CHALLENGES IN MAINTAINING DRINKING WATER QUALITY AT THE TAP: CONTAMINATION WITH TOXIC LEAD

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September 14, 2017

A little bit about me

- Bachelor's in Environmental Engineering

Technical University of Crete, Greece

- M.S. in Environmental Engineering
- Ph.D. in Civil Engineering

- Environmental Engineer at US EPA's Office of Research and Development

Outline

- Motivation

  - Overview of drinking water distribution challenges in the US

- Research Project Examples

  - Lead (Pb) in water and children's blood before Flint, MI
  - Galvanic corrosion after partial lead service line replacements
  - Lead in drinking water of US schools and biokinetic modeling of children's blood lead levels
  - In-building disinfection and unintended consequences

Paradigm Shift in Drinking Water Quality

20th Century

21st Century

Sanitary Water	Safe Water + Sanitary Water	Tasty Water + Safe Water + Sanitary Water

Sanitary Water

- Waterborne Disease
- Disinfection
- Water Quantity

Safe Water

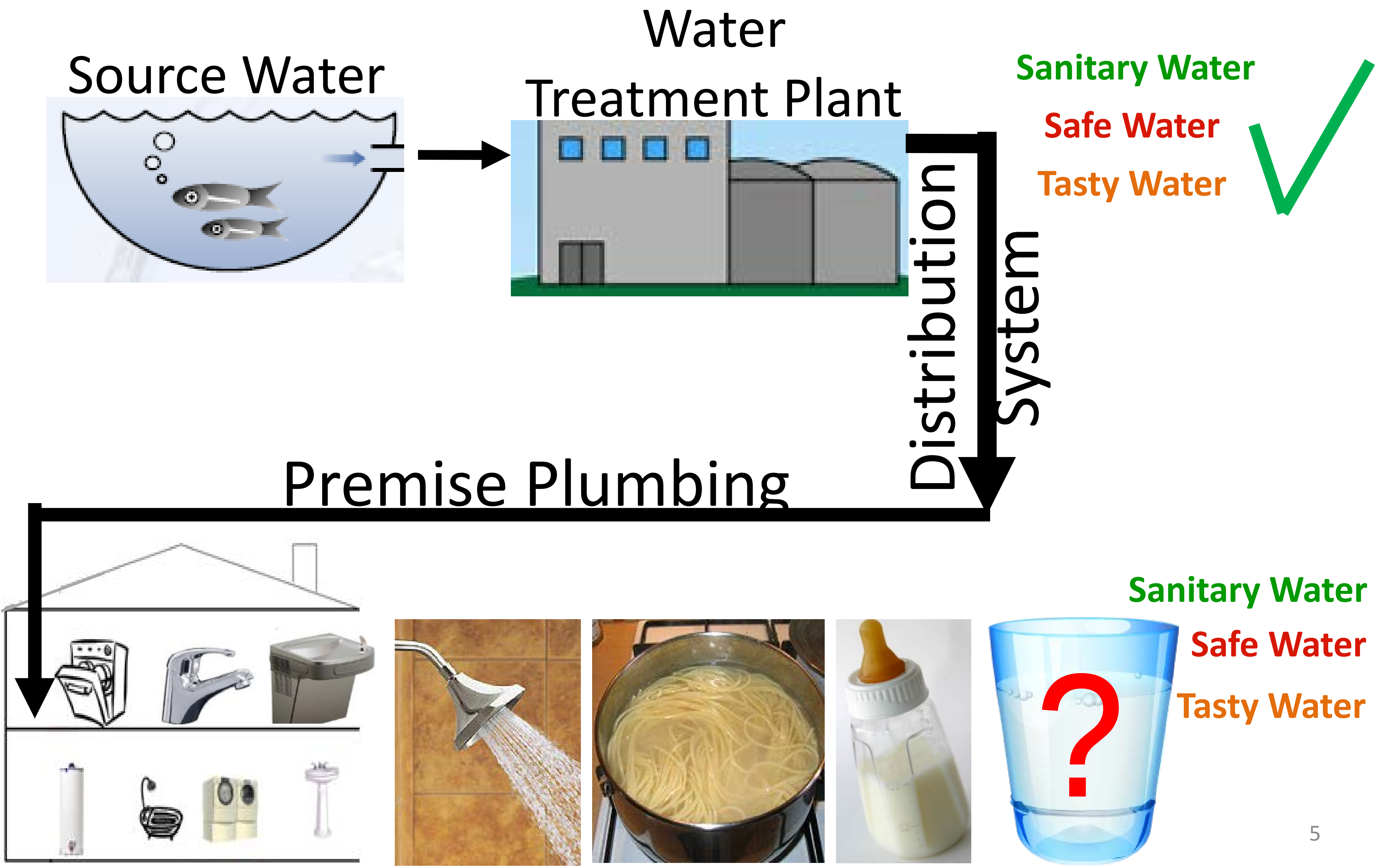
- DBPs/VOCs
- More Strict Criteria
- Water Quality

Tasty Water

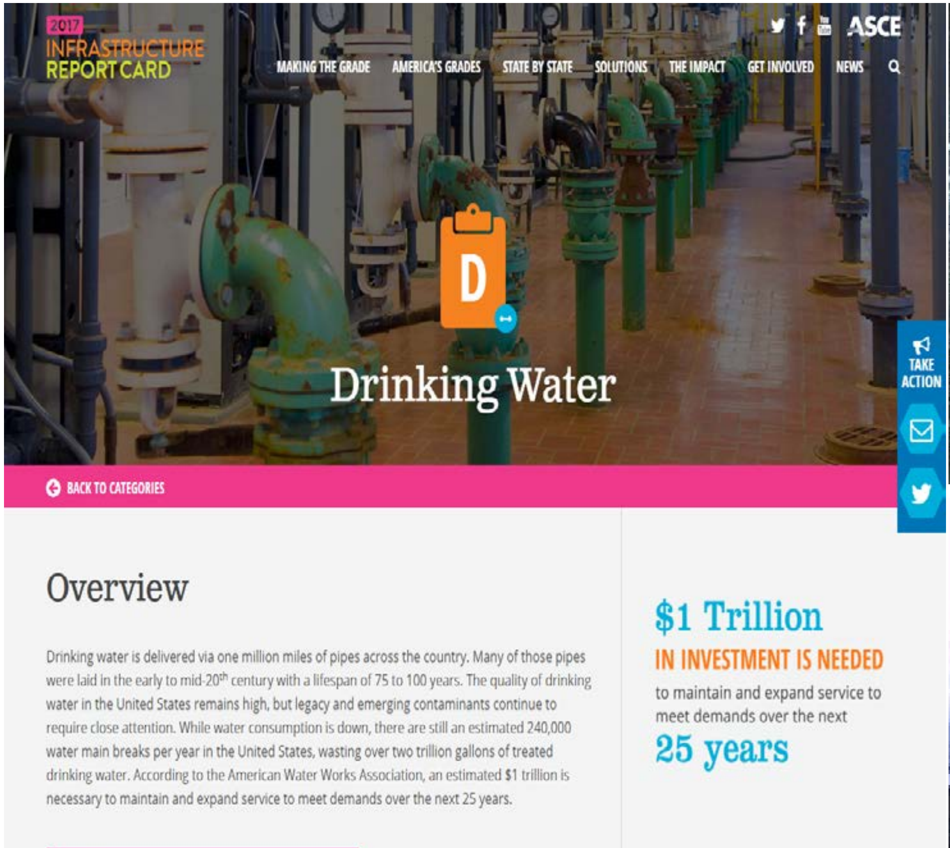
- Satisfying Consumer
- Aesthetics (Taste and Odor)
- Distribution System

Korean Ministry of Environment, modified by Jo, 2006

Drinking Water Quality AFTER treatment plant



Aging Main Distribution Systems in the US



http://www.infrastructurereportcard.org

Water Main Break
NACE, 2010

Clogged Iron Pipe due to corrosion
http://www.wrb.ri.gov

- Many DS reach or have exceeded their design lifetime
- Public health implications, resource and financial Implications

Premise plumbing challenges

<u>Every building is a dead-end</u>

- Variety of reactive pipe materials that interact with disinfectant and bacteria

  -PVC, PEX, Galvanized, Copper, Brass, Solder, Old Lead

- Variety of plumbing configurations, installation practices (good/bad), and maintenance (good/bad)

- Water use patterns affect ***Water Age***

  - Flow: Continuous Turbulent → Long Stagnation

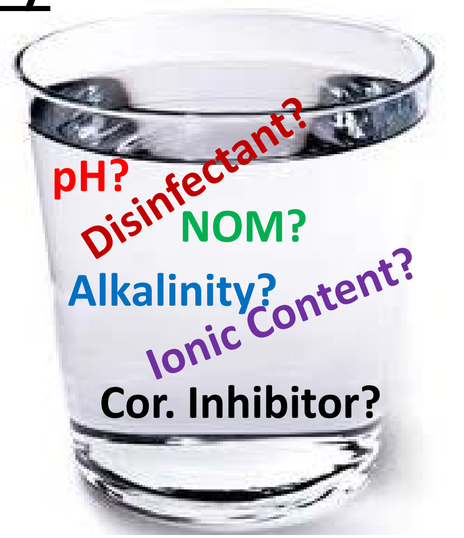
  - Temperature, Redox Potential, pH, Disinfectant Residual: Highly Variable

  - Microbes: Quantifiable diversity

modified from Marc Edwards

Premise plumbing challenges

<u>Chemistry of water affects end water quality</u>



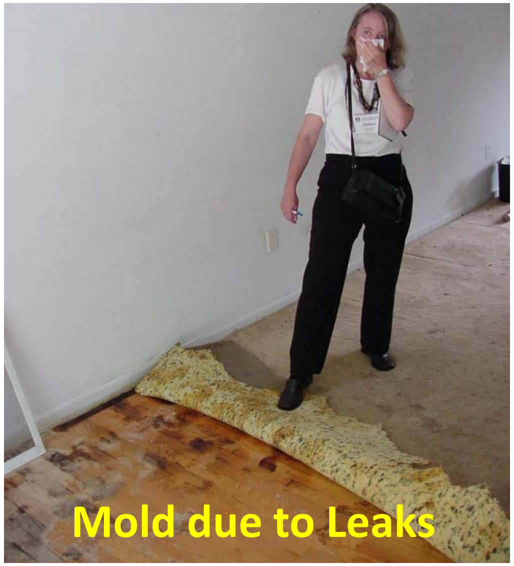
- All waters are different in terms of corrosivity and microbial re-growth potential, due to

1) Source water quality
2) Water treatment steps
3) Interaction with distribution system before building

- Water that is "aggressive" for corrosion or microbial growth for certain plumbing materials/configurations might be "harmless" to next door plumbing
  - **Variability** from building to building
  - **Variability** from tap to tap (hot spots)
  - **Variability** between **hot** and **cold** water from same tap

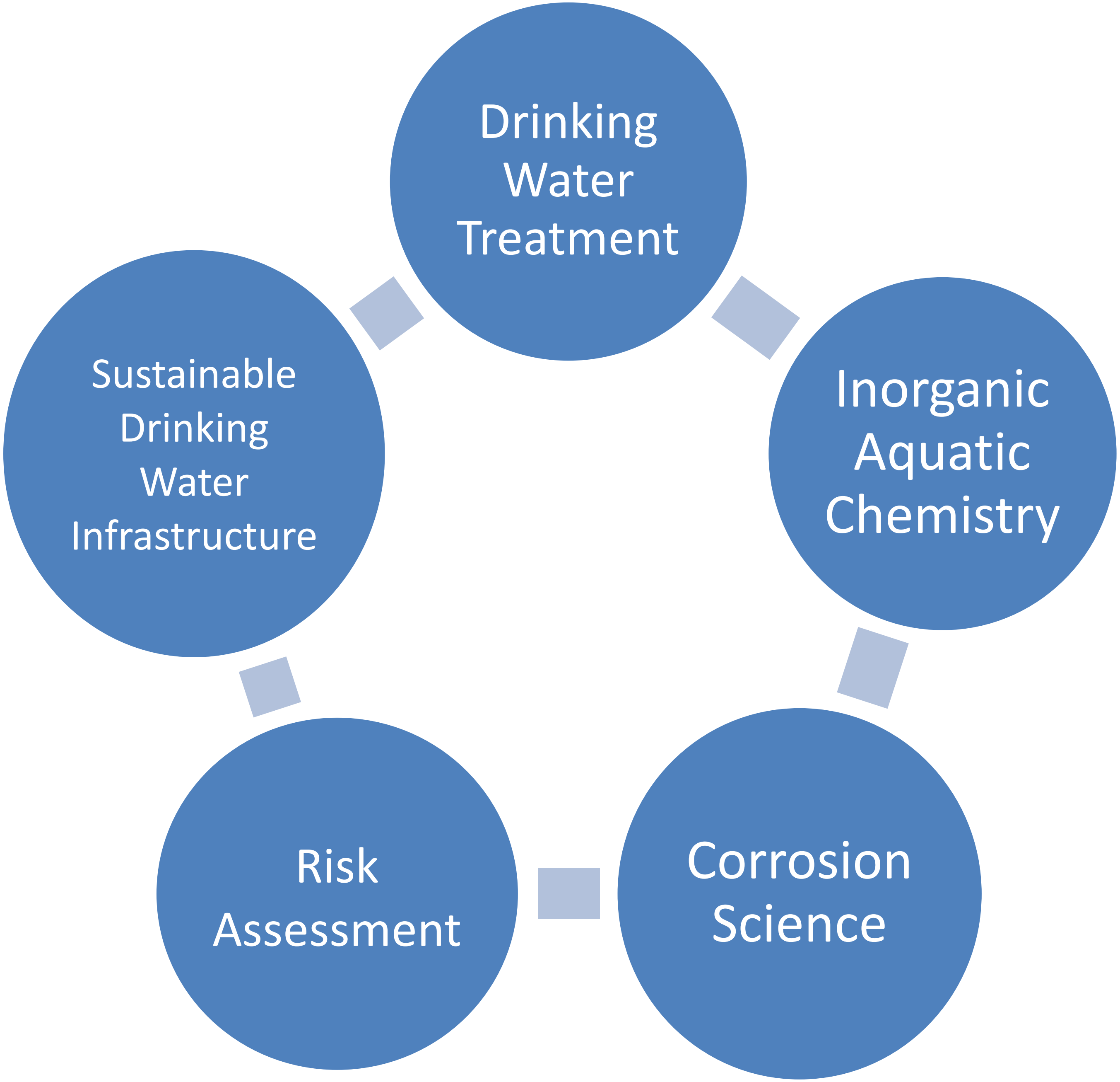
Protect water and public health from plumbing…

…Then protect plumbing from water



modified from Marc Edwards

Research Interests



Useful research tools

Visual & XRF plumbing inspection

Morphology and elemental mapping of particles in faucet aerator through SEM/EDS

Tap water collection

Analysis of water

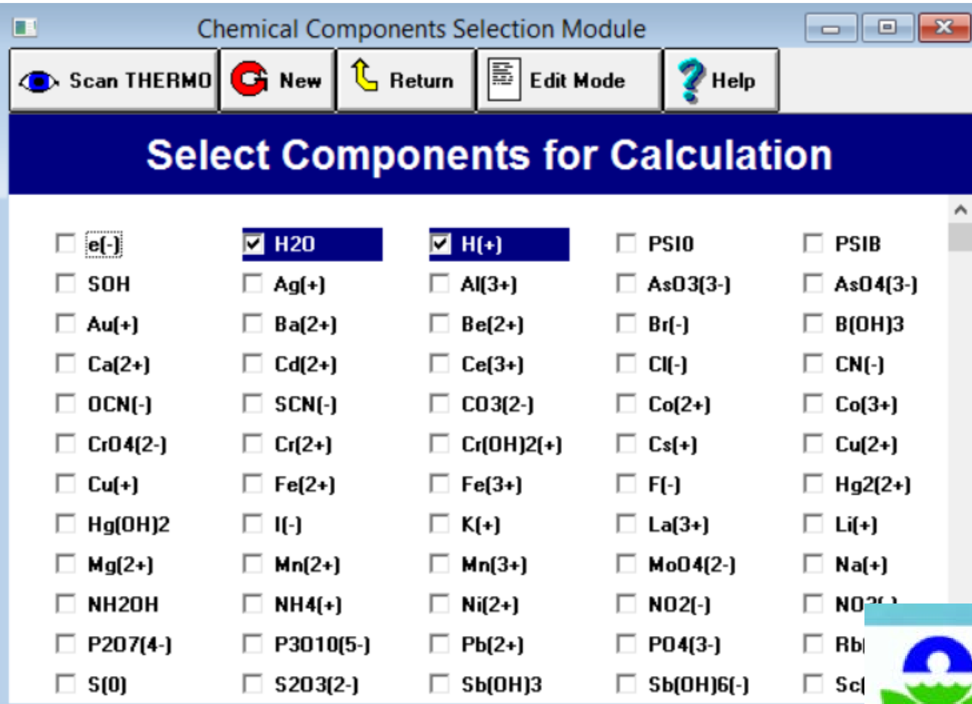
- pH, temp, chlorine, TDS
- Metals (ICP-MS)
- Chloride, sulfate, anions (IC)

Excavated lead pipe

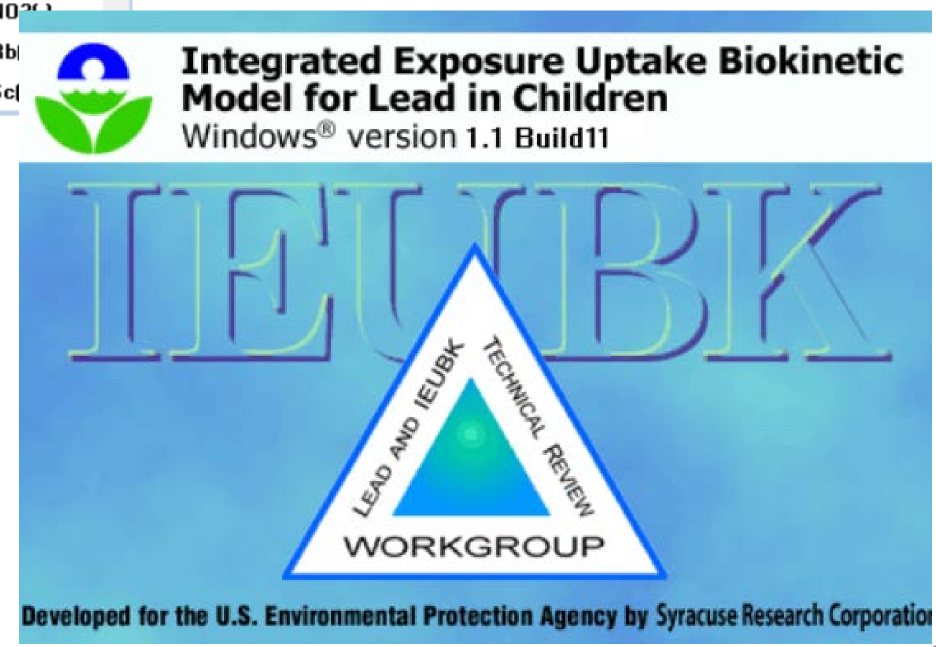
Lead scale harvesting

Analysis of scale mineralogy with XRD, SEM/EDS

Useful research tools

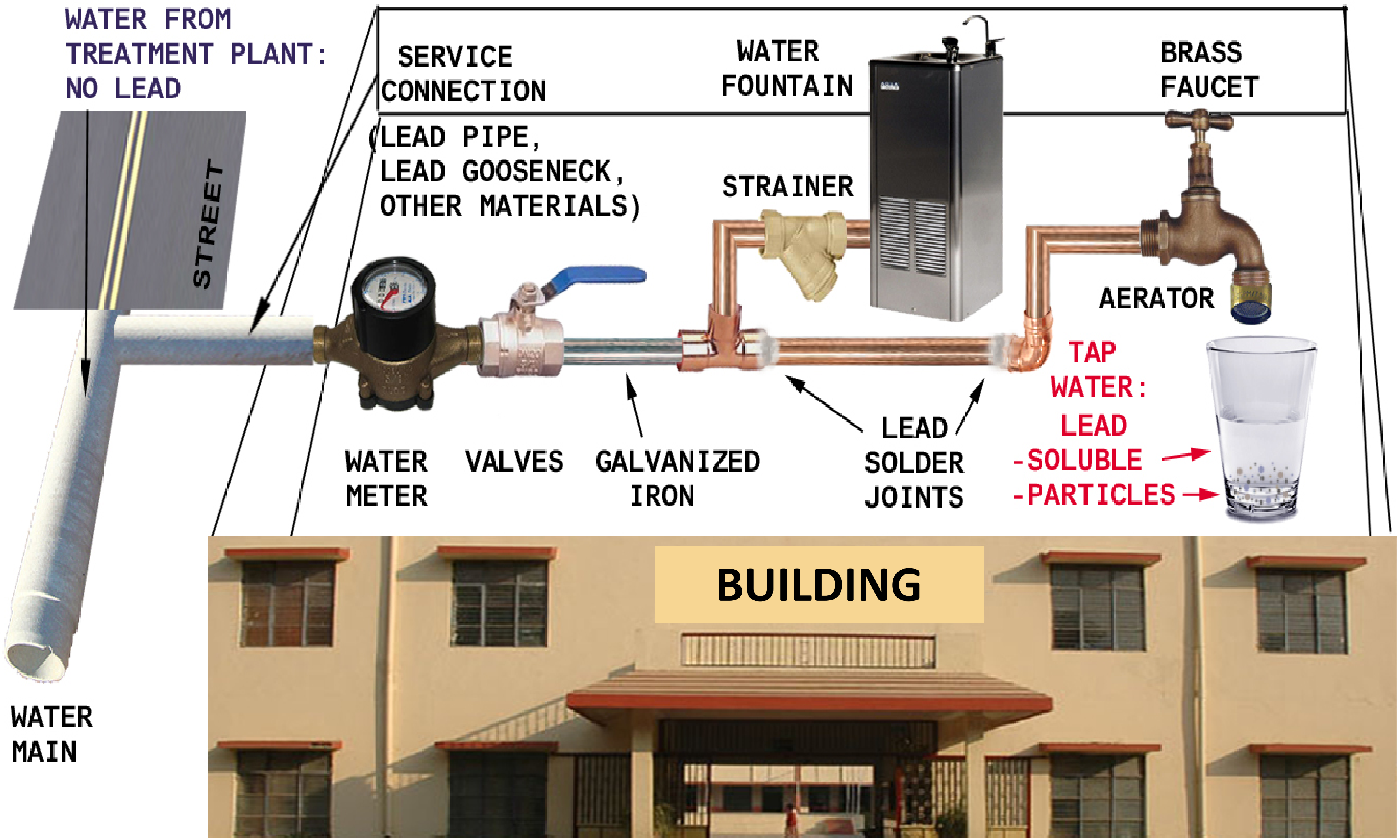


Chemical equilibrium modeling (e.g., Mineql+)



Blood lead modeling for children (e.g., IEUBK)

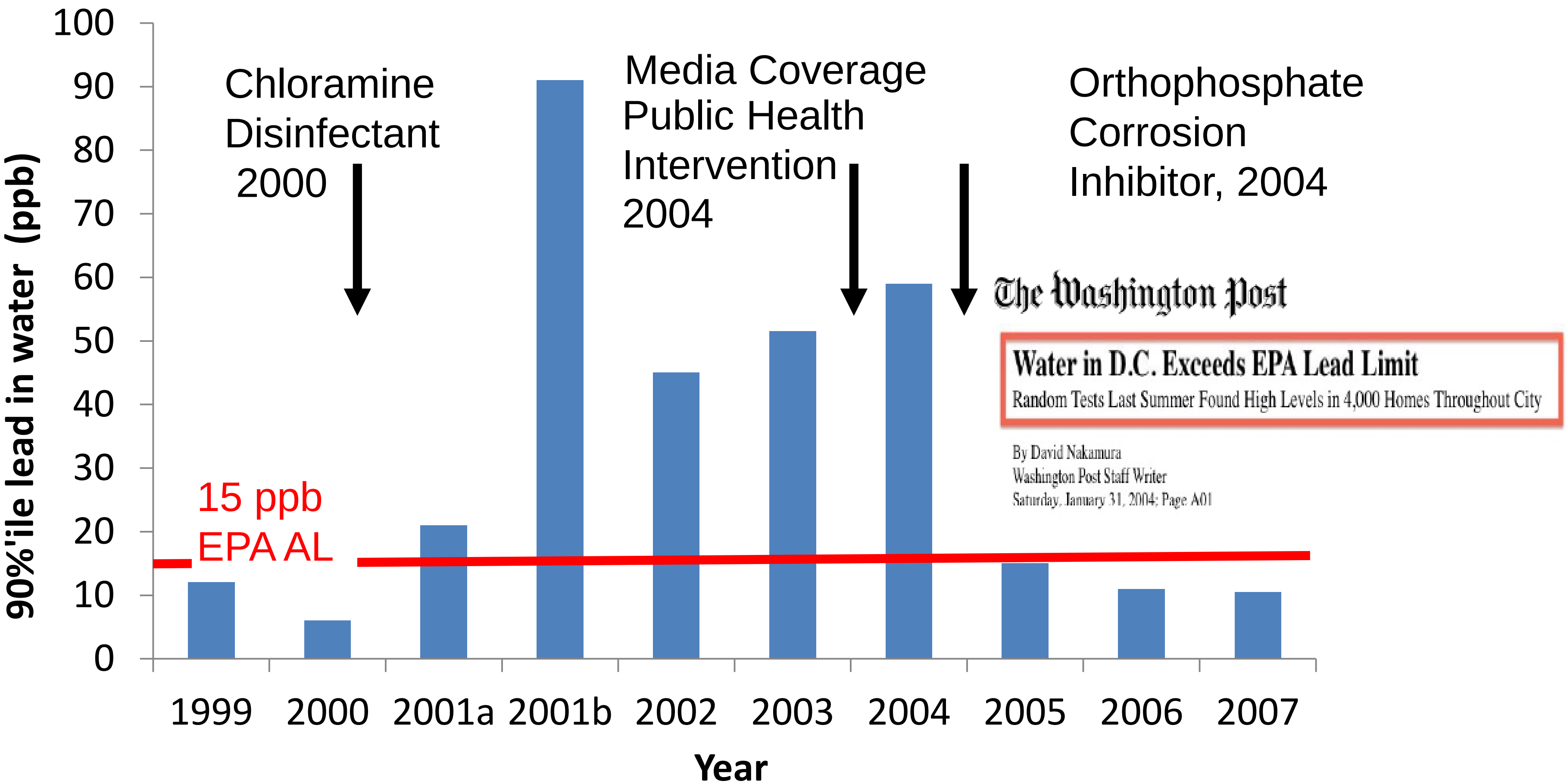
Much of US water safe, but problems remain



Triantafyllidou and Edwards, 2012

- Old Lead Pipe
- Old Leaded Solder
- Leaded Brass (valves, fittings, faucets, water fountains)

Washington DC “Lead-in-Water Crisis”



Environmental Science & Technology, 2009

Switch from chlorine to chloramine disinfectant dissolved lead from pipe scales

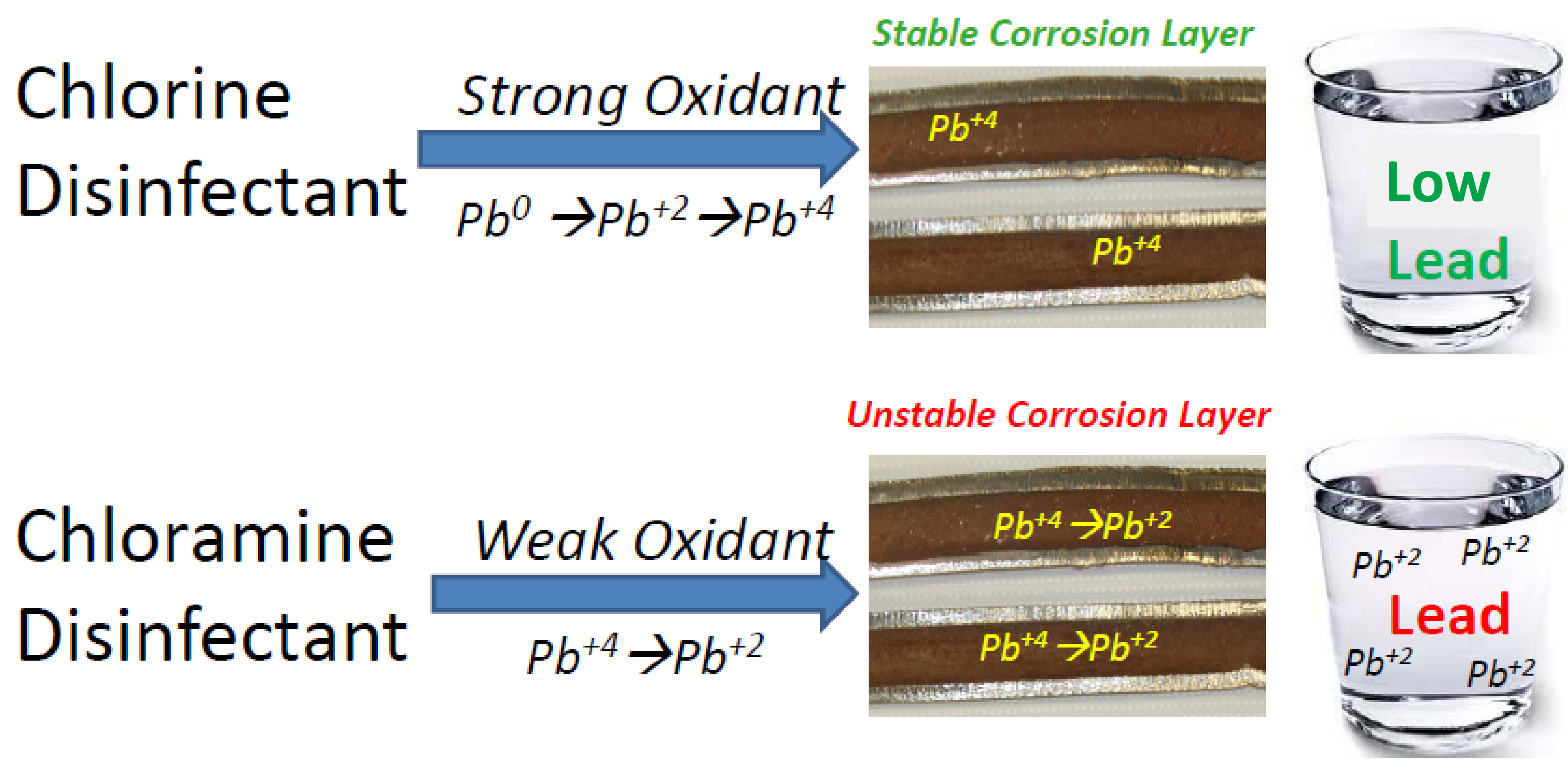


Photo of Cut Lead Service Line from M. Schock

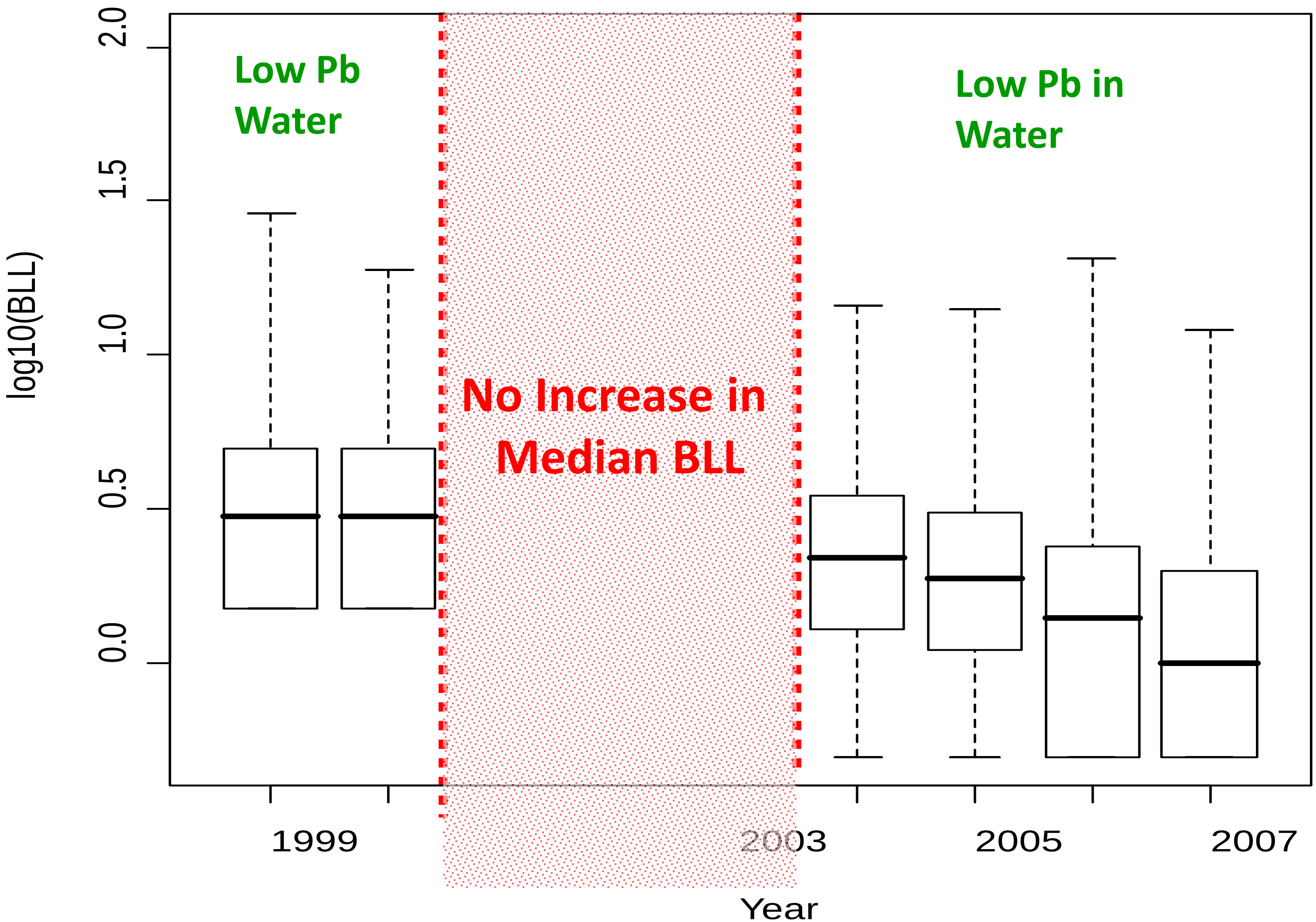
Blood Lead Level (BLL) Database

Children's National Medical Center

Birth Date	ZIPCODE	Collect Date	BLL
1/27/1997	20011	1/27/1999	<3
6/16/1997	20010	9/7/1999	9
10/19/1998	20011	9/7/2000	5
.	.	.	.
.	.	.	.
.	.	.	.
12/24/2005	20011	3/19/2007	<1.0
3/18/2005	20011	8/30/2007	12

N > 28,000

Compare Median BLL / All Children / City-wide



Same Data Revisited

- **Compare incidence of elevated blood lead** (*Moore et al., 1977)*

  % children with BLL > 10 ug/dL

- **Perform "neighborhood analysis"** (*Brown et al., 2001)*

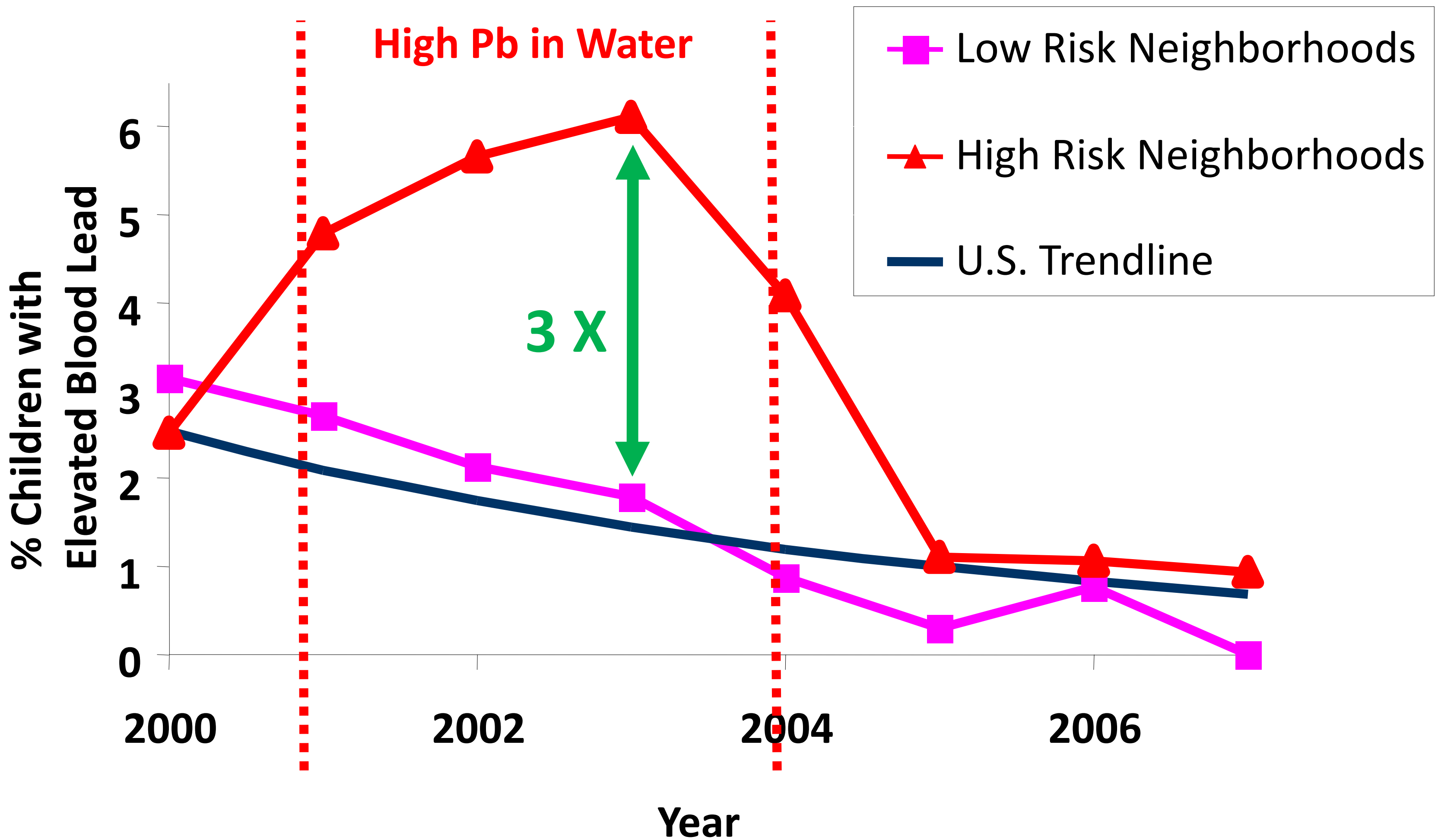
  Compare "High" vs. "Low" Risk neighborhoods, based on:

  1) prevalence of lead pipe

  2) elevated lead in water

- **Focus on sensitive sub-group** (*WHO, 2000)*
  Children ≤ 30 months of age

Compare % EBL / Zip Code Level / Children ≤ 30 months



Environmental Science & Technology, 2009

Results published in *ES and T* in 2009

Washington Post followed up

Environ. Sci. Technol. 2009, 43, 1618–1623

Elevated Blood Lead in Young Children Due to Lead-Contaminated Drinking Water: Washington, DC, 2001–2004

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Received October 2, 2008. Revised manuscript received January 13, 2009. Accepted January 16, 2009.

Incidence of EBL (blood lead ≥ 10 μg/dL) for children aged ≤1.3 years in Washington, DC increased more than 4 times comparing 2001–2003 when lead in water was high versus 2000 when lead in water was low. The incidence of EBL was highly correlated ($R^2 = 0.81$) to 90th percentile lead in water lead levels (WLLs) from 2000 to 2007 for children aged ≤1.3 years. The risk of exposure to high water lead levels varied markedly in different neighborhoods of the city. For children aged ≤30 months there were not strong correlations between WLLs and EBL, when analyzed for the city as a whole. However, the incidence of EBL increased 2.4 times in high-risk neighborhoods, increased 1.12 times in moderate-risk neighborhoods, and decreased in low-risk neighborhoods comparing 2003 to 2000. The incidence of EBL for children aged ≤30 months also deviated from national trends in a manner that was highly correlated with 90th percentile lead in water levels from 2000 to 2007 ($R^2 = 0.83$) in the high-risk neighborhoods. These effects are consistent with predictions based on biokinetic models and prior research.

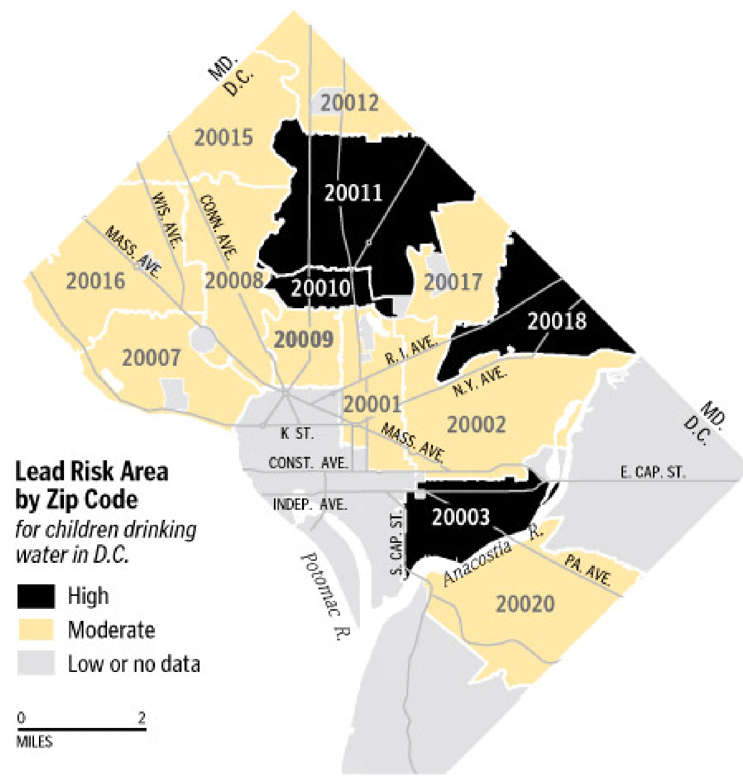
the CDC level of concern are termed "elevated blood lead" (EBL) in this work.

A close examination of the two prior studies reveals noteworthy limitations. Neither study focused on infants, who are most vulnerable to harm from lead in water (*5–7*) due to their small body weight and heavy reliance on water as a major component of their diet in the case of infants using reconstituted formula. Moreover, both studies lumped all the blood lead data for Washington, DC together, an approach that can "mask disparities among communities and camouflage pockets of high risk" relative to smaller area analysis at the neighborhood or zip code level (*8*). This research addressed these limitations.

Methodology and Data

Environmental Data. *Water Lead Data.* Measurements of "total lead (*9*)" in potable water were collected by the local water utility using EPA-approved methodology. A "first draw" sample refers to a 1 L sample collected from a tap after greater than 6 h holding time in the household plumbing. After first draw samples are collected, water is flushed for a short time period (typically 30 s to 5 min) and a 1 L "second draw" sample is collected.

Two data sets of potable water lead concentrations were used throughout this research. Data on WLLs in homes with lead pipe during 2003 were collected by the local water utility from over 6000 Washington, DC homes with lead service line pipe. The WLL EPA Monitoring Data (2000–2007) were collected by the water utility specifically for compliance with EPA regulations. Compliance is determined by using the "90th percentile lead," which is the 90th percentile of the cumulative distribution of first draw lead samples collected within a given time period. The monitoring data were reorganized into calendar year time periods for which corresponding blood lead measurements were compiled. For example, the official 2002 EPA monitoring round at the utility included water samples collected between July 1, 2001 and June 30, 2002. The samples collected between July 1, 2001 and December 31, 2001 from that round were used in calculations of the 90th percentile WLLs for the second half of 2001. The



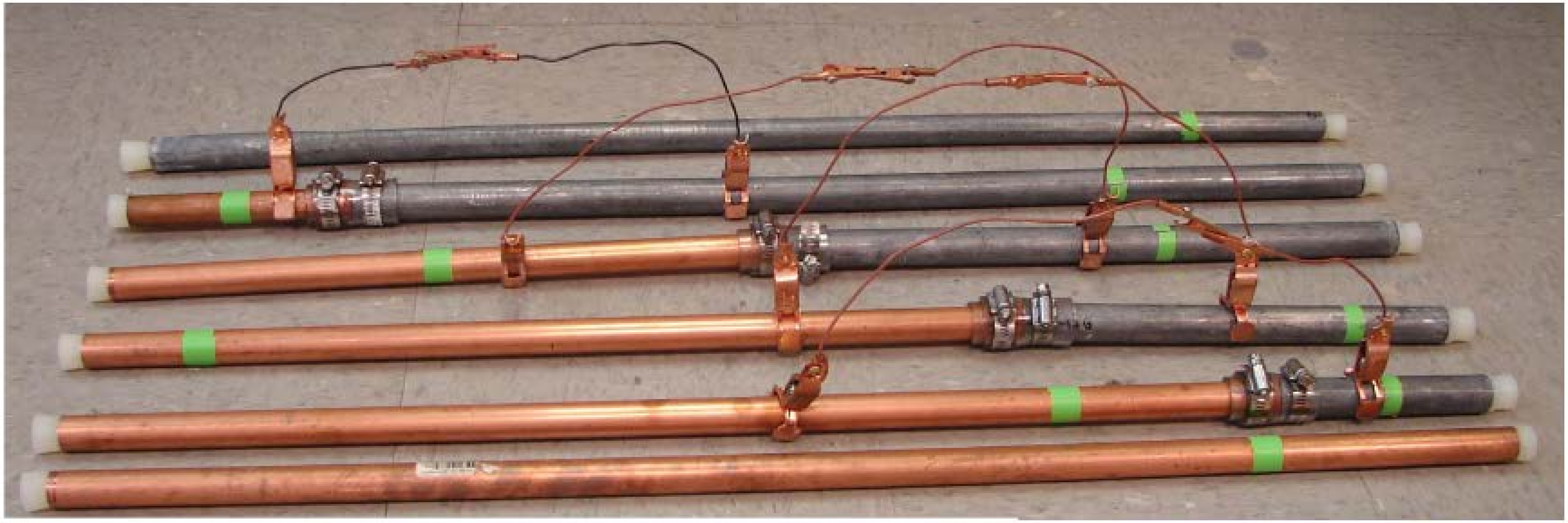
Best paper of 2009 Award
Science category, Editor's choice

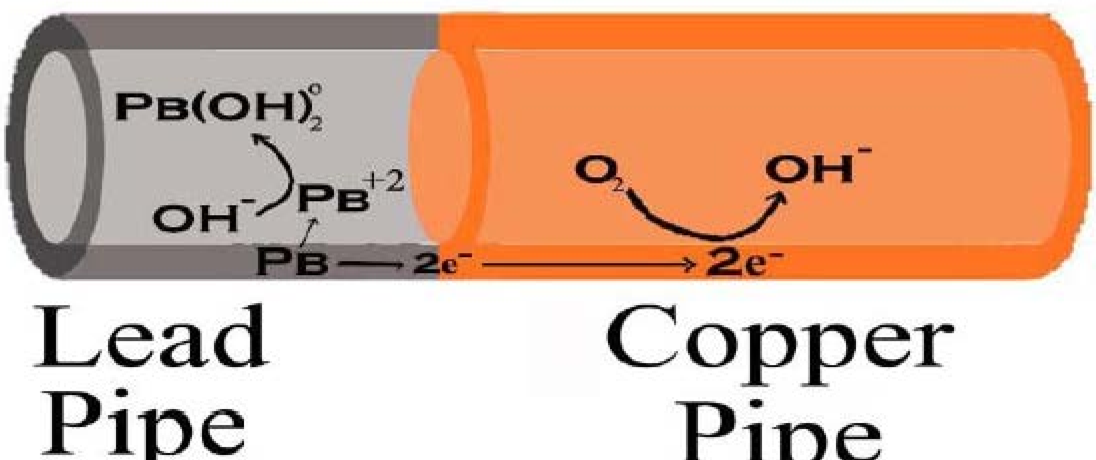
http://www.washingtonpost.com/wp-dyn/content/graphic/2009/01/27/GR2009012700721.html

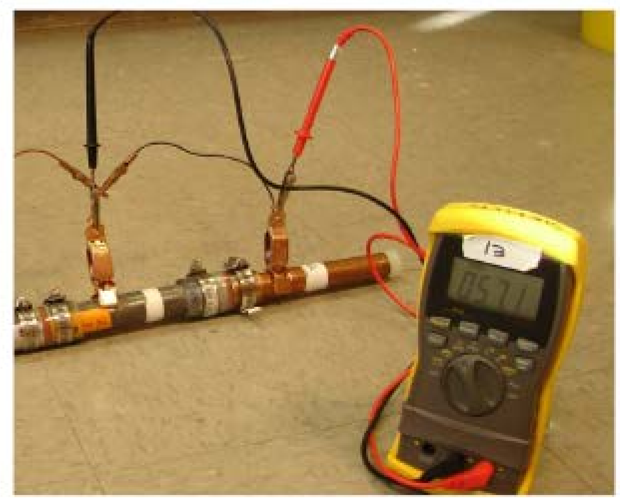
Conclusion

- Elevated lead in tap water can contribute or even cause elevated lead in blood of children, in cases of sub-optimal corrosion control at the presence of leaded plumbing

Galvanic Corrosion after Simulated Small-Scale Partial Lead Service Line Replacements

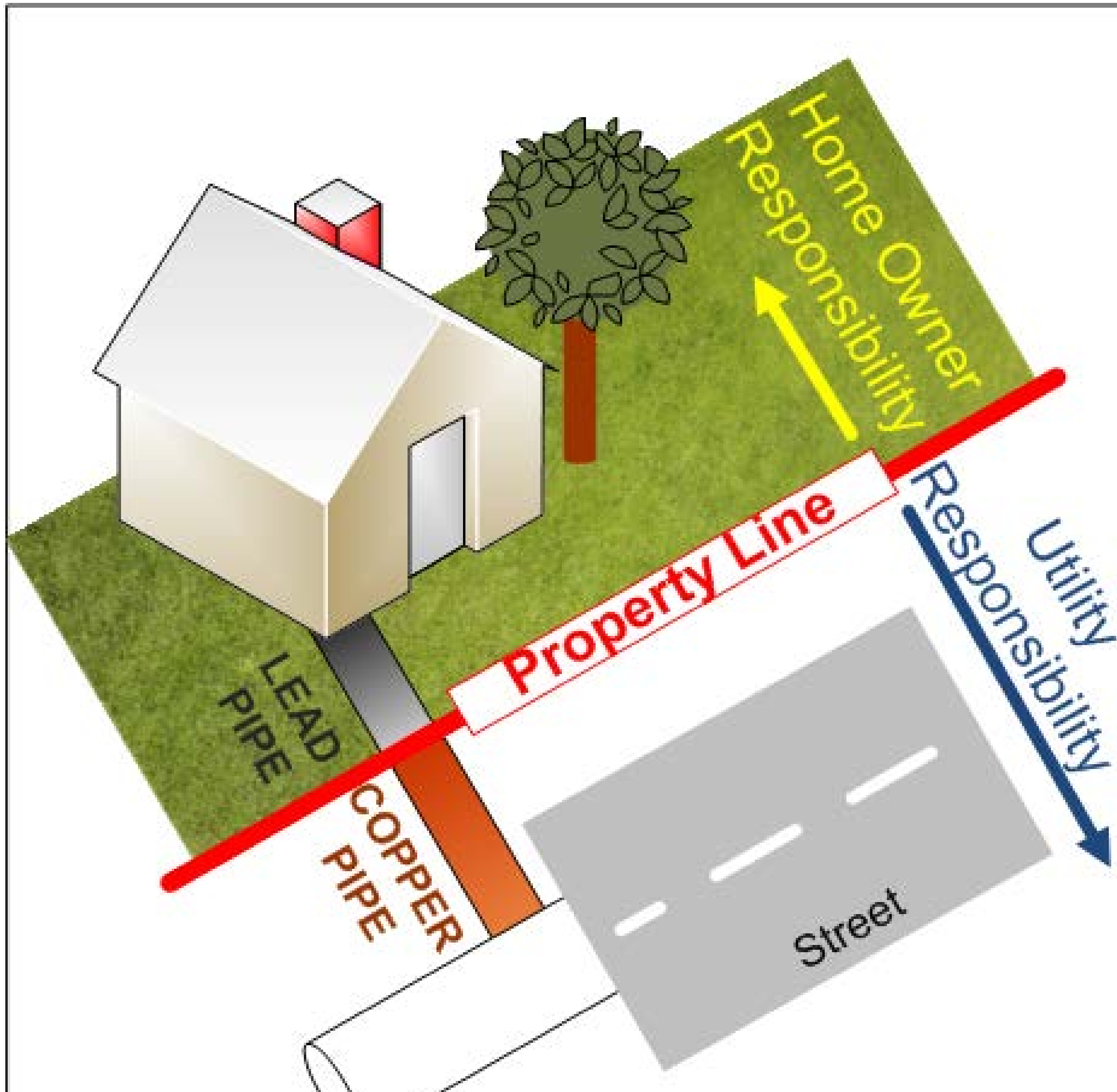




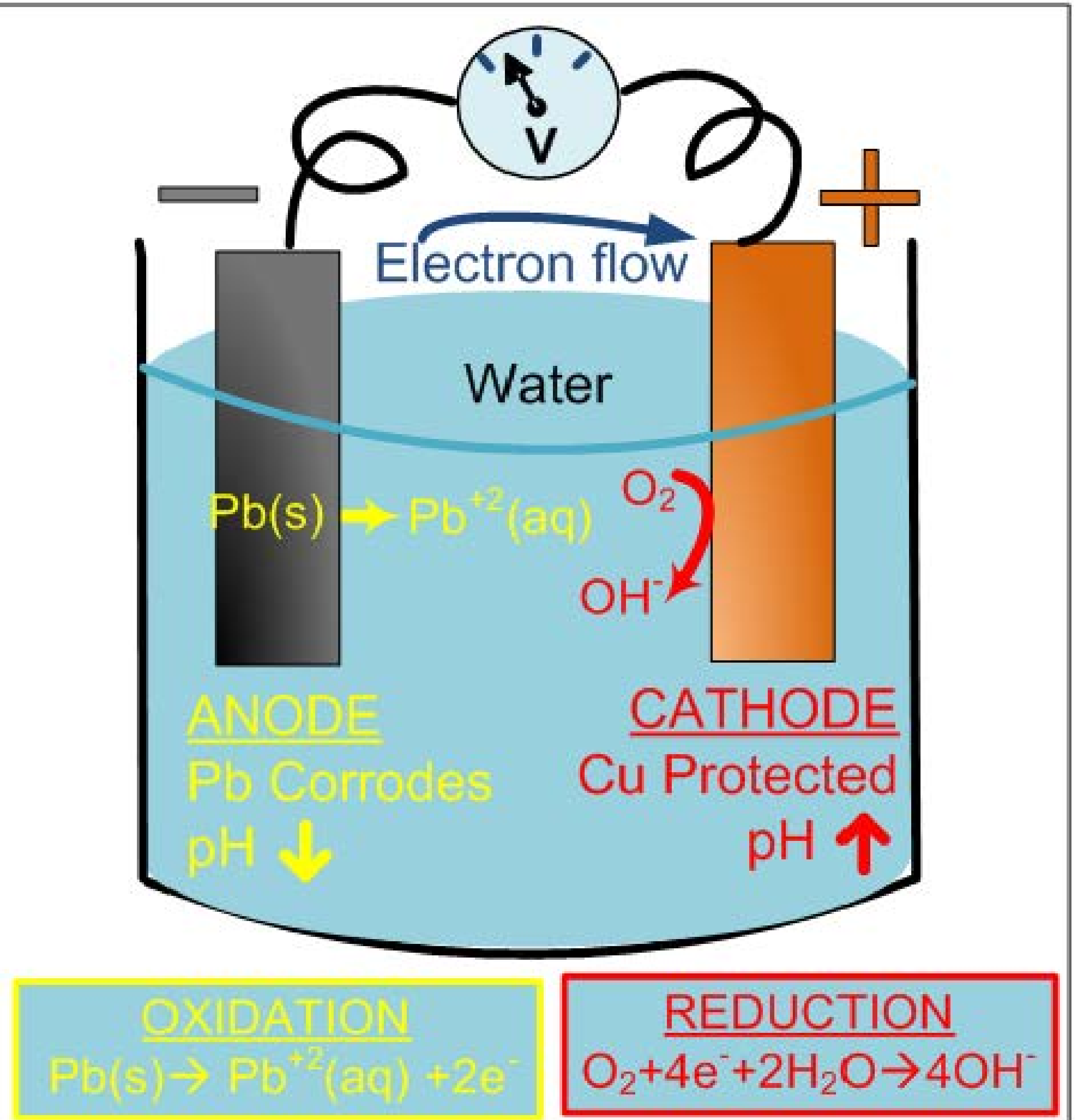


Partial Lead Service Line Replacement (PLSLR)

- 3.3 - 6.4 million US homes with old lead service lines or connections (Weston and EES, 1990)
- Contribute to 50 – 75 % of the lead in drinking water (Sandvig et al., 2008)
- Partial replacement with copper pipe mandatory remedial measure to meet water lead regulation



Journal AWWA, 2011



Galvanic Corrosion

- Electrochemical (galvanic) cell between copper and lead pipe
- Drinking water serves as electrolyte
- Galvanic corrosion may accelerate corrosion of the lead pipe

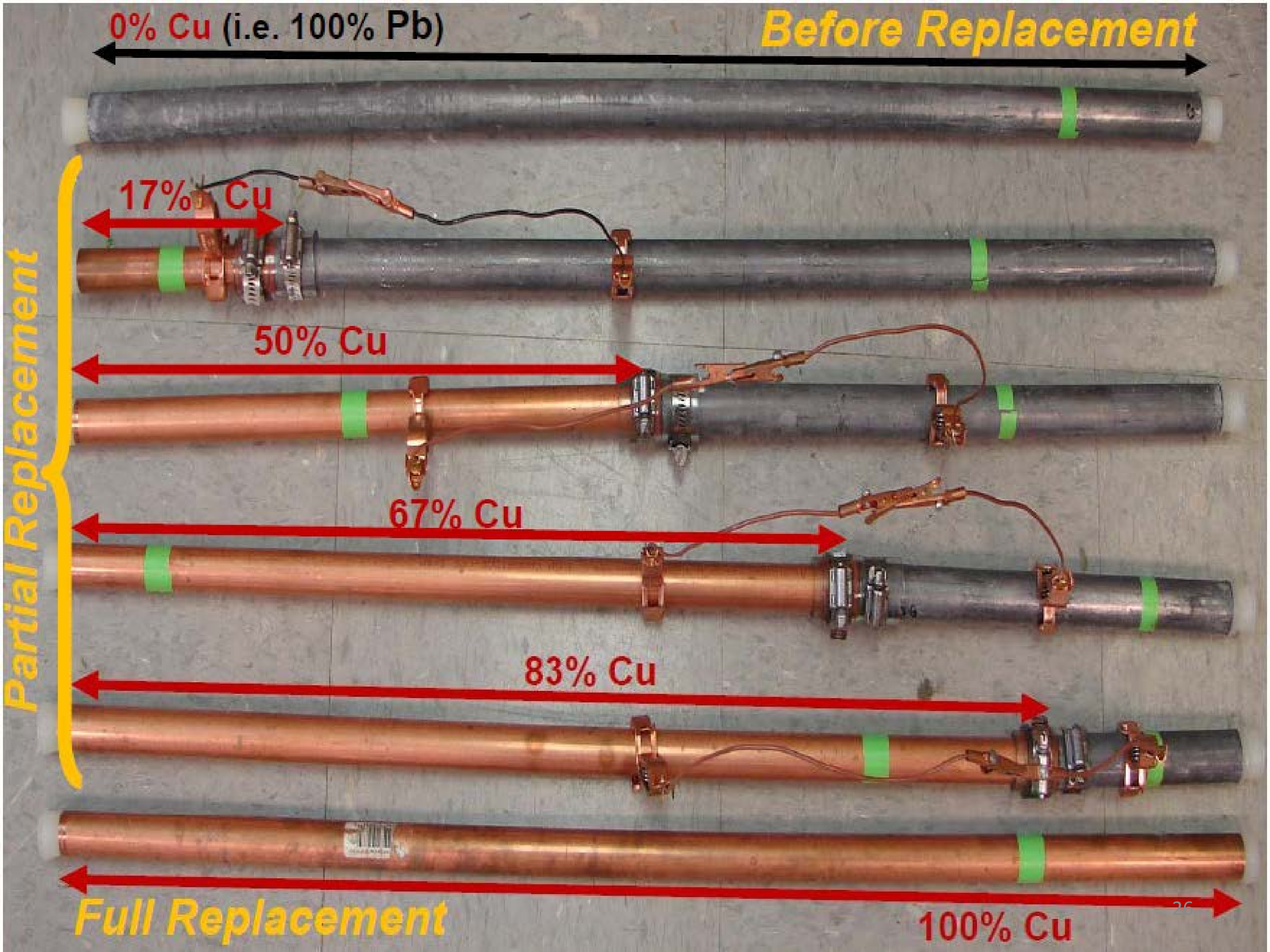
Water chemistry can turn on/off galvanic corrosion: CSMR

English studies first introduced the CSMR as a factor controlling galvanic corrosion in connections of lead solder/copper

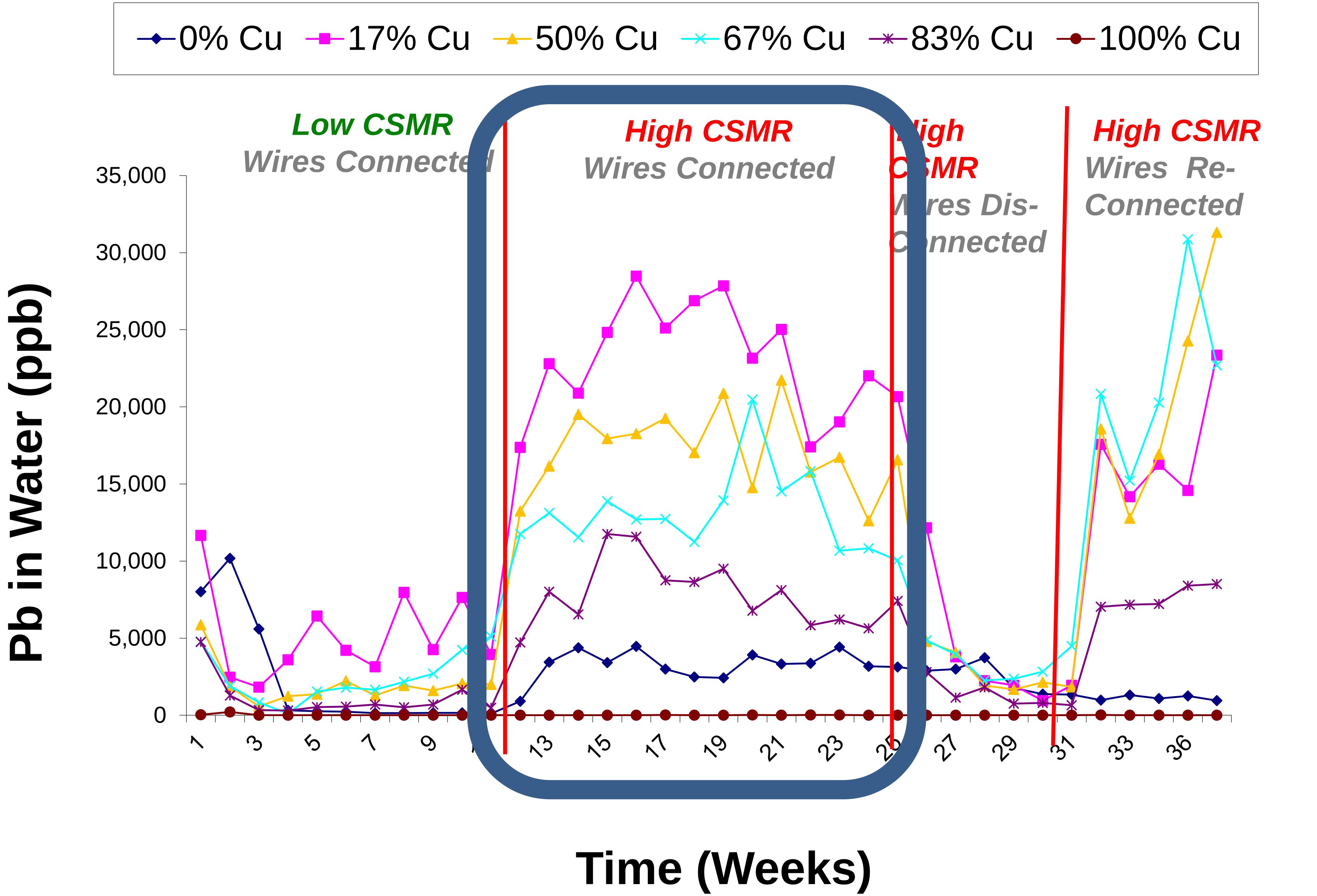
Oliphant (1983) and Gregory (1985)

Example calculation:

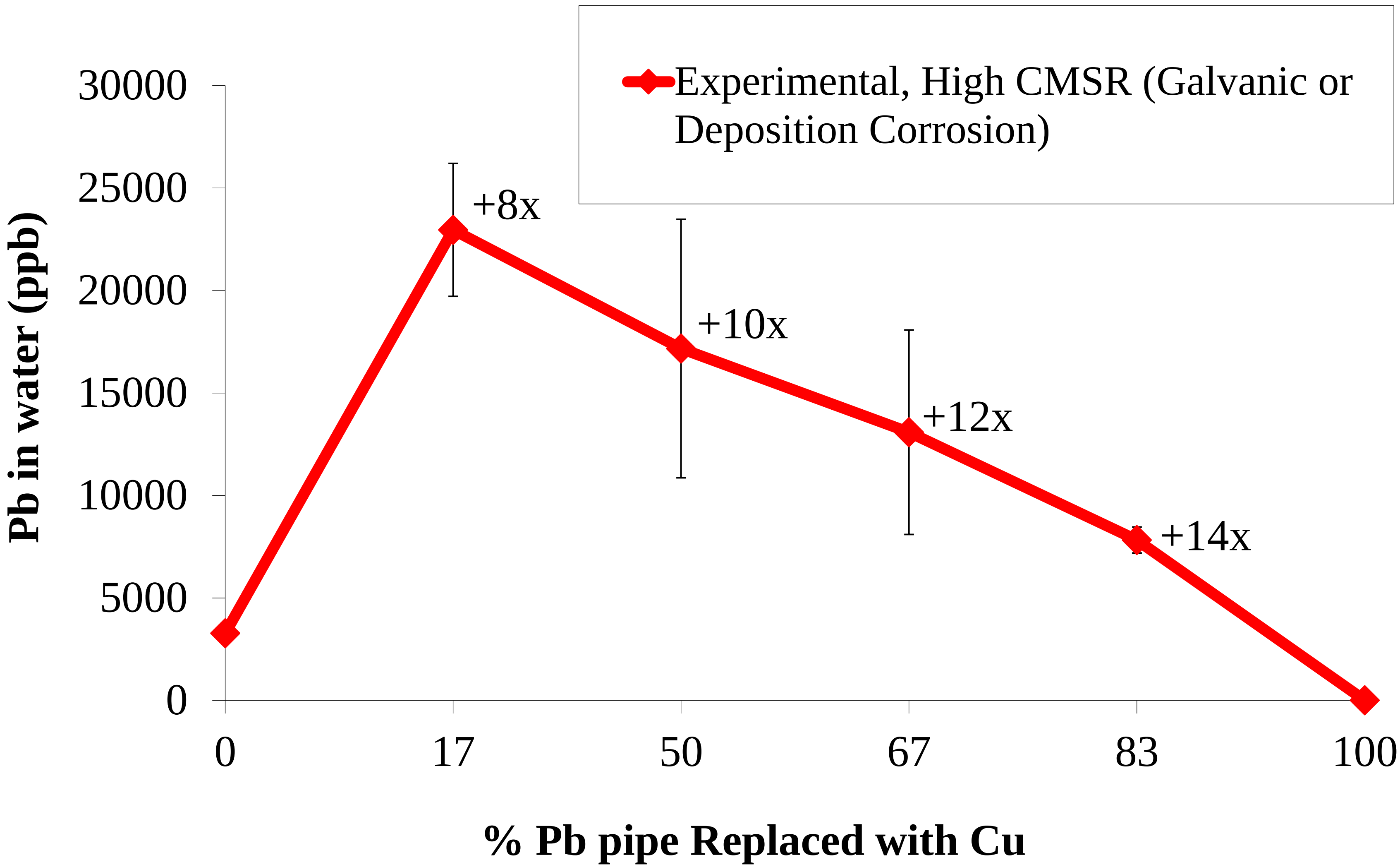
$$\text{Chloride to Sulfate Mass Ratio (CSMR)} = \frac{[Cl^-]}{[SO_4^{-2}]} = \frac{12 \text{ mg/L } Cl^-}{20 \text{ mg/L } SO_4^{-2}} = 0.6$$


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

Experimental Results



Experimental Results

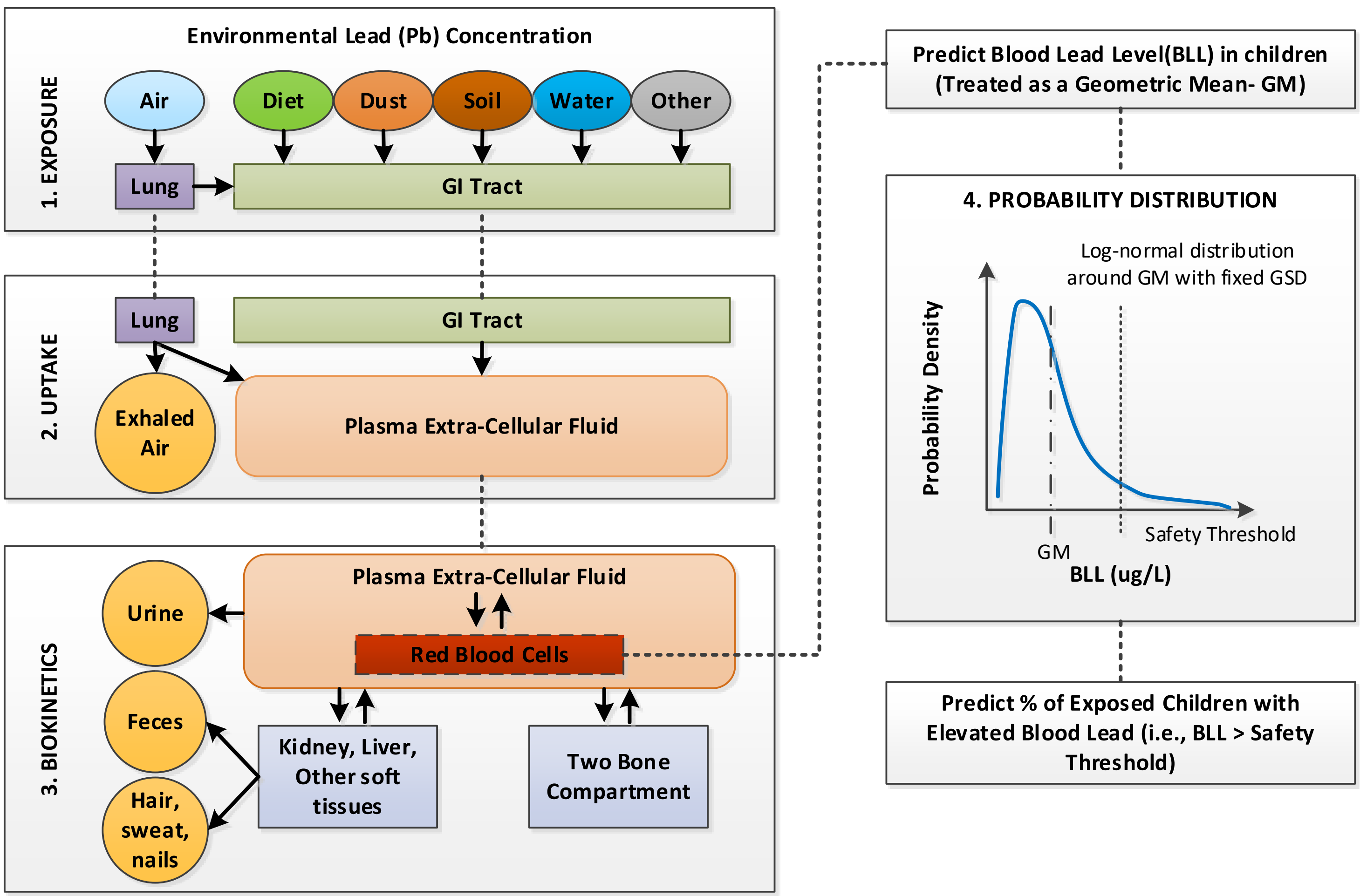


Journal AWWA, 2011

Conclusions

- Galvanic connections between copper pipe and lead pipe worsened lead release, compared to lead pipe alone
- High CSMR water released much more lead to the water than did low CSMR: Water chemistry affects the galvanic battery
- High CSMR produced high sustained galvanic currents between lead and copper (not presented here)

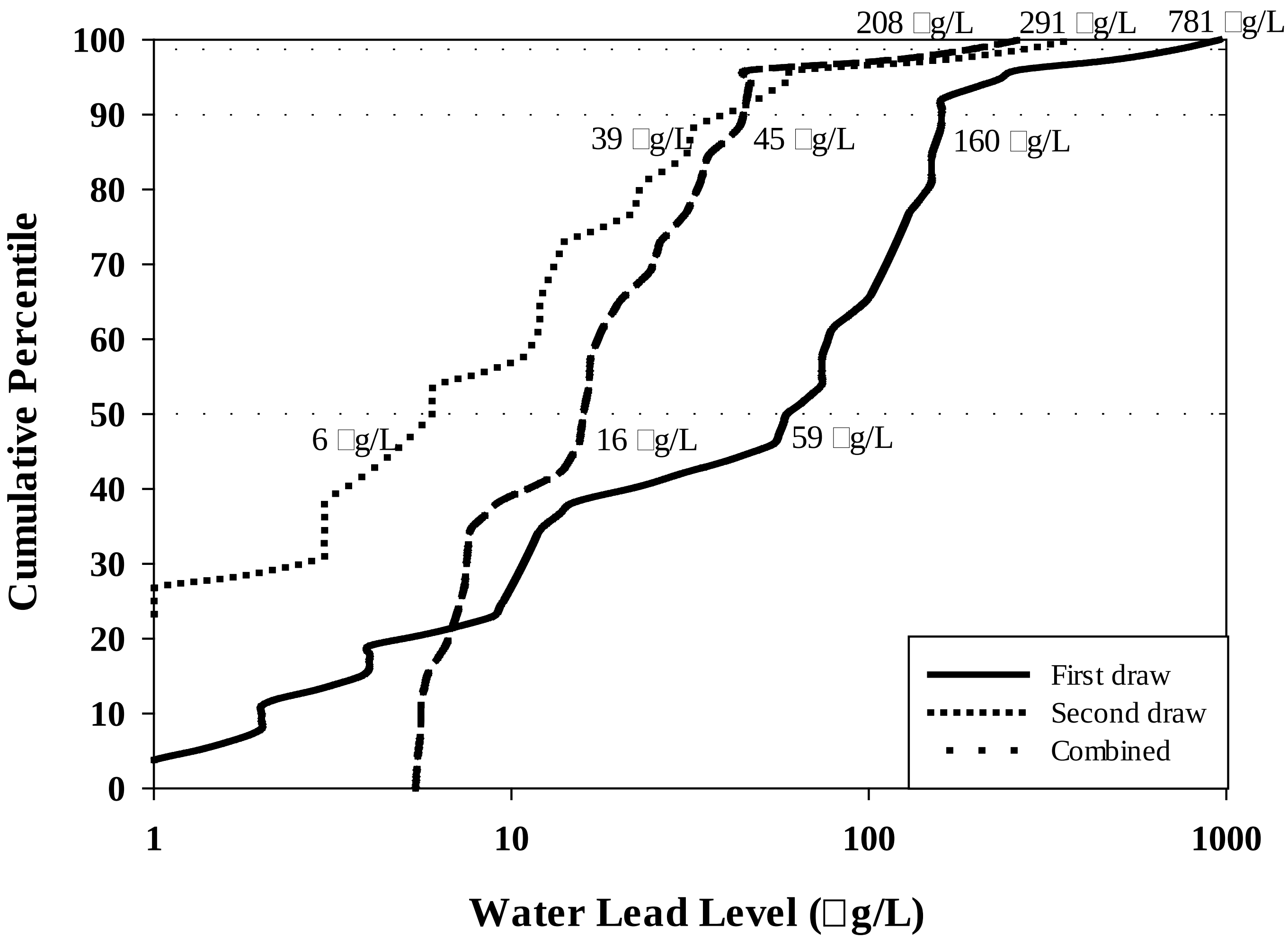
Biokinetic modeling to predict blood lead levels from water lead exposure



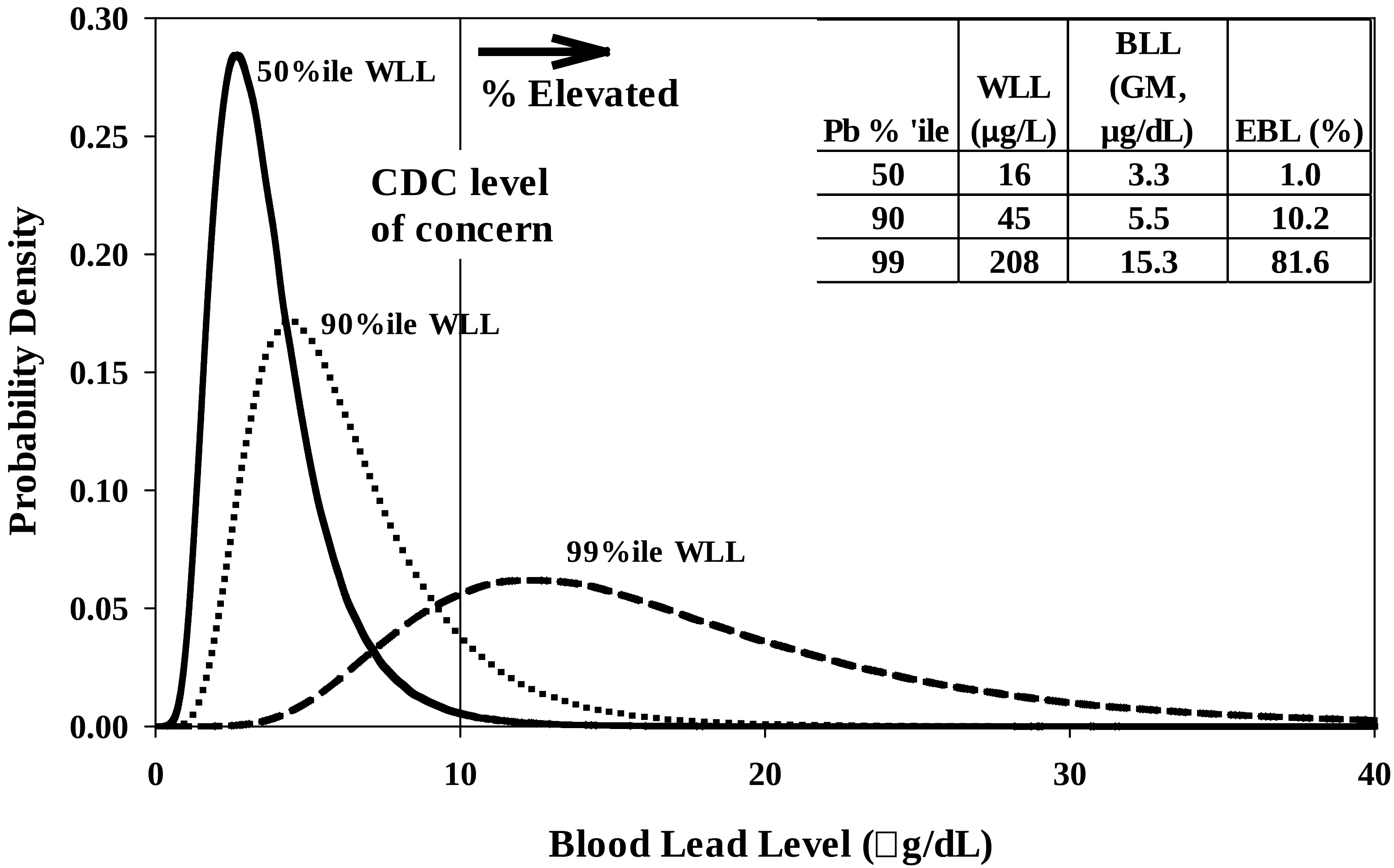
Two school districts with water lead problems

	Seattle Public Schools (SPS)	Los Angeles Unified School District (LAUSD)
Elementary Schools Sampled	63 (~3,100 taps)	601 (~51,000 taps)
Dates	Pre: 2004, Post: 2011-12	2008-2009
Range of Lead Detected, µg/L	<1 - 1,600 first-draw <1 – 370 flushed	0.2 - 13,000 first-draw 0.2 - 7,400 flushed
% school taps > 20 µg/L pre	19% of first-draw 3% of flushed (30 sec)	6% of first-draw 1% of flushed (30 sec)
pre / post RA?	Yes / No	No / No

Model Input: Combined WLL for one Seattle School, pre-remediation

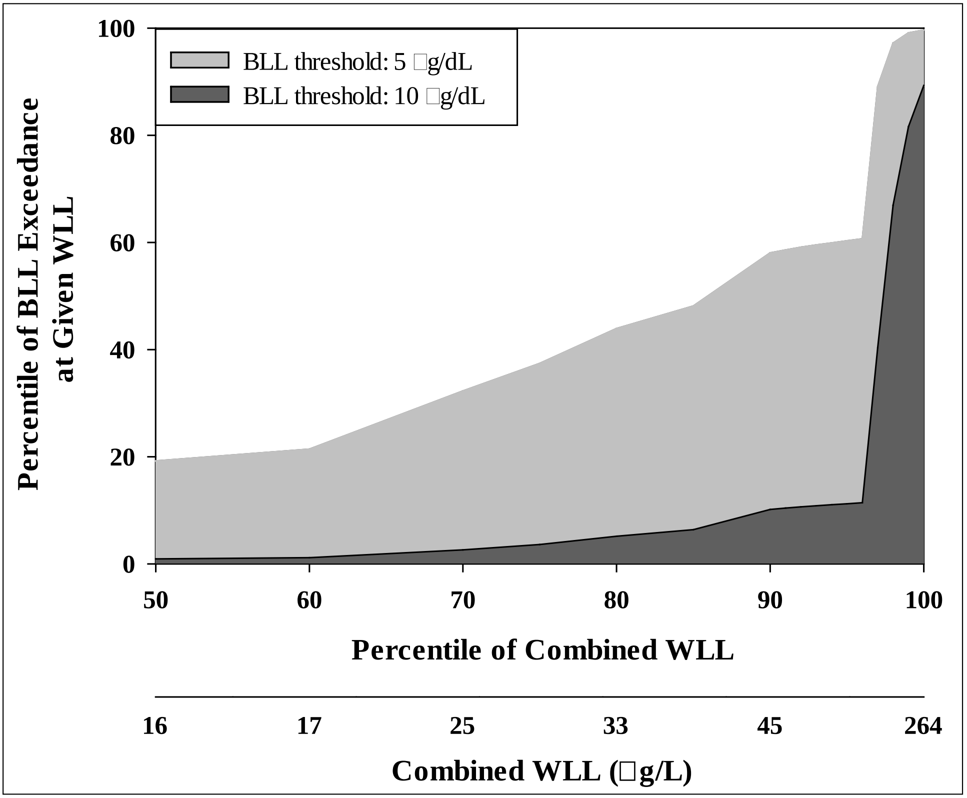


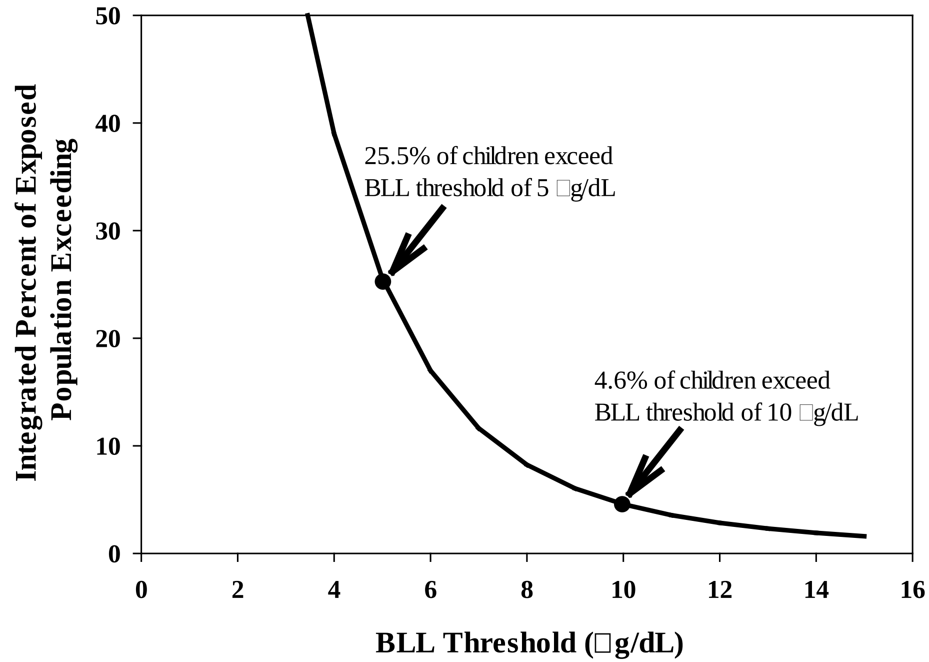
Probability Distributions of BLL, 10 ug/dL threshold



Pb % 'ile	WLL (µg/L)	BLL (GM, µg/dL)	EBL (%)
50	16	3.3	1.0
90	45	5.5	10.2
99	208	15.3	81.6

Predicted percentage of children with elevated blood lead



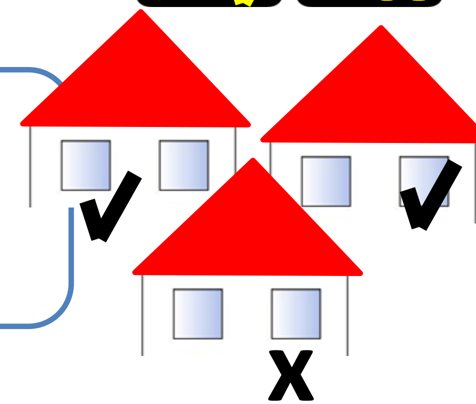


Science of the Total Environment, 2014

Conclusions

- Variability among fountains within a school

- Variability in water lead contamination among schools receiving the same water



- Accounting for variability in water lead levels, variability in children's response and stringent new public health goals predicted blood lead elevations for most sensitive or most exposed children to water lead

Hospitals also deserve increased attention

- A 2011 outbreak of hospital-acquired pneumonia in Pittsburg, from waterborne *Legionella* bacteria, caused
  - Several fatalities and lawsuits
  - Congressional investigation
  - Extensive press coverage and criticism
  - Closer look at microorganisms in hospital water

TV: CNN | CNNI | CNN en Español | HLN

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VA under scrutiny after Legionnaires' cases in Pittsburgh

By **Nelli Black** and **Drew Griffin**, CNN
updated 6:23 PM EST, Fri December 14, 2012

Pittsburgh, Pennsylvania (CNN) -- Twenty-nine patients at the Veterans Administration hospital in Pittsburgh have been diagnosed with Legionnaires' disease since January 2011, raising questions about the institution's safety practices.

Five of the cases "are known to have acquired the disease from the hospital," the VA said. Another eight were infected elsewhere, and the source of the infection in 16 cases cannot been determined.

The spate of illnesses has led relatives of two veterans who died after contracting the disease, a type of pneumonia, to blame the hospital.

http://www.cnn.com/2012/12/13/health/legionnaires-hospital-water/

In-building disinfection

→ Thermal disinfection

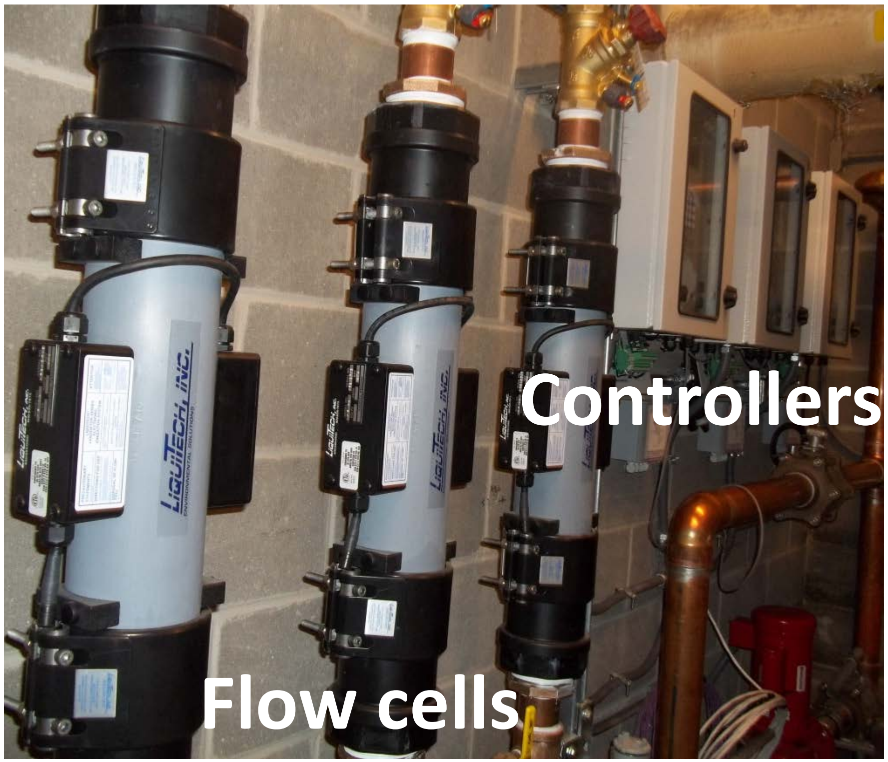
Example: ASHRAE Guideline 12-2000

- Water always stored at > 60°C in water heater
  > 51°C in hot water lines
- Different instructions after outbreaks or for periodic thermal disinfection

→ Chemical Disinfection

- Chlorine
- Chloramine
- Chlorine dioxide
- Copper-silver ionization
- UV irradiation
- Ozone

Copper-Silver Ionization (CSI) is one option

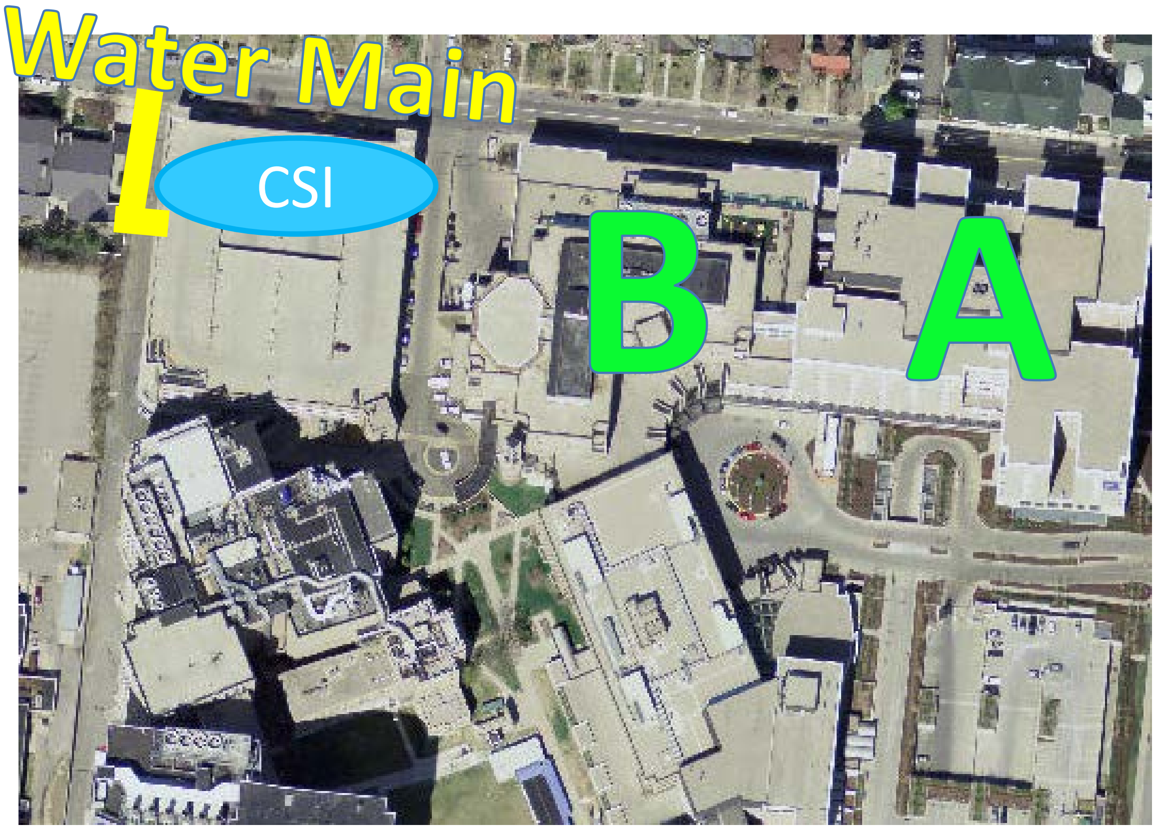


Inside a "Fresh" Flow cell

Good Maintenance Needed

- Adds copper ions (Cu^{+2}) and silver ions (Ag^{+}) to water →biocides
- Only a fraction of copper and silver will remain in free ionic form depending on water chemistry

Large Hospital in Cincinnati



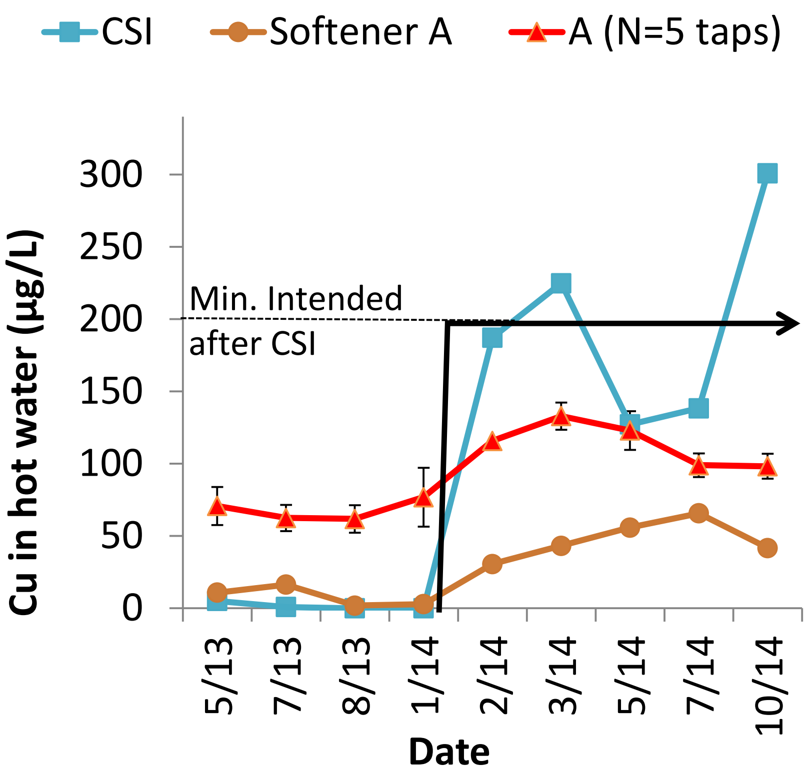
- Treated surface water
- pH 8.6
- Alkalinity

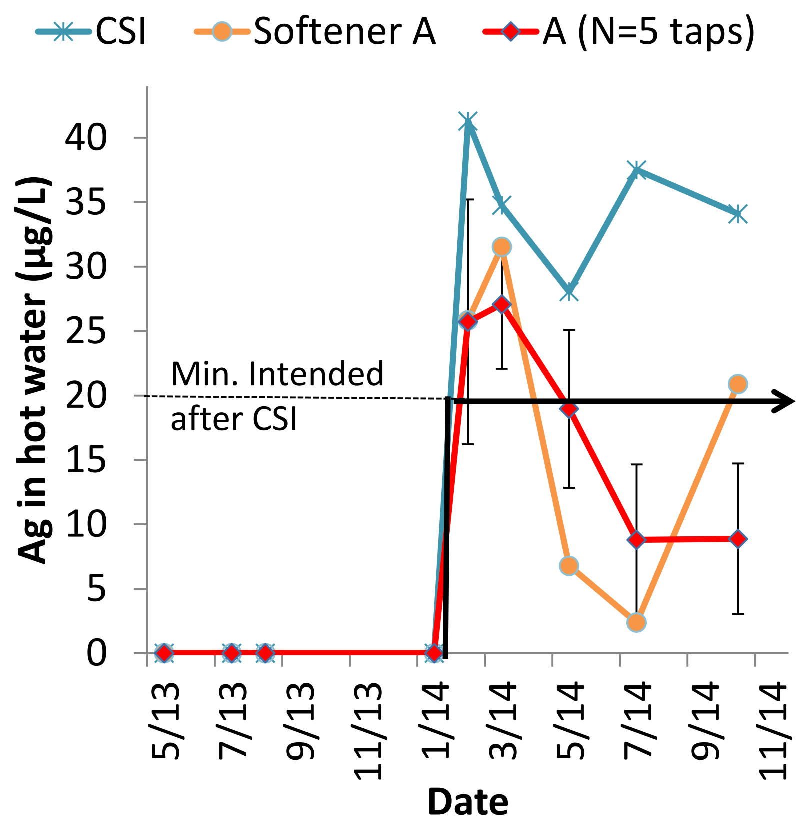
  75 mg/L as $CaCO_3$
- Free chlorine

  1 mg/L

- A & B are patient buildings supplied with the CSI-treated water
- First hospital in Ohio to be regulated under the Safe Drinking Water Act due to in-building water treatment

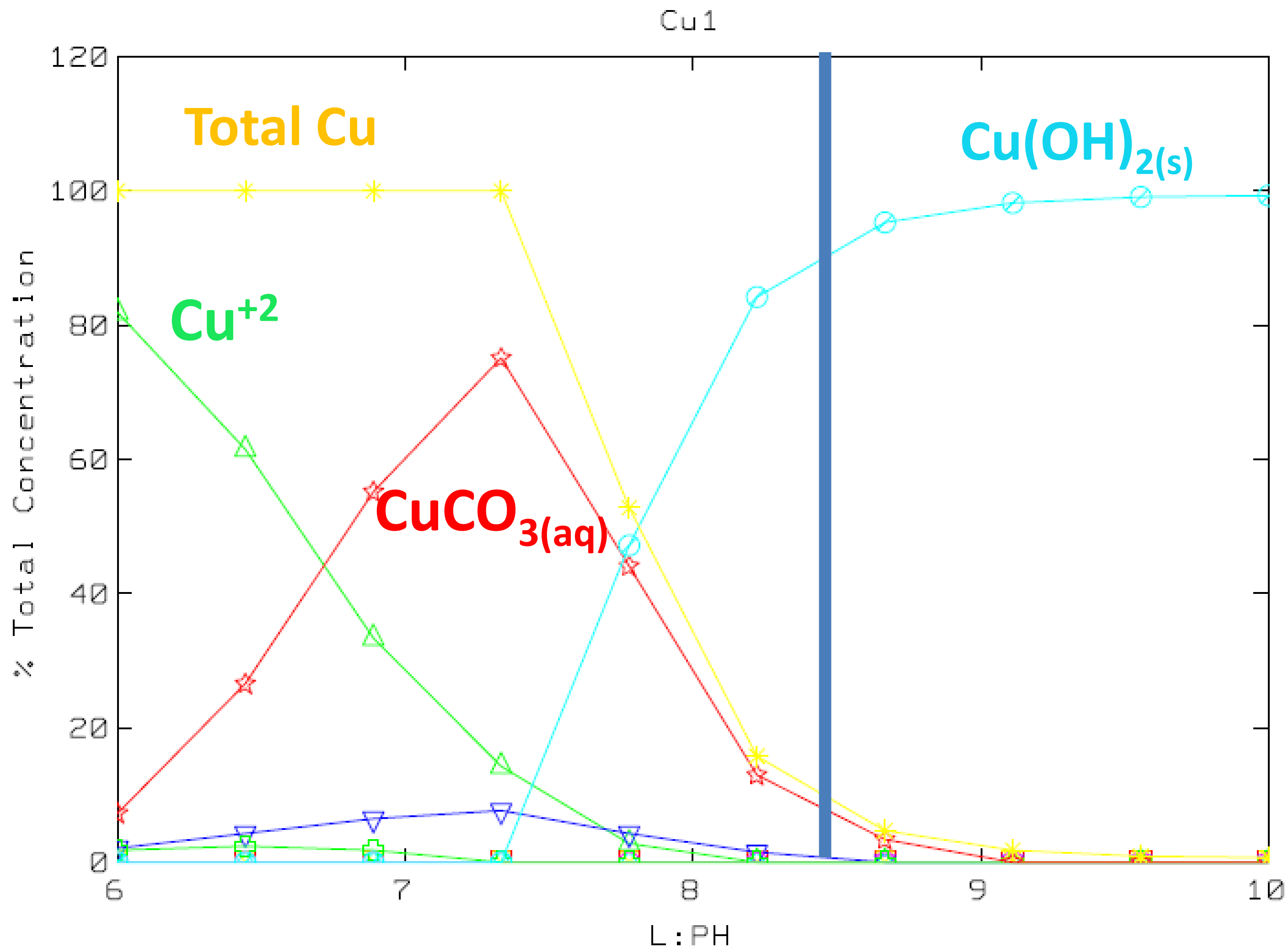
Insufficient Cu and Ag levels reaching hospital taps





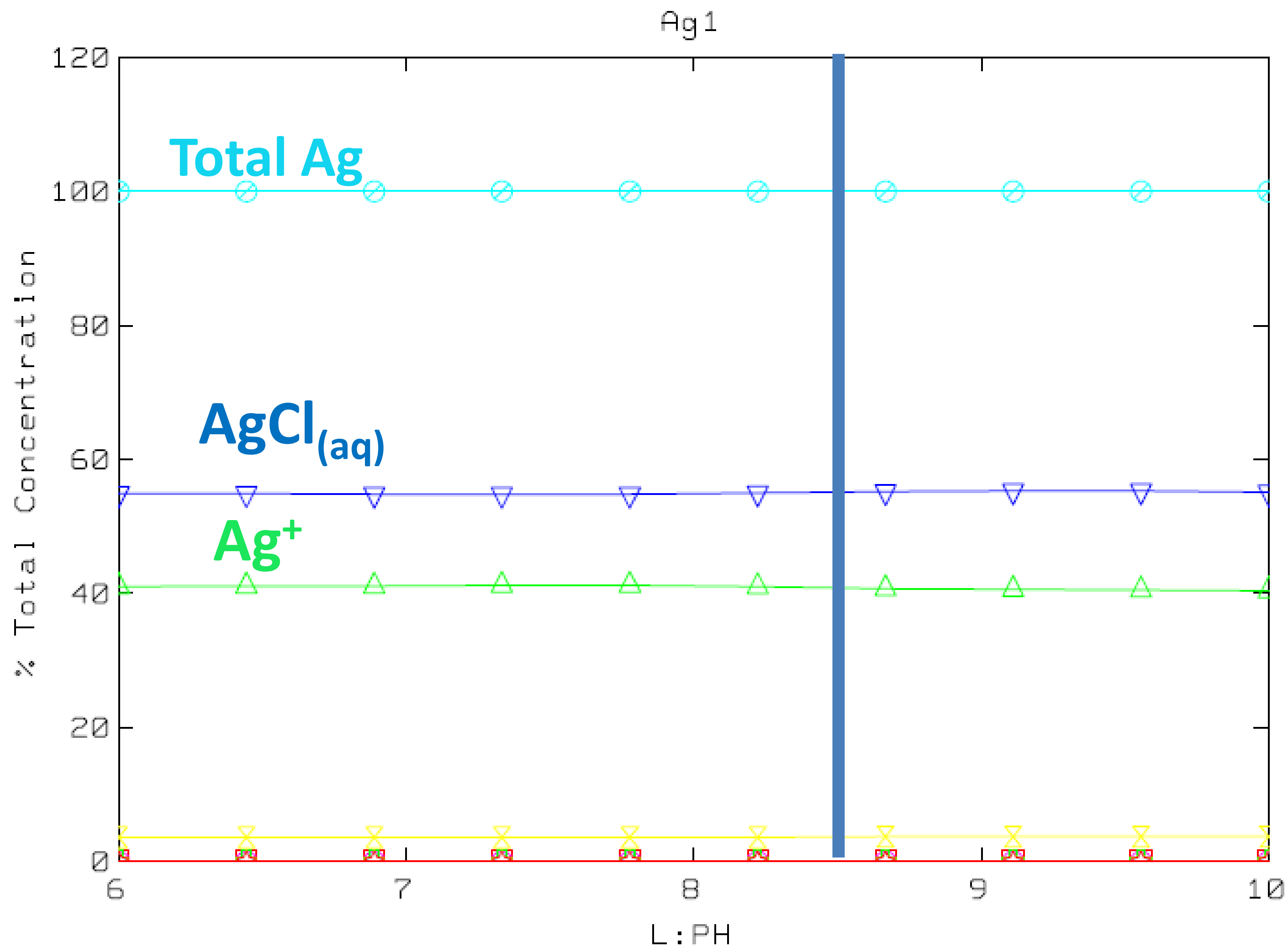
Submitted to Water Research, 2016

Solubility modeling (Mineql+) for Cu



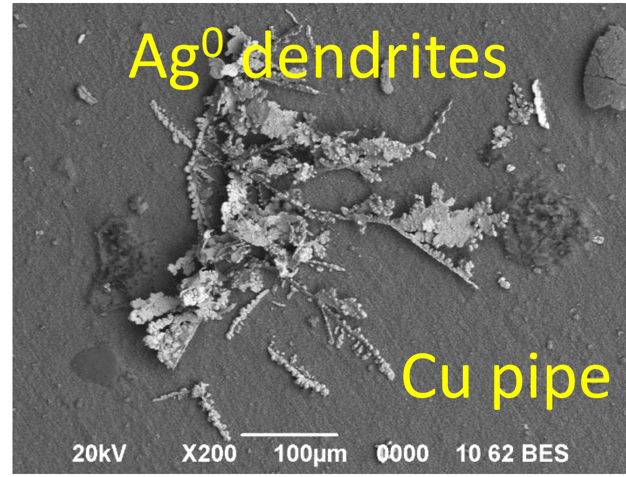
Total Cu = Cu^{+2} + $CuCO_{3(aq)}$

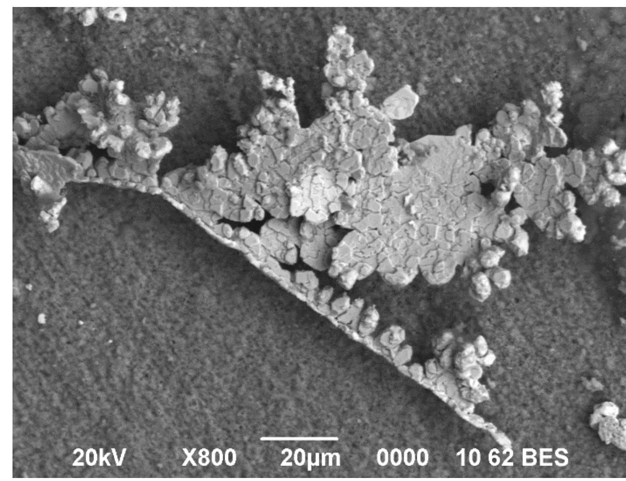
Solubility modeling (Mineql+) for Ag



Total Ag = $AgCl_{(aq)}$ + Ag^+

Plating of reduced silver onto copper pipes

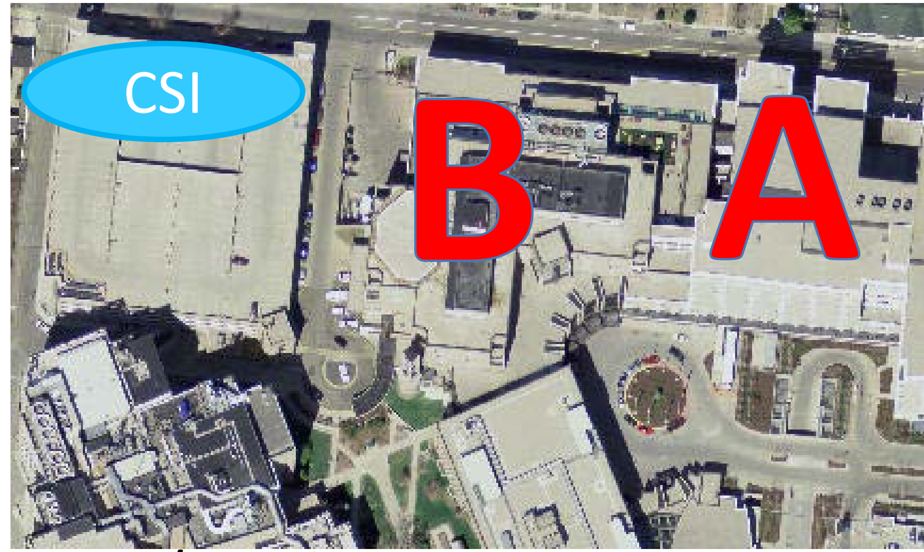




Reaction	Potential, V	Implication
$Ag^+ + e^- \leftrightarrow Ag^0$	+0.799	More Noble (Cathodic)
$Cu^{+2} + 2e^- \leftrightarrow Cu^0$	+0.342	More Active (Anodic)

- Implications on silver disinfecting ability for bulk water and for biofilms
- Possibility of deposition corrosion for Cu pipe

Aesthetic problems



- Grey/purple staining consistently observed in bathroom porcelain throughout buildings A and B
- XRD analysis identified precipitate as $AgCl_{(s)}$
- Caused temporary inactivation of CSI

$Ag^+ + Cl^- \leftrightarrow AgCl_{(s)}$ K=5.62 x 10^9 at 25 °C

Conclusions

- The cation exchange softener installed in Building A for hot water treatment countered the CSI treatment

- Negative reactions to the staining led the hospital to consider alternatives that would eliminate the staining

- Deposition of metallic silver onto copper pipes after CSI activation was verified for the first time

- Extracting and analyzing pipes hidden inside walls can proactively identify interactions not visible to the naked eye

- Although the primary aspect of CSI is the effect on controlling *Legionella* and other pathogens in water, non-microbiological implications deserve exploration to holistically evaluate in-building drinking water disinfection

Acknowledgments

- Dr. Marc Edwards, Dr. Yanna Lambrinidou, Dr. Daniel Gallagher and Trung Le (Master's student) at Virginia Tech
- Dr. Darren Lytle, Christy Muhlen and Mike Elk at EPA (hospital project)
- Michael Schock and Dr. Michael DeSantis at EPA (corrosion studies)