April 27, 2011

Re: Marc Edwards Submission to EPA SAB on the Issue of Partial Pipe Replacement

Dear Aaron,

Attached are documents that might be useful to the EPA SAB in their consideration of partial pipe replacements including the following:

1) Marc Edwards Conflict of Interest Statement (pages 1-3)
2) "Flawed Science Begets Flawed Policy" Lambrinidou/Edwards (pages 4-16)
3) 1997 E-mail of Mike Schock (produced by Freedom of Information Act) pages 17-18
4) Excerpt of Edwards' 2004 Congressional Testimony (pages 19-20)
5) Exemplary notarized letter sent from Marc Edwards to EPA in early 2004 (page 21-27)
6) No pages 28-38: Copyright permission not obtained.
8) Exemplary Use of Reiber Report to Congress, April 2008 (39)
10) Nguyen et al., 2009 WQTC presentation. (pages 69-77)
11) Nguyen et al., 2010 Webcast slides. (pages 78-95)
12) No pages 96-137: Copyright permission not obtained.
13) Cartier et al., 2011. Poster: Effect of Flow Rate and Lead/Copper Pipe Sequence and Junction Types on Galvanic and Deposition Corrosion of Lead Pipe (page 138)
14) Triantafyllidou et al., Lead (Pb) in Tap Water and in Blood: A Critical Review (139-194)
15) Edwards' Comment on Brown et. al, 2010 (195)
16) Excerpt of Edwards Congressional Testimony 2011 (pages 196-198)

My phone is (540) 231-7236 if you should have questions about this submission.

Marc Edwards

Charles Lunsford Professor of Civil Engineering
Virginia Tech
Conflict of Interest Statement: Partial Pipe Replacements.
Marc Edwards-Virginia Tech

Dr. Marc Edwards has been outspoken against partial pipe replacements as they are currently practiced under the EPA Lead and Copper Rule. He gave testimony to Congress in 2004 indicating that his experiments showed that the practice sometimes created spikes of lead in water, posed a serious public health hazard, and requesting that the practice be banned in Washington D.C. until the EPA proved that partial replacements were beneficial. Several notarized letters outlining his concerns were sent to appropriate authorities in 2004. The practice was banned temporarily in 2004.

After a study (Wujek et al, 2004) claimed that lead spikes did not occur in Washington D.C. after partial replacements, and allegedly contradicting research of Dr. Edwards and other investigators, the partial pipe replacements were resumed. Alarmed at spikes of lead that he later personally measured after partial replacements in Washington D.C. homes, Dr. Edwards conducted a Freedom of Information Act (FOIA) request of EPA RIII in 2005, 2006 and 2007 related to partial replacements in Washington DC, and to examine the scientific evidence for EPA RIII public claims that lead spikes did not occur after partial pipe replacements. The FOIAs revealed that the Wujek study was actually conducted in a brief period of time in which chloramine was not present in the water, but free chlorine was. It was perfectly obvious to EPA RIII and their consultants that free chlorine inhibited lead corrosion, and their e-mails acknowledge that the purported "benefits" from partial replacements described in Wujek et al. 2004 were probably due to the presence of chlorine. On the basis of Dr. Edwards’ work, and after reporters began to question EPA RIII on this issue, this critical omission was finally acknowledged 6 years after the study was conducted (http://www.epa.gov/dclead/links.htm):

Note (March 2010): The Wujek (2004) paper discussed in section 2.5.3 does not mention that the post-partial replacement samples were collected during a temporary free chlorine treatment period, a treatment regime associated with lower lead levels.

Dr. Edwards conducted a FOIA with Dr. Yanna Lambrinidou (Founder, Parents for Non-Toxic Alternatives) of the DC Department of Health in 2007, which revealed that a high percentage of Washington D.C. children with lead-poisoning lived in homes with partially replaced pipes.

Dr. Edwards’ FOIAs further revealed that EPA RIII and DC WASA had sampling data since late 2004, indicating lead spikes did occur after partial replacements, contradicting their prior public statements. In more than a dozen samples the lead spikes measured by the utility (and reported to EPA RIII) after partial pipe replacements exceeded 5,000 ppb lead. Dr. Edwards presented information about these spikes in testimony to the D.C. Council on this issue in 2008. That testimony helped stop partial pipe replacements in Washington D.C., although they still occur in some cases.

Dr. Edwards also determined that a DC WASA employee (Rich Giani) was mistaken about DC WASA’s practices related to partial pipe replacement. Specifically, for more than 4 years, Mr. Giani repeatedly stated that DC WASA had always used a dielectric during partial pipe replacements. This fact would imply that Dr. Edwards' concerns about galvanic...
corrosion at Washington, D.C. homes were without basis, and cast into doubt results of his voluntary sampling in homes of D.C. residents which showed long-term problems associated with the practice. Mr. Giani's mistaken assertions about the utility’s use of dielectrics appeared in a later EPA RIII report written by Dr. Steve Reiber (Reiber and Dufresne, 2006). After years of investigation on the issue by Dr. Edwards, including trips to personally observe partial replacements that did not use a dielectric in Washington D.C., DC WASA and EPA RIII eventually acknowledged that dielectrics had never been used for partial replacements. EPA RIII published a correction on this issue (http://www.epa.gov/dclead/links.htm).

Dr. Edwards has also conducted a FOIA for documents related to the above EPA RIII study (Reiber and Dufresne, 2006), which contradicted decades of prior research, and claimed that even in the worst case galvanic corrosion from partial pipe replacements had inconsequential impacts on lead in water. The study further claimed that partial pipe replacements in Washington, D.C. were part of an effective program to reduce lead in water, and the D.C. lead pipe replacement program was presented as the "Solution" to lead in water and utility liability associated with lead service lines. The Reiber et al. document has repeatedly been given to the U.S. Congress and other entities by the U.S. EPA, as "proof" that galvanic corrosion is insignificant. Other utilities in the U.S. and around the world have cited this document to support their own partial pipe replacement programs. After years of failed attempts to convince EPA RIII and Dr. Reiber to acknowledge limitations of the Reiber et al. study and to publish appropriate caveats (including several attempts before the final report was even written), Dr. Edwards grew concerned about how the report was repeatedly used in a manner that downplayed legitimate health concerns. Dr. Edwards then wrote a letter to the DC WASA Ad Hoc Committee on Drinking Water Quality documenting numerous scientific concerns about Reiber et al.. In that report Dr. Edwards characterized the EPA RIII study by Dr. Reiber as a “third rate hack job,” and highlighted issues with the studies approach, methods and conclusions. Dr. Edwards has given, and will continue to give, public presentations in which he cites this report, as an exemplar of unethical science and engineering. To date, EPA RIII and Dr. Reiber have refused to acknowledge, in writing, many of the obvious limitations and errors in the report.

Dr. Edwards also reported on his work to Congressional Investigators, which helped prompt an investigation of the U.S. Centers for Disease Control (CDC) and Prevention, related to their studies of health effects associated with high lead in Washington, D.C.’s drinking water. The congressional investigation revealed that the CDC knew about higher incidence of lead-poisoning of D.C. children living in homes in which pipes had been partially replaced—information that the CDC did not publicly acknowledge until issuing a health alert in 2010. Aspects of Dr. Edwards’ work on this issue are described in his sworn testimony to Congress in May of 2010 and in a related Congressional Report. Under severe criticism for their actions, the CDC later wrote a peer reviewed paper in which they stated that partial pipe replacements did not significantly increase the likelihood of elevated blood lead in Washington D.C. children relative to homes with intact lead service lines (Brown, M.J., et al., 2011), even though there was a higher likelihood of elevated blood lead in children living in homes with partial pipe replacements (confidence did not exceed 95%). Unfortunately, the Brown et al. report did not use data for several hundred partial pipe replacements that were conducted before corrosion control was implemented by DC WASA. Dr. Edwards has written a comment to the journal that published the CDC paper, asking that CDC acknowledge this fact, and requesting a new statistical analysis using all the available data.
During an EPA public meeting on potential revisions to the lead and copper rule October 2008, and despite previously acknowledging the study was fatally flawed, the EPA and their consultants once again tried to present the Wujek et al. 2004 study as evidence that partial replacements reduced lead in water. Yet again, the EPA and their consultants did not mention that chlorine was in the water. Dr. Edwards once again criticized the use of the study in this manner. In response to a FOIA, EPA RIII later acknowledged that they had no data to demonstrate benefits of partial pipe replacements in reducing lead in water.

Dr. Edwards has repeatedly stated that he believes there are instances in which galvanic corrosion does not cause problems, instances where galvanic corrosion does cause problems, and is committed to doing sound fundamental research to better understand the potential benefits and hazards of partial pipe replacements. He is currently collaborating with several researchers and utilities who are attempting to advance fundamental understanding of this issue. He is presenting several articles on this subject at the 2011 AWWA Conference in Washington D.C. and is advising graduate students who are conducting research on this subject. The work to date has conclusively demonstrated that galvanic corrosion is sometimes a long-term concern, consistent with decades of prior research on the subject. Dr. Edwards has also written a paper on galvanic corrosion during partial service line replacements with Simoni Triantafyllidou, parts of which were presented at AWWA National Conferences and which is under review in Journal AWWA. Several other peer reviewed papers are in progress.

Dr. Edwards was recently awarded a grant from the Robert Wood Johnson Foundation along with investigators from Northeastern University, EPA and Parents for Nontoxic Alternatives to study the issue of partial pipe replacements and conduct a cost benefit analysis. That work is underway, and involves collaboration with DC WASA, EPA, and a Providence water utility. Dr. Edwards is also collaborating with Canadian researchers who are studying impacts of partial pipe replacements on lead in water. He is co-advising a Canadian researcher who is conducting his PhD work on the subject and hosted the student in his lab at Virginia Tech where he worked on a large scale pilot rig of partial pipe replacements.

Dr. Edwards was asked to serve as an expert witness in a lawsuit served on behalf of lead poisoned children in Washington D.C. He has refused to participate as a paid expert in any lawsuit related to health impacts of elevated lead on DC children, but his testimony has been subpoenaed. Some of these lawsuits may address lead poisoning of Washington D.C. children which occurred as a result of partial pipe replacements.

As a final point, this disclosure does not reveal every publication, presentation and public statement by Dr. Edwards on the issue of partial pipe replacements, nor does it reflect on every negative public comment he has made regarding the behavior of EPA, DC WASA and their consultants in relation to this issue.
Flawed science begets flawed policy

EPA’s Lead and Copper Rule, partial lead service line replacement, and elevated blood lead levels among children

Yanna Lambrinidou, PhD, Parents for Nontoxic Alternatives, Washington, DC
Marc Edwards, PhD, Virginia Tech, Blacksburg, VA
Simoni Triantafyllidou, PhD Candidate, Virginia Tech, Blacksburg, VA

Outline

1. Why is lead in drinking water a health concern?
2. EPA’s Lead and Copper Rule (LCR) of 1991
4. 2004 and 2006 PLSLR studies
5. CDC’s 2010 announcement about analysis of Washington, DC data
6. Where is the science on PLSLR today?
7. Social justice: policy and practice

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Presenter Disclosures

The following personal financial relationships with commercial interests relevant to this presentation existed during the past 12 months:

No relationships to disclose

1. Why is lead in drinking water a health concern?

• 312 BC: Romans note high death rate of slaves involved in production of lead drinking-water pipe

• 2nd century BC: “Lead makes the mind give way”
  Dioscorides, ancient Greek physician, pharmacologist, and botanist

“...water ought by no means to be conducted in lead pipes, if we want to have it wholesome.”

Vitruvius (80–70 BC – c. 15 BC), Roman architect and engineer, in De architecture, Book VIII

2nd century BC: “Lead makes the mind give way”

Vitruvius (80–70 BC – c. 15 BC), Roman architect and engineer, in De architecture, Book VIII
November 30, 1855
New York Daily Times
“Iron and Lead Pipes for Carrying Water”

“Lead pipe is more conveniently laid down, as it is easily bent around large stones, and to fit any irregularities in the soil.

Everything considered, lead pipe is to be preferred to iron for conveying water or gases under ground, even when it is required to be of such size and thickness that the first cost will be considerably higher.”


• Around 1900, >80% of large US cities used lead service lines (LSLs), especially in the Northeast and Midwest
• In the late 1800s-early 1900s, journal articles and reports from Great Britain and the US began to document lead poisonings from drinking water
• By the 1920s, many US cities and states had begun revising plumbing codes to ban or limit the use of LSLs.

Troesken, 2006, The Great Lead Water Pipe Disaster.

• Promotional campaigns by the lead industry continued until the 1970s
• The plumbing codes of large US cities like Boston, Milwaukee, San Diego, Philadelphia, Denver, and Chicago called for LSLs well into the 20th century, and the 3 national model plumbing codes allowed the use of LSLs until the 1970s and 1980s
• It is believed that approximately 3.3-6.4 million LSLs were installed
• In some cities (e.g., Chicago), LSLs were required until 1986, when Congress passed the “Lead Ban” that prohibited the use of LSLs.

Renner, 2010, “Reaction to the Solution,” Environmental Health Perspectives.

• Surge of studies starting in the 1960s
### 1983


- **Whole cow milk in cartons with mean 10 ppb lead**
  - 10 infants (3.7-6.5 months)
- **Canned cow milk or formula with mean 70 ppb lead**
  - 7 infants (3.7-6.5 months)

*Iowa City, IA*

### 1983

- **Whole cow milk in cartons with mean 10 ppb lead**
- **Canned cow milk or formula with mean 70 ppb lead**

- **10 infants** (3.7-6.5 months)
- **7 infants** (3.7-6.5 months)

[Slight increase, but no elevated blood lead levels](#)

Elevated blood lead levels by 5.6 months

### Study Year Location

<table>
<thead>
<tr>
<th>Study</th>
<th>Year</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pocock, S. J., et al., Journal of Epidemiology and Community Health</td>
<td>1983</td>
<td>Britain</td>
</tr>
<tr>
<td>Sherlock, J. C., et al., Human Toxicology</td>
<td>1984</td>
<td>Scotland</td>
</tr>
<tr>
<td>Lacey, R., et al., Science of the Total Environment</td>
<td>1985</td>
<td>Glasgow</td>
</tr>
<tr>
<td>Bonnefoy, X., et al., Water Research</td>
<td>1985</td>
<td>France</td>
</tr>
<tr>
<td>Raab, G. M., et al., Environmental Geochemistry &amp; Health</td>
<td>1987</td>
<td>Edinburgh</td>
</tr>
<tr>
<td>Congrove, E. V., et al., Journal of Environmental Health</td>
<td>1989</td>
<td>Boston</td>
</tr>
</tbody>
</table>

### EPA’s Lead and Copper Rule (LCR) of 1991

- Enacted to protect the public from exposure to lead & copper at the tap
- "... the total drinking water contribution to overall lead levels may range from as little as 5 percent to more than 50 percent of children’s total lead exposure. Infants dependent on formula may receive more than 85 percent of their lead from drinking water.

As exposures decline to sources of lead other than drinking water, such as gasoline and soldered food cans, drinking water will account for a larger proportion of total intake.*

*Federal Register, Vol. 56, No. 110, June 7, 1991, p. 26470*
The LCR requires water utilities to:

- Treat drinking water in a way that minimizes its ability to corrode lead pipes
- Monitor drinking water by capturing worst-case lead levels at the tap under normal water use conditions


<table>
<thead>
<tr>
<th>Standard</th>
<th>Designation</th>
<th>Enforceability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 ppb</td>
<td>Maximum Contaminant Level Goal (MCLG)</td>
<td>Non-enforceable</td>
</tr>
<tr>
<td>15 ppb</td>
<td>Lead Action Level (LAL)</td>
<td>Enforceable</td>
</tr>
</tbody>
</table>

The LCR allows up to 10% of tested homes to have taps that dispense any amount of lead.

The LCR’s LAL of 15 ppb

- WHO* 10 Do Not Drink
- CDC 15 Do Not Drink
- EPA# 40 Imminent and Substantial Endangerment
- EPA 5,000 Hazardous Waste

* Also European Union (2013) and Canada
# Posted on EPA website until March 2004

If >10% of sampled homes test above the LCR’s LAL of 15 ppb, water utilities are required to take additional measures:

- Source water treatment
- Corrosion control optimization
- Public education
- LSLR

The LSLR requirement mandates:

- Annual replacement of 7% of a water utility’s total number of LSLs with levels >15 ppb in 1st draw water
- Replacement of the portion of the LSI that the water utility owns
EPA was aware of potential PLSLR risks

- Studies going back to the mid-1800s documented in some instances accelerated lead release after connecting lead pipe with other metals
- Prior to 1991, individual commentors had expressed concern about occasional increases in lead leaching after PLSLR

Why accelerated lead leaching?

- Physical disturbance of old lead pipe
  - Lead shavings and disturbed lead rust can fall into the water
- Galvanic corrosion of old lead
  - In some waters, contact between old lead pipe and new copper pipe can create battery effect that accelerates corrosion of lead pipe above what would normally occur for lead pipe alone
- Deposition corrosion of old lead
  - As the water flows from copper to lead, copper can attach to the old lead pipe and create small galvanic batteries that result in accelerated lead corrosion

Table of findings:

<table>
<thead>
<tr>
<th>Study</th>
<th>Finding</th>
<th>EPA’s interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Britton &amp; Richards 1981</td>
<td>69 homes: Occasionally, increased lead levels observed. In some cases, no low lead measurements were obtained, despite satisfactory pH control. Concluded that lead increases after PLSLR are only temporary and can be minimized, if not prevented, when water corrosivity is optimally controlled. Asserted that corrosion control in this case was “poor” when in fact the authors note the opposite.</td>
<td>Focused only on one case study in the paper that took place in a town with satisfactory pH control and rare lead-in-water problems. Concluded that lead increases after PLSLR are only temporary and can be minimized, if not prevented, when water corrosivity is optimally controlled. Asserted that corrosion control in this case was “poor” when in fact the authors note the opposite.</td>
</tr>
<tr>
<td>AWWA 1990</td>
<td>9 homes: Temporary increases (1-2 weeks) in lead levels after PLSLR in chlorinated water</td>
<td>Concluded that increases are short-lived, but also acknowledged the presence of an “effective passivation film.” Did not raise questions about lead leaching in the absence of such film.</td>
</tr>
<tr>
<td>AWWA 1991c</td>
<td>4 homes: “Very little change in lead levels ... and some increases in some cases” in chlorinated water</td>
<td>Contended that the findings were not relevant to the LCR because all pre-PLSLR values were below 15 ppb, and the LCR does not require LSLR in low lead homes.</td>
</tr>
</tbody>
</table>

Graphs:

- Pie chart showing percentage of utilities owning part of the LSL.
- Diagram illustrating accelerated lead leaching from copper to lead.
**1991 EPA:**

- PLSLR has benefits
- Removal of *any* amount of lead in plumbing reduces risk
- *Any* increases in lead-in-water levels will be *temporary*, if they occur at all
- Residents will be *protected* because water utilities will tell them how to take temporary precautions

**Commentors continued to express concern:**

EPA has *no studies* showing that lead falls below the LAL after PLSLR in different waters and different water treatments.

**1997 internal e-mail from EPA chemist:**

> [T]he bottom line is that EPA is promulgating a policy that **KNOWINGLY INCREASES LEAD LEVELS for an UNKNOWN DURATION.**

*From: Chair Brad Miller, US House Subcommittee on Investigations and Oversight, 10/5/10 Letter to EPA Administrator Jackson*

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**January 31, 2004**

*The Washington Post*


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**Lead-in-water health guidance**

<table>
<thead>
<tr>
<th>Organization</th>
<th>Lead (ppb)</th>
<th>Health Guidance</th>
</tr>
</thead>
<tbody>
<tr>
<td>WHO*</td>
<td>10</td>
<td>Do Not Drink</td>
</tr>
<tr>
<td>CDC</td>
<td>15</td>
<td>Do Not Drink</td>
</tr>
<tr>
<td>EPA*</td>
<td>40</td>
<td>Imminent and Substantial Endangerment</td>
</tr>
<tr>
<td>EPA</td>
<td>5,000</td>
<td>Hazardous Waste</td>
</tr>
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</table>

*Also European Union (2013) and Canada
# Posted on EPA website until March 2004*
• Contamination followed November 2000 change in water treatment from **FREE CHLORINE** to **CHLORAMINE**

• DC WASA knew about lead-in-water contamination since 2001 => reported LAL exceedance to EPA Region 3 in 2002

• Began replacing LSLs in 2003: of the 382 LSLRs that year, only 9 were FLSLRs

**Late 2003**: Virginia Tech research:
Began showing that the chloramine in Washington DC’s drinking water accelerated galvanic corrosion between lead and copper

**2/19/04**: Letter from Dr. Edwards to EPA:
“...replacing a half a lead service with copper is going to dramatically worsen the galvanic corrosion between copper and lead. Such partial replacements should be stopped immediately.”

**2/26/04**: “LEAD” coalition press conference

“Evidence is mounting that partial lead service line replacement often will not solve the problem, and actually can make lead levels worse by shaking loose lead in the pipes and causing galvanic corrosion that may exacerbate lead problems.”

**3/4/04**: Two homes tested 24,000 ppb and 48,000 ppb after PLSLR

“Lead contamination of tap water in two District houses is so extraordinarily high that experts say the residents might be able to taste it, but city health officials never made more than routine efforts to inform the homeowners of the health risks.”

DC Department of Health (DOH) ordered DC WASA to **stop cutting LSLs** and **conduct additional testing** to determine the duration of lead spikes and identify safe construction practices.

**3/17/04**: Letter to EPA from Congressmen Tom Davis and Henry Waxman and Delegate Eleanor Holmes Norton

Recent experience in the District indicates that replacing only the WASA-owned portion of a lead service line may actually increase lead levels at the tap. **EPA should research the effect of partial replacement of lead service lines and modify the regulations to address this issue.** If EPA confirms that partial replacement commonly causes a long term increase in lead levels or fails to produce any reduction in lead levels, it would make no sense to encourage such partial lead service line replacements.
4. 2004 and 2006 PLSLR studies

**2004 Wujek study**
- **Goal**: to measure lead levels before PLSLR and for 2 weeks after PLSLR
- **Scope**: 7 homes that underwent a 15-minute flushing of the tap immediately after PLSLR

**Conclusion**:
- Flushing for 15 minutes immediately after PLSLR reduces lead spikes that can result from construction => i.e., **no problem with the physical disturbance of the lead pipe**
- The connection between new copper and old lead does not significantly increase lead in the water => i.e., **no problem with galvanic corrosion**

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**5/4/04:**
**DC WASA request to DC DOH** (cc-ed to EPA)

“...see the attached initial sample results, together with a brief summary from John Wujek. **We would like to meet at your earliest convenience to discuss the results and obtain your approval to resume the replacement of services to the property line.**”

**DC DOH granted DC WASA permission to continue with PLSLRs**
DC WASA:
- Launched a 1,734 PLSLR program for 2004
- Signed an agreement with EPA Region 3 to partially replace ALL known LSLs (estimated at the time at 23,000) by 2010...

...beginning the largest LSLR program in US history

4/4/05: EPA on NPR-affiliate radio show

[...] WASA’s data..., they did a very extensive short-term study last spring that looked at the effects of replacing lead service lines partially and found that there was no immediate increase in lead levels in the tap water as many had suspected or had been even seen in a few other very old research studies.

[...] [Over the long-term] there is no evidence that the lead levels increase, in fact [...] you remove half the lead, you have a lot less lead in your tap water as a result. It’s not a perfect solution.

What wasn’t discussed

In the 2004 Wujek study:
- Faucet aerators were removed prior to sampling (this can result in missing lead particles)
- After PLSLR, average lead levels in water that was in contact with the copper:lead service line remained >15 ppb
- The highest post-PLSLR sample (854 ppb) was excluded from analysis because it was assumed that it was not caused by the PLSLR

What was later discovered via FOIA

- Every water sample in the study was collected during a one month period (4/2/04-5/8/04) when DC’s disinfectant was switched back to free chlorine (an effective corrosion control chemical)

NO CHLORAMINE IN THE WATER

- Every water sample was collected with a very low flow rate, which can miss lead problems

6/15/04: Environmental Science & Technology article

- Discussed Virginia Tech findings about acceleration of galvanic corrosion between copper and lead in the presence of chloramine = “Lead leaching can increase 4 to 100 times faster than normal”

7/9/04:
- In response to the ES&T article, consultants for EPA Region 3 offered to conduct a study on galvanic corrosion

“This could be especially important as WASA embarks on their aggressive program to replace all lead service lines (partial replacements mostly) in 6 years.”

- EPA Region 3 agreed to fund the research
2006 Reiber & Dufresne study

- **Goal**: “...to determine if replacing a portion of a lead pipe with copper piping might cause accelerated lead release”
- **Method**: Controlled laboratory conditions designed to exacerbate lead release. Examination of connections between new copper and new lead vs. new copper and old lead.
- **Conclusion**: Galvanic corrosion is minimal and, in the long-term, likely inconsequential when LSL surfaces are well-aged and passivated, like in Washington DC.

Reiber & Dufresne, 2006, Effects of External Currents and Dissimilar Metal Contact on Corrosion from Lead Service Lines.

2007 FOIA revealed that by 2006 DC WASA and EPA Region 3 had data showing lead spikes and ongoing lead problems in numerous homes with PLSLRs:

<table>
<thead>
<tr>
<th>Time after PLSLR</th>
<th>90th percentile lead – 1st draw</th>
<th>90th percentile lead – 2nd draw</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1 week</td>
<td>140 ppb (25,800 ppb highest)</td>
<td>95 ppb (814 ppb highest)</td>
</tr>
<tr>
<td>1 week-1 month</td>
<td>22 ppb (17400 ppb highest)</td>
<td>17 ppb (73 ppb highest)</td>
</tr>
<tr>
<td>1 month-596 days</td>
<td>17 ppb (47 ppb highest)</td>
<td>17 ppb (99 ppb highest)</td>
</tr>
</tbody>
</table>

2007 FOIA of Washington, DC environmental risk assessments at the homes of children with elevated blood lead levels revealed that in 5 of 41 assessments parents reported having a PLSLR.

Washington DC: PLSLR program

<table>
<thead>
<tr>
<th></th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLSLR*</td>
<td>9</td>
<td>81</td>
<td>845</td>
<td>674</td>
<td>458</td>
<td>699</td>
</tr>
<tr>
<td>PLSLR*</td>
<td>373</td>
<td>1,734</td>
<td>3,239</td>
<td>3,338</td>
<td>3,392</td>
<td>2,404</td>
</tr>
<tr>
<td>% of full</td>
<td>2.4</td>
<td>4.6</td>
<td>26</td>
<td>20.1</td>
<td>13.6</td>
<td>9.5</td>
</tr>
</tbody>
</table>

Total PLSLRs = 14,450 (81%)
Total cost = >$100 million in ratepayer money

What wasn’t made clear about the study:

- Conclusions based on “surface potential” measurements, at best an indirect indicator of galvanic corrosion of lead
- At least some lead-in-water levels measured, but not reported in the paper and, to date, not released to the public even after multi-year FOIA requests
- Water not allowed to stagnate in the pipes, as occurs in practice and known to worsen galvanic corrosion problems
2008

DC WASA’s accelerated LSLR program was terminated prematurely

The decision was based in part on data obtained and exposed by the public showing that PLSLR sometimes resulted in lead-in-water elevations for months after replacement.

5.

CDC’s 2010 announcement about analysis of Washington, DC data

September 4, 2009: Letter to DC WASA

Our results indicate that the risk of elevated blood lead levels (≥10µg/dL in homes with partial replacement of lead service lines is about 4 times that of the risk for lead elevations in homes without lead service lines. We also noted an increase in risk for

January 12, 2010:

CDC

Online announcement to Childhood Lead Poisoning Prevention Programs across the US

• PLSLRs are associated with increased risk for elevated blood lead levels (≥10 µg/dL).

The CDC states that it shared its findings with EPA in 2007

PLSLRs in the US

• LSLRs for LCR compliance have occurred in at least 13 states, plus Washington, DC
• This number does not include “voluntary” replacements that utilities conduct during distribution system maintenance, road repairs, and as a proactive measure to prevent lead-in-water contamination.
6. Where is the science on PLSLR today?

Real world observations: Lead pipes excavated after 70-114 years in service showed that the rust layer that can form from galvanic corrosion can contain hundreds of milligrams of lead per liter (DeSantis et al. 2009)

Lab observations:
Increases in lead leaching after PLSLR
- Can be short-term (days to weeks) or longer-term (months to years) => but there is a dearth of unambiguous data demonstrating the maximum duration, severity of this effect, and causes of worst-case leaching
- Depend on the water’s chemistry and on resident water use patterns (e.g., stagnation times, water flow)
- Can occur whether the lead pipe is new or old

(Triantafyllidou & Edwards 2010, submitted for publication)

7. Social justice: policy and practice

EPA revisions to the LCR Public stakeholder meeting 11/4/10
- EPA’s presentation on LSLR made no mention of “galvanic corrosion” as a phenomenon of potential concern
- EPA did not discuss data or concerns about long-term lead-in-water problems after PLSLR
- All stakeholders present -- water utilities, lead corrosion scientists, health professionals, and lead poisoning prevention advocates -- called for a MORATORIUM on PLSLRs.

Questions
- Unknowns remain about:
  - Longer-term galvanic corrosion effects
  - Effective ways to protect consumers from excessively high lead spikes in the short- and long-term
- Who gets to define what constitutes “acceptable risk”?
- Is it accurate and ethical to present PLSLR as an effective “remedial” action in every case?
Acknowledgments

• Marc Edwards and Simoni Triantafyllidou thank the Water Research Foundation for their financial support to study partial lead service line replacement.

• The presenters are in the process of receiving financial support from the Robert Wood Johnson Foundation for research on the Lead and Copper Rule.
MEMORANDUM

SUBJECT: More Thoughts on Partial Lead Service Line Replacement

FROM: Michael R. Scheck, Chemist
Treatment Technology Evaluation Branch
Water Supply and Water Resources Division

TO: Peter T. Lassovszky, Environmental Engineer
Targeting and Assistance Branch
Standards and Risk Management Division, OCWWD (4603)

I agree with you that the ANWA information sent did not add anything useful to the debate. After thinking about it (for several years, plus the additional focus of the LCR revisions Work Group), I still have a problem with sticking with the original proposal. In fact, this is even a BURDEN INCREASE in several respects, as noted below.

EPA essentially admits—in the original reg—that higher "short term" lead levels are likely to result (FR p. 26505). However, almost no data is presented to show cases from different water qualities and treatments where lead levels above the action level are caused to go up some, then they go back down below the AL. The Scotland data (Britten and Richards) is inappropriate—Pb levels are much above the AL and they are much above still even after they go "down." The Oakwood data (I was involved in that study) was below AL for most sites, and the before and after cases were statistically insignificantly different. The Newport News study was ambiguous because the amount of service line replaced was not clearly documented. Replacing to the meter generally would mean complete replacement in many if not most areas of the country.

So, the bottom line is that EPA is promulgating a policy that KNOWINGLY INCREASES LEAD LEVELS for an UNKNOWN DURATION. This is at least inconsistent with the policy on public notification, where a delay requested by commenters of only a few weeks to allow synchronization of notice with billing cycles was considered to be unsupportable and potentially dangerous to pregnant women and young infants (for whom a few weeks or months would be a substantial part of the most vulnerable exposure period).
It is then proposed that residents be informed of the intent of the utility to replace the owned/controlled part of the service line, and that levels might rise. Even if water samples are taken and tested in accordance with §141.84(d), THERE IS NO REMEDIATION PROVISION. The utility is potentially forced to CAUSE a WORSE acute problem than originally existed, and the resident(s) are exposed to it for at least 14 days before a sample has to be collected, and an unspecified number of days before the lab results are back and they know the situation (as of the sampling date). Finally, what if the lead levels are still high? The residents are now forced to flush their lines repeatedly, buy bottled water or install some POU treatment device for an unknown period time. This is clearly an added expense and burden which is not addressed in the CFR language. In fact, the information about precautions at the top of the rightmost column on p. 26596 are not spelled out in §141.84(d).

In conclusion, I think that relying on the suppositions of the original preamble and "...EPA believes..." leaves EPA very vulnerable to a variety of charges about potentially aggravating a bad condition, increasing the economic burden to residents (often poor ones), and not having defensible data upon which to base the suppositions. I hope the suppositions are right.

CC: Robert M. Clark  
Judith M. Lebowich (4603)  
Jeffrey B. Kempic (4603)  
Robert C. Thurnau  
James J. Westrick
March 2, 2004

Re: Written Testimony March 5, 2004

I am a Professor of Civil Engineering at Virginia Tech and have devoted much of my career to lead and copper corrosion issues for which I am internationally recognized. I was awarded a Presidential Faculty Fellowship by the White House and the National Science Foundation in 1996 for this work. I am the current President of the Association of Environmental Engineering and Science Professors. Over the last four years, I have worked intensively on corrosion issues experienced by consumers and utilities using Potomac River water. These efforts include research work with the Washington Suburban Sanitation Commission (WSSC) on copper pitting and Fairfax, VA on a desk top study to pre-empt possible problems with lead leaching in drinking water. My research team at Virginia Tech has conducted hundreds of corrosion experiments using real or simulated versions of Potomac River water.

More specific to the current issue in question, I worked for Cadmus as sub-contractor to the United States Environmental Protection Agency (US EPA) in efforts to understand the problem of excessive lead in the drinking water of the District of Columbia Water and Sewer Authority (DC WASA) customers. I have personally collected water samples in the homes of DC WASA customers in an attempt to understand the problem of copper pitting in their homes, and in the process, I discovered a very serious problem with lead contamination that is the focus of today’s discussion. I designed the sampling plan DC WASA executed through mid-December 2003, which first unambiguously illustrated the very serious nature of the existing lead problem to both DC WASA and EPA. I also designed many of the experiments that are now in progress at DC WASA to improve understanding of the problem, and I recommended mitigation strategies that they could employ to mitigate the problem. Indeed, to my knowledge, I was the only expert who gave significant advice to the US EPA and WASA on the lead problem through at least mid-December of 2004.

I have very strong concerns regarding the way in which the US EPA has handled the present crisis. I have expressed most of these concerns directly to the US EPA in detailed letters I sent to George Rizzo and Cynthia Dougherty on February 8th and February 10th. I am willing to share these letters with anyone interested in learning the full extent of my concerns or developing a detailed timeline of events. In this letter I will focus on two opinions that I have developed. The first is that US EPA actions are not adequately protecting consumers’ from excessive levels of
I point out that EPA is not even sure of the simplest things, such as the whether the required partial replacement of lead service laterals is actually beneficial or not. According to our experimental results in November 2003, the lead in water at DC WASA is being driven by a galvanic (battery) reaction between copper:lead or copper:brass. Replacing old lead with fresh copper, and connecting the fresh copper to the consumers lead pipe, would therefore be expected to make lead release much worse that it was before. Personally, I am appalled that we do not even know if the expensive partial lead service line replacement program is beneficial. In simple terms, DC WASA might very well spend $351 million to finish the job of partial lead service line replacement, leaving behind a much worse problem for consumers that if they had done nothing at all. In my letter on this subject written February 19th to the new expert team that is starting at DC WASA, I stated the following about our results at Virginia Tech:

"We have proven ...that not only does chloramine worsen galvanic corrosion between brass/copper or lead/copper, but it also increases the amount of lead leached to the water when the metals are coupled. Our findings...raise a host of problems as I mentioned yesterday. Specifically, replacing a half a lead service with copper is going to dramatically worsen the galvanic corrosion between copper and lead. Such partial replacements should be stopped immediately....."

I will point out that a term has even been coined to explain the finding that lead in drinking water is often much higher after meeting the letter of the law and replacing part of the service lateral. It is called "the partial replacement phenomena." Incredibly, because the law says to replace lead services, they will continue to do so even though their own data often shows they are making the problem worse. Some of the lead levels reported to me (second hand) in homes after such partial replacements are truly stunning, and are as high as 48,000 ppb if my source is accurate. Does the law require that we suspend common sense?

Let us be honest about what is happening here. We are learning hard lessons about corrosion control in full scale testing of real systems, while consumers are drinking the water and getting continual reassurance that everything is under control. In my opinion the situation is not under control by any rational measure.
The foregoing disclosure was acknowledged before me on March 8, 2004.

Michael R. Schock
Chemist
Treatment Technology Evaluation Branch
Water Supply & Water Resources Division, MS B-24
National Risk Management Research Laboratory, USEPA
26 W. Martin Luther King Dr.
Cincinnati, OH 45220-2242
513.569.7412 (P) 513.569.7172 (fax)

March 6, 2004

Dear Mike,

We have made some additional substantial experimental progress on the issues I raised in my letter February 19th, 2004. I am now bringing that progress to the attention of the expert team so that you can, hopefully, more strongly endorse my recommendation to immediately stop the partial lead service line replacements. As you know, this is a practice that is being required to reduce consumer exposure to lead. Since last December I have been very concerned that this practice might be making the situation much worse rather than better.

In addition to the practical data that I sent you back on the 19th proving my concern in concept, I thought it would be helpful to present additional information that shows why the partial service line replacement program is predicted to make things worse. I also add an important new concept that we have developed and tested since my last letter. Every freshman chemistry student is familiar with the galvanic series, which for metals used in drinking water is as follows:

1) Copper  
2) Brass (with lead)  
3) Lead  
4) Iron  
5) Galvanized  
6) Magnesium

Cathodic  

Anodic
The galvanic series is useful in predicting many corrosion phenomena. As per my presentation January 22, 2003 in South Carolina, if zinc is connected to copper, a battery is formed because the copper is cathodic to zinc (Figure 1). The copper is protected from corrosion whereas the zinc is eaten away and forced to corrode at a high rate. As the zinc corrodes, the zinc leaches into and contaminates the water. This concept is commonly applied to protect water heaters (Figure 2).

Figure 1. Formation of a battery when two dissimilar metals are connected.

Figure 2. Connection of aluminum or magnesium anode to steel lining inside a water heater creates a battery, protecting the metallic lining, but accelerating corrosion of the aluminum and magnesium anode. The Mg^{2+} and Al^{3+} are released to the water. The anode is said to be sacrificed.
Because brass and lead are both anodic to copper, connecting brass directly to copper can be problematic (Figure 3). Specifically, corrosion of the brass or lead is accelerated, which in turn, can dramatically increase the amount of lead leached to the water. Corrosion engineers also understand that the cathodic reaction (which is occurring at the copper pipe surface) is often rate limiting. Thus, to the extent that the reaction occurring at the copper surface is accelerated, the lead problem will be worsened, even if you decrease the amount of lead surface that is present as occurs during a partial service line replacement. This is an important concept that you and the other experts understand, but that a normal water treatment person or regulator has difficulties with.

![Copper pipe diagram]

**Figure 3.** Lead problem that arises from hooking brass or lead to copper.

In a water heater, as the steel lining passivates with age, the battery effect decreases markedly. Consequently, the rate at which the anode is sacrificed and the Mg\(^2\) or Al\(^3\) leach to the water also decreases. If the old anode is removed and connected to a new water heater with fresh exposed steel, the rate at which the old Mg\(^2\) or Al\(^3\) anode is sacrificed will increase. In the current situation, this is very important. Specifically, in response to my input in the letter of February 19\(^{th}\), 2003, some experts might assert that “the lead at WASA has been hooked directly to copper pipe for years, and therefore the partial service line replacement is not introducing a new condition that is significantly worse.” That statement is false. Connection of brand new copper to old lead will provide fresh cathodic surface that will accelerate corrosion of old lead and brass. This is due to both 1) the increased cathodic surface area, and 2) the “newness” of the copper surface.
I also point out the importance of pipe sequencing as an even more important factor. Specifically, it is well understood that problems with galvanic corrosion are lessened if the following sequence of connections is followed for water pipe (see Appendix 1):

Galvanized steel to iron to lead to copper

In addition to the fact that such connections minimize the strength of the battery effect between dissimilar metals, over the years we have learned that the above principle is even more important for another reason. Specifically, we want to avoid the dangerous problem of deposition corrosion.

Deposition corrosion can occur when ions of a more noble metal are present in the water that flows into the more anodic metal. In the present instance, deposition corrosion proceeds through the following sequence of steps (Figure 4):

1) copper ions released at the fresh copper surface  
2) copper deposits and is plated onto the old lead  
3) the new copper coating on the lead accelerates corrosion dramatically  
4) more lead is released to the drinking water

Figure 4. Placement of copper pipe upstream of lead can cause a serious long term lead problem through deposition corrosion.

In other words, it is not just the fact that new copper is directly connected to lead that is the only problem. It is also the fact that if new copper is placed before the lead, cupric ions can deposit on the old lead pipe. It does not matter if the copper came from water meters or from the new copper service lateral, this deposition is expected to dramatically accelerate lead corrosion rates.

This concept is well established scientifically. For instance, the following quote is taken from CORROSION BASICS: An Introduction, edited by L.S. Van Delinder, NACE, Houston, Texas, 1984:

"Deposition corrosion is a form of pitting corrosion that can occur in a liquid environment when a more cathodic metal is plated out of solution onto a metal surface. It generally occurs with the more anodic metals such as magnesium, zinc, and aluminum. Common cathodic
"Activators" are mercury and copper ions in solution. For example, soft water passing through a copper water pipe will accumulate some copper ions. If water is then admitted to a galvanized or aluminum vessel, particles of metallic copper will plate out, i.e., deposit on the surface and stimulate pitting by local cell action. Deposition corrosion can be avoided by preventing the pick-up of cathodic ions that will enter the equipment..."

When lead anodes are used to plate copper, it is found that copper contaminants “caused increased lead corrosion, due to the fact that lead dissolution can also couple spontaneously with copper deposition on the lead surface” (Cifuentes, 2001).²

The water industry also has experiences with deposition corrosion. Specifically, while I am not aware of previous research examining the direct effect of cupric ion on lead corrosion rates (other than those we are conducting at Virginia Tech), the fact that dissolved copper accelerates corrosion of iron pipe is well understood. Specifically, it has been reported that dissolved copper concentrations as low as 0.01 mg/L can dramatically increase iron corrosion rates in drinking water.³⁴⁵

For further information, see page 8 of Appendix 2 for additional discussion of deposition corrosion. Also, note the explicit recommendation in Appendix 1, which states “A lead service requiring repair would be best removed and replaced completely with copper.”

My final point in this development is that we have shown that the chemical conditions present at DC WASA including 1) relatively high oxidant residuals, 2) higher pH and 3) significant aluminum in the water can elevate the potential of copper by several hundred millivolts relative to the typical situation.⁶⁻¹⁰ Consequently, any copper surface in the system, whether it is plated on lead or is pure copper pipe, is going to be a much stronger cathode than normal. In other words, all of the problems noted above for a “normal” copper:lead connection will be magnified.

Apparently due to the legal advice of DC WASA and perhaps even the US EPA, my communication with the expert team seemed destined to be virtually all one way. I am not aware of what the expert team is doing, saying or recommending. Consequently, misunderstandings are possibly arising on my part regarding the advice that you are giving to the US EPA or DC WASA. As you know, I am on the record criticizing the actions of the US EPA and DC WASA in handling this incident. I personally think that this is going to be remembered as one of the biggest public health fiascos in recent memory. In my opinion, the new expert team has a critical role to play in helping to stop the damages that are still occurring to consumers as we speak.

Therefore, I am asking you to discuss, and to advise, the US EPA and DC WASA on two very important issues that deserve immediate attention. First, since last October, I have been warning the US EPA and WASA that they should not assume the problem with lead is limited to old homes with lead service lines. My sampling plan that DC WASA started to follow in November was supposed to have also sampled new homes. My own data, collected from buildings in March 2003, showed that there was once a very serious problem with lead in apartment buildings. I have been told those apartments did not have a lead service line. The recent
Arlington data also is directly supportive of my concern that the problem is not limited to old homes with lead service lines.

In the paper recently, DC WASA was quoted:

"My understanding, from what I've heard from the experts upon whom we rely, is that they're focusing on homes with lead services lines," Gerstell said at a news conference.

Obviously, I am not an expert upon whom DC WASA and the EPA rely, since I warned them of a problem with new homes and lead from brass back in October. That warning was backed up with my own field sampling data. Do you now have data that shows this problem is limited to homes with lead service lines?

I also sent a letter to the expert team on February 19th, with some strong language regarding the partial lead service lead replacement program. That program has not been stopped, but rather, it has been accelerated. We are informed of samples, collected from homes after partial service line replacements “fixed” the problem, that show lead levels as high as 48,000 ppb (more than 3200 times the EPA action level) in flushed samples. I am sending this letter, today, to re-iterate my concerns about this program. Specifically, I am asking whether DC WASA or the US EPA have actual data proving that the partial lead service replacement program is not causing a serious problem? If you do not have such data, is it not wise to recommend discontinuing the partial service line replacement program in the strongest possible terms, especially given the fact that it is predicted to cause a serious long term problem with lead? Forgive me if you have already backed up my recommendation to stop this program, and DC WASA and EPA have refused to comply, or if you have data in hand proving that the program is not causing a problem. I am very hopeful that the US EPA and DC WASA will henceforth only make complete lead service line replacements.

Regards,

Marc Edwards
Professor of Civil and Environmental Engineering
Virginia Tech

Attachment #1
Attachment #2
References

SUPPLEMENTARY INFORMATION TO TESTIMONY OF
JON M. CAPACASA
DIRECTOR, WATER PROTECTION DIVISION
ENVIRONMENTAL PROTECTION AGENCY, REGION 3
BEFORE THE
FEDERAL WORKFORCE,
POSTAL SERVICE AND THE DISTRICT OF COLUMBIA
SUBCOMMITTEE OF THE
HOUSE OVERSIGHT AND GOVERNMENT REFORM COMMITTEE
April 15, 2008

1) EPA report on effects of galvanic and grounding currents on corrosion ("Effects of External Currents and Dissimilar Metal Contact on Corrosion from Lead Service Lines")

As referenced in testimony presented on April 15, 2008, the report of a study performed on behalf of EPA Region 3 is available at:
http://www.epa.gov/delead/grounding_effects_study_final_november_2006.pdf

Please note that in March 2008, EPA Region 3 learned that a statement made on page 15 of this report regarding DCWASA's use of dielectric couplers during partial lead service line replacement (PLSLR) is incorrect. DCWASA does not use dielectric couplers when performing a PLSLR. This clarification is posted on EPA's website at (its about 1/3 down the page under the Galvanic Corrosion section, right below the link to the galvanic corrosion report):
http://www.epa.gov/delead/corrosion.htm/research
5/29/2008

Re: The US EPA Region III Study on Partial Replacements and Galvanic Effects
To: Joseph Cotruvo, DC WASA Board

I am very familiar with the history, planning, and execution of the United States Environmental Protection Agency (U.S. EPA) Region III study that is now being touted as proof that partial replacements in Washington D.C. cannot cause a long term problem of consequence, and that galvanic effects between coupled lead and copper are “inconsequential” relative to lead leaching to water. I strongly believe that this study is a third rate scientific hack-job. It should be an embarrassment to the U.S. EPA.

My abbreviated logic is presented in two sections providing evidence that:

1) The study relied on false assumptions and information which tainted its conclusions.
2) All lead in water data collected during the study, at least some of which contradicts the study’s key conclusions, have been covered up. The data that are presented do not support the study’s conclusions.

I base this analysis on information I obtained through Freedom of Information Act (FOIA) requests and other documents. Some of these materials are in the PDF attachment in the e-mail accompanying this letter.

1) The study relied on false assumptions and information

The initial proposal for the study, the Quality Assurance Plan (QAPP), the preliminary report and final report present numerous items as facts which are now known to be highly misleading or false.

1.a. Before the study was conducted and even before the first data point was collected, it was clearly believed that DC WASA already had proven that the partial replacement program reduced lead in water and did not make lead leaching worse. It was also stated that DC WASA had practical data showing there was no effect. As evidence for this, the following excerpts of relevant documents obtained via FOIA are presented.

Although DC WASA has developed substantial evidence that Partial Lead Service Line Replacement (PLSLR) does not exacerbate lead release rates, and in fact substantially reduce overall drinking water lead concentrations in the home; there is still a

Study proposal, Attachment 1, page 20, July 12 2004
INTRODUCTION

The recent DC WASA experience relative to LSL replacement indicates that PLSLR does not exacerbate lead-release rates, and can in fact reduce overall drinking water lead concentrations in the home. While this evidence appears strong, there remains a debate.

White paper. Attachment I, page 14, September 28 2004

Galvanic corrosion has been well documented and occurs when two dissimilar metals are joined together. Theoretically joining lead and copper pipes together creates an electromotive difference in the 50 to 100 mV range, which should certainly accelerate corrosion. Practically, however, this effect has not been observed in the WASA service lines. This may be because of the relatively QAPP Attachment 1, page 31 June 13th 2005

meaningfully increase LSL corrosion rates. Moreover, partial LSL replacement in the DCWASA system has not resulted in observed increases in lead release. (J. Wujek, Minimizing Peak Lead Concentrations After Partial Lead Service Line Replacement, WQTC, San Antonio, 2004)

Draft report, Attachment 1, page 28, July 23 2005

increase LSL corrosion rates. Moreover, partial LSL replacement in the DCWASA system has not resulted in observed increases in lead release (Wujek, 2004). In fact, the recent DC WASA experience relative to LSL replacement suggests that in the long term PLSLR does not exacerbate lead release rates, but rather reduces overall household drinking water lead concentrations in proportion to the amount of LSL replaced.

Final Report, November 2006

The truth is that when DC WASA was asked to present any data that PLSLR reduced overall lead in water (or refute the idea that lead in water spiked) in early 2008, they could not do so. DC WASA’s prior misleading statements and research therefore permeated the planning and interpretation of the entire US EPA study, to the point that the QAPP states that the key hypothesis supposedly being tested had already “practically” “not been observed” in the DC WASA system.

As for the 2004 Wujek study, that Dr. Reiber cites for his “proof” that no spike occurs, and that only benefits from PLSLR are observed in D.C., the record shows that this study was conducted during the time period when free chlorine was present in DC WASA water. Every datapoint of the study is therefore meaningless relative to determining whether spikes occur, or whether there are long term benefits of PLSLR in the DC WASA system. This is why the Wujek study is no longer being cited by DC WASA and US EPA as evidence of anything at all. In a phone conversation I had with Dr. Reiber in late 2007, I was shocked to learn that he was completely unaware that every point of the Wujek study had been collected when chloramine was absent from the water.
1.b. DC WASA provided false information that fed into assumptions and interpretations made for the US EPA Region III study. Specifically:

**Dielectric Insertion.**

A dielectric is an insulating device that prevents direct electrical contact between dissimilar metals, and hence avoids at least some of the problems associated with galvanic coupling. Although not always used, it is generally considered good plumbing practice to use a dielectric when different metal plumbing materials are to be connected. It is standard policy for DC WASA to use dielectric couplers when performing partial LSL replacements (DC WASA, 2004).

Figure 11 shows the effect of inserting a dielectric coupler between the passivated LSL and copper sections of the directly coupled test rig. While in the previous water quality testing it was shown that the galvanic effect of the direct coupling was largely limited to the copper line and had little effect on the LSL, the insertion of a dielectric removes any galvanic impact from either surface. This is a particularly important finding, and along with the general polarization resistance of passivated LSL sections, explains why the partial LSL replacement program in the DC WASA system has not exacerbated lead conditions, but rather has helped to reduce household lead levels.

**Final Report, page 15, November 2006**

DC WASA has now admitted that it never installed a dielectric. Their false statement created a “safety net” specifically cited by the author. That is, even if galvanic effects were important to lead leaching, because it was understood that DC WASA always installed a dielectric it could not be important in D.C..

The above also clearly reinforces the authors’ misconception that DC WASA had data showing “the partial LSL replacement program in the DC WASA system has not exacerbated lead conditions, but rather has helped to reduce household lead levels.” DC WASA does not now have, nor has it ever had, data which proves anything of the sort.

2) All lead in water data collected during the study, at least some of which contradicts key conclusions, were “buried.” The data that are presented do not support the study’s conclusions.

The only data that can be used to “prove” that galvanic connections between lead and copper do not increase lead in water, are those measurements collected during the study of actual lead in water. Documents produced via FOIA demonstrate that this data was critical to the study design and to allow conclusions to be drawn as is intuitively obvious. Extensive planning and taxpayer funds went into the collection of the lead in water data during the study.

A preliminary report obtained via FOIA indicates that at least some lead in water data was collected. For example, one conclusion stated that:

**Metal Release.** Metal release from unpassivated LSL sections (scale removed) is exceptionally high when galvanically coupled. Metal release from passivated LSL

Attachment 1, page 29 July 23, 2005

_The Commonwealth is Our Campus_  
_An Equal Opportunity/Affirmative Action Institution_
The conclusion that the galvanic connection between lead and copper could cause "exceptionally high" lead release (to water) in at least some circumstances was inexplicably deleted from the final report. This is not a trivial omission. For example, as the authors clearly note, the lead pipe in the D.C. system was unpassivated whenever chloramine was in the water:

In the DC WASA case, however, the passivating corrosion scales formed on the LSLs in the presence of chloramines are clearly less protective than those formed in the presence

Attachment 1, page 15, September 28 2004

Knowing of the critical importance of this lead in water data, I repeatedly tried to get the actual lead in water data that was collected during the study throughout 2007 by FOIA of EPA. According to the QAPP (see for example page 35 of attachment 1) lead in water measurements had to be collected "several times a day." US EPA Region III either cannot, or will not, produce this important data to me. Perhaps the DC WASA board would have better luck in trying to obtain the actual lead in water data collected during this study, and see for themselves whether high levels of lead were detected.

When asked about this issue, of drawing conclusions about lead in water without presenting any lead in water data, the authors claimed that:

The short term tests used in this study did not readily lend themselves to standard metal release monitoring used in other aspects of the DC WASA corrosion control optimization studies. While monitoring metals release rates was attempted, it was found that the physical cutting and manipulation of LSL sections generated frequent and irregular particulate release. The individual tests, which generally ran for periods of only a few days each, did not provide sufficient time to condition and stabilize the scales on the different test sections.

Page 12 and 13 of Attachment 1.

Frankly, this is a pathetic excuse. The cutting and manipulation during the study are not any more severe than the digging, cutting and manipulation that occur during an actual partial replacement. The fact that "frequent and irregular particulate release" was observed in the experiment is exactly the type of problem that we are concerned about relative to PLSLR in the DC WASA system. Rather than exclude this important data and information from the final report, the authors should have discussed the problem openly relative to potentially harmful lead exposure at the tap. The report authors had every opportunity to run this experiment for months, if necessary, to see what occurred relative to actual lead in water with time and to obtain meaningful conclusions.

If the key data for the study could not be collected, then no definitive conclusions should have been drawn at all. Moreover, caveats, such as that indicating that metals release can be exceptionally high from galvanic connections in some cases, should have been included in the final report. It is my personal suspicion that the actual lead in water measurements were "buried" because they were very high, and therefore, were illustrating a serious problem that is perfectly representative of what actually does occur in the DC WASA system. However, because the results directly contradicted DC WASA's purported experiences (which we now know do not exist and never did) the data was deemed "wrong" and hidden.
I would like to point out that it was well-understood before the US EPA Region III report that galvanic effects can sometimes have very serious impacts on lead in water leaching. For example, I am attaching a peer-reviewed journal paper by Britton that cites work in Scotland, demonstrating much worse lead leaching in situations when lead pipe is connected to copper (see relevant excerpt in appendix 1 of this letter). In addition, it notes that putting a copper pipe in front of lead pipe (as DC WASA has done) can be especially serious due to a phenomenon known as “deposition corrosion.” Similar references to problems resulting from lead pipe and copper pipe connections also appear in the standard reference book in our field (Internal Corrosion of Water Distribution Systems, 2nd Edition AWWARF). Indeed, we routinely see serious problems in the laboratory whenever we connect lead to copper pipe (using actual measurements of lead in water). I even presented data on this in March 2004 to the DC Council when I warned them of problems with partial replacements (see slides 1 and 2 in appendix 2 of this letter).

To illustrate a few final points, before the final report was written I discovered that the researchers did not even use Washington D.C. water in their testing. Instead, Seattle water was used. This makes the results completely worthless relevant to the situation in Washington D.C.. The researchers also conducted the entire study with continually flowing water, instead of imposing stagnation as frequently occurs in home plumbing. It is well-known that the worst lead in water problems are produced as a result of galvanic connections during stagnation.

I note that it is hypothetically possible that the galvanic connections between the copper and lead (with no dielectric present) may currently be increasing actual lead in water insignificantly in Washington DC. It is also possible, even likely, that the connection has created a problem with “frequent and irregular lead release” of “exceptionally high” concentration lead. The report that DC WASA and US EPA Region III have cited and distributed is completely worthless in clarifying the situation beyond these two hypothetical extremes. The fact that this “study” is even being mentioned in public by the two agencies, with all the obvious misrepresentations and false assumptions it contains, is extremely worrisome. Indeed, the entire incident is a perfect example of why these two agencies have no credibility on the issue of lead in Washington D.C. water.

Please call me at (540) 231-7236 if you should have any questions about this letter, my experiences related to this study, or my expertise about the role of galvanic corrosion in contributing to lead in water problems.

Regards,

Marc Edwards
Charles Lunsford Professor of Civil Engineering
MIXED METAL PLUMBING

Studies in Glasgow have indicated that galvanic corrosion of lead caused by dissimilar metals in the pipework could exacerbate plumbosolvency. Frequently during the repair of a lead pipe a section of copper pipe would be inserted, and this section could then raise the water lead concentration in two ways; by direct electrochemical corrosion of the adjacent surfaces of copper and lead, and by the take-up and deposition of copper on to the lead pipe as the water passes in turn through each pipe section. Each site of copper deposition has potential to act as an individual galvanic cell, depending on the nature of the lead pipe surface and the corrosion products present. Table IV shows results taken from a detailed study of 195 households in Glasgow of which 186 had all or some lead services. It was found that 69 households had some pipe sequence including at least one copper/lead/tap sequence and of these 43 yielded samples with abnormally erratic or much higher than normal lead concentrations. Thus only 38% of such properties gave satisfactory samples whereas for all other properties 89% gave satisfactory samples. Occasionally the insertion of copper pipe can produce particularly bad results and despite satisfactory pH control it may be impossible to obtain any satisfactory samples. This situation is exemplified in Fig. 5.

Of the 186 properties with lead services 155 had copper pipe abutting the tap and for 111 of these the length of 13mm copper pipe involved was less than 8m (one litre capacity). Thus the one litre first draw sample or random day time sample would include water from around the lead/copper junction. In many cases electrochemical action at this junction appears to increase lead concentration. This may help explain unexpectedly high lead concentrations in some first draw samples and may contribute to the rapid increase in water lead concentrations for the properties shown in Fig. 1. Further evidence of this effect for one of these properties is shown in Figs. 6 and 7 where the contribution to the water lead concentration from the area around the lead/copper junction is obvious. These electro-

<table>
<thead>
<tr>
<th>TABLE IV. PLUMBOSOLVENCY STUDY OF 195 HOUSEHOLDS IN GLASGOW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>total number of properties</td>
</tr>
<tr>
<td>copper plumbing systems</td>
</tr>
<tr>
<td>lead lined tanks</td>
</tr>
<tr>
<td>systems incorporating a copper/lead junction</td>
</tr>
<tr>
<td>systems terminating in copper at tap:</td>
</tr>
<tr>
<td>with lead prior to terminal section of copper</td>
</tr>
<tr>
<td>with lead and/or copper/lead prior to terminal section of copper</td>
</tr>
<tr>
<td>households giving satisfactory samples</td>
</tr>
<tr>
<td>Number</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>138</td>
</tr>
<tr>
<td>9</td>
</tr>
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<td>0</td>
</tr>
<tr>
<td>26</td>
</tr>
<tr>
<td>76</td>
</tr>
<tr>
<td>92</td>
</tr>
</tbody>
</table>
Old Situation

Iron is sacrificed, Pb and Cu protected

New Situation

0.5 V battery

Pb is “sacrificed”

Even 1 foot of lead pipe contains enough lead to contaminate every drop of water a family will use in 100 years....it is not just the amount of lead, but the rate of corrosion
From water meter, new copper pipe creates battery over whole Pb pipe surface, catalyzing attack on lead
Deposition corrosion effect presented to the D.C. Council in 2004. Because of deposition corrosion, installing a copper pipe in front of a lead pipe can generate serious long term consequences that are much worse than the galvanic connection in which copper is installed after the lead.
A White Paper Proposal to Study the Effects of External Currents and Dissimilar Metal Contact on Corrosion and Metals Release from Lead Service Lines

Prepared by

HDR Engineering
Bellevue, Washington

And

The Cadmus Group, Inc.
Arlington, VA

ABSTRACT

The suggested study design is a series of short-term laboratory-based testing protocols designed to identify whether grounding and/or galvanic currents can have a significant and prolonged impact on metals release from lead service lines (LSLs) and leaded-brass appurtenances. This determination would be made using test rigs where different forms of grounding currents (AC vs. rectified) can be impressed on both scaled and unscaled LSLs, while the internal surface potential of the pipe is monitored. Galvanic currents would be generated using the coupling of different lengths of copper tubing to the LSLs while the surface potential is measured. The testing described herein is not intended to replicate actual distribution system conditions, but rather to explore a series of scenarios where the highest possible metal release and greatest conceivable LSL surface effects are generated. If the findings of this study are negative, there will be a strong basis for discounting the claims and concerns relative to accelerated metal release associated with partial lead service line replacement (PILSR). If the findings are positive, the study could serve as a foundation and starting point for field tests that explore grounding and galvanic effects in the distribution system with greater similitude. The advantages of the protocols described here are that they are short term and relatively low cost.

INTRODUCTION

The recent DC WASA experience relative to LSL replacement indicates that PILSR does not exacerbate lead-release rates, and can in fact reduce overall drinking water lead concentrations in the home. While this evidence appears strong, there remains a debate about the potential galvanic effects associated with replacing a portion of the old LSL with new copper tubing. Claims have appeared in both the press and scientific...
publications suggesting that galvanic impacts related to PLSLR, as well as galvanic impacts on leaded-brass appurtenances, may accelerate lead release in DC homes. If so, this may negate all, or at least a portion, of the potential benefit associated with the PLSLR program.

There also remains a controversy about the effect of common grounding currents on the corrosion of LSLs. Some researchers have suggested these currents may be responsible for some of the abnormally high lead-release levels observed in isolated homes. By extension, it can be assumed that if grounding currents are important, at least a portion of the randomness associated with observed lead levels may be related to the presence of different magnitude grounding currents.

The purpose of the research described in this paper proposal is to establish under controlled laboratory conditions the absolute magnitude of the corrosion impacts potentially associated with both grounding currents and galvanic coupling to lead service lines. It is important to note that while the proposed mechanisms of the galvanic and/or impressed current influence are plausible, and anecdotal evidence is supportive, it has not been clearly demonstrated that either grounding current or galvanic coupling can in fact meaningfully increase lead release rates. The research proposed here would explore laboratory-generated worst-case situations where the respective impacts on LSLs, if they exist, can be documented and quantified. This study is not intended to duplicate actual field conditions where a PLSLR has occurred, or explore grounding currents in an existing home. Rather, this research is intended to demonstrate whether the respective phenomena can in fact accelerate lead release, or not. If a meaningful impact cannot be demonstrated under conditions designed to exacerbate lead release, then further study in the field is likely unwarranted. In short, if we cannot in this research demonstrate a meaningful impact, than conditions in the DC homes and the distribution system, which will be less challenging than the laboratory test conditions, are not likely to be contributing to accelerated lead release.

This research would not attempt to correlate laboratory experience with field conditions. It is beyond the recommended scope of work to define how differences in soil resistivity, passivation states of copper tubing, or quality of plumbing fabrication may influence the respective current impact. The testing described here is short-term, inexpensive and designed to answer the question: can grounding and/or galvanic currents meaningfully contribute to lead release?

GROUNDING EFFECTS

Background

Although this topic has been researched extensively over the past decade, there is still considerable debate about the impact of externally-imposed grounding currents on the electrochemistry of interior surfaces of domestic plumbing. The bulk of available research has focused on copper tubing – largely ignoring grounding impacts on lead service lines. While some research has suggested an important internal corrosion role for
grounding currents (Bell, 1995; Bell, 1998), other laboratory simulations and field tests have discounted them relative to copper release and associated water quality effects (AWWARF, 1996). The principal issue largely remains: does a current flowing in the pipe wall, and exiting the pipe via an external connection (grounding circuit), change the electrical character of the internal pipe surfaces? If it does, a variety of corrosion and water quality impacts are to be expected, including accelerated metal release. However, an absence of a measurable electrical change on the internal surface would mean the grounding circuit is irrelevant to the internal corrosion processes.

At first glance, it seems intuitive that imposing a (grounding) current on a buried pipe would change the surface potential of the internal and external surfaces. This is certainly true of the external surfaces as the current is dissipated to ground. However, internally, unless some portion of the grounding current is lost to the electrolyte (water in the pipe), these surfaces will show no change in surface potential relative to the water contacting them. In effect, imposing an external current on the pipeline changes the potential of all surfaces and everything in contact with the pipe. Internally, however, the surface potential relative to the electrolyte (which determines corrosion rates) may not change substantially since the electrolyte potential has also been shifted an amount equal to the internal surface.

An important component of the study described in this white paper is an electrochemical investigation of the interior surfaces relative to simulated grounding currents on both heavily scaled and non-scaled LSLs. The objective is to demonstrate under controlled conditions whether it is possible to create a grounding scenario that accelerates internal metal release, and to extrapolate the relevance of those conditions to actual household plumbing practices. Quantifying the actual interior surface potential change vis-à-vis the electrolyte (water) of these pipes is key to assessing grounding current impacts. Any meaningful change in the corrosion condition of the internal surface will be reflected by a substantial change in surface potential, which under the appropriate laboratory conditions can be monitored with a high degree of accuracy (+/- 0.1 mV).

Research Approach

A flow-through recirculation loop consisting of DC WASA lead service-line segments, water reservoir, flow control and pumping hardware would be employed for this testing. The LSL segments would be modified to accept high impedance reference electrodes penetrating the pipe wall at multiple locations along its length. The electrodes would monitor surface potential on the interior of the pipe relative to the electrolyte, yet allow for pipeline pressurization.

Internal surface potential along the pipeline would be monitored, while different current forms, amperages, voltages and grounding scenarios are applied to the test pipes. At a minimum, the testing criteria would include the following:
| Impressed grounding forms          | • Full wave AC  
|                                  | • Half wave rectified  
|                                  | • DC  
| Voltage range                    | 0 – 220 Volts  
| Current range                    | 0 – 20 Amps  
| Grounding scenarios              | • Single point ground  
|                                  | • Multi-point ground along pipe length  
|                                  | • Variable resistance reservoir ground: By providing a current path from the pipe wall through the electrolyte to ground, it will be possible to dissipate some of the applied external current to the interior surface of the pipe. The variable resistance ground to the electrolyte reservoir will make it possible to balance current dissipation between external and internal surfaces.

Because of the capacitance effects of a corrosion scale relative to alternating current, it will be important to evaluate grounding impacts on both heavily-scaled and non-scaled LSLs. This study design includes testing on these surfaces, as well as on leaded-brass appurtenances such as water meters. Lead service-line test segments and brass appurtenances will be obtained directly from DC WASA. The water meter testing will be conducted in a loop arrangement similar to the lead service-line test rig; however, due to the geometry of the water meter it will likely be possible to insert only a single reference electrode into the body of the meter.

The primary impact of the grounding current would be assessed via internal surface potential changes on the LSL and brass water meters. Potential impact on lead release would be confirmed via analysis of lead concentrations in the recirculation water. Both dissolved and particulate lead levels could be determined. The water chemistry used in the recirculation loop would consist of a synthetic water targeting the basic inorganic constituents of the DC WASA system.

**GALVANIC EFFECTS**

**Background**

Unlike the debatable and uncertain impacts of grounding currents on internal corrosion, galvanic related corrosion impacts associated with dissimilar metals coupling has been theoretically quantified and measured in both the laboratory and the field (Reiber, 1991). The magnitude of the galvanic impact relates directly to the electro-activity of the anodic and cathodic surfaces, and their respective sizes and geometries.

The relevance to LSL replacement is straightforward: a partial replacement of a portion of the lead line with a new copper service line creates a relatively strong galvanic couple.
with an initial Cu/Pb electromotive difference in the 50 – 100 mV range. If the potential of the entire remaining section of lead service line were shifted in the anodic direction by this amount, clearly there would be a substantial acceleration of the corrosion rate and associated lead-release rates. Yet, in practice, we find that a PLSLR does not usually increase lead release (DC WASA, 2004). Moreover, in other studies that have assessed lead release from intact and aged LSLs electrically connected to copper tubing for many years, no meaningful increase in lead-release rates was identified (HDR Engineering, 1994).

The answer to this conundrum likely relates to the respective geometries of the anodic and cathodic surfaces of the galvanic couple. Because sequential pipelines (LSL to copper tubing) are connected at only a single location, it is likely that only a small portion of the LSL is polarized by the galvanic current. And, given the relatively rapid rate at which both copper and lead surfaces passivate, the duration of the polarization may be relatively brief. Hence the galvanic effect may be very short term.

In the DC WASA case, however, the passivating corrosion scales formed on the LSLs in the presence of chloramines are clearly less protective than those formed in the presence of free chlorine. It will be important to distinguish between the galvanic impact associated with these different forms of corrosion scales.

Research Approach

This portion of the recommended research would explore galvanic coupling related to PLSLR in a laboratory context where the electrochemical effects of galvanic coupling can be monitored and assessed relative to geometry and passivation state of the respective lead and copper pipes. The practical objective of this effort is to assess the magnitude and duration of the galvanic impacts associated with PLSLR.

As in the grounding current portion of this study, it would be possible to assess the galvanic impact of copper and lead service-line coupling by monitoring the surface potentials along the lengths of the respective pipe sections, especially in the immediate proximity of the contact point between copper and lead lines. A recirculation test loop consisting of water reservoir, pumping and flow control equipment, and different lengths of copper and LSLs (LSLs to be provided by DC WASA) would be constructed. High impedance reference electrodes would be inserted along the lengths of both copper and lead lines, and the surface potential of the respective lines would be monitored at the initial coupling and for extended passivation periods thereafter. Water chemistry impacts relative to galvanic coupling would also be explored, including assessing the relative impacts of chlorine and chloramine across a typical distribution system concentration range.

To ensure the maximum galvanic driving potential, testing could be conducted using both scaled LSLs from the DC WASA system, and LSLs that have been scoured to remove any existing corrosion scale. The copper tubing used in these tests would consist of new tubing polished to ensure an electro-active surface. If the galvanic testing using LSLs
shows a positive result, similar tests could be conducted using leaded-brass water meters as the anodic surface.

Given the geometry of the service lines, the area of greatest galvanic influence would be in close proximity to the coupling point. A special rig with a reference electrode that can be moved and placed with precision along the bore of the pipes would be used to quantify both the magnitude and the area of influence. This research could quantify the LSL portion that is galvanically activated, the duration of activation, and associated lead-release rate increases.

RESEARCH EFFORT AND SCHEDULE

Grounding and galvanic current testing could be conducted in the HDR Engineering Water Quality and Corrosion Services Laboratory in Bellevue, Washington. The HDR facility already has available the necessary electrochemical and pipe loop equipment to conduct this work. Analytical work (i.e. water chemistry) will be performed internally.

The total estimated research effort (manpower) for HDR is approximately 400 hours, broken down as follows:
<table>
<thead>
<tr>
<th>Task</th>
<th>Effort</th>
<th>HDR Rate</th>
<th>Hours</th>
<th>Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Develop detailed study plan</td>
<td>Research Technician</td>
<td>$85.00</td>
<td>20</td>
<td>$1,700</td>
</tr>
<tr>
<td>Develop detailed study plan</td>
<td>Principal Investigator</td>
<td>$207.00</td>
<td>20</td>
<td>$4,140</td>
</tr>
<tr>
<td>Laboratory set-up</td>
<td>Research Technician</td>
<td>$85.00</td>
<td>100</td>
<td>$8,500</td>
</tr>
<tr>
<td>Testing</td>
<td>Research Technician</td>
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<td>100</td>
<td>$8,500</td>
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<tr>
<td>Testing</td>
<td>Principal Investigator</td>
<td>$207.00</td>
<td>50</td>
<td>$10,350</td>
</tr>
<tr>
<td>Report preparation</td>
<td>Principal Investigator</td>
<td>$207.00</td>
<td>50</td>
<td>$10,350</td>
</tr>
<tr>
<td>EPA coordination and management</td>
<td>Principal Investigator</td>
<td>$207.00</td>
<td>50</td>
<td>$10,350</td>
</tr>
<tr>
<td>Clerical support</td>
<td>Project Controller</td>
<td>$85.00</td>
<td>10</td>
<td>$850</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td></td>
<td>400</td>
<td>$54,740</td>
</tr>
<tr>
<td>Subcontractor Handling Costs (4.4%)</td>
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<td></td>
<td></td>
<td>$2,410</td>
</tr>
<tr>
<td><strong>Total for Subcontractor HDR (approx)</strong></td>
<td></td>
<td></td>
<td>400</td>
<td>$57,150</td>
</tr>
</tbody>
</table>

The budget above does not reflect the hours needed for Cadmus staff to process contract paperwork, work with HDR to develop an acceptable QA/QC plan, oversee the work, and review the work products. The estimated Cadmus hours needed for these tasks are 60 to 120 at an average hourly rate of approximately $75 per hour, for an estimated cost of $4,500 to $9,000. Thus, the total estimated cost for this work ranges from $61,500 to $66,000.

The overall schedule for completion is approximately three months from notice to proceed, although this is dependent on time needed for approval of the QA/QC plan.

As noted earlier, the proposed project is not a major research effort. It is intended instead to quickly identify whether or not there is a serious problem associated with galvanic coupling and grounding currents relative to LSLs. If the project demonstrates an effect, further research will be needed to quantify the extent of the problem in the distribution system, including extensive field work. If, on the other hand, the project does not identify a significant impact associated with grounding or galvanic currents, it would then be relatively clear that concerns about these electrochemical effects are out of proportion, and likely not a serious contributor to lead release in the DC WASA system.
References


AWWA Research Foundation, "Electrical Grounding, Pipe Integrity and Shock Hazard, 1996


DC WASA, personal communication with Richard Giani, 2004

HDR Engineering, Corrosion Control Assessment for the City of Tacoma, 1994
Progress Report

Effects of External Currents and Dissimilar Metal Contact on
Corrosion and Metals Release
from Lead Service Lines

Prepared by
HDR Engineering
and
The CADMUS Group

July, 2005
is in excess of 500 - 600 mV per decade of current shift. Overall, this explains, at least in part, why the galvanic coupling has little apparent effect on passivated lead surfaces.

*Metal Release.* Metal release from unpassivated LSL sections (scale removed) is exceptionally high when galvanically coupled. Metal release from passivated LSL sections is exceptionally low, even when galvanically coupled. This may be because the oxidized metal generated in the galvanic process is largely retained within the corrosion scale.

*Area of LSL Influence.* The galvanic area of influence on an LSL specimen, even when unpassivated, is relatively small – possibly less than the first few feet of pipe extending away from the point of coupling. As the LSL passivates the area of galvanic influence decreases. On a well-passivated LSL the galvanic area of influence is likely limited to at most a few inches of pipe in the immediate vicinity of the coupling.

*Length of Copper Pipe.* Anode/cathode ratio is relatively unimportant on well-passivated LSL surfaces. This means that even an exceptionally long length of copper pipe connected to a partial LSL does not elevate the galvanic effect.

*Chlorine Impacts.* A free-chlorine residual does elevate the galvanic effect by accelerating the cathodic current exchange process. Conversely, chloramine has a lesser galvanic impact than free chlorine.

*Conductivity Effects.* The area of galvanic influence on the LSL specimen is expanded as the conductivity of the electrolyte (water) increases. DC WASA distributes a low conductivity water (< 120 microSiemens), which may in part explain the minimal galvanic impacts observed. A conductivity increase of 100 microSiemens would double the area of LSL galvanic influence.

*Dielectric Effects.* While galvanic impacts relative to DC WASA partial LSLs are likely minimal, any break in electrical continuity between the copper and LSL lines effectively eliminates the potential for a galvanic effect. In short, a conventional plumbing dielectric junction removes even the minor corrosion risks associated with galvanic coupling.

**Continuing Research**

*Galvanic Impacts.* The remaining portion of the galvanic research is focused on the assessment of chloramine effects on passivated LSLs, and how changes in orthophosphate inhibitor application coupled with chloramines exposure may alter galvanic processes and metal release.

*Grounding Currents.* Does a current flowing in the pipe wall, and exiting the pipe via an external connection (grounding circuit), change the electrical character of the internal pipe surfaces? If it does, a variety of corrosion and water quality impacts are to be expected, including accelerated metal release. This is the grounding current scenario that is typical of the electrical systems in many older households. This portion of the study will be an electrochemical investigation of the interior LSL surfaces relative to simulated grounding currents on both heavily scaled and non-scaled specimens. The objective is to demonstrate under controlled conditions whether it is possible to create...
grounding scenarios that accelerate internal metal release, and to extrapolate the relevance of those conditions to actual household plumbing practices.

A flow-through recirculation loop consisting of DC WASA lead service-line segments, water reservoir, flow control and pumping hardware will be employed for this testing. The LSL segments will be modified to accept high impedance reference electrodes penetrating the pipe wall at multiple locations along its length. The electrodes will monitor surface potential on the interior of the pipe relative to the electrolyte, yet allow for pipeline pressurization. Internal surface potential along the pipeline will be monitored, while different current forms, amperages, voltages and grounding scenarios are applied to the test pipes. Following experimentation with LSL sections, a limited grounding current test protocol will be conducted using leaded-brass water meters and the same impressed current testing regimen.

This portion of the study will require 2 to 3 weeks of laboratory time.
SUPPLEMENTAL QUALITY ASSURANCE PROJECT PLAN (QAPP) FOR STUDY OF THE EFFECTS OF EXTERNAL CURRENTS AND DISSIMILAR METAL CONTACT ON CORROSION AND METAL RELEASE FROM LEAD SERVICE LINES

Submitted to:
George Rizzo
Work Assignment Manager
U. S. Environmental Protection Agency

Work Assignment 2-47, Task 4 of EPA Contract #68-C-02-069

Prepared by:
The Cadmus Group, Inc.
57 Water Street
Watertown, MA 02472

June 13, 2005
For the grounding current experiments, surface potential along the pipeline will be monitored while various voltages and grounding scenarios are applied to the pipe. The scenarios to be tried include:

**Table 1: Experimental Scenarios**

| Impressed grounding current forms | Full wave AC  
|                                  | Half wave rectified DC |
| Voltage range                    | 0 – 220 Volts          |
| Current range                    | 0 – 20 Amps            |
| Grounding scenarios              | Single point ground  
|                                  | Multi-point ground along pipe length  
|                                  | Variable resistance reservoir ground: By providing a current path from the pipe wall through the electrolyte to ground, it will be possible to dissipate some of the applied external current to the interior surface of the pipe. The variable resistance ground to the electrolyte reservoir will make it possible to balance current dissipation between external and internal surfaces. |

Scale can have a capacitance effect on alternating current, so both scaled and non-scaled pipes will be tested.

A brass water meter will also be tested to determine the effects of grounding currents on brass appurtenances. The meter will be obtained from WASA and will be outfitted with a single reference electrode.

The effect of grounding currents of lead service lines and brass water meters will be determined both by measuring the inner surface potentials and by measuring both dissolved and particulate lead in the water.

The other portion of the project will involve measuring the magnitude and duration of galvanic effects resulting from coupling of lead and copper pipes during PLSLR. The same type of flow-through recirculation loop will be used, this time coupling the lead service lines with copper pipes. Reference electrodes will be placed along the length of both the copper and lead pipes. A special electrode rig will be used in the near vicinity of the galvanic joint that will be capable of measuring with precision the distance from the joint and the potential.
Potential measurements will be taken for extended times to allow for passivation. Both scaled and unscaled lead lines will be used to examine the differences that scale makes. The effect of water chemistry will also be examined by performing the experiment separately with chlorine and chloramines as the disinfectant.

The extent of the galvanic activation, its duration, and the increase in lead release as a result will all be measured as part of this experiment.

A7. Quality Objectives & Criteria for Measurement Data

The purpose of this project is to evaluate the level of corrosion of lead service lines caused by galvanic corrosion and grounding currents. This evaluation includes the following goals:

- Measure the surface potential and corrosion rate of lead service lines impressed with a grounding current at a single point.
- Measure the surface potential and corrosion rate of lead service lines impressed with a grounding current at multiple points.
- Measure the surface potential and corrosion rate of lead service lines impressed with a variable resistance reservoir ground.
- Measure the surface potential and corrosion rate of brass water meters impressed with a grounding current at a single point.
- Measure the surface potential and corrosion rate of brass water meters impressed with a grounding current at multiple points.
- Measure the surface potential and corrosion rate of brass water meters impressed with a variable resistance reservoir ground.
- Measure the surface potential of unscaled lead service lines with a galvanic couple to a copper line.
- Measure the surface potential of scaled lead service lines with a galvanic couple to a copper line.

A8. Special Training Requirements/Certifications

No specific training will be conducted for this experiment. The two HDR personnel, Michael Britton and Sidney Hendrickson, Ph.D., who will oversee daily operations of the experiments, both have extensive experience in the water industry and with running pilot scale research experiments.
A9. Documents and Records

The Cadmus work assignment manager will distribute this QAPP and any revisions to each individual listed on the distribution list and to all personnel involved in this project.

Project personnel will keep:

- Field notes;
- Shipping receipts;
- Chain of custody forms;
- Raw water data and quality control (QC) sample records; and,
- Instrument, equipment, and model calibration information.

All standard sampling will be done on site. Weekly samples, however, will be sent off site as a QC check to the on-site measurements. Shipping receipts and chain of custody forms for these samples will be kept.

Cadmus will submit a Draft Report to the EPA Work Assignment Manager for review. The report will be submitted electronically and in hard copy as stated in the attached work plan. The report will include data collection methodologies, an analysis of data collection results, and a description of any necessary corrective actions. Cadmus does not anticipate submission of actual field logs, sample preparation and analysis logs, instrument printouts, QC sample records or receipts, or the results of calibration checks, but will include this information in the final project report, along with any revisions suggested by the EPA Work Assignment Manager.

Cadmus will keep all documents and records related to this project at its Arlington, Virginia office. Documents and records will be kept for the life of the contract under which this project was completed, or in accordance with any applicable U.S. government record retention policies, whichever is longer.

B1. Sampling Process Design

Table 2 lists the parameters that will be measured, the equipment that will be used, and the frequency of these measurements. The primary measurement that will be taken is surface potentials. Surface potentials will be measured on the interior surface of the pipe or water meter, depending on the experiment, using a multimeter coupled to saturated calomel and Ag/AgCl reference electrodes. Corrosion rates on surfaces with impressed currents will be measured using an automated potentiostat. Lead and copper concentrations will be measured using a colorimeter.
Table 2: Sampling Parameters and Equipment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Equipment</th>
<th>Sampling Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Potential</td>
<td>Fluke Multimeter coupled to a saturated calomel and Ag/AgCl reference electrode.</td>
<td>Continuous</td>
</tr>
<tr>
<td>Corrosion Rate</td>
<td>Gamry Automated Potentiostat</td>
<td>Twice a day or more often as needed</td>
</tr>
<tr>
<td>Lead</td>
<td>Hach LeadTrak (TM)</td>
<td>As needed, several times a day</td>
</tr>
<tr>
<td>Copper</td>
<td>Hach CuVer (R)</td>
<td>As needed, several times a day</td>
</tr>
</tbody>
</table>

B2. Sampling Methods

Staff are aware of the common routes of exposure when sampling, and are trained in the proper use of safety equipment and protective clothing.

Sampling will be conducted by Michael Britton and Sidney Hendrickson, Ph.D., who have extensive experience with the methods involved. Samples will be drawn from the reservoir as well as the pipe loop during circulation. Both the reservoir and pipe loop will be outfitted with sample taps. Samples for metal analysis will be drawn from the sample taps after one minute of flushing. Containers will then be rinsed with sample and discarded before the container is filled with sample to be measured. Standard methods and practices will be used for all sample gathering, preservation, packaging, and transport.

B3. Sample Handling and Custody

All sample sets will be accompanied by a chain-of-custody form. An example of the form that will be used is attached to this QAPP. When the possession of samples is transferred, both the individual relinquishing the samples and the individual receiving the samples will sign, date, and note the time on the chain-of-custody document. The original form of the chain-of-custody record will accompany each shipment. A copy will be retained by a representative of the sampling team.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Analytical Method</th>
<th>Detection Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper and Lead (for QC)</td>
<td>US EPA 200.8</td>
<td>0.003 μg/L (Cu) and 0.005 μg/l (Pb)</td>
</tr>
</tbody>
</table>

**B5. Quality Control**

Corrective action procedures are described in Section 10.4.2 of the Cadaus QMP (CGI-821; Revised).

Table 4 provides the data quality indicators and the determination methodology that will be used for the samples collected during this study.

<table>
<thead>
<tr>
<th>Data Quality Indicator</th>
<th>Definition</th>
<th>Determination Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precision</td>
<td>Measure of agreement among repeated measurements of the same property under identical or substantially similar conditions.</td>
<td><strong>Split samples</strong> Daily samples will be split and measured for lead and copper</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Conforming to ASTM techniques</strong> Electrochemical techniques will conform to ASTM G3-74</td>
</tr>
<tr>
<td>Bias</td>
<td>The systematic or persistent distortion of a measurement process that causes errors in one direction.</td>
<td><strong>Blanks</strong> Blanks of Milli-Q water will be analyzed for lead and copper</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Calibration with standards</strong> Manufacturer provided standards will be measured and used to prepare calibration curves for lead and copper each day.</td>
</tr>
</tbody>
</table>

Table 4: Acceptance Criteria for Primary Data
Sampling personnel will adhere closely to all sample storage, preservation and handling protocols. Sample bottles and preservatives required by the analytical method will be used. Sample collection time will be included on the chain-of-custody form so that holding times will not be exceeded.

B4. Analytical Methods

To obtain reliable and reproducible results, all laboratory analyses will adhere to prescribed analytic methods. All analyses will be performed on-site by HDR personnel experienced with the procedures. To verify measured lead and copper concentrations, weekly lead and copper samples will be split and duplicate samples will be sent to North Creek Analytical in Bothell, WA. North Creek Analytical is certified by EPA and the state of Washington to perform lead and copper analyses. Results will be reported back to the on-site personnel, so that gaps in the QA/QC can be detected and corrected.

QA oversight for sampling will be provided by HDR’s Dr. Reiber. In the event that a sample is invalidated due to laboratory or handling error, HDR and Cadmus will take the necessary corrective action including collecting another sample at the same sampling location using an identical procedure.

Table 3 provides the analytical methods, detection limits, and holding times that will be used for the samples collected during this study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Analytical Method</th>
<th>Detection Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Potential</td>
<td>Pipe section flow cell method (AWWARF 1996), where applicable will conform to ASTM G3-74</td>
<td>0.1 mV</td>
</tr>
<tr>
<td>Corrosion Rate</td>
<td>Potentiodynamic sweep, will conform to ASTM G3-74</td>
<td>0.1 mV</td>
</tr>
<tr>
<td>Lead</td>
<td>Hach LeadTrak</td>
<td>0.004 mg/L</td>
</tr>
<tr>
<td>Copper</td>
<td>Hach Method 8506</td>
<td>0.04 mg/L</td>
</tr>
</tbody>
</table>
TECHNICAL PROGRESS REPORT

EPA Contract No. 68-C-02-069
Work Assignment No. 2-47

District of Columbia Water System - Direct Implementation Support

May 2005

Work Assignment Manager: George Rizzo
Effective Date: August 1, 2004
Completion Date: July 31, 2005
Subcontractors: HDR Engineering, Anne Camper, Ph.D., Gregory Korchin, Ph.D., Virginia Military Institute (VMI)

Summary of Activities for Current Month:

Task 1: Development of Work Plan

• Cadmus performed routine work assignment management activities, including writing and submitting the monthly progress report, tracking budget expenditures, and managing the subcontractors.

• Cadmus continued developing quality assurance plans for the new studies in Amendment 1 that require collection of original data.

Task 2: Sanitary Survey of the Washington Aqueduct

• None.

Task 3: Sanitary Survey of Consecutive Water Systems

• None.

Task 4: Review of Corrosion Control Treatment Recommendations

• Cadmus and its subcontractor, Dr. Steve Reiber of HDR Engineering, continued to review data collected from the electro-chemical pipe loop studies and discussed results with the DC Water and Sewer Authority (WASA).
Task 3: Sanitary Survey of Consecutive Water Systems

- Upon receipt of comments from the EPA WAM on the sanitary survey report developed under a previous work assignment, Cadmus will revise the report.

Task 4: Review of Corrosion Control Treatment Recommendations

- Cadmus and its subcontractor, Dr. Reiber, will continue to review data collected from the electro-chemical pipe loop studies and discuss results with DC WASA personnel.

- Cadmus and its subcontractors will participate in the Technical Expert Working Group (TEWG) conference call scheduled for July 3, 2005, and prepare a conference call summary. Cadmus will participate in additional TEWG conference calls as scheduled by the EPA WAM.

- Cadmus and its subcontractor, Dr. Reiber, will continue writing the interim OCCT report.

- Cadmus and its subcontractor, Dr. Reiber, will continue conducting a study to determine the effects of external currents and dissimilar metals on corrosion and metals release from lead service lines.

Task 5: Review of the Impact of Corrosion Control Treatment Recommendations on Waste Water

- Cadmus' subcontractor, Dr. Bott, will continue training VMI students in preparation of Phase III of the study, scheduled to begin in early June 2005.

- VMI students will begin Phase III of the study to be performed on-site at the Arlington County Water Pollution Control Plant.

Task 6: Review of Sampling Plans for the District of Columbia Distribution System

- Cadmus will review additional monitoring plans at the direction of the EPA WAM.

Task 7: Sanitary Survey of the District of Columbia Distribution System

- Cadmus will continue to conduct follow-up interviews as needed to complete the sanitary survey of the DC distribution system.

Task 8: Prepare Draft Report of the Sanitary Survey

- Cadmus will continue preparing the draft report of the sanitary survey.
The Effect of Partial Lead Service Line Replacements on Lead Leaching

Caroline Nguyen, Virginia Tech
Simoni Triantafyllidou, Virginia Tech
Jie Hu, Wuhan University
Marc Edwards, Virginia Tech
San Diego, CA
June 14, 2009

If utility exceeds 15 ppb AL, partial pipe replacements may be required up to property line.

Boyd et al., 2004
- Only examined cutting of lead pipe
- Observed higher lead release for over 2 weeks
- Intermittent flow: total Pb > 15 ppb after 2 weeks
- Continuous flow: total Pb consistently < 15 ppb after 2 days (high flow) or 6 days (low flow)

Adverse Consequences of Partial Replacements
- Disturbing rust scale (Boyd et al., 2004)
- Galvanic Corrosion (Britton et al., 1981)
- Deposition Corrosion (Britton et al., 1981)

- Cincinnati: lead spikes after partial line replacements, lasted 1-4 weeks
- “But even after 1 year of sampling, partial lead service line replacement did not show an improvement over keeping a complete line in place.” (Swertfeger et al., 2006)
Galvanic corrosion important for roofs

Urban rainfall on roofs
- Large increase in Pb corrosion rates if Pb connected to Cu
- Some increase in marine atmosphere (higher Cl)

(Kucera et al., 1982)

Britton and Richards, 1984
- 186 = all or some Pb service lines
- 69 = had at least 1 Cu/Pb connection

Early work on galvanic corrosion and lead
- Solution of lead was assisted by contact with other metals, such as copper-lead connections.
  (Wolffhügel, 1887)
- "In practice, contact with iron pipes, solder, etc., is an important factor in assisting the attack on lead by water.”
  (Lindsay, 1859)
- "Galvanic action is a most powerful agent in promoting the corrosive action of certain waters upon lead.”
  (Stirling, 1859)

Britton and Richards, 1984
- "...anomally erratic or much higher than normal lead concentrations when Pb connected to Cu"
- "Occasionally the insertion of copper pipe can produce particularly bad results and despite satisfactory pH control it may be impossible to obtain satisfactory samples."
- "...the contribution to the water lead concentration from the area around the lead-copper junction is obvious.”
What are the practical concerns related to galvanic corrosion and PSR?
- Creation of new Pb-Cu junctions
- Placing copper before lead in flow sequence

Causes for Concern: High CSMR
- English studies measured galvanic current and voltage in connections of lead solder to copper
  - Oliphant (1963) and Gregory (1955)
  - Dodds & Edwards (1995) and Triantafyllidou (2007): more lead with higher chloride and lower sulfate
  - Pb action level exceeded when coagulant changed from alum to PAC; isolated cases of lead poisoning

Scenarios

<table>
<thead>
<tr>
<th></th>
<th>Galvanic Junction(s)</th>
<th>Copper Deposition on Lead?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb - PVC</td>
<td>None</td>
<td>No</td>
</tr>
<tr>
<td>Pb - Cu</td>
<td>1</td>
<td>No</td>
</tr>
<tr>
<td>Cu - Pb - Cu</td>
<td>2</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Experimental Plan
- Deposition corrosion from Cu\(^{2+}\)
  - Stagnant
  - Flow
- Galvanic corrosion (Pb - Cu)
- Simulated small scale partial replacement

Chloride to Sulfate Mass Ratio (CSMR) Sample Calculation

Chloride to Sulfate Mass Ratio (CSMR) = \(\frac{[\text{Cl}^-]}{[\text{SO}_4^{2-}] = \frac{10 \text{ mg/L Cl}^-}{20 \text{ mg/L SO}_4^{2-}} = 0.5\)

Experimental Design: Cu\(^{2+}\) Deposition Corrosion

<table>
<thead>
<tr>
<th>Cl(^-) (mg/L)</th>
<th>SO(_4^{2-}) (mg/L)</th>
<th>CSMR</th>
<th>pH (mg/L CaCO(_3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>129</td>
<td>16</td>
<td>10</td>
<td>8.3</td>
</tr>
</tbody>
</table>

- Free chlorine and chloramine (4 mg/L Cl\(_2\))
**Experimental Design: Cu²⁺ Deposition Corrosion**

**Stagnant:**
- 3 Replicates
- Drain & refill 3x/week

**Flowing:**
- Continuous flow
- Water change once/wk

Q = 2.75 gpm

- 0 or 5 mg/L Cu²⁺
- 4 mg/L free chlorine or chloramine

---

**Cu²⁺ Deposition Corrosion – Flowing Free Chlorine**

---

**Cu²⁺ Deposition Corrosion – Stagnant (Chloramine)**

Avg. of Weeks 8-15

---

**Cu²⁺ Deposition Corrosion**

**Conclusions**

- Trace levels of Cu²⁺ (even 0.03 mg/L) increased lead release from lead pipe w/ no galvanic connection to Cu²⁺
- Deposition corrosion significant concern in terms of lead leaching as per prior research
- Putting a copper pipe before a lead pipe in the flow path, as occurs in partial replacement, is a concern

---

**Mechanisms of Galvanic Corrosion (Pb Pipe – Cu Pipe)**

New vs. Aged Pb Pipe CSMf
Experimental Design

- New Pb Pipe
- Passivated Pb Pipe
  - Simulate pipes exposed to free chlorine
  - Pb(IV) scaling

Water Chemistry

\[ \text{pH} 8.3 \]

<table>
<thead>
<tr>
<th></th>
<th>Cl(^{-}) (mg/L)</th>
<th>SO(_4^{2-}) (mg/L)</th>
<th>CSMR</th>
<th>Alkalinity (mg/L CaCO(_3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>22</td>
<td>112</td>
<td>0.2</td>
<td>10</td>
</tr>
<tr>
<td>High</td>
<td>129</td>
<td>8</td>
<td>16</td>
<td>10</td>
</tr>
</tbody>
</table>

Disinfectants:
- Free chlorine & chloramine

Experimental Design

- Dump and fill
- 3 X/week

Measurements:
- Pb and other metals
- Galvanic current
- Local pH

Aged and New Pb (End of Study)
**Current over time**

- Low CSMR, C2
- Low CSMR, NIDC
- High CSMR

![Current over time graph](graph1)

**pH vs. Galvanic Current**

- Low CSMR, C2
- Low CSMR, NIDC
- High CSMR, C2
-High CSMR, NH2C2

![pH vs. Galvanic Current graph](graph2)

**Effect of Cu: Pb Length after Partial Lead Service Line Replacements on Lead Release**

- 0% Cu (i.e., 100% Pb) - Before Replacement
- 17% Cu
- 50% Cu
- 67% Cu
- 83% Cu
- 100% Cu - Full Replacement

![Effect of Cu: Pb Length graph](graph3)

**Water Chemistry**

<table>
<thead>
<tr>
<th></th>
<th>CF (mg/l)</th>
<th>SO4^2- (mg/l)</th>
<th>CSMR</th>
<th>Alkalinity (mg/l CaCO3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low CSMR</td>
<td>22</td>
<td>112</td>
<td>0.2</td>
<td>15</td>
</tr>
<tr>
<td>High CSMR</td>
<td>129</td>
<td>8</td>
<td>16</td>
<td>15</td>
</tr>
</tbody>
</table>

Dump & fill 3 X/week
Low CSMR - Weeks 1-11
High CSMR - Weeks 12-24
Effect of Galvanic & Deposition Corrosion on Pb Release – Low CSNR

Effect of Galvanic & Deposition Corrosion on Pb Release – High CSNR

Effect of Galvanic & Deposition Corrosion on Pb Release – Low CSNR

Effect of Galvanic & Deposition Corrosion on Pb Release – High CSNR

% Pb increase – Low CSNR

% Pb increase – High CSNR

- 17% Cu / 83% Pb was the worst case
- Less copper relative to lead worsened galvanic corrosion
Conclusions

- Cu⁺⁺ in water increases Pb in water (deposition corrosion)
- Galvanic corrosion of Pb/Cu couples can be significant
- Lower pH and higher Cl⁻ at Pb junction during stagnation
- Pb is sacrificed

Conclusions

- Simulated partial service line replacement
  - Higher Pb (> 200%) in low CSMR water
  - Higher Pb (> 165%) in high CSMR water
  - Short length of Cu relative to Pb had highest Pb release

First Definitive Laboratory Data

indicating potential long-term detriments from galvanic and deposition corrosion arising from partial replacement.

Acknowledgements

- EPA/Water Research Foundation
  (Project 4088)
- Traci Case
- PAC members
  - Chris Hill
  - France Lemieux
  - Joseph Marenko
  - Anne Spiesman
- Edwards Research Group
Impact of Chloride:Sulfate Mass Ratio (CSMR) Changes on Lead Leaching in Potable Water
Jointly sponsored by:
US EPA/Water Research Foundation (Project #4088)
Caroline Nguyen, Simoni Triantafyllidou, Kendall Stone, Brandi Clark, and Marc Edwards
(Virginia Tech)
Graham Gagnon and Alisha Knowles
(Dalhousie University)

Early Work on Galvanic Corrosion of Lead
- "...solution of lead was assisted by contact with other metals" such as copper-lead connections
  (Wolfhugel, 1887)
- "...in practice, contact with iron pipes, solder, etc., is an important factor in assuring the attack on lead by water"
  (Lindsay, 1859)
- "...galvanic action is a most powerful agent in promoting the corrosive action of certain waters upon lead"
  (Stirling, 1859)
- "Occasionally the insertion of copper pipe can produce particularly bad results and despite satisfactory pH control it may
  be impossible to obtain satisfactory samples"
  (Britton and Richards, 1981)

Previous Work on Chloride & Sulfate
  linked lead contamination of waters to galvanic corrosion of lead solder
  - Found benefits from SO₄²⁻ and detriments from Cl⁻

Previous Work
- Dodrill & Edwards (1995): more lead with higher chloride and lower sulfate
  - Pb poisonings in NC
  - Pb action level exceedance when coagulant changed from alum to PACI, shifting CSMR from low to high

Outline
- Galvanic corrosion theory
- Mechanistic study
- How concerned should you be?
  - Practical studies
    - Solder
    - Brass
    - Lead pipe

A 2-year old has been diagnosed with lead poisoning... They took the aerator off the sink [faucet] and taped it in to the counter. It looked like asphalt pebbles, but it was solder

Raleigh News and Observer, 2005
Outline

- Galvanic corrosion theory
  - Mechanistic study
  - How concerned should you be?
  - Practical stories:
    - Solder
    - Brass
    - Lead pipe

Sulfate “Good”

- Sulfate precipitates lead at the anode
  \[ \text{Pb}^{2+} + \text{SO}_4^{2-} \rightarrow \text{PbSO}_4 \text{ solid} \]
- Insoluble even at very low pH

Chloride “Bad”

- Chloride complexes lead
  \[ \text{Pb}^{2+} + \text{Cl}^- \rightarrow \text{PbCl}^+ \]
  - Soluble
  - Prevents formation of solid
Chloride to Sulfate Mass Ratio (CSMR)\textsuperscript{*}

Sample Calculation

\[
\text{Chloride to Sulfate Mass Ratio (CSMR)} = \frac{\text{Bad}}{\text{Good}} = \frac{[\text{Cl}^-]}{[\text{SO}_4^{2-}]} = \frac{10 \text{ mg/L Cl}^-}{20 \text{ mg/L SO}_4^{2-}} = 0.5
\]

\textsuperscript{*} Oliphant, 1983; Gregory, 1985; Dodrill and Edwards, 1995

Macroscopic Simulated Soldered Joint

Mechanistic Study – Setup
Mechanistic Study – pH at Microlayers

This provides 1st mechanistic explanation for why CSMR “works” in explaining trends in certain lead corrosion problems.

Mechanistic Study – Cl\(^-\) at Microlayers

Mechanistic Study - Water Quality (Utility I, MD)

<table>
<thead>
<tr>
<th>Water Conditions</th>
<th>CSMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Alum-treated, free chlorine</td>
<td>1.4</td>
</tr>
<tr>
<td>2) Alum-treated, monochloramine</td>
<td>1.3</td>
</tr>
<tr>
<td>3) PACI-treated, free chlorine</td>
<td>5.3</td>
</tr>
<tr>
<td>4) PACI-treated, monochloramine</td>
<td>8.5</td>
</tr>
<tr>
<td>5) PACI-treated, +20 mg/L Cl(^-), free chlorine</td>
<td>8.4</td>
</tr>
<tr>
<td>6) PACI-treated, +20 mg/L Cl(^-), monochloramine</td>
<td>8.4</td>
</tr>
</tbody>
</table>

- pH 7.7 ±0.1
- 3.5 mg/L Cl\(^-\)
- 1 mg/L PO\(_4\)^-P

Mechanistic – Pb vs. Current

Outline

- Galvanic corrosion theory
- Mechanistic study
- How concerned should you be?
  - Practical analyses
    - Solder
    - Brass
    - Lead pipe

Lead in water versus current measured during 15 weeks of the study.
How Concerned Should You Be?

- Lead solder or partially replaced lead pipe in distribution system?
  - Yes
  - CSMR < 0.2
    - Yes
    - Significant Concern
  - No
  - CSMR > 0.2 but < 0.5
    - Yes
    - Significant Concern
  - No
  - CSMR > 0.5 and alkalinity < 50 mg/L as CaCO₃
    - Yes
    - Serious Concern

Elevated CSMR from:

- Coagulants
  - Changing from sulfate-based coagulant to chloride-based coagulant
- Hypochlorite generator brine leak
  - Switching from chlorine gas to hypochlorite on-site generator
- Anion exchange
- Use of desalinated water
- Road salt runoff

Outline

- Chemical corrosion theory
- Mechanical stress
- Raw corrosion of lead water

- Practical studies:
  - Solder
    - Coagulants
    - Anion Exchange
    - Hypochlorite Brine Leak
    - Desalination
    - Illustrative Case Study

Simple Bench Scale Case Studies

- Simulated copper joints - 50:50 Pb:Sn solder placed inside copper coupling
  - 50:50 Pb:Sn solder - 1” length, 3 mm diameter
  - Cu coupling - 1” length, ½” diameter
  - Exposed to 100 mL of test water in triplicate

Finished Water Chloride and Sulfate

<table>
<thead>
<tr>
<th>Coagulant</th>
<th>Cl⁻ (mg/L Cl⁻)</th>
<th>SO₄²⁻ (mg/L SO₄²⁻)</th>
<th>CSMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% Alum</td>
<td>16</td>
<td>40</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>30</td>
<td>0.7</td>
</tr>
<tr>
<td>Alum and PACI Blends</td>
<td>22</td>
<td>24</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>18</td>
<td>1.5</td>
</tr>
<tr>
<td>100% PACI</td>
<td>22</td>
<td>12</td>
<td>1.8</td>
</tr>
<tr>
<td>Raw Water</td>
<td>16</td>
<td>12</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Outline

- Water naturally contained arsenic (As)
- Anion Exchange used to remove As by replacing it with Cl⁻ in water
- SO₄²⁻ also exchanged for Cl⁻ → infinite CSMR
- Following Anion Exchange, Pb in an apartment complex spiked >1,000 ppb
- One child’s BLL exceeded CDC BLL of concern (10 µg/dL) *

* Edwards and Triantafyllidou, 2007

Anion Exchange to Remove Arsenic

Anion Exchange Treatment

<table>
<thead>
<tr>
<th>Water Treatment</th>
<th>[As] (µg/L As)</th>
<th>[Cl⁻] (mg/L)</th>
<th>[SO₄²⁻] (mg/L)</th>
<th>CSMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prior to Anion Exchange</td>
<td>4.5</td>
<td>4.4</td>
<td>4.1</td>
<td>1.1</td>
</tr>
<tr>
<td>After Anion Exchange</td>
<td>1.8</td>
<td>13.2</td>
<td>3.7</td>
<td>7.8</td>
</tr>
</tbody>
</table>
Anion Exchange

Water Treatment

Average lead release for each of the three water treatments at Utility F, ME, water during the first six weeks of the study.

Hypochlorite Brine Leak

Water Type

This utility plans to blend desalinated water with their current distribution water:

<table>
<thead>
<tr>
<th>Blend</th>
<th>[Cl⁻] mg/L</th>
<th>[SO₄²⁻] mg/L</th>
<th>CSMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% distribution</td>
<td>54</td>
<td>88</td>
<td>0.8</td>
</tr>
<tr>
<td>100% desalinated</td>
<td>110</td>
<td>Below detection</td>
<td>∞</td>
</tr>
</tbody>
</table>
**Desalination**

![Graph showing lead release from nanofiltered water blend](image)

Average lead release from 50:50 Pb:Sn solder between Weeks 6-8 for the Utility K, CA study.

**Outline**

- Gallium vs tin in dopes
- Mechanistic study
- How equipment should be used?

**Practical studies:**

- Solder
  - Corrugation
  - Atom exchange
  - Metallurgical damage
  - Desalination
- Illustrative case study
  - Grass
  - Lead fill

**Illustrative case study – Greenville, NC**

![Graph showing changes in lead concentration](image)

(Data from Edwards and Triantafyllidou, 2007)

**Illustrative case study – Greenville, NC**

![Graph showing changes in lead concentration](image)

(Data from Edwards and Triantafyllidou, 2007)

**Illustrative case study – Greenville, NC**

![Graph showing changes in lead concentration](image)

(Data from Edwards and Triantafyllidou, 2007)

- Chloramines had little effect
- High CSMR had a major effect
- Phosphate did not stop the problem

- Edwards and Triantafyllidou, 2007
Outline

- Galvanic corrosion theory
- Mechanistic study
- How concerned should you be?
- Practical studies:
  - Solder
  - Brass
  - Lead pipe

Conclusions (Solder)

- Simple bench scale test protocol
  - Test treatment changes on lead leaching from solder-copper couplings
- Low pH measured at anode (pH 3.3)
- Anions (Cl\(^-\) and SO\(_4^{2-}\)) migrate to the lead anode
- Lead sulfate is relatively insoluble, while chloride complexes lead and increases lead leaching
- Increased lead levels correlated with increased galvanic current
  - Galvanic effects are very persistent in some systems.

Conclusions (Solder)

- Changes that increase CSMR can increase Pb release (and 90th percentile Pb)
  - Coagulants
  - Hypochlorite generator
  - Anion exchange
  - Desalination
  - Road salt runoff
Effect limited to galvanic connections between Pb and Cu.

Conclusions (Solder)

- Effects of Alkalinity and Orthophosphate are site-specific
  - High orthophosphate or high alkalinity do not eliminate galvanic effects, but sometimes can reduce them.
  - Sometimes they make it worse
Because no universal solution exists, effects of inhibitors and treatment changes have to be evaluated on a site-specific basis using a simple protocol similar to that proposed here.

Outline

- Galvanic corrosion theory
- Mechanistic study
- How concerned should you be?
- Practical studies:
  - Solder
  - Brass
  - Lead pipe
  - How big is a problem stream?
Lead Service Lines

- "One of the most serious environmental disasters" is US history (Troeseck, 2006)
- 3.3 - 6.4 million US homes with old lead service lines or connections, as of 1990 (Wesson and EES, 1990)
- Contribute to an estimated 50 - 75 % of the lead in drinking water (Sandvig et al., 2008)
- Can contribute to violations of the 15 ppb LCR action limit for lead in drinking water

Potential Adverse Consequences of Partial Lead Service Line Replacements

- Disturbing rust scale and/or creating metallic lead particles when the lead pipe is cut (Boyd et al., 2004; Sandvig et al., 2008)
- Galvanic corrosion of lead (Britton and Richards, 1981)
- Deposition corrosion of lead (Britton and Richards, 1981)

Galvanic Corrosion

Can accelerate corrosion of the lead pipe, above and beyond what would normally occur for lead pipe alone

Flushing water is electrolyte

Galvanic Corrosion

Lead that is galvanically corroded does not all go into the water.
Recent Work on Galvanic Corrosion

- "Partial replacement using copper piping can result in the creation of a galvanic cell, giving rise to increased and erratic levels of lead observed in the tap. The effect can be persistent and may well mask any beneficial effects of replacing the length of lead pipe in the system" (Chamber & Hulthom, 1992)

- "Sedimentary deposits lead levels as high as 65,000 parts per million" galvanically connecting an old lead pipe to a new one of new copper under varying water conditions" (Kerese, 2004)

- "The magnitude of galvanic impact on aged and passivated galvanism in more and on new copper surfaces is minimal, and in the long term, likely to be insensible" (Parker and Unwin, 2006)

- "Direct corrosion localized in the area immediately adjacent to the pipe joints suggests a galvanic mechanism" (Debrees, Welsh and Shurlock, 2009)

Definitive data are not available on the long-term implications relative to PSLRs.

Scenarios of Galvanic and Deposition Corrosion

<table>
<thead>
<tr>
<th>Plumbing Type/Sequence</th>
<th>Galvanic Junction(s)</th>
<th>Copper Deposition on Lead?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Service to House</td>
<td>0</td>
<td>No</td>
</tr>
<tr>
<td>Service to House</td>
<td>1</td>
<td>No</td>
</tr>
<tr>
<td>Service to PSLR House</td>
<td>2</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Sequence is important

"Possible concern from inserting copper pipes or other apparatus upstream of and electrochemically linked to lead. Utilities should have clear advice/information systems so that such practices are avoided both by their own staff and by customers or tradesman." (Breach et al., 1991)
Simulated Small Scale PLSLR-Experimental Setup

Research questions

- Do Cu-Pb connections always passivate quickly in terms of galvanic current or lead leaching?
- Are effects of galvanic corrosion consequential in PLR?
  - Low CSMR water
  - High CSMR water

Evaluate worst case scenario of long stagnation

No cutting or other opportunity to mobilize scale from pipes

All effects attributable to galvanic/deposition corrosion alone

Water Chemistry/Experimental Protocol

<table>
<thead>
<tr>
<th></th>
<th>Cl⁻ (mg/L)</th>
<th>SO₄²⁻ (mg/L)</th>
<th>CSMR</th>
<th>Alkalinity (mg/L as CaCO₃)</th>
<th>NH₄Cl (mg/L as Cl⁻)</th>
<th>pH</th>
<th>Ionic Strength (mmol/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low CSMR Water</td>
<td>22</td>
<td>112</td>
<td>0.2</td>
<td>15</td>
<td>4</td>
<td>8.0</td>
<td>4.6</td>
</tr>
<tr>
<td>High CSMR Water</td>
<td>129</td>
<td>8</td>
<td>10</td>
<td>15</td>
<td>4</td>
<td>8.0</td>
<td>4.4</td>
</tr>
</tbody>
</table>

Static "fill and dump" protocol:
Water change 3 times/week

Effect of CSMR

Simulated partial replacement → more lead in water
Laboratory study proves potential long-term detriments from galvanic and deposition corrosion arising from partial replacement.

Partial Replacement of Pb with Cu \(\rightarrow\) Beneficial

- Even in low CSMR water, detriments of galvanic corrosion do counter benefits of reduced lead surface area
- Net benefit depends on magnitude of galvanic corrosion, % LSL replaced, and other factors
High CSMR water, Deviation from Linear model

- Detriments of galvanic corrosion outweigh the benefits of reduced lead surface area, in every simulated partial replacement
- Net benefit only when replacing 100% Pb pipe

High CSMR water, Deviation from 100% Pb pipe

Visual Observations

Visual Observations

Effect of Alkalinity under High CSMR
Conclusions from simulated PLSLR

Galvanic effect can be persistent.

We therefore confirm prior research that shows galvanic effect may "well annul any beneficial effects of reducing the length of lead pipe in the system."

Future research questions on galvanic corrosion after simulated PLSLR

- Realistic flow patterns
- Effects of flow velocity (low versus high)
- Effects of protective film (harvested/passivated lead pipe versus new lead pipe)
- Effects of realistic couplings between lead and copper

Outline

- Galvanic corrosion theory
- Mechanistic study
- How concerned should we be?
- Practical studies
  - Nodes
  - Hubs
  - Lead pipe
- How big a problem is this?
HDR-CADMUS-EPA REGION III Study (2006)*
"Can...galvanic currents under a worst-case scenario meaningfully contribute to lead corrosion and metals release?"

The study provides a strong basis for discounting claims and concerns relative to accelerated metal release associated with PLSLR.

http://www.epa.gov/lead/Grounding_Effects_Study_Final_November_2006.pdf

-----

Important update: lead-based water lines *

*The study of children in Washington DC...'sugges[that] when lead service lines are partially replaced...children are more likely to have blood lead levels greater than or equal to 10 μg/dL...

* (Frumkin, 2010)

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Explanations for disagreement

HDR/Cadmus/EPA R3 conclusion

• is not based on the worst case
• did not measure lead release

-----

Explanations (cont’d)

For passivated lead pipe, galvanic impact is limited to only 1” of lead pipe next to joint, therefore, the galvanic effect is inconsequential.

New Cu Pipe | Old Pb Pipe

-----

1” length of typical lead pipe half eaten away by galvanic corrosion

= 24 g Pb

Sufficient to contaminate every drop of water consumed by a family of 4, over a more than a 10 year period, with lead concentrations above the 15 ppb AL.
It is sometimes even possible to see the effects of galvanic corrosion by eye.

Mineralogical Evidence of Galvanic Corrosion in Domestic Drinking Water Pipes
DeSantis, M., Welch, M. M., and Schock, M. R.
2009 WOTC

Obvious effects of galvanic corrosion sometimes apparent to naked eye

Consider rate at which Pb is generated at galvanic connection

<table>
<thead>
<tr>
<th>Galvanic Current</th>
<th>Pb (µg/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 µA</td>
<td>Very low rate</td>
</tr>
<tr>
<td>5 µA</td>
<td>Low rate</td>
</tr>
<tr>
<td>30 µA</td>
<td>High rate</td>
</tr>
<tr>
<td>100 µA</td>
<td>Very high rate</td>
</tr>
</tbody>
</table>

Bad News: "accessible lead greater than 175 µg could result in elevated blood lead levels in children" CPSC (2005)

Good News: Sometimes less than 1% of this lead is released to water; the rest goes into scale

There are many waters in which we are quite sure that Pb:Cu galvanic corrosion is not problematic at all.

Conclusions
The worst case can be quite bad.

When problems occur, they can be very hard to detect, due to erratic release of lead scale at joint. Sloughing of lead "rust" to a single sample could cause health concerns.

More research is needed to understand issues associated with sloughing of scale and galvanic corrosion.
Acknowledgements

- Participating Water Utilities and Collaborators
  - Davidson Water (NC), City of Durham (NC), Greenville Utilities
    Commission (NC), Halifax Water (Nova Scotia), Jordan Valley
    Water Conservancy District (UT), Long Beach Water (CA), City
    of Minneapolis (MN), Portland Water Bureau (OR), City of
    Raleigh (NC), South Bexar County Utility District (TX), Ville de
    Laval (Quebec), Washington Suburban Sanitary Commission
    (MD)
  - I HDR, Glen Boyé, Anne Sandvig, and Al Veternov
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  - Project Advisory Committee
    - France Lamyoux, Chris Hill, Joseph Marcinko, Anne Spießmann,
      Traci Case (Project Manager)
  - Edwards Research Group

References


List of Presentations


Contact Information

- Marc Edwards
  Email: edwardsm@vt.edu
- Caroline Nguyen
  Email: cknghuyen@vt.edu
- Simoni Triantafyllidou
  Email: striant@vt.edu
Objectives

- Determine the impact of long term galvanic corrosion following partial service line replacement on lead release using:
  - Excavated lead pipe stabilized over 1 year
  - Typical configurations, junctions, and flow rates
  - 4 water conditions including corrosion inhibitors

Acknowledgment

- CNRC-NSERC
- City of Montreal (supports, lead pipes, head analyses)
- Yves Fontaine (pipe loop assembly and operation)
- Geneviève Senécal-Léonard and Stéphanie Puy (inhibitors)
- Roger Arnold, Simon Triantafyllidou et Jeff Parks (VT)

Water utilities have been spending billions on partial lead service line replacements with copper. However, limited data is available on its effectiveness.

Recent pipe rig research conducted at Virginia Tech suggested that lead release can be exacerbated by galvanic corrosion attributable to the contact between copper and lead. Deposition corrosion was also suspected.

Adapted from Triantafyllidou and Edwards, accepted in JAWWA, 2011

Results - after one month

Under low flow:
- Short-term lead "spike" was observed for few weeks after partial replacement due to galvanic effect comparing to full lead pipe. During 3 following months, as scale became accumulated at the junction, the partial pipes released less lead than the 100% Pb pipe.
- For 50% Pb-D pipe, lead release was never proportional to the length of lead pipe comparing to 100% Pb pipe.
- At the end of the experiment, lead release from Pb-D and 100% Pb were comparable.

Under medium/High flow:
- Even if lead release was decreasing with time, lead release was exacerbated by the flow events for Pb-D and Pb-U conditions.
- Under high flow, lead release was significant for Pb-U and Pb-D conditions even if the samples were taken at a higher frequency which confirms the presence of mobilized lead scales.

In terms of mass balance:
- For 50% lead pipe upstream of copper pipe (Pb-U), lead release is slightly higher than expected based on lead pipe length which confirms the galvanic effect.
- The difference between Pb-D and Pb-U can be explained by deposition corrosion.
- At longer-term, under low flow, the slight benefit of partial pipe replacement disappears, and may even be reversed eventually, due to lead release scale accumulated at joint from galvanic connection.
- Considering relatively stable high current (not presented here), this situation persist indefinitely.

Preliminary conclusions
- Higher lead release was observed under galvanic corrosion conditions.
- Corporation valves (as used usually on the field) are the worst case.
- At Longer-term, under low flow, the slight benefit of partial pipe replacement disappears, and may even be reversed eventually, due to lead release scale accumulated at joint from galvanic connection.
- Considering relatively stable high current (not presented here), this situation persist indefinitely.
- Upcoming experiments: Investigate lead release specific to the fittings.
The following is a draft version of a paper submitted to Critical Reviews in Environmental Science and Technology, and which was accepted for publication in that journal after minor revisions to this draft (this version is unreviced). The title for the published version has been changed to Lead (Pb) in Tap Water and in Blood: Implications for Lead Exposure in the United States

Lead (Pb) in Tap Water and in Blood: A Critical Review

Simoni Triantafyllidou, Marc Edwards
Department of Civil and Environmental Engineering, Virginia Tech, Durham 418, Blacksburg, VA

ABSTRACT

Lead is widely recognized as one of the most pervasive environmental health threats in the United States (US), and there is increased concern over adverse health impacts at levels of exposure once considered safe. Lead contamination of tap water was once a major cause of lead exposure in the US and, as other sources have been addressed, the relative contribution of lead in water to lead in blood is expected to become increasingly important. Moreover, prior research suggests that lead in water may be more important as a source than is currently believed. This review describes sources of lead in tap water, chemical forms of the lead, and relevant US regulations/guidelines, while considering their implications for human exposure. Research that examined associations between water lead levels and blood lead levels is critically reviewed, and some of the challenges in making such associations, even if lead in water is the dominant source of lead in blood, are highlighted. Better protecting populations at risk from this and from other lead sources is necessary, if the US is to achieve its goal of eliminating elevated blood lead levels in children by 2020.

KEY WORDS: plumbing, tap water, dissolved lead, particulate lead, regulations, health effects, blood lead level, correlation

Portions of sections VI and VII were presented at the Yale University Drinking Water Symposium in April 2009 and appeared as a supplemental paper of that symposium.

Address correspondence to Marc Edwards, Department of Civil and Environmental Engineering, Virginia Tech, Durham 418, Blacksburg, VA 24061, USA. E-mail: edwardsmi@vt.edu
I. INTRODUCTION

Lead (Pb) is widely recognized as one of the most pervasive environmental health threats in the United States (US). Dramatic progress has been made over the last four decades to reduce lead exposure from gasoline, paint, dust, food/drink cans and drinking water (Shannon, 1996). However, despite reduced exposure from nearly all sources, clinical evidence has demonstrated adverse health impacts at blood lead levels once considered safe (Fadrowski et al., 2010; Jusko et al., 2008; Bellinger and Needleman, 2003). As a result, while the incidence of elevated blood lead (EBL) has markedly decreased, public sensitivity and medical concern about even low level lead exposure has increased. In order for the US to achieve its goal of eliminating all instances of EBL in children by 2020 (US Department of Health and Human Services, 2010), improved understanding of exposure to all lead sources is necessary.

Defining a "typical" case for childhood lead exposure can be misleading, because lead exposure affects individuals whose behavior and environments are infinitely variable. Nonetheless, it is often stated that in the typical case, drinking water consumption is believed to account for up to 20% of total lead exposure nationally (US EPA, 2006). But the US EPA also acknowledged that for infants consuming formula it may account for more than 50% of their total lead exposure, and further predicted that the relative importance of lead in water as a source would increase as other lead sources were being addressed (US EPA, 1991). Recent work has demonstrated that in exceptional cases, lead from water can be the dominant source of exposure in children with EBL. For example, isolated cases of childhood lead poisoning in North Carolina and in Maine were tied to drinking water (Triantafyllidou et al., 2007). In addition, a 2009 study linked the incidence of EBL in Washington DC during a period of very high lead-in-water contamination, with effects of water much more significant for the youngest children tested (Edwards et al., 2009). Finally, the Centers for Disease Control and Prevention (CDC) publicized preliminary results of an epidemiological study, which demonstrated associations between children's EBL and partially replaced lead water pipes (Frunkin, 2010).

The goal of this work is to conduct a critical review of the literature, with emphasis on:
- The release of hazardous levels of lead in tap water from old lead-bearing plumbing materials
- Lead contamination of tap water as a public health concern even in modern buildings, and in cities that might meet federal regulations for lead in tap water
- The absence of federal regulations for lead in drinking water of US schools and day care facilities
- The difference between dissolved and particulate lead release into tap water, and the challenges in monitoring and exposure assessment associated with the particulate lead fraction
- Some of the challenges in associating Water Lead Levels (WLLs) to Blood Lead Levels (BLLs) in population studies or in case studies
- Important aspects of population studies that did, or did not, find associations between lead in water and lead in blood.
II. SOURCES OF LEAD IN TAP WATER, HOUSEHOLDS AT POTENTIAL RISK, AND POTENTIAL IMPORTANCE COMPARED TO OTHER ENVIRONMENTAL LEAD SOURCES

Sources of Lead in Tap Water. Drinking water usually contains little or no lead when it leaves the water treatment plant and as it travels through water mains (Figure 1). But as it enters building plumbing through service line connections, it may come into contact with lead-containing plumbing materials (Figure 1). These materials include lead pipe, lead-containing solder used to join copper and other metallic pipes together, and plumbing devices made of lead-containing brass (e.g., water meters, valves, components in water fountains and in faucets) (Figure 1). As water flows through or sits stagnant in the pipes and in other plumbing devices, it can become contaminated with lead through a variety of complex electrochemical, geochemical and hydraulic mechanisms (Schock et al., 1996). Lead that is released from the plumbing can contaminate water at the tap in one of two forms: as particulate lead or as dissolved lead (Figure 1).

Lead pipe. Lead pipe was used for the conveyance of drinking water, because it is easily formed, cut and jointed, and because its flexibility provides resistance to subsidence and frost (Schock et al., 1996). An advertisement by the National Lead Company in 1923 (National Geographic, 1923) illustrated that in many cities the law required that “lead pipe alone be used to bring water from street mains into the building” (Figure 2). Use of lead pipe in service lines was standard practice in many US cities through the 1950’s, and despite well-known health concerns was even occasional practice until the Congressional ban effective 1986. Considering health impacts from drinking water contamination, one historian characterized use of lead pipes in major cities as “one of the most serious environmental disasters” in US history (Troesken, 2006). Even though the use of lead pipe in service lines or premise plumbing was prohibited in the US by the Safe Drinking Water Act (SDWA) of 1986 (US EPA, 2006), older buildings may still be connected to lead service lines, lead goosenecks and other pure lead components. Depending on their length and diameter, water corrosivity, water use patterns as well as hydraulic patterns, lead service lines generally account for 50-75% of lead contamination at the tap in older homes where they are present (Sandvig et al., 2008).

Partially Replaced Lead Pipe. In the US, ownership of the lead pipe in service lines is shared between water utilities and homeowners. The controversial and expensive practice of replacing the utility’s portion of an old lead service line with copper, while leaving behind the customer’s portion, has been conducted in many cities with the purported goal of reducing lead in drinking water at the tap. Such replacements are termed “partial lead pipe replacements.” This practice can actually increase water lead concentrations at least in the short-term (days to weeks), and for an undetermined duration beyond that time (Sandvig et al., 2008). The short-term effect is due to disturbance of the lead rust (i.e., corrosion scale) that has accumulated on the lead pipe over decades/centuries of use, and/or from creation of metallic lead particles when the lead pipe is cut. Recent research has also shown that in some situations, the creation of a galvanic cell (i.e., battery) between the lead pipe and the copper pipe may create serious water lead contamination in both the short-term and longer-term (Triantafyllidou et al.,
2009a), confirming long-held concerns (Chambers and Hitchmough, 1992). This might explain the higher incidence of EBL in children living in homes with partially replaced lead pipe, when compared to homes with full lead pipes (Frumkin, 2010).

**Lead solder.** Solder is melted to join metallic plumbing materials together in a strong and water-tight seal (Figure 1). An increased lead content in the alloy improves ease of use and reduces leaks, and solder containing 40-50% lead by weight was used in US buildings until banned in 1986. Thereafter, only “lead-free” solder, containing less than 0.2% lead by weight, was allowed in buildings. Unfortunately, lead solder is still available in hardware stores because it is legal for use in hobby electronics, and plumbers still illegally use lead solder in some new buildings in the US (Goss, 2008) and in Scotland (Ramsay, 2003). In fact, a Scottish study found links between illegal use of leaded solder in new homes and blood lead of residents (Ramsay, 2003). The contribution of lead solder to lead in water at a given tap is extremely variable, and is dependent on the number of joints, their age, workmanship when the joint was created, surface area of the solder exposed to water at each joint, and the water chemistry (Sandvig et al., 2008). Recent cases of childhood lead poisoning from drinking water in North Carolina and in Maine were tied to lead solder particles that corroded and detached into the water supply (Triantafyllidou et al., 2007).

**Brass (and bronze) plumbing components.** Brass and bronze are copper alloys that contain lead. Historically, lead was added to these alloys to reduce leaks (Showman 1994). According to congressional definition, “lead-free” brass components (e.g., strainers, check valves, water meters, couplings, fittings, faucets, drinking fountains, bubblers and water coolers) used in modern homes can legally contain up to 8% lead by weight (Figure 1). The contribution of a brass component (e.g., a faucet) to lead levels measured at the tap depends on the lead content of the brass (typically ranging from 1.5-8% by weight), the volume of water in contact with the faucet, the physical configuration of the faucet, and how it was manufactured, water corrosivity and water flow conditions (Sandvig et al., 2008).

Recent problems with persistent lead contamination of tap water (up to 300 μg/L lead) in new buildings at the University of North Carolina at Chapel Hill were attributed to “lead-free” brass/bronze ball valves, installed before drinking water fountains. Locating and removing these ball valves was necessary to eliminate the lead problems at the fountains (Eilfland et al., 2010). There are also case studies, in which elevated lead in water from brass was suspected to be the primary contributor to cases of childhood lead poisoning (CDC, 1994). Sampling of homes in the Netherlands also revealed some severe cases of high lead release (up to 5030 μg/L) from brass faucets (Slaats et al., 2007). New brass alloys have been developed that contain very low lead (0.1-0.25% lead by weight) (Sandvig et al., 2008), and California and several other US states are beginning to require their use in new construction (Sandvig et al., 2007).

**Other lead sources in tap water.** Galvanized pipes are steel pipes coated with a protective layer of zinc, and high levels of lead can be present as impurities in the zinc coating (Shock et al. 1996). The iron rust in these pipes can also accumulate and store
lead from other plumbing sources (HDR Engineering, 2009). Thus, even after lead pipe is replaced, lead accumulated in this iron rust can contribute elevated lead to tap water for years (HDR Engineering, 2009).

**Rough estimation of US households at potential risk due to the presence of lead-bearing plumbing materials, and occurrence of lead pipe in other countries.** While poor record keeping makes it practically impossible to determine the exact type of plumbing materials at individual US households, without exhumining and forensically evaluating plumbing materials underground and in walls, consideration of rough estimates is useful. Weston and EES (1990) determined through anonymous surveys of water utilities, that there were about 3.3 million lead service lines and 6.4 million lead pipe gooseneck connections in the US (Table 1). For solder, it is estimated that 81 million US housing units constructed prior to the federal ban of lead pipe and lead solder in 1986 (US Census, 2010) are virtually certain to contain lead solder joints (Table 1). In addition, all housing units built after 1986 are almost certain to have “lead free” brass plumbing devices that contain 1.5-8% lead by weight (Table 1). Only new housing units that incorporate non-lead brass faucets and other non-lead brass components (<0.1% lead by weight), can completely eliminate the presence of lead in plumbing, and it was only recently that such products could be purchased in non-lead forms. It should be noted that the rough estimates presented (Table 1) refer to potential risk, and that like lead paint, degradation of leaded plumbing via corrosion and flaking of scale or rust to the water can dramatically increase the hazard to residents. In some situations lead in water for homes containing lead pipe, lead solder and/or leaded brass is virtually below detection, due to formation of protective surface coatings.

To offer an additional perspective, simple calculations suggest that the mass of lead present in a typical lead service line is about 19 kg (Table 1). If only 0.1% of this lead pipe is “eaten away” at the pipe wall due to corrosion and is released to the water, the released lead mass of 19 grams is sufficient to contaminate every drop of water used by a US family of three for 3 years over the federal action level of 15 μg/L (calculation based on 1135 L/day water usage for the whole family). Before half the pipe wall (i.e., 50% of the lead pipe) is eaten away, likely subjecting the lead pipe to leaks and mandatory replacement with unleaded materials, the potential lead release is sufficient to contaminate every drop of water used by a family for 1,500 years. Coupled with the direct path to possible human ingestion, this analysis puts the potential magnitude of the lead pipe problem into perspective, and highlights the importance of corrosion control and safe water use practices in avoiding potentially harmful exposure. In 1993, the US EPA estimated that more than 40 million US residents used water that can contain lead in excess of the federal action level of 15 μg/L (US EPA, 1993).

Lead pipes are more common in other countries. For example, the percentage of lead service lines in France, UK and Germany as of 1999 was estimated at 40-50% (Hayes and Skubala, 2009). As of 1999, premise (building) plumbing in Portugal, France and UK also contained 30-40% lead pipes (Hayes and Scubala, 2009). In Japan, as of 2002, a total of 667 km lead pipe were found below roads and 3,248 km of lead pipe were found in residential areas (Osawa, 2002).
Other sources of environmental lead exposure and perceptions regarding their relative importance. Lead products have been used in numerous other applications, all of which constitute potentially harmful exposure sources worthy of mitigation. Before improvements in corrosion control reduced lead in potable water in the 1950’s and then again in the 1970’s (Karakekas et al., 1976; Moore et al., 1985), it was widely accepted that lead in water was a dominant pathway of human exposure and that high incidence of miscarriages, infant and even adult mortality were attributable to this source (Troesken, 2006; Renner, 2007). While it is accepted that exposure to lead from any source is potentially harmful, maximizing public health gains with scarce available financial resources has necessitated creation of a modern hierarchy of perceived risk and reward for public health interventions. This, in turn, has occasionally put the different lead sources in competition with one another.

EPA has recently acknowledged the fear of certain individuals that “the focus on lead in drinking water reduces attention on other and, potentially more important, sources of lead in the household environment (e.g., paint, dust)” (Blute, 2008). This mindset reinforces reports that in the early 1990’s the then CDC director of the former Center for Environmental Health “…railed against doing much in drinking water because he did not want to disarm lead in paint” (Powell, 1999). There has been some speculation that the scientific presentation of research results and public health messaging, in response to a well-publicized incident of elevated high lead in drinking water of Washington, DC, was affected by these concerns (US Congressional report, 2010; Edwards, 2010). On occasion, the lead paint: water risk: reward analysis has been invoked to justify diverting a portion of funding originally intended for reducing the public’s exposure to lead in water, towards creation of lead paint educational programs (Renner, 2010). It is important to acknowledge these issues, because neither scientists nor popular perception can be assumed to be completely immune from bias, and continued debate about where to invest scarce resources will intensify with reduced availability of funding.

Clearly, peeling lead paint chips and associated dust pose a great health concern to US children (Levin et al., 2008; Jacobs 1995). Although the conventional wisdom in the US is that lead-based paint is the predominant source of lead poisoning in children, and all other lead sources are a distant second, a few potential weaknesses in this argument and alternative perspectives have been provided by authors such as Mielke and Reagan (1998). Based on their work, lead in soil and in dust, even when deteriorating lead paint is not a contributing factor (e.g., soil contamination attributable to smelter emissions, past use of leaded gasoline and other sources), can be an equally important exposure pathway, compared to lead paint that is deteriorating in place (Mielke and Reagan 1998). Much has been done to address all environmental lead sources, and much more needs to be done. Since 1977 the Consumer Product Safety Commission (CPSC) has limited the lead content of paint in the US to 600 parts per million (or else 0.06% by dry weight of the paint), but older residences may have paint present with much higher lead content (up to 50% lead before 1955) (ATSDR, 2007). The US EPA’s Office of Chemical Safety and Pollution Prevention also recently issued the lead renovation, repair and painting rule to protect against exposure from renovations that disturb lead-based paint (US EPA, 2010).
After the landmark phase-out of commercial leaded gasoline, which was completed in 1995, 78% of air lead in the US is attributed to industrial emissions (Levin et al., 2008). The US EPA has set an enforceable national quality standard for lead in ambient air, while the Occupational Health and Safety Administration (OSHA) has set an enforceable permissible exposure limit for lead in workplace air (ATSDR, 2007). Lead is also present in consumer products. Dietary supplements, crystal glassware and ceramic pottery, polyvinyl chloride (PVC) miniblinds, synthetic turf, imported candy and foods, and imported children’s toys have been found to contain high levels of lead (Levin et al., 2008). The CPSC has recalled thousands of imported products, including children’s toys, which contained lead and did not meet US standards (Levin et al., 2008).

While the conventional wisdom is that lead in paint and in dust account for a majority of EBLs in US children, the CDC estimated that 30% or more of current EBL cases do not have an immediate lead paint source identified (Levin et al., 2008). The EPA (EPA, 2010) has recently expressed an opinion, shared by many others (Levin et al., 2008, Scott, 2009), that “as other agencies and EPA offices focus primarily on other sources of lead exposure (e.g. lead-based paint, lead in dust and soil, etc.) lead in drinking water as an exposure path is becoming a bigger percentage of a smaller number” (EPA, 2010).

III. INTENT AND LIMITATIONS OF US REGULATIONS/GUIDELINES FOR LEAD IN TAP WATER, AND OTHER RELEVANT PUBLIC HEALTH GUIDANCE

Lead and Copper Rule (LCR) of 1991. The US Environmental Protection Agency (EPA) regulates public water supplies under the Lead and Copper Rule (LCR) through an “action level” for lead at home taps of 15 parts per billion (µg/L) (US EPA, 1991). If lead concentrations exceed this action level (AL) in more than 10% of customer taps sampled, the water utility must take measures to control plumbing corrosion and inform the public about steps they should take to protect their health (Table 2). The EPA has also set a maximum contaminant level goal (MCLG) of zero for lead at the tap. As an MCLG, this guideline is not enforceable, but represents the optimal lead-in-water level below which there is “no known or expected risk to health”.

Implementation of the LCR in 1991 significantly controlled lead contamination at the tap, as evidenced by a recent review of monitoring data from homes in many large US cities. The review showed that 96% of US utilities were below the lead AL of 15 µg/L (US EPA, 2006a). The LCR replaced the previous standard of 50 µg/L, which was ineffective because it measured lead at the entry point to the distribution system and before contact with lead containing plumbing (Figure 1). The LCR requires sampling at homes known to have plumbing with highest potential for lead contamination, and after a minimum of 6 hours in which the sampled water has to contact the plumbing (US EPA, 1991).

Obviously, reliance on the 90th percentile lead level to determine compliance with the LCR means that there is no maximum contaminant level (MCL) for lead in consumers’ water to meet the Federal regulation. The US EPA explicitly acknowledged this in 1991, by stating that “the AL does not determine the compliance status of a system as does an
MCL, but merely serves as a surrogate for a detailed optimization demonstration” (US EPA, 1991). The EPA further clarified that the LCR “is aimed at identifying system-wide problems rather than problems at outlets in individual buildings” and that “the 15 μg/L action level for public water systems is therefore a trigger for treatment rather than an exposure level” (US EPA, 2006).

To illustrate, consider actual lead-in-water data for consumers in a large US city living in homes that are not necessarily at high risk, and which has been in consistent compliance with the LCR (i.e., 90th percentile lead in water =10 μg/L < 15 μg/L) (Figure 3). One percent of the population is exposed to over 70 μg/L lead, and 0.1% of the population is exposed to lead over 1717 μg/L. If the US goal of eliminating EBL in all children by 2020 is to be achieved, the higher risk at the upper tail of the WLL distribution needs to be acknowledged and remediated. Consistent with the above points, it is not surprising that a recent case of lead poisoning was attributed to lead contaminated tap water in Durham, North Carolina, even though the city was compliant with the LCR (Triantafyllidou et al., 2007). Unfortunately, because the LCR is designed to monitor effectiveness of corrosion control and does not protect individual consumers, only 100 homes must be tested in large cities (USEPA, 1991), which translates to far less than 1 out of 1,000 households. The key point of this discussion is that compliance with the LCR lead action level does not guarantee, or even imply, that all individuals in the city are protected from lead-in-water hazards.

Moreover, LCR testing loopholes may allow high lead levels to be “missed”, either accidentally or intentionally, in the relatively small number of homes that are sampled (Renner, 2009; Scott, 2009). For example, failure to pick the worst-case houses, not allowing water to stagnate long enough inside the plumbing before sampling, removing the faucet aerator screen before sampling, or sampling in cooler months, can allow compliance with the LCR AL for lead, and effectively hide serious water contamination (Renner, 2009). Sampling practices that can "miss" lead-in-water hazards have been employed in major US cities (Leonig, 2004), although it is the authors' experience that the majority of US water utilities sample tap water and report monitoring data with the safety of their consumers in mind.

**Lead Contamination Control Act (LCCA) of 1988.** The LCR also applies to the 10% of US schools that have their own water supply (Table 2). However, it does not extend to the majority of US schools and daycare facilities, which rely on public water systems for their water supply (Table 2). Instead, the Lead Contamination Control Act (LCCA) provides non-enforceable guidelines for these schools and daycare facilities, recommending that drinking water should not exceed 20 μg/L lead in any 250 mL first-draw sample (US EPA, 2006) (Table 2). In other words, aside from the 10% of US schools that are regulated as public water systems under the LCR due to use of their own water supply or well, the remaining 90% of US schools and daycare facilities are not subject to any enforceable national lead-in-water standard (Table 2).

The recommended guideline of 20 μg/L applied to lead in school water is considered more stringent than the 15 μg/L lead action level for homes, because a 250 mL water
sample under the LCCA tends to concentrate the lead in collected samples, compared to
the 1-L samples collected under the LCR (US EPA, 2010). Passage of the LCCA in 1988
prompted many schools to test for lead in drinking water, but state adoption and
enforcement of the guideline was often weak and even nonexistent (Lambrinidou et al.,
2010). By 1990 many schools had not repaired or removed lead-tainted coolers, used
sampling protocols other than that recommended by EPA, carried out very limited or
inappropriate sampling, or failed to conduct water testing at all (Lambrinidou et al.,
2010).

A recent investigative report by the Associated Press (Burke, 2009) and subsequent
congressional hearing (Freking, 2009) revealed problems with high lead in water of
hundreds of schools regulated as public water systems under the LCR. In response, the
EPA has stated it plans to better address and enforce lead standards in such situations
(Freking, 2009). Although much less information is available for the 90% of schools not
subject to any sampling requirements, case studies in Baltimore MD, Seattle WA,
Philadelphia PA, Washington DC, Maryland suburbs and Los Angeles CA revealed
serious problems with lead contamination of school water in recent years (Table 3). In
the vast majority of these cases, lead-in-water hazards were not revealed by the schools
under the LCCA, but by parents/students or investigative reporters (Table 3). With only
one exception, at least three years elapsed from the time the schools recognized a
problem to the time the public was informed. Another key point is that a large
percentage of taps in some of the schools (up to 80%) had lead in water above the LCCA
standard of 20 μg/L. In addition, some schools had taps dispensing water with lead-
levels exceeding “hazardous waste” criteria (i.e., > 5,000 μg/L lead) (Table 3).

Remedial measures in these school systems varied from replacing bubbler heads or
installing new fountains to installing filters, flushing, turning off fountains, and providing
bottled water (EA Engineering, Science and Technology, 2007; Boyd et al., 2008b;
Greenwire, 2004, Montgomery County Public Schools, 2007; Grover, 2008c). These
remedial measures invariably relied on a “trial and error” approach. Thankfully, some of
these school systems appear to have resolved the majority of lead-in-water problems, at
least in the short-term. However, remediation sometimes involved millions of dollars to
replace fixtures and fountains, only to have the problem return a few months later (Bach,
2005). Like lead paint, lead in water problems can never be considered fully resolved,
until the lead-bearing materials have been completely removed. It is also worth noting
that the schools described in Table 3 represent the “good news,” since most other school
systems in urban areas have not systematically tested their water for lead in nearly three
decades. Not shown in Table 3, are other case studies from: 1) Davidson, NC where a
problem was discovered after a high school chemistry experiment failed and the teacher
eventually traced it to high lead (Edwards, 2007), 2) Durham, NC where sampling
revealed hazardous lead levels in some water fountains at 8 schools (Biesecker, 2006)
and 3) cases in New Jersey (Burney and Dwight, 2003).

The limited attention on lead in drinking water of schools and day-care facilities is
disconcerting, given the potential public health risk. First, school children are much more
vulnerable to adverse health effects from lead exposure relative to adults (Needleman,
2004). Second, the intermittent pattern of water consumption, with periods of little or no water use on weekends, holidays and over summer break, produces very long stagnation periods of water inside the piping and can be worst case for releasing hazardous levels of lead from the plumbing into the water supply (Levin et al., 2008). Finally, school buildings have intricate plumbing systems, sometimes very old, containing multiple potential sources of water lead contamination. In 2004, the US EPA requested information and compiled a summary of state programs, regarding implementation of LCCA guidance (US EPA, 2004). More recently, acknowledging the lack of information on drinking water of schools, the US EPA announced that it is developing a draft "Charge on Safer Drinking Water in Schools and Child Care Facilities Initiative" that will seek input on how to assess the risks of lead in school drinking water (US EPA, 2010).

Despite these recently acknowledged problems with elevated lead in school water, one analysis that was conducted to examine the health risks, suggested that there was little cause for concern. Sathyaranarayana et al. (2006) simulated typical-case and worst-case scenarios of drinking water consumption at Seattle schools, and predicted reassuring blood lead levels for school children of below 5.0 µg/dL in all cases. However, these authors dismissed the highest detected lead-in-water measurements as unrepresentative, and only considered the geometric mean blood lead level of the student population using a bio-kinetic model. It is likely that explicit consideration of the highest measured lead-in-water samples, and resultant impacts on blood lead of more sensitive children as opposed to only the geometric mean (i.e., the 50th percentile of blood lead levels), would indicate a much more serious risk. In support of this hypothesis, it was recently revealed that a child with elevated blood lead from water in Greenville, NC was exposed in a day care center (Robertson, 2006), and environmental assessments in Washington DC attributed a child's elevated blood lead to contaminated water (7,300 µg/L lead) at an elementary school (Lambrinidou et al., 2010). Concerns related to a case of adult lead exposure for a teacher in an Oregon school in 2008, gave impetus to testing of tap water for water fountains at work which revealed high lead in water (Lambrinidou, 2008). Reports of harmful exposure are more consistent with common sense expectations, considering that the higher levels of lead detected in some schools (Table 3) indicate that a single glass of water can contain up to 29 times more lead than that deemed to constitute an acute health risk according to the CPSC (i.e., 20,000 µg/L lead in a 250 mL sample constitutes a single dose of 5000 µg lead, while the CPSC criterion is set at 175 µg lead).

Unregulated drinking water systems. About 15% of Americans operate their own private drinking water supplies (e.g., private wells and cistern type systems) (US EPA, 2006c). These systems are not subject to federal standards for lead monitoring (and other contaminants), although the major lead sources are similar to those found in public water supplies (Table 2). As a result, the magnitude of lead-in-water problems at these homes and the potential public health risks have not been studied (Schock et al., 1996).

Other public health guidance as it relates to lead contamination of tap water

The LCR and LCCA line limits were derived from an estimation of lead concentrations considered at the time economically and technologically feasible to achieve, and as such,
are not entirely health-based (Lambrinidou et al., 2010). A compilation of other health-based thresholds (Table 4) indicates that the US EPA Maximum Contaminant Level Goal (MCLG) for lead in water is equal to zero and that the state of California has developed its own Public Health Goal (PHG) for lead in water at 2 μg/L. The US EPA at one time indicated that 40 μg/L lead in water poses an “imminent and substantial endangerment to children” (Table 4). Health Canada (1992) and the World Health Organization (1993) have both developed a health-based guideline of 10 μg/L lead for drinking water, while the CDC (2010) advises children and pregnant women to not consume water that contains more than 15 μg/L lead (Table 4). As a further point of reference, the US Consumer Product Safety Commission (CPSC) classified a lead dose of 175 μg as an “acute health risk” to children (CPSC, 2005). This CPSC standard was used as a trigger for recalling millions of children’s toy jewelry (CPSC, 2005). If this standard, which was applied to children’s jewelry and toys (products not intended for human consumption), was applied to lead in water (a product intended for human consumption), the one-time ingestion of 250 mL of water at 700 μg/L lead (resulting in a lead dose of 175 μg) would also be classified as an “acute health risk” to children (Table 4). Finally, water containing more than 5,000 μg/L lead exceeds “hazardous waste” criteria (US EPA, 2009).

IV. FORMS OF LEAD IN TAP WATER AND IMPLICATIONS FOR MONITORING AND EXPOSURE

Dissolved versus particulate lead in tap water. Lead that is released from plumbing into drinking water can be present in a variety of distinct physicochemical forms including free aqueous ions, inorganic complexes, organic complexes, associations with highly dispersed colloidal matter, suspended particles of insoluble salts, or adsorbed on inorganic particulates (De Rosa and Williams, 1992). In some practical tests, the total lead content of drinking water is often demarcated into two fractions: the “dissolved lead” fraction and the “particulate lead” fraction (Table 5). Dissolved lead is operationally defined as the fraction of total lead in water that is small enough to pass through a filter of 0.45 μm pore size (McNeill and Edwards, 2004). Particulate lead is the fraction of total lead in drinking water that is retained by a filter of 0.45 μm pore size (Table 5). At the upper end of particulate lead sizes, these particles are big enough to be seen by the naked eye.

Lead particles in tap water can originate from detachment of lead-bearing scale or rusts from plumbing, or by scouring/sloughing-off during water flow (Schock, 1990). Lead corrosion rusts in water plumbing materials are analogs of peeling lead paint, in that degradation of the underlying plumbing material can dramatically increase the creation of these particles, their detachment, and resulting human exposure. Indeed, the mineralogical forms of many lead rusts (i.e., cerrusite and hydrocerrusite, see Table 5) are identical to those lead paint. Lead particles in tap water may also originate from physically degraded pieces of leaded brass, lead solder or lead pipe (Triantafyllidou et al., 2007). Unlike the case of dissolved lead in water, which is not controlled by nuances of water flow from the tap, the mobilization of particulate lead from plumbing can be highly
variable, depending on changes in pressure and water flow velocity/direction (Schock, 1990).

Numerous investigators have reported lead particles in water. Flaking lead particles larger than 12 μm in diameter were observed detaching from pipe, along with colloidal lead fractions associated with iron oxides and humic acids (De Mora et al. 1987; De Rosa and Williams, 1992). An extensive British survey reported that the flaking lead problems were caused by large black/brown particles visible to the consumer, whereas colloidal lead problems were caused by smaller particles that were not visible (De Rosa and Williams, 1992). The British report further concluded that problems with particulate lead were often associated with the presence of iron particulates, and that these problems were exacerbated by high water flows, especially during periods of high water demand (i.e., in the summer), as was recently highlighted in the US (HDR Engineering, 2009).

A small survey of lead in potable water from around the US revealed numerous instances in which lead was also present as particulates, sometimes at concentrations greater than 1,000 μg/L (McNeill and Edwards, 2004). Particulate lead was also clearly demonstrated to detach from lead-tin solder joints (Bisogni et al., 2000) and from lead pipes (Triantafyllidou et al., 2009a) in laboratory test rigs. In these laboratory studies, particulate lead was the predominant form of lead, comprising up to 99% of the total lead concentration in water samples (Triantafyllidou et al., 2009a).

Field investigations at various US locations with significant lead-in-water problems revealed that particulate lead release from the plumbing was often the cause (Figure 4; Table 6), and in some cases the source of the lead problem could be forensically linked to either lead pipe, lead solder or leaded brass (Table 6). A key point is the extraordinarily high levels of lead (up to 190,000 μg/L, or else more than 12,000 times the EPA action level) occasionally present in the water due to these particles, and their varying mineralogical content ranging from 3% to 100% lead (Table 6). The massive lead contamination occasionally resulting from partial lead pipe replacements is especially noteworthy, in light of the CDC report of EBL in Washington DC children (Frumkin, 2010).

**Implications of particulate lead in tap water for monitoring, exposure assessment and corrosion control.** Chemical lead solubility models, human exposure models, water sampling protocols, and analytical quantification methods are often based on the presumed dominance of dissolved lead in drinking water. It has only recently been recognized that particulate lead can occasionally be the dominant form of lead in drinking water (Triantafyllidou et al., 2007). A preliminary synthesis (Table 6) indicates that such problems may not be an isolated occurrence, especially given the rarity of such measurements.

It is useful to highlight some of the challenges associated with the presence of particulate lead in tap water, in terms of environmental monitoring and exposure. All models predicting lead at the tap, do so by considering soluble lead (Schock, 1990). Because the release of particulate lead in drinking water is often caused by physical factors and is erratic, its contribution is impossible to predict (Schock, 1990). At the same time,
capturing actual particulate lead spikes in tap water via field sampling is very challenging. Schock et al. (2008) warned that if lead (and other contaminants) were mobilized into solution or released as particulates, this would result in long-term intermittent exposures of unknown impact that can easily go undetected.

Particulate lead in water can be ingested, and presumably be dissolved or mobilized by human stomach acid (Schock, 1990). Mahaffey (1977) reported that lead absorption from small lead particles is greater than lead absorption from large particles. However, she also reported that when large pieces of lead are ingested, they may lodge in the gastrointestinal tract, and cause severe lead poisoning as they slowly dissolve. Bioavailability tests on lead solder particles collected from homes of lead-poisoned children in Greenville, NC and Durham NC, revealed that a significant fraction of the particulate lead from solder dissolved in simulated gastric fluid (Triantafyllidou et al., 2007). Additional case studies of childhood lead poisoning in Maine and in Washington DC (Table 6), which were attributed to lead-bearing particles that detached from the plumbing and contaminated tap water, also provide unambiguous proof that these lead particles were indeed bio-available once ingested.

In order to protect consumers from such exposures, corrosion control programs need to account for/prevent particulate lead release into the water. Modern corrosion control strategies were designed to reduce leaching from lead pipe, solder and brass materials by encouraging formation of low solubility lead hydroxyl-carbonate and phosphate films on the plumbing material surface, which can limit contamination to flowing water. But control of particulate release is dependent on minimizing the destabilization of the protective rust layer from water quality changes or hydraulic disturbances, and this process is poorly studied. The drinking water industry currently lacks the tools or knowledge to completely prevent or control particulate lead release.

V. BLOOD LEAD LEVEL AND MAJOR LEAD TOXICITY MECHANISMS

Potential harm from exposure to lead is typically tracked by measurements of the blood lead level (BLL). BLLs above 10 µg/dL are considered elevated (EBLLs) for infants and children, since they exceed the Centers for Disease Control and Prevention (CDC) threshold at which detectable mental impairment and behavioral changes have been documented (CDC, 2005). Cases in which blood lead exceeds 10 µg/dL or 20 µg/dL are also termed “lead poisoning”, dependent on the specific US jurisdiction. Depending on the extent of uptake by the blood stream (Table 7), lead disturbs the heme biosynthetic pathway and can lead to anemia (Singhal and Thomas, 1980), causes kidney malfunction or even kidney failure (Loghman-Adham, 1997), but most importantly generates brain disorders in children (Needleman, 2004). Recent studies suggest that decreased IQ and cognition occur in children even at BLLs as low as 3.0 µg/dL (Jusko et al., 2008; Bellinger and Needleman, 2003), and that impaired kidney function occurs in adolescents even at BLLs as low as 1.5 µg/dL (Fadrowski et al., 2010). Emerging clinical evidence is therefore strongly reinforcing the notion that no safe level of lead exposure exists. Lead toxicity (Table 7) is notoriously difficult to diagnose, and creates a wide range of symptoms which are easily overlooked (Kalra et al., 2006).
In light of these and other evidence, the US Department of Health and Human Services had established the ambitious goal of eliminating EBLLs in US children by 2010 (US Department of Health and Human Services, 2000). This was a qualitatively different goal from earlier policy, which focused on reducing the BLL considered toxic by various target amounts (CDC, 2005). Meeting the Healthy People 2010 objective to eliminate EBLLs (i.e., BLLs ≥10 μg/dL) in children was not achieved, and the US is extending this goal to 2020 (US Department of Health and Human Services, 2010).

VI. IMPORTANT CONSIDERATIONS IN ASSOCIATING LEAD IN WATER TO LEAD IN BLOOD

Troesken (2006) acknowledged that exposure to water lead is subject to “an error-in-variables problem”, which makes it challenging to find an association to health risks, and introduces a downward bias into commonly applied statistical techniques attempting to link Water Lead Levels (WLLs) to Blood Lead Levels (BLLs). In order to avoid such a bias, it is necessary to meet several preconditions when attempting to associate BLLs to WLLs in population studies or in case studies:

- Water lead measurements and blood lead measurements need to be available, and without significant sampling delays between the two.
- Water lead measurements need to quantify the actual lead content of the water.
- Individual water consumption patterns need to be accounted for, and
- Individual responses to the same lead dose need to be understood.

Some of the difficulties in meeting the above criteria (Table 8) are highlighted in this section.

Paired BLLs and WLLs are not always available. It is obviously necessary to obtain BLL and WLL data, in order to examine any potential association between the two. For a variety of reasons (Table 8) described below, such data are often unavailable.

Lack of BLL Data for sensitive sub-populations. In the US children’s blood lead screening is targeted to children at highest risk for exposure to lead paint and lead dust hazards (CDC, 2002), typically aged 1 to 6 years with developed hand-to-mouth activity (Linakis et al., 1996). Relatively little data is available for children aged less than 9 months, who are most vulnerable to lead exposure through water, due to use of reconstituted milk formulas (Shannon et al., 1992; Edwards et al., 2009).

General lack of WLL Data at Schools and Day Care Facilities. As of 2006, a survey by the CDC found that nearly half of all schools nationwide do not test their water for lead (Lambrinidou et al., 2010). A 2006 analysis by the US Government Accountability Office (GAO) revealed that few states have developed voluntary comprehensive testing and remediation programs for lead in school drinking water, and that about half the states
have not developed programs at all (Lambrinidou et al., 2010). A recent nationwide 
Associated Press survey on the 10% of US schools that are subject to the LCR, revealed 
that lead-contaminated drinking water affects schools in at least 27 states (Lambrinidou et 
all., 2010). There is no scientific or practical reason to believe that the problem does not 
extend to other schools and to other states, which are not being monitored for lead-in-
water problems.

Relative exclusion of water lead measurements during assessments of lead-poisoned 
children. Management strategies for childhood lead poisoning in the US have been 
developed based on the assumption that the LCR eliminated elevated water lead and that 
other environmental sources (e.g., lead in paint, dust or soil) are the most likely culprit. 
Current CDC guidance states that “if prior testing of a public water system shows that 
lead contamination is not a problem in homes served by that system, no additional testing 
is necessary, unless no other source of a child’s BLL can be found” (CDC, 2002). 
Public health agencies routinely misinterpret compliance with the LCR action level as 
eliminating the need for water sampling in homes, schools or day care facilities of lead-
poisoned children.

A Virginia Tech survey in 2006 verified that drinking water sampling is not standard 
practice during home assessments of lead-poisoned children. From the seventeen states 
that responded to the survey, only two required water testing in all cases of EBLL. Three 
of the jurisdictions “often” tested the water, eight of the jurisdictions “sometimes” tested 
the water, while four said they “never” did. A follow-up survey by the Alliance of 
Healthy Homes (Scott, 2009) revealed that in a state with a severe lead-poisoning rate 
“water is tested when no lead paint violations are identified, but this is virtually never”. 
Another state with similar problems claimed to “occasionally do this [test the water] if it’s 
the only way to convince the parents that the real hazard is lead-based paint in their 
home” (Scott, 2009). A different survey by the CDC (Renner, 2009) showed that fifteen 
lead grantee municipalities “routinely” collected water samples during home inspections, 
and that sixteen “sometimes” sampled drinking water (if lead was not found in paint/dust, 
or if drinking water was provided by a private well/ unregulated water system), while 
seven “never” tested drinking water.

Even when sampling is conducted, the CDC does not provide specific guidance on when 
and how to test water for lead (Renner, 2009). If a water sample is taken at all, it is 
typically a flushed sample taken during the inspection. This means that in the few 
instances where health agencies do collect tap water at homes of lead poisoned children, 
they are usually not collecting “worst-case” samples, and are thus not capturing worst-
case lead-in-water exposures (Renner, 2009).

WLL measurements do not always reflect actual lead in water. In order to assess the 
public health risk from elevated lead in tap water, it is obviously necessary to first 
measure the actual lead content of the water. But lead-in-water measurements can be 
controlled by the season, day, hour of measurement, and subtle differences in sample 
collection procedures can either detect or completely miss lead spikes (Table 8).
Improper water sampling/preservation methods at “high-risk” taps may miss some of the lead present in water. Standard sampling/analytical protocols are adequate in quantifying lead in water in the typical case. In exceptional cases, e.g. when childhood lead poisoning may be caused by water, the detection of lead hazards can be critically dependent on the specifics of sampling.

Flow rate during sample collection. The most recent guidance for schools (EPA, 2006) suggests to “induce a small (e.g., pencil-sized) steady flow of water from the outlet”. These instructions translate to an unrealistically low flow rate of less than 1 L/min. Yet every-day water consumption typically employs higher flow rates, at which it has been long known that the water may physically scour lead deposits from the pipe (Britton & Richards, 1981; Schock, 1990). Sampling at a higher flow rate would therefore more likely capture lead spikes due to particulate lead release, and would be more representative of typical water usage. Collecting water from a “high-risk” tap at the EPA-recommended low flow rate “missed” 90% of the particulate lead present (Edwards, 2005), during a home investigation in Washington DC in 2006 (Figure 5).

Sampling of hot versus cold water. Existing protocols under the LCR and lead poisoning case management only require sampling of cold tap water. Instead of sampling hot tap water, which is occasionally known to contain much higher lead, the EPA (2006) simply recommends that consumers never drink hot water or use it for cooking. A case study in Australia, where three individuals were diagnosed with lead poisoning, revealed that hot tap water contained 260 times more lead than did cold tap water (Mesch et al., 1996). The family members used hot water to prepare instant coffee and to cook. In another Australian study, water was collected from water boilers, coffee machines from restaurants, offices, workplaces and schools. Excessive levels of lead were found in 67% of the samples, probably due to the contact of brass components with the hot water (McCafferty et al., 1995). In Washington DC, review of environmental risk assessments in the homes of children with elevated BLLs during 2006-2007, revealed that more than 50% of caregivers who were asked, stated that they had used unfiltered hot tap water to mix infant formula, powdered milk, and juice (Lambrinidou and Edwards, 2008). Clearly, individuals consume hot tap water even though advised not to, and this risk is not quantified.

Sample Preservation. Existing analytical methods are based on the assumption that lead in water is dissolved, and that standard preservation of water samples at pH ≤ 2.0 with addition of 0.15% nitric acid is adequate for detecting all the lead that is present in the water. Digestion of samples with heat or stronger acid is not required unless turbidity exceeds certain thresholds (EPA, 1994). Edwards and Dudi (2004) first showed that the standard EPA preservation protocol can sometimes “miss” much of the lead that is actually present in water. For instance, water samples actually containing 508 μg/L lead in Washington DC, only measured as 102 μg/L, using the standard preservation protocol (Edwards and Dudi, 2004). The reason for the discrepancy is that particulate lead can settle or adhere to the plastic sampling containers, and is "missed" when aliquots are taken for that measurement (Triantafyllidou et al., 2007).
Inherent variability in lead release from plumbing cannot be captured by “single sample” WLL measurements. Due to spatial and temporal variability in lead release from plumbing, especially in the case of particulate lead, surveys based on a single water sample may be inadequate to characterize exposure (Mathew et al., 1981; Pocock, 1980). Yet current monitoring programs under the LCR or the voluntary LCCA are based on a single water sample from each outlet, due to practical and financial constraints. Schock (1990) warned that if water monitoring programs do not account for this inherent variability, then the measurements will be unrepresentative and irreproducible.

Spatial Variability. Lead-in-tap water fluctuations are possible within a city (see Figure 4), a neighborhood, or a single home, even if water is collected under a standard protocol. For example, infrequent water consumption in municipal buildings or in schools, with periods of little or no usage during weekends and breaks, results in long stagnation periods of the water inside the piping and causes it to undergo chemical changes (Levin, 2008). This translates to more variability in the lead concentration, compared to homes where water consumption is much more frequent and regular. In addition, pH or other chemical fluctuations, depending on how far from the treatment plant water is transported in order to reach consumer’s taps, also affects its corrosivity to ledged plumbing. Physical factors, such as the several interconnecting lines within a household plumbing system which route water to exterior faucets/bathrooms/kitchens/utility rooms, and the presence and type of leaded plumbing (e.g. leaded solder, leaded brass faucets, lead pipe) greatly affect lead levels at the tap (Schock 1990).

Temporal Variability. Fluctuations in lead levels from a single tap, depending on season or even on time of day, are possible. Seasonal fluctuations in temperature and chemical constituents, as well as seasonal variations in chlorination practice by the water utility may cause variable corrosivity of the water entering a household plumbing system (Schock 1990). In the course of one day, first-draw water, drawn from a tap in the morning after overnight stagnation, is considered worst-case in terms of lead release from the plumbing. Flushed water, or water collected after short holding times, tend to contain lower lead levels. Pocock (1980) argued that whatever type of water sample is collected, a single sample cannot provide a reliable estimate of the resident’s exposure to water lead. To illustrate, during an environmental assessment of a lead-poisoned child in Washington DC in 2004, the DC Department of Health (DOH) concluded that drinking water was not a potential hazard, based on collection of a single flushed water sample which measured lead at a reassuring concentration of 11 μg/L. Freedom of information act (FOIA) requests revealed that in four other flushed samples collected by the local water utility, lead in water ranged between 19-583 μg/L (Table 9). The samples collected by the utility provided strong indication that elevated lead in water was a potentially serious hazard, but the health agency sampling failed to make that connection based on their collection of a single flushed sample.

Individual Water Consumption Patterns Affect Individual Exposure

Variability in Individual Water Consumption Patterns. In over-simplified terms the individual risk from lead-contaminated drinking water, or any other hazard, is also a
function of exposure to that hazard. Prior research has demonstrated a strong dependence
between the quantity of tap water consumed and overall exposure. For example, Potula
et al. (1999) found that Bostonians who consumed medium or high levels of tap-water (≥
1 glass/day) that contained greater than 50 μg/L of lead, developed progressively higher
patella lead levels later in life, compared to those Bostonians with low levels of ingestion
of the contaminated water (< 1 glass/day). Similarly, Galke et al. (2006) determined that
the more glasses of tap water consumed, the higher the chance of an elevated blood lead level
for children in Milwaukee and in New York. Consumption of two glasses of tap water per
day corresponded to a very high (50%) probability of having elevated blood lead (Galke
et al., 2006).

Individual water consumption patterns may vary markedly between different age groups,
and should be taken into consideration when assessing potential exposure. For instance, a
Canadian survey on drinking water intake showed that infants less than one year
consumed on average 122 mL/kg-day of water if they were formula-fed. This amount is
about three times higher than the 44 mL/kg-day intake proposed by EPA (Levallois et al.,
2008). These authors concluded that due to their high water intake on a body weight
basis, formula-fed infants may be particularly susceptible to water contaminants
(Levallois et al., 2008).

The use of tap, filtered tap or bottled water, also has an obvious impact. During the
Washington DC lead-in-water crisis, BLLs were measured in residents of homes with
water lead levels greater than 300 μg/L. All residents had BLLs lower than the CDC
levels of concern (16 μg/dL for children and 25 μg/dL for adults), which was at first
interpreted as indicating that the high lead in water was not harmful (Stokes et al., 2004).
However, later analysis revealed that only a few individuals (and no children) had been
consuming tap water for months prior to having their blood lead collected, and that
virtually all were using lead filters and bottled water (Edwards et al., 2009; Edwards,
2010; CDC, 2010b). The key take away message from the "300 μg/L" study is that use
of water filters, bottled water or even flushing, can be very effective at mitigating risk.

Underestimated indirect contribution of water to the total dietary lead intake. The
potential for massive accumulation of lead in food during cooking is not commonly
realized. Use of relatively large quantities of water to boil vegetables, pasta, or other
food, and effective concentration of the lead into food via adsorption has been
demonstrated (Moore, 1983; Little et al., 1981, Baxter et al., 1992). Specifically,
vegetables can absorb 90% or more of the lead from the water they are cooked in (Moore
(1983). Smart et al. (1981) showed that lead-in-water concentrations of 100 μg/L could
contribute 74 μg/day of lead to the total dietary lead intake from vegetables and
beverages, and at a total lead-in-water concentration of 500 μg/L the contribution was
378 μg/day. Green vegetables, carrots, rice and spaghetti concentrated more lead than
many other foods (Smart et al., 1983). While humans generally absorb lead from
drinking water more readily (30% to 50%) than lead from food (10% to 15%) (US EPA,
1986), the concentration effect can outweigh the reduced absorption factor. In addition to
the report by Mesch et al (1996), in which an Australian family was poisoned by use of
lead-contaminated hot tap water to prepare instant coffee and cook meals, two cases of
childhood lead poisoning occurred from contaminated water, even when the children did
not directly consume the water. In both cases cooking of pasta, rice or potatoes was implicated as the source of the children's lead poisoning (Copeland, 2004; Triantafyllidou et al., 2007).

**Individual risk factors affect individual response to a fixed lead dose.** Variations in age, diet and genetics will produce a range of health effects in a population, in response to a fixed lead dose from water (or other sources).

**Age.** The gastro-intestinal absorption rate of ingested lead is inversely related to age. The typical lead absorption rate for infants is 50%, compared to just 10% in adults (WHO, 2000).

**Dietary Habits.** Diets low in calcium and/or in iron, inadequate total calories and infrequent meals are believed to be associated with enhanced absorption of ingested lead (Shannon, 1996). In dietary experiments with twenty three adult volunteers, the lead retention from consumption of lead acetate was controlled by the type/timing of meals and beverages (James et al., 1985). Another study determined that subjects absorbed up to 50% of the lead on an empty stomach, 14% of the lead was absorbed when taken with tea or coffee, and 19% of the lead when taken with beer (Heard et al., 1983). Much lower uptakes (≥ 7%) were reported when lead was ingested in the course of a meal or with large amounts of calcium or phosphate (Heard et al., 1983).

**Genetics.** Genetic differences may result in different individual patterns of lead uptake and biokinetics (EPA, 2002). An increasing body of evidence suggests that tiny differences in the DNA sequence can modify the uptake, distribution, and elimination of lead by the body. For example, a 1991 study of lead workers in Germany and of environmentally exposed children in New York showed that small differences in two genes affected the absorption and excretion of lead by the participants (Wetmur et al., 1991). Another 2000 study that was performed in the Republic of Korea, with the participation of lead workers as well as persons without occupational lead exposure, reached similar conclusions (Schwartz et al., 2000).

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**VII. SUMMARY OF STUDIES ON THE ASSOCIATION BETWEEN LEAD IN WATER AND LEAD IN BLOOD**

The contribution of drinking water lead to the body’s lead burden (i.e., blood lead) is a subject of an extensive body of literature, which at first glance can appear contradictory. Marcus (1986) synthesized relevant studies as part of a broader evaluation of lead health effects from drinking water, and an update of that synthesis is undertaken herein. Various approaches have been used throughout the years in population studies, in an attempt to correlate water lead levels (WLLs) to blood lead levels (BLLs) (Table 10). These include, but are not limited to:

- Focus on the most sensitive age groups (e.g. formula-fed infants, young children, or pregnant/breast-feeding women), versus lumping different age groups together.
Different types of tap water sampling to capture actual lead intake through water consumption, versus utilization of available water lead data from other sources

- Parametric correlations (assuming normal distribution of WLL and BLL) versus non-parametric correlations
- Linear regression models versus curve-linear models to fit the original WLL and BLL data, or regression after logarithmic transformation of the original data
- Exclusive focus on the contribution of WLL to BLL, versus contribution of other environmental lead sources (e.g. lead in paint, dust, soil) to BLL as well
- Association between WLL and BLL, versus association between WLL and % of study population with EBLL

Few studies are directly comparable, but nonetheless, critically evaluating the available literature provides useful insights.

Studies that found an association between WLL and BLL

Association between WLL and BLL in formula-fed infants. For infants and young children up to 5 months of age, milk, formula, and drinking water are considered highly significant sources of exposure to lead (WHO, 2000). In fact, for bottle-fed infants using reconstituted formula with tap water, about 90% of their diet by weight is actually tap water, since formula is typically prepared by adding 8 parts of water to 1 part of powder (Sherlock and Quinn, 1985). Additionally taking into account that the typical lead absorption rate for infants is 50%, compared to just 10% in adults (WHO, 2000), elevated lead in water is a very significant concern for this population group. Infants typically consume 500-1000 mL of formula per day (WHO, 2000). If the water used to reconstitute formula contains 90 µg/L of lead, an infant receiving 750 mL of such formula daily would ingest 61 µg Pb/day, based on the illustrative calculation:

\[
\frac{90 \mu g \text{ Pb}}{L \text{ water}} \cdot \frac{0.75 \text{ L formula}}{day} \cdot 90\% \text{ water in formula} = 61 \mu g \text{ Pb/day} \quad \text{Equation (1)}
\]

In a study by Ryu et al. (1983), conducted when infant formula commonly had elevated lead derived from solder, infants consuming daily formula with 61 µg Pb from 3.7-6.5 months of age, had elevated blood lead levels by 5.6 months of age (Figure 6). Another group of infants, exposed to only 16 µg Pb/day through their diet did not develop elevated blood lead (Figure 6). On this basis Ryu et al. (1983) concluded that a lead intake of 16 µg/day, or else 3-4 µg/kg/day, is not associated with elevations in blood lead level above 10 µg/dL. This roughly corresponds to the provisional tolerable weekly intake (PTWI) of 25 µg/kg/week (or else 3.5 µg/kg/day) set by the World Health Organization (WHO, 2000). The Ryu et al. (1983) study is unique, because it provides unambiguous results for infants whose dietary lead intake was completely controlled. Due to obvious modern ethical concerns, similar experimental studies with infants are unlikely to be repeated.

Later studies also derived strong associations between Glasgow infants' dietary lead (mainly consisting of drinking water) and blood lead (Lacey et al., 1985). For 13 week-
old infants, a duplicate of their formula was collected for a week so that their total lead intake could be unambiguously quantified. A simple linear relationship between lead in water collected from kettles and infant blood lead level was derived, with a correlation coefficient of $R^2 = 0.32$ (Table 10). This work demonstrates that due to genetic and other factors mentioned earlier, perfect correlations are not to be expected between lead in water and lead in blood, even for the most susceptible sub-population to lead exposure from water.

An investigation by Shannon and co-authors revealed nine cases where lead poisoning occurred in Boston infants, after consuming instant formula reconstituted with lead-contaminated water (Shannon et al., 1992). In one such case, the formula was prepared each morning with first-draw water from the kitchen tap, which contained 130 µg/L lead attributable to lead solder (Shannon et al., 1989). Other cases of elevated blood lead from consumption of formula, with no other source of lead in the child’s environment, have been reported (Cosgrove et al., 1989; Lockitch et al., 1991).

Association between WLL and BLL in young children and adults before implementation of modern corrosion control. The first survey to show a curve-linear relationship between water lead and blood lead was that of Moore et al. (1977), which yielded a correlation coefficient of $R^2=0.52$ by analyzing data from different sectors of the Scottish population (Table 10). That work concluded that “Perhaps the most important aspect of this problem is the effect that high water lead has on the chances of a person having an unduly raised blood lead level”. In that study, 18% of people with first-flush water lead ≥298 µg/L had BLLs ≥ 41 µg/dL, compared to only 0.3% of those with water lead < 50 µg/L.

Sherlock et al (1984), who analyzed lead in water and lead in blood of mothers in Ayr, Scotland, reinforced Moore’s notion of a curve-linear relationship (Table 10). Initially, lead in water and in blood were measured for 114 mothers during 1980-1981, when the Ayr water supply was very corrosive and lead pipes were predominant. That analysis yielded a correlation coefficient of $R^2=0.56$ between kettle water lead and blood lead level (Table 10). After changes in water treatment were implemented by increasing the pH from 5.0 to 8.5, and after some of the lead pipes had been removed, the same analysis was repeated during 1982-1983. The sample of women in the subsequent analysis included many of the same women as the 1980-1981 analysis (Sherlock et al., 1984). Combination of both data sets yielded a correlation coefficient of $R^2=0.65$ between kettle water lead and blood lead (Table 10). After increasing the pH of the water supply, water lead levels significantly dropped, and median blood lead levels also dropped from 21 µg/dL to 13 µg/dL.

A study of 321 adults in an area of France with relatively corrosive water and high incidence of lead pipe (Bonnefoy et al., 1985) revealed that the concentration of lead in tap water was significantly correlated to the residents’ BLL (Table 10). For water lead levels up to 20 µg/L, the BLLs of both men and women remained relatively constant, but if lead in water exceeded 20 µg/L BLLs increased substantially. Elwood et al. (1985) assessed the relative contributions of water lead, dust lead and air lead to blood lead of
192 women in various areas of Wales. The regression model indicated that even in areas with relatively low water lead levels for that time period, water was an important source of blood lead. An increase of lead in water from 0 to 60 µg/L, resulted in an increase of 5.5 µg/dL in blood lead level (Elwood et al., 1985).

Raab et al. (1987) assessed the relative contributions of water lead and dust lead to blood lead of 6-9 year-old children in a part of Edinburgh with a high incidence of lead pipes and corrosive water supply. Their resulting model, accounting for exposure to water and dust, explained 43% of the variation in blood lead levels (Table 10). Coefficients for both water and dust were significant in their model (Table 10), and the authors concluded that water lead was more important than dust in this population. A follow-up study of the same individuals in central Edinburgh eight years later, showed a dramatic decrease in both their water lead and blood lead levels, which was attributed to improved corrosion control and removal of lead pipes from plumbing (Macyntire et al., 1998).

Maes et al. (1991) assessed the contribution of lead from drinking water, dust, soil, and paint to BLLs of 384 individuals of various ages in Hawaii. This study relied on measurements from exterior house faucets previously conducted on behalf of the Department of Health. Lead in paint, dust and soil was measured, and information on water consumption patterns and demographics was obtained through questionnaire responses of the participants. Because this population was exposed to relatively high levels of lead from water and low levels of lead from soil, dust, and paint, the authors found a stronger rank-based correlation of BLLs with WLLs (r = 0.53), compared to other environmental sources (r = 0.35 for soil, 0.30 for dust, and 0.14 for interior paint) (Maes et al., 1991). Blood samples in this study were collected more than 2 months after residents had been informed to avoid tap water, unless it tested below 20 µg/L, and virtually no vulnerable young children (< 1 year of age) were tested. Even though the work of Maes et al. (1991) was never published, it was submitted to EPA to influence formulation of the 1991 US EPA LCR, which in turn introduced modern corrosion control strategies for lead in US drinking water.

**Association between WLL and BLL in young children and adults after implementation of modern corrosion control.** More recent studies, conducted after the phase-out of lead in gasoline and other lead reduction strategies, and with much lower water lead levels due to modern corrosion control, still indicate strong relationships between lead in blood and lead in water. An epidemiological study in Hamburg, Germany (Fertmann et al., 2004) found a statistically significant correlation between average lead concentration in tap water and lead concentration in blood for 142 young women (Spearman's rho = 0.43, p<0.0001) (Table 10). For those women who were exposed to water lead >10 µg/L, an intervention program was tested, which either involved eliminating tap water lead exposure (by consuming bottled water) or minimizing exposure (by flushing water prior to consumption). Overall, after about 10 weeks of intervention, the median blood lead level decreased by 1.1 µg/dL (p ≤0.001). Individuals flushing the water lowered their blood level by 21% whereas those drinking bottled water reduced their blood lead level by 37% (Fertmann et al., 2004). The authors
concluded that “lead in tap water stands for an avoidable surplus exposure” (Feistmann et al., 2004).

In another German study conducted in Southern Saxonia, lead in blood and lead in tap water were measured for school children from two locations, A and B (Englert et al., 1994). Lead pipes were used in about 50% of their houses. After log-transformation of both their blood lead levels and their drinking water lead levels, 34% of the variation in blood lead levels was explained by log(WLL) in location A (i.e. $R^2=0.34$ for location A), and 41% of the variation was explained in location B (i.e. $R^2=0.41$ for location B) (Table 10). These authors concluded that in this part of Germany, lead exposure through drinking water was a greater concern than lead paint and other sources, due to the lead pipes in the water supply which had not yet been removed. Seven years later, after many lead pipes had been replaced with alternative materials, another study quantified WLLs in homes of new-born babies in various regions of Southern Saxonia (Zietz, 2001). Overall, 3.1% of the 1434 stagnation samples had lead higher than 10 μg/L. But certain geographic regions were at higher risk (>5% above 10 μg/L), and these authors concluded that the exceptional cases were due to leaching of domestic plumbing and fittings containing lead (Zietz, 2001).

Following a case of lead intoxication by drinking water in Ste-Agathe-des Monts, a Canadian study demonstrated a link between EBLLs and WLLs, as well as presence of lead service lines (Savard, 1992). Canada did not provide guidance for national corrosion control programs until 2009 (Health Canada, 2009) and this town still distributed corrosive water. On the basis of field investigations and 383 blood lead analyses, BLLs higher than 20 μg/dL were associated with the presence of lead service lines (Yates’ Chi-square test: 5.85; $p=0.02$) (Savard, 1992). A mathematical model was developed for the 72 citizens for which WLLs were measured (Table 10). Lead concentrations in those samples were as high as 4200 μg/L. Water consumption was obtained on the basis of a questionnaire. Using a linear regression between BLL and the estimated lead daily intake, a correlation coefficient of $R^2=0.25$ was obtained (Savard, 1992). The water corrosivity was rapidly identified as the problem (pH as low as 4.8 measured in some houses) and corrective measures were taken by increasing the pH to 8.4. After less than a month, WLLs were reduced by more than 90%, and the measured BLLs were significantly reduced by 24% in less than a year. Work with lead paint or dust mitigation has also demonstrated that, in some cases, mitigation of the suspected lead hazard only slightly reduces blood lead, if high levels of lead have been stored in bone (Rust et al., 1999; Gwiazda et al., 2005).

Watt et al. (1996) assessed the relationship between tap water lead and maternal blood lead concentrations in Glasgow, after the water supply was subjected to maximal water treatment to reduce plumbosolvency. Tap water lead remained the main correlate of raised maternal blood lead concentrations, accounting for 76% of cases of maternal blood lead concentrations above 10 μg/dL. The authors concluded that although tap water lead and maternal blood lead concentrations had fallen substantially since the early 1980s, tap water lead was still a public health problem in that area, especially for the estimated 13%
of infants who were exposed via bottle feeds to tap water lead concentrations exceeding the WHO guideline of 10 μg/L.

Lanphear et al. (2002) assessed the contribution of lead in water versus other sources to children’s blood lead levels during early childhood. Children from 6 until 24 months of age were monitored in Rochester New York, a community not considered to have lead-in-water problems according to the EPA LCR. Samples of tap water, house dust, soil and paint were quantified for lead, with house dust being determined as the main source of lead exposure. Even so, water lead concentration was also directly associated with blood lead levels (p<0.001). Children who lived in housing with water lead concentration greater than 5 μg/L had slightly higher (1.0 μg/dL) blood lead levels than children who had home water lead levels below 5 μg/L (Lanphear et al. 2002).

Taking into account geographic risk factors during an incident of sub-optimal corrosion control, Edwards et al. (2009) found a strong correlation between the frequency of EBL and the 90th percentile lead in water concentration from 2000-2007 in Washington DC. In neighborhoods determined to have the greatest frequency of lead pipe and highest lead concentrations, a correlation was found for children less than 30 months of age (Table 10). Older children, children living in neighborhoods with relatively few lead pipes or measurements of elevated lead in water, showed lesser impacts. But the youngest children (<1.3 years) showed very strong correlations between the incidence of EBL and the reported 90th percentile lead in water concentration. Earlier studies on Washington DC (Stokes et al., 2004; Guidotti et al., 2007) did not focus on the youngest children or geographical factors, and saw little or no increased incidence of EBL during the time of high lead in water.

Studies that did not find an association between WLLs and BLLs

Many other studies have found little or no relationship between lead in blood and lead in water. These studies are occasionally cited as if results are contradictory to those highlighted in the preceding section. That work is critically reviewed herein, in an attempt to reconcile results that are superficially in conflict, but which are consistent with bio-kinetic understanding of relationships between lead in water exposure and lead in blood.

Lack of Association between WLL and BLL When Lead in Water was reportedly Low.

There are many areas in the US (and other countries) in which water lead concentrations are very low. This can occur in situations with modern plumbing which has no lead pipe, lead solder or leaded brass, and with optimized corrosion control which can dramatically reduce lead leaching. Some older cities with high incidence of lead pipe and lead solder, have pipes that are virtually completely lined by scale such as calcium carbonate, which effectively eliminates contact between the lead-bearing plumbing and the water. In such circumstances lead in water will not be a dominant, or even a significant contributor, to overall lead exposure.
For instance, in a study by Lubin et al. (1984), where water samples were collected in the homes of 50 children with BLL > 30 µg/dL in Columbus, Ohio, lead in water was always low (< 10 µg/L). It is believed that the water supply in that study was atypically non-corrosive (high pH of 9.6 and high hardness of 101 mg/L). Not surprisingly, there was no correlation between lead in water and lead in blood, even in the presence of lead pipes at the children's homes. Likewise, a study in Germany (Meyer et al. 1998) in a town where lead in tap water was extremely low (< 1 µg/L) found no significant association between lead in domestic water and in blood for children. Another study of children's BLL in Miami Inner City, Florida (Gasana et al., 2006), also found no association of BLLs to WLLs (Spearman’s rho = 0.03 for flushed water samples and 0.005 for first draw water samples). Water lead measured in 120 homes was reportedly low (< 15 µg/L), with the exception of 3 homes. However, correlations between BLL and floor dust (rho = 0.27) and window sill (rho = 0.28) were statistically significant (p < 0.05) (Gasana et al., 2006).

Another important study by Rabinowitz et al. (1985) examined the association of BLLs of infants in Boston with lead in dust, soil, indoor air, paint and tap water. The authors found statistically significant correlations of children's BLL at age 24 months with lead in dust (Spearman’s rho = 0.4, P<0.0001), with lead in soil (Spearman’s rho = 0.3, P < 0.001), and with lead in paint (Spearman’s rho = 0.2, P < 0.01), but not with lead in water (Spearman’s rho = 0.14, not statistically significant). The conclusions of that work regarding important contributions of dust, soil and paint to BLL are consistent with expectations. However, analytical limitations in quantification may have masked any potential contribution of WLL to BLL, if it were present. Specifically, lead in water was quantified using anodic stripping voltammetry. This analytical technique has recently been shown to accurately measure dissolved Pb⁺⁺, but to not measure particulate lead or Pb⁺⁺⁺⁺ levels in water (Cartier et al., 2009). The latter species have recently proved to be present in drinking water under at least some circumstances (Triantafyllidou et al., 2007), but were not understood at the time of the Rabinowitz study. Moreover, samples were allowed to sit unacidified before analysis, which is now recognized to potentially miss some of the lead present in water (Rabinowitz, 2006). Perhaps, partly because of these issues, only very low levels of lead (3.7 – 7.3 µg/L) were reported for Boston drinking water samples (Rabinowitz et al., 1985).

To provide a historical perspective for Boston, Potula et al. (1999) found lead in water of Boston homes as high as 169 µg/L during the same time period. Boston water, which was linked to lead poisoning via infant formula was reported by Shannon et al. (1982) to contain 132 µg/L. Even as late as 1996-2000, lead levels in first-draw tap water samples from Boston were 159 µg/L on average, and as high as 311 µg/L in the worst case for children with elevated blood lead (State of Massachusetts, 2009). Even flushed water samples for lead poisoned children in the 2009 data from Massachusetts contained as high as 146 µg/L lead.

**Lack of Association between WLL and BLL When Lead in Water was reportedly High.** Some studies have found no association between elevated lead in water and elevated lead in blood. Key aspects of such studies are critically reviewed herein, especially as they
relate to potential limitations described in preceding sections (see Table 10). For example, Costa et al. (1997) reported that very high water lead levels in a public school in rural Utah (up to 840 μg/L) did not cause EBLL. In that study, measurements of blood lead were undertaken for only 40% of students, more than 16 days after notification of the problem and advice to drink bottled water, during which time lead in blood could drop, considering its half-life of around one month (WHO, 2000). Even though one case of elevated blood lead was identified, it was dismissed as un-related to water lead (Costa et al. 1997).

A CDC study reported that in 201 cases where home tap water contained more than 300 μg/L of lead in Washington DC, none of the individuals were found to suffer from EBLL (Stokes et al., 2004). Another study on the same topic cited the same data, and did not find an association between elevated lead in water and lead in blood, concluding that “there appears to have been no identifiable public health impact from the elevation of lead in drinking water in Washington DC, in 2003 and 2004” (Guidotti et al., 2007). Neither study focused on infants, who are most vulnerable to harm from lead in water. In addition, both studies lumped all the blood lead data for Washington, DC together, an approach which masked disparities among different neighborhoods (Edwards et al., 2009). Finally, as mentioned earlier, virtually no residents had been consuming tap water for months prior to having their blood lead drawn, rendering the data useless for assessing impacts of lead in water on lead in blood (Edwards et al., 2009; CDC, 2010b). The “no-harm” conclusion of Guidotti et al. (2007) has since been removed (Errata in Environmental Health Perspectives, 2009).

Studies That Did Not Measure Lead in Water at Homes

Some researchers attempted to assess the contribution of lead in water to lead in blood, without measuring lead in tap water at homes. For example, studies occasionally relied on qualitative data obtained from questionnaires regarding consumers’ water consumption habits (tap water versus filtered or bottled water), and/or knowledge regarding the presence of lead pipes in consumers’ home plumbing. Other studies relied on lead-in-water measurements obtained from the distribution system and not home taps, which can result in overlooking tap water as a potentially important source.

For example, a broad Cincinnati study aimed to investigate different lead sources and factors which result in excessive intake for children in urban settings (Bornschein et al., 1985; Clark et al., 1985). Blood lead levels were systematically monitored from birth through 5 years of age and a broad range of lead sources in the children’s environment were accounted for, including painted surfaces and dust, soil samples in outside playing area, street dirt, and any suspicious items which the children were mouthing. Water samples were not collected in this otherwise very thorough and definitive study. Instead, sampling data collected by the water utility from the distribution system, before the water even enters the service line where lead hazards are introduced (see Figure 1), were cited as having lead concentrations < 6 μg/L (Clark et al., 1985). Exposure from water was thus deemed to be insignificant when in fact, samples were never collected in a manner that would allow risks to be quantified if they were present. Historical data from Greater
Cincinnati Water Works suggest that even in recent years, with modern corrosion control, some Cincinnati schools had tap water lead levels above 15 μg/L, while some homes tested at 180 μg/L after partial lead pipe replacements (DeMarco, 2004).

A study in Northern France (Leroyer et al., 2000) showed that BLLs doubled for children who reported consuming tap water in homes with lead plumbing identified under the kitchen sink. In cases where lead pipes were not visible under the kitchen sink, children drinking tap water still had significantly higher BLLs compared to those consuming bottled water (Leroyer et al., 2000). The authors (Leroyer et al., 2000) qualified their conclusions by suggesting that water sampling should be conducted more carefully assess their findings, which relied on visual identification of lead plumbing and qualitative answers to a questionnaire.

Synthesis of studies on the association between lead in water and in blood

Rigorous scientific studies prior to implementation of modern corrosion control provided strong links between elevated lead in water and elevated blood lead (i.e., greater than 10 μg/dL) of exposed populations. As would be expected based on current understanding of dietary intake and hand-mouth behavior relative to significance of lead sources, impacts of elevated lead in water on lead in blood become more significant the younger the child, with especially high risks for children consuming reconstituted infant formula. The work of Lacey et al. (1985) and Ryu et al. (1983) exemplify rigorously controlled studies that are unlikely to be improved upon in the near future, and which served as the basis for the US EPA LCR and models predicting BLL developed by the US EPA.

Two landmark multimedia US studies (Bornschein et al., 1985 and Rabinowitz et al., 1985), did not find any association between lead in water and in blood for children in Cincinnati and Boston. The strong relationships established in that research between lead in paint, dust and soil and children's blood are not disputed, but each study had limitations or gaps in quantifying lead in water risks.

More recent studies in Canada, Germany, the UK and the US, sometimes found strong associations between WLLs and BLLs, and sometimes not. These studies reflect marked differences in the extent of lead in water exposure based on plumbing materials, corrosivity of the water, and other nuances of exposure. Some recent work by the CDC and others that concluded very high lead in water (> 300 μg/L) did not impact incidence of EBL in an exposed population has been re-analyzed, corrected or clarified (Edwards et al., 2009; Errata in Environmental Health Perspectives, 2009, CDC, 2010b: Edwards, 2010; US Congressional report, 2010). That work is no longer inconsistent with decades of prior research. Other work has demonstrated strong links between lead in water and lead in blood even at much lower levels of lead in water exposure, in systems conducting "optimized corrosion control" or its equivalent (Lamphere et al., 2002; Englert et al., 1994; Fertmann et al., 2004).
VIII. SUMMARY AND CONCLUSIONS

As efforts shift from addressing pervasive lead sources that elevate the blood lead of large percentages of the population, to more isolated individual cases requiring exceptional attention, it will be necessary to more carefully consider lead in water as a potential source.

Although routine blood lead monitoring and environmental assessments are not designed to detect lead in water hazards when present, several recent cases of elevated blood lead in the US and other countries have been attributed to lead-contaminated drinking water. Existing US regulations/guidelines have not eliminated lead in water hazards in systems served by public water supplies, schools, daycares and privately owned homes.

Lead in drinking water originates from lead-bearing plumbing materials, which undergo corrosion reactions, and may severely contaminate the water supply. Contrary to popular belief that lead in water problems invariably decrease as water systems age and rust/scale develops on pipes, problems with sporadic detachment of rust/scale on lead-bearing plumbing might create acute human health risks that are hard to detect and link to elevations of lead in blood. Up to 81 million US homes are estimated to be at potential risk due to the presence of lead pipe and lead solder, and even new homes can occasionally experience high lead from brass/bronze plumbing. The occurrence of particulate lead in US drinking water has not been adequately examined, but case studies suggest that the highest doses of lead are associated with the presence of particulate (and not dissolved) lead in tap water.

When water lead measurements are not available at “high risk” taps, or when they fail to quantify the actual lead content of drinking water, correlations of water lead with health risks may be missed. A strong association between lead in water and lead in blood has been documented through decades of prior scientific research. Epidemiological studies in the US, the UK, Germany, France, and Canada indicate that elevated lead in water can occasionally be the dominant, or a major contributor, to elevated blood lead. Re-evaluation of the public health risk from lead in water, with emphasis on particulate lead and sensitive sub-populations, is timely considering forthcoming revisions to the LCR and acknowledged deficiencies in addressing lead in school drinking water.

IX. RESEARCH NEEDS

This literature review highlighted the need for additional research on lead occurrence in tap water and associated public health risks. Specifically, the occurrence of lead in drinking water at US schools needs to be systematically monitored, using sampling protocols that will allow identification of the source(s) of potential problems and development of concise remedial actions. Detailed case studies on lead-in-school water could then be synthesized, and serve as a guide for schools that encounter similar problems in the future.
The effects of sampling protocol (e.g., flow rate, cold versus hot water) and sample handing (e.g., sample preservation and holding time) on lead detection need to be evaluated for all situations including schools, homes and other buildings. Subtle differences in sample collection procedures can either detect or completely miss lead spikes, especially when problems with particulate lead in water are important. The occurrence of particulate lead spikes in US drinking water needs to be better characterized, because it may result in intermittent exposures of acute health concern, which can easily go undetected. Acute health effects from lead in water, concentration of lead in food, and potential exposure to elevated lead from hot water deserve explicit consideration.

Old lead service lines are a major contributor to lead levels at the tap, when they are present. Partial replacements of lead service lines in response to provisions of the LCR, as a means of reducing lead-in-water exposure, require re-evaluation in light of preliminary data showing short- and long-term problems with lead spikes and increased risks of elevated blood lead in children. Laboratory studies quantifying the long-term impacts in a range of waters, as well as the cost; benefit of the procedure, are necessary. Likewise, evaluation of impacts from newly installed leaded-brass plumbing devices is also needed.

Past approaches in modeling health impacts from elevated lead in water, based on prediction of the geometric mean BLL, was useful when considering impacts on populations. But as society shifts its concern to tracking and addressing individual cases of childhood lead poisoning, modeling approaches need to consider and predict impacts on susceptible individuals exposed to the highest sampled lead in water concentrations.

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FIGURES AND TABLES (in the order they are discussed in the text)

FIGURE 1: Potential sources of lead contamination in tap water of homes, schools and other buildings.
FIGURE 2: Advertisement of the National Lead Company promoted the use of lead in various products, including piping. The accompanying text stated that lead in water heaters, paint and piping was invaluable in assuring comfort and proper sanitation (National Geographic, 1923).
TABLE 1: Estimated number of US homes at potential risk from tap water lead contamination, depending on presence of lead-bearing plumbing materials. The year 1986 marked the federal ban of lead pipe and lead solder, and established a maximum lead content of 8% by weight for “lead-free” brass plumbing components.

<table>
<thead>
<tr>
<th>Lead-Bearing Plumbing Material</th>
<th>Age of US Homes at Potential Risk</th>
<th>Estimated number of US homes at potential risk</th>
<th>Estimated Mass of Lead per home at potential risk (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brass Plumbing Components</td>
<td>All</td>
<td>All</td>
<td>0.1&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>If 2% lead by weight</td>
<td>All</td>
<td>All</td>
<td>0.3&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>If 8% lead by weight</td>
<td>Pre 1986</td>
<td>All</td>
<td>0.4&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>&gt; 8% lead by weight</td>
<td></td>
<td>81 million&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Lead pipes, lead service lines, and lead goosenecks (100% lead by weight)</td>
<td>Pre 1986</td>
<td>3.3 million - 6.4 million&lt;sup&gt;c&lt;/sup&gt;</td>
<td>19.1&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>Lead solder (40% - 50% lead by weight)</td>
<td>Pre 1986</td>
<td>81 million&lt;sup&gt;a&lt;/sup&gt;.</td>
<td>Highly variable, but believed very significant&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td>Lead joints in water mains (100% lead by weight)</td>
<td>Pre 1986</td>
<td>All homes served by water mains installed pre 1986</td>
<td>Unknown but believed inconsequential&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup>Estimation based on year of home built from US Census (2000)
<sup>b</sup>Assumed one residential brass water meter of body weight 5 lbs (2.3 kg) and eight brass devices similar to brass ball valves of individual body weight: 0.5 lbs (0.2 kg)
<sup>c</sup>Estimation by Weston and EES (1990). More recent estimations have not been conducted
<sup>d</sup>Calculation for typical lead service line of 25 ft (7.6 m) length, internal diameter of ¾ inch, external diameter of 1 inch, and lead density of 11.3 g/cm³
<sup>e</sup>Depends on workmanship of the soldering process at joints and resulting mass of solder in contact with water, believed one of the major sources of tap water lead contamination
<sup>f</sup>Currently believed that lead in these lead joints will not contact the water
FIGURE 3: Cumulative distribution of lead-in-water levels (in logarithmic scale) at consumers’ home taps in a large US city from 1998 to 2005. Compiled from monitoring data of city residents, who voluntarily collected tap water samples and submitted them for lab analysis (Patch, 2006).
**TABLE 2:** US federal regulations and guidelines for lead in drinking water of homes and schools.

<table>
<thead>
<tr>
<th>Federal Statute</th>
<th>Lead and Copper Rule (LCR) of 1991 for homes served by public water systems</th>
<th>Lead Contamination Control Act (LCCA) of 1988</th>
<th>No regulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applies to</td>
<td>- Homes and other buildings served by a public water system (~85% of US homes)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Schools/daycares regulated as &quot;public water systems&quot;*</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(~10% of US schools)</td>
<td>Schools/daycares served by a public water system (~90% of US schools)</td>
<td>Homes with private water system (~15% of US homes)</td>
</tr>
<tr>
<td>Enforceable?</td>
<td>Yes, federal regulation</td>
<td>No, voluntary guidance</td>
<td>Not Applicable</td>
</tr>
<tr>
<td>Required sample number</td>
<td>5-100 taps, depending on the size of the population served (reduced to 5-50 taps, for utilities previously compliant with the rule)</td>
<td>Each school water outlet used for drinking and cooking</td>
<td>None</td>
</tr>
<tr>
<td>Sampling Frequency</td>
<td>every 6 months (reduced to as little as once every 3 years for utilities previously compliant with the rule)</td>
<td>Not specified</td>
<td>None</td>
</tr>
<tr>
<td>Sampling Requirements</td>
<td>1 Liter cold water samples after at least 6 hours of stagnation</td>
<td>250 mL cold water samples after 8-18 hours of stagnation</td>
<td>None</td>
</tr>
<tr>
<td>Lead Limit</td>
<td>15 μg/L, termed “Action level” (AL)</td>
<td>20 μg/L</td>
<td>None</td>
</tr>
<tr>
<td>“Failure criterion”</td>
<td>Over 10% of samples exceeding AL of 15 μg/L lead (or else 90th percentile lead &gt; AL)</td>
<td>Any water sample exceeding 20 μg/L lead</td>
<td>None</td>
</tr>
<tr>
<td>Remediation Measures</td>
<td>Corrosion control optimization, lead service line replacement, public education</td>
<td>Flushing, point-of-use filters, remove plumbing, bottled water, public education</td>
<td>None</td>
</tr>
</tbody>
</table>

*Schools that regularly provide water to at least 25 individuals per day and use their own water source (e.g., private well), or treat, or sell their water, are regulated as "public water systems".
TABLE 3: Representative Case Studies on Lead-in-Water Problems at US Schools.

<table>
<thead>
<tr>
<th>School System Location</th>
<th>Year School Knew of Problem</th>
<th>Year Public Informed</th>
<th>How Discovered</th>
<th>Average % taps above LCCA Guidance of 20 μg/L*</th>
<th>Highest Reported Pb in water (μg/L)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baltimore, MD</td>
<td>1992</td>
<td>2003</td>
<td>Parent inquired as to why water fountains had been turned off and a teacher turned whistleblower.</td>
<td>20% of fountains</td>
<td>655</td>
<td>City of Baltimore, 2007 Williams, 2008</td>
</tr>
</tbody>
</table>
| Seattle, WA            | 1990                        | 2003                 | A parent was concerned due to discolored water, collected and analyzed sample finding high lead. | 1990: 33-40% 2004: 25%                        | 1,600                              | Odell, 1991          
|                        |                             |                      |                                                                                 |                                               |                                     | Cooper, 2008          
|                        |                             |                      |                                                                                 |                                               |                                     | Boyd et al., 2008a |
| Philadelphia, PA       | 1993                        | 1998                 | A source “ unofficially” provided lead-in-water test results to EPA, after EPA had been told to get a search warrant when requested to sample water. | 2000: 38% of fountains 48% of faucets N/A but 17% of schools >100 μg/L                  |                                     | Fitzgerald, 2000     
|                        |                             |                      |                                                                                 |                                               |                                     | Bryant, 2004         |
|                        |                             |                      |                                                                                 |                                               |                                     | Lambrinidou & Edwards, 2008 |
|                        |                             |                      |                                                                                 |                                               |                                     | Lambrinidou et al., 2010 |
| Washington Suburban, MA| 2004                        | 2004                 | School system voluntarily collected samples to participate in LCCA after problems were revealed in Washington DC | 2004: 18%                                      | 36,372                                        | Gervin, 2004          
|                        |                             |                      |                                                                                 |                                               |                                     | Montgomery County Public Schools, 2004       |
| Los Angeles, CA        | 1998                        | 2008                 | Local news station. School personnel falsified daily reports regarding remedial flushing to reduce lead. | 2008: 30%                                      | N/A                                             | Lambrinidou et al., 2010     
|                        |                             |                      |                                                                                 |                                               |                                     | Grover, 2008a;2008b |

N/A: Not Available

*All data from Washington DC schools in this table use 15 μg/L as a failure criterion

Bold italics indicate lead-in-water levels that were high enough (i.e., > 5000 μg/L) to classify the drinking water as "hazardous waste", based on the Toxicity Characteristic Leaching Procedure (TCLP) test, which regulates lead in waste at a level of 5 ppm or else 5,000 μg/L (US EPA, 2009)
**TABLE 4:** Public health guidance regarding various levels of lead in tap water.

<table>
<thead>
<tr>
<th>Agency</th>
<th>Lead Threshold (µg/L)</th>
<th>Health Guidance and/or Warning</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>US Environmental Protection Agency</td>
<td>0</td>
<td>Maximum Contaminant Level Goal (MCLG), below which there is no known or expected risk to health</td>
<td>US EPA (1991)</td>
</tr>
<tr>
<td>California Environmental Protection Agency</td>
<td>2</td>
<td>Public Health Goal (PHG) for all age groups</td>
<td>Cal/EPA (1997)</td>
</tr>
<tr>
<td>Health Canada</td>
<td>10</td>
<td>Maximum Acceptable Concentration (MAC) based on chronic health effects, for all age groups</td>
<td>Health Canada (1992)</td>
</tr>
<tr>
<td>World Health Organization</td>
<td>10</td>
<td>Health-based guideline for all age groups</td>
<td>WHO (1993)</td>
</tr>
<tr>
<td>CDC</td>
<td>15</td>
<td>Children and pregnant women should not drink the water</td>
<td>CDC (2010a)</td>
</tr>
<tr>
<td>US Environmental Protection Agency</td>
<td>40</td>
<td>Imminent and substantial endangerment to children (warning removed in 2004)</td>
<td>Renner (2010)</td>
</tr>
</tbody>
</table>

* Lead dose of 175 µg translated to lead exposure through water consumption of 250 mL (one glass)

*Based on the Toxicity Characteristic Leaching Procedure (TCLP) test for waste
**TABLE 5:** Classification of lead species in tap water and distinction between dissolved lead and particulate lead. Adapted from De Rosa and Williams (1992).

<table>
<thead>
<tr>
<th>Operational Definition</th>
<th>Approximate Diameter Size (μm-log scale)</th>
<th>Class</th>
<th>Example(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Dissolved” Lead</td>
<td>0.001</td>
<td>Free aquo ions</td>
<td>Pb$^{+2}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Organic chelates, other inorganic ions, ion pairs and complexes</td>
<td>Pb-EDTA, PbCO$_3$</td>
</tr>
<tr>
<td></td>
<td>0.01</td>
<td>Bound to macromolecules</td>
<td>Pb-fulvic acid complexes</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>Highly dispersed colloidal material</td>
<td>Adsorbed on hydrous iron and manganese oxide colloids</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>Adsorbed on inorganic particulates</td>
<td>Adsorbed on hydrous iron and manganese oxides and clay minerals</td>
</tr>
<tr>
<td></td>
<td>10+</td>
<td>Minerals and precipitates</td>
<td>PbCO$_3$(s)-Cerussite, Pb$_3$(CO$_3$)$_2$OH$_2$(s)-Hydrocerussite</td>
</tr>
<tr>
<td>“Particulate” Lead</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
FIGURE 4: Lead-bearing particles were identified as the cause of severe tap water contamination during field investigations. (A, B) Brass particles trapped in two different strainers adjacent to two drinking water fountains at UNC, Chapel Hill-Photos from Elfland et al., (2010). (C) Lead solder particles trapped in home faucet aerator screen in Washington, DC-Photo from Edwards (2005). (D) Lead solder particles trapped in home faucet aerator screen in Greenville, NC- Photo from Triantafyllidou et al. (2007).
TABLE 6: Origin of representative lead particles identified in drinking water during field investigations, and level of resulting water contamination.

<table>
<thead>
<tr>
<th>Location of case study</th>
<th>Surface composition of Lead-Bearing Particle(s)</th>
<th>Origin of lead particle(s)</th>
<th>Total Pb Concentration in Water (federal standard is 15 µg/L)</th>
<th>Documented Lead Poisoning?</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>University of North Carolina at Chapel Hill, NC</td>
<td>3-22 %Pb, 26-66% %Cu 4-40 %Zn (3-19 %Fe, 0% Sn)</td>
<td>Leaded brass</td>
<td>Up to 350 µg/L</td>
<td>No</td>
<td>Etfland et al. (2010)</td>
</tr>
<tr>
<td>Greenville, NC</td>
<td>4 – 51% Pb 1-70% Sn (0-8% Cu)</td>
<td>Lead solder</td>
<td>Up to 16,500 µg/L</td>
<td>Yes</td>
<td>Triantafyllidou et al. (2007)</td>
</tr>
<tr>
<td>Durham, NC</td>
<td>17-52% Pb 37-66% Sn</td>
<td>Lead solder</td>
<td>Up to 650 µg/L</td>
<td>Yes</td>
<td>Edwards et al. (2006)</td>
</tr>
<tr>
<td>Raleigh, NC</td>
<td>3% Pb 97% Sn</td>
<td>Lead solder</td>
<td>2,413 µg/L</td>
<td>No</td>
<td>Parks and Edwards (2008)</td>
</tr>
<tr>
<td>Manchester, ME</td>
<td>Pb and Sn (levels not specified)</td>
<td>Lead solder</td>
<td>Up to 3,200 µg/L</td>
<td>Yes</td>
<td>Unpublished (2006)</td>
</tr>
<tr>
<td>Washington D.C. (after partial lead service line replacement)</td>
<td>Unknown, but presumably metallic lead (i.e., 100% Pb) and lead rusts</td>
<td>Lead Service Line</td>
<td>Up to 190,000 µg/L</td>
<td>Yes</td>
<td>Frunkin (2010) DC WASA (2008)</td>
</tr>
<tr>
<td>Washington, D.C.</td>
<td>63% Pb 37% Sn</td>
<td>Lead solder</td>
<td>Not available</td>
<td>No</td>
<td>Edwards (2005)</td>
</tr>
<tr>
<td>Washington DC Suburban Area</td>
<td>1.6-9.9 % Pb, 60-79% Sn, 1.8-5.0% Cu</td>
<td>Lead solder, leaded brass</td>
<td>Up to 1,403 µg/L*</td>
<td>No</td>
<td>Unpublished (2006)</td>
</tr>
<tr>
<td>Small Community, TN</td>
<td>Not Analyzed</td>
<td>Lead solder, confirmed onsite via Spot Test</td>
<td>Up to 2,886 µg/L</td>
<td>No</td>
<td>Edwards et al. (2007)</td>
</tr>
</tbody>
</table>

*Aside from lead and tin presence, high amounts of copper and zinc in water samples suggested that brass was also contributing to the problem.
TABLE 7: Blood lead level (BLL) and adverse health effects in children and in adults. The “Blood lead level of Concern” is currently set at 10 µg/dL. Adapted from Troesken (2006) and National Research Council (1993).

<table>
<thead>
<tr>
<th>BLL (µg/dL)</th>
<th>Children</th>
<th>Adverse Health Effects</th>
<th>Adults</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;10</td>
<td>IQ (-), Hearing (-), Growth (-)</td>
<td>Uncertain</td>
<td></td>
</tr>
<tr>
<td>&gt;10</td>
<td>Erythrocyte protoporphyrin (+)</td>
<td>Hypertension</td>
<td></td>
</tr>
<tr>
<td>&gt;20</td>
<td>Nerve conduction (-)</td>
<td>Erythrocyte protoporphyrin (+)</td>
<td></td>
</tr>
<tr>
<td>&gt;30</td>
<td>Vitamin D metabolism (-)</td>
<td>Systolic blood pressure (+)</td>
<td>Hearing (-)</td>
</tr>
<tr>
<td>&gt;40</td>
<td>Hemoglobin synthesis (-)</td>
<td>Nerve conduction (-), infertility (men), kidney failure</td>
<td></td>
</tr>
<tr>
<td>&gt;50</td>
<td>Colic, frank anemia, kidney failure, brain disorders</td>
<td>Hemoglobin synthesis (-)</td>
<td>frank anemia, brain disorders</td>
</tr>
<tr>
<td>&gt;100</td>
<td>death</td>
<td>death</td>
<td></td>
</tr>
</tbody>
</table>

(-) Decreased function, (+) Increased function.

Hemoglobin: the molecule which carries oxygen throughout the body.
Nerve Conduction: ability to send the impulse from the nerve to the muscle.
Vitamin D: necessary for the absorption of calcium and phosphorus, and for bone growth.
Erythrocyte protoporphyrin: intermediate in heme biosynthesis.
### TABLE 8: Potential difficulties in associating lead in water to lead in blood in population studies or in case studies.

<table>
<thead>
<tr>
<th>Issue</th>
<th>Illustrative Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BLLs and WLLs are not always available</strong></td>
<td></td>
</tr>
<tr>
<td>General lack of BLL measurements for sensitive populations</td>
<td>Binder et al., 1996</td>
</tr>
<tr>
<td>General lack of WLL measurements in schools/daycares under the LCCA</td>
<td>Lambrinidou et al., 2010</td>
</tr>
<tr>
<td>Relatively small number of WLL measurements under the LCR</td>
<td>Renner, 2009</td>
</tr>
<tr>
<td>Relative exclusion of water lead measurements during home assessments of lead-poisoned children</td>
<td>Renner, 2009</td>
</tr>
<tr>
<td><strong>WLL measurements do not always reflect actual lead in water</strong></td>
<td></td>
</tr>
<tr>
<td>Improper water sampling/preservation methods at “high-risk” taps under the LCR:</td>
<td></td>
</tr>
<tr>
<td>- Flow rate</td>
<td>Triantafyllidou et al., 2007</td>
</tr>
<tr>
<td>- Cold versus hot water</td>
<td>Triantafyllidou et al., 2009</td>
</tr>
<tr>
<td>Inherent variability in lead release from plumbing:</td>
<td></td>
</tr>
<tr>
<td>- Spatial (fluctuations within a city, a neighborhood, or even a single home)</td>
<td>Levin, 2008</td>
</tr>
<tr>
<td>- Temporal (fluctuations in a single tap depending on season, or even time of day)</td>
<td>Schock, 1990; Matthew, 1981</td>
</tr>
<tr>
<td><strong>Individual water consumption patterns affect individual exposure</strong></td>
<td></td>
</tr>
<tr>
<td>Variability in individual water consumption patterns:</td>
<td></td>
</tr>
<tr>
<td>- Amount of water consumed in/outside of home</td>
<td>Troesken, 2006</td>
</tr>
<tr>
<td>- Use of tap/filtered tap/bottled water</td>
<td>Matthew, 1981</td>
</tr>
<tr>
<td>Underestimated indirect contribution of water to the total dietary lead intake:</td>
<td></td>
</tr>
<tr>
<td>- Preparation of foods and beverages</td>
<td>Triantafyllidou et al., 2007</td>
</tr>
<tr>
<td>- Mesch et al., 1996</td>
<td>Moore, 1983</td>
</tr>
<tr>
<td><strong>Individual risk factors affect individual response to a fixed lead dose</strong></td>
<td></td>
</tr>
<tr>
<td>Bioavailability of lead varies between individuals, depending on:</td>
<td></td>
</tr>
<tr>
<td>- Age</td>
<td>Troesken, 2006</td>
</tr>
<tr>
<td>- Diet</td>
<td>Lanphear et al., 2002</td>
</tr>
<tr>
<td>- Genetics</td>
<td>Matthew, 1981</td>
</tr>
</tbody>
</table>
FIGURE 5: Lead measurement in flushed tap water samples versus flow rate in a home with lead pipe. Error bars represent 95% confidence intervals over triplicate samples collected on subsequent days at each indicated flow rate. Sample collection at the kitchen tap was timed to collect water derived from the lead pipe. (Edwards, 2005)
TABLE 9: Repeated flushed tap water sampling results from home of lead-poisoned child in Washington, DC. Data obtained through freedom of information act requests (Edwards, 2005).

<table>
<thead>
<tr>
<th>Date</th>
<th>Lead Determination (μg/L)</th>
<th>Sampling Conducted by</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/26/2003</td>
<td>75</td>
<td>Water utility</td>
</tr>
<tr>
<td>3/23/2004</td>
<td>19</td>
<td>Water utility</td>
</tr>
<tr>
<td>3/23/2004</td>
<td>11</td>
<td>Department of Health</td>
</tr>
<tr>
<td>10/8/2004</td>
<td>21</td>
<td>Water utility</td>
</tr>
<tr>
<td>11/2/2004</td>
<td>583</td>
<td>Water utility</td>
</tr>
</tbody>
</table>
**FIGURE 6:** Average blood lead level (BLL) versus age for two groups of formula-fed infants, at two levels of dietary lead intake. Adapted from data in Ryu et al. (1983).
**TABLE 10:** Representative population studies on the association between lead in water and lead in blood (in chronological order).

<table>
<thead>
<tr>
<th>Sample Population</th>
<th>Independent Variable(s)</th>
<th>Dependent Variable</th>
<th>Measure of Association</th>
<th>Model</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Different sectors of Scottish population (n=949)</td>
<td>First-draw water lead (µg/L)</td>
<td>Blood Lead Level (µg/dL)</td>
<td>R = 0.52</td>
<td>BLL=11.0+2.36(WLL)</td>
<td>Moore et al., 1977</td>
</tr>
<tr>
<td>Individuals in greater Boston (n=524)</td>
<td>First-draw water lead (µg/L), other variables such as age, sex, education, dust lead</td>
<td>Blood Lead Level (µg/dL)</td>
<td>Model explains 19% of variance</td>
<td>Ln(BLL)=2.73(WLL-4.70WLL²+2.17WLL³+other terms for age, sex, education, dust [WLL was best predictor])</td>
<td>Worth et al., 1981</td>
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<tr>
<td>Mothers in Ayr, Scotland (n=114)</td>
<td>Kettle water lead (µg/L)</td>
<td>Blood Lead Level (µg/dL)</td>
<td>R²=0.56</td>
<td>BLL=4.7+2.78(WLL)</td>
<td>Sherlock et al., 1984</td>
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<tr>
<td>Mothers in Ayr, Scotland (n=114 from 1980-81, and n=116 from 1982-83)</td>
<td>Kettle water lead (µg/L)</td>
<td>Blood Lead Level (µg/dL)</td>
<td>R²=0.65</td>
<td>BLL=5.6+2.62(WLL)</td>
<td>Sherlock et al., 1984</td>
</tr>
<tr>
<td>Bottle-fed infants in Scotland (n=93)</td>
<td>Composite kettle water lead (µg/L)</td>
<td>Blood Lead Level (µg/dL)</td>
<td>R = 0.57</td>
<td>BLL=14+0.062WLL, BLL=15.6+0.052WLL, BLL=14.7+0.054WLL, BLL=15.4+0.052WLL</td>
<td>Lacey et al., 1985, WHO, 2000</td>
</tr>
<tr>
<td>Women in Wales (n=192)</td>
<td>Kettle water lead (µg/L) Air Lead (µg/m³) Dust Lead (µg/g)</td>
<td>Blood Lead Level (µg/dL)</td>
<td>Model explains 38% of variance</td>
<td>Log(BLL)=1.06+0.62(WLL) + 0.18Log(ALL)-0.02Log(DLL)</td>
<td>Elwood et al., 1985</td>
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<tr>
<td>Adults in Vosgian Mountains, France (n=155 men, n=166 women)</td>
<td>Tap water lead after 5 seconds of flushing (mg/L)</td>
<td>Blood Lead Level (µg/dL)</td>
<td>Spearman’s rho =0.30 for men =0.47 for women</td>
<td>Not determined</td>
<td>Bonnefoy, et al., 1985</td>
</tr>
<tr>
<td>Children in Edinburgh (n=397)</td>
<td>Tap water lead (µg/L), dust lead (µg/g)</td>
<td>Blood Lead Level (µg/dL)</td>
<td>Model explains 43% of variance</td>
<td>Log(BLL)=0.5Log(5326+103WLL+3.81DLL) [WLL was best predictor]</td>
<td>Raab et al., 1987</td>
</tr>
<tr>
<td>Different sectors of population in Hawaii, with rain catchment systems (n=384)</td>
<td>Tap water lead (µg/L), other water-related terms, other terms for soil and demographics</td>
<td>Blood Lead Level (µg/dL)</td>
<td>linear model explains 77% of variance</td>
<td>Linear model: BLL=5.62+0.025WLL+0.0008(GLASSES<em>WLL)-0.017(FILTER</em>WLL)+other terms related to water, soil, age,</td>
<td>Maes et al., 1991</td>
</tr>
<tr>
<td>Study Description</td>
<td>Average water lead from 5 samples (mg/L) and estimated daily water consumption (L/day)</td>
<td>Blood lead level (μg/dL)</td>
<td>R²=0.25</td>
<td>BLL = 10 + 7 x WLL x Water Consumption (units adjusted)</td>
<td>Savard, 1992</td>
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<tr>
<td>School children in Southern Saxonia, Germany (n = 69 for location A, n = 44 for location B)</td>
<td>Composite tap water lead (μg/L)</td>
<td>Blood Lead Level (μg/dL)</td>
<td>Location A: R²=0.34</td>
<td>Location A: Log(BLL)=0.74 + 0.14Log(WLL)</td>
<td>Englert et al., 1994</td>
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<tr>
<td>Mother's in Glasgow, Scotland (n=342)</td>
<td>Water lead (μg/L)</td>
<td>Blood Lead Level (μg/dL)</td>
<td>Location B: R²=0.41</td>
<td>Location B: Log(BLL)=0.81 + 0.14Log(WLL)</td>
<td>Watt et al., 1996</td>
</tr>
<tr>
<td>Women in Hamburg, Germany (n=142 for subsample with detectable water lead)</td>
<td>Average water lead (μg/L) from 3 specimens</td>
<td>Blood lead level (μg/dL)</td>
<td>Spearman's rho=0.39</td>
<td>Not determined</td>
<td>Fertmann et al., 2004</td>
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<tr>
<td>Children in Washington DC (n=2698 in “High Risk”, n=4731 in “Moderate Risk”, n=2621 in “Low Risk”)</td>
<td>90th Percentile Water Lead (μg/L)</td>
<td>% Increase in Children with EBLL Compared to US average</td>
<td>R² = 0.83 in “High Risk”</td>
<td>R² = 0.71 in “Moderate Risk”</td>
<td>Edwards et al., 2009</td>
</tr>
</tbody>
</table>

WLL: Water Lead Level; BLL: Blood Lead Level; EBLL: Dust Lead Level; ALL: Air Lead Level

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The recent article by Brown et al. (2010) has a section which would benefit from further analysis and/or elaboration. Specifically, the authors state that:

"Chloramine with orthophosphate was the water disinfectant used during the period of time when the WASA LSL replacement program was conducted."

The authors then limit their analysis to blood lead data from children living in homes with partial replacements from 7/1/2004–12/31/2006, which is indeed the time period when phosphate was in the water. However, hundreds of partial pipe replacements were conducted by WASA before 7/1/2004 and when phosphate was not in the water.

If the authors analyze all the data from D.C. children living in homes with partial pipe replacements, including those whose blood leads were collected before 7/1/2004, how does it impact the results that are obtained? The concern is that a decision to exclude this data might mask the magnitude (and significance) of possible adverse health impacts from partial pipe replacements. Specifically, orthophosphate was added to water to inhibit lead release, and including the data from when orthophosphate was not added, might provide stronger evidence of harm.

Marc Edwards
Charles Lunsford Professor of Civil Engineering
Virginia Tech
Testimony of Marc Edwards, PhD before the
US House of Representatives Committee on Science and Technology, 111th Congress
Preventing Harm—Protecting Health. Reforming CDC’s Environmental Public Health Practices

EXPERIENCES AND OBSERVATIONS FROM THE 2001-2004 “DC LEAD CRISIS”

INTRODUCTION

I am the Charles Lunsford Professor of Civil and Environmental Engineering at Virginia Tech, where I conduct research at the interface of basic science, public health, corrosion control and environmental engineering. I have published over 100 peer-reviewed journal articles, made hundreds of technical presentations, and have been recognized with numerous awards including a Presidential Faculty Fellowship from the White House/National Science Foundation (1996) and a MacArthur Fellowship (2008). Time magazine named me amongst the 4 most important “Innovators” in water from around the world (2004) and just this year Villanova University awarded me the Praxis Award in Professional Ethics.
Partial Lead Service Line Replacements. My worry was reinforced when, in 2008, in partnership with a coalition of public health advocates in DC, we discovered that DC WASA’s 5-year and $100 million “accelerated” lead in water “remediation” program was not nearly the success that DC WASA and US EPA R3 had claimed. Thousands of lead water pipes were dug up and replaced with copper pipe, but only the publicly owned portion of the old lead pipe was replaced. The privately owned portion was left in the ground. This program of partial lead service line replacement-worsened lead in water levels in many homes for an undetermined duration. For years the agencies repeatedly claimed in public and in written scientific reports (again contradicting decades of prior experience and research), that partial replacements in DC were not causing lead to spike:

"...there was no immediate change, or immediate increase in lead levels in the tap water"..."there is no evidence that the lead levels increase"..."remove half the lead...you have a lot less lead in your tap water as a result."

Rick Rogers EPA R3, Interview on WAMU Radio, May 2004

In 2004, I had testified to the US Congress that partial lead service line replacements were a waste of money and that my research had shown the procedure could increase residents’ risk for lead exposure. After years of denial and false statements by DC WASA and US EPA R3, I eventually proved that the two agencies had themselves collected hundreds of data points showing severe problems with DC residents’ exposure to high lead in water, following DC WASA’s partial lead service line replacement “remedy” at their homes.

But the public health implications of our work were to be neutralized by what was becoming a well-oiled tag team effort by Dr. Guidotti and the CDC. Dr. Guidotti provided testimony and “public education” at community meetings, asserting that even the highest levels of lead in DC’s water after partial lead service line replacement (sometimes exceeding 100,000 pph) probably did not pose a health risk. Dr. Guidotti wrote:

"it has been alleged that spiking lead levels after partial lead service line replacements present a health risk. This is probably not correct."

Testimony of Dr. Guidotti, March 10, 2008

The CDC attended two of several DC WASA public meetings on this issue, and consistently supported Dr. Guidotti with silent acquiescence, no matter how outrageous the George Washington University professor’s proclamations. The CDC repeatedly refused to answer direct questions from DC residents, that could have put Dr. Guidotti’s testimony into some context. At these meetings, DC WASA distributed written “public education” materials embellishing on the already ludicrous CDC MMWR conclusion. For instance, the water utility’s fact sheet stated that:

"In 2004, the CDC analyzed results from a District Department of Health examination of blood lead levels among children during the period of elevated lead levels in tap water at many homes. According to the CDC report, there were no children, from a sample group of 201, identified with blood lead levels above the CDC level of concern (>10 micrograms/deciliter) that were not explained by other sources, primarily the conditions of the household paint."

Even ignoring the already distorted analysis of the 201 residents portrayed in the original CDC MMWR, clearly, the CDC MMWR never looked at 201 children. The CDC MMWR itself stated that only 17 of the 201 targeted “worst-case” residents were under the age of 6. Moreover, the CDC MMWR study involved no environmental risk assessments at the homes of DC children with elevated blood lead levels. Finally, although the CDC MMWR implied that virtually all detected blood lead elevations in DC were due to lead paint, it never stated this.
When two DC public health advocates called on the CDC to demand that DC WASA correct the misleading presentation of the CDC’s own research results, the CDC failed to do so. A CDC employee who claimed to have consulted a CDC lawyer, claimed that there was nothing CDC could do to redress the inaccuracies in already distributed versions of DC WASA’s fact sheet. However, the official assured the two advocates that he would request all future versions of the DC WASA fact sheet prior to dissemination in order to correct any misleading statements. Despite that assurance, the fact sheet was once again distributed on May 1, 2008 with the same misleading language in place.

As perplexing as CDC’s behavior was in relation to the above incident, what was going on behind the scenes was even worse. Unbeknownst to either myself or the DC residents who were pleading with the CDC in 2008 to correct Dr. Guidotti’s and DC WASA’s assertions that lead-contaminated drinking water does not pose a significant public health concern, the CDC had been researching the impacts of partial lead pipe replacements on blood lead levels of DC children probably since at least 2005. Based on accounts of individuals who attended a November 2007 meeting between EPA, CDC, DC DOH and Dr. Guidotti, and as substantiated in later e-mails in my possession, the CDC actually had data in late 2007 that indicated public health risks from DC’s partial lead service line replacements. It was not until February 2009, long after the time when disclosure of their results could have been used to prevent more needless harm to DC children, and to properly guide public debate, that CDC eventually issued online an “important update” based on their research in DC:

“CDC’s Healthy Homes and Lead Poisoning Prevention Branch has conducted an epidemiological study of the relationship between children’s blood levels and lead water service lines. Our preliminary results suggest that when lead service lines are partially replaced, that is the public portion of the line from the the main to the meter is replaced, children are more likely to have blood lead levels greater than or equal to 10 μg/dL, compared to children living in housing with either undisturbed lead service lines or service lines that are not made of lead” (bold emphasis added).

The ethics of how CDC conducted its “research work” given extensive prior knowledge about lead spikes after partial pipe replacement, their duplicity in covering up what was actually occurring to children in these homes, and their failure to inform the public about their knowledge of the potential harm throughout the numerous public meetings on this subject in 2008, strikes me as highly unethical and deserving of future scrutiny. Yet it is also completely consistent with CDC’s past actions, to withhold and control any information that may cast doubt on their message that lead in water is not a significant public health concern.

**DC WASA Sampling Inconsistent with Intent of LCR.** The coalition of concerned DC residents also discovered that since 2005 DC WASA, again with the full knowledge and approval of US EPA R3, had achieved compliance with the Lead and Copper Rule by monitoring DC’s water via the use of a sampling protocol that required flushing taps for 10 minutes the night before sampling. In the water industry, pre-flushing is understood as a well-known method to game the US EPA lead standard, by temporarily reducing lead concentrations at the tap. After reviewing the coalition’s appeal of DC WASA’s protocol, Cynthia Dougherty, the Director of US EPA HQ Office of Ground Water and Drinking Water, determined in a letter to the coalition that flushing on the eve of compliance sampling was inconsistent with the intent of the Lead and Copper Rule: