Evaluation of Lead Sampling Strategies

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Subject Area: Water Quality
Evaluation of Lead Sampling Strategies
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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

OBJECTIVES

The project conducted a side-by-side comparison of different water sampling strategies to determine the lead levels in the home. This information will help utilities understand how different sampling procedures compare. In addition, this research will help inform the regulatory review process for the Long-Term Lead and Copper Rule (LTLCR).

BACKGROUND

The current Lead and Copper Rule (LCR) requires collection of compliance samples from the first liter at the tap following a minimum six-hour stagnation period. There is debate among experts as to whether this sampling protocol is effective at capturing elevated lead levels. Some data has indicated that lead levels can be higher in water that was stagnant in the lead service line compared to lead levels in the first liter. Stagnant water in the lead service line usually reaches the tap later (i.e., sometime after the first L), generally by the 4th to 7th liter, depending on site-specific conditions.

Profile sampling, the collection of multiple sequential one-liter (1-L) samples from a household sampling location that has remained stagnant for at least six hours, is a method used to identify and quantify peak lead levels at one sampling location on a given date. This procedure has been used in previous lead sampling studies to determine the peak lead level (e.g., Del Toral et al. 2013). Profile sampling effectively pinpoints the specific location where the peak total lead concentration peaks within the premise plumbing or service line under the conditions evaluated (e.g., specific time and flow regime). However, the collection of sample profiles presents complex logistical issues, even during special studies like this one with specially-trained water system staff collecting the samples. For example, there are significantly more sample bottles to prepare and label, more forms to fill out, more samples to analyze and keep track of, etc. These complexities can increase the likelihood of sampling and collection error. In addition, many utilities already face challenges with getting customers to collect samples using the current simplified collection procedures. More complex sampling protocols will likely make it harder for water systems to recruit and maintain customer sample collection volunteers and ensure quality control of the samples. Therefore, an ideal lead sampling strategy should be able to estimate the peak lead level while considering reasonable logistics and accurate results.

APPROACH

The project conducted a side-by-side comparison of five lead sampling techniques. Each strategy’s effectiveness at detecting peak total lead levels was evaluated. These strategies were compared to results collected during a minimum 12-L profile on each sampling date. The five sampling strategies are listed below:

a) Run tap water until a temperature change is detected and then sample
b) Collect a full profile during a one-time sampling event at each location, determine the profile volume with the peak lead concentration, and collect future samples for lead at this peak profile volume (the “initial peak” method)
c) Sample a fixed sample volume (e.g., the 5th liter)
d) Sample the middle of the service line (SL) or lead service line (LSL) based on site specific calculations
e) Collect a composite sample (e.g., the first gallon or first ~4 liters)

Samples were collected, either by water system staff at customer houses or by recruiting customers to collect samples at home. The study included eight participating utilities, 37 sampling locations (homes), and 96 sampling events. The samples were collected between May and December 2014, except for one set of November 2011 sample data used at one participating water system for comparison with the study results at their monitoring locations. Samples were taken according to sampling protocols listed in Appendix A and B. The two sampling protocols are nearly identical, with one listing all tasks to be conducted by water system staff (Appendix A), and the other listing a subset of these tasks for use by customer volunteers (Appendix B). The samples were analyzed for dissolved and total lead, iron, manganese, and copper. Analyses of other metals were also performed by some participating utilities. The sampling protocols directed customers to avoid using water during the 6-hour stagnation period prior to sample collection. Aerators were removed prior to sample collection so particulates could be captured, and then the customers were instructed to open the taps to a normal flow condition for sample collection.

KEY FINDINGS RELATED TO LEAD SAMPLING STRATEGIES

Results from sampling methods were compared to the peak found from the full profile in two ways. First, it was determined if the sampling strategy actually located the peak as found by the full profile. Second, it was determined whether the sampling strategy resulted in a lead level that was within 70 percent of the peak.

Key findings of the five sampling strategies are as follows:

1. No sampling method was particularly proficient at finding the peak lead level compared to doing a full profile for each sampling event.
2. Figure ES.1 summarizes the sampling method results from the study, characterizing the results by the percentage of observations that produced a total lead result within 70 percent of the peak total lead value. The peak total lead value was the highest lead level found during each profile sampling event.
   i) The initial peak profile method (see “Approach” discussion above, item “b”) of conducting one profile in a home and then using that peak volume for subsequent sampling was within 70 percent of the peak total lead 48 percent of the time. This was the highest of any method but it also found a value less than 30 percent of the peak 30 percent of the time. In other words, about half the time this method was a good approximation of the peak, but a third of the time it was only a fraction of the peak.

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¹ One participating utility did not analyze total or dissolved iron.
ii) The 6th L sample volume was within 70 percent of the peak total lead 44 percent of the time and was the second best method using the criteria stated, and the best single 1-L profile volume for approximating the lead peak.

iii) The SL midpoint was similarly able to produce a total lead result within 70 percent of the peak about 44 percent of the time. Note that the “SL midpoint” is the midpoint of the complete service line, not the midpoint of the lead portion of the service line. The midpoint of the lead portion of the service line (LSL) was within 70 percent of the peak about 41 percent of the time. This could indicate errors in tabulation or calculation of the LSL location, or it could indicate that the lead concentrations within the LSL may not necessarily correspond to peak total lead values. The researchers, including participating utility staff, carefully checked LSL location information and associated calculations.

3. The 1st L sample was the best method of finding the peak lead (27 percent of the time), though 6th and 7th L were similar (26 and 23 percent, respectively). However, the 1st L samples that were not the peak value typically were not within 70 percent of the peak total lead value for the entire profile. The 6th and 7th L results were better than the 1st L (or any other discrete profile volume) at finding results within 70 percent of the peak total lead value. In fact, only the “initial peak” method was a better peak lead predictor than the 6th L.

4. The water temperature change method and the composite first four liters were not good methods to locate total lead values within 70 percent of the peak.

OTHER KEY FINDINGS

Particulate Lead Considerations

Some assumptions were made in order to assess particulate and dissolved lead contributions. First, although not exactly correct, dissolved lead was equated to the lead value after filtering the sample before analysis. Particulate lead was defined as the total lead without filtering minus the filtered lead value. A sample was considered particulate dominated if the particulate content was greater than 70 percent of the total. Similarly, a sample was considered dissolved dominated if the dissolved fraction was greater than 70 percent of the total. A mixed dissolved and particulate sample was one that fell in between.

Of all the peaks, 38 percent of them were particulate-dominated, as compared to 33 percent of the peaks being dissolved lead-dominated, and 29 percent in between. Therefore, of all the profile peaks, only about one-third of the peaks were primarily dissolved lead, and two-thirds were either particulate-dominated or were a mix of particulate and dissolved.

All eight participating water systems had a combination of locations that were either dominated by dissolved lead, dominated by particulate lead, or something in between. No water system had exclusively dissolved lead-dominated sites or exclusively particulate-dominated sampling locations. This implies that utilities with lead lines will have some homes with primarily particulate lead, and other homes with primarily dissolved lead, all in the same distribution system. Independent of the corrosion control method used, none of the utilities were dominated system-wide by any one lead form.

Of the 33 houses studied in the research (excluding locations only sampled once and those with all samples below the detection limit), seven were always particulate lead dominated
(21 percent of the houses) and four were always dissolved lead dominated (12 percent of houses). The other 22 houses (67 percent of the houses) had particulate lead-dominated water on some dates and dissolved-dominated on other dates. This finding would indicate that even at a specific site, on some occasions the sampling can be particulate dominated, and on other dates the lead can be dissolved dominated or some combination.

**Water Temperature Changes for Water within the Service Line at End of the Stagnation Period**

At the 24 locations where both water temperature data and boundaries of the SL were known, the temperature change occurred within the SL at 12 locations (50 percent of the houses). At three locations, the temperature change occurred before the SL (13 percent of houses). At nine locations, the temperature change occurred after the SL (38 percent of the houses). Similarly for the LSL, at 12 of the houses, the water temperature change occurred within the LSL (50 percent of the houses). At six of the houses, the water temperature changed before the LSL (25 percent of the houses). At the remaining six houses (25 percent), the water temperature change was noted after the LSL. There were two instances where information on SL was known but where no information on whether lead was present or not was provided.

**Peak Profiles for Total Levels of Metals Other than Lead**

As with total lead, the highest total metal levels for aluminum, copper, iron, manganese, and zinc typically occurred in the 1st L of a sample profile. As shown in Figure ES.2, a greater percentage of the peak total lead results occurred in the 1st L as in other profile volumes, but there were significant number of peaks in other profile volumes (i.e., 27 percent of the results peaked in the 1st L, but the 6th and 7th L found 26 and 23 percent of the peaks). By contrast, except for total aluminum and manganese, the profile volumes after the 1st L did not have nearly as many peaks as in the 1st L. In two cases, copper and zinc, 70 percent or more of the peak observations occurred in the 1st L. Therefore, for these metals it appears that when a full profile is not possible, collecting the 1st L might give the best chance at finding the peak overall total levels of these metals. For aluminum, the 2nd L was associated with the peak 26 percent of the time and the 1st L 37 percent. Therefore, in this case a 2-L composite might be needed to find the peak total aluminum (though aluminum was only measured in 19 samples from this study). Figures ES.3, ES.4, and ES.5 illustrate the profiles with peak total metal levels for iron, copper, and aluminum in a similar manner as shown in Figure ES.2 for total lead.

**Peak Total Levels of Other Metals as Predictors of Peak Total Lead**

The results from this study suggest that total levels of some metals are more closely associated with peak total lead occurrence than are other metals. For example, 39 percent of the peak total aluminum results had total lead levels in the same profile sample that were within 70 percent of the overall peak total lead for the profile. By contrast, 30 percent of the peak total copper results were associated with total lead levels within 70 percent of the peak total lead for the profile. For other metals (iron, manganese, zinc) less than a third of the peak total metals results were associated with total lead levels that were within 70 percent of the peak total lead. Therefore, aluminum was more likely than other metals to peak at the same time as high total
lead levels were observed. Interestingly, peak iron did not correspond to a peaking of lead, even in the peak lead samples that were dominated by particulate lead (i.e., 70 percent of total lead was particulate lead). Of the 24 times\(^2\) when the peak total lead was particulate-dominated, the peak total iron profile only produced a total lead result within 70 percent of the peak in 8 of the 24 instances.

**RESEARCH PARTNER**

American Water Works Association

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Figure ES.1  Percentage of results within 70 percent of the peak using each sampling method

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\(^2\) There were 40 instances where peak total lead was particulate-dominated (i.e., >70 percent particulate lead), but 16 of these either did not have an iron sample collected or had total lead results in all 12 profile samples that were below the detection limit.
Figure ES.2  Peak profile for total lead

Figure ES.3  Peak profile for total iron
Figure ES.4  Peak profile for total copper

Figure ES.5  Peak profile for total aluminum
CHAPTER 1
PURPOSE AND BACKGROUND

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 IN DRINKING WATER

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/buildings. 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. It is not, however, 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. In addition, if oxidized conditions are present, reduced lead that is typically soluble is oxidized and so 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 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.

3 Or lead-containing “scale” deposited on plumbing that originated from these lead sources (see Figure 1.3)
These 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 homeowner, 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.

Figure 1.1 Depiction of water main, service line, and household plumbing

Note: The part of the service line closest to the water main is typically owned by the utility/city to the property line and the remainder owned by customer (derived from Hayes 2010)

Distribution system pipelines, pumps, valves, fittings, etc. in the utility-owned distribution system up to the service line are not major sources of lead in the US. They are generally not expected to be issues 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 (Irish Examiner 2013), and additional lead pipe in service lines. By 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 lead solder and lead lined fittings should have 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 percent lead by weight.

One source of concern with lead are lead particles that adhere to pipe surfaces (see later “Lead Chemistry in Drinking Water” discussion regarding the original source of lead comprising particulate lead). Figure 1.2 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 Science Advisory Board (SAB) report (EPA 2011), there is a significant increase in total lead levels in water, principally particulate material, following a lead service line (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 2015) investigated high velocity flushing following partial LSL replacement. The study compared 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 on the day after a 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.

In the above study, the one-time high velocity flushing event was associated with a partial LSL replacement the day before flushing. Consequently, the observed results were impacted by a combination of partial LSL replacement and flushing activities. A subsequent WRF funded study (WRF 4584), still in progress at the time this report was prepared, is
investigating the impact of a single high velocity flushing event from inside the house (same as item “b” above). A few of these flushing events are being conducted after partial LSL replacement, as above, but most are at houses with LSLs that either have never had a LSL replacement or that have had partial LSL replacement several years in the past. The goal then of the new study (WRF 4584) is to attempt to isolate the impact of flushing on the observed lead levels, as well as conducting the flushing at houses in different water systems than in Brown and Cornwell (2015).

LEAD CHEMISTRY IN DRINKING WATER

As described above, lead can only be present in the drinking water at the 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.

Figure 1.3 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.

Even though separate terms are used in this figure for “scale” and “particulate matter”, they are essentially identical in most respects, including their chemical composition and origins.
KEY DEFINITIONS

**Dissolved (Soluble) lead** can result from the corrosion of lead-containing plumbing or from dissolution of scale or particles. This form of lead is mobile and can be transported to the customer tap.

**Scale** can only be produced by electrochemical precipitation of soluble lead at various points in the distribution system or in household plumbing. This form of lead is considered non-mobile in this report, unless it becomes "particulate".

**Particulate lead** is the result of abrasion, dislodgement, and transport of broken off pieces of scale or lead containing pipe and plumbing (including solder). This form of lead has the potential to be mobile, as defined in this report, if it is suspended in water.

**Sorbed lead** is the result of sorption of soluble lead onto the surfaces of suspended particulate material or deposited onto surfaces of particulates and scale. Sorbed lead is potentially mobile, as defined in this report, if associated with particulates suspended in water.

(e.g., mixtures of lead oxides, hydroxides, carbonates, etc., physically and chemically deposited on surfaces). 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. Once formed, particulate lead 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 2011).

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. However, it is of concern because the scale and particulate matter can break off, become suspended in water, and reach the tap as particulate lead (see Figure 1.2). The particulate material that breaks off can not only contain insoluble lead and other metals but can also contain soluble lead and other metals sorbed onto the particulate surfaces.

Unlike dissolved lead and other metals that have an upper concentration limit due to the metal solubility in water, an unlimited amount of insoluble lead and sorbed lead can be associated with particulate material. Consequently, when this particulate material becomes suspended in water within the service line or household plumbing, the total lead levels at the water tap can be considerable depending on how much particulate lead is transported to the tap.
Table 1.1  
Comparison of the terms “particle” and “scale” as used in this document

<table>
<thead>
<tr>
<th>Term used in this document</th>
<th>Scale</th>
<th>Particulate material (also &quot;particles&quot; or &quot;particulates&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formed by</td>
<td>Electrochemical precipitation of soluble lead</td>
<td>Physical abrasion of scale, present either as:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>a. particles suspended in water or</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. particles physically deposited (settling out) elsewhere, subject to later suspension</td>
</tr>
<tr>
<td>Mobility</td>
<td>Not mobile unless it breaks off as particulate matter (which then can be subject to suspension in water) or is chemically converted into soluble metal.</td>
<td>Can be suspended in water, then physically deposited elsewhere, and then subject to re-suspension into water phase. Alternatively, particle can dissolve and mobilize as soluble lead.</td>
</tr>
<tr>
<td>Chemical composition</td>
<td>Oxides, carbonates, hydroxides, etc. or mixtures/combinations</td>
<td>Whatever original &quot;scale&quot; is made of</td>
</tr>
<tr>
<td>Variations</td>
<td>Scale can be chemically precipitated onto any surface, including onto a previously deposited scale layer (can be deposited onto or co-deposited with scale of different composition), or deposited as a layer on suspended particulate material (i.e., scale on a particle).</td>
<td>Particles can settle out from suspension then before they can be remobilized by water flow can become embedded into scale layer that electrochemically precipitates on top of deposited particle.</td>
</tr>
<tr>
<td></td>
<td>Scale or particulate material can dissolve and then electrochemically precipitate elsewhere in the system as a scale, which then can later break off to form a particle.</td>
<td>Part of new scale produced as outlined to the left can break off and form one or more new discrete particles.</td>
</tr>
</tbody>
</table>
Dissolved levels of lead and other metals in water can generally be controlled by systematic refinements in water chemistry conditions (Brown et al. 2013). Therefore, if pH, alkalinity, orthophosphate residual, or free chlorine residual are adjusted and maintained, it should be possible to control dissolved lead levels (except for dissolved lead sorbed onto particulates). However, particulate material can sporadically be released at unpredictable frequencies and variable quantities, thereby possibly releasing lead and other metals associated with this particulate material (Brown et al. 2015). Consequently, in general, dissolved lead releases are more systematic than releases of lead associated with particulate material (insoluble lead or sorbed lead). Therefore, it may be easier to develop sampling strategies to monitor systematic changes in soluble metal levels than it is to develop appropriate sampling methods to reliably monitor metals associated with fluctuating particulate material releases (e.g., particulate metals and sorbed soluble metals).

IN-HOME LEAD SAMPLING

During this project, the samples were often collected by trained water sample collection staff from the participating water system. Past LCR compliance samples generally depend on customer volunteers for sample collection. Volunteer customers may have more difficulties with more complicated procedures like those evaluated during this study than will the utility-trained staff who performed most of the sampling in this study. Therefore, in addition to demonstrating the inherent suitability of different sampling approaches to determine the peak lead occurrence, this project also included an evaluation of the suitability of the sample collection procedures for sampling by customers.

Several basic in-home methods could be performed in order to obtain a sample representative of the lead level. An approach used in this study for determining the highest lead level during a flowing tap after a 6 hour stagnation period is “profile sampling” like that described in other lead sampling investigations (e.g., Del Toral 2013). In this study a minimum of twelve sequential 1-L profile samples were collected at all locations for all sampling events. In a few cases with longer service lines (i.e., more volume), the profile included more than twelve 1-L samples. In this study, the peak lead occurring in these profile samples was used to demonstrate the peak lead at a given location on the sampling date. Similar profile samples on other dates were used to determine the peak lead on each of these other dates. Results from the other sampling approaches were evaluated by comparison to the peak lead occurring in the profile samples.

Profile sampling is effective at pinpointing the specific peak lead level location within the premise plumbing or service line under the conditions evaluated (e.g., specific time and flow regime). Collection of sample profiles presents complex logistical issues even during special studies like this one with specially trained water system staff doing most of the sample collection. For example, there are significantly more sample bottles to prepare and label, more forms to fill out, more samples to analyze and keep track of, etc. These complexities can increase the likelihood of sampling and collection error. In addition, many utilities already face challenges with getting customers to collect samples using the current simplified collection procedures. Sampling protocols that add complexity will likely make it harder to recruit and maintain customer sample collection volunteers and ensure quality control of the samples. Therefore, selection of a lead sampling strategy must balance the need for estimation of the peak lead level while considering reasonable logistics and accurate results.
The sampling approaches evaluated in this project included:

- Assigning a fixed volume (1st L, 5th L, etc.) for all locations, regardless of site conditions (i.e., whether LSL is long or short, proximity of house to water main, etc.)

- Calculate the midpoint of the service line (SL) or the midpoint of the lead portion of the SL (LSL)
  - Requires field measurement, review of records, or estimation of pipe length and diameter between the sampling point (e.g., kitchen sink) and the start and end of the SL

- Monitor water temperature and collect sample when the temperature changes
  - Alternatively, collect several profile samples, immediately measure water temperature, then discard all samples except the volume where first temperature change is noted

- Collect a composite sample (e.g., first gallon or first ~4 L)

- Collect one complete set of profile samples during a one-time sample event. Determine the profile volume with peak lead in this initial profile and then collect future compliance samples at this same profile volume.
  - This approach assumes the peak lead observed in the initial profile will occur at the same profile volume in later samples.
CHAPTER 2
SAMPLING METHODS

SAMPLING PROTOCOLS

The sampling protocols listed in Appendices A and B were used for lead profile sampling of household plumbing at each participating study location. The two protocols are nearly identical, with one listing all tasks to be conducted by water system staff (Appendix A), and the other listing a subset of these tasks associated with sample collection activities for use by customer volunteers (Appendix B). These procedures are summarized in Figure 2.1. The procedures from “Remove aerator” to “Record water temperature change” are described in both Appendices A and B and were performed either by sample collection staff from the participating water system in cooperation with the customer or were collected directly by the customer using materials and directions provided by the water system. The other tasks were performed by water system sample collection staff, staff from the water system’s own laboratory, or staff from a contract laboratory (i.e., the same laboratory that handles LCR compliance samples for the water system).

The first step in this process was the identification and selection of suitable sample collection locations. An important part of this process was not just finding the right locations, but finding locations with homeowners willing to either collect samples as directed or willing to provide access to water system sample collection staff. The homes tested during this study were known to have either a full or a partial lead service line. In most cases, the participating water systems were able to identify all the materials between the water main and sampling location, but in a few cases, they were not able to identify the pipe materials, even though they suspected or knew that some part of the plumbing still contained lead (see Chapter 3).

“Profiling” is a sampling strategy to identify the location(s) and source(s) of lead contributing to lead in household drinking water, including lead solder or a lead water service pipe. To create the profile, twelve or more one-liter samples of tap water were sequentially collected from a faucet in the home, typically in the kitchen. In all cases, the sampler was directed to use a normal flow velocity, described in the protocols as “a rate that would normally be used by the homeowner”. Each of these 1-L samples were analyzed for total (unfiltered) and dissolved (filtered) lead concentration, as well as copper, manganese, and iron in all cases and a few other metals in some cases (see Chapter 3). In order to help ensure that any mobilized particulate lead (and other metals associated with particulates) were collected in the profile samples, the aerator was removed prior to sample collection, as outlined in step 4 of Figure 2.1.

PARTICIPATING UTILITIES

The participating public water systems (PWSs) are listed and characterized in Table 2.1. The five water systems listed at the bottom in this table arranged with the customer to allow water system sample collection staff into their homes to collect samples for this study. The other water systems provided bottles and directions to customer volunteers and asked them to collect the samples and then contact the water system for sample pick up.

The last column describes the lead control strategy (see Brown et al. 2013 for descriptions and comparisons of lead control strategies). All but PWS 6 & 7 add orthophosphate
(PO₄) to control lead and copper solubility. These maintain the pH near 7.4 (± 0.4), except water system 1 maintains the pH at ~8.3. PWS 7 uses pH and alkalinity control (pH ~9.3 and alkalinity ~40 mg/L as CaCO₃). PWS 6 also controls pH (8.5 at one entry point and 9.2 at another) but also removes precursors of regulated disinfection by-products (precursors of trihalomethanes and haloacetic acids) thereby allowing maintenance of stable free chlorine residuals, and as such has been able to demonstrate the formation and maintenance of an insoluble lead (IV) scale.

MATERIALS FOR SAMPLE COLLECTION AND ANALYSIS

- Twelve (or more) one-liter wide mouth sample bottles, glass or polypropylene. Sample bottles were prepared (cleaned and acid washed) and labeled as per normal LCR collection procedures, except no preservative (acid) was added to the sample prior to collection.
- Permanent marking pen or sample bottle labels.
- Jar opener pad to help remove faucet aerator. Provide new replacement aerators if desired by customer.
- Wet wipes for hand cleaning, specifically processed and labeled “lead-free” (e.g., “D-Lead” brand available at www.grainger.com).
- Data collection form/chain of custody.
- Filtration apparatus and media that do not leach or sorb lead – see Table 2.2 for the filter media used by each participant (Figures 2.2 through 2.4 are photos of the three filter types listed in Table 2.2 – Figure 2.2 for “plunger type”, Figure 2.3 for “syringe filter”, and Figure 2.4 for “filter media disc”. Filter pore sizes in Table 2.2 are all at least 0.45 µm or smaller.
- Only a small volume, e.g. 50 mL was removed from the 1-L sample for filtration in order to minimize any errors associated with particles adhering to the bottle walls.
- After acidification of the 50 mL sample and the remaining 950 mL sample, filtered and unfiltered samples were held for at least 16 hours prior to analysis. Samples were not subjected to additional sample processing (e.g., “digestion”). Samples were analyzed using the same laboratory and analytical techniques as used for compliance samples.
Figure 2.1  Schematic of general sample collection and analysis profile for this study
Table 2.1
Characteristics of source water and treated water at participating water systems

<table>
<thead>
<tr>
<th>Participant</th>
<th>Geographic location</th>
<th>Water source</th>
<th>Free chlorine (Cl₂) or combined chlorine (NH₂Cl)</th>
<th>Lead control strategy</th>
<th>Target finished water conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWS 6</td>
<td>Midwest</td>
<td>SW</td>
<td>Free Cl₂</td>
<td>lead (IV)</td>
<td>pH 8.5 Orthophosphate 7.2 mg/L as P</td>
</tr>
<tr>
<td>PWS 4</td>
<td>Northeast</td>
<td>SW</td>
<td>Free Cl₂</td>
<td>PO₄</td>
<td>7.2 0.7</td>
</tr>
<tr>
<td>PWS 8</td>
<td>Midwest</td>
<td>SW</td>
<td>Free Cl₂</td>
<td>PO₄</td>
<td>7.3 0.3</td>
</tr>
<tr>
<td>PWS 7</td>
<td>Northeast</td>
<td>SW</td>
<td>NH₂Cl</td>
<td>pH/alkalinity 9.3</td>
<td>Not applicable</td>
</tr>
<tr>
<td>PWS 1</td>
<td>Southeast</td>
<td>SW</td>
<td>NH₂Cl</td>
<td>PO₄</td>
<td>8.3 0.4</td>
</tr>
<tr>
<td>PWS 2</td>
<td>Mid-Atlantic</td>
<td>SW</td>
<td>NH₂Cl</td>
<td>PO₄</td>
<td>7.2 0.8</td>
</tr>
<tr>
<td>PWS 3</td>
<td>Midwest</td>
<td>SW</td>
<td>NH₂Cl</td>
<td>PO₄</td>
<td>7.6 0.6</td>
</tr>
<tr>
<td>PWS 5</td>
<td>Southeast</td>
<td>SW</td>
<td>NH₂Cl</td>
<td>PO₄</td>
<td>7.6 0.5</td>
</tr>
</tbody>
</table>

SW  = surface water
PO₄  = orthophosphate
Lead (IV) = lead in the +4 oxidation state – generally insoluble in water – lead (IV) formation is promoted by maintenance of oxidizing conditions (e.g., free chlorine residual) in the distribution system
<table>
<thead>
<tr>
<th>Water system</th>
<th>Filter characteristics</th>
<th>Vendor</th>
<th>Model No.</th>
<th>Diameter (mm)</th>
<th>Pore size (µm)</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Syringe Filters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PWS 1</td>
<td></td>
<td>VWR International</td>
<td>28145-503</td>
<td>25</td>
<td>0.45</td>
<td>Polyethersulfone</td>
</tr>
<tr>
<td>PWS 3</td>
<td></td>
<td>Millipore</td>
<td>SLGP033NS</td>
<td>33</td>
<td>0.22</td>
<td>Polyethersulfone</td>
</tr>
<tr>
<td>PWS 5</td>
<td></td>
<td>VWR International</td>
<td>28145-497</td>
<td>25</td>
<td>0.45</td>
<td>Polytetrafluoroethylene (PTFE)</td>
</tr>
<tr>
<td>PWS 7</td>
<td></td>
<td>Pall</td>
<td>4614 (Acrodisk ®)</td>
<td>25</td>
<td>0.45</td>
<td>Supor® (polyethersulfone)</td>
</tr>
<tr>
<td>PWS 8</td>
<td></td>
<td>Whatman</td>
<td>F25-210</td>
<td>25</td>
<td>0.45</td>
<td>PVDF (Kynar® - polyvinylidene fluoride)</td>
</tr>
<tr>
<td></td>
<td>Plunger type</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PWS 6</td>
<td></td>
<td>Environmental Express</td>
<td>SC409 (Filtermate)*</td>
<td>33</td>
<td>0.45</td>
<td>PVDF with PTFE pre-filter</td>
</tr>
<tr>
<td></td>
<td>Filter media disc</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PWS 2</td>
<td></td>
<td>Pall</td>
<td>63069</td>
<td>47</td>
<td>0.45</td>
<td>Mixed cellulose esters</td>
</tr>
<tr>
<td>PWS 4</td>
<td></td>
<td>Millipore</td>
<td>GSWP04700</td>
<td>47</td>
<td>0.22</td>
<td>Mixed cellulose esters</td>
</tr>
</tbody>
</table>

Notes:
* = Vial and cap are model number SC475
Figure 2.2  Photo of “plunger type” filter apparatus

Note: This device includes a cap shown at the top of the figure, then plunger below, then filter, then vial – image to the right is a close up of the filter and plunger.
Figure 2.3   Photo of “syringe filter” apparatus

Note: The filter is shown at the end of the syringe at bottom right
Figure 2.4  Photo of “filter media disc” filter apparatus

Note: Includes vacuum pump, vacuum flask, filter housing, and filter media discs (insert in top left corner shows a box of filter media)
CHAPTER 3
RESULTS AND DATA SUMMARY

The findings from this study are listed, described, and summarized in this chapter. The discussion primarily focused on the comparison of various sampling methods to a full sample profile for prediction of peak total lead levels at the customer tap. The particulate content of peak total lead occurrences and peak occurrences of total metals other than lead are also presented and discussed. This chapter begins with a description of the data collected, then discussion of the sampling strategies, a comparison of particulate versus dissolved content of peak lead results (see Chapter 1 discussion, including Figure 1.3), an assessment of total levels of metals other than lead in the profile samples, and then ending with a summary of all these findings.

DATA COLLECTED

Samples were collected at the eight participating utilities (PWSs) between May and December 2014. There were 96 samples collected at 37 different sampling locations (37 houses sampled) in these eight water systems, as summarized in Table 3.1. The table also characterizes the kind and amount of other information provided by the participating water systems, including a) length and diameter of household and service line pipe, b) identification of profile volume where water temperature changed, c) locations where more than twelve 1-L samples were collected (because service line or household pipe contained more than 12 L), and d) metals analyses performed on collected samples. In the latter case, all systems provided data from unfiltered (total) samples for lead, and copper, and all but one participant also provided data for iron. All participants provided results from filtered (dissolved) samples for lead and most also provided dissolved results for copper, iron, and manganese. In addition, some provided total and dissolved data for a few other metals.

The information provided by the public water systems regarding diameter, length, and material type (lead, copper, etc.) of household and service line plumbing was tabulated and used to estimate service line locations. The information sources for the plumbing materials were water system records (including geographic information system (GIS) data), inspection at the household or excavated pipe material. Sample profiles for each of the 37 locations are shown in Appendix C. Figure 3.1 is an example of one of these sample profiles (PWS 3, location HS) for a location where the entire service line is lead. Figure 3.2 is an example of a location with lead on the customer side and the utility side is copper (location HH, PWS 7). When the service line and household data were provided as needed to calculate the start and end of the service line, it was depicted in the figures in Appendix C as a black bar/oval with no fill (i.e., interior of bar is white). If a portion of the service line contains lead then the black bar/oval is filled with blue. If all or part of the service line contains material other than lead (copper of iron) or was undefined (“unknown” or “not reported”) then the black bar/oval remains unfilled (still white). So in Figure 3.1, the service line is all lead (the black bar/oval is all filled with blue). For Figure 3.2, the part of the service line on the customer side is known to be lead (filled with blue) while the utility side of the service line is copper (no fill – i.e., white).

All data reported by the PWS were rounded to the nearest 1 µg/L (0.001 mg/L). This included some instances where the reported result for total (unfiltered) metals was lower than for
filtered (dissolved) metals. Any data discrepancies were double checked with the utility and verified to be as accurate as possible.

**Figure 3.1**  Example profile for dissolved and total lead at a location with a full LSL (PWS 3, location HS)

**Figure 3.2**  Example profile for dissolved and total lead at a location with a partial LSL (PWS 7, location HH)
Table 3.1
Sample and information collection from participating utilities

<table>
<thead>
<tr>
<th>Water system</th>
<th>Sample locations</th>
<th>Total samples</th>
<th>Service line length and diameter</th>
<th>Household plumbing length and diameter</th>
<th>Water temperature change</th>
<th>Did utility provide information on:</th>
<th>Samples in addition to Pb, Cu, Mn, and Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>pipe material</td>
<td>pipe material</td>
<td></td>
<td>Metals analyzed, in addition to Pb, Cu, Mn, and Fe</td>
<td></td>
</tr>
<tr>
<td>PWS 1</td>
<td>2</td>
<td>6</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Some</td>
<td></td>
</tr>
<tr>
<td>PWS 2</td>
<td>6</td>
<td>17</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Al + Zn</td>
</tr>
<tr>
<td>PWS 3</td>
<td>6</td>
<td>17</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>ALL</td>
</tr>
<tr>
<td>PWS 4</td>
<td>2</td>
<td>6</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Some ‡</td>
<td>Yes</td>
</tr>
<tr>
<td>PWS 5</td>
<td>6</td>
<td>9</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Some</td>
<td></td>
</tr>
<tr>
<td>PWS 6</td>
<td>4</td>
<td>17</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Some</td>
<td>19 other metals †</td>
</tr>
<tr>
<td>PWS 7</td>
<td>3</td>
<td>8</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Some</td>
<td></td>
</tr>
<tr>
<td>PWS 8</td>
<td>8</td>
<td>16</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>ALL</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>37</td>
<td>96</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:

‡ = temperature not recorded in the initial samples from PWS 4 collected prior to this study
† = Fe (iron) not measured
Al = aluminum, Zn = zinc, Pb = lead, Cu = copper, Mn = manganese, and Fe = iron
RESULTS FROM EACH PARTICIPATING UTILITY

The data from each participating utility are summarized below.

PWS 1

Two household locations (HW and KT) were sampled at PWS 1. Both locations included three samples – an initial sample (~October 1, 2014) and follow-up samples one and two months later. Each sample was collected using the standard study protocol of twelve 1-L sequential samples collected after a stagnation period of at least 6 hours. Samples were collected by PWS staff at scheduled times and dates pre-arranged with homeowners. Samples were analyzed for dissolved and total lead, copper, manganese, and iron. The profile volume where the water temperature changed was recorded for each sample at location KT, but only in the initial sample at location HW. Data provided by the water system allowed the estimation of the volume of water in household plumbing and the service line, but the composition of the plumbing was not reported.

Most of the results for all metals, including lead, were below the detection limit (DL) in dissolved and total samples at location HW. The highest total lead result was 10 µg/L in the 1st L on the initial sample date. All other total lead results were <2 µg/L (most were below the 1 µg/L DL).

At location KT there were no detectable amounts of iron (DL = 100 µg/L), manganese (DL = 50 µg/L), or copper (DL = 50 µg/L) in any dissolved or total sample on any date. However, the lead results at this location were typically above the 1 µg/L DL in all dissolved and total samples. The highest total lead result was 27 µg/L in the 1st L of the initial sample. One month later, the peak total lead occurred in the 7th L (past the estimated end of the service line) and was slightly lower (19 µg/L). In the second month sample the results were all <10 µg/L, though the peak lead did occur within the predicted volume of the service line. Therefore, for total lead, the peak occurred before the service line (1st L from tap), after the service line one month later, and within the service line one month after that. On each sample date at this location, the dissolved lead was about 50 percent or less of the total result, but the results followed the same general trend with respect to profile volume.

The temperature change data at location HW was limited, but on the one date it was collected, the peak lead occurred well before the temperature change. At location KT, the temperature change occurred prior to the peak lead in the 1st and 2nd month, though the peak lead and detected temperature change did occur within the first two liters on the initial date, and this was not too far off from the estimated beginning of the service line (~2.4 L estimated within household).

PWS 2

As with PWS 1, samples at PWS 2 were collected by PWS staff at scheduled times and dates pre-arranged with homeowners. Five locations were sampled three times each – an initial sample and follow-up samples one and two months later. A sixth location was only sampled twice (initial and one month later). The initial sample collection date for PWS 2 varied from May to September 2014, depending on the location. Location HM and KX included 15 to 20 sequential consecutive 1-L samples, while the other locations collected the standard 12
sequential 1-L samples. All locations were sampled after a stagnation period of at least 6 hours. As with all other participating water systems, dissolved and total samples were analyzed for lead, copper, manganese, and iron, plus a few samples were analyzed for aluminum and zinc. Water temperature change data was recorded at two locations. All information needed to estimate household and service line volume was provided. Pipe composition information was provided (including location of lead) for most locations, though some of the information was not available for one or more segments at some locations.

One day prior to the “1 month” sample at location HM, the last 36 ft of the LSL was replaced with copper (plus household and service line plumbing flushed after replacement). Consequently, in the “initial” sample, the volumes represented by the LSL were from 6.4 L to 19.1 L, but in the later samples, the LSL volumes were from 6.4 to 13.5 L, with volumes 13.5 to 19.1 L representing the final 36 ft of copper. As shown in Appendix C, the profiles at this location included peak total lead levels about 10 times higher in the “1 month” sample (i.e., one day after the partial lead service line replacement [PLSLR]) than in the “initial” sample collected prior to the replacement or the “2 month” sample which was collected about one month after the disturbances caused by the PLSLR and associated flushing.

Most of the peak lead results for all PWS 2 locations occurred within the volume estimated for the service line, typically within the lead-containing portion of the service line when the pipe composition was known. The only peak that occurred outside the volume predicted for the service line was the 1st L sample during the 2nd month at location QJ. Except for the 1st L sample from QJ just mentioned, the peak lead in the dissolved samples generally followed the same trend as in the total samples. The vertical scale in all the lead profile graphs in Appendix C is arithmetic (also called “linear”), but for location HM at PWS 2 the scale is logarithmic. At this location the total lead results peak at <3 µg/L, except in the 1st month sample where half the total lead results are >10 µg/L, peaking at 54 µg/L (three dissolved lead results on this date were >10 µg/L following a similar profile trend as the total results). All results at locations AX and KX were <10 µg/L. At location QJ, one total lead result in the 6th L on the initial date was 10 µg/L. The 1st L in the 2nd month sample was 28 µg/L, most results were <5 µg/L, and all were <10 µg/L. Locations KS and KQ had peak total lead levels above 10 µg/L. All but 1st month at KQ had peak total lead levels >15 µg/L, and two sample dates at each location had peak total lead levels >20 µg/L. Overall, four locations (HM, KQ, QJ, and KS) had a peak lead >22 µg/L on at least one sample collection date.

**PWS 3**

As with PWS 1 & 2, samples at PWS 3 were collected by PWS staff at scheduled times and dates pre-arranged with homeowners. Five locations were sampled three times each – an initial sample and follow-up samples one and two months later. A sixth location was only sampled twice (initial and one month later). The initial sample collection date for PWS 3 was late July to early August 2014, depending on the location. All locations included the standard 12 sequential 1-L samples. All locations were sampled after a stagnation period of at least 6 hours. Dissolved and total samples were analyzed for lead, copper, manganese, and iron. Water temperature change data and all information needed to estimate household and service line volume, including identification of pipe composition, was recorded for all locations and all sample dates.
For this system, the entire service line is owned by the customer, but the utility chooses to maintain the part between the curbstop and the water main. At all locations, the entire service line was lead (i.e., LSLs). The results for this water system indicate that the lead results within the volume estimated for the LSL was either the peak lead value, or equal to the peak lead value when the peak occurred outside the volume predicted for the service line. Peak total lead results at locations KM, HT, KK, and QE were <10 µg/L in all samples. Location AM was about the same, except a few results on two dates were between 10 and 11 µg/L. The water temperature change typically occurred within the volume predicted for the LSL (except at KM and KK – both <10 µg/L in all cases). As opposed to PWS 1 and PWS 2, the dissolved lead appeared to comprise a larger fraction of the total lead, though generally the dissolved and total results followed the same trends with respect to profile volume.

The detection limits for copper, iron, and manganese were lower at PWS 2 and PWS 3 than at PWS 1, but there were: a) only a few results at PWS 2 (mostly in 1st L) and none at PWS 3 with copper above the 50 µg/L DL used at PWS 1, b) no results at PWS 2 or 3 above the 50 µg/L DL from PWS 1 for manganese, and c) a few results at PWS 3 (all with peak in 1st L) and no results at PWS 2 above the 100 µg/L DL for iron used at PWS 1.

PWS 4

Samples at PWS 4 were collected by city staff at their own homes, though these were all staff that had performed similar sampling events at their homes as part of previous PWS 4 studies. As part of an agreement between PWS 4 and their state regulatory authority, the 1st L at both PWS 4 locations was not collected. Otherwise, the 1st L samples would have to be included as LCR compliance samples.

Sampling at location QA included 14 sequential 1-L samples from 2-L to 15-L. 19 samples from 2-L to 20-L were collected at location AW (this included the “initial” November 2011 sample). All locations were sampled after a stagnation period of at least 6 hours. All dissolved and total samples were analyzed for lead, copper, manganese, and iron. Water temperature change data were recorded in all of the 2014 samples, but not the November 2011 samples. Information on length, diameter, and composition of the service line and household plumbing was provided.

The results from the studies at this water system indicate that the trends in total and dissolved lead are similar on all three sampling dates at a given location. At location QA, the dissolved and total lead peaked at the 10th to 11th L. The SL was estimated to include water in the 4.3 to 6.3 L of the profile, meaning that the peak total and dissolved lead occurred after the end of the service line. At location AW, the peak total and dissolved lead occurred at the 7th L. This was within the volume estimated for the lead service line (4.3 to 11.3 L).

The detection limits (DLs) at PWS 4 were lower for iron, manganese, and copper than reported earlier for PWS 1, but none of the detected iron or manganese results at PWS 4 were greater than 50 µg/L, lower than the DLs reported for PWS 1 (100 µg/L for iron and 50 µg/L for manganese). However, more than half of the copper results at PWS 4, including the peak total copper on all copper sampling dates, were greater than the 50 µg/L DL reported for copper at PWS 1. While it is not known whether similar requirements are in place at other water systems participating in this study, the plumbing code for new service line and household plumbing in this water system does not allow plastic pipe or fittings (i.e., copper, brass, stainless steel, and iron required). This possibly increases the likelihood that plumbing inside the house or in the
service line contain copper, and hence may result in higher observed copper levels. The highest reported total copper at PWS 4 was 166 µg/L, for manganese 12 µg/L, and for iron 33 µg/L.

**PWS 5**

Samples at PWS 5 were collected by PWS staff at scheduled times and dates pre-arranged with the customers. Six locations were sampled during an initial event in August or September 2014 then another sample one month later was collected at three of these locations (i.e., three locations only have data from the initial sample). All locations included the standard 12 sequential 1-L samples. All locations were sampled after a stagnation period of at least 6 hours. Dissolved and total samples were analyzed for lead, copper, manganese, and iron. Water temperature change data was recorded for all initial samples, but only one of the three samples collected one month later. No data were reported for length, diameter, or composition of the household plumbing or the service line, though all were selected because they were expected to contain lead in the service line.

The results at the water system were below the DL (2.5 µg/L at PWS 5) at three locations (KE, AA, and KW). Similarly, at location AS there were some results <4 µg/L within the first 2 L on both sample dates, but all other profile samples at this location were <DL. Location AH had a peak above 15 µg/L in the 9th L in the initial sample, but the next month the results in all profile volumes were <3 µg/L. At location AQ, only an initial sample was collected. The shape of the total lead profile graph in Appendix C for this location was similar to many others in the study indicating a possible sub-peak at about the 5th or 6th L, possibly within the volume of the service line (information not available for this PWS). However, the overall peak in this sample was in the 1st L (19 µg/L in the peak 1st L and ~13 µg/L in the sub-peak later at 5th and 6th L). It was difficult to say whether the temperature change was a predictor of peak lead since so many of the lead results were <DL. However, when the lead was above the DL the temperature change did not coincide with the peak lead profile volume. A few sample dates at PWS 5 did not include an analysis of dissolved water, but in all cases where dissolved lead was measured, it was never found above the 2.5 µg/L DL. Similarly, no dissolved or total iron was found in any samples above the 50 µg/L DL for iron, nor above the 5 µg/L DL for manganese. Copper was detected in several dissolved and total samples using a lower DL than at PWS 1, but only the peak results at location AH were above 50 µg/L DL used at PWS 1.

**PWS 6**

Samples at PWS 6 were collected by city staff at their own homes, or the homes of relatives. Locations HA, HJ, and AE were sampled five times each – an initial sample and follow-up samples one, two, three, and four months later. A fourth location was only sampled twice (initial and one month later) before the homeowner moved away. The initial samples at each location were collected in July 2014. All locations included the standard 12 sequential 1-L samples. All locations were sampled after a stagnation period of at least 6 hours. All dissolved and total samples were analyzed for lead, copper, manganese, and 19 other metals, but not iron. Water temperature change data was recorded in the initial sample at all locations, but temperature change data was missing for some of the later samples. All information needed to estimate household and service line volume, including identification of pipe composition, was recorded for all locations.
At all locations, the customer and water system owned portions of the service line were both lead (i.e., LSLs). The results from studies at this water system indicate that when the water temperature change was noted it occurred within the LSL. At location HA the peak lead also occurred within the LSL, but all results were <10 µg/L, except for one 17 µg/L result. At location HJ the results were also <10 µg/L (except one dissolved result that was >10 µg/L in a sample with total lead <2 µg/L). The peak total lead on this date occurred just prior to predicted start of the LSL. At location AE, the peak occurred after the predicted end of the LSL, and after the water temperature change was noted, although there was one abnormally large peak (2,000 µg/L in 1st L of the 2nd month). Excluding the abnormally high 2,000 µg/L peak, all other peak total lead results at this location were >30 µg/L but <50 µg/L. At location AK, a high total lead result was measured within the LSL but the 1st L on each date was slightly higher, with peak lead >200 µg/L. Except for the sample with the abnormally high total lead at location AE, the dissolved lead appeared to comprise a larger fraction of the total lead, though generally the dissolved and total results followed the same trends with respect to profile volume. The percent dissolved lead appeared even higher at PWS 6 than at PWS 3, frequently >90 percent dissolved.

**PWS 7**

Samples at PWS 7 were collected by PWS staff at scheduled times and dates pre-arranged with homeowners. Eight samples were collected at PWS 7, two locations sampled three times each (an initial sample and follow-up samples one and two months later) and a third location only sampled twice (initial and one month later). The initial sample collection date for PWS 7 was September or October 2014, depending on the location. All locations included the standard 12 sequential 1-L samples. All locations were sampled after a stagnation period of at least 6 hours. Dissolved and total samples were analyzed for lead, copper, manganese, and iron. Water temperature change data was recorded once at one location, twice at a second location, and not recorded at all at the third location. All information needed to estimate household and service line volume, including identification of pipe composition, was recorded for all three locations.

Location HE was discovered to contain copper throughout (all service line and household plumbing). Location KJ had lead on both the customer and utility side of the service line. A partial LSL replacement has been performed at location HH, so now it has lead on the customer side and copper on the utility side. For this water system, a water temperature change was noted and recorded near the end of the service line on the three occasions where temperature data was collected. As shown in Appendix C, the total and dissolved lead results appeared to follow the same trend with respect to profile volume. At location HH, the lead peaked prior to the service line, including the highest overall value at this location which occurred at >90 µg/L in the 1st L from the initial sample. At location HE (all copper as noted above), the lead results were <6 µg/L. At location KJ, the peak lead occurred within the LSL, prior to the temperature change. At this location the peak total lead was highest in the initial sample (70 µg/L), then ~25 µg/L lower one month later (47 µg/L), then ~30 µg/L lower a month after that (16 µg/L). Overall, two of the locations appeared to have a peak lead occurrence well above 15 µg/L.
PWS 8

Samples at PWS 8 were collected by city staff at their own homes. All eight locations at PWS 8 were sampled twice each – an initial sample followed by another sample about two weeks later. The initial samples at each location were collected in late July 2014. All locations included the standard 12 sequential 1-L samples. All locations were sampled after a stagnation period of at least 6 hours. All dissolved and total samples were analyzed for lead, copper, manganese, and iron. Water temperature change data was recorded in all samples, and all information needed to estimate household and service line volume, including identification of pipe composition, was recorded for all locations and all sample dates. The utility side of the service line was lead at all eight locations, but the customer side of the service line was copper at five locations, iron in two locations, and lead at one location. The results from PWS 8 indicate that the 1st L profile from the initial sample at location AT was the only result from any profile volume at any location on any data at PWS that was >5 µg/L. The peak lead at this location in the initial 1st L sample was 18 µg/L. Most of the water temperature change results occurred within the service line, typically within the LSL, though at locations KH and AJ the temperature change was not noted until after the LSL. The particulate fraction seemed to be greater than dissolved at this location, even though the total lead was such a low concentration (more than half the samples had particulate lead content of >70 percent).

COMPARISON OF SAMPLING STRATEGIES

This study included collection of profile samples during each sampling event in order to identify the peak lead level on each sample date and the volume in which it occurred. Additional information was collected along with the profile in order to evaluate various methods to estimate the peak value without a profile. In this report, the peak was defined as any occurrence of the peak value (there may be more than one in a 12 L profile). Therefore, if the peak value was 11 µg/L and it occurred in the 3rd and 7th L, then both were identified as peak values. If all twelve profile samples were below the detection limit (<DL), then the sample profile was excluded from the evaluations described in this chapter. There were some parts of the following evaluations that required a single peak value to characterize a given profile, so in this case the first occurrence of the peak was used (i.e., in the above example, that would be the 3rd L). This was needed for the “initial peak” approach and the evaluations of particulate versus dissolved lead dominated peaks, as described later in this chapter.

Peak values determined in this manner were used as the basis for comparison to the results from the other sampling strategies methods described below:

- Use an initial profile to predict the profile volume where the peak will occur in future samples. As defined in this report, this sampling method means that a full profile is collected during a one-time sampling event at each location, the profile volume with peak lead in this initial profile is identified (e.g., 7th L), and future samples for total lead are collected from a single 1-L bottle at the same volume identified from the initial profile.
- Assign a fixed volume for all locations, regardless of site conditions (e.g., collect a single 1-L sample from 1st L, 6th L, 12th L, or some other discrete sample volume).
• Calculate the midpoint of the SL or LSL and collect a sample from that profile volume
• Monitor water temperature and collect sample when temperature changes
• Collect a composite sample (e.g., first gallon or first ~4 L)

Details regarding the assessment of individual sampling methods are discussed separately below. The results from comparing these methods are summarized in graphs and tables discussed below. The “initial profile” evaluations were performed on a per location basis (37 in this study) and all other evaluations were performed on a per sample profile basis (96 sample profiles in this study). The tabulated data and the associated discussion includes a breakdown of results equal to the peak (100 percent), less than the peak but ≥70 percent of the peak value (meaning the total lead in the sample was within 70 percent of the peak lead value for the same profile), 30 to 70 percent of the peak, or 0 (i.e., not detected) to 30 percent of the peak. Also included is the sum of these first two groups, the values equal either to the peak or within 70 percent of the peak total lead. Values equal to the peak or within 70 to 100 percent of the peak were considered reasonably close estimates of the peak. The results of these evaluations are discussed separately below.

In order to facilitate the discussion below on each of the lead sampling strategies, a comparison table was produced as shown in Table 3.2. The comparison table shows the sampling method as outlined above, the number of profiled used in the analysis when appropriate, the number of times and percent of times when the sampling method located the peak lead, as well as the various percentages of the peak lead found by this method. Each of the subsequent sections on sampling methods refer back to this table.
Table 3.2
Sampling approaches to approximate peak total lead at the customer tap in given profile

<table>
<thead>
<tr>
<th>Sampling approach evaluated per profile event</th>
<th>Total profiles†</th>
<th>Percentage (%) of peak associated with each sampling approach</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of sampling events</td>
<td>Peak</td>
</tr>
<tr>
<td>Middle of SL</td>
<td>85</td>
<td>9</td>
</tr>
<tr>
<td>Middle of LSL</td>
<td>79</td>
<td>9</td>
</tr>
<tr>
<td>Temperature change</td>
<td>60</td>
<td>10</td>
</tr>
<tr>
<td>Composite of first four 1-L samples</td>
<td>90</td>
<td>1</td>
</tr>
<tr>
<td>1st L</td>
<td>84</td>
<td>23</td>
</tr>
<tr>
<td>2nd L</td>
<td>90</td>
<td>9</td>
</tr>
<tr>
<td>3rd L</td>
<td>90</td>
<td>5</td>
</tr>
<tr>
<td>4th L</td>
<td>90</td>
<td>10</td>
</tr>
<tr>
<td>5th L</td>
<td>90</td>
<td>12</td>
</tr>
<tr>
<td>6th L</td>
<td>90</td>
<td>23</td>
</tr>
<tr>
<td>7th L</td>
<td>90</td>
<td>21</td>
</tr>
<tr>
<td>8th L</td>
<td>90</td>
<td>13</td>
</tr>
<tr>
<td>9th L</td>
<td>90</td>
<td>14</td>
</tr>
<tr>
<td>10th L</td>
<td>90</td>
<td>13</td>
</tr>
<tr>
<td>11th L</td>
<td>90</td>
<td>5</td>
</tr>
<tr>
<td>12th L</td>
<td>90</td>
<td>4</td>
</tr>
<tr>
<td>Sampling approach evaluated per profile event</td>
<td>Total profiles†</td>
<td>Percentage (%) of peak associated with each sampling approach</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>-----------------</td>
<td>-------------------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>Total profiles†</td>
<td>Percentage (%) of peak associated with each sampling approach</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Peak</td>
</tr>
<tr>
<td>Middle of SL</td>
<td>11%</td>
<td>33%</td>
</tr>
<tr>
<td>Middle of LSL</td>
<td>11%</td>
<td>29%</td>
</tr>
<tr>
<td>Temperature change</td>
<td>17%</td>
<td>20%</td>
</tr>
<tr>
<td>Composite of first four 1-L samples</td>
<td>1%</td>
<td>9%</td>
</tr>
<tr>
<td>1st L</td>
<td>27%</td>
<td>2%</td>
</tr>
<tr>
<td>2nd L</td>
<td>10%</td>
<td>8%</td>
</tr>
<tr>
<td>3rd L</td>
<td>6%</td>
<td>8%</td>
</tr>
<tr>
<td>4th L</td>
<td>11%</td>
<td>11%</td>
</tr>
<tr>
<td>5th L</td>
<td>13%</td>
<td>21%</td>
</tr>
<tr>
<td>6th L</td>
<td>26%</td>
<td>19%</td>
</tr>
<tr>
<td>7th L</td>
<td>23%</td>
<td>16%</td>
</tr>
<tr>
<td>8th L</td>
<td>14%</td>
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<tr>
<td>9th L</td>
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<td>18%</td>
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<tr>
<td>11th L</td>
<td>6%</td>
<td>11%</td>
</tr>
<tr>
<td>12th L</td>
<td>4%</td>
<td>9%</td>
</tr>
</tbody>
</table>

Notes:
† = There were 96 profiles (see Table 3.1), but many were missing SL, LSL, water temperature, or 1st L information.
§ = The 1st L was not collected during six sampling events (PWS 4), but all profile volumes were collected during the other 90 sampling events.
SL = service line
LSL = portion of the SL that contains lead
PWS = public water system (project participants are labeled PWS 1 through PWS 8)
Initial Profile to Estimate Peak Profile Volume

The analysis in this section includes an evaluation of data by location (individual house). Table 3.1 indicates that there were 37 monitoring locations, but three of these were only sampled once, leaving 34 locations (houses) with more than one sampling date as needed to perform the evaluations in this section. One of these 34 had two sampling dates, but all results on these dates were below the DL. Consequently, this location was excluded from the “initial profile” evaluation, leaving 33 household locations. Details of the data analysis for this method are included in Table 3.3.

In this analysis, the profile volume with the peak lead in the initial sample at a given location was noted, and then the lead value in all subsequent samples in this profile volume was compared to the peak lead on each sample date. The evaluation of this approach requires a single peak identified for the initial profile. Consequently, if there were more than one peak in the initial profile, the “initial peak” in the analysis below was defined as the first profile equal to the peak value. As an example, if the peaks in the initial sample were 29 µg/L in the 6th L and 11th L, then results from the 6th L were compared to the peak value in subsequent samples. If the sample at this same location a month later had a peak of 20 µg/L in the 3rd L and 12th L, and if the 6th L result for the one-month sample was 15 µg/L, then the initial peak was able to predict 75 percent (15 ÷ 20) of the peak in the one-month sample. If there were more than two samples, then similar evaluations were made using data from other sampling dates and the lowest result would be used. For example, if a later sample in the above example had a peak lead of 40 µg/L in the 2nd L but had a 20 µg/L result in the 6th L, then in this case the initial peak was able to predict 50 percent of the peak (20 ÷ 40). Since this is lower than 75 percent, the initial peak would be described as capable of estimating up to 50 percent of the peak in subsequent samples at this location.

Table 3.3 indicates the total number of locations evaluated (PWS 5 had three locations with only one sample, plus one location with all samples <DL, so these locations were excluded from this analysis), and then separate columns to indicate if the volume with the peak in the initial sample was able to predict the exact peak, a value not equal to the peak but within 70 percent of the peak (labeled “≥70 to <100%”), 30 to 70 percent of the peak, or 0 to 30 percent of the peak. Also listed is the sum of the first two groups (labeled “≥70 to 100 percent”) and equal to the peak or within 70 percent of the peak. For example, at PWS 6 there were four total locations. Two had the exact same peak volume in all subsequent samples, one had at least one sample with lead in initial peak profile that was 30 to 70 percent of the peak, and one location similarly had one result 0 to 30 percent of the peak in a subsequent sample.

These results indicate that 12 of 33 times the lead in the sample volume with peak initial lead had identical lead values to the peak lead results in all subsequent samples at the same location, and 16 times the lead was at least 70 percent of the peak value. In other words, only about half the time did the initial peak approach described above associate with a lead value within 70 percent of the peak total lead value on every subsequent sample date.

These results showed that for 48 percent of the houses, a sampling strategy that involved conducting a sample profile once and then using the peak liter from this profile for subsequent sampling would have produced a lead result reasonably close (within 70 percent of peak) to the actual peak lead measured by performing a complete sample profile on these later dates at the same location. However, there are potential limitations and questions about this approach, as follows:
a) There is some evidence noted above that when the liter designated as the peak was actually not the peak or not within 70 percent of the peak it was often vastly different from the peak (<30 percent of the peak), as shown in Table 3.3.

b) With the additional effort needed to collect the initial full profile, the results using this option were not substantially better at finding peak values than some of the other options.

c) Common with many of the other methods, developing the mechanism for collecting a single discrete sample volume, other than the 1st L, may involve some challenges for the water system and may be complicated for untrained customers volunteering for sample collection to implement.

In the above discussion, the analysis was performed on a per location basis. In the subsequent evaluations, the analysis is performed on a per sample basis. For example, as noted in Table 3.1, there are four locations used in the above analysis for PWS 6, but 17 total sample collection dates were evaluated in the subsequent evaluations.

Assigning a Fixed Volume

In this approach, the goal was to determine if there was any particular discrete profile volume that reliably produced similar lead levels to the peak result. Table 3.2 compares the observations from each discrete 1-L sample in a profile versus the peak lead on a given sample date. Note that in Table 3.1, there were some locations with more than twelve 1-L samples collected, but this analysis only used the first twelve samples (the peak never occurred later than the 12th L).

Figure 3.3 plots the number of times the peak total lead occurred within a given profile volume during the 90 profile sample collection dates. This figure includes all “peak” values (see definition described earlier). Figure 3.4 compares the 1st L lead result to the numerical value of the peak lead result in a given profile. As shown in Table 3.2 and Figure 3.3, the 1st L was most frequently the peak volume (27 percent or 23 of 84). However, using only the 1st L would have missed more than two-thirds of the peak values. About half the time, the peak occurred within the first four 1-L samples – 47 of 84. However, the 6th and 7th L identified values equal to the peak approximately as often as the 1st L – 23 of 90 times (26 percent) for the 6th L versus 21 of 90 (23 percent) for the 7th L.

In addition to evaluating the peak (i.e., 100 percent), the portion of the samples that were within 70 to 100 percent of the peak (but not equal to the peak) were also tabulated in Table 3.2. During 23 events, the peak occurred in the 1st L but only two more times was the 1st L within 70 percent of the peak, meaning 25 of 84 or about 30 percent of the results were within 70 percent of the peak. For the 6th L there were 23 peak events and 17 events with total lead lower than the peak but still within 70 of the peak value. Overall, 40 of 90 the 6th L profile samples were within 70 percent of the peak value.

4 There were 6 sampling events that were excluded because all the results were reported under the detection limit. 84 other sampling events included all profile volumes (1st L through 12th L). However, 6 additional sampling events include only the 2nd through 12th L (see earlier discussion regarding PWS 4).
Therefore, while overall these results show that using the 1st L misses the peak much of the time, there is also no specific fixed volume that was substantially better at finding the peak total lead. The first four 1-L samples are just as likely to be the peak as the 4th to 7th L (typical ranges for start of LSL). The 1st L was identified as the peak more than any other discrete sample volume, although the 6th and 7th L were similar. By contrast, the 6th, 7th, or 8th L had the most instances “near” the peak (70 to 100 percent of the peak – middle column of table), with 40, 35, and 34 observations out of 90, or 44, 39, to 38 percent of the observed results, respectively. Therefore, while the 1st L, 6th L, 7th L, and 8th L had more results exactly equal to the peak than other profile volumes, the 6th and 7th profile volumes had more results within 70 percent of the peak. The 6th, 7th, and 8th L are more likely to come from within the SL or LSL than the 1st L. For example, of the 47 peaks that occurred in locations where the start and end of the LSL are known, the 6th through 8th L were within the LSL at 20 locations but the 1st L was never within the LSL. Conversely, SL information was available at 56 locations and the 6th through 8th L were within the SL at 36 locations, plus two instances where the start of the SL was within or at the end of the 1st L.

Table 3.3

<table>
<thead>
<tr>
<th>Water system</th>
<th>Total locations†</th>
<th>Number of locations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Peak</td>
</tr>
<tr>
<td>PWS 1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>PWS 2</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>PWS 3</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>PWS 4</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>PWS 5†</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>PWS 6</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>PWS 7</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>PWS 8</td>
<td>8</td>
<td>2</td>
</tr>
</tbody>
</table>

Notes:
PWS = public water system (project participants are labeled PWS 1 through PWS 8)
† = There were 37 locations (see Table 3.1) but three locations (all at PWS 5) had only one sampling event, and one of the locations (also PWS 5) had no results in two sampling events above the detection limits.
Figure 3.3  Peak profile volume for total lead

Figure 3.4  First 1-L lead as a predictor of peak lead
Calculate the Middle of the SL or LSL

In the earlier discussion, the individual profile volumes (1st through 12th L) were compared to the peak lead. This approach uses a discrete profile volume to see if it can predict the peak lead. The discrete liter selection is applied to all locations without taking into account local conditions. The approach described below takes this earlier approach one step further by accounting for local conditions, specifically the calculated midpoint of the service line or the midpoint of the lead portion of the service line. Table 3.2 summarized the results for two approaches. One approach assumes little knowledge about the service line, other than the start of the SL at the house and the end at the water main (with volume of pipe in indoor plumbing known or estimated). This approach is less site-specific than the LSL approach described next, but is more straightforward and may be more easily and more universally implemented. The second approach looked only at the known LSLs. This required knowledge of the start and end of the lead-containing pipe, and its diameter, as well as the calculated or estimated volume of the rest of the service line and household plumbing between the LSL and the household tap sampling point. In this study some service lines had copper, iron (galvanized), brass, or else an unidentified material (“unknown” or “not reported”) in one or more parts of the service line. All of these were excluded from the LSL portion of the analysis.

Figure 3.5 and the top data row in Table 3.2 compared the lead in the profile volume associated with the midpoint of the service line with the actual peak lead and Figure 3.6 and the second row in Table 3.2 showed similar calculations for the midpoint of the LSL. Of the 85 times that data were available for the SL comparison, 37 times (44 percent) the lead result in the middle of the service line was within 70 percent of the peak value. For the middle of the LSL, the results were slightly lower, 32 of 79 or 41 percent of the observations were within 70 percent of the peak.

Figure 3.7 compares the profile volume with the peak lead to the beginning and end of the service line. A value of “0” means the peak occurred between the beginning and end of the service line (74 of 147 times or ~50 percent of the time). Values >0 are associated with the peak occurring after the end of the service line (49 of 147 times or ~30 percent), and <0 occurring inside the house (29 of 147 times or ~20 percent). Figure 3.5, 3.6, and 3.7 and Table 3.2 show that this approach is similar in accuracy to the approaches discussed so far (e.g., peak from initial profile), but it also fails about as many times as the other approaches investigated. In this case, 37 of 85 observations were within 70 percent of the peak, but an even greater number (48 of 87) were not. Figure 3.7 in particular shows that this is not necessarily just the midpoint either. In Figure 3.7 there are quite a few peaks occurring somewhere within the service line (“0” values), but many other peaks occurred before or after the service line.
Figure 3.5  Total lead at predicted midpoint of SL as a predictor of peak lead

Figure 3.6  Total lead at predicted midpoint of lead portion of SL as a predictor of peak lead
Zero means within SL, negative means before SL starts, positive means after SL ends

![Graph showing the difference in profile volume for peak relative to SL (L).]

Figure 3.7  Peak profile volume versus predicted volumes within SL (when known)

Temperature Change

Table 3.2 indicated that there were 60 observations where water temperature change data were recorded to see how well peak lead coincided with the profile volume where a water temperature change (up or down) was noted. Some locations noted more than one temperature change, but this data analysis only takes into account the first temperature change. The basis for this is that water temperature in the exposed household plumbing is expected to be different than in the buried service line, so a change in water temperature could be an indication of water from the service line reaching the sample faucet. The profile volume with the first detected temperature change was equal to the peak or within 70 percent of the peak 22 of 60 times (37 percent of the observations), but the remainder were farther away from the peak. It is possible that results with this approach would improve if more accurate methods of determining the temperature change could be used (e.g., use of temperature probe or gun), but getting this to work using customer volunteers may create other difficulties. Overall, this approach may be similar but is not an improvement over simpler methods, like using the 1st L, and this approach was worse than some of the other approaches investigated (e.g., a) initial profile to determine sample volume to use for subsequent compliance samples or b) use of known or estimated SL or LSL midpoint). Figure 3.8 is analogous to previous graphs and compares lead in the sample with the temperature change versus the peak lead in the profile.

Review of the SL and LSL data indicates that of the 24 locations where both water temperature data and boundaries of the SL were known, the temperature change occurred within the SL at 12 locations (50 percent of the houses), 3 times before the SL (13 percent of houses), and 9 locations after the SL (38 percent of the houses). Similarly, for the LSL, there were 12 of
24 times the water change occurred within the LSL (50 percent of the houses), 6 times before the LSL (25 percent of the houses), and 6 times (25 percent of the houses) the water temperature change was noted after the LSL.

Figure 3.8  Temperature change as a predictor of profile volume with peak lead

Composite of First 4-L Samples

Figure 3.3 and Table 3.2 indicated that about half the time the peak occurred within the first 4 L. However, the non-peak values in these first four liters were very low because the average of the first 4 L (simulating collection of a 4-L composite) produced many results in Table 3.2 that were <70 percent of the peak (81 of 90). This approach, like other averaging approaches, tends to bring the results more towards the middle. Therefore, while there were fewer results within 70 percent of the peak, there were also fewer results <30 percent of the peak. More than half of the results were between 30 to 70 percent of the peak. Figure 3.9 is similar to previous graphs, in this case comparing composite lead versus peak lead.

Since this approach involves collecting the sample the first thing after the water has been stagnant, this is an easier approach to implement for customers. It is similar to the current compliance LCR sampling procedure, except the current 1st L sample will be replaced by a larger sample (i.e., a 4-L container, four 1-L bottles, or perhaps an approximation with a single 1-gallon container (~3.8 L)). However, in spite of its simplicity, it is not an improvement over the single 1st L sample, and some of the other approaches (initial peak and midpoint of SL or LSL) appear better.
Figure 3.9  Potential for a composite sample (average of first four 1-L samples in this case) as a predictor of peak lead

Particulate Versus Dissolved Lead in Profile Samples

This discussion evaluates the particulate content of total lead levels. In this discussion, if a sample has 10 µg/L total lead and 1 µg/L lead in the dissolved sample, then this sample has 90 percent particulate lead and 10 percent dissolved lead. Therefore, if the percentage of particulate lead is known then the percentage of dissolved lead is known. Partially because there are inherent uncertainties in separating dissolved lead from particulate lead, a conservative approach was used to classify profiles as being dominated by particulate or dissolved (soluble) lead. If a sample profile (sum of all samples in a profile) was ≥70 percent particulate, it was classified as “particulate dominated” (called particulate lead). If the sample profile was >70 percent dissolved (<30 percent particulate) it was classified as “predominately soluble” (called dissolved lead). Samples 30 to 70 percent particulate or dissolved were classified as “mixed particulate and soluble” (called mixed lead). The following discussion focuses on peak lead data, specifically targeting only the first occurrence of the peak within a given profile (i.e., if the 5th and 7th L are equal to the peak value, only the 5th L is evaluated in this analysis). This assumption results in evaluation of a single peak per sample profile (excluding profiles where all samples were <DL).

Table 3.4 and Figures 3.10 and 3.11 evaluate the peaks dominated by particulate lead (>70 percent particulate), dissolved lead (<30 percent particulate), or mixed lead (30 to 70 percent particulate). Of all the first peak occurrences, 38 percent were particulate dominated as compared to 29 percent of the peaks being dissolved lead dominated and 33 percent containing a mix. Therefore, of all the profile peaks, only about one-third were primarily dissolved lead and two-thirds were either particulate dominated or were a mix of particulate and dissolved. Review
of the data in Figure 3.10 and Table 3.4 indicates that when the peak occurred in the 1st L it tended to be particulate dominated (61 percent of time) whereas the 6th and 7th L were particulate dominated <30 percent of the time when these profile volumes had the peak total lead levels. Figure 3.11 is a graphical presentation of the last row of data in Table 3.4.

![Particulate Dominance in the First Peak Occurrence in Each Profile](image)

**Figure 3.10** Particulate versus mixed versus dissolved dominated peak lead results evaluated for the 90 sampling profiles
<table>
<thead>
<tr>
<th>Profile volume</th>
<th>Particulate lead (&gt;70%)</th>
<th>Mixed lead (30 to 70%)</th>
<th>Dissolved lead (&lt;30%)</th>
<th>Total peak occurrences</th>
</tr>
</thead>
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<td>12th</td>
<td>1</td>
<td>1</td>
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<tr>
<td>Total ‡</td>
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<td>30</td>
<td>26</td>
<td>90</td>
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</table>

Percent of observations for each profile volume

<table>
<thead>
<tr>
<th>Profile volume</th>
<th>Particulate lead (&gt;70%)</th>
<th>Mixed lead (30 to 70%)</th>
<th>Dissolved lead (&lt;30%)</th>
<th>Total peak occurrences</th>
</tr>
</thead>
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<td>33.3</td>
<td>28.9</td>
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</table>

Notes:

‡ = 6 instances where all profile volumes were <DL are excluded
The above discussion focused on the particulate lead content of peak values. The following paragraph focuses on the particulate lead results versus total lead concentration in all samples. Overall there were 96 profiles, 12 samples per profile, resulting in >1,000 samples. Of these samples, 885 were >DL. These included a mixture of particulate and dissolved dominated results – 291 (33 percent) were dissolved dominated, 280 (32 percent) were particulate dominated, and 314 (35 percent) were between 30 to 70 percent particulate. Overall, 513 profile results (58 percent) were ≥50 percent particulate. For the 143 profiles with a total lead result ≥15 µg/L, 45 (31 percent) were dissolved dominated, 30 (21 percent) were particulate dominated, and 68 (48 percent) were between 30 and 70 percent particulate. More than half of the results ≥15 µg/L (74 profiles or 52 percent) were ≥50 percent particulate. As in the previous discussion concerning the peak values of lead in each profile, one-third of all results were dissolved dominated and two-thirds were >30 percent particulate.

Particulate Versus Dissolved Dominated Sampling Locations

The above two subsections described particulate lead evaluations for individual sample profile events. The following discussion deals with each sampling location to see if: a) all the samples at a given location were particulate or dissolved dominated and b) to see if all of the locations in a given water system were similarly particulate or dissolved dominated. The evaluations use the first occurrence of the peak, as described in the previous discussion, in order to evaluate only one peak per profile. Table 3.5 is similar to Table 3.4, except this table reviews all the samples at each of the 37 locations and evaluates whether all the samples (see 3rd column
in table) were <DL, always particulate dominated, always dissolved dominated, always mixed, or always in more than one group. Table 3.6 is similar, except Table 3.5 summarizes data from all sampling events at each sampling location (one row per location) while Table 3.6 groups the data by PWS. Inspection of these tables reveals that none of the water systems were solely dominated by particulate lead at every single location studied (even though some water systems only included two study locations) nor were all the sites dominated by dissolved lead. The water system that came closest was PWS 5, which had two particulate lead dominated houses, plus one location with two samples on two collection dates that were all below the DL, and three other locations that were only sampled once (two of which had only <DL data). Therefore, no water system can be classified as either wholly particulate or wholly dissolved dominated – all utilities independent of corrosion control type had some mixture of either particulate or dissolved lead dominated houses.

Similarly, Table 3.5 depicts data for individual houses (i.e., Figure 3.10 is evaluated for all 90 sample profiles (above the DL) while Figure 3.12 is evaluated by sampling location (if sampled more than once)). Of the 37 houses, only seven were always particulate dominated and only two were always dissolved dominated. Therefore only 11 of the 37 houses (30 percent) could be classified as always receiving the same form of lead; 70 percent of houses sometimes received particulate and sometime dissolved or a mixture thereof; only 5 percent of the houses always had predominately dissolved lead.

![Particulate Dominance of the First Occurrence of Peak Lead At Each Sampling Location](image)

**Figure 3.12  Particulate dominance at each study sampling location**

Note:
DL = detection limit
Table 3.5

Evaluation of the predominance of particulate lead in peak lead results at each location

<table>
<thead>
<tr>
<th>PWS location</th>
<th>Sample events</th>
<th>&lt;DL</th>
<th>Particulate lead &gt;70 percent particulate</th>
<th>Mixed lead 30 – 70 percent particulate</th>
<th>Dissolved lead &lt;30 percent particulate</th>
<th>More than one group†</th>
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(continued)
Table 3.5 (Continued)

First occurrence of peak lead in all profiles at this location were:

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<th>Sample events</th>
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<th>Particulate lead &gt;70 percent particulate</th>
<th>Mixed lead 30 – 70 percent particulate</th>
<th>Dissolved lead &lt;30 percent particulate</th>
<th>More than one group†</th>
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Notes:
† = For example, the peak lead in the three samples at location HW at PWS 1 included one with >70 percent particulate lead, one with <30 percent particulate lead, and one with 30-70 percent particulate lead
‡ = one sample date had less than detection limit in all profile samples
§ = excluded because only one sample date
Table 3.6
Evaluation of the predominance of particulate lead in peak lead results at each PWS

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<th>PWS locations</th>
<th>First occurrence of peak lead in all profiles at this location were:</th>
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Notes:
† = three other locations had only one sample date for each
‡ = Two locations, one at PWS 3 and one at PWS 6, had less than detection limit in all profile samples, but the other sample profiles were >70 particulate (PWS 3) or <30 percent particulate (PWS 6). See details in Table 3.5.
Peak Total Levels of Other Metals as Predictors of Peak Total Lead

The results from this study suggest that total levels of some metals are more closely associated with peak total lead occurrence than are other metals. For example, 39 percent of the peak total aluminum results had total lead levels in the same profile sample that were within 70 percent of the overall peak total lead for the profile. By contrast, 30 percent of the peak total copper results were associated with total lead levels within 70 percent of the peak total lead for the profile. For other metals (iron, manganese, zinc) less than a third of the peak total metals results were associated with total lead levels that were within 70 percent of the peak total lead. Therefore, aluminum was more likely than other metals to peak at the same time as high total lead levels were observed. Interestingly, peak iron did not correspond to a peaking of lead, even in the peak lead samples that were dominated by particulate lead (i.e., 70 percent of total lead was particulate lead). Of the 24 times when the peak total lead was particulate dominated, the peak total iron profile only produced a total lead result within 70 percent of the peak in 8 of the 24 instances.

Peak Metal Levels as a Function of Profile Volume for Metals Other than Lead

The focus of this research is lead occurrence in samples collected after stagnant conditions. However, since data were collected for other metals, listed below are some data and observations about the other metals similar to the above discussion regarding lead.

Analogous to Figure 3.3, Figure 3.13 illustrates the profile volume with peak total iron occurrence. Similarly, Figure 3.14 is for manganese, Figure 3.15 for copper, Figure 3.16 for zinc, and Figure 3.17 for aluminum. In each case, the peak was typically in the 1st L. Therefore, for lead the best that can be said for using the current LCR 1st L assumption is that none of the other evaluated approaches may be appreciably better, and all will probably be more difficult to implement using volunteer customers. However, for the other metals evaluated, the 1st L was typically the peak value.

---

5 There were 40 instances where peak total lead was particulate dominated (i.e., >70 percent particulate lead), but 16 of these either did not have an iron sample collected or had total lead results in all 12 profile samples that were below the detection limit.
Figure 3.13  Peak profile volume for total iron

Figure 3.14  Peak profile volume for total manganese
Figure 3.15  Peak profile volume for total copper

Figure 3.16  Peak profile volume for total zinc
SUMMARY OF FINDINGS

Key Findings Related to Lead Sampling Strategies

Results from sampling methods were compared to the peak found from the full profile in two ways. First, it was determined if the sampling strategy actually located the peak identified by the full profile. Second, it was determined if the sampling strategy results in a lead level that was within 70 percent of the peak. The second determination evaluated whether the sampling procedure resulted in a lead level that was at least close to the peak value rather than requiring an actual peak match. Key findings regarding the assessment of the five sampling strategies are as follows:

1. No sampling method was particularly proficient at finding the peak lead level compared to doing a full profile for each sampling event.
2. Figure 3.18 summarizes the sampling method results from the study, characterizing the results by the percentage of observations that produced a total lead result within 70 percent of the peak lead value. The peak lead value was the highest lead level found during each profile sampling event.
   i) The initial peak profile method (see “Approach” discussion above, item “b”) of conducting one profile in a home and then using that peak volume for subsequent sampling was within 70 percent of the peak lead 48 percent of the time. This was the highest of any method but it also found a value less than 30 percent of the peak 30 percent of the time. In other words, about half the time this
method was a good approximation of the peak, but a third of the time it was only a fraction of the peak.

ii) The 6th L sample volume was within 70 percent of the peak lead 44 percent of the time and was the second best method using the criteria stated, and the best single 1-L profile volume for approximating the lead peak.

iii) The SL midpoint was similarly able to produce a lead result within 70 percent of the peak about 44 percent of the time. Note that the “SL midpoint” is the midpoint of the complete service line not the midpoint of the lead portion of the service line. The midpoint of the lead portion of the service line (LSL) was within 70 percent of the peak a little less often, about 41 percent of the time. This could include errors in tabulation or calculation of the LSL location, or it could indicate that the lead concentrations within the LSL may not necessarily correspond to peak lead values. The researchers, including participating utility staff, carefully checked LSL location information and associated calculations.

3. The 1st L sample was the best method of finding the peak lead (27 percent of the time), though 6th and 7th L were similar (26 and 23 percent, respectively). However, the 1st L samples that were not the peak value typically were not within 70 percent of the peak lead value for the entire profile. The 6th and 7th L results were better than the 1st L (or any other discrete profile volume) at finding results within 70 percent of the peak lead value. In fact, only the “initial peak” method was a better peak lead predictor than the 6th L.

4. The water temperature change method and the composite first 4 liters were not good methods to locate lead values within 70 percent of the peak.

Other Key Findings

Particulate Lead Considerations

Some assumptions were made in order to assess particulate and dissolved lead contributions. First, although not exactly correct, dissolved lead was equated to the lead value after filtering the sample before analysis. Particulate lead was defined as the total lead without filtering minus the filtered lead value. A sample was considered particulate dominated if the particulate content was greater than 70 percent of the total; similarly a sample was considered dissolved dominated if the dissolved fraction was greater than 70 percent of the total. A mixed dissolved and particulate sample was one that fell in between.

Of all the peaks, 38 percent of them were particulate dominated as compared to 33 percent of the peaks being dissolved lead dominated and 29 percent in between. Therefore, of all the profile peaks, only about one-third of the peaks were primarily dissolved lead and two-thirds were either particulate dominated or were a mix of particulate and dissolved.

All eight participating water systems had a combination of locations that were either dominated by dissolved lead, dominated by particulate lead, or something in between. No water system had exclusively dissolved lead dominated sites or exclusively particulate dominated sampling locations. This implies that utilities with lead lines will have some homes with primarily particulate lead, and other homes with primarily dissolved lead, all in the same distribution system. Independent of the corrosion control method used, none of the utilities were dominated system-wide by any one lead form.
Of the 33 houses studied in the research (excluding locations only sampled once and those with all samples below the detection limit), seven were always particulate lead dominated (21 percent of the houses) and four were always dissolved lead dominated (12 percent of houses). The other 22 houses (67 percent of the houses) had particulate lead dominated water on some dates and dissolved dominated on other dates. This finding would indicate that even at a specific site, on some occasions the sampling can be particulate dominated and on other dates the lead can be dissolved dominated or some combination.

Water Temperature Changes for Water within the Service Line at End of the Stagnation Period

At the 24 locations where both water temperature data and boundaries of the SL were known, the temperature change occurred within the SL at 12 locations (50 percent of the houses), three times before the SL (13 percent of houses), and nine locations after the SL (38 percent of the houses). Similarly for the LSL, there were 12 of 24 times the water temperature change occurred within the LSL (50 percent of the houses), six times before the LSL (25 percent of the houses), and 6 times (25 percent of the houses) the water temperature change was noted after the LSL. There were two instances where information on SL was known but where no information on whether lead was present or not was provided.

Peak Profiles for Total Levels of Metals Other than Lead

As with total lead, the highest total metal levels for aluminum, copper, iron, manganese, and zinc typically occurred in the 1st L of a sample profile. As shown in Figure 3.3, a greater percentage of the peak total lead results occurred in the 1st L as in other profile volumes, but there were significant number of peaks in other profile volumes (i.e., 27 percent of the results peaked in the 1st L, but the 6th and 7th L found 26 and 23 percent of the peaks). By contrast, except for total aluminum and manganese, the profile volumes after the 1st L did not have nearly as many peaks as in the 1st L. In two cases, copper and zinc, 70 percent or more of the peak observations occurred in the 1st L. Therefore, for these metals it appears that when a full profile is not possible, collecting the 1st L might give the best chance at finding the peak overall total levels of these metals. For aluminum, the 2nd L was associated with the peak 26 percent of the time and the 1st L 37 percent. Therefore, in this case maybe a 2-L composite might be needed to find the peak total aluminum (though aluminum was only measured in 19 samples from this study). Figures 3.13 through 3.17 illustrate the profiles with peak total metal levels for iron, manganese, copper, zinc, and aluminum in a similar manner as shown in Figure 3.3 for total lead.

Peak Total Levels of Other Metals as Predictors of Peak Total Lead

The results from this study suggest that total levels of some metals are more closely associated with peak total lead occurrence than are other metals. For example, 39 percent of the peak total aluminum results had total lead levels in the same profile sample that were within 70 percent of the overall peak total lead for the profile. By contrast, 30 percent of the peak total copper results were associated with total lead levels within 70 percent of the peak total lead for the profile. For other metals (iron, manganese, zinc) less than a third of the peak total metals
results were associated with total lead levels that were within 70 percent of the peak total lead. Therefore, aluminum was more likely than other metals to peak at the same time as high total lead levels were observed. Interestingly, peak iron did not correspond to a peaking of lead, even in the peak lead samples that were dominated by particulate lead (i.e., 70 percent of total lead was particulate lead). Of the 24\(^6\) times when the peak total lead was particulate dominated, the peak total iron profile only produced a total lead result within 70 percent of the peak in 8 of the 24 instances.

Figure 3.18 Percentage of results within 70 percent of the peak using each sampling method

\(^6\) There were 40 instances where peak total lead was particulate dominated (i.e., >70 percent particulate lead), but 16 of these either did not have an iron sample collected or had total lead results in all 12 profile samples that were below the detection limit.
APPENDIX A
UTILITY GUIDELINES ON HOW TO COLLECT AND ANALYZE WATER SAMPLES FOR LEAD PROFILE

ENVIRONMENTAL ENGINEERING & TECHNOLOGY, INC.
In Conjunction With
WATER RESEARCH FOUNDATION
AMERICAN WATER WORKS ASSOCIATION

SUMMARY

These are instructions for a sampling protocol used to create a lead profile of a home’s plumbing. The home being tested in this study must have either a full or a partial lead service line. “Profiling” is a sampling strategy to identify the location(s) and source(s) of lead contributing to lead in household drinking water, including lead solder or a lead water service pipe. To create the profile, twelve or more one-liter samples of tap water will be collected one after another from a faucet in the home. Each of these 1-liter samples will be analyzed for total and dissolved lead concentration.

EE&T staff will also work with you to document the length of the lead line and the length of line from the lead service line to the tap used for sampling.

MATERIALS FOR SAMPLE COLLECTION

You can prepare a kit for the homeowners to use with the following suggested items:

- Twelve one-liter wide mouth sample bottles, glass or polypropylene. Prepare bottles (clean and acid washed) and label as per your normal lead collection procedures. Do not add a preservative (acid) to the sample prior to collection.
- Permanent marking pen or sample bottle labels.
- Jar opener pad to help remove faucet aerator. Provide new replacement aerators if desired by customer.
- Wet wipes for hand cleaning (D-Lead brand is optional, available at www.grainger.com).
- Data collection form/chain of custody.

PREPARATION

Set up sample containers before you start. The faucet must run continuously while you fill the twelve (12) containers without allowing any water to flow to drain.
1. Select the home to be sampled. The home must have a full or partial lead service line.
2. If possible, find an assistant to help with sampling. Taking a profile requires rapidly handling the twelve (12) or more bottles without losing any water. Having an assistant is very helpful.
3. **Choose the time for the sample collection event after the home plumbing system has not been used for at least six hours.** This is typically early morning before any water has been used, including shower, toilet, automatic sprinklers, etc. If the home is vacant during the day, and water is stagnant in the home plumbing for six hours, it is possible to collect the samples in the late afternoon.
4. Read through this protocol to be sure your bottles are ready and that you understand the procedure. Once the tap is open and sampling begins, sample collection must be completed. If the process is interrupted, the entire collection must be rescheduled for another day using clean bottles.
   Select a water faucet from which to sample:
   a. The faucet should be one that is used often by the family, such as the kitchen sink faucet.
   b. Faucet does not have an aerator, or has an aerator that can be removed.
   c. There is adequate room to arrange both empty and full sample bottles.
5. Label the sample bottles“1”, “2” through “12” with marker or on container labels before sampling.
6. Set all twelve (12) bottles (with caps removed) near the sample tap so the sampling can be done without interruption. Align them numerically 1 - 12 and place on one side of the sink to facilitate filling.
7. Make sure there is adequate room to handle sample bottles quickly without spilling them.

**WARNING**

**USE COLD WATER ONLY.**

**PROCEDURE**

1. Remove faucet aerator.
2. Fill out data form to record time and location of sampling event.
3. Wipe hands with wet wipes if finger method is used for temperature change.
4. Place finger in the sample container “1.” Alternately, after collecting all twelve (12) samples, measure the temperature of each bottle with a thermometer or temperature gun and record the temperature.

5. Set bottle labeled “1” under the faucet and open faucet to allow cold water to flow at a rate that would be normally be used by the homeowner. We are not setting a specific low flow or high flow, but asking for tap to be opened as it would be normally used—cold water only. Do not adjust flow during the entire sampling period. As soon as the faucet is turned on, all water must be collected – do not let any water flow to the drain. The water must remain flowing and constant until all twelve (12) containers are filled.

6. Fill bottles “1,” and then “2,” etc. to one liter mark until all twelve (12) bottles are filled, not allowing any water to go down the drain between bottles. Move finger to the bottle being filled as you fill each of the bottles noting mentally which bottle received water cooler water (e.g., water from outside the structure).

**WARNING**

**DO NOT ADJUST FLOW DURING THE ENTIRE SAMPLING PERIOD. AS SOON AS THE FAUCET IS TURNED ON, ALL WATER MUST BE COLLECTED. THE WATER MUST REMAIN FLOWING AND CONSTANT UNTIL ALL TWELVE (12) CONTAINERS ARE FILLED.**

The water's change in temperature is detected by holding your finger in the tap water during sampling and noting when the water becomes colder. You can also measure the water temperature in each bottle using a temperature probe or gun immediately after
7. Once all of the sample bottles are collected:
   a. Turn off water.
   b. Mark the sample bottle that first received cooler water with the symbol “T”.
   c. Alternatively, instead of using the finger to detect a temperature change, measure the water temperature in each sample bottle with a temperature gun or thermometer after the samples have been collected and record the temperature on the data form.
   d. Cover each sample container tightly.
   e. Re-attach the faucet aerator using a new washer or aerator if need be.
8. Review the sample tracking sheet.
   a. Are all the bottles accounted for?
   b. Is the information for each sample bottle complete?
   c. Were there any difficulties with the sample protocol to note?
9. Transport sample bottles to the lab and prepare the samples for analysis as described in the next section. Preparation needs to be completed on the same day as the samples were collected so please arrange for same day delivery to the lab.

SAMPLE PREPARATION

WARNING
SAMPLE MUST NOT BE ACIDIFIED UNTIL AFTER IT IS FILTERED FOR THE DISSOLVED SAMPLE.

WARNING
THESE INSTRUCTIONS ARE FOR ANALYSIS BY STANDARD METHOD 3111B. ADJUST PRESERVATION METHOD TO YOUR METHOD IF YOU DO NOT USE SM 311B.

Note: Sample preparation at your utility may vary based on the analytical method used by your lab but in all cases, the “dissolved” sample must be filtered with the filter specified here, and acidified after filtration.

   1. In addition to your usual analysis procedures you will need:
      a. Luer-lock plastic 20 mL syringes or lab vacuum filter apparatus.
      b. Osmonics Cameo 30N- 0.1 µm syringe filter-30 mm or similar for vacuum apparatus. This material does not sorb or leach lead.
   2. From each of the twelve (12) sample containers, prepare two samples for analysis, labeled “total” and “dissolved” (i.e., filtered).
   3. For the “dissolved” sample, shake or mix the one-liter sample well. Lead particulates tend to adhere to the sample container.
      a. After mixing the 1-L sample, remove the minimum volume needed for metals analysis – typically 100 mL from the 1-L bottle.
      b. Record the volume that was removed and the volume remaining in the original 1-L bottle for later calculations.
d. Filter the removed water into a new sample bottle using the luer-lock plastic syringes and filters or vacuum filter apparatus and the designated filter paper.
e. Record the filtering date and time.
f. Add nitric acid to lower the pH to <2.
g. Label this new sample bottle as “dissolved”.

4. For the “total” sample, **do not filter and do not transfer to any other bottle until after acidification**.
   a. **Acidify the remaining approximate 900 mL in the original 1-L bottle.** It is necessary to acidify the entire remaining sample to dissolve all the particles including those sticking to the bottle.
   b. After acidifying the sample to pH< 2 and mixing the 1 L bottle, allow it to stand for 16 hours.
   c. Record the date and time.
   d. Label this sample bottle “total”.

5. Repeat this procedure creating total and dissolved samples from each of the twelve (12) containers.

6. Analyze all sample bottles (24 total) for lead, copper, iron and manganese. The research team requests any water systems that are willing and able to report results of full metal scan (e.g., ICP) to report all these data. Concentrations need to be reported as µg/L for each bottle. Reported results must include the concentrations of each sample and the volume of sample removed from the 1 L container for the dissolved and the volume remaining in the original container for the total. We will adjust the total analysis for the amount removed from the original bottle if necessary. To get an exact mass, the filter could also be analyzed. We will discuss this with you.
APPENDIX B
GUIDELINES ON HOW TO COLLECT WATER SAMPLES FOR LEAD PROFILE

ENVIRONMENTAL ENGINEERING & TECHNOLOGY, INC.

In Conjunction With
WATER RESEARCH FOUNDATION
AMERICAN WATER WORKS ASSOCIATION

SUMMARY

These are instructions for a sampling protocol used to create a lead profile of a home’s plumbing. “Profiling” is a sampling strategy to identify the location(s) and source(s) of lead contributing to lead in household drinking water, including lead solder or a lead water service pipe. To create the profile, twelve or more one-liter samples of tap water will be collected one after another from a faucet in the home. Your utility will provide you a sample kit and the exact number of samples to use.

PREPARATION

1. If possible, find an assistant to help with sampling. Taking a profile requires rapidly handling the twelve (12) or more bottles without losing any water. Having an assistant is very helpful.

2. Choose the time for the sample collection event after the home plumbing system has not been used for at least six hours. This is typically early morning before any water has been used, including shower, toilet, automatic sprinklers, etc. If the home is vacant during the day, and water is stagnant in the home plumbing for six hours, it is possible to collect the samples in the late afternoon.

3. Read through this protocol to be sure your bottles are ready and that you understand the procedure. Once the tap is open and sampling begins, sample collection must be completed. If the process is interrupted, the entire collection must be rescheduled for another day using clean bottles.

Select a cold-water faucet from which to sample:
WARNING
ONCE THE WATER TAP IS OPEN AND SAMPLING BEGINS, SAMPLE COLLECTION MUST BE COMPLETED. IF THE PROCESS IS INTERRUPTED, THE ENTIRE COLLECTION MUST BE RESCHEDULED FOR ANOTHER DAY USING CLEAN BOTTLES.

a. The faucet should be one that is used often by the family, such as the kitchen sink faucet.
b. Faucet does not have an aerator, or has an aerator that can be removed.
c. There is adequate room to arrange both empty and full sample bottles.

4. Set all twelve (12) bottles (with caps removed) near the sample tap so the sampling can be done without interruption. Align them numerically 1 - 12 and place on one side of the sink to facilitate filling.

5. Make sure there is adequate room to handle sample bottles quickly without spilling them.

WARNING
USE COLD WATER ONLY.

PROCEDURE

Remove faucet aerator.

1. Fill out data form to record time and location of sampling event.
2. Wipe hands with wet wipes
3. The utility will ask you to either use your finger to detect when a temperature change occurs or will ask you to use a thermometer to record the temperature of the bottles after the sampling is complete.
   a. For the “finger” method, place finger in the sample container as the bottle is filling. Continue to place your finger in the sample containers until you detect a temperature change. Record which sample bottle had the temperature change.
   b. Alternatively, after collecting all twelve (12) samples, measure the temperature of each bottle with a thermometer or temperature gun and record the temperature.
4. Set bottle labeled “1” under the faucet and open the faucet to allow cold water to flow at a rate that would be you would normally use. Note that with the aerator off, the flow rate will be higher than normal. Use a flow as if you were filling a glass of water or cooking pot.

5. Fill bottles “1,” and then “2,” etc. to one liter mark until all twelve (12) bottles are filled, not allowing any water to go down the drain between bottles. Move finger to the bottle being filled as you fill each of the bottles noting mentally which bottle received water cooler water (e.g., water from outside the structure).

6. Once all of the sample bottles are collected:
   a. Turn off water.
   b. Mark the sample bottle that first received the temperature change with the symbol “T”.
   c. Alternatively, instead of using your finger to detect a temperature change, measure the water temperature in each sample bottle with a temperature gun or thermometer after the samples have been collected and record the temperature on the data form.
   d. Cover each sample container tightly.
   e. Re-attach the faucet aerator.

7. Review the sample tracking sheet.
   a. Are all the bottles accounted for?
   b. Is the information for each sample bottle complete?
   c. Were there any difficulties with the sample protocol to note?

8. The utility will arrange with you to collect the samples. They must be collected the same day as sampling.
APPENDIX C

GRAPHS OF SAMPLE PROFILES AND SERVICE LINE LOCATIONS

Location HW - All Data (T change data missing after initial) - Initial 10/2014

Figure C.1  Total and dissolved lead (Pb) profile – PWS 1, location HW

Location KT - All Data - Initial 09/2014

Figure C.2  Total and dissolved lead (Pb) profile – PWS 1, location KT
Figure C.3  Total and dissolved lead (Pb) profile – PWS 2, location HM

Figure C.4  Total and dissolved lead (Pb) profile – PWS 2, location KX
**Figure C.5** Total and dissolved lead (Pb) profile – PWS 2, location KQ

**Figure C.6** Total and dissolved lead (Pb) profile – PWS 2, location QJ
Figure C.7  Total and dissolved lead (Pb) profile – PWS 2, location KS

Figure C.8  Total and dissolved lead (Pb) profile – PWS 2, location HX
Figure C.9 Total and dissolved lead (Pb) profile – PWS 3, location AM

Figure C.10 Total and dissolved lead (Pb) profile – PWS 3, location HS
Figure C.11  Total and dissolved lead (Pb) profile – PWS 3, location KM

Figure C.12  Total and dissolved lead (Pb) profile – PWS 3, location HT
Figure C.13  Total and dissolved lead (Pb) profile – PWS 3, location KK

Figure C.14  Total and dissolved lead (Pb) profile – PWS 3, location QE
Figure C.15  Total and dissolved lead (Pb) profile – PWS 4, location QA

Figure C.16  Total and dissolved lead (Pb) profile – PWS 4, location AW
Figure C.17  Total and dissolved lead (Pb) profile – PWS 5, location KE

Figure C.18  Total and dissolved lead (Pb) profile – PWS 5, location AS
Figure C.19  Total and dissolved lead (Pb) profile – PWS 5, location AQ

Figure C.20  Total and dissolved lead (Pb) profile – PWS 5, location AA
Figure C.21  Total and dissolved lead (Pb) profile – PWS 5, location KW

Figure C.22  Total and dissolved lead (Pb) profile – PWS 5, location AH
Figure C.23  Total and dissolved lead (Pb) profile – PWS 6, location HJ

Figure C.24  Total and dissolved lead (Pb) profile – PWS 6, location HA
Figure C.25  Total and dissolved lead (Pb) profile – PWS 6, location AK

Figure C.26  Total and dissolved lead (Pb) profile – PWS 6, location AE
Figure C.27  Total and dissolved lead (Pb) profile – PWS 7, location HH

Figure C.28  Total and dissolved lead (Pb) profile – PWS 7, location HE
Figure C.29  Total and dissolved lead (Pb) profile – PWS 7, location KJ

Figure C.30  Total and dissolved lead (Pb) profile – PWS 8, location  HQ
Figure C.31  Total and dissolved lead (Pb) profile – PWS 8, location KA

Figure C.32  Total and dissolved lead (Pb) profile – PWS 8, location AX
**Figure C.33** Total and dissolved lead (Pb) profile – PWS 8, location QH

**Figure C.34** Total and dissolved lead (Pb) profile – PWS 8, location HK
Figure C.35  Total and dissolved lead (Pb) profile – PWS 8, location AJ

Figure C.36  Total and dissolved lead (Pb) profile – PWS 8, location AT
Figure C.37  Total and dissolved lead (Pb) profile – PWS 8, location KH
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)),


# ACRONYMS AND ABBREVIATIONS

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>percent</td>
</tr>
<tr>
<td>1st, 2nd, 3rd L etc.</td>
<td>1st L, 2nd L, etc. are the terms used in this document to refer to a specific profile volume (i.e., “5th L” is the fifth 1-L sample collected)</td>
</tr>
<tr>
<td>AL</td>
<td>Action level</td>
</tr>
<tr>
<td>Al</td>
<td>aluminum</td>
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<tr>
<td>AWWA</td>
<td>American Water Works Association</td>
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<tr>
<td>Cu</td>
<td>copper</td>
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<tr>
<td>DL</td>
<td>detection limit for a given analytical method – also commonly referred to as the “MDL” or method detection limit</td>
</tr>
<tr>
<td>EPA</td>
<td>US Environmental Protection Agency</td>
</tr>
<tr>
<td>Fe</td>
<td>iron</td>
</tr>
<tr>
<td>GPO</td>
<td>US Government Publishing Office</td>
</tr>
<tr>
<td>Initial Profile</td>
<td>Initial profile is specific terminology used in this document to refer to a sampling strategy that includes collecting samples from a complete sample profile, then determining the profile volume with the peak lead for this profile. Then on subsequent dates, samples would be collected from this profile volume instead of collecting an entire new profile. For this study, the peak from the initial sample was noted, then full profiles were collected on subsequent dates and the true peak lead in these later samples was compared to the lead in the same profile volume as in the initial sample profile, in order to see if this approach would have produced a suitable approximation of the true peak on the later sample date (see text for examples).</td>
</tr>
<tr>
<td>L</td>
<td>liter</td>
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<tr>
<td>LCR</td>
<td>The current Lead and Copper Rule</td>
</tr>
<tr>
<td>Lead (IV)</td>
<td>Lead in the +4 oxidation state – generally insoluble in water – lead (IV) formation is promoted by maintenance of oxidizing conditions (e.g., free chlorine residual) in the distribution system</td>
</tr>
<tr>
<td>LSL</td>
<td>Abbreviation for the portion of the SL that contains lead (i.e., “lead service line”)</td>
</tr>
<tr>
<td>LTLCR</td>
<td>Long-term LCR</td>
</tr>
<tr>
<td>LTLCR</td>
<td>The pending revision to the LCR currently under review by EPA</td>
</tr>
</tbody>
</table>

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µg Microgram (10⁻³ mg)
µm Micrometer (10⁻³ meter)
mg Milligram
mL L/1000
Mn Manganese

NH₂Cl Monochloramine
NSF National Sanitation Foundation International

P Phosphorus or elemental phosphorus
Pb Lead. Terms used in this report for different forms of lead include:

Total lead is defined as any mobile lead, i.e., any dissolved or particulate lead that was transported to the tap and into the sample bottles). Total lead includes all dissolved and particulate lead, as defined below.

Dissolved (Soluble) lead can result from the corrosion of lead-containing plumbing or from dissolution of scale or particles. This form of lead is mobile and can be transported to the customer tap.

Filtered lead was equated to dissolved lead in this document. Though not strictly correct, this assumption was used in the discussion of results from this study.

Scale can be produced by electrochemical precipitation of soluble lead at various points in the distribution system or in household plumbing. This form of lead is considered non-mobile in this report, unless it becomes “particulate”.

Sorbed lead is the result of sorption of soluble lead onto the surfaces of suspended particulate material or deposited onto surfaces of particulates and scale. Sorbed lead is potentially mobile, as defined in this report, if associated with particulates suspended in water.

Particulate lead is the result of abrasion, dislodgement, and transport of broken off pieces of scale or lead containing pipe and plumbing (including solder). This also includes any sorbed lead, as defined above. This form of lead has the potential to be mobile, as defined in this report, if it is suspended in water. Consequently, in this document particulate lead = total lead – dissolved lead.

Peak lead is the largest concentration of lead (or other metal) in a sample profile. If the same numerical value for concentration occurs in more than one profile volume, then each is a “peak” value

pH Activity of H⁺ ion
PLSLR Partial lead service line replacement
PO₄ orthophosphate
Profile see "sample profile"
Profile sample  See “profile volume”
Profile volume  Profile volume is an individual 1-L sample within a “sample profile” – see “1st L, 2nd L, etc.”
PTFE  Polytetrafluoroethylene
PVDF  polyvinylidene fluoride (Kynar)
PWS  PWS 1 through PWS 8 are the names used to refer to the eight participating water systems in this project

SAB  Science Advisory Board
Sample profile  Sample Profile is the collection of 12 or more sequential 1-L samples as described in this document, in order to monitor fluctuations in measured levels of lead and other metals as water from household, plumbing, service line, and water main flow to the sample tap.
SL  Abbreviation for the service line (can include copper, lead, or other materials)
SW  surface water
US  United States of America
WRF  Water Research Foundation (formerly AwwaRF)
Zn  zinc