PRACTICAL IMPACTS OF GALVANIC CORROSION IN WATER SERVICE LINES AND PREMISE PLUMBING

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ABSTRACT

There is emerging concern about the potential for elevated lead in water after water utilities conduct EPA mandated (or voluntary) partial replacements of existing lead service lines. Connections between dissimilar metals results in the accelerated corrosion of the less noble metal via galvanic attack, increasing metal concentrations in water and posing potential public health risks. Many practical problems associated with stopping galvanic attack between copper:galvanized iron and copper:lead via use of dielectrics have also been raised.

Galvanic corrosion can be effectively stopped by isolating the dissimilar metals; however, completely eliminating electrical continuity may not always be practical or allowed by code. Instead, increasing separation distance between the two metals was hypothesized to considerably reduce galvanic corrosion. Galvanic corrosion and lead leaching were evaluated for lead:copper connections with varying separation distances while maintaining electrical continuity. Increased distance between lead and copper pipe dramatically reduced the galvanic current and the magnitude of lead release. Galvanized iron and copper connections were also investigated using various commercial fittings, and results verified that a controlling factor was separation distance between the two dissimilar metals.

When considering the long-term behavior of partially replaced lead service lines, detrimental effects from galvanic corrosion worsened with time. Even when water was sampled consistently at moderate flow rate, the condition representing traditional partial service line replacement was 40% worse than a full lead service line. At elevated flowrates, lead concentrations and variability increased for partly replaced lead pipe versus full lead pipe due to reservoirs of lead rust formed via galvanic corrosion. At low flowrates, these negative impacts were not observed. Finally, crevices formed by the use of commercial couplings increased lead release.

Overall, the results enhance practical understanding of galvanic corrosion impacts and use of dielectrics in water service lines and premise plumbing.

AUTHORS PREFACE

This thesis was prepared according to the guidelines of Virginia Tech manuscript format. Each chapter was written as an individual manuscript for publication. I served as first author for all three manuscripts in collaboration with my advisor. I am grateful for the contributions of other undergraduate research assistants, graduate research assistants, and supporting research scientists: Chris Stamopoulos, Brent Casteele, Brandi Clark, Jeff Parks, and others.

Chapter 1 was published in September, 2012, as a Technical Note in *Corrosion* and was co-authored by Chris Stamopoulos, an NSF REU student who spent a summer semester at Virginia Tech. In addition, Chapters 1 and 2 were presented together at the American Water Works Association (AWWA) Annual Conference and Exposition in June, 2012, and Chapter 2 will be submitted to *Journal AWWA* in 2013. Portions of Chapter 3 were presented at both the AWWA Water Quality Technology Conference, 2011, as well as the AWWA Annual Conference and Exposition, 2012. I also plan to present the final portion of Chapter 3 at the 2013 AWWA Inorganic Contaminants Symposium and submit the manuscript to *Water Research* in 2013.

The first chapter examines the relationship between separation distance, galvanic corrosion rate and lead release for copper and lead connections. Chapter 2 further investigates galvanic connections between dissimilar metals by considering the practical use of dielectrics to control galvanic corrosion between copper and galvanized iron pipes. Lastly, Chapter 3 is a continuation of a pilot developed to investigate the long term behavior of partially replaced lead service lines.

In addition to the three chapters contained in this thesis, I served as a coauthor for a manuscript titled “Effects of Commercial Connectors on Galvanic Corrosion between Pb/Cu Pipes” by Brandi Clark from contributions during research as an undergraduate at Virginia Tech. The results of that work were presented at the AWWA Annual Conference and Exposition in June, 2011, and have been submitted for publication in *Journal AWWA* in 2012.

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CHAPTER 1: INCREASED DISTANCE BETWEEN GALVANIC LEAD:COPPER PIPE CONNECTIONS DECREASED LEAD RELEASE

Abstract

It has recently been proposed that lead contamination of drinking water arising from galvanic corrosion of lead and copper pipe will be minimized if the lead and copper pipes are brought into direct contact when compared to pipe separations of 1-15 cm and external electrical contact via a grounding strap (Boyd et al., 2012). A direct 4 month test of this hypothesis was conducted with measurement of galvanic current and lead release to water. Increased distance between lead and copper pipe, obtained by incorporating an insulating spacer between the pipes, can dramatically reduce the galvanic current and the magnitude of lead release consistent with expectations based on galvanic theory and the plumbing code.

1 Introduction

Sustained problems with elevated lead in potable water arising from galvanic corrosion between lead and copper pipe have been reported in field studies (Britton & Richards, 1981; Chambers & Hitchmough, 1992) and in many recent well-controlled laboratory experiments (Cartier et al., 2012; Giammar et al., 2011; Hu et al., 2012; Triantafyllidou & Edwards, 2011). Connections between new copper and old lead pipes are currently created at many water utilities during "partial lead pipe replacement" activities (either voluntarily or in response to United States Environmental Protection Agency regulations) with a goal of reducing lead in water (USEPA, 2011). During a partial lead pipe replacement, part of the old lead pipe is replaced with copper pipe forming a new galvanic connection between lead and copper. The cost for partial lead pipe replacements can range from $1000 up to over $10,000 per home, and one city recently spent over $100 million dollars on such efforts (Leonnig, 2008).

Recent research by the Centers for Disease Control revealed that partial pipe replacements do not decrease the incidence of childhood lead poisoning, but rather, may actually increase the likelihood of lead poisoning compared to homes with an undisturbed lead pipe (Brown et al., 2011; Frumkin, 2010). The higher lead in water arising from galvanic or deposition corrosion between lead and copper is one possible cause for the lack of any observed health benefits (and the possible increased incidence of childhood lead poisoning) after partial pipe replacements (Triantafyllidou & Edwards, 2011; USEPA, 2011).

A new theory of galvanic corrosion between Pb:Cu pipe has recently been proposed (Boyd et al., 2012) which attempts to explain why high lead in water has been noted in in some laboratory studies (Cartier et al., 2012; Triantafyllidou & Edwards, 2011) but not in others (Boyd et al., 2010; Boyd et al., 2012). Unfortunately, for the cases in which it was claimed that higher lead in water was not observed, (Boyd et al., 2010; Boyd et al., 2012) either no lead in water data was presented or the authors did not use methods that detected "all of the lead released from the pipe, so these measurements represent lower bounds on the total lead released" with inherent errors ranging from a factor of 2-10 (Giammar et al., 2012). It is therefore unclear whether a discrepancy between data exists or if observations would be reconciled by use of methods that actually detected lead release (Boyd et al., 2010; Boyd et al., 2012; Giammar et al., 2012). In any case, the new theory (Boyd et al., 2012) asserted that if lead and copper pipe are directly connected together, galvanic corrosion is "limited to the immediate vicinity (≈ 5 mm) of the lead-copper" connection and that "accelerated metal release associated with this type of galvanic coupling may be minimal." In contrast, if the lead and copper pipe are separated by 1-15 cm and electrical contact was maintained via an external wire, the potential of “the entire lead coupon shifts in an anodic direction” and “the galvanic coupling has likely accelerated lead release by up to ten-fold.” The authors supported this theory indirectly with measurements of E_{corr} over the galvanically connected lead and copper pipe surfaces—no direct support was provided in the form of lead-in-water concentrations or galvanic current measurements.

The assertions by Boyd et al. (2012) are contrary to decades of prior research showing that impacts of pipe galvanic corrosion are usually localized to a range of roughly 1.5 pipe diameters (Scully & Hack, 1988) and that increased distance between anode and cathode is expected to reduce galvanic corrosion by a distance or ohmic resistance effect (Bradford, 2001; Frankel & Landolt, 2007; Hack & Wheatfall, 1995). Indeed, the approach of providing distance between anode and cathode in dissimilar pipe connections by an insulating spacer is routinely employed in homes to dramatically *reduce* incidence of galvanic corrosion between copper and galvanized iron pipe while meeting electrical codes (with an external grounding wire connecting the pipes) as noted by Bradford (2001).

The objective of this work was to directly test the Boyd et al. (2012) hypothesis for lead and copper pipe connections, by measuring galvanic current and lead contamination of water as a function of increased pipe separation by use of an electrochemically inert spacer. If lead leaching was to increase with separation as proposed by these authors, then use of dielectrics bridged with external connections in practical situations would be expected to cause serious problems and should be avoided. In contrast, if lead leaching were to decrease with separation, then this approach could be used to mitigate lead contamination of potable water; moreover, use of bridged dielectrics in prior research (Triantafyllidou & Edwards, 2011) would have underestimated (and not overestimated) impacts from direct connections in practice. Prompt resolution of this issue is therefore of considerable practical importance.

2 Methods

New lead and copper pipes (internal diameter of 1.9 cm or else 3/4 in.) consisting of a 30.5 cm (12 in.) copper pipe section were electrically connected via an external grounding strap to a 15.3 cm (6 in.) lead pipe section. The lead and copper were separated to targeted distances using lengths of PVC pipe sections and were coupled using Tygon tubing and external clamps (Figure 1-1). The total length of the pipes was held constant by coupling additional PVC piping to the lead sections, creating an overall length of 107 cm (42 in.) and equal water volumes in all cases. Separation distances of 0.6, 2.5, 7.6, 30.5 and 61.0 cm (¼, 1, 3, 12, and 24 inches, respectively) between the lead and copper pipe were tested. In one case lead and copper were connected directly via abutting tubes. The lead section was first heated to connect to copper via an external coupling and the connection was further reinforced by external application of epoxy commonly used in premise plumbing systems. A final condition with a 15.3 cm (6 in.) lead section and no copper pipe was designed to illustrate results with no galvanic corrosion.

All conditions were tested in triplicate over a four month experiment during which time water was generally changed inside the pipes three times per week using a “dump and fill” protocol. Boyd et al. (2012) used a similar water change protocol with new lead and copper surfaces, to obtain their data on behavior of separated and directly connected lead/copper surfaces. Stagnation times between water changes were 48, 72, and 48 hours in this study each week, with the exception of weeks 8 and 9 during which a two week stagnation event was used. Galvanic currents between copper and lead were measured weekly for both stagnant and fresh water conditions. Composites from each water change were collected weekly from each replicate and analyzed for lead by inductively coupled plasma mass spectrometer after acidification with nitric acid to a concentration of 2% by volume. This approach has been shown to recover all soluble and particulate lead in the potable water (Triantafyllidou et al., 2012).

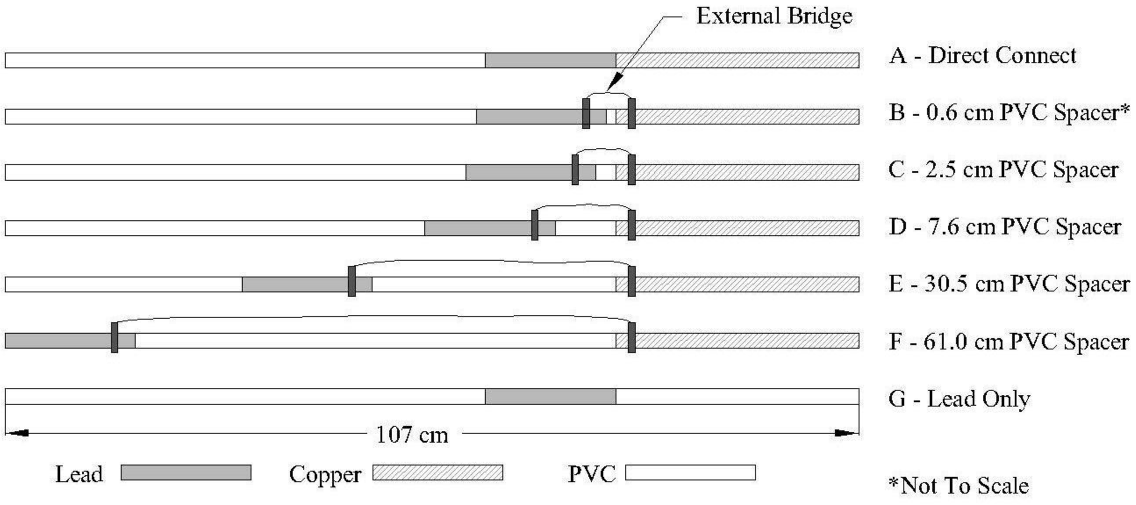

Figure 1-1 Experimental setup schematic (triplicates were tested for each condition). Blacksburg, VA tap water was used during this experiment after flushing for ten minutes prior to filling the pipes. Lead in water was confirmed to be at least three orders of magnitude lower in tap water compared to that from the pipe rigs. Blacksburg water has a typical pH of 7.4, alkalinity of 31 mg/L as $CaCO_3$, and lead corrosion is controlled by dosing of a zinc orthophosphate inhibitor (0.5 mg/L as P). The chloride and sulfate level averages 15 and 6 mg/L, respectively.

3 Results

Increased separation distance between anode and cathode drastically reduced galvanic current and lead in water from galvanic corrosion between lead and copper pipe (Figure 1-2, Figure 1-3). For lead in water, the condition where lead and copper were directly coupled and the gap was 0 cm (A) was indeed the worst case scenario, but it was not statistically different from a condition with a 0.6 cm (1/4 in.) separation (B) used in prior experiments (Hu et al., 2012; Triantafyllidou

& Edwards, 2011). Comparison between the directly coupled pipe section (A) and a 7.6 cm (3 in.) separation (D) resulted in a statistically significant reduction of 60% in lead release. At 61.0 cm (24 in.) separation (F), lead concentrations were not statistically different from those of the lead only condition (G) suggesting that galvanic effects diminished completely and were nearly negligible at this distance. Trends in measured galvanic current mirrored the trends in metal release. The measured galvanic currents and lead release were very persistent and only decreased slightly over the four month duration (Figure 1-3, Figure 1-4). Additionally, lead release was not markedly elevated during the one long stagnation event during this study compared to stagnation events of 48 or 72 hours.

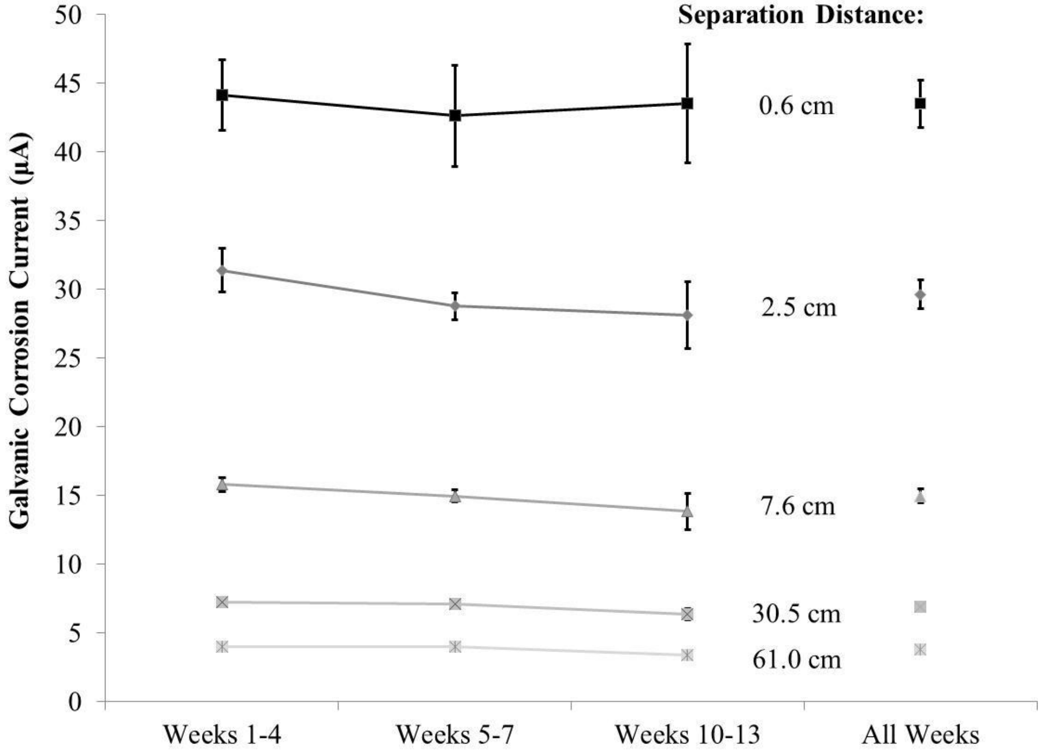

Figure 1-2 Galvanic corrosion currents measured immediately after water change between copper and lead pipe section pooled by time period. It is not possible to directly measure galvanic current with a direct connection. (Error bars indicate 95% confidence intervals)

While no attempt was made to quantify the localization of galvanic current or metal release at different sections of the lead pipe surface, at the end of the testing it was visually obvious that much more lead scale accumulated at the portion of the lead pipe surface closest (≈ 1 cm) to the copper pipe (Figure 1-5). The volume of the lead scale deposit was also markedly reduced with greater separation between the lead and copper pipe, consistent with expectations based on measurement of reduced galvanic corrosion. Hence, the localized nature of lead corrosion from galvanic corrosion was maintained even when lead and copper were separated, consistent with theory (Hack & Wheatfall, 1995; Scully & Hack, 1988), yet contrary to statements in Boyd et al. (2012).

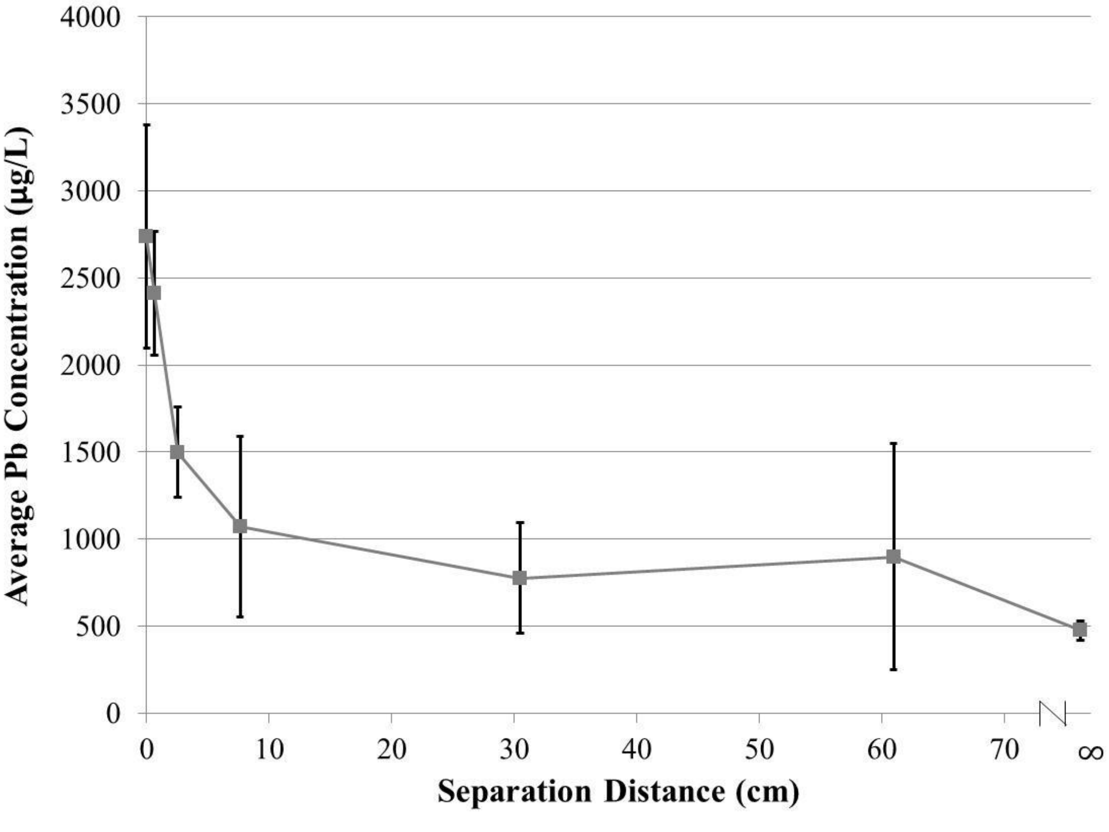

Figure 1-3 Weekly total lead concentrations by separation distance. Error bars indicate 95% confidence intervals on pooled data from triplicate pipe rigs and represent 33 results for total lead (11 weeks analyzed X triplicate). Lead sample with no copper is graphed at a distance of ∞ on the graph.

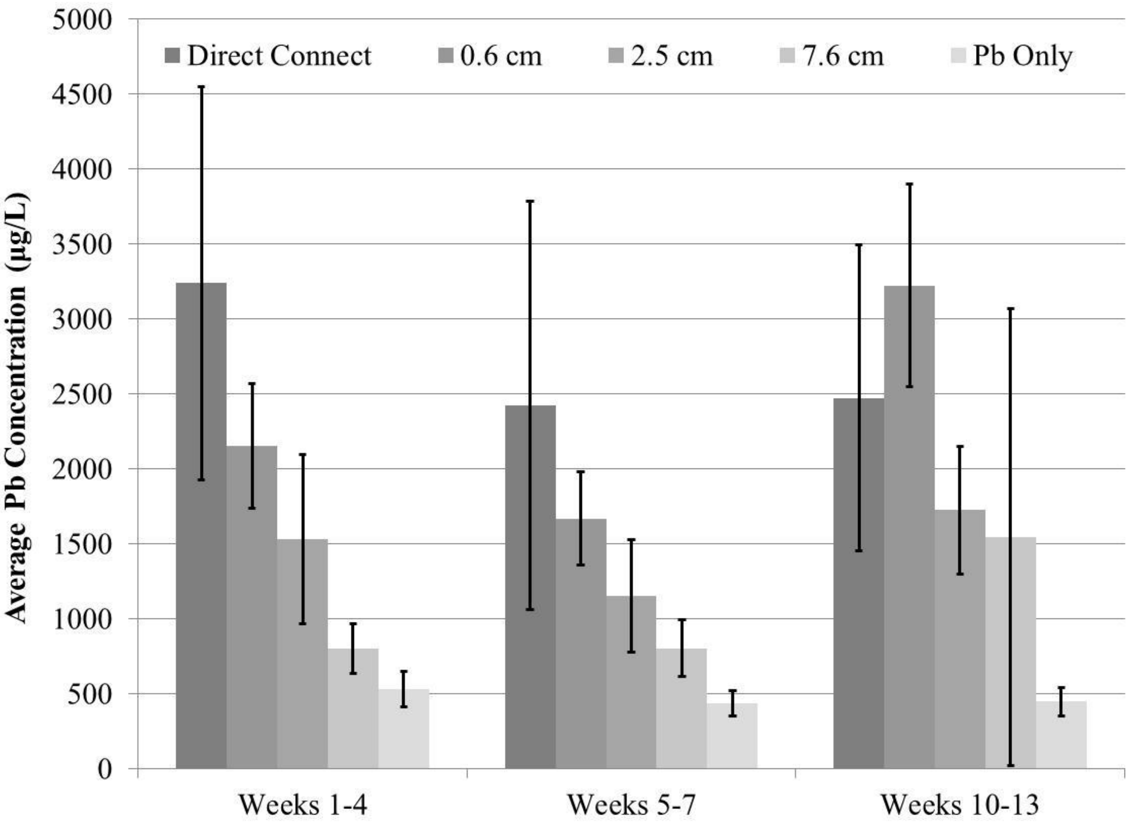

Figure 1-4 Average total lead concentrations by separation distance pooled by time period. (Error bars indicate 95% confidence intervals)

Much additional research needs to be completed on the issue of galvanic corrosion during partial replacements including use of passivated (existing) lead pipe surfaces, more realistic flow regimes, effects of water chemistry, long-term testing of galvanic impacts, and the role of flow rates during sampling amongst other issues. However, there is no reason to believe that any of these additional factors would cause separated lead and copper pipe to pose a greater health hazard to consumers than direct connections between lead and copper pipe. Even small separations can significantly reduce lead release to water in some cases. Recently, at least one water utility that had proposed to use bridged dielectrics to maintain electrical grounding and reduce galvanic corrosion after partial replacements, instead opted to use simpler direct connections that would avoid the concerns raised by Boyd et al. (2012) (Providence Water, 2012). Such decisions should be re-evaluated based on theory and practical data presented herein.

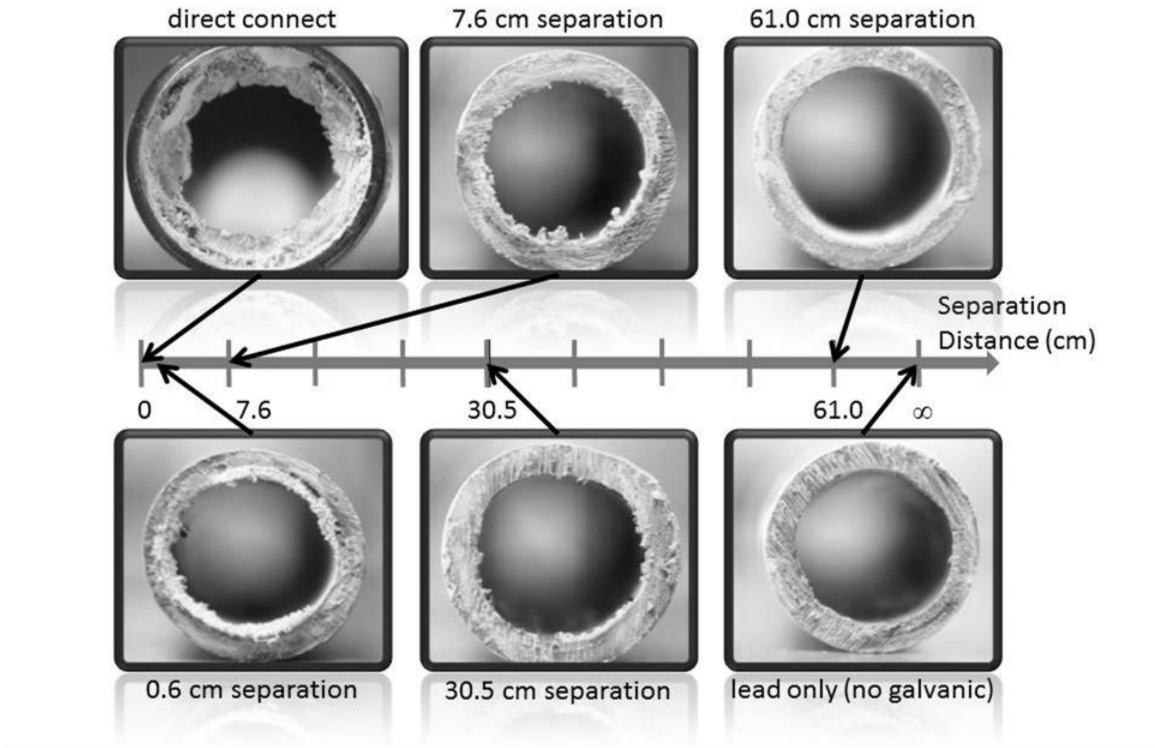

Figure 1-5 Lead scale buildup localized at galvanic junction of lead pipe. The quantity of lead deposit was maximized in direct connections and decreased markedly with distance. Virtually all the deposit (lead rust/scale) occurred at the lead pipe surface closest to the copper pipe. No deposit was visually apparent along the length of the pipe, indicating that corrosion was still highly localized.

4 Conclusions

This four month direct test confirmed expectations that increasing distance between galvanically connected lead and copper pipe (with an insulating spacer) reduces the extent of the galvanic corrosion current and resulting lead contamination of water. These findings agree with previous research and theory, but disagree with the claim that separating lead and copper pipe by 1-15 cm will likely accelerate “lead release by up to ten-fold” (Boyd et al., 2012) and increase galvanic corrosion over large portions of lead pipe surfaces. Galvanic corrosion and lead leaching to water from both direct connections and bridged connections were very persistent under the conditions studied, although increased lead leaching arising from separations at or over one foot was relatively minor. Use of bridged dielectrics by water utilities practicing partial lead pipe replacements and for other practical applications should not be discontinued based on results of Boyd et al. (2012). Past research results with small (0.25 cm) separations between lead and copper pipe, provide a conservative estimate of galvanic corrosion when compared to direct connections, and are necessary to measure trends in galvanic current.

Acknowledgements

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References

Boyd, G., Reiber, S., & Korshin, G. V. (2010). *Effects of Changing Water Quality on Lead and Copper Release and Open-Circuit Potential Profiles.* Paper presented at the Proceedings of the 2010 AWWA Water Quality Technology Conference, Savannah, GA.

Boyd, G., S., R., McFadden, M., & Korshin, G. (2012). Effect of Changing Water Quality on Galvanic Coupling. *Journal AWWA, 104*(3), E136-E149.

Bradford, S. A. (2001). *Corrosion control* (2nd ed.). Edmonton: CASTI Pub.

Britton, A., & Richards, W. N. (1981). Factors influencing plumbosolvency in Scotland. *J. Inst. Water Eng. Scient.*, 35:349-364.

Brown, M. J., Raymond, J., Homa, D., Kennedy, C., & Sinks, T. (2011). Association between children's blood lead levels, lead service lines, and water disinfection, Washington, DC, 1998–2006. *Environmental Research, 111*(1), 67-74. doi: 10.1016/j.envres.2010.10.003

Cartier, C., Arnold Jr, R. B., Triantafyllidou, S., Prévost, M., & Edwards, M. (2012). Effect of Flow Rate and Lead/Copper Pipe Sequence on Lead Release from Service Lines. *Water Research, 46*(13), 4142-4152. doi: 10.1016/j.watres.2012.05.010

Chambers, V. K., & Hitchmough, S. M. (1992). Economics of lead pipe replacement (TMU. 9030). Final report to the UK Department of the Environment, DE 2956/1.

Frankel, G. S., & Landolt, D. (2007). Kinetics of Electrolytic Corrosion Reactions *Encyclopedia of Electrochemistry*: Wiley-VCH Verlag GmbH & Co. KGaA.

Frumkin, H. (2010). Important update: lead-based water lines. Announcement to Childhood Lead Poisoning Prevention Program Managers, from http://www.cdc.gov/nceh/lead/waterlines.htm

Giammar, D. E., Wang, Y., He, J., Cantor, A., & Welter, G. J. (2011). *Experimental investigation of lead release during connection of lead and copper pipes. Water Quality Technology Conference.* Paper presented at the Water Quality Technology Conference, Phoenix, AZ, American Water Works Association.

Giammar, D. E., Welter, G. J., & Cantor, A. (2012). Review of Previous Water Research Foundation Projects on Galvanic Corrosion. *Water Research Foundation*. Retrieved from http://www.waterrf.org/ProjectsReports/ProjectPapers/Lists/PublicProjectPapers/Attachments/3/4349_LiteratureReview.pdf.

Hack, H. P., & Wheatfall, W. L. (1995). *Evaluation of Galvanic and Stray Current Corrosion in 70/30 Copper-Nickel/Alloy 625 Piping Systems.* (CARDIVNSWC-TR-61-94/15).

Hu, J., Gan, F., Triantafyllidou, S., Nguyen, C. K., & Edwards, M. (2012). Copper-Induced Metal Release from Lead Pipe into Drinking Water. *Corrosion,* Accepted.

Leonnig, C. D. (2008, February 23). Spikes in Lead Levels Raise Doubts About Water Line Work Increases Followed D.C. Agency's Pipe Replacements, *Washington Post*. Retrieved from http://www.washingtonpost.com/wp-dyn/content/article/2008/02/22/AR2008022202850.html

Scully, J. R., & Hack, H. P. (1988). Prediction of tube-tubesheet galvanic corrosion using finite element and Wagner number analyses. *Galvanic Corrosion, ASTM STP, 978*, 136.

Triantafyllidou, S., & Edwards, M. (2011). Galvanic corrosion after simulated small-scale partial lead service line replacements. *Journal American Water Works Association 103(9), 85*.

Triantafyllidou, S., Nguyen, C. K., Zhang, Y., & Edwards, M. A. (2012). Lead (Pb) quantification in potable water samples: implications for regulatory compliance and assessment of human exposure. *Environ Monit Assess*. doi: 10.1007/s10661-012-2637-6

USEPA. (2011). Science Advisory Board Evaluation of the Effectiveness of Partial Lead Service Line Replacements, EPA-SAB-11-015 Retrieved 2012/02/15, from http://yosemite.epa.gov/sab/SABPRODUCT.nsf/RSSRecentHappeningsBOARD/964CCDB94F4E6216852579190072606F/$File/EPA-SAB-11-015-unsigned.pdf

CHAPTER 2: PRACTICAL UNDERSTANDING OF ISSUES ASSOCIATED WITH THE USE OF DIELECTRICS IN SERVICE LINES AND PREMISE PLUMBING

Abstract

Performance of dielectrics commonly used in premise plumbing while maintaining electrical continuity were examined and ranked as follows in regards to their galvanic corrosion current: plastic pipe section > dielectric nipple > dielectric union > brass nipple ≈ dielectric spacer. When dielectrics were bridged with a grounding strap, the primary factor affecting galvanic performance was separation distance between the anodic and cathodic metal, although some dielectrics offered additional advantages such as greater corrosion allowances (i.e., wall thickness) or reduced likelihood of clogging due to scale buildup (i.e., higher cross sectional flow area). Although bridged dielectrics do not completely stop galvanic corrosion, they can dramatically reduce galvanic corrosion while maintaining electrical continuity (and meeting grounding requirements) between pipe sections.

1 Introduction

Contact of dissimilar metals and resulting galvanic corrosion is a common cause of failure in water mains, service lines and premise plumbing (Gehring et al., 2003; Holler, 1974; Romer & Bell, 2001). In service lines and premise plumbing, galvanic connections of primary concern are between copper, lead, galvanized iron, and old galvanized iron which effectively behaves as unlined iron. Galvanic corrosion between copper and other metals is not significant in the absence of oxidants such as oxygen or chlorine (Smart et al., 2004; Smart et al., 2005), and other factors such as water conductivity, relative surface area and separation distance also play important roles in determining the rate of galvanic attack (Nguyen et al., 2011; Revie & Uhlig, 2011; St. Clair et al., 2012).

Dielectrics are plumbing devices used to join two dissimilar pipe materials, that can prevent (or markedly reduce) the electron flow (galvanic current) that can cause localized failures from galvanic corrosion. However, use of dielectrics to stop galvanic corrosion may compromise other expectations of metal service lines such as electrical grounding or electrical thawing in cold climates (Table 2-1, Figure 2-1) (Bohlander, 1963; Hack & Wheatfall, 1995; Nelson, 1976; US EPA, 2011). There have also been concerns that placing a dielectric between copper service lines and iron mains to prevent galvanic corrosion of iron (Ferguson & Nicholas, 1991) might hinder cathodic protection of the valuable copper service lines and increase its rate of failure (Horton, 1995). Obviously, this potential benefit of galvanic corrosion must be weighed against more rapid attack and failures of the iron mains at copper service line connections, however no cost:benefit analysis of these tradeoffs has ever been conducted (Gehring et al., 2003; O'Day, 1989; Rajani & Kleiner, 2003). Finally, in at least some cases, installation of dielectrics on lines carrying AC/DC currents can induce stray current corrosion and cause elevated iron, lead, and copper in water (Bell & Duranceau, 2002; Horton, 1995).

The use of a dielectric does not eliminate all issues of galvanic corrosion. For example, deposition corrosion can occur if a more noble metal is ever placed upstream of the anodic metal in the flow sequence, contrary to established water system practices of placing metals in flow from more anodic to more cathodic in the galvanic series (Breach et al., 1991; Britton & Richards, 1981; Cartier et al., 2012a; Clark et al., 2011; Copper Development Association, 1999; Triantafyllidou & Edwards, 2010, 2011).

Table 2-1 Issues associated with dielectrics and related effects.

Issue	Benefit of Dielectric	Possible Detriment of Dielectric	Reference
Galvanic corrosion	Stops galvanic current	Less noble metal (e.g., iron main) no longer serves as sacrificial anode to more noble metal (e.g, copper service line)	(Ferguson & Nicholas, 1991; Gehring et al., 2003; Horton, 1995; O'Day, 1989; Rajani & Kleiner, 2003)
Pipe thawing to allow water flow in cold environment	None	Electrical currents used to heat pipes are not possible	(Nelson, 1976)
Grounding to prevent electrocution and meet plumbing code	None	Reduces grounding effectiveness	(Carlton, 1974; Duranceau et al., 1998; Horton, 1995; Welter, 2008)
Water quality (Higher Pb, Fe in water)	Reduces lead or iron in water resulting from direct galvanic corrosion	Can actually increase corrosion and metals in at least some cases if stray AC/DC currents are carried on pipes	(Bell & Duranceau, 2002; Holtsbaum, 2007; St. Clair et al., 2012)
Deposition Corrosion	Deposition corrosion not stopped		(Hu et al., 2012; Triantafyllidou & Edwards, 2010)

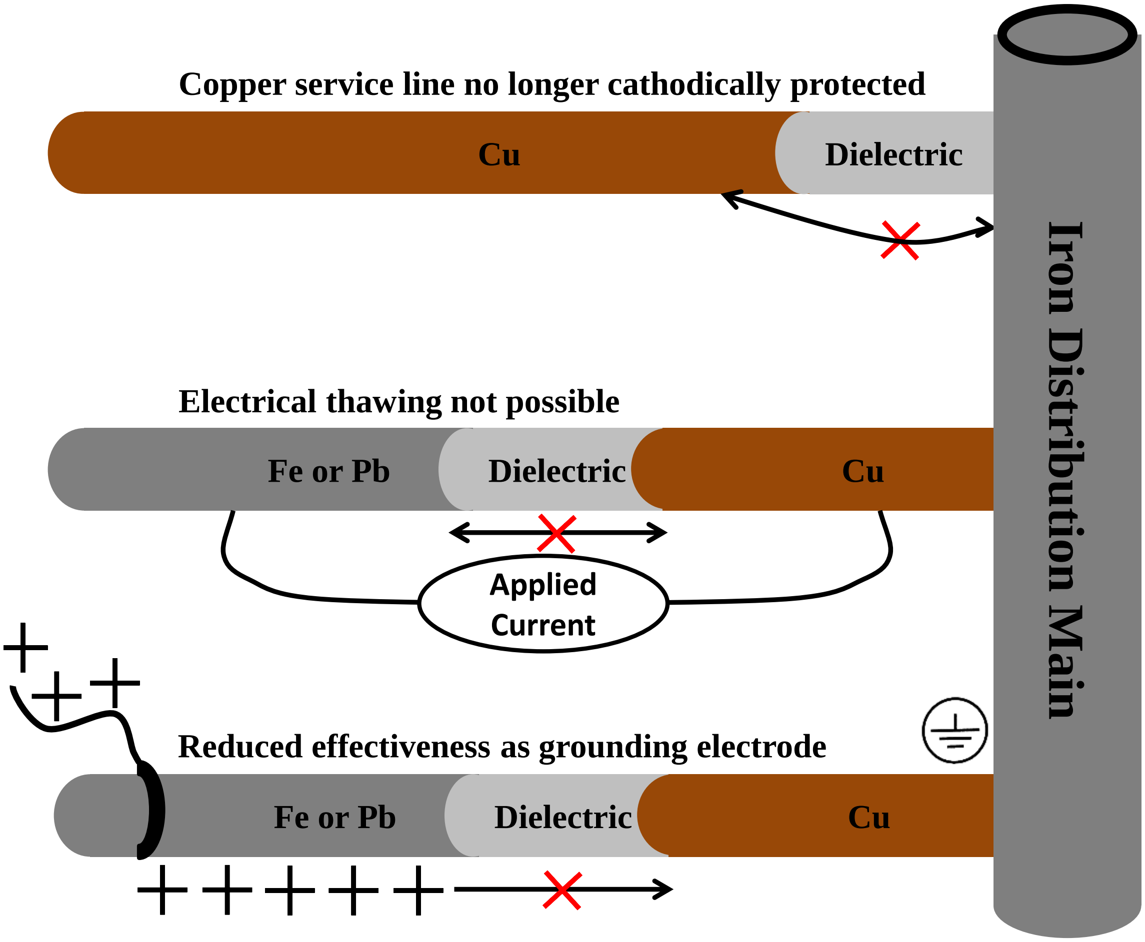

Figure 2-1 Illustration of some possible detriments due to interrupted galvanic currents or applied currents (stray currents or thawing current) due to installation of dielectrics.

Use of water pipes for electrical grounding has long been a controversial subject (Carlton, 1974; Duranceau et al., 1998; Horton, 1995), and there have been well-documented cases of service line failure due to external corrosion, electrocution of utility employees, and even evidence of excessive metal leaching to potable water for unusual configurations of plumbing (Bell & Duranceau, 2002; Carlton, 1974; Duranceau et al., 1998; Horton, 1995). Some current building construction codes require that electrically continuous metallic water lines extend at least 3 m (≈ 10 ft) from the structure if they are to be used as an effective grounding electrode for homes (IRC E3608.1.1). Other studies indicate that dielectrics will reduce stray currents flowing on pipes (Carlton, 1974; Horton, 1995), but it has also been shown that if stray currents are allowed to persist, then use of a dielectric can contribute to excessive internal corrosion in some plumbing configurations (Bell & Duranceau, 2002; Holtsbaum, 2007).

1.1 Dielectrics in Premise Plumbing Systems

Dielectrics can also be used in a number of situations in premise plumbing systems. Dielectrics are often required by the plumbing code between connections of galvanized iron and copper (IRC P2905.17). Various connectors designed to mitigate galvanic corrosion have also been installed between copper piping and steel tanks in hot water heaters. In either of these situations, the use of the dielectric might break electrical continuity on the pipe for grounding. However, practical observation of service failures has indicated that even if a dielectric is installed and functioning properly, galvanic failures sometimes still occur because the two metals remain in circuitous electrical contact via the cold water plumbing system, metal structures and pipe hangers or the electrical system (Carlton, 1974; Hack & Wheatfall, 1995). As a result of these factors, true galvanic separation of dissimilar pipe metals via installation of a dielectric is often not obtained, and may be prohibited by the plumbing code via required use of bridged dielectrics.

1.2 Bridged Dielectrics

In practice, the plumbing code often requires bridged dielectrics to be installed for grounding purposes (IRC E3609.6-7). In concept, the bridged dielectric can provide many benefits to galvanic corrosion without the drawbacks associated with unbridged dielectrics (Table 2-1). Electrical continuity along the pipe for grounding and other purposes is provided by a “bridge” or external grounding strap (i.e., a wire connecting the two pipes). Separation of the two metals by distance still reduces net galvanic corrosion due to the resistance of the water, via an “ohmic drop" or "distance effect" (Bradford, 2001; Frankel & Landolt, 2007; Hack & Wheatfall, 1995; Holtsbaum, 2007). Recent experiments confirmed that separation of a copper pipe cathode and lead pipe anode with a bridged dielectric 61 cm long reduced internal galvanic corrosion currents and lead contamination of water to insignificant levels, and even a 7.6 cm separation distance reduced galvanic currents and lead contamination by 60-69% (St. Clair et al., 2012).

1.3 Types of Dissimilar Metal Connections

There are a range of dielectrics in commercial use that can be expected to vary dramatically in terms of practical performance (Figure 2-2, Table 2-2). Dielectric unions have a rubber spacer (0.6 cm) and a plastic washer to maintain electrical isolation between the two pipe sections. Dielectric nipples (7.6 cm long) do not offer electrical isolation but are coated internally with plastic, and therefore essentially function as a bridged dielectric with effective separation of 7.6 cm. A brass nipple (15.2 long) does not electrically isolate pipe sections and is not coated internally like a dielectric nipple, but zinc in the brass might provide a sacrificial effect. Plastic pipe sections can separate the pipe sections at various distances with true dielectric separation. The point of comparison in terms of performance, is directly coupling two pipe sections together without a connector with dielectric capabilities.

Recent concerns associated with elevated lead in water arising from connections between new copper pipe and old lead pipe (Cartier et al., 2012a; Cartier et al., 2012b; Triantafyllidou & Edwards, 2010), associated reports raising concerns associated with dielectrics (Boyd et al., 2012; US EPA, 2011; Welter, 2008), and a general lack of knowledge regarding practical performance of each dielectric in premise plumbing systems prompted this practical investigation for a model system of copper and galvanized iron pipe. Practical understanding of mechanisms and secondary effects of dielectric connections are emphasized including 1) effect of separation distance on galvanic current in bridged dielectric, 2) sacrificial effect of connector material, and 3) design advantages to increase longevity and reduce negative impacts of corrosion.

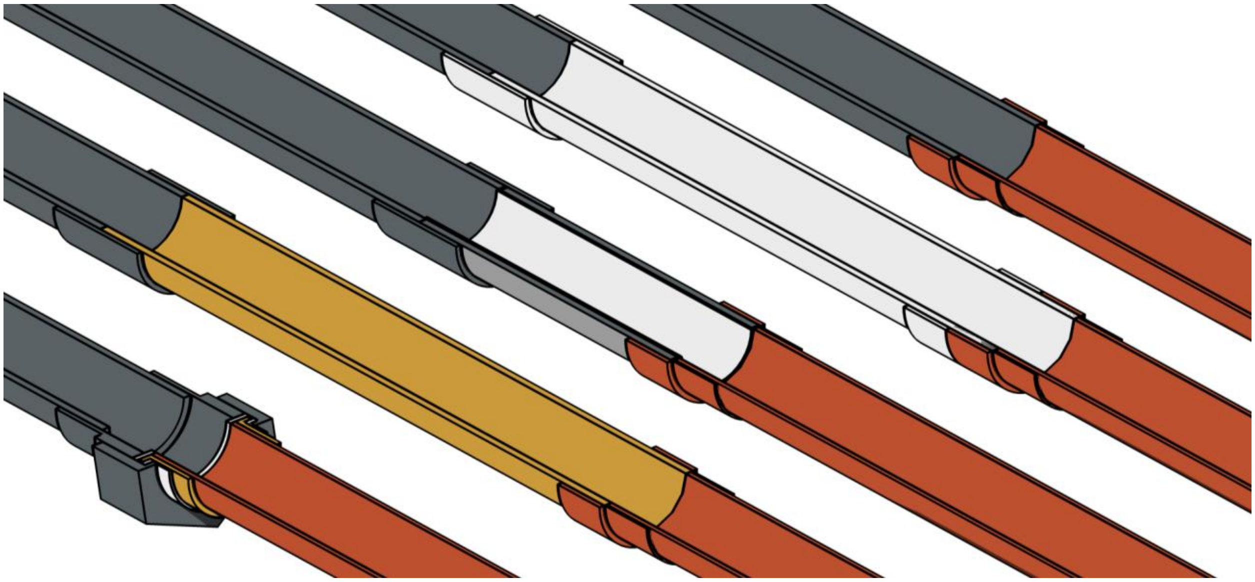

Figure 2-2 Cross sections of connection methods between dissimilar metals (left to right: dielectric union, brass nipple, dielectric nipple, plastic pipe section, direct connect).

Table 2-2 Summary of dissimilar metal connection methods and experimental galvanic corrosion currents. Variants sorted from best to worst performance during experiment on the basis of galvanic corrosion current. GI = Galvanized Iron

Connector	Grounding Automatically Maintained Without Bridge	Cu/GI Metal Separation Distance	Dielectric Mechanism	*Galvanic Current no bridge	* Galvanic Corrosion Current with bridge
Plastic Pipe Section	No	Length of pipe (*15.3 cm)	True dielectric: Separation of cathode and anode with plastic	0	19 µA
Dielectric Nipple	Yes	7.6 cm	Distance effect: Galvanized pipe section coated internally with plastic	26 µA	26 µA
Dielectric Union	No	0.6 cm	True dielectric: Rubber and plastic washers isolate pipe sections	0	63 µA
Brass Nipple[ǂ]	Yes	0 cm (*0.3 cm)	Sacrificial effect: Zinc content of brass may decrease surface potential	> 97 µA	97 µA
Direct Connect (*Bridged Dielectric)	Yes	0 cm (*0.3 cm)	None	> 96 µA	96 µA

[ǂ] Acceptable substitute for a dielectric union. IRC P2905.17

*Experimental conditions and results of current research presented herein

2 Materials and Methods

2.1 Effect of Separation Distance on Galvanic Current

Short duration experiments determined how separation distance influenced galvanic corrosion current between copper and galvanized iron pipe with a grounding strap. New copper pipe (305 cm, 1.9 cm internal diameter) was coupled to new galvanized iron pipe (305 cm, 2.2 cm internal diameter) using various lengths of clear plastic tubing (0.2, 0.6, 1.3, 2.6, 7.6, 15.2, 30.4, 61.0 cm). Pipes were filled with tap water and direct galvanic current was measured between the copper and galvanized iron section using a multimeter at the various separation distances. QA/QC testing demonstrated that a zero resistance ammeter and the multimeter used for routine experiments gave equivalent results to within +/- 5%.

Blacksburg tap water was used for this experiment after flushing for ten minutes. Tap water pH is 8.01, alkalinity 31 mg/L as calcium carbonate ($CaCO_3$), with chloramines residual of 3.10 mg/L total chlorine (Cl_2). For corrosion control, zinc orthophosphate ($Zn_3(PO_4)_2$) is dosed at the treatment facility at a concentration of 0.5 mg/L as P. Chloride and sulfate levels average 15 mg/L and 6 mg/L, respectively.

2.2 Effect of Various Connectors on Galvanic Corrosion

New copper pipe sections (30.5 cm, 1.9 cm internal diameter) were coupled to new galvanized iron pipe sections (30.5 cm, 2.2 cm internal diameter) using commercially available connectors including a dielectric union, dielectric nipple, and brass nipple (sometimes termed “poor mans” dielectric). Additionally, a 15.3 cm polyvinyl chloride (PVC) pipe and 0.3 cm dielectric rubber spacer were tested (Figure 2-2, Figure 2-3). For conditions where the connectors could act as true dielectrics (actually electrical isolate two pipes), conditions were also tested such that copper and galvanized iron sections were electrically connected via an external grounding strap (Figure 2-3). In all other cases very small plastic spacers (0.3 mm) were used between connections so that galvanic current flows between sections could be quantified. Dielectric unions were coupled to the threaded galvanized iron sections and then attached to copper using epoxy commonly used in premise plumbing systems.

The total length of the conditions tested was held constant by adding PVC piping to the galvanized iron sections, creating an overall length of 76.2 cm and equal water volumes in all cases. A galvanized iron section with PVC and no copper pipe was used as a control condition without galvanic corrosion. A total of eight conditions were tested in triplicate resulting in a total number of 24 conditions. Prior to the beginning of the experiment, pipes were rinsed out three times with ultra-pure water.

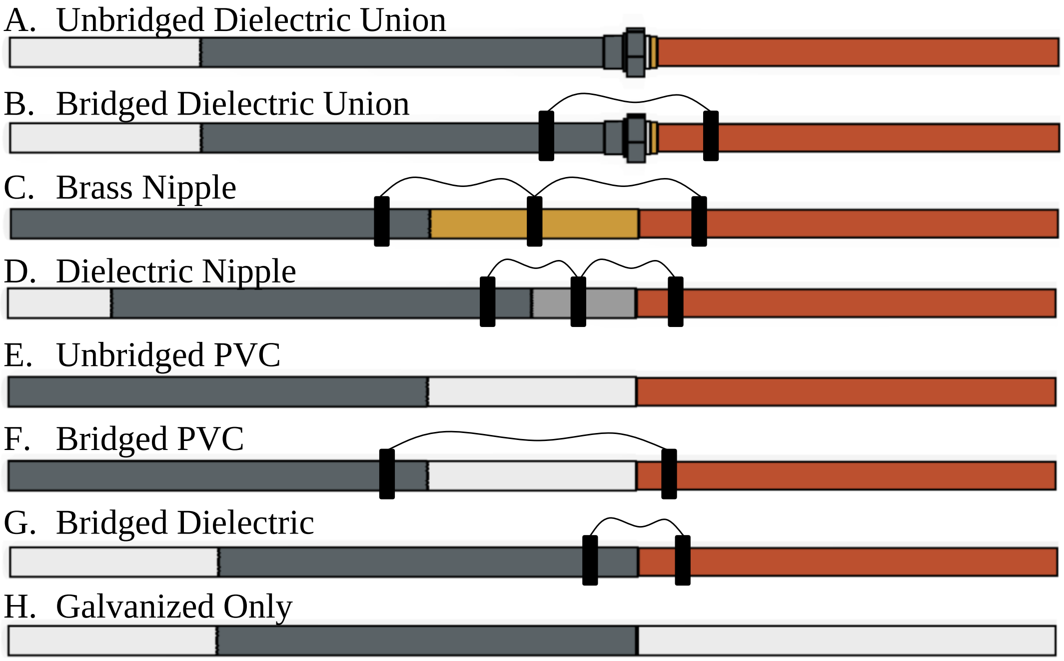

Figure 2-3 Schematic of experimental conditions (tested in triplicate).

Water was changed inside the pipes three times per week using a “dump and fill” protocol with stagnation times of 48, 72, and 48 hours each week. Blacksburg tap water was used for the experiment after flushing for ten minutes as described above. Prior to each water change, pH and chlorine levels were measured.

Galvanic currents between pipe sections were measured weekly for both stagnant and fresh water conditions (prior to and immediately after water change, respectively). Weekly composites from each water change were collected from each replicate and acidified with nitric acid (HNO_3) to a concentration of 2% by volume. Metals were analyzed by inductively coupled plasma mass spectrometer after a minimum of four days digestion.

2.3 Interaction of Metals in Hot Water Heaters

A short-term, bench-top experiment was conducted to determine how the typical metallic components of a hot water heater interact galvanically (Figure 2-4). A 20 gallon hot water heater was connected to copper pipe sections (15.3 cm long each, 1.9 cm internal diameter) by a short length of clear plastic tubing (7.6 cm, similar to that of dielectric nipple) and filled with Blacksburg tap water (described earlier). Thereafter, the magnesium sacrificial anode rod was disconnected from the steel tank, but left submerged in the water. The steel tank, magnesium anode rod, and copper pipe sections were externally connected electrically to measure galvanic currents. Current was measured for each component with a multimeter to determine individual contributions to galvanic corrosion in the system. Four conditions representing various situations were tested: (a) all three components connected (copper piping, steel tank with anode rod in place), (b) copper pipes disconnected from tank and anode rod , (c) anode rod disconnected from tank and copper pipes (d) steel tank disconnected from connection between anode rod and copper piping.

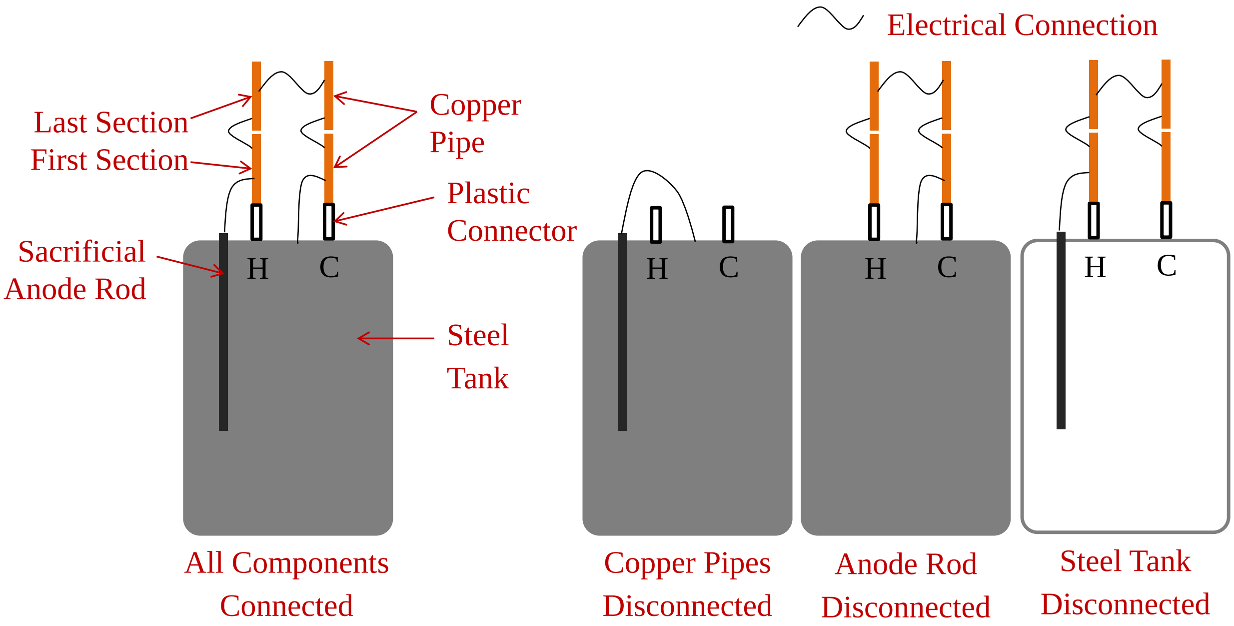

Figure 2-4 Experimental conditions to measure galvanic corrosion in a hot water heater.

3 Results and Discussion

After examining the effect of separation distance on galvanic corrosion, the influence of connection methods of dissimilar metals is presented. Lastly, the galvanic interactions of metal components in a water heater are explained.

3.1 Effect of Separation Distance on Galvanic Current

Galvanic current decreased markedly with increased separation distance in the experiment in section 2.1 (Figure 2-5). At a separation of 30 cm, galvanic current decreased by 90% compared to that estimatedat no separation distance by extrapolation of data at short distances (189 µA at 0 cm separation). As suggested by Bradford (2001), even small insulated spacers provide enough separation to sufficiently decrease galvanic corrosion. Indeed, with only a short separation distance of 0.6 cm, galvanic corrosion current decreased by 46% in this experiment. For comparison between the current system of copper:galvanized iron and a previous copper:lead system, data of St. Clair et al. (2012) obtained in the same water were also plotted as percent decrease versus separation distance (48 µA at 0 cm separation). As would be expected given electrochemical theory (assuming resistances at the cathodic, anodic and electrical connection are similar) nearly identical trends were obtained for the two different metal couples of Cu:Pb or Cu:GI (Song et al., 2004). The primary difference was that the Cu:GI system had about 2.7 times greater galvanic current than for Cu:Pb.

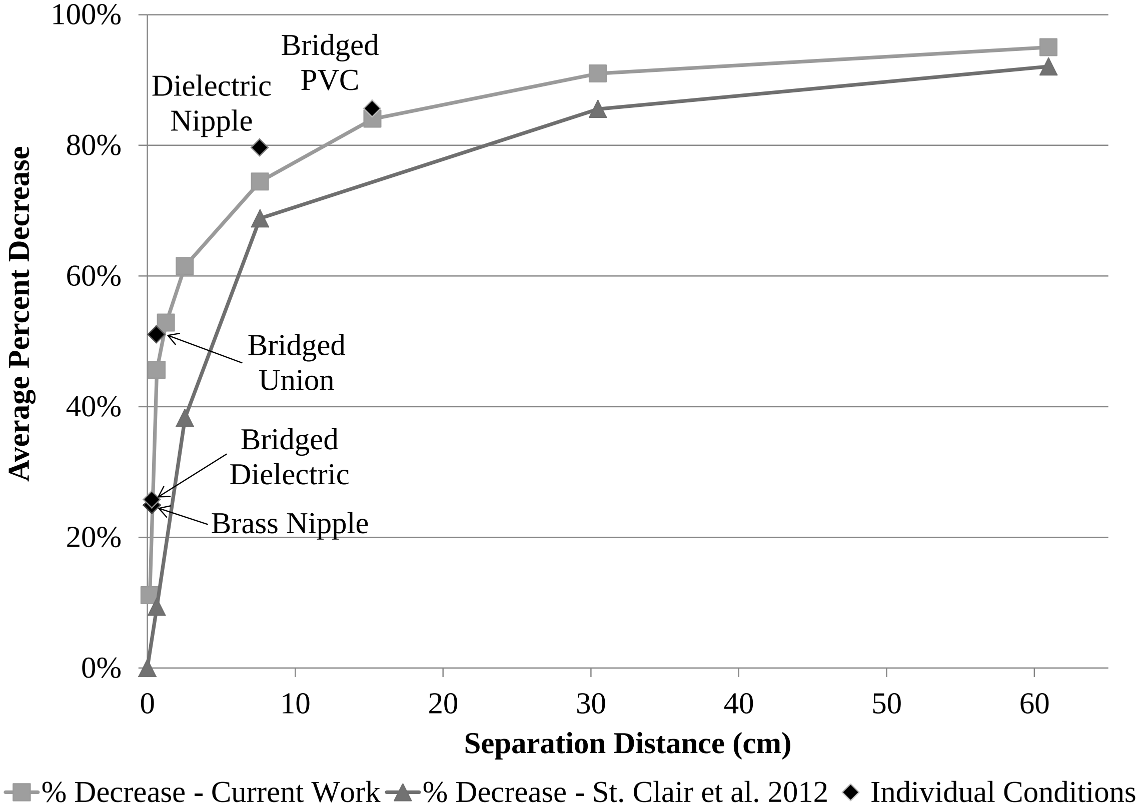

Figure 2-5 Direct galvanic current measured between iron and copper pipe section by various separation distances from this work and St. Clair et al. (2012). (Percent reduction based on direct connect current determine by extrapolaiton of data at short distances)

3.2 Effect of Various Connectors on Galvanic Corrosion

Galvanic Currents. Measurements of direct galvanic corrosion currents between the various pipe sections and commercially available connectors confirmed that copper or brass connector sections always behaved as the cathode relative to the galvanized iron pipe section. Overall, galvanic currents immediately after a water change (termed fresh current herein) decreased with increasing separation distance and were higher than currents after a 48-72 hour stagnation (stagnant current; Figure 2-6).

For all true dielectrics without any external bridging the galvanic currents were zero. The brass nipple did not significantly decrease the sacrificial galvanic current for the galvanized iron, indicating that the brass was completely ineffective as a dielectric, and in fact, the brass nipple did not perform significantly different from a copper pipe directly connected to galvanized iron. As effective separation between the copper and galvanized iron pipes increased, galvanic current decreased for each of the other connector types. Galvanic current with a bridged dielectric union was reduced 35% at 0.6 cm separation, 70% with a dielectric nipple with 7.6 cm separation, and 80% with bridged PVC with 15.2 cm when compared to expectations for a direct connection to pure copper (i.e., the bridged dielectric) or a brass nipple (Figure 2-6).

Similarly, the galvanic currents directly after a water change corresponded to that exhibited by the short-term experiment when comparing separation distances (Figure 2-5, 0 cm separation galvanic current estimated as described previously). Galvanic corrosion currents from all bridged conditions matched expectations based on separation distance of GI from either copper pipe or brass, indicating that separation distance is the major factor influencing galvanic corrosion rates.

During stagnation events, galvanic currents should not be significant if dissolved oxygen is completely consumed (Smart et al., 2004; Smart et al., 2005). Conditions with the highest galvanic current after a water change, which are expected to deplete the oxygen more rapidly, decreased nearly 80% during stagnation. As separation distance increased and galvanic currents decreased, the reduction in galvanic current during stagnation was also lessened to only 25-60%.

The design of the experiment with the brass connector between the copper and galvanized iron, allowed the location of the cathodic reaction with oxygen to be tracked, and as the stagnation progressed and as oxygen was presumably depleted in the brass connector during stagnation, a greater percentage of the overall sacrificial current was eventually derived from the copper (Figure B-1). A key point of this analysis is that for bridged dielectrics, greater distance between anode and cathode produces a large benefit during flow or with fresh water, but with prolonged stagnation events of days or weeks less benefit is obtained since the total galvanic corrosion is limited by the supply of oxygen in the water.

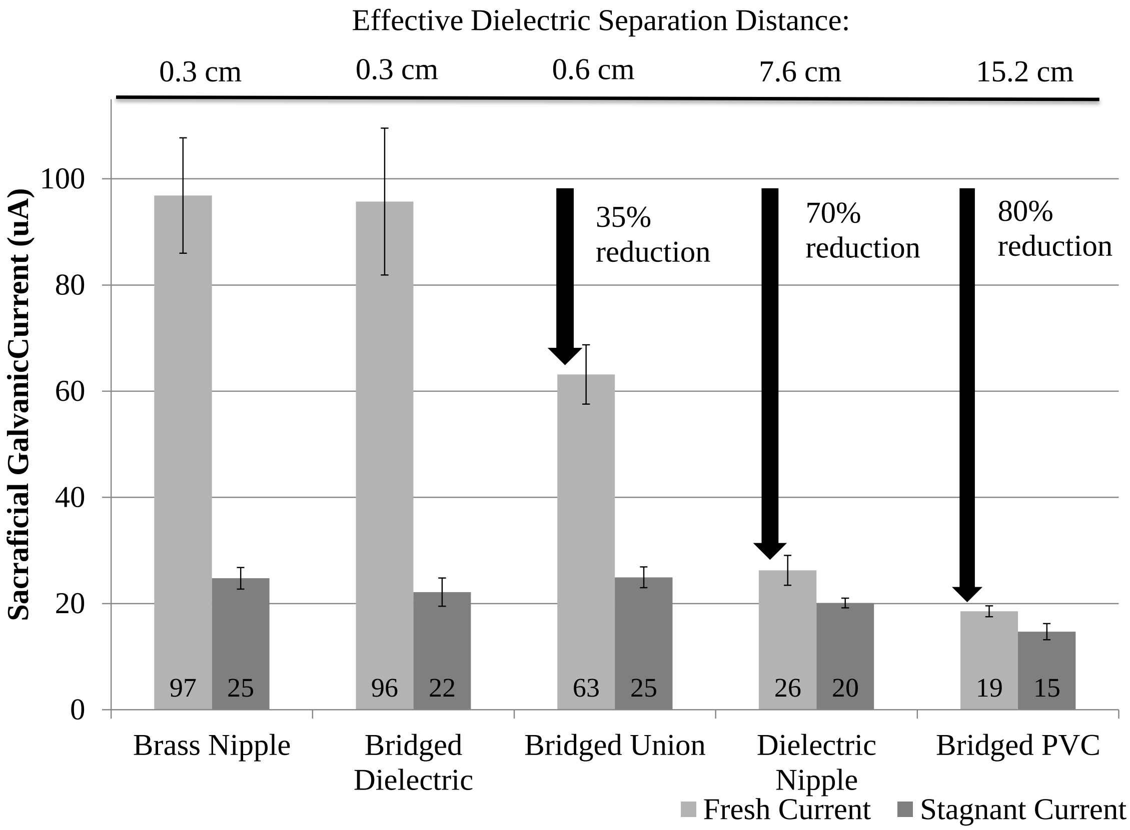

Figure 2-6 Average sacrificial galvanic current to galvanized iron for connected conditions and separation distance. (Percent reduction based on conditions with highest galvanic current. Error bars indicate 95% confidence interval)

Dissolved Metals. The amount of oxidized metal or rust, created as a result of direct galvanic corrosion can be estimated from the measured galvanic current using Faraday's Law. A portion of this oxidized metal can go into scale and another portion can go into the water. In the case of lead galvanically connected to copper, there is sometimes a strong relationship between galvanic corrosion and lead release (St. Clair et al., 2012; Triantafyllidou & Edwards, 2010) but in this short-term investigation the total iron concentrations did not correlate with galvanic corrosion current. Dissolved iron concentrations were highly variable and not significantly different from the galvanized iron control; however some individual conditions were statistically different from others (Figure B-2). Average zinc concentration in water was also not significantly different between many experimental conditions (Figure B-3), but all conditions did have 50% higher zinc ($p < 0.05$) when compared to the galvanized iron control. The dielectric unions also contributed to an additional slight increase in zinc leaching.

Because sacrificial corrosion of the galvanized iron pipe decreases the corrosion of copper, it is expected that copper levels in the water decrease as a result of galvanic connections. This was sometimes evident in this work. For instance, comparing bridge PVC to a dielectric nipple, galvanic corrosion current was 2.4 times higher and copper levels were 25% lower.

Evaluation of individual connection methods. Considering conditions which maintain electrical connection between copper and galvanized iron, galvanic effects were worst for the bridged dielectric and brass nipple (Table 2-2). Surface potential of the brass nipple might be less noble compared to pure copper given its elevated zinc content (87% Cu, 13% Zn), but this did not translate to a reduction in galvanic corrosion current. Thus, in this water, a slight short-term advantage of higher zinc content in the copper alloy was not detected, as was observed in prior research (Clark et al., 2012; Zhang & Edwards, 2011).

Although the bridged dielectric union only reduced direct galvanic corrosion by 35% (Table 2-2, Figure 2-6), it does offer some other significant advantages to consumers. For example, the greater wall thickness in proximity to the copper creates a corrosion allowance that can dramatically increase the lifetime of the joint compared to a normal galvanized iron pipe. Moreover, the cross sectional area of the dielectric can be as much as 20% higher than galvanized iron pipe, allowing a more significant accumulation of corrosion products without blocking flow.

3.3 Galvanic Interaction of Metals in Hot Water Heaters

Considering that water heaters are designed with a sacrificial anode, it is possible that there is really no need for an effective dielectric between the heater and copper pipe. To test this hypothesis, several configurations were tested. When all components were connected the steel tank was indeed cathodically protected by a very high galvanic current (~1000 uA) via the sacrificial anode rod. The copper piping to the tank was also slightly protected for short distance (i.e., by a current of approximately12-13 μA); however, this protective current to the copper did not change if the anode rod was disconnected (Table B-1). Overall, the sacrificial anode in the hot water tank did not seem to prevent localized galvanic corrosion between copper and the steel tank.

4 Conclusions

- Unbridged dielectric unions or intervening plastic were able to eliminate galvanic corrosion between copper and galvanized iron.
- In cases where bridged connectors were used to maintain electrical grounding, or if electrical continuity was maintained via other electrical pathways, separation distance between copper and galvanized iron pipe controlled the galvanic corrosion. Even small

separation distances could dramatically decrease galvanic corrosion current between the dissimilar metals. At separation distances of 0.6 cm and 30 cm, galvanic current decreased by 46 and 90%, respectively.

- Use of a short, unlined section of brass between copper and galvanized iron did not decrease galvanic corrosion significantly. But dielectric nipples which have a plastic inner liner, and effectively separate the copper and galvanized iron by 7.6 cm, decreased the galvanic current by 70%. A dielectric union bridged externally with an effective separation distance of 0.6 cm decreases galvanic current by only 35%. Lastly, PVC pipe with a separation distance of 15.2 cm decreases galvanic current by 80%.
- Galvanic corrosion currents were not linked to higher leaching of iron or zinc in these short-term experiments, and these metals do not pose a significant health risk nor are there regulatory limits of concern. Thus, the main concern of galvanic corrosion is joint failure due to wall penetration or blockage of water flow due to accumulation of corrosion products.
- Copper piping connected to the steel tank of a hot water heater was cathodically protected by the steel tank solely and for only a short distance from the junction. The sacrificial anode rod did not contribute to cathodic protection of the copper piping and did not prevent galvanic corrosion between the copper and steel tank.
- While true dielectrics effectively stopped direct galvanic corrosion, the use of bridged dielectrics between dissimilar metals to decrease galvanic effects is a viable alternative when maintaining electrical continuity between the pipe sections is required.

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References

Bell, G. E. C., & Duranceau, S. J. (2002). Effect of grounding and electrical properties on water quality. *Journal-American Water Works Association, 94*(5), 113-125.

Bohlander, T. W. (1963). Electrical Method for Thawing Frozen Pipes. *Journal - American Water Works Association, 55*(5), 602.

Boyd, G., S., R., McFadden, M., & Korshin, G. (2012). Effect of Changing Water Quality on Galvanic Coupling. *Journal AWWA, 104*(3), E136-E149.

Bradford, S. A. (2001). *Corrosion control* (2nd ed.). Edmonton: CASTI Pub.

Breach, R. A., Crymble, S., & Porter, M. J. (1991). *A Systematic Approach to Minimizing Lead Levels at Cosumers' Taps.* Paper presented at the American Water Works Association Annual Conference and Exposition, Philadephia, PA.

Britton, A., & Richards, W. N. (1981). Factors influencing plumbosolvency in Scotland. *J. Inst. Water Eng. Scient.*, 35:349-364.

Carlton, E. (1974). Electrical Grounding and Resulting Corrosion. *Journal American Water Works Association*, *66*(8), 471-472.

Cartier, C., Arnold Jr, R. B., Triantafyllidou, S., Prévost, M., & Edwards, M. (2012a). Effect of Flow Rate and Lead/Copper Pipe Sequence on Lead Release from Service Lines. *Water Research, 46*(13), 4142-4152. doi: 10.1016/j.watres.2012.05.010

Cartier, C., Doré, E., Laroche, L., Nour, S., Edwards, M., & Prévost, M. (2012b). Impact of Treatment on Pb Release from Full and Partially Replaced Harvested Lead Service Lines (LSLs). *Water Research*(0). doi: 10.1016/j.watres.2012.10.033

Clark, B., Cartier, C., St. Clair, J., Triantafyllidou, S., Prévost, M., & Edwards, M. (2012). Effects of Commercial Connectors on Galvanic Corrosion between Pb/Cu Pipes. *Submitted to Journal American Water Works Association*.

Clark, B., Hernandex, A. L., & Edwards, M. (2011). *Deposition Corrosion of Water Distribution System Materials.* Paper presented at the Water Quality Technology Conference, Phoenix, AZ.

Copper Development Association. (1999). Copper Tube in Domestic Water Services Publication 33. from http://www.copperinfo.co.uk/plumbing-heating-and-sprinklers/downloads/pub-33-copper-tube-in-domestic-water-services.pdf

Duranceau, S. J., Schiff, M. J., & Bell, G. E. C. (1998). Electrical grounding, pipe integrity, and shock hazard. *Journal-American Water Works Association, 90*(7), 40-52.

Ferguson, P., & Nicholas, D. (1991). External Corrosion of Buried Iron and Steel Water Mains. *Corrosion Australasia(Australia), 17*(4), 7-10.

Frankel, G. S., & Landolt, D. (2007). Kinetics of Electrolytic Corrosion Reactions *Encyclopedia of Electrochemistry*: Wiley-VCH Verlag GmbH & Co. KGaA.

Gehring, G., Lindemuth, D., & Young, W. T. (2003). Break Reduction/Life Extension Program for Cast and Ductile Iron Water Mains *New Pipeline Technologies, Security, and Safety* (pp. 321-331).

Hack, H. P., & Wheatfall, W. L. (1995). *Evaluation of Galvanic and Stray Current Corrosion in 70/30 Copper-Nickel/Alloy 625 Piping Systems.* (CARDIVNSWC-TR-61-94/15).

Holler, A. C. (1974). Corrosion of water pipes. *Journal American Water Works Association, 66*(8), 456-457.

Holtsbaum, W. B. (2007). Internal stray current interference from an external current source. *Materials performance, 46*(8), 40-43.

Horton, A. (1995). Corrosion effects of electrical grounding on water pipe. *Originally presented as CORROSION/91 Paper 519,* 115-134.

Hu, J., Gan, F., Triantafyllidou, S., Nguyen, C. K., & Edwards, M. (2012). Copper-Induced Metal Release from Lead Pipe into Drinking Water. *Corrosion, 68*(11), pp. 1037-1048.

Nelson, L. V. M. (1976). Frozen Water Services. *Journal - American Water Works Association, 68*(1), 12.

Nguyen, C. K., Clark, B. N., Stone, K. R., & Edwards, M. A. (2011). Role of Chloride, Sulfate, and Alkalinity on Galvanic Lead Corrosion. *Corrosion, 67*(6), 065005-065001-065005-065009. doi: 10.5006/1.3600449

O'Day, D. K. (1989). External corrosion in distribution systems. *Journal - American Water Works Association*, 45.

Rajani, B., & Kleiner, Y. (2003). Protecting Ductile-Iron Water Mains: What Protection Method Works Best for What Soil Condition? *Journal American Water Works Association, 95*(11), 110-125.

Revie, R. W., & Uhlig, H. H. (2011). *Uhlig's corrosion handbook* (3rd ed.). Hoboken, N.J.: Wiley.

Romer, A. E., & Bell, G. E. C. (2001). Causes of External Corrosion on Buried Water Mains *Pipelines 2001* (pp. 1-9).

Smart, N., Fennell, P., Rance, A., & Werme, L. (2004). *Galvanic corrosion of copper-cast iron couples in relation to the Swedish radioactive waste canister concept.* Paper presented at the Proceedings of the 2nd International Workshop on Prediction Of Long Term Corrosion Behaviour in Nuclear Waste Systems, Nice, France.

Smart, N., Rance, A., & Fennell, P. (2005). Galvanic corrosion of copper-cast iron couples: Svensk kärnbränslehantering AB, Swedish Nuclear Fuel and Waste Management Company.

Song, G., Johannesson, B., Hapugoda, S., & StJohn, D. (2004). Galvanic corrosion of magnesium alloy AZ91D in contact with an aluminium alloy, steel and zinc. *Corrosion Science, 46*(4), 955-977. doi: 10.1016/S0010-938X(03)00190-2

St. Clair, J., Stamopoulos, C., & Edwards, M. (2012). Technical Note: Increased Distance Between Galvanic Lead:Copper Pipe Connections Decreases Lead Release. *Corrosion, 68*(9), 779-783. doi: 10.5006/0745

Triantafyllidou, S., & Edwards, M. (2010). Contribution of Galvanic Corrosion to Lead in Water After Partial Lead Service Line Replacements. *Water Research Foundation. Report No. 4088.*

Triantafyllidou, S., & Edwards, M. (2011). Galvanic corrosion after simulated small-scale partial lead service line replacements. *Journal American Water Works Association 103(9), 85*.

US EPA. (2011). Science Advisory Board Evaluation of the Effectiveness of Partial Lead Service Line Replacements, EPA-SAB-11-015 Retrieved 2012/02/15, from http://yosemite.epa.gov/sab/SABPRODUCT.nsf/RSSRecentHappeningsBOARD/964CCDB94F4E6216852579190072606F/$File/EPA-SAB-11-015-unsigned.pdf

Welter, G. J. (2008). Memorandum: Non-use of Dielectric Couplings in Partial Lead Service Line Replacements. Lead Services Replacement - Joint Venture.

Zhang, Y., & Edwards, M. (2011). Zinc content in brass and its influence on lead leaching. *American Water Works Association. Journal, 103*(7), 76.

Appendix B

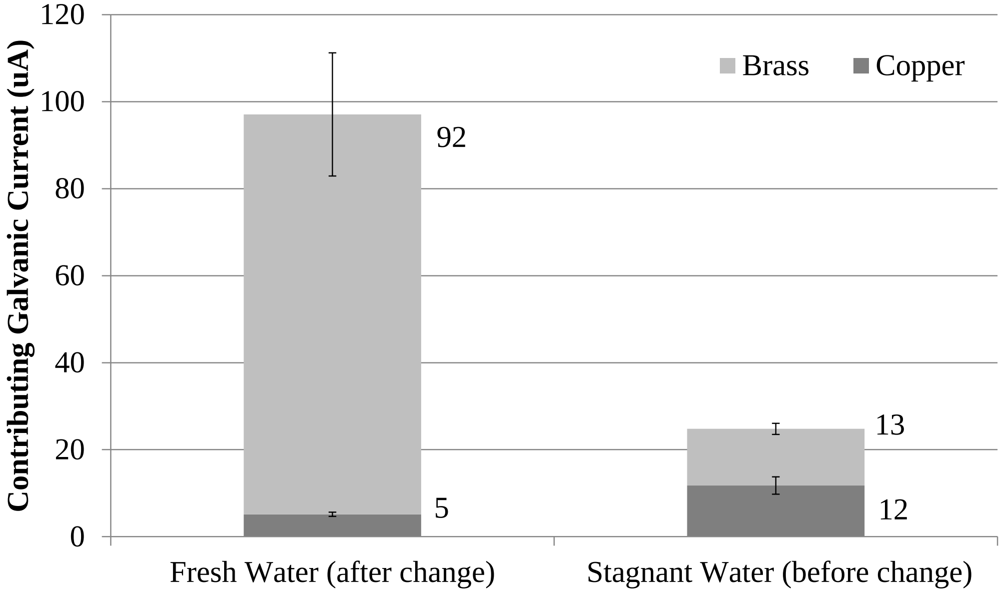

Figure B-1 Contributing galvanic current for both brass and copper under fresh water and stagnant water conditions. (Error bars indicate 95% confidence interval)

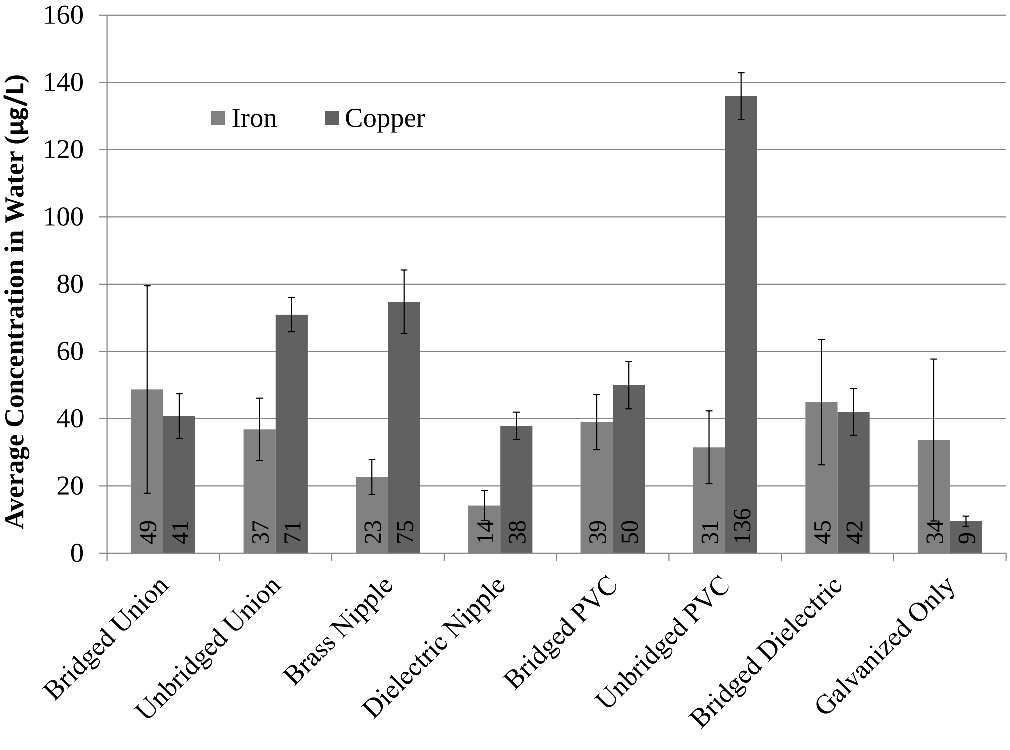

Figure B-2 Average iron and copper concentrations in water by condition. Week 1, bridged union replicate 2 and galvanized only replicate 2 are excluded. (Error bars indicate 95% confidence interval)

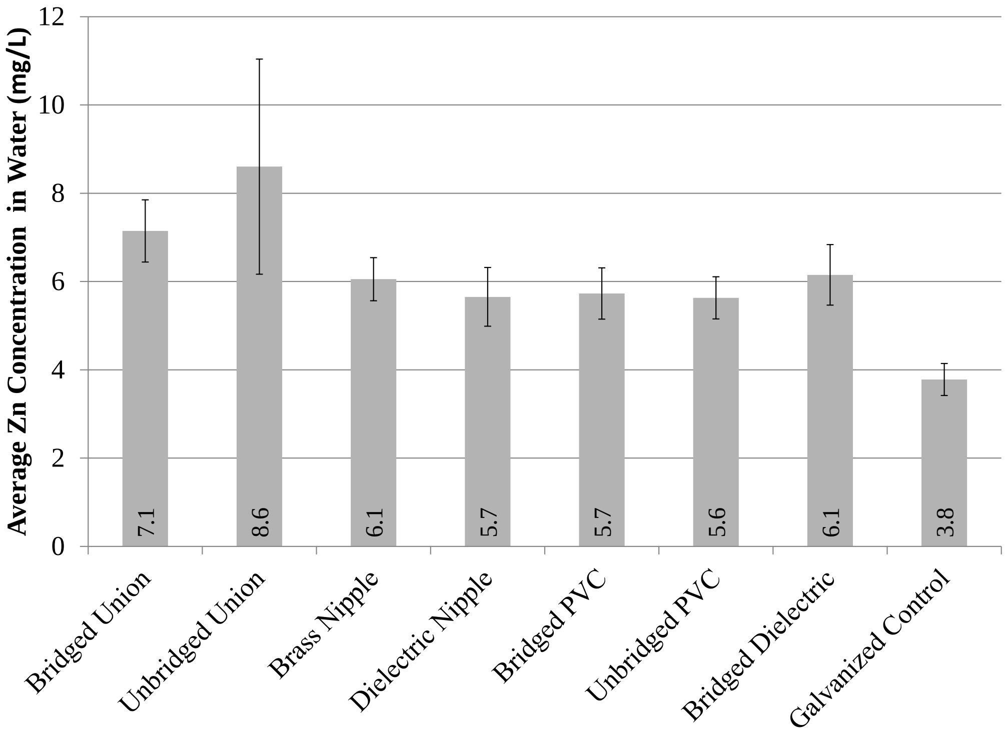

Figure B-3 Average zinc concentration in water. (Error bars indicate 95% confidence interval)

Table B-1 Galvanic corrosion currents in a hot water heater.

Component	All Components Connected	No Copper Pipe	No Sacrificial Anode Rod	Steel Tank Disconnected
Anode Rod	-1115	-1090	--	-80
Tank	1077	1090	-28.6	--
Cold Inlet – First 15.2 cm	13.1	--	13.4	41
Cold Inlet – Last 15.2 cm	1.1	--	1.1	1.1
Hot Outlet – First 15.2 cm	11.9	--	12.9	35.7
Hot Outlet – Last 15.2 cm	1.5	--	0.7	2.4
Negative values are sacrificial currents; all values are in amperes.				

CHAPTER 3: LONG TERM BEHAVIOR OF PARTIALLY REPLACED LEAD SERVICE LINES

Abstract

A pilot experiment examined impacts of copper:lead partial service line replacements without potentially confounding factors of different pipe exposure pre-history or disturbances from cutting lead pipe. Lead release was tracked from three lead service line configurations including: 1) 100% lead, 2) traditional partial replacement with 50% copper upstream of 50% lead, and 3) 50% lead upstream of 50% copper, over a period of 2.5 years as a function of flowrate, connection types and sampling methodologies. Detrimental effects from galvanic corrosion continued to worsen with time, with 140% more lead release from configurations representing traditional partial replacements at ≈ 14 months compared to earlier data in the first 8 months. Even when sampled consistently at moderate flow rate (8 LPM) and all water passing through the service line was collected, the condition representing traditional partial service line replacement was significantly worse (≈ 40%) when compared to 100% lead pipe. If sampled at high flow rate (32 LPM) and collecting 2 L samples from the service lines, lead release to service line samples of traditional partial replacement configurations had a 100% incidence at levels posing an acute health risk versus a 0% risk of such samples with 100% lead pipe. Removal of lead accumulations from lead pipe near the junction, in the copper pipe and in other plastic pipe reduced the risk of partial replacements to that observed for 100% lead. When typical brass compression couplings were used to connect pre-passivated lead pipes, lead release spiked up to 10 times higher, confirming concerns raised at bench scale regarding adverse impacts of crevices on lead release. Whole house filters show promise in quantifying semi-random particulate lead release from service lines in the field versus other methodologies.

1 Introduction

The Environmental Protection Agency's (EPA) Lead and Copper Rule (LCR) was implemented to minimize lead and copper exposure from drinking water; however, there is growing concern that certain remedial actions intended to reduce consumer lead exposure may not always be effective, and in fact may actually increase exposure (Britton & Richards, 1981; Muylwyk et al., 2011; Swertfeger et al., 2008; Swertfeger et al., 2011; US EPA, 1991, 2011). Specifically, when utilities partially replace lead service lines with copper pipe, either in response to requirements of the LCR or voluntarily, galvanic corrosion between the lead and newly installed copper and brass connectors can increase lead corrosion rates, which can either cancel or reverse anticipated benefits of having less lead pipe (Cartier et al., 2012a; Triantafyllidou & Edwards, 2010, 2011).

A range of factors are suspected to influence the extent of galvanic corrosion between copper and lead including flowrate, connector type, deposition corrosion, lead surface passivation, relative position of lead versus copper pipe, presence of crevices, and corrosivity of water (Cartier et al., 2012a; Cartier et al., 2012b; Clark et al., 2012a; Hu et al., 2012; Triantafyllidou & Edwards, 2010; US EPA, 2011; Wang et al., 2012; Xie & Giammar, 2011). The duration of the adverse galvanic effects is extremely important as early practical work suggested that such impacts could be sustained for years or decades (Britton & Richards, 1981), but recent reports by EPA and others speculated that such effects would be insignificant and sustained only for days to weeks (Boyd et al., 2012; National Drinking Water Advisory Council, 2011; Reiber & Dufresne, 2006; US EPA, 2011). The most recent studies that rigorously examined the issue at bench or pilot scale using techniques quantifying all lead release over time periods of 6 weeks to 8 months, concluded that problems with elevated lead from galvanic corrosion and partial replacements were sustained over the entire duration of the experiments (Cartier et al., 2012a; Cartier et al., 2012b; Doré et al., 2012; Triantafyllidou & Edwards, 2011; Wang et al., 2012).

The detection of elevated lead problems from galvanic corrosion has been complicated by differing trends as a function of flow rate. If samples are collected at low flow, lead particulates and sediments are not mobilized, which can hinder detection of massive deposits of lead scale created at the lead:copper pipe connection due to galvanic corrosion (Cartier et al., 2012a; Deshommes et al., 2010; Triantafyllidou & Edwards, 2011). Samples collected at moderate (8 LPM) and higher flow rates (32 LPM) revealed sporadic detachment of lead particulates at levels posing an acute health risk from partially replaced lead pipes (Cartier et al., 2012a). The latter observation could explain why higher incidence of elevated blood lead in children was reported in homes with partial pipe replacements versus undisturbed lead service lines (Brown & Margolis, 2012), even when routine sampling of these homes did not detect serious problems (Giani, 2008; Giani et al., 2004). Sampling methods are needed that are capable of detecting semi-random release of lead particulates which can pose an acute health risk to consumers (McNeill & Edwards, 2004; Triantafyllidou et al., 2007).

Other factors have been speculated to play a role in service line corrosion and galvanic impacts arising from lead:copper connections. For instance, copper and lead pipe sections are cathodic to iron water mains, which implies that lead connections to unlined iron might be somewhat protected from corrosion (Clark et al., 2012a). This is consistent with other field evidence suggesting that iron mains cathodically protect copper service lines when they are directly connected in the distribution system (Gehring et al., 2003; Rajani & Kleiner, 2003). It is hypothetically possible that an iron main coupled to a lead service line could provide cathodic protection to the lead, or possibly, eliminate galvanic corrosion of the lead in a partial pipe replacement if unlined iron mains are present. If this protection was significant, replacement of unlined iron mains with either new lined pipes or plastic, as occurs routinely with infrastructure upgrades, might produce increased corrosion. There are no laboratory studies refuting or supporting these effects. Also, prior bench-scale research by Arnold and Edwards (2012) suggested that partially replaced lead pipes can create much more serious problems with lead contamination of water during prolonged stagnation events when compared to a situation with a 100% lead pipe.

The goal of the current work is to 1) extend the 8 month study of Cartier et al. (2012a) on duration of galvanic impacts to a time period of 2.5 years, 2) better define the nature and causes for elevated lead release after partial pipe replacements, 3) examine galvanic impacts on pre--passivated lead pipes using “real” brass connectors, 4) evaluate the strengths/weaknesses of sampling protocols that could detect public health concerns arising from partial pipe replacements, 5) conduct preliminary analysis of unlined iron main impacts on corrosion of service lines, and 6) determine how prolonged stagnation periods influence lead release.

2 Materials & Methods

2.1 Experimental Design

The pilot is that described by Cartier et al. (2012a) using relatively non-corrosive Blacksburg tap water, extending the previously reported results from 8 months to a total time of 31 months of operation. Three configurations representing a full lead service line (100% Pb), a PLSLR with lead downstream of copper (Pb-D; 50% Cu and 50% Pb), and a PLSLR with lead upstream of copper (Pb-U; 50% Pb and 50% Cu) were tested in triplicate. A 100% copper control was also tested. Four phases of research tested three different sampling methods (Table 3-1). During all test phases, galvanic corrosion currents were continually measured by a zero-resistance ammeter using a GAMRY Potentiostat.

Table 3-1 Experimental Phases.

Phase	**Time Period (months during experiment)**	**Experimental Change From Cartier et al. (2012a)**	**Sampling Method**
A	13-14	No Change	Same as Cartier et al. (2012a), First 2 L draw and grab samples
B-1	15-17	Consistent 8-9 LPM flowrate	Collection of all water passing through pipes
B-2	17-18	Removed 4" coupons	
B-3	19-22	Replaced copper piping	
C	22-25	Installed Connectors	Collection of all water passing through pipes
D	26-27	Prolonged Stagnation Events	First 2 L draw
E	28-31	Increased flowrate (~18-20 LPM)	Filters

Phase A – The pilot was operated and sampled like that described by Cartier et al. (2012a) during months 13-14 including low, moderate, and high flowrates; whereas from months 8-13, the pilot operated at low flow and was not sampled. A first draw, 2 L, sample was collected after 16 hour stagnation periods for all three flow rates. After the flushing events, filtered samples were immediately collected from the 2 L sample to quantify soluble lead using a 0.45 micron filter. Thereafter, the 2 L first draw and filtered sample were acidified with nitric acid to a concentration of 2% v/v and allowed to digest for a minimum of five days before analysis using ICP-MS.

Phase B – From months 15-22, consistent flow rates emulating a household faucet (8-9 LPM) were tested, in contrast to the earlier work in which flow rates were generally 1.3 LPM in months 0-15. Daily composites of all water flowing through the pipes from three flow events per day (2 minutes of flow after 8 hours stagnation) were collected in separate bins for each replicate (48 L total per rig). On Mondays, the composite included a flow event after a 54 hour weekend stagnation period. Sample aliquots from each unacidified bin were collected after rigorously stirring the bins to mobilize any particulates; QA/QC by decanting the top fraction and acidification of the remaining 2 L demonstrated that this approach did not systematically under-quantify particulate lead (< 10% error).

To evaluate how accumulations of lead deposits (i.e., reservoirs in the plumbing including lead scale on pipe at the copper junction, or walls of copper and downstream plastic plumbing that might have been coated with lead) were contributing to lead release, the reservoirs were systematically removed and replaced from the system. Specifically, after 17 months (492 days) the lead with heavy galvanic corrosion products at the copper junction was removed, the rigs were then sampled during months 17-18 (days 493-524). Thereafter, in both the Pb-U and Pb-D replicates, the old copper pipes were replaced with new copper during month 19 (day 560) and sampled for lead release during months 21-22 (days 623-643) and the rig was sampled for lead release.

The mass of lead deposits in each of the above sections was quantified. Easily removed lead rust was cleaned from the lead coupons and total lead mass and weight loss was calculated. Copper pipe sections were filled with deaerated 10% hydrochloric acid to dissolve most of the lead that remained on the copper pipe sections. Finally, the plastic plumbing downstream of the metal pipe sections were acid cleaned and the mass of lead was quantified.

Phase C – This portion of the research explored how new brass connectors might enhance lead leaching from passivated lead service lines via galvanic corrosion without any pipe cutting. Three types of connections representing extremes encountered in practice were tested including a brass compression fitting, copper sleeve (which has crevices similar to compression fitting, but made of copper only and thus presents no potential for lead contamination), and the existing, clear plastic tubing connection with small dielectric spacer. A baseline for lead release was established for each of the pipe rigs during the final stage of Phase B. On the basis of the baseline results, the pipe with the highest lead release remained connected as before with plastic tubing. The pipe with the lowest baseline lead release was connected using a copper sleeve, and the pipe with the middle level of lead release was connected using a brass compression fitting (same corporation valve as Clark et al., 2012a). From months 22-25, all water flowing from each rig was collected in bins from each condition and sampled as per Phase B.

Phase D – During months 26-27 the rigs underwent two, one-month long stagnation events. The prolonged stagnation events represented conditions with seasonal water use with long periods of little to no flow. After each stagnation event, a 2 L first draw was collected from each rig at a flowrate of 15 LPM during a 5 minute flow event. The 2 L samples were acidified and analyzed as described previously.

Phase E – After extensive bin sampling during Phase C, whole-house filters (polypropylene, 1 micron), used to filter water at the point of entry, were installed downstream of the various rigs to collect and quantify lead release. Three times per day, rigs were flushed at 18-20 LPM for 5 minutes to achieve a total daily volume of ~300 L per rig; during this phase flow events continued over weekend periods with no 54 hr stagnation event. Filters were allowed to collect lead for a total of 37 days. Thereafter, filter housings and cartridges were removed and acidified with nitric acid to a concentration of 5% v/v. Sample aliquots were taken after 120 hours digestion and analyzed via ICP-MS.

2.2 Exploring concerns related to unlined iron main connections to service line

A small 10.2 cm lead pipe section was coupled to a 305 cm galvanized iron pipe section via varying lengths of copper pipe ranging from 2.5 to 305 cm copper using clear plastic tubing; a control condition consisted of the lead and galvanized iron (no copper in between) connected by the plastic tubing. The apparatus was filled with Blacksburg water (described elsewhere), and the sacrificial galvanic currents to the lead were measured using a handheld multimeter. Then the experiment was repeated with varied lengths of copper pipe. Testing demonstrated that a zero resistance ammeter and the multimeter gave equivalent results to within +/- 5%.

Another short term experiment briefly connected 3 m of galvanized iron to the first section of the pilot in the flow sequence. Each rig was filled with water and the galvanic current sacrificing the lead was quantified.

3 Results & Discussion

The six experimental objectives of the work are addressed sequentially in the sections that follow.

3.1 Phase A - Low, Moderate, High Flow Sampling

Trends in lead release through 9-14 months mirrored those obtained during the 8 month pilot by Cartier et al. (2012a), confirming that serious water contamination problems arising from galvanic connections can persist for years as suggested by earlier field sampling (Britton & Richards, 1981). Lead release increased for samples collected at higher flowrate for all three conditions (100% Pb, Pb-U, and Pb-D), but the worst case was that created during partial replacement with lead pipe after copper pipe in the flow sequence, as would be the case in PLSLRs (Pb-D rigs; Figure 3-1). Specifically, at low flow rates over this time period, average lead concentrations were not statistically different amongst the difference service line configurations, but at moderate and high flowrate sampling the condition with Pb-D vs 100% full lead pipe was 7 and 26 times higher, respectively ($p < 0.05$). Filtered samples were analyzed to determine the soluble fraction of lead in the first 2 L flush (Figure 3-1). During low flow, a major fraction of lead was soluble (70-80%) for all conditions. As flowrate increased particulate lead became the dominant fraction of lead released (e.g., at high flow, soluble lead <5% of the total lead in both the Pb-U and Pb-D conditions).

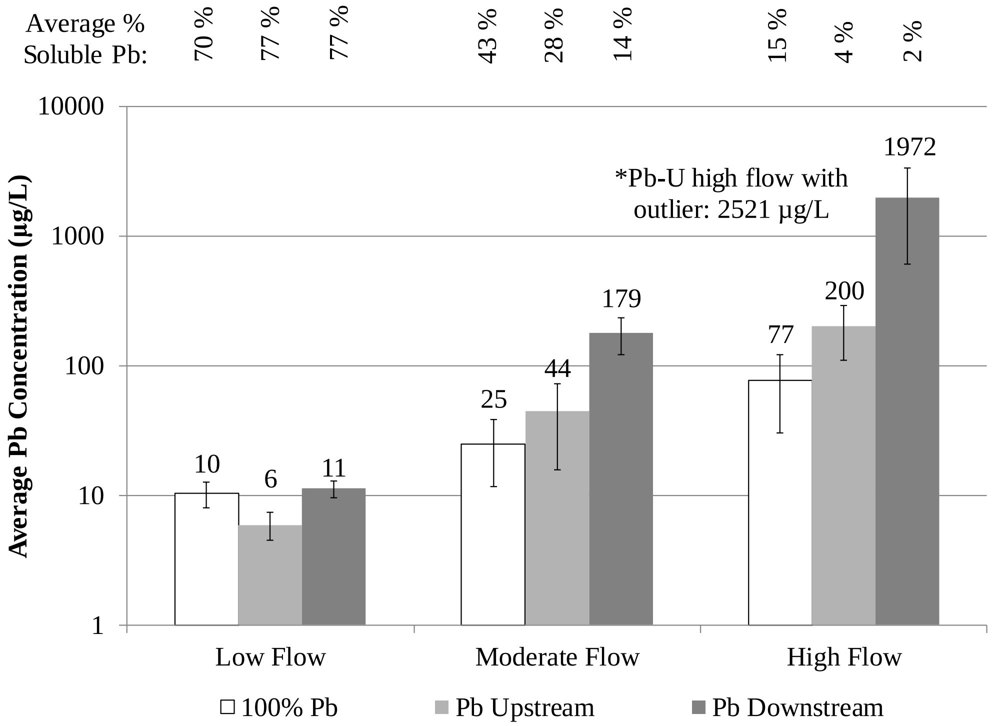

Figure 3-1 Average lead concentration in water after 14 months from three sampling periods as described by Cartier et al. (2012a) with average soluble lead percentage in samples. Error bars represent 95% confidence interval. *High flowrate, Pb-U condition excludes high outlier of 20,090 µg/L.

Comparison of these results to those of Cartier et al. (2012a) obtained earlier in the study: at high flowrate lead release decreased 68% (240 µg/L to 77 µg/L) for 100% Pb and 52 % for Pb-U (416 µg/L to 200 µg/L) at the higher pipe age. Conversely, for Pb-D, lead release ***increased*** 135 % (839 µg/L to 1972 µg/L) during months 13-14 compared to the first 8 months of the pilot.

This is unambiguous data indicating that the problems of partial replacements do not necessarily ameliorate with time, but can actually worsen.

At low flow, only one sample (11%) from the service line for the condition with 100% Pb and Pb-D exceed the action level of 15 μg/L; while at high flow, 100% of samples exceeded the 15 ppb EPA action level (Figure 3-2). Moreover, lead concentrations in 100% of samples collected from the Pb-D service line at high flow even exceeded acute health risk standards of > 700 ug/L per treatment of Cartier et al. (2012a), whereas only 11% of Pb-U or 0% of full-lead pipe samples exceeded this threshold (Figure 3-2). This result affirms the veracity of warnings to avoid placing copper in front of lead in the flow path sequence (Breach et al., 1991; Britton & Richards, 1981; Cartier et al., 2012a; Clark et al., 2011; Copper Development Association, 1999; Triantafyllidou & Edwards, 2010, 2011).

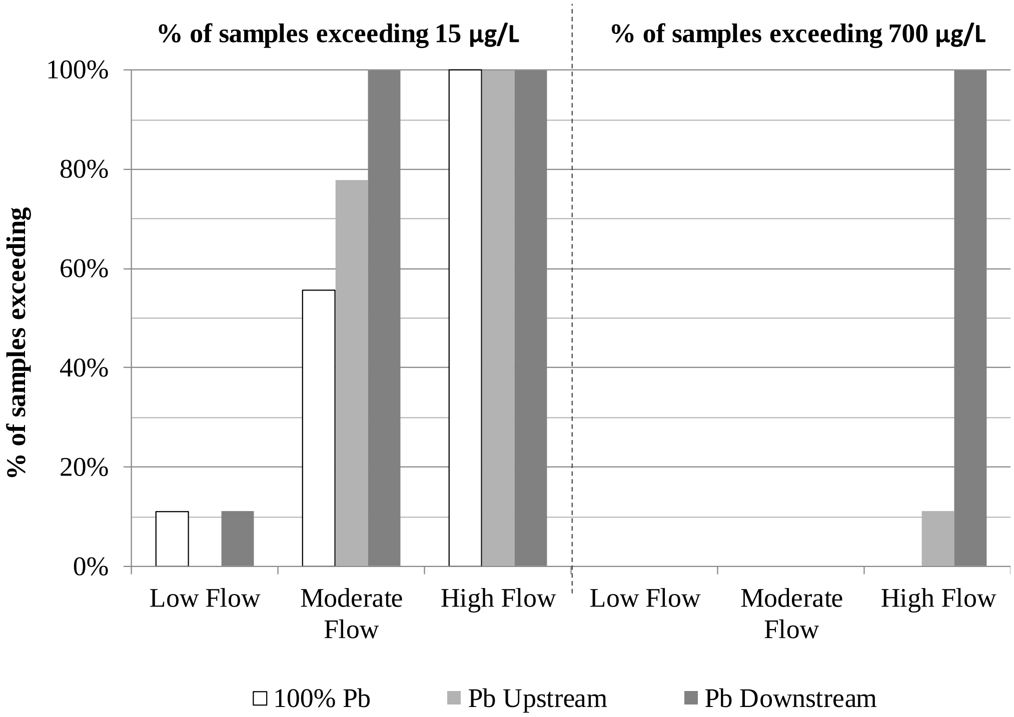

Figure 3-2 Percentage of first 2 L service line samples exceeding 15 μg/L (LCR action level) and 700 μg/L (acute health risk level) during Phase A – Low, Moderate, High Flow Sampling.

3.2 Phase B - Consistent Moderate Flow Sampling

It was hypothesized that detriments of partial replacements and galvanic corrosion might disappear if flow rates were maintained at very consistent levels and all water from the rig was collected. During the first 8 weeks of sampling with flow at 8 LPM and collecting all the water, the concentration of lead was not statistically different for conditions representing 100% Pb pipe or if a lead service line was followed by copper (Figure 3-3). However, the typical partial replacement conducted by utilities with copper upstream of lead (Pb-D) was 40% worse than the 100% Pb condition (100% Pb: 4.3 ppb, Pb-D: 6.0 ppb, $p< 0.05$). Thus, even considering a relatively large dilution effect from collecting all the water, and changes in flow rate that might tend to create spikes of lead particulates, typical partial replacements (Pb-D) were statistically worse than an intact lead service line with twice the lead pipe surface area.

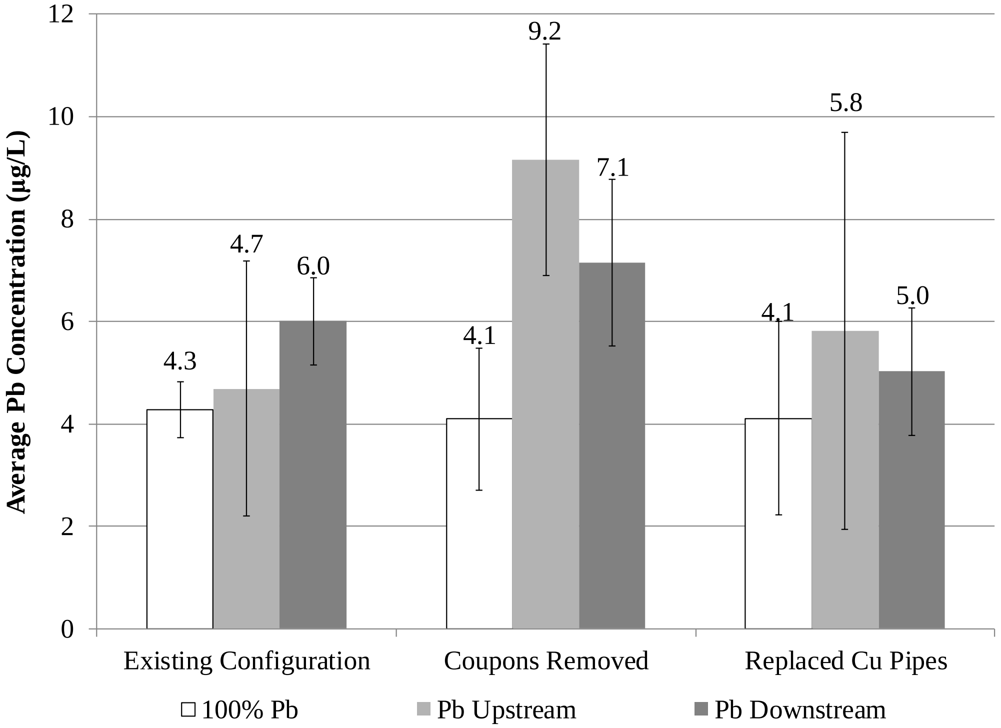

Figure 3-3 Average Pb release during the various stages of Phase B. Error bars represent 95% confidence interval (data from replicated pooled for each individual condition).

3.3 Lead Reservoirs

Elevated galvanic currents are expected to contribute to a reservoir of lead in the pipe rigs and especially in the junction between lead and copper (Cartier et al., 2012a; Triantafyllidou & Edwards, 2011). The mounds of lead corrosion products at the lead:copper junction became more prominent as the study progressed (Figure C-1). However, lead reservoirs might also accumulate on other surfaces in the rigs (copper, plastic pipe downstream of the metal pipe), similar to prior observations made in homes with galvanized iron installed downstream of lead service lines (HDR Engineering Inc., 2009). The potential contribution from these reservoirs to elevated lead in water was examined sequentially.

After the 10 cm segments of lead pipe immediately adjacent to the copper pipe (with the mounded lead rust) were completely removed from the rig, the Pb-D condition remained 48% higher than the 100% Pb condition (Figure 3-3; $p > 0.05$), and the Pb-U condition was 125% higher than the 100% Pb condition ($p < 0.05$). Clearly, removal of the section of lead with visible mounded corrosion products immediately adjacent to the copper, by itself, did not temporarily eliminate the long-term problems of galvanic connections.

After the existing copper and plastic piping was also replaced, lead release was not statistically different amongst the three conditions (Figure 3-3). Hence, removal of all three possible reservoirs of particulate lead (lead junction, copper pipe, plastic pipe) finally produced a situation in which conditions with 50% lead pipe was at least temporarily not worse than 100% lead pipe . This restored the rig to relative performances noted in the earliest phases (months 1-3) of the study (Cartier et al., 2012a), before massive reservoirs of lead had accumulated in the rig. Replacing the old passivated copper pipe with new copper pipe, did not worsen the galvanic corrosion currents (comparing coupons removed to Cu replaced in Figure 3-6).

Quantification of the mass of lead rust accumulation on the different parts of the plumbing system was revelatory and consistent with previously defined trends for lead release. Visually, a larger accumulation of lead rust was present on the lead surface nearest to the galvanic junction in the PLSLR conditions, whereas there was little or no accumulation on the lead pipe surface of the 100% Pb rigs (Figure 3-4). When rust was later gently removed from all the pipe surfaces and weighed (Figure 3-5), the Pb-D and Pb-U conditions had much more lead accumulation than the 100% Pb condition. Mass recovered in the conditions with galvanic corrosion was markedly greater than the 100% Pb replicates (Pb-U: 2.4 times higher, Pb-D: 3.5 times higher). This verifies the concerns originally expressed by Triantafyllidou and Edwards (2011) regarding galvanically-induced accumulations of lead deposits, and provides mechanistic support for the observation that the galvanic sections had a greater mass of lead mobilized at higher flow.

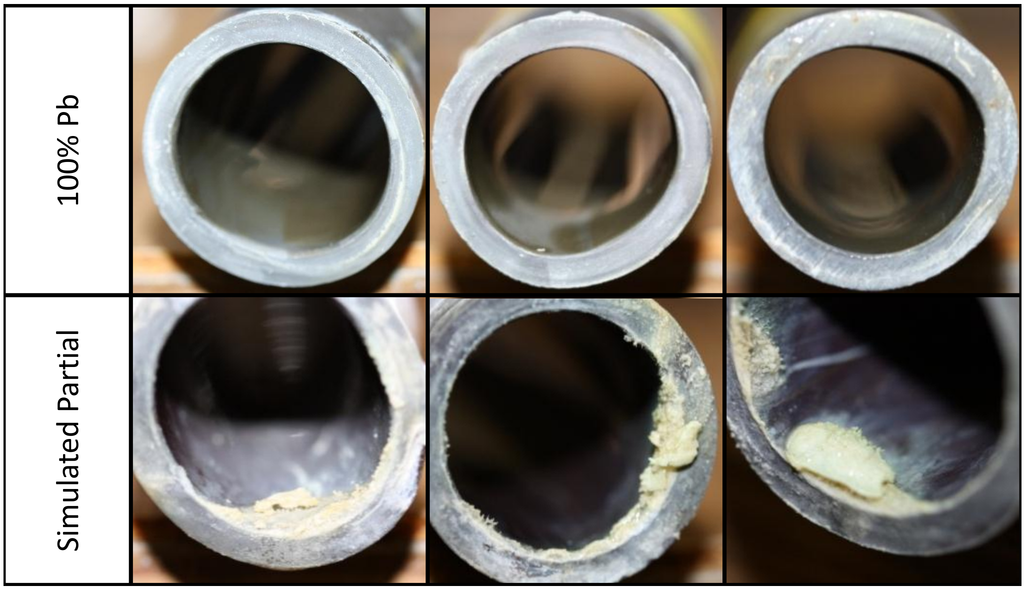

Figure 3-4 – Visual comparison of lead rust buildup on pipe coupons with and without galvanic corrosion after 17 months of experiment. Large mounds of rust from partials were localized at the end closest to the Cu:Pb junction.

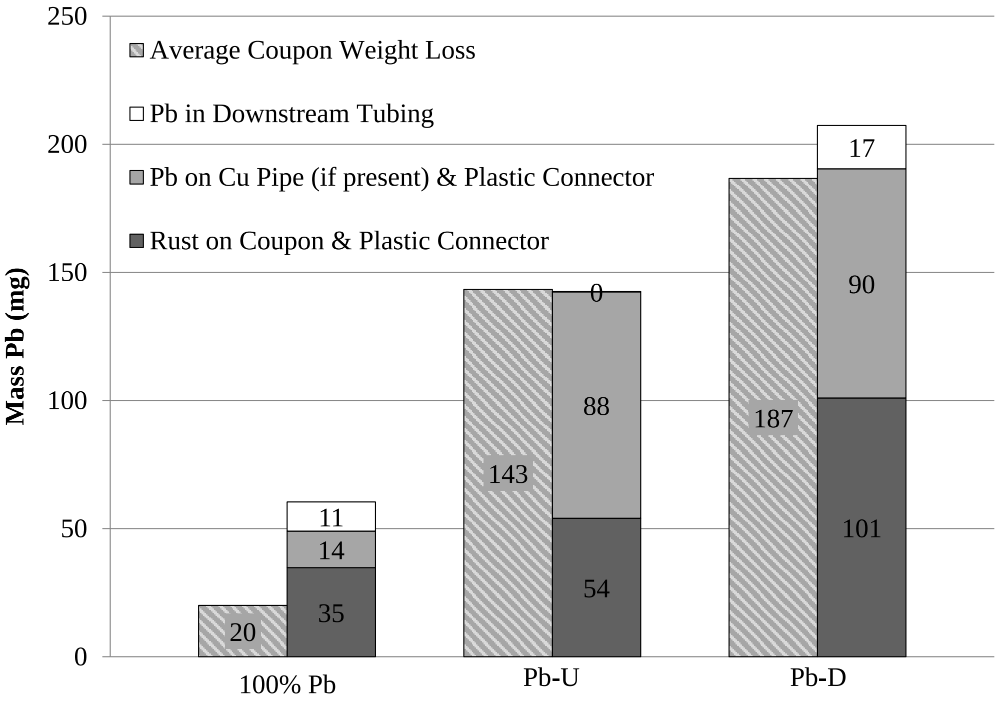

Figure 3-5 Average weight loss from 10 cm lead sections (coupons) and average mass of lead recovered from individual reservoirs for each condition.

3.4 Galvanic Corrosion Current

In theory, as long as galvanic corrosion currents persist between lead and copper, problems with sporadic and elevated lead can also persist, and expected benefits of having a 50% lower lead surface area may not be fully realized. Galvanic currents remained elevated throughout the entire 31 months of the study, but eventually decreased somewhat relative to levels observed during the first year (Figure 3-6). Removing the lead coupons or replacing the old copper with new copper pipe did not result in an increase of galvanic current. From initial experimental conditions to the final stage of Phase B (months 20-22), galvanic currents decreased 35-50% over the nearly two year period. Pb-U galvanic corrosion current decreased from 25 µA to 20 µA after the first year and decreased further to 16 µA after 22 months. The Pb-D galvanic current decreased from 29 µA to 19 µA in the first year and then to 14 µA after 22 months.

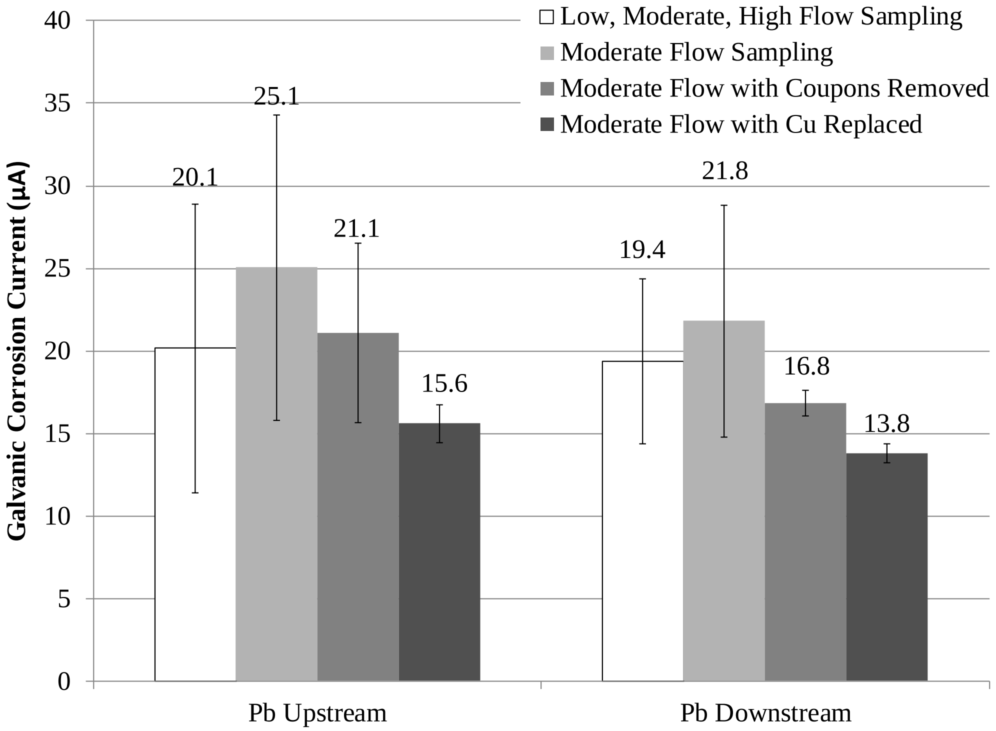

Figure 3-6 Galvanic corrosion currents during Phase A and Phase B. Pb-U and Pb-D averages and 95% confidence intervals calculated from average current of individual triplicates from each condition.

Weight loss of the short Pb pipe sections should be at least that calculated by Faraday's Law and the integrated sacrificial current (Figure 3-7). In this work, Faraday's Law over estimated actual weight loss by a factor of 4-5, however it is clear that there was a greater weight loss with higher galvanic current (Figure 3-5) compared to the condition with 100% lead and no galvanic current. Additionally, galvanic current for Pb-U was generally higher than Pb-D ($p > 0.05$), but average weight loss was greatest for Pb-D (Figure 3-5). This might be due to deposition corrosion or other mechanisms of increased lead leaching after exposure to copper ions in flow (Hu et al., 2012), and the ratio of copper to lead in the scale did increase for cases with partial replacements (Figure 3-8). The discrepancy between actual weight loss and the minimum predicted by Faraday's law, might be due to 1) any of the sacrificial galvanic current from copper that passed to the larger section of lead pipe, 2) failure to remove all the lead deposits from the gentle abrasion used herein, or 3) presence of reactions other than lead oxidation contributing to galvanic corrosion currents.

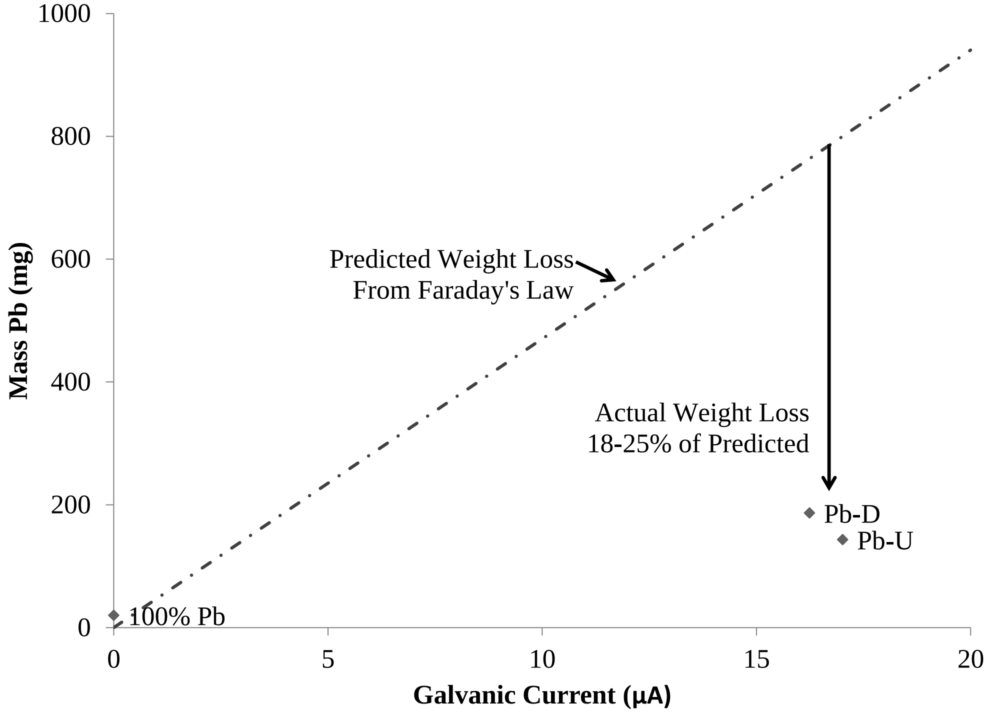

Figure 3-7 Average weight loss versus average sacrificial current of 10 cm Pb coupon located immediately adjacent to copper pipe, vs. the estimated weight loss calculated by Faraday's Law.

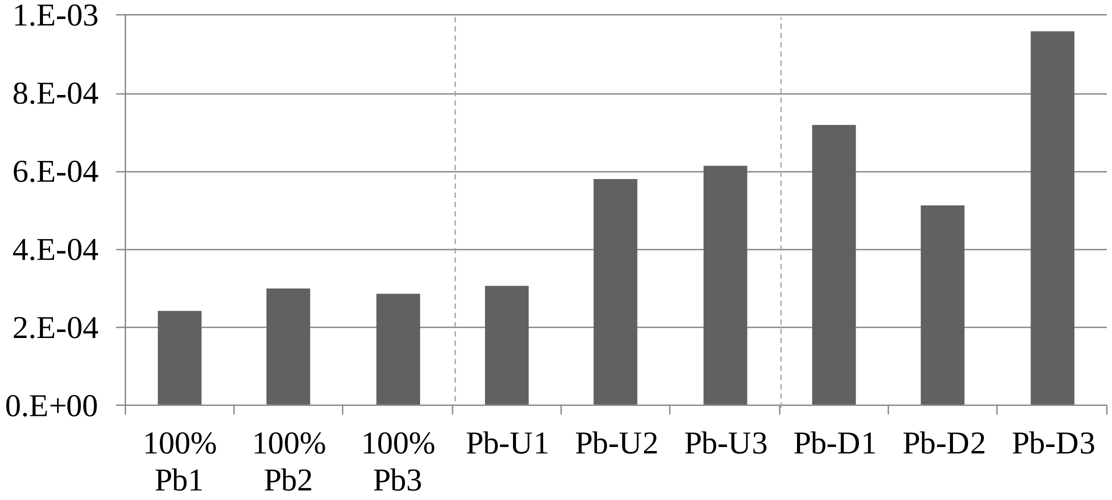

Figure 3-8 Mass ratio of Copper/Lead in rust removed from short Pb sections

3.5 Phase C - Influence of Connectors

Many different types of brass devices can be used to connect lead to copper pipe, and it has recently been demonstrated that certain brass devices with crevices can have a high propensity to cause much worse elevated lead in water than direct connections between lead and copper pipe (Cartier et al., 2012b; Clark et al., 2012a). Others have speculated that connection of well passivated lead to copper or brass will not create significant problems with elevated lead in water (Reiber & Dufresne, 2006). These issues were tested for the lead pipe pre-passivated for 2 years in this research and with no freshly cut lead surfaces present.

Before the brass or copper connections were made, there was no statistical difference in the average concentration of total lead in water between each replicate during the initial 3 week baseline experiment without brass connectors (last 3 weeks of Phase B; 100% Pb = 4.1 ppb, Pb-U = 5.8 ppb, Pb-D = 5.0 ppb). After installation of a commercially available brass device with crevices or a copper sleeve (to simulate brass without lead), lead release for the control conditions (existing plastic connector) decreased, but the lead concentrations for the copper sleeve increased significantly by 3.7 times (Figure 3-9, $p < 0.05$). Lead release from the 100% Pb rig coupled with a brass compression connector increased 10 fold ($p < 0.05$), and the Pb- U and Pb-D rigs with brass connectors increased significantly by 6.2 times and 3 times ($p < 0.05$), respectively.

The galvanic corrosion current sacrificing the lead pipe, increased by 215 and 357%, for the conditions connected with the copper sleeve or brass compression fitting, respectively (Figure 3-10; galvanic current is zero for 100% Pb conditions when connected with the plastic tubing). The higher galvanic current compared to the prior situation where lead pipe was connected to copper with a plastic connector and 0.3 cm distance, is likely due to 1) changing the separation distance between lead and copper, 2) adding a third metal such as brass, and 3) creating crevices, as illustrated by Clark et al. (2012a). Across all conditions, the sacrificial galvanic current of the lead pipe (via connection to brass or copper) strongly correlated to lead release (Figure 3-11).

Interestingly, the "worst case condition" of lead release and galvanic corrosion, occurred when two lead pipes were connected via a brass connector (Figure 3-9). While the magnitude of this effect was initially surprising, in retrospect it is easily explained by the fact that this condition creates two lead:copper alloy junctions and crevices. Lead release increased sharply (14-19 times higher) for the two 100% Pb conditions with brass or copper connectors immediately after connection (Figure 3-12). Lead in water for the copper sleeve connection returned to levels slightly above the plastic connector at the end of the sampling period while lead release from the brass compression connector remained elevated. This finding further confirms prior research results in experiments using lead pipe connected to copper pipe are conservative in terms of galvanic impacts on lead release relative to "real world" connectors (Edwards, 2012). Clearly, well-passivated lead pipe connected to copper pipe via commercial brass connectors can sometimes create severe lead contamination from galvanic corrosion, consistent with other recent work using harvested lead pipe that had been exposed for decades in distribution systems (Cartier et al., 2012b; Wang et al., 2012).

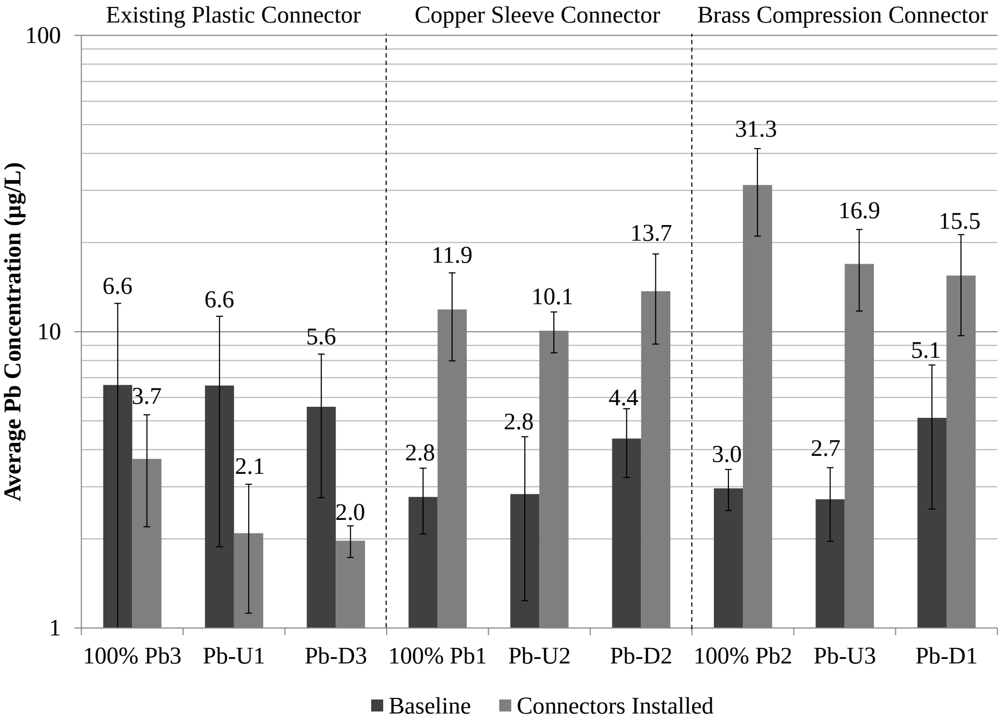

Figure 3-9 Average Pb concentration in water during baseline period and after installing connectors. Error bars represent 95% confidence interval. High outlier excluded from Pb-U3 baseline.

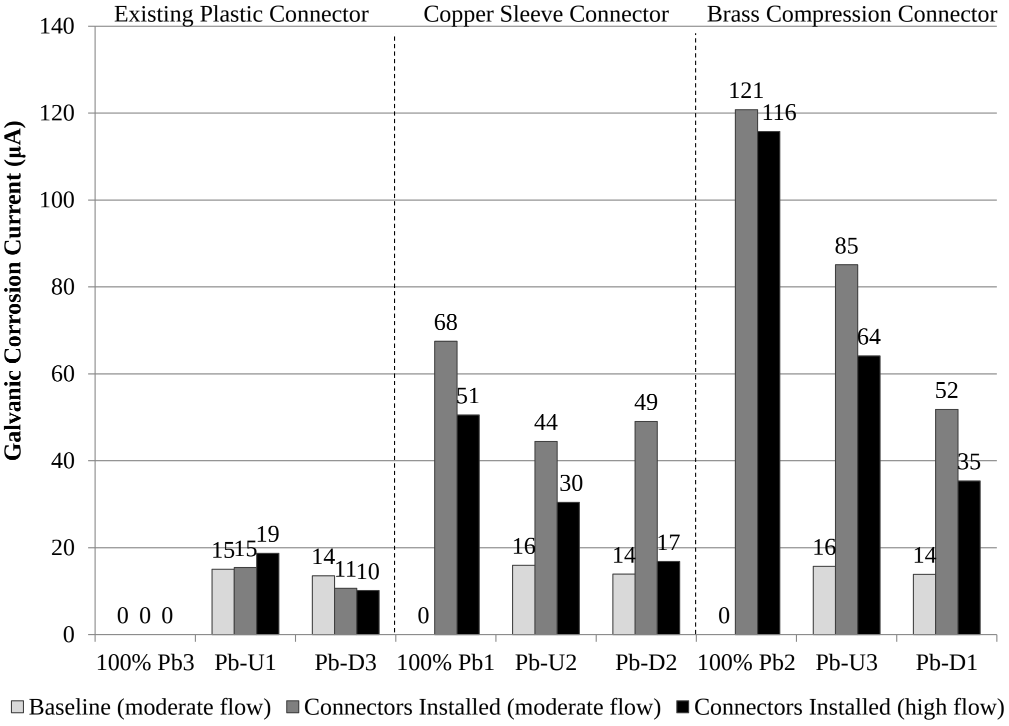

Figure 3-10 Galvanic corrosion currents before and after installing connectors and Phase E.

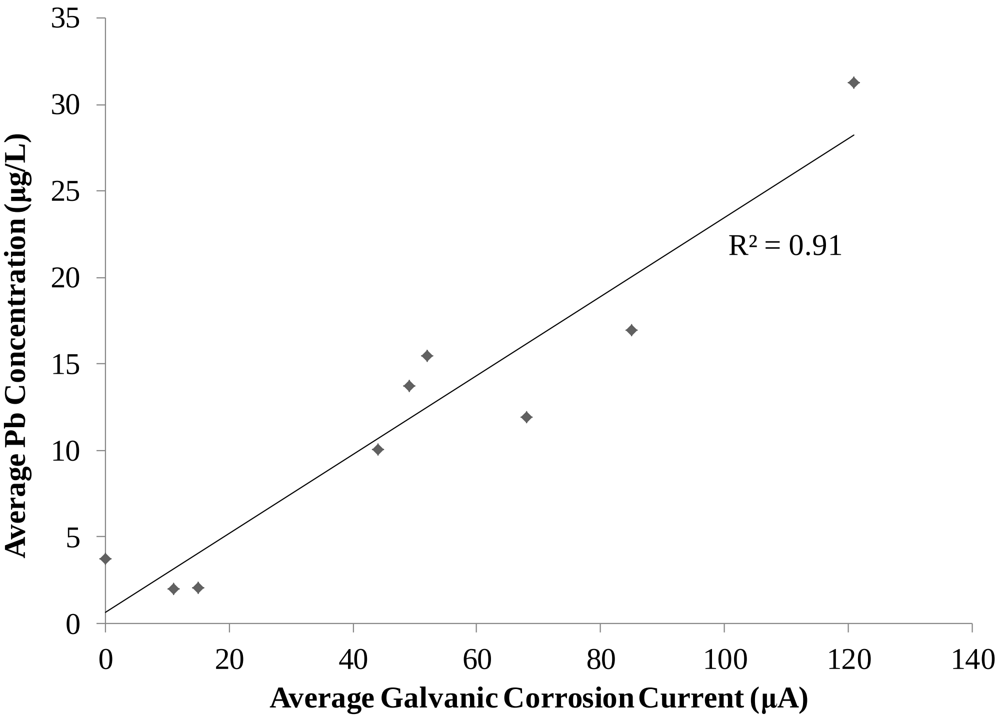

Figure 3-11 Average Pb in water versus average galvanic current with connectors installed.

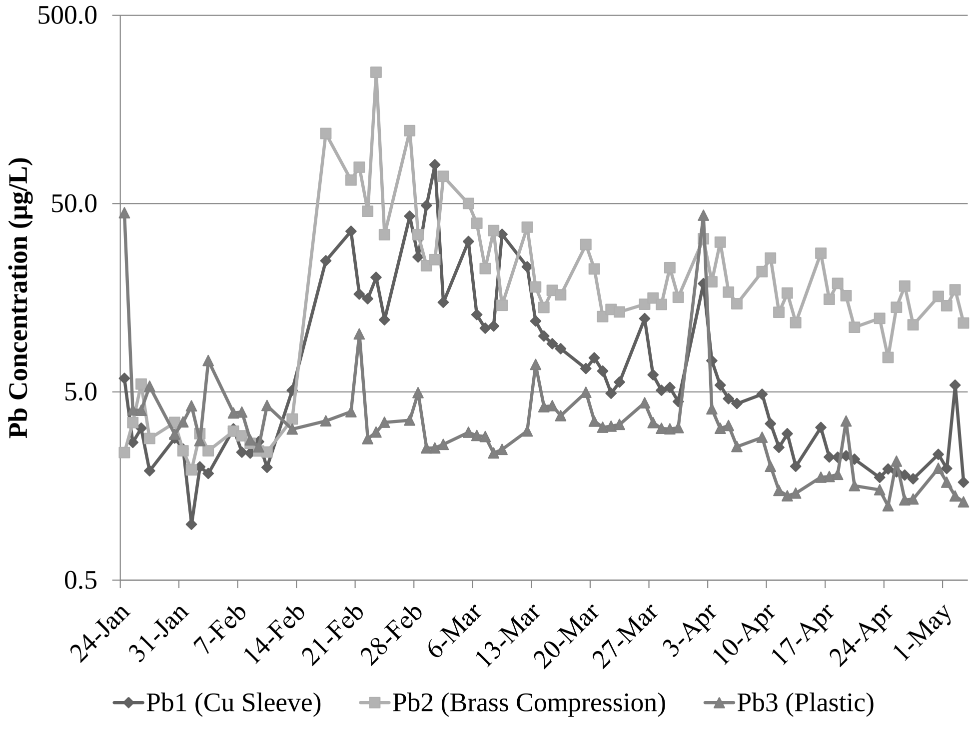

Figure 3-12 Lead in water for 100% Pb conditions with connectors installed for duration of Phase C.

3.6 Phase E - Detecting Problems with Particulate Lead using Filters and Synthesis of Sampling Methods

Filters were installed downstream of the various conditions and allowed to collect lead for 37 days while operating the rig at a relatively high flowrate (18-20 LPM) for short periods of time (separated by long periods of stagnation). With the exception of two conditions, the daily mass collected on the filters correlated strongly with prior data in which all the flow was collected in bins the prior 5 weeks and at a lower flowrate (Figure 3-13). Thus, it seems that whole house filters have promise in detecting problems arising from particulate lead release from service lines in real systems. Galvanic currents decreased slightly (~20%) during this phase. This decrease could be explained by the passivation of the lead pipe from the initial increased galvanic corrosion rates, and might explain the outlier data points (Figure 3-13).

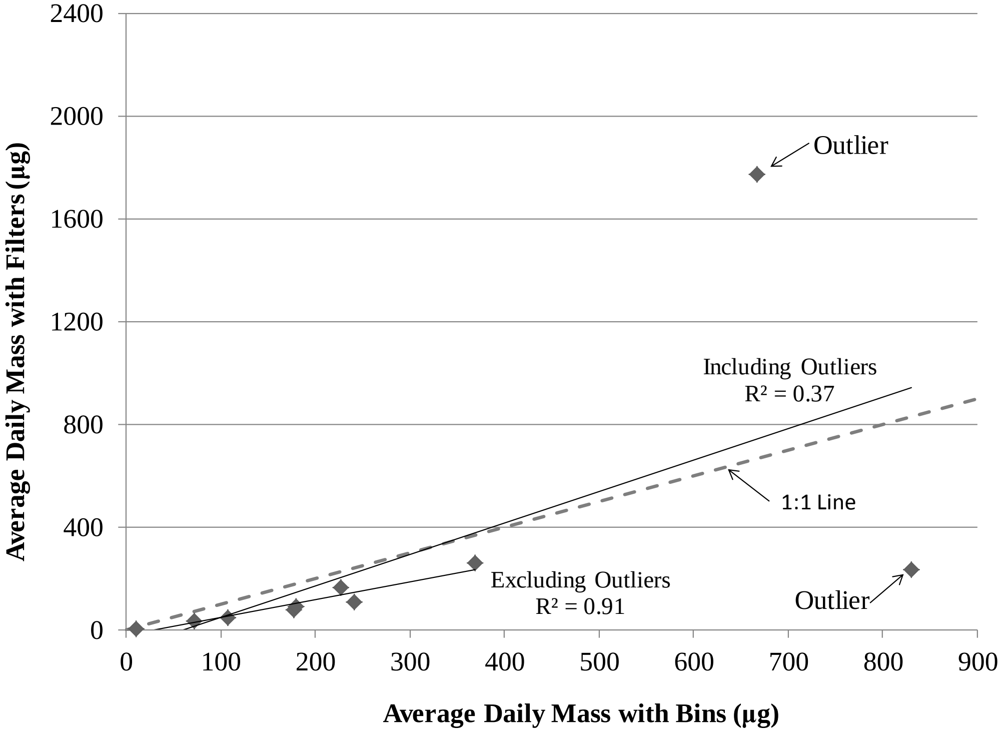

Figure 3-13 Daily Pb release collected by filters versus average daily release collected by bins from last 5 weeks of Phase C (same duration as collection using filters).

The array of sampling methods used in this work to detect health risks to consumers arising from sporadic particulate lead release from service lines had potential benefits and drawbacks (Table 3-2). Profiling at high or low flow is a useful tool to quantify lead release, but large numbers of samples must be collected at a range of flow rates to quantify the nature of particulate lead release, and it is always possible that a propensity for very large spikes in water lead might be missed (Cartier et al., 2012a; Clark et al., 2012b). Collecting a few grab samples (e.g., second draw) is even more prone to missing semi-random release of particulate lead. Proportional samplers can be used to collect fractions of total daily flow (van den Hoven, 2006); however, conventional designs may systematically "miss" larger lead particulates as the momentum of particles carries them past small side stream sample collecting ports. Conversely, it can be expected that other designs may concentrate lead particulates in water.

A definitive approach used in this research, via collecting and sampling all the water passing through the service line over a period of weeks and which could not miss sporadic lead spikes, is obviously not practical in consumer homes. However, if the whole house filters capture particulate lead (the dominant fraction of lead released), filters can detect problems from service lines in a single sample (the filter), improve the quality of consumed water via removal of particulates, eliminate required stagnation events before collection, and create little intrusion on the consumers' daily routine. These advantages of using filters in field work on partial lead service lines may outweigh the disadvantages of not detecting soluble lead (which can be detected in a simple low flow rate profile).

Table 3-2 – Sampling methods for once-through flow events.

Method	Description	Volume Sampled	Pros/Cons	Likelihood to detect soluble and particulate lead
First Draw & Profiling	Collect first amount of water during flushing and subsequent samples	1-2 L or extent of profile	Quantifies all lead in samples collected, very sensitive to flowrate, likelihood of missing spikes	Detects all Pb in water (particulate and soluble) collected but can miss sporadic spikes
Grab Samples	Collect small samples periodically	10 mL	Provides profile of soluble lead, doesn't sample large portion of flow event, sensitive to flow	Detects soluble lead, may miss particulate spikes
Proportional Sampler	Splits flow such that a portion is collected for analysis	A fraction of daily flow	Conventional designs "miss" particulates. Other designs could concentrate particulates.	Depends on design
Bins to collect every drop of water from pipe system	Collects all water during a daily flush	Entire daily	Collects all water and quantifies suspended fraction, including spikes but not practical	Confined to laboratory. Likely to detect all Pb (particulate and soluble)
Whole House Filters	Filters lead from all water for an extended period of time	Entire	Samples large volumes with minimal effort. Misses soluble and small colloidal lead.	Potentially quantifies a large fraction of particulates Pb > 1 micron

3.7 Exploring concerns related to unlined iron main connections to service line

If there was no copper pipe installed between the iron main and lead pipe, the iron cathodically protected the lead pipe with an initial current of 92 μA. But in all cases when the length of copper installed between the two pipes was > 2.5 cm, the lead was sacrificed by the connection to copper. Thus, in a conventional partial replacement, where copper pipe lengths of > 2.5 cm are used, a connection of the service line to unlined iron is not expected to influence galvanic corrosion problems.

This was further confirmed by temporarily connecting a 3 m galvanized iron pipe section to the individual pipe rigs in this work. The iron pipe section did sacrificially reduce lead corrosion (12-15 μA) in cases where the iron was directly connected to lead as occurs before partial replacement. But for the case in which 5’ of copper was placed between the lead and iron as per a traditional partial replacement, the galvanic current sacrificing the lead was not affected. In summary, this short-term experiments suggests that there could be some small benefits to lead release if a lead pipe is connected to an unlined iron main, but an unlined iron main will not reduce galvanic impacts of copper on lead pipe corrosion in a traditional partial service line replacement.

3.8 Phase D - Prolonged Stagnation Event

During a one month stagnation event, the mass of lead released to water from either 100% lead pipe or simulated direct Pb:Cu pipe connections was 3-4 mg in a 2 L sample (Figure 3-14). The use of copper sleeves and brass connectors had between 3-7 times higher lead release. Over the month long stagnation event galvanic corrosion currents dropped 42-82% compared to that measured after an 8 hour stagnation time.

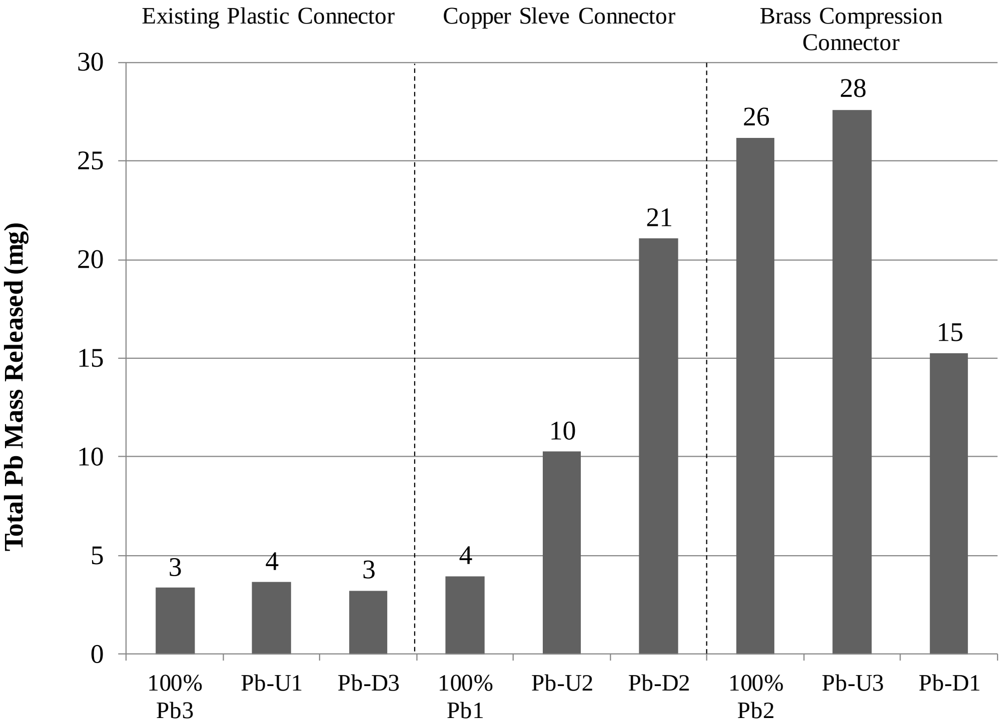

Figure 3-14 Total mass released in first 2 L draws during prolonged stagnation events.

4 Conclusions

- After 14 months, starting with new lead pipe and no scale, partials continued to release much more lead than full lead pipe at moderate and high flowrates. At low flow, galvanic corrosion effects were not discernible between the three conditions, reducing the likelihood to detect negative impacts of the galvanic connections. At moderate and high flowrates, galvanic corrosion increased lead in water for Pb-D by a factor of 26 compared to 100% Pb at highest flow.
- Even during a consistent, moderate flowrate, effects of galvanic corrosion increased lead release from partials which continued for a period of at least 18 months. Only after removing all reservoirs of lead were the negative impacts from galvanic corrosion with

50% Pb and 50% Cu pipe equal to that of a 100% Pb pipe; lead release from partials (50% Cu, 50% Pb) was not statistically higher than 100% Pb.

- Galvanic current contributed to a reservoirs of lead rust/scale at the copper:lead junctions increasing variability and total lead in water. Galvanic corrosion currents decreased 35-50% from initial rates after two years of operation, but still persisted at rates greater than 10 µA for conditions connected with plastic tubing and a small dielectric spacer.
- The addition of brass and copper connectors increased lead corrosion and subsequent lead in water by the formation of crevices even when coupled to passivated Pb pipe. Lead leaching was markedly higher in conditions with brass compression fittings compared to plastic connectors with a dielectric spacer.
- Collecting all water using bins captured and quantified total daily lead release during flow events that first draw and grab samples may not capture. While further research is required, whole-house filters can be utilized as an experimental collection method, capable of quantifying total lead release and potentially used for public health to mitigate elevated lead in water.
- Cathodic protection from iron coupled to lead provides a trivial level of protective current especially when copper is connected between the lead and iron; any protective effect that may have existed is eliminated by the presence of the nobler copper pipe. Replacement of an unlined iron distribution main or a partial lead service line replacement with plastic pipe would not induce excess corrosion by eliminating a cathodic protection by iron.
- Negative effects from galvanic corrosion and connectors persisted during prolonged stagnation events representing sporadic and seasonal water use. Galvanic corrosion from brass connectors coupled to lead increased total lead mass release 5-7 times.

Furthermore, galvanic currents decreased, but were persistent even with long stagnation periods.

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References

Arnold, R. B., & Edwards, M. (2012). Potential Reversal and the Effects of Flow Pattern on Galvanic Corrosion of Lead. *Environmental Science & Technology, 46*(20), 10941-10947. doi: 10.1021/es3017396

Boyd, G., S., R., McFadden, M., & Korshin, G. (2012). Effect of Changing Water Quality on Galvanic Coupling. *Journal AWWA, 104*(3), E136-E149.

Breach, R. A., Crymble, S., & Porter, M. J. (1991). *A Systematic Approach to Minimizing Lead Levels at Cosumers' Taps.* Paper presented at the American Water Works Association Annual Conference and Exposition, Philadephia, PA.

Britton, A., & Richards, W. N. (1981). Factors influencing plumbosolvency in Scotland. *J. Inst. Water Eng. Scient.*, 35:349-364.

Brown, M. J., & Margolis, S. (2012). Lead in Drinking Water and Human Blood Lead Levels in the United States. *Morbidity and mortality weekly report. Surveillance summaries (Washington, DC: 2002), 61*, 1.

Cartier, C., Arnold Jr, R. B., Triantafyllidou, S., Prévost, M., & Edwards, M. (2012a). Effect of Flow Rate and Lead/Copper Pipe Sequence on Lead Release from Service Lines. *Water Research, 46*(13), 4142-4152. doi: 10.1016/j.watres.2012.05.010

Cartier, C., Doré, E., Laroche, L., Nour, S., Edwards, M., & Prévost, M. (2012b). Impact of Treatment on Pb Release from Full and Partially Replaced Harvested Lead Service Lines (LSLs). *Water Research*(0). doi: 10.1016/j.watres.2012.10.033

Clark, B., Cartier, C., St. Clair, J., Triantafyllidou, S., Prévost, M., & Edwards, M. (2012a). Effects of Commercial Connectors on Galvanic Corrosion between Pb/Cu Pipes. *Submitted to Journal American Water Works Association*.

Clark, B., Hernandex, A. L., & Edwards, M. (2011). *Deposition Corrosion of Water Distribution System Materials.* Paper presented at the Water Quality Technology Conference, Phoenix, AZ.

Clark, B., Masters, S., & Edwards, M. (2012b). *3-D Lead Profiling Detects Particulate Lead-in-Water Risks as a Function of Flow Rate.* Paper presented at the Water Quality Technology Conference, Toronto, ON.

Copper Development Association. (1999). Copper Tube in Domestic Water Services Publication 33. from http://www.copperinfo.co.uk/plumbing-heating-and-sprinklers/downloads/pub-33-copper-tube-in-domestic-water-services.pdf

Deshommes, E., Laroche, L., Nour, S., Cartier, C., & Prévost, M. (2010). Source and occurrence of particulate lead in tap water. *Water Research, 44*(12), 3734-3744. doi: 10.1016/j.watres.2010.04.019

Doré, E., Cartier, C., Edwards, M., DeSantis, M., Schock, M., Laroche, L., . . . Prévost, M. (2012). *Impact of Treatment on Scale Formation and Lead Release from aged LSLs.* Paper presented at the American Water Works Association, WQTC, Toronto, CA.

Edwards, M. 2012. Discussion: Effect of Changing Water Quality on Galvanic Coupling. Journal American Water Works Association 104: 65-82. doi:10.5942/jawwa.2012.104.0151.

Gehring, G., Lindemuth, D., & Young, W. T. (2003). Break Reduction/Life Extension Program for Cast and Ductile Iron Water Mains *New Pipeline Technologies, Security, and Safety* (pp. 321-331).

Giani, R. (2008). *Possible Influence of Galvanized Plumbing in Elevated Lead Levels.* Paper presented at the American Water Works Association Annual Conference and Exposition, Atlanta, GA.

Giani, R., Edwards, M., Chung, C., & Wujek, J. (2004). *Use of Lead Profiles to Determine Source of Action Level Exceedances from Residential Homes in Washington.* Paper presented at the DC Proceedings AWWA Water Quality Technology Conference Sunday Workshop. San Antonio, TX.

HDR Engineering Inc. (2009). An Analysis of the Correlation Between Lead Released from Galvanized Iron Piping and the Contents of Lead in Drinking Water. Bellevue, WA: HDR Engineering Inc.

Hu, J., Gan, F., Triantafyllidou, S., Nguyen, C. K., & Edwards, M. (2012). Copper-Induced Metal Release from Lead Pipe into Drinking Water. *Corrosion, 68*(11), pp. 1037-1048.

McNeill, L. S., & Edwards, M. (2004). Importance of Pb and Cu particulate species for corrosion control. *Journal of environmental engineering, 130*(2), 136-144.

Muylwyk, Q., Waller, M., Spielmacher, A., Olesiuk, J., & Suffoletta, V. (2011). *Full versus partial lead service line replacement and lead release in a well buffered groundwater.* Paper presented at the American Water Works Association, Water Quality Technology Conference, Phoenix, AZ.

National Drinking Water Advisory Council (2011). [Letter to U.S. EPA Concerning Partial Lead Service Line Replacements].

Rajani, B., & Kleiner, Y. (2003). Protecting Ductile-Iron Water Mains: What Protection Method Works Best for What Soil Condition? *Journal American Water Works Association, 95*(11), 110-125.

Reiber, S., & Dufresne, L. (2006). Effects of External Currents and Dissimilar metal contact on Corrosion of Lead from Lead Service Lines. *Final Report to USEPA region III.*

Swertfeger, J., Harman, D. J., Shrive, C., Metz, D. H., & DeMarco, J. (2008). *Water quality effects of partial lead line replacement.* Paper presented at the American Water Works Association Annual Conference and Exposition, San Antonio, TX.

Swertfeger, J., Metz, D. H., & Webb, D. (2011). *Benefits of a utility lead research program.* Paper presented at the American Water Works Association Annual Conference and Exposition, Washington, DC.

Triantafyllidou, S., & Edwards, M. (2010). Contribution of Galvanic Corrosion to Lead in Water After Partial Lead Service Line Replacements. *Water Research Foundation. Report No. 4088.*

Triantafyllidou, S., & Edwards, M. (2011). Galvanic corrosion after simulated small-scale partial lead service line replacements. *Journal American Water Works Association 103(9), 85*.

Triantafyllidou, S., Parks, J., & Edwards, M. (2007). Lead particles in potable water. *Journal American Water Works Association, 99*(6), 107-117.

US EPA. (1991). *Maximum Contaminant Level Goals and National Primary Drinking Water Regulations for Lead and Copper*. (Federal Register 56, 26460).

US EPA. (2011). Science Advisory Board Evaluation of the Effectiveness of Partial Lead Service Line Replacements, EPA-SAB-11-015 Retrieved 2012/02/15, from http://yosemite.epa.gov/sab/SABPRODUCT.nsf/RSSRecentHappeningsBOARD/964CCDB94F4E6216852579190072606F/$File/EPA-SAB-11-015-unsigned.pdf

van den Hoven, T., & Slaats, N. (2006). *Analytical Methods for Drinking Water: Advances in Sampling and Analysis, Lead Monitoring*.

Wang, Y., Jing, H., Mehta, V., Welter, G. J., & Giammar, D. E. (2012). Impact of galvanic corrosion on lead release from aged lead service lines. *Water Research*(0). doi: 10.1016/j.watres.2012.06.046

Xie, Y., & Giammar, D. E. (2011). Effects of flow and water chemistry on lead release rates from pipe scales. *Water Research, 45*(19), 6525-6534. doi: 10.1016/j.watres.2011.09.050

Appendix C

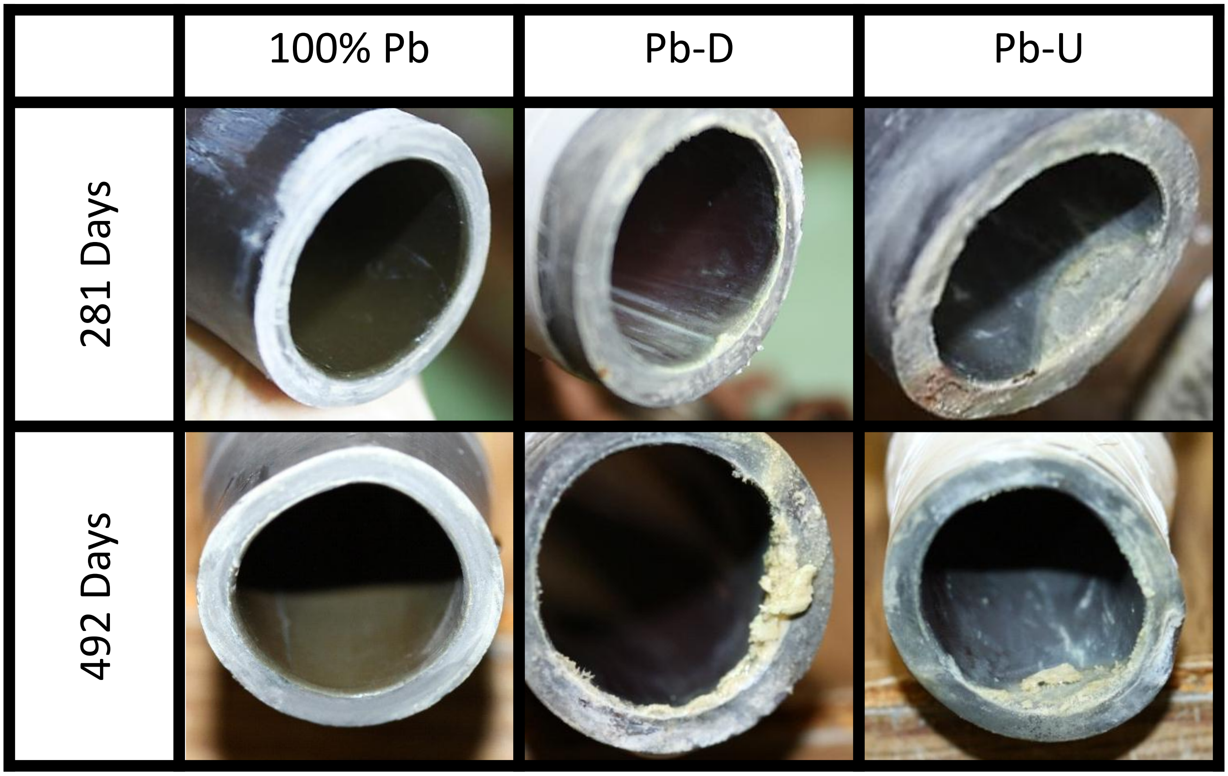

Figure C-1 Mounds of lead rust evident at copper:lead junctions at 281 and 492 days of pilot.

CHAPTER 4: IMPLICATIONS FOR UTILITIES, CONSUMERS, AND FUTURE WORK

Negative effects from galvanic corrosion continued to increase lead in water after more than 18 months for a simulated partially replaced lead service line starting with new lead pipe. At low flow (1.3 LPM), there was no apparent benefit from a partial replacement versus a 100% lead pipe, while at moderate and high flow rates (8 and 32 LPM) lead release increased dramatically. Even when sampled repeatedly using a consistent, moderate flowrate, lead release was 40% higher for the condition representing a field partial lead service line replacement (PLSLR) with copper placed upstream of lead pipe. The relative performance of partial versus full lead pipe worsened as lead rust accumulated with time, demonstrating that adverse impacts of galvanic corrosion can worsen over the long-term.

Full replacement of an existing lead service line is preferred to a PLSLR to reduce short term and long term (from galvanic corrosion) elevated lead in water arising from copper and lead connections. If a full replacement is not possible, the use of a dielectric would effectively stop direct galvanic corrosion, however lead release via deposition corrosion would still be possible. If the use of a dielectric is prohibited either by code or for practical reasons (and electrical continuity of the service line is required), a bridged dielectric can be used to reduce the threat of elevated lead from galvanic corrosion. Separating the externally connected copper and lead pipe reduces the magnitude of galvanic corrosion between the two metals, reducing lead corrosion and lead in water. Furthermore, restricting the use of metallic couplings that form crevices around lead pipe is beneficial to prevent excess lead corrosion.

While collecting water for consumption or cooking, maintaining a low flowrate can reduce the risk of consumer exposure to elevated lead in water. Additionally, the use of aerators on kitchen faucets can provide two benefits that reduce the risk of high lead in water: the aerator restricts flow, decreasing the velocity of the water and reducing the likelihood of lead rust particle mobilization, and it also functions as a screen to prevent consumption of large particulates mobilized during flow disturbances.

It was once deemed possible that cathodic protection of a copper service line connected to an iron distribution main might be lost if a dielectric was inserted; however, initial results from a short duration bench scale experiment suggest that installation of a dielectric would not reduce the lifetime of a copper service line. Additional research would be necessary to confirm these results and a cost-benefit analysis would be necessary to compare electrically isolated service lines, to those that may be cathodically protected by iron distribution mains.

Sampling methodologies, from this research including use of whole house filters to capture particulates from service lines, are recommended in longer term field studies to examine whether the trends from the pilot work reported herein occur in systems with well-aged pipe and normal water use patterns in homes.