corrosion control for distribution systems in residential and non-residential settings. The guidance document outlines the steps that should be taken to reduce population exposure to lead and is meant to complement the information provided in the Guidelines for Canadian Drinking Water Quality for lead

(Health Canada 1992). The new EU “drinking water” directive increases the requirements with respect to several parameters (turbidity, chlorites, arsenic, volatile organohalogens, nickel) and in particular on lead ($25\ \mu\text{g}/\text{L}$ at the end of 2003 and $10\ \mu\text{g}/\text{L}$ at the end of 2013). This obliges utility services to replace all existing lead pipes in the long term. It also increases information requirements on the quality of water supplied. Stagnation time and sampling methodologies are the primary differences between the corrosion control monitoring programs established or suggested by the various countries.

The biggest challenge that faces governmental agencies or health professionals in either assessing the effectiveness of corrosion control or in determining the extent of metal ingestion from drinking water is the variability of the concentrations of metals such as lead in drinking water and the interpretation of the results when using different approaches for monitoring. Ultimately, the approaches need to vary (i.e. stagnation time, sample volume, sample location, number of samples) depending on the intended goal of the monitoring or assessment program. For this reason, it is crucial that agencies involved in all aspects of drinking water understand the importance of sampling and the limitations of any sampling regime.

FACTORS AFFECTING LEACHING OF LEAD FROM PLUMBING MATERIALS

Water quality and plumbing age

Lead is present in plumbing materials (pipes, goosenecks, solders, faucets, meters, control valves, etc.) in the form of elemental lead (Pb). In alloys such as brasses used in faucets, meters and valves, the lead in the alloy becomes oxidized predominantly to the Pb(II) valence state when the material comes in contact with potable water.

Many factors contribute to the corrosion and leaching of metals from drinking water distribution system materials. However, the principal factors are the type of materials, plumbing system age, water quality in the distribution system and stagnation time of the water. The concentrations of all dissolvable metals present in the distribution system will be influenced by some or all of these factors.

In drinking water, secondary disinfectants play an important role in corrosivity and metal release by impacting the oxidation reduction potential (ORP) of the bulk water, the corrosion potential of the surface of the metal, or by direct reaction mechanisms. The choice and amount of secondary disinfectant can play the dominant role in bulk water ORP, and needs to be considered when determining the potential for metal release, exposure potential and treatment change impacts.

Pb in the Pb(IV) valence state as PbO_2 , has been identified, in lead pipe deposits under highly oxidizing conditions from numerous different US water systems (Schock *et al.* 1996, 2001, 2005; Schock & Giani 2004; Renner 2004, 2005), as either the principal plumbosolvency-controlling solid phase, or as an accessory phase to other protective Pb(II) hydroxycarbonates. In some systems, fluctuating redox potential causes cyclical formation and dissolution of PbO_2 , which creates intermittent lead release episodes. Experimentally, this was confirmed by Lytle & Schock (2005) who demonstrated that Pb(IV) solids easily formed at pH 6–6.5 in weeks to months in the presence of persistent high free chlorine residuals. The oxidation of elemental Pb to Pb(II) and reduction of Pb(IV) enables the mobilization and subsequent transport of lead into the drinking water (Schock *et al.* 2005; Rajasekharan *et al.* 2007; Schock & Lytle 2010).

The effect of various background water constituents, such as (but not only) hydrogen, hydroxide, bicarbonate, orthophosphate, polyphosphate, chloride and sulfate ions, differ substantially in their effect on the solubility and transport of Pb(IV) species versus Pb(II) species (Schock *et al.* 1996; Schock & Lytle 2010). Aqueous complexation rather than free ion dominates plumbosolvency when Pb(II) is the stable oxidation state.

Little is known about aqueous speciation for Pb(IV) species. PbO_2 solid, however, is observed to be even less soluble than Pb(II) orthophosphates at a wide range of drinking water pH in systems where the solid has been found (approximately pH 7–9.5).

Plumbing material age is also a critical factor for the corrosion of premise plumbing materials, particularly copper, lead and galvanized steel. Over time, the corrosion byproduct materials become more ordered and “age” by various mechanisms (Schock *et al.* 1995) or they change in

fundamental form, such as when galvanized coatings are removed, and replaced by ferric oxyhydroxides (Trussell & Wagner 1996; Schock & Lytle 2010).

The corrosion of lead solder is complicated. Lead migration into the water through galvanic corrosion of the joint between the lead solder, which is typically anodic relative to the copper pipe, can result in high lead concentrations (Oliphant 1983; Gregory 1990; Reiber 1991; Singley 1994; Oliphant & Schock 1996; Edwards & Triantafyllidou 2007; Schock & Lytle 2010). The flux used for soldering can also serve as an electrolyte and directly attack the solder (Schock 1990a,b). Because of this galvanic driving force for oxidation and lead release, mitigation of solder corrosion may follow slightly different water chemistry trends than the control of simple plumbosolvency.

The role that lead plays in brass corrosion is not well established although it is likely that the internal galvanic coupling of the copper and lead may result in preferential lead oxidation, similarly to solder. Further, brass fittings are often connected to lead or copper pipes, and therefore are also prone to galvanic corrosion and dealloying, depending on the background water chemistry (Oliphant & Schock 1996; DeSantis *et al.* 2009).

Though research has not been done to sufficiently generalize relationships, several investigators have suggested that the highest lead concentrations from lead-soldered joints and brass fittings level off after a number of years of service (Sharrett *et al.* 1982; Boffardi 1988). When lead is released as a particulate, or particulate-bound form, observed lead levels become far more inconsistent and erratic. The relative importance of particle release versus true plumbosolvency may itself be somewhat diagnostic of the type of corrosion occurring.

Stagnation time and variability

Water chemistry and physical factors affect metal release but the relationship between this release and stagnation time must also be considered. The concentration of lead and copper in drinking water from various sources of leaded material can increase significantly following a period of water stagnation. Various stagnation modeling approaches for lead suggest a near-equilibrium plateau in concentration is often achievable in the 8–12 hour range (Bailey & Russell

1981; Kuch & Wagner 1983; Schock & Gardels 1983; Bailey *et al.* 1986; Schock *et al.* 1996; Lytle & Schock 2000). Unfortunately, copper exhibits a more complex behavior, and should not be monitored in the same way as lead (Schock & Lytle 2010).

The radial diffusion model work by Kuch & Wagner (1983) also provides curves that predict rather reliably the effects of pipe diameter and length on soluble lead uptake into the water under constant turbulent flow. Longer lengths of lead pipe and smaller diameter facilitate more lead release in flowing water. This work shows, by simple substitution and calculation, in a typical lead pipe internal diameters of 1.9 cm and a length of 20 m, a water with a plumbosolvency of even 200 µg/L would correspond to about 30 µg/L in a 1 L sample taken at the end of the lead pipe with only 30 minutes of stagnation time, and only 10 µg/L for a 5 m length of lead pipe.

Water taps or “upstream” (of the sampling tap) water devices such as toilets, showers, humidifiers, etc. in a household are frequently used, causing water to be stagnant for much shorter time periods (minutes to a few hours).

The net effect of temperature on stagnation profiles is complicated, because some solids decrease in solubility as temperature increase, and both dissociation and complexation side reactions vary with temperature, usually neither linearly or unidirectionally. Further, the location of heating or air conditioning duct work, or the location of water pipes in a basement or slab foundation, can strongly affect the temperature of water within the pipes. Depending on the house or building, the water might be warmer during the winter if the cold water pipes are proximate to heating ducts, and conversely, water could be cooler in the summer if influenced by air conditioning ductwork.

Sample volume and longitudinal position of lead sources

A very useful shift in approach to develop effective sampling programs for forensic and corrosion control diagnostic purposes, is to begin thinking about water samples not as “volumes”, but as “distances” from the sampling tap. An increasing number of studies in the US have been using this approach, through the use of “sequential sampling” (successive samples of differing volumes) to identify lead

sources. Britton & Richards (1981) employed this, and there are several good recent examples (Sandvig *et al.* 2008; HDR Engineering 2009; Schock & Lytle 2010). Simple tables can be constructed of sample volume per linear distance in pipe materials of different internal diameters, to facilitate interpretation and use. Depending on the flow rate, distance, pipe diameter, and number of bends and flow constrictions within the plumbing lines, some axial dispersion will occur, decreasing the precision of contamination source location. Nonetheless, with a good balance of small sample volumes for complex plumbing areas with larger volumes where more uniform sources are suspected, and with sufficient stagnation time, acceptable resolution can almost always be obtained.

Because of the different locations and types of lead or other contamination sources within a building or residential plumbing system, the volume of water drawn for a sample is particularly important as a potential source of variability (AwwaRF 1990, 2007). Recent studies (Campbell & Douglas 2007; Huggins 2007; Kwan 2007; US EPA 2007; Craik *et al.* 2008; Sandvig *et al.* 2008) demonstrated that the highest concentration of lead generally occurred in samples that represented water that has been stagnant in a lead service line, provided that the lead service line contained Pb(II) solids. Collection of multiple liters of water from sampling sites is considered onerous, especially in addition to requiring a stagnation period. As such, research efforts are ongoing to assess the feasibility of smaller, targeted volumes and shorter stagnation times to conduct system-wide corrosion assessments.

The variability of lead levels will also be impacted by the usage of water from any of the several interconnecting lines within a household plumbing system which provide water to exterior faucets, bathrooms, kitchens, utility rooms, etc. Even if the faucet from which the monitoring samples are taken has not been used for some time, there can be undetected mixing and dilution within the water sample volume. This creates undetectable variability from sampling event to event.

Existing internal pipe scales

An underappreciated factor, as yet unrecognized by many regulators, water utilities and health agencies is the ability of

pipe scale deposits to accumulate even low levels of upstream contaminants and then release them in either dissolved or particulate form (Schock 2005; Renner 2008). The validity of this mechanism has recently been affirmed and demonstrated for multiple metals of concern (Schock *et al.* 2008; Friedman *et al.* 2009) such as arsenic (Lytle *et al.* 2010), vanadium (Gerke *et al.* 2009) and lead (HDR Engineering 2009; McFadden *et al.* 2009). The latter two studies clearly show that even after full lead service lines are removed, residual lead retained by the old galvanized pipes within houses continues to create elevated lead exposures. Noteworthy in these cases is the necessity and importance of the use of sequential sampling to isolate and identify the lead sources.

CONCLUSIONS

The challenges of stagnation time, sample volume and sampling frequency to assess corrosion control are multiple. These new findings are crucial to inform regulators and health professionals on how to understand the lead solubility and release conditions at different points within a residential or building plumbing system, and thus correctly interpret corrosion control effectiveness, exposure, and risk.

Typical sampling programs can easily “miss” the parcels of water containing elevated levels of contaminants such as lead, which occur in non-uniform distributions throughout building and residential plumbing systems. They need to take into account both the water flow variables, as well as the water chemistry ones.

While monitoring programs based on random daytime samples may statistically represent overall exposure probability in a population better, it is a very misleading monitoring approach for either forensic investigations or detrimental health effects such as elevated blood lead levels in individuals resulting from high concentrations of lead in drinking water. Similarly, the “grab” samples commonly taken by health investigators are unrepresentative of the actual water usage and exposure conditions.

There are two emerging metal release issues, particularly for lead, that warrant more research. First, is the likely presence of different controlling solid phases and reaction mechanisms between the lead service lines and interior

plumbing materials, particularly under highly oxidizing conditions. Secondly, lead and other metal contaminants of concern can accumulate in corrosion byproduct scales or in surficial pipe scale layers. The scale layers are frequently composed of large amounts of iron, manganese and aluminum-based solids. The accumulated metals of concern are often associated with particulates and can be released into the tap water through this mechanism. Therefore, release mechanisms for lead and other contaminants can depend either on lead chemistry factors, or chemical/hydraulic factors destabilizing the other solids to which the contaminants are attached.

Conservative sampling strategies to identify whether or not the most dangerous metal release conditions are adequately mitigated by corrosion control also need to be built around a sophisticated understanding of the origin of the contaminant, background chemistry impacts, stagnation conditions, and plumbing age.

Treatment changes, undertaken to address other goals such as a disinfection changes to reduce disinfection byproducts, can significantly alter water chemistry and impact lead solubility and release, as well as the mobility of other corrosion byproducts or toxic metal contaminants. Ensuring a good understanding of the potential impacts of any treatment change is critical, particularly when they result in changes in water chemistry. In order to do this, the contaminant sources within the water piping networks—premise, building and distribution—must be accurately located and characterized through proper sampling schemes.

Similarly, a proper forensic sampling program must be developed that is consistent with capturing the location of origin of the contaminants within the plumbing system, and which reflects the usage conditions of the residents.

Although not the principal subject of this paper, it should be noted that copper has a very different stagnation profile to lead, a different spatial distribution within most plumbing systems, and in the absence of phosphate, has a dramatic decrease in solubility and change in speciation as the plumbing scales age (Schock *et al.* 1995; Schock & Lytle 2010). This illustrates a further sampling and monitoring issue for corrosion control investigators, regulators and other agencies. There is no “one size fits all” sampling program for all metallic contaminants. Full consideration must be given and adjustments in sampling protocol made for the

differences in occurrence, chemical behavior, and relation to plumbing materials for each contaminant of interest.

Disclaimer

This paper has been subjected to agency administrative review and has been approved for external publication. Any opinions expressed by the authors do not necessarily represent those of the US EPA or Health Canada, therefore, no official endorsement should be inferred.

REFERENCES

- AwwaRF 1990 Lead control strategies. AWWA Research Foundation and American Water Works Association, Denver, CO.
- AwwaRF 2007 Performance and metal release of non-leaded brass meters, components, and fittings. AWWA Research Foundation, Denver, CO (Report 91174).
- Bailey, R. J. & Russell, P. F. 1981 Predicting drinking water lead levels. *Environ. Technol. Lett.* **2**, 57–66.
- Bailey, R. J., Holmes, D., Jolly, P. K. & Lacey, R. F. 1986 Lead Concentration and Stagnation Time in Water Drawn Through Lead Domestic Pipes. Technical Report: Water Research Centre; October 1986. Report No.: TR 243.
- Boffardi, B. P. 1988 Lead in drinking water—causes and cures. *Public Works* **119**(11), 67–70.
- Britton, A. & Richards, W. N. 1981 Factors influencing plumbosolvency in Scotland. *J. Inst. Water Eng. Sci.* **35**(4), 349–364.
- Campbell, A. & Douglas, I. 2007 Corrosion control in Ottawa. In: *Proceedings of the Ontario Water Works Association Distribution System Workshop, Toronto, ON*, Ontario Water Works Association, Markham, ON.
- CDC 2010 *National Report on Human Exposure to Environmental Chemicals: Factsheet on Lead*. Centers for Disease Control and Prevention (CDC), Atlanta, GA. Available at: http://www.cdc.gov/exposurereport/Lead_FactSheet.html
- Craik, S., Gammie, L., Gao, M., Melnychuk, P. & Bruineman, C. 2008 Lead at customer's taps: results of the 2007 sampling program. Final report by EPCOR Water Services (Quality Assurance), Edmonton, AB.
- DeSantis, M. K., Welch, M. M. & Schock, M. R. 2009 Mineralogical Evidence of Galvanic Corrosion in Domestic Drinking Water Pipes. In: *Proc. AWWA Water Quality Technology Conference, Seattle, WA*.
- Edwards, M. & Triantafyllidou, S. 2007 Chloride-to-sulfate mass ratio and lead leaching to water. *J. AWWA* **99**(7), 96–109.
- European Commission 1999 Developing a new protocol for the monitoring of lead in drinking water. Directorate General for Science, Research and Development, European Commission, Brussels (Report No. REPORT EUR 19087 EN).

- Friedman, M. J., Hill, A. S., Reiber, S. H., Valentine, R. L. & Korshin, G. V. 2009 *Assessment of Inorganics Accumulation in Drinking Water System Scales and Sediments*. Water Research Foundation.
- Gerke, T. L., Scheckel, K. G. & Schock, M. R. 2009 **Identification and distribution of vanadinite ($Pb_5(V^{5+}O_4)_3Cl$) in lead pipe corrosion by-products**. *Environ. Sci. Technol.* **43**(12), 4412–4418.
- Gregory, R. 1990 Galvanic corrosion of lead solder in copper pipework. *J. IWEM* **4**(2), 112–118.
- HDR Engineering 2009 An Analysis of the Correlation between Lead Released from Galvanized Iron Piping and the Contents of Lead in Drinking Water. Summary Report; 2009 September 1.
- Health Canada 1992 Guidelines for Canadian Drinking Water Quality: Guideline Technical Document—Lead. Water, Air and Climate Change Bureau, Healthy Environments and Consumer Safety Branch, Health Canada, Ottawa, Ontario. Available at: <http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/lead-plomb/index-eng.php> (accessed 13 June 2010).
- Health Canada 2009 Guidance on Controlling Corrosion in Drinking Water Distribution Systems. Water, Air and Climate Change Bureau, Healthy Environments and Consumer Safety Branch, Health Canada, Ottawa, Ontario. Available at: <http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/corrosion/index-eng.php> (accessed 13 June 2010).
- Huggins, D. 2007 City of London lead testing and remediation programs. In: *Proceedings of the Ontario Water Works Association Distribution System Workshop, Toronto, ON*. Ontario Water Works Association, Markham, ON.
- Kuch, A. & Wagner, I. 1983 **Mass transfer model to describe lead concentrations in drinking water**. *Water Res.* **17**(10), 1303.
- Kwan, P. 2007 Lead in water: release before and after a lead service line replacement. In: *Proceedings of the Ontario Water Works Association Distribution System Workshop, Toronto, ON*. Ontario Water Works Association, Markham, ON.
- Lanphear, B. P., Hornung, R., Khoury, J., Yolton, K., Baghurst, P., Bellinger, D. C., Canfield, R. L., Dietrich, K. N., Bornschein, R., Greene, T., Rothenberg, S. J., Needleman, H. L., Schnaas, L., Wasserman, G., Graziano, J. & Roberts, R. 2005 **Low-level environmental lead exposure and children's intellectual function: an international pooled analysis**. *Environ. Health Perspect* **113**, 894–899.
- Lytle, D. A. & Schock, M. R. 2000 Impact of stagnation time on metal dissolution from plumbing materials in drinking water. *J. Water Supply Res. Technol.—Aqua* **49**(5), 243–257.
- Lytle, D. A. & Schock, M. R. 2005 The formation of Pb(IV) oxides in chlorinated water. *J. AWWA* **97**, 102–114.
- Lytle, D. A., Sorg, T. J., Muhlen, C. & Wang, L. 2010 Particulate arsenic release in a drinking water distribution system. *J. AWWA* **102**(3), 87–98.
- McFadden, M., Reiber, S., Kwan, P. & Giani, R. 2009 Investigation of Sorptive and Desorptive Processes between Lead and Iron Corrosion Scales in Plumbing Materials. In: *Proceedings AWWA Water Quality Technology Conference, Seattle, WA*.
- Oliphant, R. 1983 Summary report on the contamination of potable water by lead from soldered joints. *Water Research Centre External Report 125E*.
- Oliphant, R. J. & Schock, M. R. 1996 Copper alloys and solder. In: *Internal Corrosion of Water Distribution Systems*, 2nd edition. AWWA Research Foundation/DVGW-TZW, Denver, CO, pp. 269–312, (Ch. 6).
- Rajasekharan, V. V., Clark, B. N., Boonsalee, S. & Switzer, J. A. 2007 **Electrochemistry of free chlorine and monochloramine and its relevance to the presence of Pb in drinking water**. *Environ. Sci. Technol.* **41**(12), 4252–4257.
- Reiber, S. 1991 Galvanic stimulation of corrosion on lead-tin solder-sweated joints. *J. AWWA* **83**(7), 83–91.
- Renner, R. 2004 **Plumbing the depths of D.C.'s drinking water crisis**. *Environ. Sci. Technol.* **38**(12), 224A–227A.
- Renner, R. 2005 Chloramines again linked to lead in drinking water. *Environ. Sci. Technol.* **39**(15), 314A.
- Renner, R. 2008 **Pipe scales release hazardous metals into drinking water**. *Environ. Sci. Technol.* **42**(12), 4241.
- Sandvig, A., Kwan, P., Kirmeyer, G., Maynard, B., Mast, D., Trussell, R. R., Trussell, S., Cantor, A. F. & Prescott, A. 2008 Contribution of Service Line and Plumbing Fixtures to Lead and Copper Rule Compliance Issues: American Water Works Association Research Foundation; Report No.: 91229.
- Schock, M. R. 1990a **Causes of temporal variability of lead in domestic plumbing systems**. *Environ. Monit. Assess.* **15**(1), 59–82.
- Schock, M. R. 1990b Internal corrosion and deposition control. *Water Quality and Treatment: a Handbook of Community Water Supplies*. McGraw-Hill, Inc, New York, NY (for the American Water Works Association), (Chapter 18).
- Schock, M. R. 2005 Distribution systems as reservoirs and reactors for inorganic contaminants. In: MacPhee, M. J. (ed.) *Distribution System Water Quality Challenges in the 21st Century*. American Water Works Association, Denver, CO, pp. 105–140, (Ch. 6).
- Schock, M. R. & Gardels, M. C. 1983 Plumbosolvency reduction by high pH and low carbonate-solubility relationships. *J. AWWA* **75**, 87.
- Schock, M. R. & Giani, R. 2004 Oxidant/disinfectant chemistry and impacts on lead corrosion. In: *Proceedings of the 2004 AWWA Water Quality Technology Conference, San Antonio, TX*. American Water Works Association, Denver, CO.
- Schock, M. R. & Lytle, D. A. 2010 Internal corrosion and deposition control. In: Edzwald, J. K. (ed.) *Water Quality and Treatment: A Handbook of Community Water Supplies*, 6th edition. McGraw-Hill, Inc, New York, (Ch. 20), in press.
- Schock, M. R., Lytle, D. A. & Clement, J. A. 1995 *Effect of pH, DIC, Orthophosphate and Sulfate on Drinking Water Cuprosolvency*. USEPA Office of Research and Development, Cincinnati, OH, EPA/600/R-95/085, <http://www.epa.gov/NRMRL/pubs/600r95085/600r95085.pdf>

- Schock, M. R., Wagner, I. & Oliphant, R. J. 1996 Corrosion and Solubility of Lead in Drinking Water. In: *Internal Corrosion of Water Distribution Systems*, 2nd edition. American Water Works Association Research Foundation and DVGW Technologiezentrum Wasser, Denver, CO, pp. 131–230, (Ch. 4).
- Schock, M. R., Harmon, S. M., Swertfeger J. & Lohmann, R. 2001 Tetravalent lead: a hitherto unrecognized control of tap water lead contamination. In: *Proceedings AWWA Water Quality Technology Conference, Nashville, TN*.
- Schock, M. R., Scheckel, K. G., DeSantis, M. & Gerke, T. L. 2005 Mode of Occurrence, Treatment and Monitoring Significance of Tetravalent Lead. In: *Proc. AWWA Water Quality Technology Conference, Quebec City, Canada*, November 6–10, 2005.
- Schock, M. R., Hyland, R. N. & Welch, M. M. 2008 Occurrence of contaminant accumulation in lead pipe scales from domestic drinking-water distribution systems. *Environ. Sci. Technol.* **42**(12), 4285–4291.
- Sharrett, A. R., Carter, A. P., Orheim, R. M. & Feinleib, M. 1982 Daily intake of lead, cadmium, copper and zinc from drinking water: the seattle study of trace metal exposure. *Environ. Res.* **28**, 456–475.
- Singley, J. E. 1994 Electrochemical nature of lead contamination. *J. AWWA* **86**(7), 91–96.
- Trussell, R. R. & Wagner, I. 1996 Corrosion of galvanized pipe. In: *Internal Corrosion of Water Distribution Systems*. AWWA Research Foundation/TZW, Denver, CO, pp. 71–129, (Ch. 3).
- US ATSDR 2007 Toxicological Profile for Lead. US Department of Health and Human Services, Agency for Toxic Substances and Disease Registry (ATSDR), Public Health Service, Atlanta, GA.
- US EPA 1991a 40 CFR Parts 141 and 142, Maximum Contaminant Level Goals and National Primary Drinking Water Regulations for Lead and Copper; Final Rule. US Environmental Protection Agency, Washington, DC.
- US EPA 1991b Memorandum from J. Cohen to the Record on Required Number of Samples, May 6, 1991. Office of Water US Environmental Protection Agency, Washington, DC.
- US EPA 1992 Lead and Copper Rule guidance manual. US Environmental Protection Agency, Washington, DC (Report No. EPA/811/B-92/002).
- US EPA 2007 Elevated lead in D.C. drinking water—a study of potential causative events, final summary report. Office of Water, US Environmental Protection Agency, Washington, DC (Report No. EPA 812-B-94-002).