Controlling Lead in Drinking Water
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Controlling Lead in Drinking Water

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FOREWORD

The Water Research Foundation (WRF) is a nonprofit corporation dedicated to the development and implementation of scientifically sound research designed to help drinking water utilities respond to regulatory requirements and address high-priority concerns. WRF’s research agenda is developed through a process of consultation with WRF subscribers and other drinking water professionals. WRF’s Board of Trustees and other professional volunteers help prioritize and select research projects for funding based upon current and future industry needs, applicability, and past work. WRF sponsors research projects through the Focus Area, Emerging Opportunities, and Tailored Collaboration programs, as well as various joint research efforts with organizations such as the U.S. Environmental Protection Agency and the U.S. Bureau of Reclamation.

This publication is a result of a research project fully funded or funded in part by WRF subscribers. WRF’s subscription program provides a cost-effective and collaborative method for funding research in the public interest. The research investment that underpins this report will intrinsically increase in value as the findings are applied in communities throughout the world. WRF research projects are managed closely from their inception to the final report by the staff and a large cadre of volunteers who willingly contribute their time and expertise. WRF provides planning, management, and technical oversight and awards contracts to other institutions such as water utilities, universities, and engineering firms to conduct the research.

A broad spectrum of water supply issues is addressed by WRF’s research agenda, including resources, treatment and operations, distribution and storage, water quality and analysis, toxicology, economics, and management. The ultimate purpose of the coordinated effort is to assist water suppliers to provide a reliable supply of safe and affordable drinking water to consumers. The true benefits of WRF’s research are realized when the results are implemented at the utility level. WRF’s staff and Board of Trustees are pleased to offer this publication as a contribution toward that end.

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EXECUTIVE SUMMARY

OBJECTIVE

The Lead and Copper Rule of 1991 created a sampling process that must be followed to determine levels of lead at customer taps. If lead exceeds 15 µg/L in 10 percent of the samples, the water utility must reduce the level of lead in its water.

In order to accomplish this, it is important to understand why lead is present at the tap and how it can be prevented. The chemistry of the water that determines both of these factors is described in this report. Control strategies used by water utilities are described, including a detailed discussion of one of the most common strategies—lead service line replacement.

BACKGROUND

Lead is a contaminant that is commonly found in a number of environmental sources. The most common source of exposure is from lead-based paint, which was common in homes and industries until it was banned for residential use in 1978. Children and other sensitive subpopulations are especially susceptible to lead from paint, paint chips, and respirable or ingestible dust and debris containing lead.

Drinking water is not normally a significant source of lead exposure. However, in an effort to reduce all exposure to lead, water systems, state and federal drinking water regulators, and public health organizations, are developing and implementing measures to minimize lead exposure at the customer tap.

This document describes some of the characteristics of lead in drinking water and strategies for utilities to control lead at the customer tap. The lead control approaches discussed have been described in greater detail elsewhere (Schock 1989; Schock et al. 1996, 2014a & b; Schock and Lytle 2011). This paper focuses on contamination caused by lead service lines.

DISCUSSION

Chapter 1 focuses on the important characteristics of lead chemistry in water. Lead in drinking water at the customer tap is almost exclusively the result of water contact with lead-containing components in the distribution system or household plumbing. These components can include piping, fixtures, or fittings in the service line from the utility distribution system pipe to the household, other plumbing within the house prior to the tap, as well as water contact with lead-containing scales precipitated inside service lines and premise plumbing. Lead distribution system pipes were not commonly used by U.S. water systems, but lead can be present in brass and solder in distribution system fittings. Lead can only be present in the drinking water at customers’ taps if corrosion of lead-containing piping, fixtures, or fittings occurs.

If these lead-containing materials are present in the system, and the water causes corrosion through contact, lead can be released in a soluble or insoluble form, depending on the water chemistry. Soluble lead is dissolved in water, so it easily reaches customers’ taps and is therefore undesirable. Insoluble lead precipitates onto the pipe surface, so it is less likely to reach consumer taps. It is still of concern, as the scale and particulate matter can break off and reach the tap as particulate lead.
Chapter 2 describes how these characteristics can be manipulated or accounted for in drinking water systems to control lead levels at the customer tap. The most common methods to minimize lead in drinking water are:

- Adjusting the water chemistry to produce stable water quality conditions that inhibit lead release
- High velocity flushing (especially inside the home) to remove particulate lead
- Removing service lines and plumbing materials that contain lead

Since many water systems target the removal of the lead service line between the utility water main and the house as a major originating source of lead reaching the customer tap, Chapter 3 describes an example of a lead service line replacement strategy used by water systems.

Lead service line replacement has been used by many utilities either directly or indirectly to reduce the occurrence of lead at consumers’ taps. The experiences of utilities and their recommended procedures, including customer education described in this report have been successfully used to minimize lead levels at the taps.

RESEARCH PARTNER

American Water Works Association
CHAPTER 1
LEAD OCCURRENCE IN DRINKING WATER

BACKGROUND

The Lead and Copper Rule (LCR) promulgated by the U.S. Environmental Protection Agency (EPA) in 1991 currently regulates lead and copper in drinking water. Lead monitoring is required at multiple locations in each community water system on a routine basis ranging from once every six months to once every nine years. Most monitoring is done once every three years. Action levels (AL) were established at 0.015 mg/L (15 μg/L) for lead and 1.3 mg/L for copper. If at least 10 percent of the samples tested are above the AL then the water system must increase monitoring, undertake additional corrosion control efforts, and develop/implement training and public education for customers. Some of the details of the LCR were modified in 2000 and 2007, but the basic regulatory framework outlined above remains. EPA is currently developing the Long-Term LCR (LTLCR) revisions, and once the draft version is published, the final LTLCR would likely be promulgated two years later.

LEAD SOURCES

Leads Sources Prior to Distribution Systems and Customer Plumbing

The presence of lead (Pb) in drinking water results from the contact of treated drinking water with lead-containing pipes, valves, faucets, meters, pipe solder, and other plumbing fixtures and fittings within the distribution system or inside customer houses/buildings1. Lead is typically not found in drinking water sources (Schock and Lytle 2011, Hayes 2010, Durum et al. 1971, Fishman and Hem 1976) or in drinking water treatment chemicals (Brown et al. 2004, MacPhee et al. 2002). Lead is fairly abundant and widely distributed in geologic formations, particularly sedimentary rocks, but is not very mobile in groundwater and surface water due to low solubility of lead hydroxycarbonates (Hem and Durum 1973, Hem 1976b, and Bilinski and Schindler 1982) and lead phosphates (Nriagu 1974), sorption of lead onto organic and inorganic sediment surfaces (Hem 1976a), and co-precipitation of lead with manganese oxide (Hem 1980).

Even if lead is present in source water or treatment chemicals, the clarification and filtration processes used for particulate removal in drinking water treatment should remove any soluble or particulate lead present (Sorg et al. 1978, Durfor and Becker 1964, AWWA 1988). Particulate lead is removed as long as water treatment processes are optimized for particulate removal. Also, if oxidized conditions are present, reduced lead that is typically soluble is oxidized and becomes insoluble, and removed as particles. When raw water turbidity is present, soluble lead that is not converted (oxidized) to particulate lead is removed because the soluble lead sorbs onto any particulate material present – the more particles present prior to clarification and filtration the better the soluble lead will be removed.

Lead Sources in Distribution Systems and Customer Plumbing

Lead in drinking water at the customer tap is almost exclusively the result of water contact with lead containing components of the distribution system or household plumbing. These

1 Or lead-containing “scale” deposited on plumbing that originated from these lead sources (see Figure 1.2)
components include piping, fixtures, or fittings in the service line from the utility distribution system pipe to the household and other plumbing within the house prior to the tap as well as water contact with lead-containing scales precipitated inside service lines and premise plumbing. Figure 1.1 depicts a typical home plumbing system connected to a utility water system. It shows the main water line owned by the drinking water utility in the street, the utility owned portion of the service line into house, the portion of the service line owned by the home owner, and the premise plumbing and fixtures inside the house. In most cases, the utility owns the service line up to the property line or meter, but some utilities do not own any portion of the service line and others own all the service line.

Source: Adapted from Hayes 2010

Figure 1.1 Depiction of water main in street, household plumbing, and the service line owned by utility/city to the property line and the remainder owned by customer

Distribution system pipelines, pumps, valves, fittings, etc. in the utility-owned distribution system up to the service line are not typically major sources of lead in the US. They are generally not expected to be an issue except in parts of the world that still have lead pipes in the utility owned parts of the distribution system. For example, Ireland still has a small amount of lead pipe used for water mains (O’Doherty 2013), and additional lead pipe in service lines. In contrast, there has been limited historical use of lead pipes in distribution systems in the US aside from service lines, but there are distribution system components made of brass and other materials that contain lead.

Contribution of lead at the customer tap from the distribution system prior to the service line has probably never been a large factor. This contribution would have further decreased after
the 1986 EPA requirements banning lead solder and limiting lead-content of fittings (EPA 1986), and should be further reduced in response to tightening federal (GPO 2014) and state requirements for lead-content outlined in National Sanitation Foundation International (NSF)/American National Standards Institute (ANSI) Standards 372 and 61 – Annex G (NSF 2013). The federal “Reduction of Lead in Drinking Water Act” (GPO 2014) mandated that as of January 2014, wetted surfaces of every pipe, fixture and fitting sold or installed for potable water cannot contain more than 0.25% lead by weight.

LEAD CHEMISTRY IN DRINKING WATER

As described above, lead can only be present in the drinking water at customers’ taps if corrosion of materials made of lead in the distribution system or in household plumbing occurs. If these materials are present in the system, and the water in contact with them causes corrosion to occur, lead can be released in a soluble or insoluble form depending on the water chemistry. The following sections describe how different water quality parameters affect the presence and form of lead in the water.

Particulate Lead and Lead Scale vs. Soluble Lead

![Figure 1.2 Sources and fates of lead in drinking water](image)

Figure 1.2 illustrates the sources and possible fates of lead in drinking water. The original source of all lead in this figure is the corrosion or dissolution of the lead-containing source (pipe,
fixtures, fittings, solder, etc.). The soluble lead can theoretically remain in solution all the way to the customer tap, but can also precipitate as scale, subject to later dissolution or dislodgement.

In this figure “scale” is considered separate from “particulate matter” or “particles” even though they are chemically identical (e.g., mixtures of lead oxides, hydroxides, carbonates, etc.). The criteria differentiating these two terms are summarized in Table 1.1. “Scale” implies a more stable or more permanent deposit of solid material electrochemically precipitated in layers on different surfaces in the system, including pipe, fixtures, fittings, etc. When part of this scale breaks off and is suspended in the flowing water, then the liberated “scale” is called a “particle” or “particulate matter” in this document. Using this definition, “scale” is not mobile but stays where electrochemically deposited unless it dissolves and becomes soluble lead or if part of the scale breaks off to become a particle.

Particulate material is mobile, or potentially mobile, because it can be suspended in water and move as the water flows. Particles can be physically deposited, subject to later re-suspension and mobilization as flow rate changes and surges. Furthermore, like scale, a particle can also dissolve and become soluble lead. Particulate lead, once formed, can either dissolve and become soluble lead, or it can be transported as particulates to the customer tap. The water the customer is exposed to can contain soluble lead or any particulate material transported from sources near and far to the tap.

Variations in the above described relationship between particles and scale could include: (a) particulate matter physically deposited on a surface can become embedded as scales deposit over it, (b) soluble lead could chemically precipitate as scale on a particle surface (even a particle that does not contain lead), (c) lead in particulate matter could dissolve in water then later chemically precipitate as scale, or (d) scale can chemically precipitate onto a previously deposited scale, including scale deposited onto or co-deposited with scale of a different composition (Schock and Lytle 2012).

Soluble lead is dissolved in water, so it easily reaches customers’ taps and is therefore undesirable. Insoluble lead precipitates onto the pipe surface, so it is less likely to reach consumer taps. It is of concern, though as the scale and particulate matter can break off and reach the tap as particulate lead.

<table>
<thead>
<tr>
<th>KEY DEFINITIONS</th>
</tr>
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<tbody>
<tr>
<td><strong>Soluble lead</strong> can result from the corrosion of Pb-containing plumbing or from dissolution of scale or particles.</td>
</tr>
<tr>
<td><strong>Scale</strong> can only be produced by electrochemical precipitation of soluble lead at various points in the distribution system or in household plumbing.</td>
</tr>
<tr>
<td><strong>Particulate lead</strong> is the result of abrasion, dislodgement, and transport of broken off pieces of scale or lead containing pipe and plumbing (including solder).</td>
</tr>
<tr>
<td>Term used in this document</td>
</tr>
<tr>
<td>---------------------------</td>
</tr>
<tr>
<td>Formed by</td>
</tr>
<tr>
<td>Mobility</td>
</tr>
<tr>
<td>Chemical composition</td>
</tr>
<tr>
<td>Variations</td>
</tr>
</tbody>
</table>

Part of new scale produced as outlined to the left can break off and form one or more new discrete particles
Lead Oxidation State – Insoluble Pb$^{+4}$ or Pb(IV) vs. Pb$^{+2}$ or Pb(II)

Lead solubility is complex, and varies due to site-specific conditions. The following discussion describes how various water characteristics impact lead solubility, starting with the oxidation state. As described earlier, water chemistry conditions that result in insoluble corrosion by-products, including lead, are preferred to those that produce soluble lead, since soluble lead will pass directly to the consumers’ tap. Insoluble lead products can also coat the lead and separate the water from exposed lead thereby reducing corrosion.

For water that is at equilibrium, various water quality factors can impact lead solubility. Under most conditions in drinking water, when oxidized conditions can be maintained “high” enough for lead to be in the Pb(IV) state, then lead will be insoluble. Conversely, under less oxidized conditions there is a much wider range of possibilities. Lead is more soluble in drinking water under reduced conditions (Pb(II)). Fortunately, even under reduced conditions, pH, DIC, and orthophosphate can be managed through treatment to produce insoluble Pb(II) hydroxycarbonate or orthophosphate containing Pb(II) solids.

It is possible to explore theoretical lead solubility as a function of oxidation state using Pourbaix diagrams. For example, Figure 1.3 is a Pourbaix diagram from Xie et al. (2010) showing the combined impact of pH and oxidation state for a fixed set of conditions (no orthophosphate, total lead 0.015 mg/L and constant dissolved inorganic carbon (DIC) of 30 mg/L as C). The details of the diagram in Figure 1.3 are not directly applicable to conditions other than these specific conditions. However, the species involved and their relative relationship in the figure are illustrative of most situations, although the exact transitions between one phase or one species and another depends on site-specific conditions.

In this figure the diagram indicates that:

- Under oxidizing conditions, i.e., when free chlorine residual is present (above the free chlorine line), lead is present in the +4 oxidation state, expressed as either Pb$^{+4}$ or Pb(IV). Pb(IV) is not very soluble at equilibrium and tends to form Pb(IV) scale deposits, almost exclusively lead oxide solids (PbO$_2$ (s)) where Pb(IV) is present as precipitated PbO$_2$ (s), except at pH >12.
- Under less oxidized conditions, i.e., below the monochloramine line, lead is present in the +2 oxidation state (Pb$^{+2}$ or Pb(II)) is present as soluble Pb(II) complexes (e.g., Pb(CO$_3$)$_2^{2-}$).

---

2 Required residual to be maintained to ensure reliable establishment and maintenance of Pb(IV) scale can depend on site-specific conditions, though this could require free chlorine residuals of 1 mg/L as Cl$_2$ or higher.

3 Developed from information published in Pourbaix (1966)
Total Pb = 15 μg/L, DIC = 30 mg/L as C, no orthophosphate. Solid (insoluble Pb) species are shaded green. Non-shaded areas indicate soluble Pb species. Pb(0) or "elemental lead" has an oxidation state of zero [Pb(0)]. The lead in PbO₂(0) (lead oxide solid) has an oxidation state of +4 [Pb(IV)]. All other lead species in diagram have an oxidation state of +2 [Pb(II)]. Note dashed lines represent the following conditions:
(a) O₂ (dissolved oxygen) = oxidation state (electron activity or Eₜ) provided by 1.26 μM dissolved oxygen, in equilibrium with 0.001 atm prior to distribution system and customer plumbing
(b) Monochloramine (NH₂Cl) = Eₜ provided by NH₂Cl at a concentration of 2 mg/L as Cl₂ with a free chlorine to nitrogen ratio of 0.79 mg Cl₂ / mg N
(c) Free chlorine (Cl₂) = Eₜ provided by 2 mg/L as Cl₂ free chlorine

Source: Adapted from Xie et al. 2010

Figure 1.3 Pourbaix diagram for the Pb(IV)-Pb(II)-Pb(0) system

Impact of pH, Alkalinity (DIC), and Orthophosphate on Pb(II) Solubility

This section addresses the condition favoring Pb(II) formation as depicted in Figure 1.3. Both pH and alkalinity are important factors in Pb(II) soluble versus insoluble formation. The water’s pH represents the concentration of hydrogen ions (H⁺) which accept electrons given up by a metal, in this instance lead, when it corrodes (Ontario 2009). Alkalinity is a measure of the buffering capacity against a pH change (up or down). Alkalinity is a function of the concentrations of bicarbonate, carbonate and hydroxide ions. Dissolved inorganic carbonate (DIC) is the sum of all dissolved carbonate-containing species (Ontario 2009).
At pH values below about pH 5, iron, lead, and copper corrode (soluble Pb(II)). At pH values higher than pH 9 and depending on the alkalinity, these metals are protected (insoluble Pb(II)). At pH values where soluble Pb(II) dominates phosphate inhibitors are often used. Phosphate-based inhibitors are typically used at pH levels ranging between 7.4 and 7.8, and pH affects the mineralogy of the resulting scales. (Ontario 2009). Figures 1.4 and 1.5 show the theoretical solubility of Pb(II) as a function of pH and DIC when no orthophosphate is present. Figure 1.4 shows Pb(II) solubility as a function of pH when no orthophosphate is present for eight different values of DIC from 1 to 100 mg/L as C. Figure 1.5 shows a contour diagram of lead solubilities under the same set of conditions as in Figure 1.4 (no orthophosphate, reducing conditions, lead concentration as function of pH and DIC). The minimum predicted Pb(II) solubility under these conditions is ~0.07 mg/L at pH ~10 and DIC ~8 mg/L as C (~66 mg/L as CaCO₃), indicating these are the most favored theoretical conditions for Pb(II) scale formation (i.e., if total lead is >0.07 mg/L, all but 0.07 mg/L will precipitate as lead hydroxycarbonate solids (i.e., Pb(II) scale)).

Source: Adapted from Schock and Lytle 2011

Figure 1.4  Theoretical impact of pH and DIC on lead solubility in drinking water under ideal equilibrium conditions - assumes Pb(II) and no orthophosphate

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Figure 1.5  Theoretical Pb(II) solubility diagram as a function of pH and DIC in absence of orthophosphate (I=0.005, T=25°C)]

Figure 1.6 is a similar theoretical curve under the same conditions as Figure 1.5 except 0.5 mg/L as PO₄ (0.16 mg/L as P) is present. This figure shows that similar or even slightly lower Pb(II) solubility is possible when a little orthophosphate is present, and this can occur at a pH between ~7.4 and ~7.8 instead of pH 9 or 10. As shown in Figure 1.6, the presence of 0.5 mg/L as PO₄ produces a minimum Pb(II) solubility of ~0.04 mg/L at about pH ~7.4, DIC ~6 mg/L as C (50 mg/L as CaCO₃). Figure 1.7 illustrates lead solubility as a function of orthophosphate concentration at pH 8.0 for six different alkalinity levels from 5 to 200 mg/L as CaCO₃. Each line represents constant pH and alkalinity, so DIC is also constant along a given line. At pH 8, almost all DIC is present as bicarbonate (~98 percent). Consequently, DIC of the lines in Figure 1.7 also ranges from 5 to 200 mg/L as CaCO₃ (0.6 to 24 mg/L as C). This figure shows that at all orthophosphate doses shown, more DIC at pH ~8 produces higher lead solubility. For each DIC line in Figure 1.7, higher orthophosphate doses produce lower lead solubility, although lead solubility appears to level off at doses >5 mg/L as PO₄. Even with higher DIC, optimal lead solubility with orthophosphate is still normally lower than without

**OBSERVATIONS**

- Control of pH and alkalinity or application of orthophosphate-based corrosion control can limit soluble Pb to comparable levels.
- Use of orthophosphate controls Pb solubility within a pH range typical of most water systems and consistent with managing other treatment and operational goals.
orthophosphate (compare Figures 1.4 and 1.5 without orthophosphate vs. Figures 1.6 and 1.7 with orthophosphate)\(^4\).

Adjusting the water’s pH and alkalinity will result in decreasing lead solubility in distributed water, but, under the right conditions, orthophosphate addition can decrease lead solubility more, and this can be achieved at a lower pH than lead solubility control by adjusting pH/alkalinity alone.

Source: EES 1990

Figure 1.6 Theoretical Pb(II) solubility diagram as a function of pH and DIC in presence of 0.5 mg/L as PO\(_4\) (~0.16 mg/L as P) (I=0.005, T=25°C))

\(^4\) Note that details in Figure 1.4, 1.5, 1.6 and 1.7 are valid only for the specific theoretical conditions specified, and are not necessarily valid for other conditions, although general trends are valid.
Source: Schock 1989

Figure 1.7  Theoretical impact of DIC and orthophosphate on lead solubility at pH 8

The ability to use orthophosphate to produce a lower lead solubility at lower pH values is often preferred because the high pH needed to control lead typically requires large doses of pH adjustment chemicals (lime, caustic soda, soda ash) unless it is a softening plant. Water systems using coagulants may have raw water at pH 7 to 8 but then they drop the pH to 6 or lower for optimal coagulation, thereby requiring even more pH adjustment chemicals to get to pH 9 or higher as needed to control lead solubility without orthophosphate. Conversely, smaller amounts of pH adjustment chemicals are needed to achieve pH ~7.4 to ~7.8, the typical pH targets for optimal corrosion control using orthophosphate.

Another benefit of the lower pH possible with orthophosphate for corrosion control is that high pH and high free chlorine residuals can increase the potential for DBP formation, if sufficient precursors are present. Brown et al. (2012) reported one instance where a water system was able to reduce total trihalomethane (TTHM) formation by about 40 percent (TTHM <40 μg/L) as an additional benefit associated with changing their lead control strategy from control of high pH and low DIC

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OBSERVATIONS

- Adjusting a high DIC water to a high pH (>9) will reduce soluble Pb but runs the risk of operational challenges and customer concerns from calcium carbonate scale deposition.

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5 Maintenance of conditions suitable for Pb(IV) scale can possibly limit lead solubility without use of orthophosphate or high pH (and low DIC) (Schock et al. 2008 and 2014a) but it is not normally considered a distinct lead control strategy.
(pH 9.2 to 9.5 and DIC 4 to 6 mg/L as C) to lower pH and addition of orthophosphate (pH ~7.8 and orthophosphate dose of ~1 mg/L as PO₄ (0.3 mg/L as P)).

Furthermore, there is increasing potential to form calcium carbonate scale (CaCO₃ (s)) as DIC increases, especially as pH increases. Although the calcium carbonate scale can protect the underlying pipe, thereby controlling corrosion of the iron, lead, or other materials in the pipe, it can be difficult in some cases to keep CaCO₃ (s) scale formation under control. If DIC is high and if scale formation is uncontrolled then calcium carbonate solids can build up in water system piping, reduce effective size and increase “roughness” of pipes, and consequently can negatively impact hydraulics of the water system. If DIC is high enough (alkalinity >300 mg/L as CaCO₃, i.e., DIC >36 mg/L as C), scaling can occur even at near neutral pH, with an even greater tendency towards scale formation at higher pH.

Some water systems deal with this issue by using lime softening. In high DIC water, lime softening produces high pH conditions that cause the calcium and magnesium that would otherwise precipitate as carbonate solids (i.e., scale) in pipes to precipitate instead in clarifiers and basins where the solids can be collected and removed prior to distribution. Therefore, lime softening not only removes hardness ⁶ but as a consequence also reduces alkalinity to about 30 to 60 mg/L as CaCO₃ (i.e., DIC about 6 mg/L as C) and a pH typically adjusted to between 9 and 10 prior to distribution. However, systems with high DIC that do not soften have potential for scaling at high pH needed for lead corrosion control and therefore may need to control lead corrosion by using lower pH and by either adding orthophosphate or possibly by maintaining high free chlorine residuals (to maintain Pb(IV) scale).

In addition, even when high pH and low DIC are possible, the lead level achievable by systems using orthophosphate or Pb(IV) scale formation to control lead is typically lower than can be achieved with pH and alkalinity control alone. Therefore, if water systems cannot maintain high free chlorine residuals in order to develop Pb(IV) scale, if high pH and low DIC are not sufficient to achieve desired lead levels, or if these systems have too high DIC levels to increase pH >9 (i.e., too much potential for scaling ⁷), then the only option available to these systems may be use of orthophosphate.

Figure 1.8a thru 1.8f show that greater orthophosphate doses are needed to decrease lead solubility as DIC ⁸ increases or as pH increases above eight (note Figure 1.7 and Figure 1.8d are identical). As in Figures 1.4 and 1.5, when the orthophosphate dose is zero, comparison of Figures 1.8a thru 1.8f show that lead solubility decreases as pH increases above eight and as DIC increases at all pH values.

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**OBSERVATIONS**

- Higher doses of orthophosphate under the same pH and DIC conditions produces even lower lead solubility.
- Systems with high DIC levels that cannot increase pH >9 will likely use orthophosphate to lower Pb solubility.

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⁶ As well as metals and other contaminants, including lead, iron, manganese, uranium and other radionuclides, etc.

⁷ Also, at high DIC and high pH this approach may be moot because lead solubility produced might be too high for compliance anyway – see Figures 1.4 and 1.5

⁸ Labeled lines in each graph in Figure 1.8 depict constant alkalinity. But each separate graph depicts constant pH. Therefore, DIC of each line is also constant for a given graph. On each graph, DIC/alkalinity lines increase from bottom to top in each graph. Since pH is different in each of Figure 1.8a through 1.8f, DIC for constant alkalinity lines are different (e.g., top line at 200 mg/L as CaCO₃ alkalinity for Figure 1.8a (pH 6.5) has DIC ~39 mg/L as C but in Figure 1.8f (pH 9) DIC for same alkalinity line is ~24 mg/L as C)
Each graph in Figures 1.8a thru 1.8f also illustrate that the orthophosphate dose needed to achieve a particular lead solubility value increases as DIC increases. Figures 1.8a thru 1.8f also illustrate that there are a number of possible combinations of pH, DIC, and orthophosphate that can produce lead solubility <0.015 mg/L, but higher doses of orthophosphate under the same pH and DIC conditions produces even lower lead solubility. For example, at pH 7.5 and an orthophosphate dose <0.2 mg/L as PO₄ (~<0.06 mg/L as P), the lead solubility is <0.1 mg/L when the alkalinity is ~30 mg/L as CaCO₃ (DIC ~4 mg/L as C), but increasing orthophosphate dose to about 3.3 mg/L as PO₄ (~1 mg/L as P) decreases the lead solubility by about a factor of ~14 (~<0.007 mg/L).

Lead in drinking water is a result of the corrosion of materials in plumbing and service lines containing lead. How much lead is present at a consumer’s tap depends on the presence of lead containing materials and on how corrosive the water is toward these materials. How corrosive the water is, and what form the lead is in is the result of many factors that were described in this chapter. Lead can be in insoluble or soluble forms. Since insoluble lead typically precipitates and stays in the piping, that form is preferable since it keeps the lead from the customer’s tap. However, insoluble lead can also be problematic if the precipitates and scales break off and deliver particulate lead to consumer taps.
(a) – pH 6.5  
(b) – pH 7.0  
(c) – pH 7.5  
(d) – pH 8.0  
(e) – pH 8.5  
(f) – pH 9.0

Source: Schock 1989

Figure 1.8 Impact of DIC and orthophosphate dose at six different pH values
CHAPTER 2
METHODS FOR CONTROLLING LEAD AT THE CUSTOMER TAP

Possible mechanisms for limiting lead release at the customer’s tap include:

- Controlling the chemistry of water entering the customer service line to limit the solubility of any lead in contact with water,
- Removing any lead sources in the service lines and customer plumbing,
- Minimizing particulate lead release to the customer tap during typical use by flushing to remove any loose scale or particulates,
- Installing an additional treatment barrier at the tap such as a point of use filter,
- Lining or coating of lead service lines.

The use of the last two mechanisms – point of use devices and lining the interior of lead service lines were not specifically authorized by the LCR and so have had limited use. They will not be discussed here, although they could potentially provide barriers to lead release to customer taps. The following discussion will focus on the first three mechanisms in greater detail.

CONTROL WATER CHEMISTRY

There are a number of practices to control lead in drinking water through manipulation of water chemistry delivered to customers. These approaches are based on the lead chemistry described in Chapter 1. By evaluating combinations of treatment conditions (pH, chemical dose, DIC target, free chlorine residual target, orthophosphate residual target, etc.) individual water systems can arrive at a corrosion control solution appropriate for their source water and community. The term Optimized Corrosion Control Treatment (OCCT) was defined in the LCR and is used to refer to the solution chosen for a given water system that produces the optimum, i.e., minimum, lead level possible. The term “OCCT” is a specific requirement of the LCR under which utilities are required to investigate alternatives and come up with an OCCT strategy, including treatment goals and operating practices, to achieve the desired minimum lead concentration in water delivered to customer. The LCR definition of OCCT is:

*Optimal corrosion control treatment*, for the purpose of subpart I of this part only, means the corrosion control treatment that minimizes the lead and copper concentrations at users’ taps while insuring that the treatment does not cause the water system to violate any national primary drinking water regulations. Utilities need to meet many treatment goals, however. In some cases, utilities have not been able to completely eliminate lead corrosion while still meeting other water quality requirements (CFR-2011 title 40 vol. 23 part 141.2).

As illustrated in Chapter 1, it is feasible for some water systems to use low doses of orthophosphate for corrosion control and achieve a 90\textsuperscript{th} percentile value for their LCR compliance monitoring data below 0.015 mg/L. It is important to note that minimizing lead must be accomplished while also: (a) achieving a larger set of water quality objectives, (b) supporting ongoing water and wastewater system operations, and (c) not impairing the ecology of receiving water.
Among other considerations, efforts to control lead by adjusting pH, alkalinity, and/or adding orthophosphate must balance lead control benefits against potentially negative impacts on: (a) scaling of pipes and appurtenances, (b) microbial growth, (c) ability to comply with other regulatory requirements (e.g., DBPs), and (d) wastewater facilities and associated discharges due to constituents in corrosion control chemicals such as zinc and orthophosphate.

In some instances, it may be true that water systems could achieve lower lead levels with more aggressive corrosion control practices. However, it is also true that compliance with LCR is not the only issue facing water system management, regulatory compliance, and operation staff. US drinking water systems are challenged to achieve multiple objectives when finding sources, providing treatment, and then distributing water to customers that protect customers from exposure to drinking water contaminants, provides sufficient high quality water to meet customer needs in a cost effective manner.

A particular challenge to water systems is meeting the other regulatory requirements while controlling lead. As noted in the definition of OCCT cited earlier, water systems are not required to optimize lead if it means DBP, turbidity control, or some other factor is compromised. For example, one water system described in Brown et al. (2012) found that the OCCT approach proposed by their state regulatory agency included pH targets that would cause scaling and DBP concerns, and so the water system was able to implement a modified strategy that achieved low lead and low DBP levels, without scaling, by using a lower pH target.

OCCT strategies are generally limited to three options described in Brown et al. (2013), including:

- The maintenance of oxidized conditions with high free chlorine residuals (typically >1 mg/L as Cl₂) to form and maintain insoluble Pb(IV) scale,
- The control of pH and alkalinity (DIC),
- The use of orthophosphate within appropriate pH ranges.

There are a few other alternatives, but they are not used frequently. For example, silicate-based corrosion inhibitors can be used; however it is unclear whether the associated lead and copper control is due to presence of silicate or the high pH it causes.

The maintenance of oxidized conditions to retain a Pb(IV) scale is not normally considered a corrosion control strategy. Attempting to rely on a Pb(IV) scale formation for corrosion control necessitates preserving a free chlorine residual throughout the distribution system and into customer’s homes 100 percent of the time. The Pb(IV) scale can be compromised by small changes in the oxidation state in the distribution system. This is sometimes difficult to reliably monitor and control, resulting in intermittent problems exceeding the lead AL (Schock and Lytle 2012). Meeting DBP control goals can be another constraint with this approach as utilities with DBP challenges may not be able to maintain high enough free chlorine residual in all parts of the distribution system to develop Pb(IV) scale. Utilities that currently use or convert to monochloramine (NH₂Cl) cannot develop conditions suitable for maintenance or formation of Pb(IV) scale (Schock et al. 1996), which means that the use of chloramination eliminates this corrosion control approach.

Therefore, when source water is sufficiently corrosive to require treatment, the principal available options are either pH and alkalinity control or orthophosphate addition. Adjusting pH and alkalinity may not be suitable at all water utilities for reasons including scaling, formation of
regulated DBPs, and difficulty in maintaining the required pH and alkalinity conditions. This is often the case for systems that rely on multiple water supplies with different water qualities.

Available information indicates that orthophosphate addition is typically the preferred choice between these two treatment approaches, but it is not without limitations. Use of orthophosphate can impact galvanic corrosion, encourage microbial growth, and elevate phosphorus content of wastewater discharges.

Figure 2.1 illustrates a stepwise process flow chart for re-evaluating an existing corrosion control strategy, and Figure 2.2 outlines the steps involved in evaluating all available corrosion control approaches.

AL = Action Level, OCCT = Optimized Corrosion Control Treatment
†For example, DBP precursor removal to improve maintenance of free chlorine residuals

Source: Brown et al. 2013

Figure 2.1   A decision-tree outlining re-evaluation of an existing OCCT strategy
C = carbon, DIC = dissolved inorganic carbon, OCCT = optimized corrosion control treatment, PO4 = orthophosphate, Pb(IV) = lead in the +4 oxidation state

1 Higher pH may be acceptable.
2 Typically < 10–20 mg/L as C, but depends on site-specific conditions
3 A high free chlorine (Cl2) residual may require a concentration of 1 mg/L as Cl2 or higher throughout the distribution system, depending on local conditions (e.g., water quality, type and age of pipe, and water age in certain parts of system).
4 For example, in a chloraminated system

Source: Brown et al. 2013

Figure 2.2 A decision-tree outlining OCCT corrosion control strategies

Brown et al. (2013) provides a more detailed discussion of OCCT strategies, including advantages and disadvantages, beneficial and detrimental supporting

KEY REFERENCES ON OCCT

conditions, as well as the opinions and recommendations of various lead corrosion control experts. It is also important to note that lead can be associated with particulate material released as a result of iron and manganese corrosion of galvanized, ductile iron, cast iron, and other pipes and appurtenances (Camara et al. 2013, Schock et al. 2008 and 2014b). This includes lead-content of the particles themselves, as well as soluble lead sorbed onto the particle surface or lead scale precipitated onto the particle surface. Therefore, controlling iron and manganese corrosion is not only important by itself, but it can also indirectly improve lead control.

**REMOVE ALL LEAD SOURCES FROM THE SERVICE LINES AND HOUSEHOLD PLUMBING**

Removing all plumbing components that contain lead eliminates virtually all potential for customer exposure to lead from drinking tap water. If there is no lead in contact with water in the service line or premise plumbing, then there is no possibility of additional lead getting into the water, and water chemistry is no longer critical. In the US a national ban on lead pipes and service lines, and a limit on maximum Pb-content of new plumbing fixtures, fittings, etc. took effect in 1986 (EPA 1986). Further tightening of lead-content limits for new plumbing fixtures took effect in 2014 as outlined in “Reduction of Lead in Drinking Water Act” (GPO 2014) and implemented through NSF/ANSI Standards 372 and 61 (NSF 2013).

These bans do not require removing existing plumbing but as existing plumbing is replaced, new materials will have lower lead content.

Replacement of all lead plumbing and solder as a utility lead control strategy is only a viable and effective solution for the limited number of systems, such as small water systems that own the service line and/or indoor plumbing. This could include schools, medical facilities, housing complexes, or prisons that operate as a community water system. For most systems, this solution is complicated by logistical and legal constraints, and can become prohibitively expensive. Over time this solution will ultimately eliminate the issue of lead in drinking water but in the near term it will only be a feasible LCR compliance strategy in a select number of small systems.

A further consideration is that it may be necessary to replace more than just the lead-containing plumbing and solder. Lead-containing plumbing is the original source of lead in a structure but lead from these sources can migrate over the years and be deposited on other plumbing between the lead sources and the customer’s tap. Therefore, in many cases, even if all of the original lead sources are replaced (brass faucets, soldered copper piping, and lead service lines), the lead levels can still be high due to lead migrating from the lead scale deposits on the remaining plumbing. In these cases, all the plumbing, not just the original lead-containing plumbing, needs to be replaced, thereby adding to the cost and complexity of this approach to lead control, even in small systems.

**HIGH-VELOCITY FLUSHING TO REMOVE PARTICULATE LEAD AND LOOSE SCALE**

While lead service line (LSL) replacement removes the source of lead, it also has the potential to increases lead release, especially from release of particulate lead. Disturbing the LSL and associated lead scale creates the opportunity for particulate lead to be released. Both full- and partial-LSL replacement can create vibration and other disturbances that could cause dislodgement.
and release of scale and other particulate matter inside premise plumbing and appurtenances. Experience with LSL replacement, especially partial replacements, has indicated that it can take weeks to months after the disturbance for the lead releases to be reduced to acceptable levels, chiefly due to sporadic releases of distributed particulate lead. Utility experience with partial lead service line replacement was described in a recent Water Research Foundation study (Welter et al. 2013). That report included guidance for water utilities on strategies for minimizing lead release from partial LSL replacements.

Research has documented the problem associated with lead release after partial-LSL replacement, as noted in the September 28, 2011 SAB report (EPA 2011) and references cited within (e.g., Sandvig et al. 2008). Numerous sources confirm that flushing the night before sampling, even for as little as 10 minutes, can reduce the lead collected the following morning (Murphy 1993, Triantafyllidou et al. 2009, Cantor 2010, and others), though high lead levels return if flushing is not repeated on subsequent days. Murphy (1993) found that 10 minutes of flushing reduced lead levels by about 50 percent. These flushing studies were conducted at low velocity, not the higher velocity conditions analogous to unidirectional flushing in the distribution system.

While it has been established that flushing can have short-term impacts on removal of lead and other particulates, limited work has been reported evaluating the development of more rigorous flushing practices in order to produce longer-range benefits. Data reported by Boyd et al. (2004) for simulations of LSL replacements in laboratory studies indicated that at continuous low flow conditions, lead levels equilibrated at <10 µg/L after about a week of flushing following simulated LSL replacement, and after about 48 hours at a flow of 0.3 gpm. Under intermittent conditions (including stagnation periods) there was no improvement within the first two weeks at either flow rate. These results suggest that even low flushing rates can accelerate the return to stable conditions after partial LSL replacement, and that higher flow rates may accelerate the remediation even further.

Sandvig et al. (2008) cited information from a survey of drinking water and public school system participants indicating that flushing after partial LSL replacement did improve lead levels after the LSL was disturbed by the replacement activities, though in some cases a short duration of flushing may not have been enough. For example, 15 minutes or less of flushing was shown to have some positive impact in some cases, but not in others.

Cantor (2010) identified two utilities in WI that were approved by the state to employ “non-chemical” solutions to LCR compliance which included unidirectional flushing of the distribution system to control lead, iron, manganese, and other particulates in the distribution system.

In comments to the Science Advisory Board (SAB), Edwards (2011) provided an example demonstrating that for a given tap location the particulate lead increased as sampling velocity increased from <2 L/min to ~21 L/min (~7 gpm). At the highest rate, the particulate lead level was still increasing, but the results trend suggests that at some rate greater than ~21 L/min the particulate lead release would level off. The purpose of the data presented was to demonstrate that higher sampling velocities may be needed to mobilize some of the particulate lead that may be present. However, these data also suggest that it may be possible to determine a maximum flushing velocity, above which little additional release of particulate lead will occur.

Once the optimal velocity needed to dislodge and remove particulate material is estimated, then some remaining questions for flushing as a lead reduction strategy include: (a) what duration of flushing at this velocity is needed to keep customers from being exposed to particulate lead releases and (b) does flushing at this velocity and duration produce long lasting effects, or do these flushing conditions need to be repeated later (and how much later).
Figure 2.3 is a schematic depicting how particles and loose scale can be dislodged and released at a given pipe velocity. At a higher velocity it would be expected that greater amounts of the material would be dislodged and moved, suggesting that sufficiently aggressive flushing practices could remove large deposits of lead-containing particles, loose scale, and other debris that could easily be transported to the customer tap if not removed by flushing or some other mechanism. As noted in the SAB report (EPA 2011), there is a significant increase in total lead levels in water, principally particulate material, following a LSL replacement, especially partial LSL replacements due to cutting, vibrations, and other disturbances during replacement. It may be beneficial for utilities to employ high velocity flushing following a LSL replacement in order to dislodge and remove particulate material created during these replacement activities.

A recently completed project (Brown and Cornwell [N.d.]) investigated high velocity flushing following partial LSL replacement. The study compares additional high velocity flushing of the LSL after replacement via two mechanisms: (a) opening the outside hose bibs for a longer time and higher flow rate than during normal flushing following LSL replacement (duration ~20 minutes) or (b) flushing from inside the house by the customer opening all indoor household taps for 30 minutes. Samples were taken for three months following the LSL replacement. The results indicated that additional flushing of the service line did not improve lead levels observed during at least the first three months. However, in a number of cases, a single high velocity flushing event inside the house later in the day after an LSL replacement produced lead levels below detection limits within the first month, and this level was maintained until at least three months following the flushing event.

CUSTOMER PUBLIC EDUCATION AND RECOMMENDATIONS FOR CUSTOMER PRACTICES

The current LCR includes a requirement for public education materials that water systems must supply to their customers to help customers develop appropriate practices to protect themselves from lead exposure in drinking water (EPA 2008). This required communication includes recommendations for flushing their tap after water has been sitting stagnant overnight (for 0.5 to 2 minutes, until cold, or until steady temperature), cook and prepare baby formula with cold water, etc. Customer behavior and usage practices may have an impact on customer exposure to lead as the practices limit the use of the water that has been stagnant in the home plumbing and service lines and so could potentially contain lead.
CHAPTER 3
LEAD SERVICE LINE REPLACEMENT

BACKGROUND

Lead pipe was used for service lines in the US during a period that began before 1900 and continued to the middle of the 20th century. Lead pipe was favored for use in service lines because of its malleability, durability, and reasonable cost. Many plumbers and contractors stopped using lead pipe as early as 1920s, more during 1930s-1940s and onward.

Even though replacement of LSLs does not eliminate any lead scale that may be inside the household premise plumbing due to migration of lead from the LSL, it still may be beneficial to remove the LSL since it represents a substantial quantity of lead in contact with water. Furthermore, during the normal course of operations, service lines are routinely replaced either because of emergency repairs or because new water or wastewater lines are installed causing some service lines to be cut.

There are a number of reasons why LSLs may be cut and replaced: (1) emergency repairs (2) scheduled utility work in street (3) efforts to remove/replace LSLs as part of lead reduction strategy and (4) as part of a utility’s infrastructure replacement plan or (5) customer-requested and/or home renovations.

Buildings constructed before the 1920s are most likely to have lead service lines. Those built between 1920s and 1950s may have some lead. The use of lead for service lines continued to decrease until the 1980s, and its use was banned in 1986. Figure 3.1 compares lead service line occurrence (Weston and EES 1990) against the backdrop of statewide percent of houses built prior to 1940. As expected, houses west of Nebraska (NE) are newer and less likely to have LSLs than eastern states. States with older houses are more likely to have LSLs including a collection of states stretching from the northern Midwest to New England (NE, MN, IA, WI, IL, MI, IN, OH, KY, PA, NY, MA, CT, and RI).

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9 Cast iron was the preferred choice for water mains, with lead typically limited to service lines.

10 For example, if a new water line is installed, the existing services are cut, the old water line removed, and the service lines re-connected to the new water pipeline. Typically, if lead service lines are detected, the lead is replaced at least to the end of utility ownership, and including the owner side if possible (see later discussion).
LSL REPLACEMENT STEPS

Most of the logistical steps associated with completing a full- or partial-LSL replacement are the same regardless of why the replacement is occurring, although if the replacement occurs during an emergency repair, some of the steps may be not be possible. An important first step before digging, cutting, installing, etc. is to identify locations with LSLs.

During the flushing study described by Brown and Cornwell ([N.d.]), one of the most difficult tasks was identifying locations where LSL could be found. In some cases utilities had extensive records, but a substantial number of locations (>50 percent) that were thought to be suitable for the study had either been misidentified as lead or the LSL had been replaced by the customer or the customer’s plumber without the water system’s knowledge.

In other systems with less extensive data records, the ability to identify LSL locations was even more problematic. Inspection of the service line once it has entered the customer’s home can supplement system records. Some systems have captured this information when installing meters or replacement meters.

Given that lead service lines have been installed for over fifty years, in most cases excavation will be the only certain way to determine the service line pipe material present over the entire length of the line. Several researchers have looked for other approaches, including sampling for lead. One approach is to use lead profiling to identify possible LSL locations. Lead profiling involves the collection of 10 consecutive 1.0 L samples that are analyzed for lead. Elevated lead levels, especially in 4th to 8th liter suggests the presence of a lead service line. Bannier (2011) and Cartier et al. (2012) have presented research using water sample profiling, supplemented by field measurement of lead using anodic stripping voltammetry.

Table 3.1 summarizes one utility’s approach to identifying lead service lines and documenting LSL replacements in their system. Appendix A is a Standard Operating Procedure (SOP) developed by a water utility for crews engaged in lead service renewal.
Table 3.1  
Decision matrix for lead service renewals in one water system

<table>
<thead>
<tr>
<th>Situation</th>
<th>Action</th>
<th>Justification</th>
<th>Follow-Up</th>
</tr>
</thead>
<tbody>
<tr>
<td>The service has been identified as containing lead through review of GIS and other files</td>
<td>Profile Service</td>
<td>Electronic database indicates that lead is present in the service line</td>
<td>Provide information to Project Manager</td>
</tr>
<tr>
<td>⅝ inch copper found in vault</td>
<td>GIS records indicate service is lead</td>
<td>Renew Entire Service</td>
<td>Complete Service Installation Data Sheet or Work Order indicating that service has been renewed, include date completed and return to supervisor for updating service records</td>
</tr>
<tr>
<td>GIS identified as lead, but copper found in field – Query of Work Order System for address reveals a previous service run with a code of “077” indicating that the service has been renewed in the past</td>
<td>Work done in 2008 or later</td>
<td>Do Not Renew</td>
<td>Complete Service Installation Data Sheet or Work Order indicating that service has been renewed; include date completed if applicable and return to supervisor for updating of service records</td>
</tr>
<tr>
<td>GIS identified as lead, but copper found in field – Query of Work Order System for address reveals a previous service run with a code of “077” indicating that the service has been renewed in the past</td>
<td>Work done before 2008</td>
<td>Renew Entire Service</td>
<td>Complete Work Order or Service Installation Data Sheet indicating that service has been renewed; including date completed and return to supervisor for updating of service records</td>
</tr>
<tr>
<td>¾ inch or larger copper tubing and compression stops found in meter vault (front and back) with evidence of road cut over main, or recent full-width repaving</td>
<td>Do Not Renew</td>
<td>City service and maintenance crews started using compression stops in the mid-1990s; use by Contractors is even more recent. Service work completed during the last ten years would have included a complete renewal of the service. A road cut indicates recent work, but recent paving may hide the road cut.</td>
<td>Complete Service Installation Data Sheet or Work Order indicating that service has been renewed; include date completed and return to supervisor for updating of service records</td>
</tr>
<tr>
<td>Copper in vault and curb stop key tube still in ground but inaccessible (rag or other debris in tube)</td>
<td>Renew Entire Service</td>
<td>Past practice may have included renewal of the service line from vault to the curb stop. Rags or other debris would have typically been placed in the key tube to prevent operation of the stop.</td>
<td>Complete Service Installation Data Sheet or Work Order indicating that service has been renewed; include date completed and return to supervisor for updating of service records</td>
</tr>
</tbody>
</table>
The activities necessary to complete the replacement associated with water main work or other routine scheduled utility work may include the following steps, while other types of LSL replacement (e.g., emergency repairs, LSL replacement as part of a lead reduction strategy, etc.) will typically require all but step 2:

1. **Contact with Customer** – If possible, this should include direct personal contact between utility staff and customer. This can more readily be done as part of the plan for a scheduled street water main replacement project. Direct contact, through letters to targeted homes will be the primary outreach strategy, perhaps supplemented by door hangers or phone calls. Written information provided should include a description of the project (what you are doing, why, how long it will take, etc.) and any precautionary notes about how customer water usage should be adjusted after replacement. This communication should include encouragement to customers to replace their portion of the LSL in conjunction with water system replacement of the utility portion of the LSL. Outreach to customers should occur sufficiently early in the project schedule to allow coordination between the utility, customers, and the customer’s plumber.

2. **Replace Water Main** – In cases where a water main is being replaced, this work needs to be completed before service lines are connected. If LSLs were not expected to be present but are detected during excavation and installation of the water main, contact customers with LSLs to let them know that the utility will be replacing the portion of LSL on utility property and advising the customer to arrange to also replace their portion of LSL. This typically will require the customer to find a contractor and pay for LSL replacement on their property, but some water systems may offer to pay for some of the customer’s LSL replacement cost.

3. **Excavate Utility Owned Portion of LSL** – If trenching is needed, this step is necessary prior to Step 4. If trenchless techniques are used, then lead pipe is pulled out and replacement pipe is drawn in as part of step 4.

4. **Cut, Remove LSL, Replace with Service Line that does not Contain Lead** – A cutting tool like the one shown in Figure 3.2 is preferred to other available tools that use a sawing or other abrasive action. As noted in Step 1, if this work can be coordinated with the property owner, the owner can arrange to have their portion of the service line replaced as well. Such replacement of both the customer and utility portions of the LSL should be strongly encouraged whenever possible. If copper is used to connect to the remaining LSL on the customer side, it may be necessary to install a dielectric to protect against or reduce galvanic corrosion effects, though this will also mean taking precautions to limit potential hazards from electrical shock. Water service pipes are often used for bonding home electrical systems and home wiring may be deliberately or inadvertently grounded to the water supply line. These connections to the service line can place an electric current on the service line (Welter et al. 2013). The current National Electric Code (2011) provides for bonding to water service lines (Section 250.104) and requires at least

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11 For example, one water system will reimburse customer up to $100/ft and up to $500 to penetrate a wall if customer agrees to replace customer’s portion of LSL while the water system is replacing their portion of service line. This information should be relayed to the customer during other discussions between water system staff and customer during step 1.
10 feet of metal (water) pipe in direct contact with soil (Section 250.52(A)(1)). Consequently, item 4.1 in the SOP in Appendix A includes the following:

The Contractor or CITY Crew shall check each service for electric current before working on the service by clamping an ammeter around the service line. If the amperage is greater than or equal to 2 amps, the electrically charged water service shall immediately be brought to the attention of the CITY Inspector or Crew Supervisor. The work shall then cease and the electric utility shall be called to report an electrically hot service line and to have the electrical service and grounding system inspected. Work may resume once the electric utility has corrected the problem.

When the water service line is serving as grounding for the home, actions that shorten the required 10 feet of metal pipe in direct contact with soil are important to the structure’s compliance with the current electric code.

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**Figure 3.2**  LSL cutting tool used to reduce cuttings and disturbance during LSL replacement

5. **Flush** — See earlier discussion about high velocity flushing. Some flushing following LSL replacement should always be provided. Research described in Brown and Cornwell ([N.d.]) suggests greater benefit from a longer duration and higher velocity flushing procedure than often used after LSL replacement, in particular if this includes high velocity flushing (with screens, aerators, filters, etc. removed) from inside the house. In the work described by Brown and Cornwell ([N.d.]), the standard procedure was to flush with all taps open inside the house for 30 minutes. One utility has been performing similar procedures for all replacements since 2011, except they use a 60-minute duration instead of 30 minutes. Another utility flushes at highest velocity from three different taps operated one at a time for 10 min each. Another system conducted flushing before and after sampling studies and found that 60 minutes of flushing from an outside spigot met utility goals for removal of particulate lead after LSL replacement.

6. **Collect Samples After Four to Six Months** — As noted above, one utility uses high velocity flushing and finds that lead levels are at acceptable levels after four to six months, at least at locations where customers agreed to collect samples. Unless a lead service line replacement is required under the LCR, post-LSL replacement sampling is optional, but may be a useful precaution for water systems.
to consider. Taking these samples will involve re-engaging the customer. If LSL renewal was not a complete replacement then obtaining a lead profile might be a useful and informative sampling protocol. Prior to post-LSL renewal sampling, the utility should determine an acceptable goal for lead levels in these samples, and a plan of action if lead levels exceed this goal (i.e., provide more water filters, re-sample at later date, etc.). Water systems should be prepared with recommended practices and precautions for customers in situations where lead levels are above utility goals in any of these samples.

7. **Record Location** – Maintaining a record of the renewal and characterizing the service line will be beneficial for compliance with the LCR, future interactions with customers at that address, and the system’s asset management planning.

Below are some observations from one utility performing tasks like those outlined above during full and partial LSL replacements:

- Some residents did not want their sidewalks, yards/landscapes, patios, etc. dug-up to install curbstops at the property-line. In these cases the customer had to sign an agreement stating that they would take ownership of the “public-side” of the line so that curbstops could be moved further away from the premises.
- A great deal of time and effort was spent on dealing with lawsuits and FOIA (Freedom of Information Act) requests regarding property damage.
- Mis-markings by “Miss Utility” (a “call before you dig” service operated by many state governments) have caused delays in work schedule.
- One customer location required asbestos abatement in the crawl space prior to the LSL replacement. A great deal of time and expense (e.g. adding an additional foot of dirt in crawl space following abatement; insulation for pipes; “dry dirt”; etc.) was incurred by the water system in order to complete the work.
- Homeowners on one block did not want to have the LSL replacement work performed because they recently had ‘historic’ brick sidewalks and granite curbs installed.
- Split service caused delays and greater construction cost. Split services are unauthorized, but exist. For example, one house arranged to have the service line replaced, but investigation revealed a service from a main split before the meter was feeding a second house.

**CUSTOMER PARTICIPATION AND COOPERATION**

Sampling for lead under the LCR must be undertaken in private homes after the water hasn’t been used for at least 6 hours. This usually means that the customer is asked to sample the tap early in the morning before anyone uses water in the household. This requires utility coordination and customer cooperation to assure that the samples are collected correctly. Water systems routinely report difficulty obtaining customer participation in LCR compliance sampling. There are reports of customers at compliance locations with low lead levels dropping out of the sampling program thereby increasing the proportion of higher lead locations in the compliance sampling pool. Actively engaging customers is important on an array of fronts beyond LCR compliance monitoring.
Encouraging customers with LSLs to replace their portion of the LSL whenever the water system replaces the utility portion of the LSL appears to be even more important than previously realized. Some utilities have within their own finances or through partner organizations developed strategies to provide financial assistance to challenged customers. Identifying viable strategies to extend such assistance to LSL renewal might encourage greater participation.

Other utilities have identified contractors that are qualified to replace LSLs at clearly described costs. Water systems need to consider state law and local considerations when developing innovative approaches like these. Assisting customers and identifying appropriately trained and equipped plumbers eliminates a number of risks of concern to both the water system and customers but may not be legal in some states and could represent a liability for a water system if something goes wrong with the installation.

Some form of high velocity flushing for 30 min or more after LSL replacement may be beneficial for customers. Available data suggest it is important to flush thoroughly from inside the house. Consequently, this increases the reliance on the customer to do the flushing, and to do it correctly. If there is a need for lead sampling after a LSL replacement, the interaction with the customer continues.

Effectively engaging customers entails a substantial and sustained effort. While each water system’s approach will be unique to the communities they serve, there are likely to be common considerations: (1) clear, concise communication, (2) financial assistance such as water bill reduction for flushing after a LSL replacement, or cash or prepaid credit cards to customers that provide samples.

Lead service line replacement has been used by many utilities either directly or indirectly to reduce the occurrence of lead at consumer’s taps. The experiences of utilities and their recommended procedures, including customer education described in this chapter have been successfully used to minimize lead levels at the taps.
REFERENCES


GPO (U.S. Government Publishing Office). 2014. 42 US Code, Section 300g–6 - Prohibition on use of lead pipes, solder, and flux (as amended by “Reduction of Lead in Drinking Water Act” (P.L. 111-380)),


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Schock, M., S. Triantafyllidou, and M. DeSantis. 2014a. Peak lead levels and diagnostics in lead service lines dominated by PbO2. Proc. of AWWA Annual Conference (Boston, MA).

Schock, M., A. Cantor, S. Triantafyllidou, and M. DeSantis. 2014b. Importance of Fe and Mn pipe deposits to lead and copper rule compliance. Proc. of AWWA Annual Conference (Boston, MA).


## ABBREVIATIONS

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>µg</td>
<td>Microgram ($10^{-3}$ mg)</td>
</tr>
<tr>
<td>µM</td>
<td>Micromolar ($10^{-6}$ moles/L)</td>
</tr>
<tr>
<td>AL</td>
<td>Action level</td>
</tr>
<tr>
<td>ANSI</td>
<td>American National Standards Institute</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials International</td>
</tr>
<tr>
<td>atm</td>
<td>Atmosphere (standard) – a measure of pressure equal to 14.7 psi (pounds per square inch) or 101 kPa (kilopascal)</td>
</tr>
<tr>
<td>AWWA</td>
<td>American Water Works Association</td>
</tr>
<tr>
<td>AwwaRF</td>
<td>AWWA Research Foundation (now WRF)</td>
</tr>
<tr>
<td>C</td>
<td>Carbon</td>
</tr>
<tr>
<td>CaCO₃</td>
<td>Calcium carbonate</td>
</tr>
<tr>
<td>Cl₂</td>
<td>Chlorine</td>
</tr>
<tr>
<td>DBP</td>
<td>Disinfection by-product</td>
</tr>
<tr>
<td>DBPR</td>
<td>DBP Rule</td>
</tr>
<tr>
<td>DIC</td>
<td>Dissolved inorganic carbon</td>
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<tr>
<td>Eₚ</td>
<td>Electron activity, a measure of oxidation state, measured in units of V or mV</td>
</tr>
<tr>
<td>EPA</td>
<td>U.S. Environmental Protection Agency</td>
</tr>
<tr>
<td>FOIA</td>
<td>Freedom of Information Act</td>
</tr>
<tr>
<td>ft</td>
<td>feet</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographical information systems</td>
</tr>
<tr>
<td>gpm</td>
<td>Gallons per minute</td>
</tr>
<tr>
<td>H⁺</td>
<td>Hydrogen +1 ion</td>
</tr>
<tr>
<td>IWA</td>
<td>International Water Association</td>
</tr>
<tr>
<td>L</td>
<td>Liter</td>
</tr>
<tr>
<td>LCR</td>
<td>Lead and Copper Rule</td>
</tr>
<tr>
<td>LSL and LSLs</td>
<td>Lead service line(s)</td>
</tr>
<tr>
<td>LTLCR</td>
<td>Long-term LCR</td>
</tr>
<tr>
<td>mg</td>
<td>milligram</td>
</tr>
<tr>
<td>min</td>
<td>minute</td>
</tr>
<tr>
<td>mV</td>
<td>Millivolts ($10^{-3}$ volts)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
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<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>N</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>NH₂Cl</td>
<td>Monochloramine</td>
</tr>
<tr>
<td>NJ DEP</td>
<td>State of New Jersey Department of Environmental Protection</td>
</tr>
<tr>
<td>NSF</td>
<td>National Sanitation Foundation International</td>
</tr>
<tr>
<td>O₂</td>
<td>Oxygen gas from atmosphere dissolved in water</td>
</tr>
<tr>
<td>OCCT</td>
<td>Optimized Corrosion Control Treatment</td>
</tr>
<tr>
<td>P</td>
<td>Phosphorus or elemental phosphorus</td>
</tr>
<tr>
<td>Pb</td>
<td>Lead</td>
</tr>
<tr>
<td>Pb(II)</td>
<td>Lead in +2 oxidation state</td>
</tr>
<tr>
<td>Pb(II) scale</td>
<td>Any combination of Pb(II) hydroxycarbonate solids (no orthophosphate)</td>
</tr>
<tr>
<td>Pb(IV)</td>
<td>Lead in +4 oxidation state</td>
</tr>
<tr>
<td>Pb(IV) scale</td>
<td>PbO₂ (s)</td>
</tr>
<tr>
<td>Pb(0)</td>
<td>Elemental lead</td>
</tr>
<tr>
<td>Pb⁺²</td>
<td>Pb(II)</td>
</tr>
<tr>
<td>Pb⁺⁴</td>
<td>Pb(IV)</td>
</tr>
<tr>
<td>Pb₃(CO₃)₂⁻²</td>
<td>A particular soluble lead carbonate complex. Other soluble lead complexes in this figure include: PbHCO₃⁺, PbCO₃ (aq), Pb(OH)₂ (aq), Pb(OH)⁻³, Pb(OH)⁺⁻², PbO₃⁻²</td>
</tr>
<tr>
<td>Pb-content or Pb-containing</td>
<td>Solder or plumbing containing some amount of lead</td>
</tr>
<tr>
<td>PbO₂ (s)</td>
<td>Lead oxide solids</td>
</tr>
<tr>
<td>pH</td>
<td>Activity of H⁺ ion</td>
</tr>
<tr>
<td>PO₄ or PO₄⁻³</td>
<td>Orthophosphate or orthophosphate ion</td>
</tr>
<tr>
<td>POU</td>
<td>Point of use</td>
</tr>
<tr>
<td>s</td>
<td>second</td>
</tr>
<tr>
<td>SAB</td>
<td>Science Advisory Board</td>
</tr>
<tr>
<td>SOP</td>
<td>Standard operating procedures</td>
</tr>
<tr>
<td>THM</td>
<td>Trihalomethane</td>
</tr>
<tr>
<td>TTHM</td>
<td>Total THM</td>
</tr>
<tr>
<td>UL</td>
<td>Underwriter’s Laboratory</td>
</tr>
<tr>
<td>US</td>
<td>United States of America</td>
</tr>
<tr>
<td>USGS</td>
<td>U.S. Geological Survey</td>
</tr>
<tr>
<td>V</td>
<td>Volts</td>
</tr>
<tr>
<td>WaterRF</td>
<td>Water Research Foundation (formerly AwwaRF)</td>
</tr>
<tr>
<td>WI</td>
<td>Wisconsin</td>
</tr>
<tr>
<td>WQA</td>
<td>Water Quality Associates</td>
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1.0 PURPOSE

The purpose of this document is to provide CITY employees with guidelines to be followed when replacing lead service lines.

2.0 SCOPE

This work instruction is to be followed when replacing lead service lines that are encountered as part of the City’s Lead Service Renewal and Point Renewal Projects.

3.0 RESPONSIBILITIES

The Project Manager will be responsible for reviewing information from the available historic service database to identify potential lead service lines. The Project Manager will show the lead service lines on the project plans. The Project Manager shall ensure that the existing services are profiled in the field to verify the presence of lead service lines in the meter vaults.

The Inspector, Contractor or CITY Crew will be responsible for field verifying the service line material on both sides of the property line connection during construction and following this work instruction.

4.0 WORK INSTRUCTIONS

4.1 The Contractor or CITY Crew shall check each service for electric current before working on the service by clamping an ammeter around the service line. If the amperage is greater than or equal to 2 amps, the electrically charged water service shall immediately be brought to the attention of the CITY Inspector or Crew Supervisor. The work shall then cease and the electric utility shall be called to report an electrically hot service line and to have the electrical service and grounding system inspected. Work may resume once the electric utility has corrected the problem.

4.2 The Contractor, CITY Crew or Inspector will identify the property line location which is usually a few feet away from the meter vault and excavate the service line. Vacuum excavation or hand digging is the preferred method of excavating the service line. If the property line connection is not found, the Contractor or CITY Crew shall seek permission from the property owner to excavate on private property and continue to excavate up to 3' beyond the suspected property line location onto the private property in an effort to find the connection and determine the customer’s service line material.
4.3 The Inspector or CITY Crew shall determine the service line material on the customer’s side of the property line connection. If the material on the customer’s side is not lead, then the Contractor or CITY Crew shall replace the entire CITY lead service from the main to the property line connection.

4.4 If the material on the customer’s side of service line is lead, the Inspector/Crew Supervisor shall contact the customer to make them aware of the replacement work to be completed by CITY and the existence of lead on the customer’s side of the property line connection. The Inspector/Crew Supervisor shall then provide the customer an informational letter on lead service lines and recommend that the customer hire a private plumber to replace all private lead service line material. If the customer has questions about their lead service line, the Inspector/Crew Supervisor shall direct the customer to the Project Manager. If the Inspector/Crew Supervisor is unable to make contact with the customer, the inspector/Crew Supervisor shall leave a note on the customer’s door asking them to call to discuss their water service line. The Inspector/Crew Supervisor shall document the name of the customer who was informed of the existence of the lead service line and provided the lead information on the construction/installation data sheet.

a) If the customer is willing to replace their private lead service line, the Contractor or CITY Crew shall coordinate the replacement of CITY’s lead service work with the customer’s plumber.

b) If the customer is not willing to replace their lead service line and the meter vault will not be relocated as part of this project, then the Contractor or CITY Crew shall replace the portion of the lead service line between the main and the meter vault only and leave the lead tailpiece in place and note this on the construction/installation data sheet.

c) If the customer is not willing to replace their lead service line and the meter vault will be relocated as part of this project, or the tailpiece is leaking, or the vault contains a dual metersetter or coppersetter (i.e., when two property’s meters are in one vault, the meter that is not located on the correct property will be relocated) then the Contractor or CITY Crew shall replace the entire CITY lead service line and install a dielectric between the end of the new CITY service tail piece and the private lead service line. The dielectric shall be composed of a 24” section of like diameter schedule 80 PVC pipe and a Philmac/Harco plastic universal transition coupling to convert from the schedule 80 PVC to the private lead service line. The schedule 80 PVC and universal transition coupling act as a dielectric coupling at the property line connection to separate the copper line from the lead line. An electrical jumper shall
not be installed between the private lead service line and CITY’s new copper service line. When installing the dielectric coupling, if the customer’s service line is less than 10 feet in length as measured from the building to the dielectric connection, then a licensed electrician will be retained to install an appropriate grounding system.

4.5 The Inspector/Crew Supervisor shall document the service replacement information on the service construction/installation data sheet.

POLICY UPDATE: CITY reserves the right to review and update its policies and procedures, as deemed necessary, at any time.