2. Summary of Research Relevant to the D.C. Lead Issue

As noted in the previous chapter, the TEWG was formed in early 2004 in response to the elevated lead levels in D.C. drinking water. The TEWG consists of representatives from EPA, WA, DCWASA, the D.C. Department of Health (DOH), the Centers for Disease Control and Prevention (CDCP), Arlington County, Virginia, and Falls Church, Virginia. Its primary mission was to develop a plan to reduce the corrosivity of treated water in D.C. In their Action Plan (U.S. EPA 2004) the TEWG identified the following seven priorities for their work:

1. Communicate actions and progress to the community on a regular basis;
2. Choose a revised OCCT based on desktop analysis and verified through partial system application and DCWASA and WA pipe loop studies;
3. Consider demonstration of revised OCCT in a partial system test;
4. Leave open the possibility of immediate full system implementation;
5. Obtain EPA interim and final approval of selected re-optimization of corrosion control treatment;
6. Execute full system operations; and
7. Use ongoing pipe loop studies to refine chemistry and determine the cause of the elevated lead levels.

A complete copy of the TEWG action plan is available on-line at http://www.epa.gov/region03/Action_Plan_to_Reduce_Pb_3_10_04.pdf.

The TEWG has accomplished the first six of the priorities listed above. They also made significant steps in identifying the cause of the elevated lead levels, although research is ongoing. The group continues to coordinate research and meet on a regular basis to evaluate and refine the corrosion control treatment.

The purpose of this chapter is to provide a brief summary of the research done by various TEWG members to identify the cause of elevated lead levels and select the best corrosion control treatment option for D.C. For each section, we highlight key findings of each research effort. The reader is referred to other reports (or they are included by way of Appendices) for detail on the various study protocols and other findings.

Conclusions based on the combined research findings and water quality data are presented in Chapter 4 of this report.

2.1 Desktop Corrosion Control Study

In April of 2004, the Washington Aqueduct and its contractor, CH2MHILL, completed a Desktop Corrosion Control Study (WA and C2HMHILL, 2004). The study summarized findings of recent engineering reports dealing specifically with corrosion control treatment and alternative methods of pH and alkalinity control. The study reviewed the feasibility of a wide range of corrosion control options including pH and alkalinity adjustment, calcium adjustment to precipitate a layer of calcium carbonate ($CaCO_3$), phosphate inhibitor addition, and silicate inhibitor addition. A copy of the full desk top study report is available on-line at http://www.epa.gov/dclead/CorrosionControl.pdf.

Key findings of the desktop study are summarized below.

- Although an earlier report suggested adjusting pH to 8.8 for corrosion control, subsequent studies and mathematical modeling results concluded that adjustment of finished water pH by 8.5 or greater using the existing lime treatment would cause excessive precipitation of calcium carbonate in DCWASA's distribution system. This is a very undesirable side effect, reducing the carrying capacity of pipes and causing water to have a white or cloudy appearance. Thus, pH control to 8.5 or greater is not a viable corrosion control option.
- Based on solubility models and experience of other similar systems, phosphoric acid appeared to be the best corrosion inhibitor for D.C.

2.2 Lead Pipe Scale Analysis

By characterizing the nature of the lead scales, TEWG researchers gained important insights into understanding how the corrosion scales formed and why lead began dissolving into the water after the conversion from free chlorine to chloramines.

When corrosion occurs (i.e., a metal undergoes chemical oxidation), oxidized metal either goes into the solution or segregates itself into a different mineral form on the corrosion surface. The product of this segregation is generally referred to as a corrosion scale. Under aqueous chemistry typical of drinking water systems, almost all corroding metals will form a corrosion scale, and, frequently, this corrosion scale will consist of multiple mineral forms of the same oxidized metal. When corrosion scale forms, the pipe can lose structural integrity and, if enough scale accumulates, lose carrying capacity. Corrosion scales themselves can undergo dissolution, releasing oxidized metal into the water.

To understand the nature of the lead corrosion scale in DCWASA's system, researchers from EPA's Office of Research and Development (ORD) performed x-ray diffraction on extracted LSLs from the D.C. distribution system. The majority of tests discussed here were performed in early 2004. A description of the lead scale analysis and detailed discussion of findings was presented at a special workshop held during the American Water Works Association (AWWA) Water Quality Technology Conference (WQTC) in November, 2004 (Schock and Giani, 2004). A copy of the paper from this conference is included as Appendix B to this report for reference.

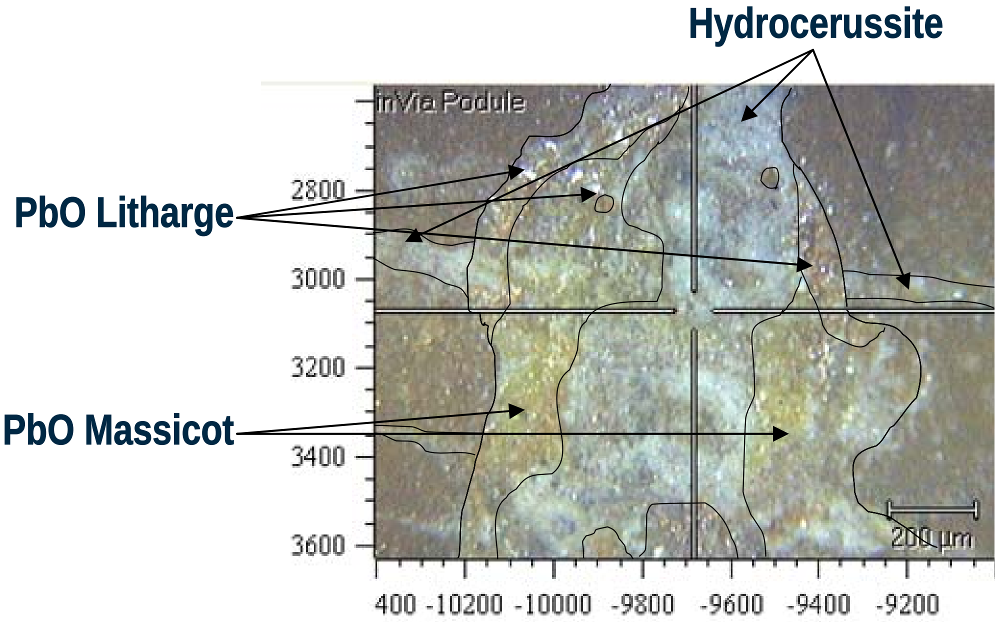
In summary, the x-ray diffraction method involves first scraping the inside of the LSL samples to remove the corrosion scale and then bombarding ground scale material with a series of x-rays. The diffraction patterns of the x-rays are analyzed to identify the mineral content of the scale. Other analytical methods were used to confirm the x-ray diffraction findings. (For a description of other methods, see Appendix B.)

Results of several analyses showed that the corrosion scale on LSLs in the DCWASA distribution system consists primarily of lead oxide (PbO_2) compounds, specifically plattnerite and scrutinyite. The presence of lead oxide scales is associated with water of consistently high oxidation reduction potential (ORP). A high ORP can be caused by several mechanisms, one of which is very high levels of free chlorine. WA and DCWASA had historically maintained a high free chlorine residual for biofilm control. The working theory developed by ORD researchers based on pipe scale analysis is that when the ORP level dropped with the conversion from free chlorine to chloramines, the lead corrosion scale began slowly dissolving into the water.

There has been considerable research into the occurrence and chemistry of lead oxide scales since the paper by Schock and Giani was presented at the AWWA WQTC workshop in 2004 in support of these findings (Giani, Donnelly et al., 2005; Korshin 2005; Lytle and Schock 2005; Schock 2005; Vasquez et al. 2006). Many studies continue today.

The DCWASA experience has also spurred the development and application of new analytical tools. One tool now being applied is Raman Spectroscopy, which can simultaneously assess both the topology and crystallography of corrosion scales. Exhibit 2.2.1 is a Raman spectrograph of a DCWASA LSL corrosion scale destabilized by exposure to chloramines (Maynard and Mast, 2005).

Exhibit 2.2.1 Raman spectrograph of a transforming LSL showing the spatial distribution of Pb(IV) and Pb(II) mineralogy



Source: (Maynard and Mast, 2005).

2.3 DCWASA Circulation Pipe Loop Studies

In early 2004, DCWASA initiated a set of bench/pilot scale studies to assess lead (and in some cases copper) corrosion rates and metals release. The combination of bench/pilot scale studies consists of two circulation loop testing apparatus:

1) Stagnation loop testing focusing primarily on metal release from relatively long LSL sections.
2) Electrochemical (EC) pipe loop testing focusing on corrosion rates and EC parameters measured on short sections of LSL and domestic copper tubing.

These complementary analyses measure corrosion rates and metal release under simulated distribution system conditions. Study protocols and test conditions were designed to overlap such that one set of tests could provide confirmatory evidence for the others. Both protocols tested similar water quality regimens.

The studies were performed at DCWASA's Fort Reno facilities beginning in March 2004, and have continued with minor modifications since that time (Reiber et al. 2004).

2.3.1 Purpose of Study

The purpose of these studies was to quickly screen several potential corrosion control strategies. A secondary objective of the testing program was to help determine the cause of the lead corrosion problem. After selection and implementation of the new corrosion control treatment for D.C. in August 2004, the loops have been used to evaluate the impact of changes in water quality on lead release and continue to be used today. Because a final report of findings is not currently available, all discussions and conclusions are based on interim reports from DCWASA.

The focus of this testing is primarily on LSLs, although copper tubing was also included in the program to provide an EC reference point and to ensure that any adverse potential corrosion impacts on other plumbing surfaces were fully investigated. The LSL test specimens were pipe sections that had been removed from the DCWASA system and reflected the history and scaling conditions of in-situ DCWASA LSLs. The basis for much of the bench and pilot scale testing was a relative comparison, meaning that a baseline condition (corrosion rate or metal release rate) was established; then the water chemistry is changed, and the effect on the test parameter is observed over time.

2.3.2 Summary of Key Findings

- Pipe loop data (i.e., total lead levels after stagnation) correlated well with the maximum lead concentrations observed in the lead profiles (lead profile results are presented in Section 3.3), indicating that the circulation studies are a useful tool for predicting optimal corrosion conditions in the DCWASA system.

- Multiple pipe loops operated for 2 years show that orthophosphate is highly effective at controlling corrosion of LSL surfaces in the D.C. system.

- Other corrosion control strategies, such as raising the pH with lime and using ortho/polyphosphate blends, were not successful in reducing lead leaching from DCWASA LSLs.

- Adjustments in orthophosphate dose and changes in oxidant type (from chloramines to free chlorine back to chloramines) may have a very slight impact on lead release, although it is too early to make firm conclusions.

2.3.3 DCWASA Pipe Loop Protocol

EC testing was performed in accordance with the methodology for “Pipe Section Flow Cells” contained in “Internal Corrosion of Water Distribution Systems,” second edition (AwwaRF, 1996). The electrochemistry testing protocols were considered useful because they estimate the actual corrosion rate (electron exchange) on the test specimens, which in turn provides an indication of how water quality conditions are influencing overall corrosion conditions. They are, however, very sensitive to changing redox potential, and can vary substantially as disinfectant concentrations vary, as was the case in this testing protocol. It is important to note that EC measurements of corrosion rate are a crude indicator of the corrosion processes occurring on the test specimens.

The text, “Internal Corrosion of Water Distribution Systems” also contains a description of pipe-loop stagnation testing of the type carried out for DCWASA. While the principal advantages of the EC approach are its speed and ease of measurement, the stagnation loops are more time-consuming, and require substantially more effort, but yield a result that is more reflective of actual lead release.

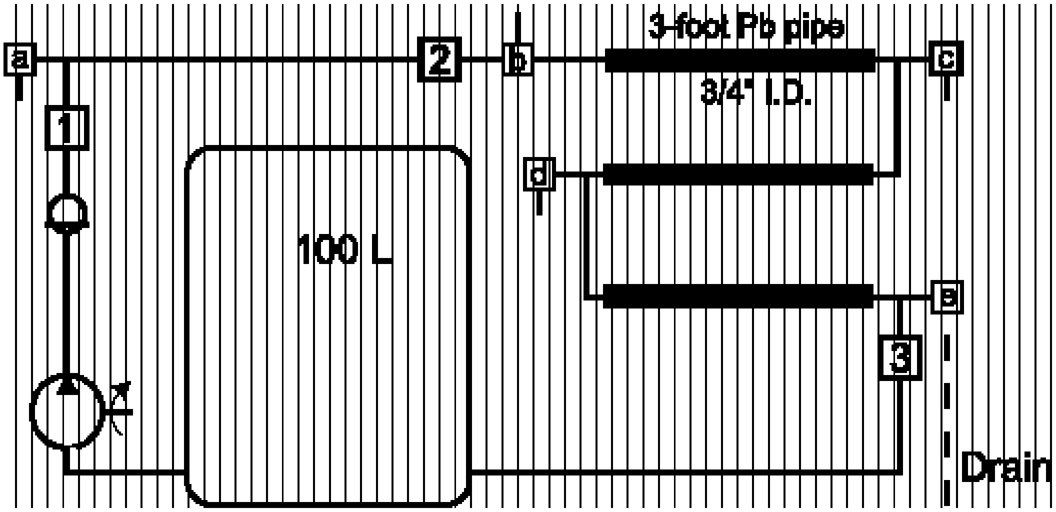
A total of 12 circulation loops, comprising six EC loops and six stagnation loops, were constructed to test the various corrosion control strategies. Exhibit 2.3.1 is a photograph of the EC pipe loops. Exhibit 2.3.2 is a schematic of the stagnation loops.

At the beginning of the study, all pipe loops were run with distribution system water (with chloramines) prior to testing in order to condition the pipe specimens and to establish a baseline metal release rate. After the conditioning period, the sample water was dosed with the appropriate chemical regime. The stagnation loop test consisted of 8 hour stagnation periods, representing conventional operation of in-service lines, followed by a 16-hour circulation period. EC loop tests consisted of a 24 hour circulation. Water quality analyses were performed for multiple parameters, as shown in Exhibit 2.3.3.

Exhibit 2.3.1 Photograph of Electrochemical Polarization Cell Used in the EC Pipe Loop System

Source: EPA. http://www.epa.gov/dclead/corrosion.htm

Exhibit 2.3.2 Stagnation Loop Schematic



Source: Reiber et al. (2004).

Exhibit 2.3.3 Water Quality Parameters Evaluated During the DCWASA Study

WQP	EC Loop Testing		Stagnation Loop Testing		
	Pre-24 hr circulation	Post-24 hr circulation	Pre-8 hr stagnation	Post-8 hr stagnation	Post 16 hr circulation
pH	√	√	√	√	√
temperature	√	√	√	√	√
alkalinity	√	√	√		√
hardness	√		√		
free chlorine	√	√	√	√	√
total chlorine	√	√	√	√	√
Total dissolved solids (TDS)	√		√		
ORP		√			√
lead		√		√	√
copper		√			
phosphate (as applicable)		√			√

Source: Reiber et al. (2004).

Although the testing conditions were modified as the testing proceeded, the original strategies evaluated in both types of loops are summarized in Exhibit 2.3.4. These were the original lead mitigation strategies, and the first six months of testing focused largely on establishing their relative effectiveness. As it became clear that certain strategies were going to be ineffective relative to lead release, the equipment devoted to these efforts was reassigned to explore other options. Testing beyond the original scope included evaluation of corrosion mitigation strategies as well as the impact of various distribution system operational conditions. Some of these additional testing efforts included:

- Application of stannous chloride as a supplemental inhibitory in conjunction with phosphoric acid;
- Evaluation of periodic, short-term free chlorine “burn out” on lead release;
- Assessment of changes in orthophosphate dose.

These and other strategies and operational criteria continue to be tested as needed by DCWASA

Exhibit 2.3.4 Original Corrosion Control Strategies Tested by DCWASA

Strategy	Description	Rationale
1	Chloraminated (3.5 mg/L) finished water without any additional chemical treatment.	Control. Represents the finished water discharged from the Dalecarlia Plant.
2	Add lime to raise the calcium carbonate precipitation to 1 mg/L, maintain chloramines concentration at 3.5 mg/L	Initiate the development of supposedly protective calcite scales.
3	Add monosodium phosphate (MSP) at 10 mg/L, adjust pH to 7.5 – 7.8	Test effectiveness of orthophosphate under high chloramine residual. Given the short duration of the testing, a high phosphate dose is necessary in order to rapidly passivate the lead surfaces and assess whether phosphate has likely value as a corrosion inhibitor.
4	Add 50/50 blended ortho/polyphosphate at a total phosphate dose = 1 - 2 mg/L.	Test the effectiveness of polyphosphates.
5	Add monosodium phosphate (MSP) at 10 mg/L, adjust pH to 7.5 - 7.8. Decrease chloramine residual to 1 mg/L.	Test the effectiveness of strategy 3 under low chloramine conditions.
6	Add lime to raise the calcium carbonate precipitation to 1mg/L, reduce chloramine concentration to 1 mg/L.	Test the effectiveness of strategy 2 under low chloramine conditions.

Source: Reiber et al. (2004).

2.3.4 Results

A factor that helped make the DCWASA pipe loop testing a useful assessment tool is that it was demonstrated early on that the test rigs were able to simulate the lead release process from LSLs in the distribution system. Lead levels measured in the pipe loops closely approximated the highest lead levels recorded during the household lead profiling events (generally greater than 100 ppb total lead, see Section 3.3 for detailed results of DCWASA's lead profiling program). This relatively high initial level of lead made it easier to do comparative evaluations of the various test strategies.

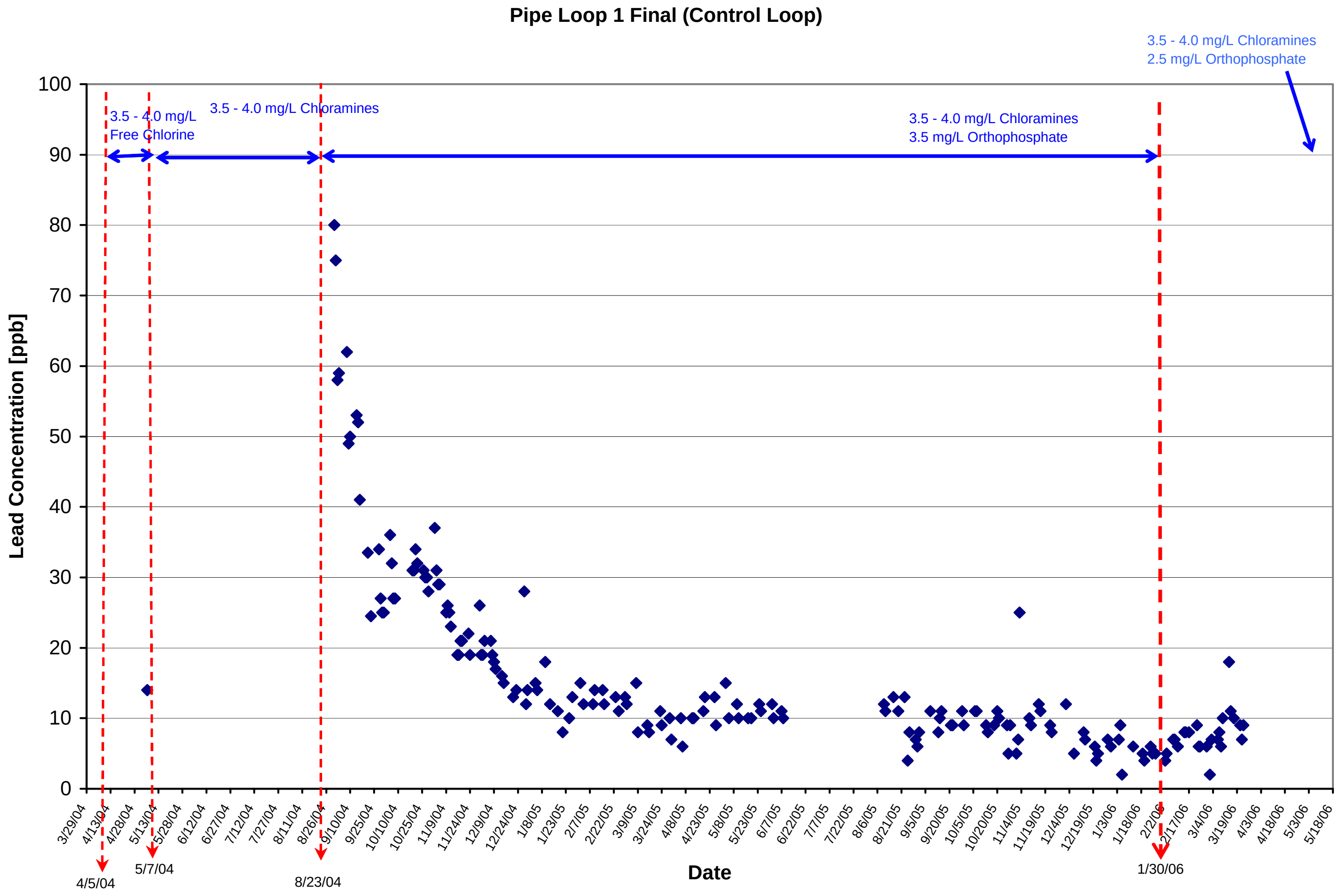
Using these test protocols, DCWASA collected a substantial body of data relative to the various mitigation strategies. One of the most important findings of this study has been the reduction in corrosion rate and lead release resulting from application of orthophosphate. Exhibit 2.3.5 displays a substantial amount of pipe loop data from March 2004 through March 2006 for four stagnation loops treated with orthophosphate.

All loops show substantial and continuous reductions in lead leaching resulting from the orthophosphate treatment. Results from the EC loops were similar and showed a comparable although slightly delayed initial reduction in EC corrosion rate with the orthophosphate treatment. Exhibit 2.3.6 is an example of the corrosion rates measured for Pipe Loop Number 1.

A second important finding regarding the screening of corrosion control strategies is that other corrosion strategies *did not* reduce lead release rates under chloramines conditions. Exhibit 2.3.7 shows total lead concentration for Pipe Loop 2, which was treated with lime to raise the calcium carbonate precipitation potential. This potential strategy did not appear to have any impact on lead release. Exhibit 2.3.8 shows total lead concentration for Pipe Loop 4, which was initially fed a 50/50 ortho/polyphosphate blend at between 1 and 2 mg/L. Lead release in this loop fell slightly, but very little in comparison to the orthophosphate loops. In 2006, Stannous Chloride was tested in Pipe Loop 5. Preliminary results show an increase in total and dissolved lead concentrations.

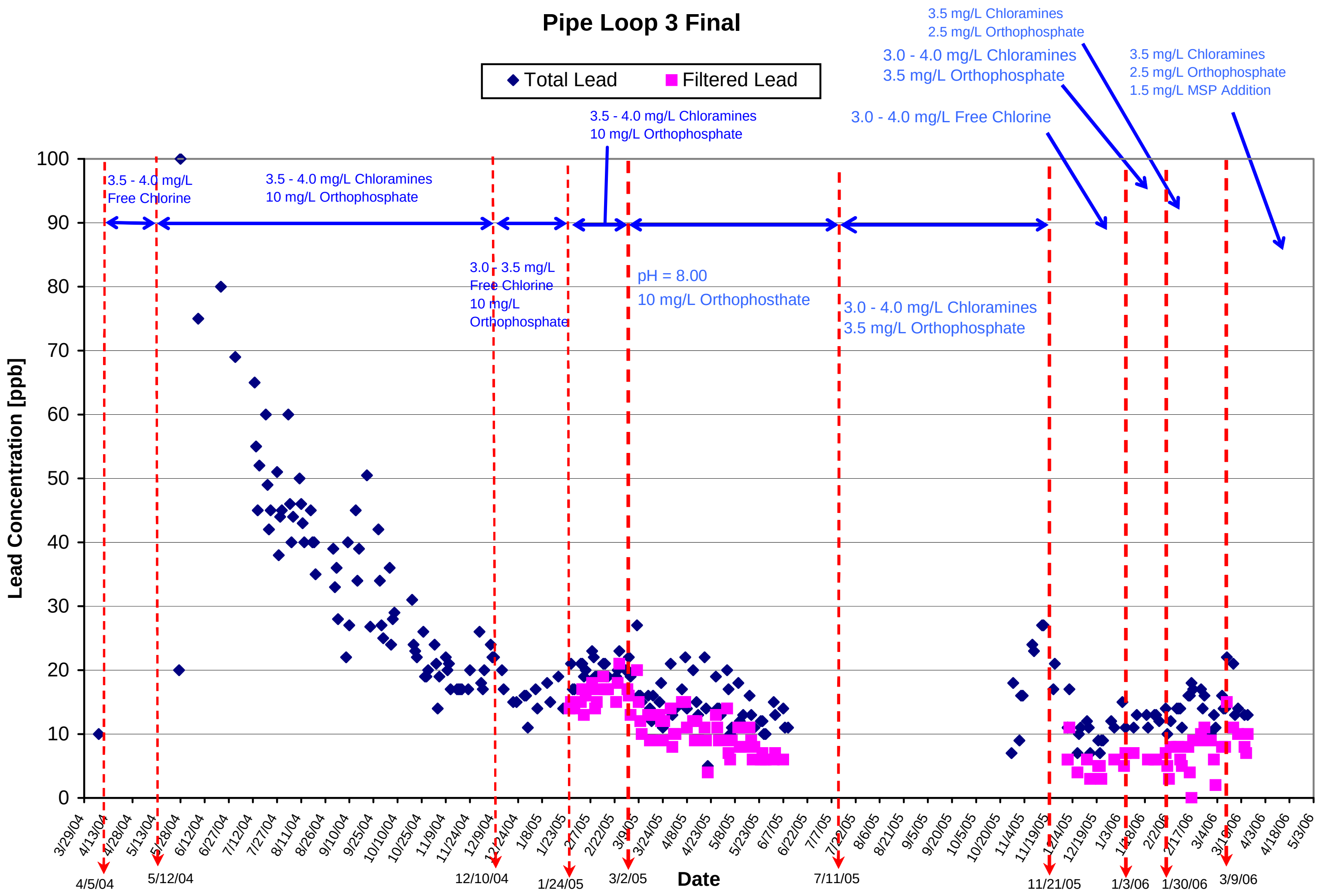
In addition to evaluating inhibitors and other mitigation strategies, the DCWASA bench and pilot-scale efforts were useful in evaluating operational and dosage regimen criteria. In Pipe Loop 3, DCWASA switched to free chlorine in late November 2005 to simulate a free chlorine burn then switched back to chloramines in the first part of January 2006. Lead levels exhibited a very slight increase, although conclusions are difficult due to the inherent variability in the lead data. Pipe Loops 1, 3, and 6 have recently undergone a reduction in orthophosphate dose from 3.5 mg/L for 2.5 mg/L. Exhibit 2.3.5 shows a very slight increase in lead concentration following this change in all loops, but there are too few data points to draw any firm conclusions regarding the potential impact of this change.

Exhibit 2.3.5 Results from Four DCWASA Stagnation Loops Showing Reduction in Lead Release as a Function of Orthophosphate Treatment



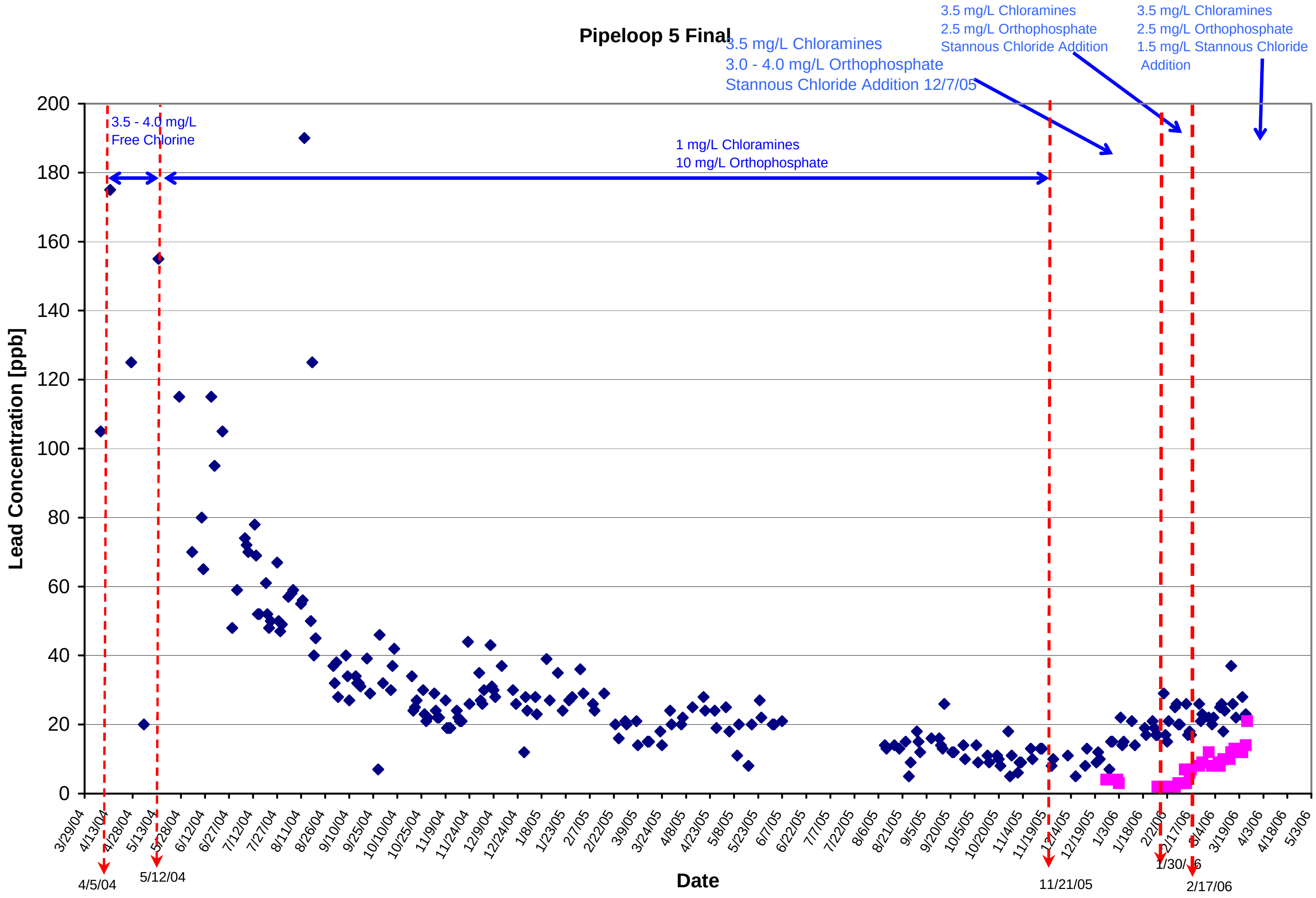
Source: Distributed to the TEWG by DCWASA.

Exhibit 2.3.5 (continued)



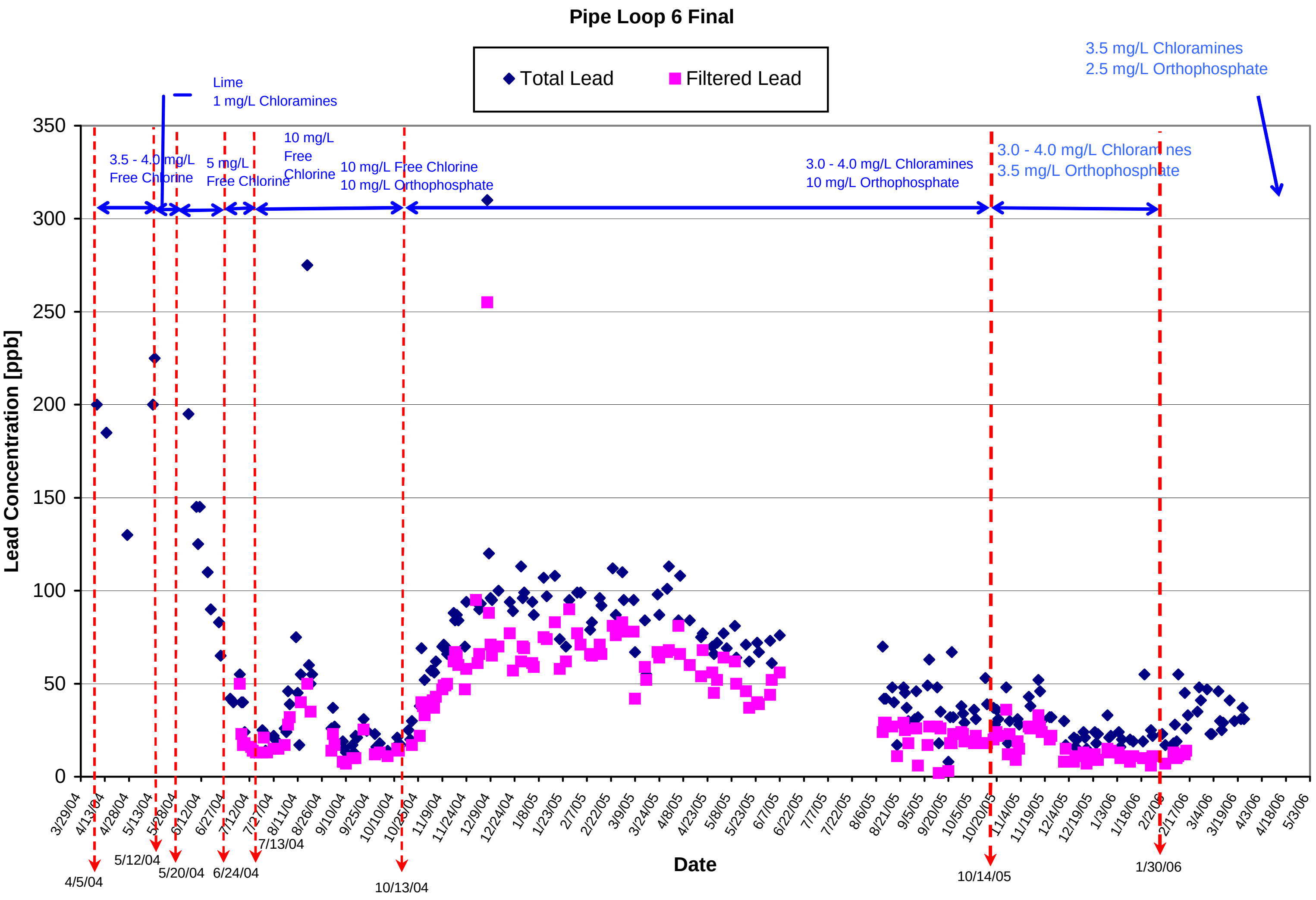
Source: Distributed to the TEWG by DCWASA

Exhibit 2.3.5 (continued)



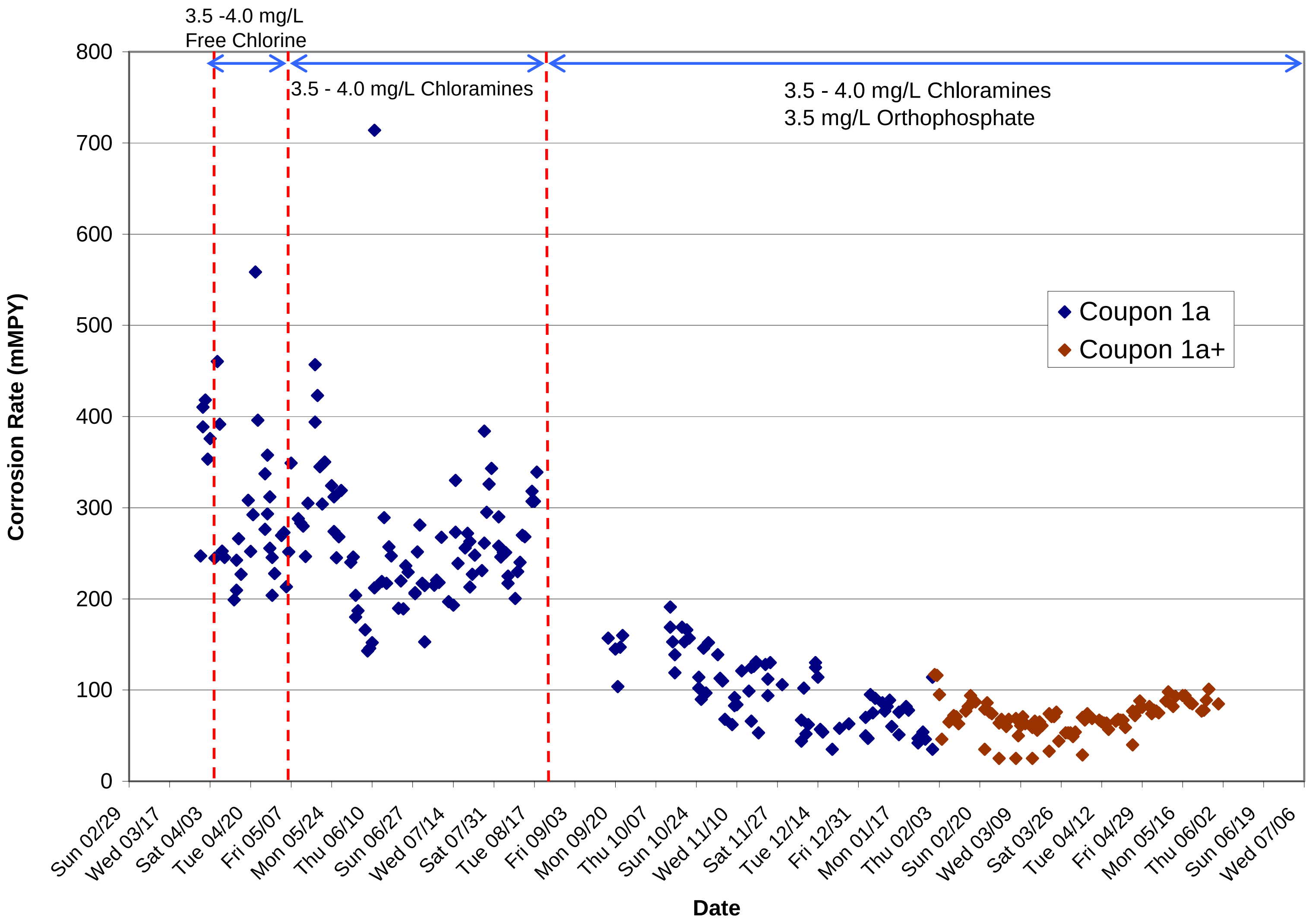
Source: Distributed to the TEWG by DCWASA

Exhibit 2.3.5 (continued)



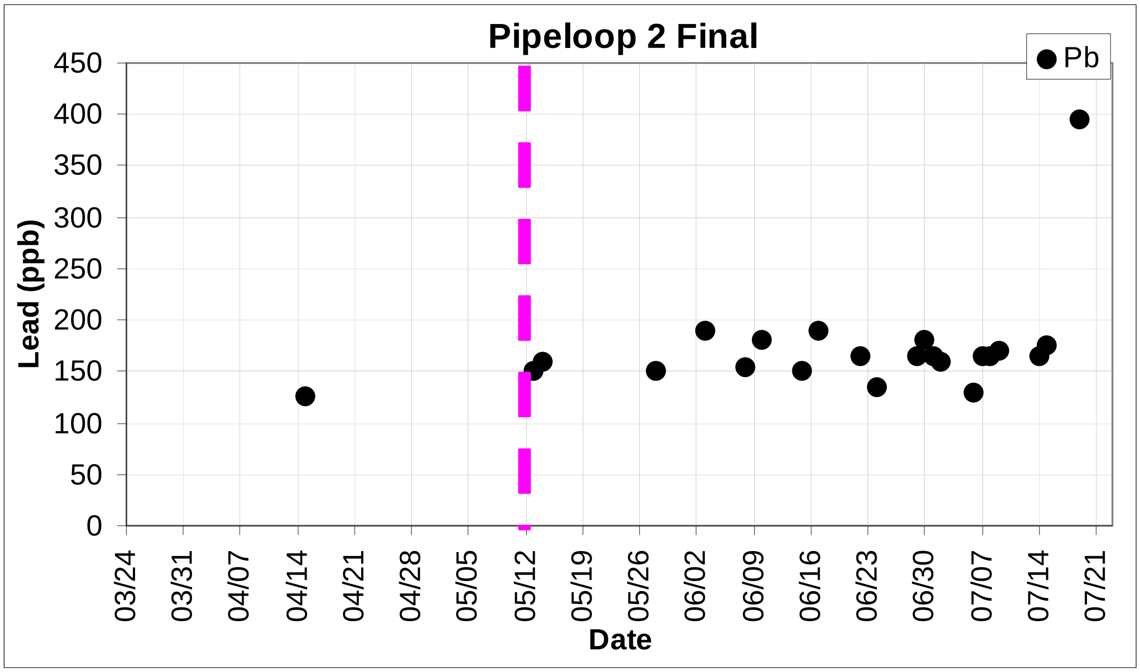
Source: Distributed to the TEWG by DCWASA

Exhibit 2.3.6 Change in Corrosion Rate (Measured in mils per year, MPY) for EC Loop Number 1



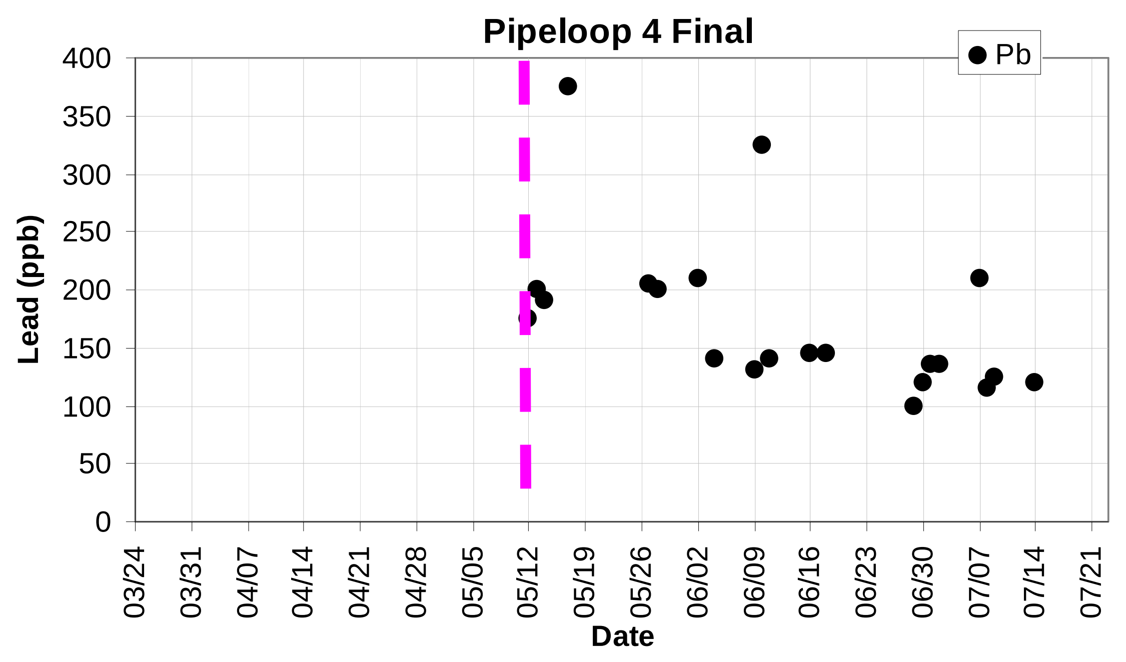
Source: Distributed to the TEWG by WA.

Exhibit 2.3.7 Results from Pipe Loop 2 (March 2004 - July 2004)



Source: Distributed to the TEWG by WA.

Exhibit 2.3.8 Results from Pipe Loop 4 (March 2004 – July 2004)



Source: Distributed to the TEWG by WA.

2.4 Washington Aqueduct Flow-Through Pipe Loop Studies

This section describes the flow-through lead pipe loop testing conducted by WA and its contractor, CH2MHill at the Dalecarlia Water Treatment Plant. The study began in January 2005 and complements the DCWASA recirculation loop testing described in Section 2.3. Several experiments have been completed, but others are ongoing at the time of this report. Because a final report of findings is not currently available, all discussions and conclusions are based on interim reports from WA and its contractors.

2.4.1 Purpose of Study

The WA pipe loop study was designed to answer the following four main questions:

- Does zinc orthophosphate perform better or worse than orthophosphate?
- What is the optimum long-term dose of phosphoric acid for the DCWASA distribution system?
- What is the approximate timeframe for reducing lead concentrations in the DCWASA distribution system?
- Does periodically switching from chloramines to free chlorine have any impact on lead concentrations? If so, what is the impact and approximately how long does the effect last?

2.4.2 Summary of Key Findings

Based on preliminary results presented by WA and CH2MHill to the TEWG, key findings of the WA pipe loop study are as follows:

- Orthophosphate was very effective at reducing lead release from LSLs.
- The study found no additional benefit of zinc orthophosphate over orthophosphate (added as phosphoric acid). In fact, addition of zinc may serve to destabilize corrosion scales.
- Lead release appears to be sensitive to changes in orthophosphate dose.
- A temporary change to free chlorine then back to chloramine may cause slight increases in metal release from LSLs.

Most findings of the WA study were similar to the DCWASA study, although there are some differences that warrant mention. Overall lead levels were lower in the WA loops, although the particulate portion of the lead was higher compared to DCWASA circulation loop study results. Also, the operational time needed to observe meaningful lead reduction was longer for the WA loops, although this may be attributable to the high initial dose of 10 mg/L used by DCWASA to accelerate results. Other differences may be attributable to different loop fabrication techniques or handling of the LSL specimens prior to fabrication, as discussed in the next section.

2.4.3 Washington Aqueduct Pipe Loop Protocol

WA uses finished (i.e., potable) water as source water for testing. Additional treatment chemicals are added to the filtered water flow stream to “simulate” finished water quality under a variety of conditions. All pipe loops in the test are operated with chloramines or a combination of free chlorine and chloramines (i.e., no free chlorine pipe loops were used).

The WA pipe loops were initially tested under a total of seven different operating conditions (i.e., racks), as defined in Exhibit 2.4.1. Three replicate pipe loops were provided in each of the seven racks to ensure that the test results were statistically significant and reproducible. Twenty-one lead pipe loops were provided in all. One rack (set of three loops) was assigned to evaluate lead release associated with the finished water produced at the Dalecarlia WTP. No additional chemical conditioning of the finished water was performed prior to testing this flow stream. This set of loops served as a control for the study.

Salvaged LSLs excavated from the DCWASA distribution system were used to construct the pipe loops. Note that this is the same pool of LSL pipe sections from which the DCWASA pipe loops were fabricated. Each loop included two or three separate sections of LSL, for a total length of 13 feet, of ¾-inch-diameter pipe. This length was selected because it yields a total sample volume of 1.1 liters per pipe loop. Exhibit 2.4.2 shows how the pipe loops were constructed using salvaged LSLs from the distribution system. LSLs used in the WA study were allowed to dry out before the pipe loop study began. This contrasts with the DCWASA LSL portions, which remained wet.

At initialization, all of the pipe loops were conditioned with finished water for a period of one month to allow for the scale on the pipes to reach a common baseline. After the one-month conditioning period, the pipe loops (with the exception of the control loop) were fed “filtered” water with chemicals added according to the Test Plan presented in Exhibit 2.4.1.

Exhibit 2.4.1 Operating Conditions, Objectives and Rationale for the Seven Pipe Racks used in WA Study

Pipe Rack Number	Rack Name	Water Source	Chemicals to be Added to Water	Chemical Dose (mg/l)	Pipe Rack pH	Question to be Addressed by this Rack
1	High Chloramines with Zinc Ortho, Decrease Zinc Ortho Dose over Time	filtered water	zinc orthophosphate	3.5 mg/l as phosphate, ramp down once lead levels drop below action level	7.7	1. What dose of zinc orthophosphate should be used to control lead levels in the distribution system once the system has been passivated? What is the lowest effective dose that will still ensure compliance with the LCR lead action levels? 2. How does zinc orthophosphate performance compare with phosphoric acid (i.e., compare Rack 1 and 2 results).
			sodium hydroxide	as needed for pH control		
			sodium hypochlorite	as needed to maintain 3.5 mg/L chloramine concentration		
			ammonia	as needed to maintain 3.5 mg/l chloramine concentration		
			fluoride	1.0 mg/l		
2	High Chloramines with Phosphoric Acid, Decrease Phosphoric Acid Dose over Time	filtered water	phosphoric acid	3.5 mg/l as phosphate, ramp down once lead levels drop below action level	7.7	1. What dose of phosphoric acid should be used to control lead levels in the distribution system once the system has been passivated? What is the lowest effective dose that will still ensure compliance with the LCR lead action levels? 2. How does zinc orthophosphate performance compare with phosphoric acid (i.e., compare Rack 1 and 2 results).
			sodium hydroxide	as needed for pH control		
			sodium hypochlorite	as needed to maintain 3.5 mg/l chloramine concentration		
			ammonia	as needed to maintain 3.5 mg/l chloramine concentration		
			fluoride	1.0 mg/l		
3	Switch Between Free Chlorine and Chloramines with Constant Phosphoric Acid Dose	filtered water	phosphoric acid	3.5 mg/l as phosphate, no change over time	7.7	1. How are lead levels impacted by periodically swinging back and forth from free chlorine to chloramines in the presence of a corrosion inhibitor? 2. Does switching disinfectants inhibit the effectiveness of phosphoric acid for some period of time? An item to be resolved here involves whether to initially condition this loop with free chlorine or chloramines???
			sodium hydroxide	as needed for pH control		
			sodium hypochlorite	3.5 mg/l +/-, or as needed to achieve distribution system microbial goals		
			ammonia	as needed to maintain 3.5 mg/l chloramine concentration		
			fluoride	1.0 mg/l		
4	High Chloramines, No Corrosion Inhibitor	filtered water	sodium hydroxide	as needed for pH control	7.7	1. What lead levels can be expected with chloramines in the absence of a corrosion inhibitor? 2. How do chloramine lead levels compare with and without orthophosphate (i.e., compare racks 1, 2, and 4)?
			sodium hypochlorite	as needed to maintain 3.5 mg/l chloramine concentration		
			ammonia	as needed to maintain 3.5 mg/l chloramine concentration		
			fluoride	1.0 mg/l		
5	Low Chloramines with Constant Phosphoric Acid Dose	filtered water	phosphoric acid	3.5 mg/l as phosphate, no change over time	7.7	1. How do lower chloramine concentrations impact lead concentrations in the presence of a corrosion inhibitor (I.e., compare racks 5 and 6)?
			sodium hydroxide	as needed for pH control		
			sodium hypochlorite	as needed to maintain 1.0 - 2.0 mg/l chloramine concentration		
			ammonia	as needed to maintain 1.0 - 2.0 mg/l chloramine concentration		
			fluoride	1.0 mg/l		
6	High Chloramines with Constant Phosphoric Acid Dose	filtered water	phosphoric acid	3.5 mg/l as phosphate, no change over time	7.7	1. How do lead levels compare if phosphoric acid concentrations are lowered over time after passivation versus maintained at a constant concentration after passivation (I.e., compare racks 2 and 6)?
			sodium hydroxide	as needed for pH control		
			sodium hypochlorite	as needed to maintain 3.5 mg/l chloramine concentration		
			ammonia	as needed to maintain 3.5 mg/l chloramine concentration		
			fluoride	1.0 mg/l		
7	Finished Water Control Rack	finished water	phosphoric acid	full scale plant dose during test period (3.5 mg/l dose anticipated)	7.7	1. Control loop - finished water conditions during the pipe loop test period. 2. Lead-containing faucets will be installed in a separate pipe loop on this rack.
			lime	full scale plant dose as needed for pH control during test period		
			sodium hypochlorite	full scale plant dose during test period (3.5 mg/l chloramine concentration anticipated)		
			ammonia	full scale plant dose during test period (3.5 mg/l chloramine concentration anticipated)		
			fluoride	full scale plant dose during test period (1.0 mg/l dose anticipated)		

Source: Distributed to the TEWG by WA.

Exhibit 2.4.2 Photograph of the pipe rack elements installed at the Dalecarlia Water Treatment Plant

Source: Distributed to the TEWG by WA.

The pipe loops were operated on a 16-hour flow period, followed by an 8-hour stagnation period. Unlike the DCWASA system, water was not recirculated within the loop and exchanged on a daily basis. Instead, all WA racks were a single pass-through operation. The flow-through pipe loop facilities were operated seven days per week. Periodic water quality samples were collected Monday through Friday and delivered to the WA Laboratory for analyses. The standard analysis set consisted of the following:

- Total and dissolved lead
- pH
- Alkalinity (as $CaCO_3$)
- Calcium (as Ca)
- Total Dissolved Solids (TDS)
- Calcium Carbonate Precipitation Potential (CCPP)
- Turbidity
- Dissolved Inorganic Carbon (DIC)
- Periodic Heterotrophic Plate Counts (HPCs)
- NH_3 (as N)
- Nitrite and Nitrate (as N)

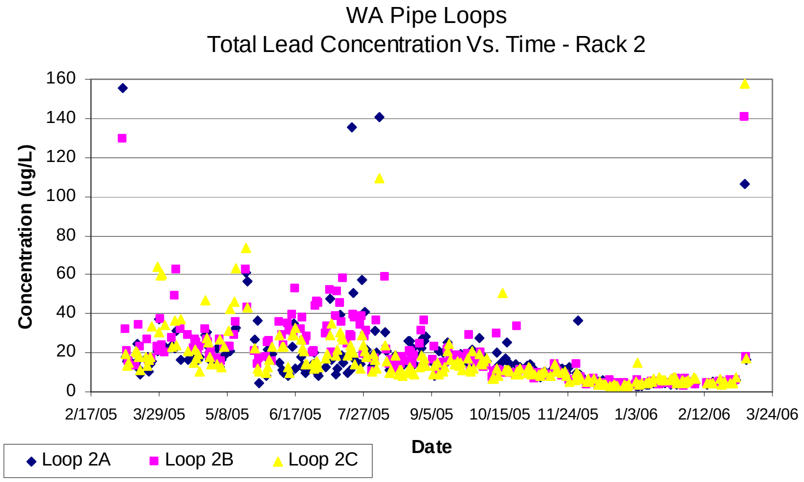
2.4.4 Results

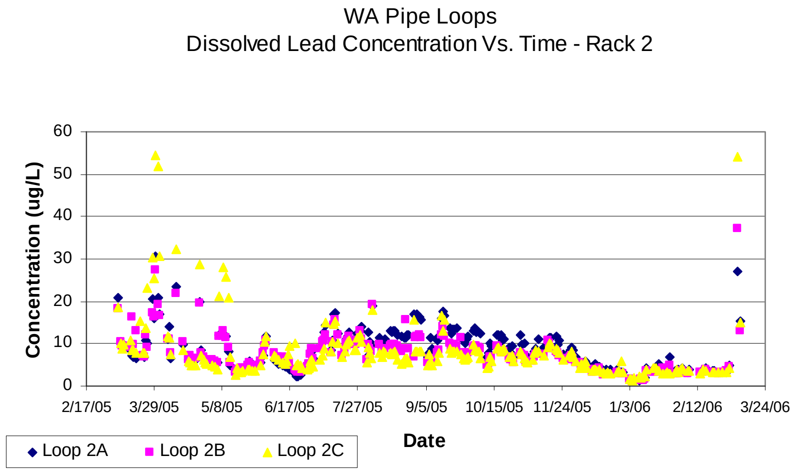
The pipe racks became operational in January 2005. All seven racks operated continuously for approximately twelve months. In February of 2006 it was believed that sufficient data had been collected from some of the racks to allow conclusions to be drawn and resolve the questions they were designed to answer. Operation of the following racks has been halted:

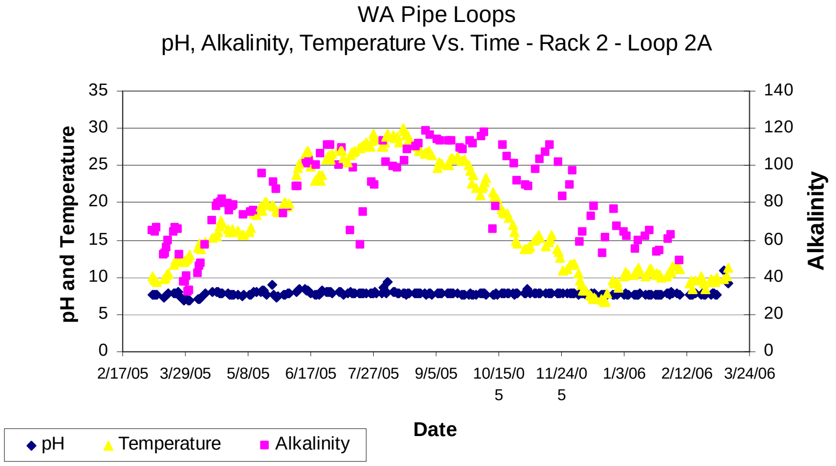
- Rack 1. High chloramines, zinc orthophosphate addition;
- Rack 4. High chloramines, no orthophosphate inhibitor; and
- Rack 5. Low chloramine dose, constant orthophosphate feed.

The data set collected by the WA research team is substantial. Exhibits 2.4.3a through 2.4.6b graphically portray findings from the WA pipe loop study through early March 2006. The “a” exhibits contain three graphs: total lead over time, dissolved lead over time, and a combination of pH, alkalinity, and temperature over time for each of three loops in the Rack. The “b” exhibits are a larger version of dissolved lead over time with notations as to treatment regime changes. Key findings as they relate to the OCCT follow these exhibits.

Exhibit 2.4.3a Results for Rack 2, Decrease Orthophosphate over Time

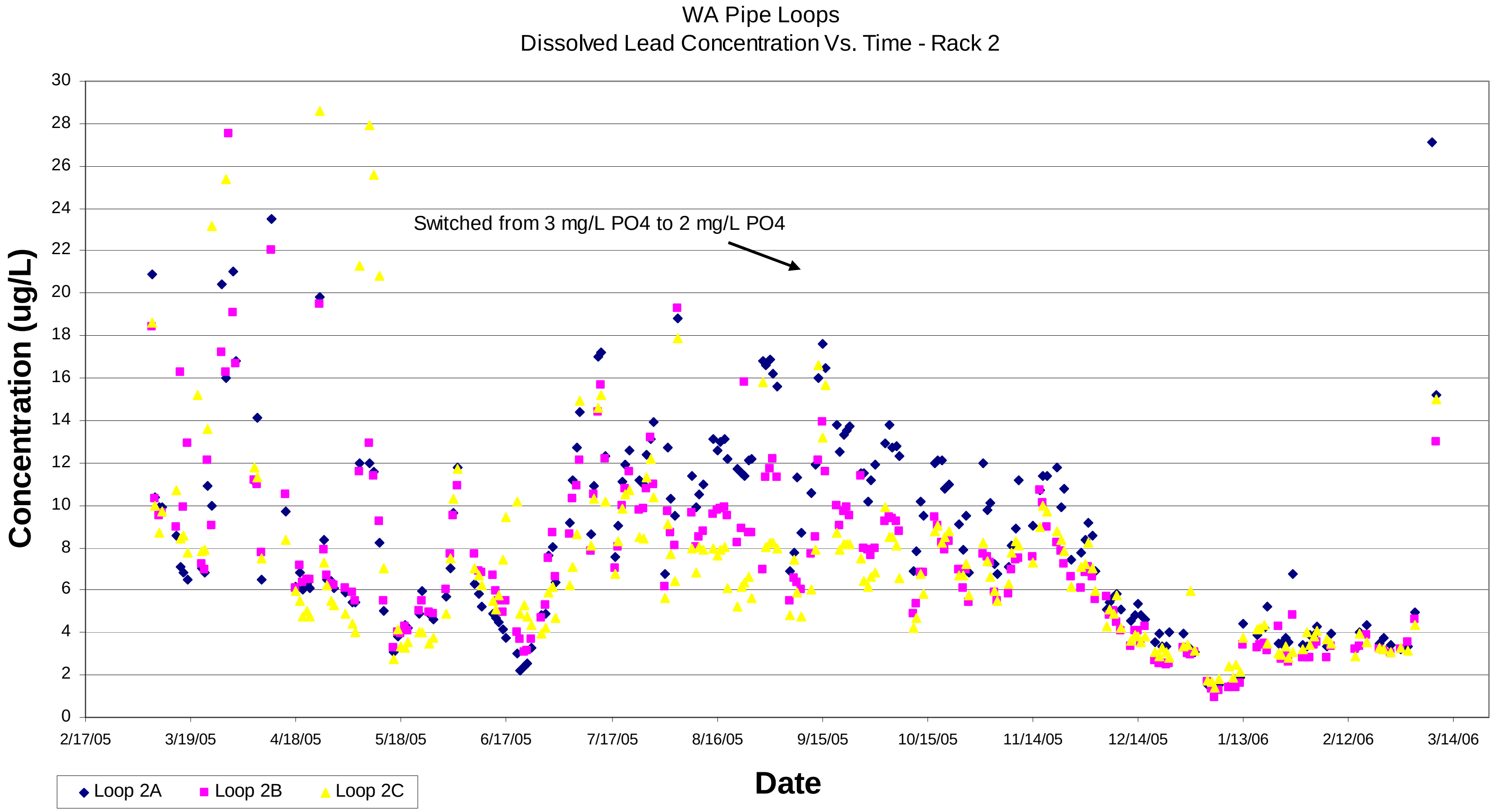






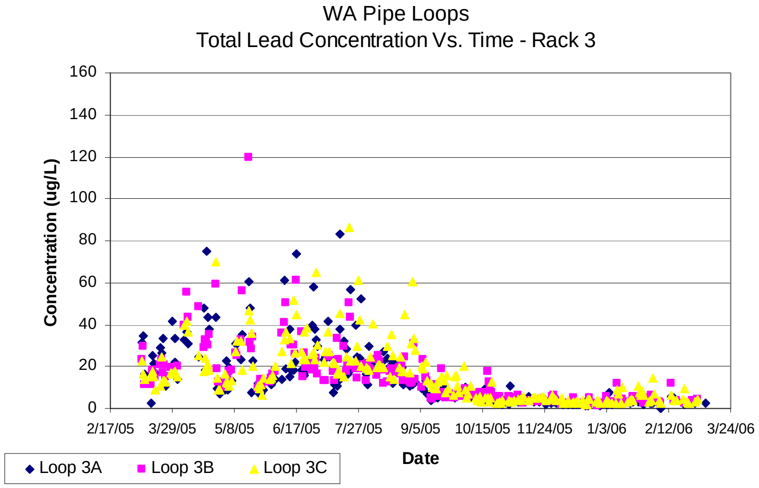
Source: Distributed to the TEWG by WA.

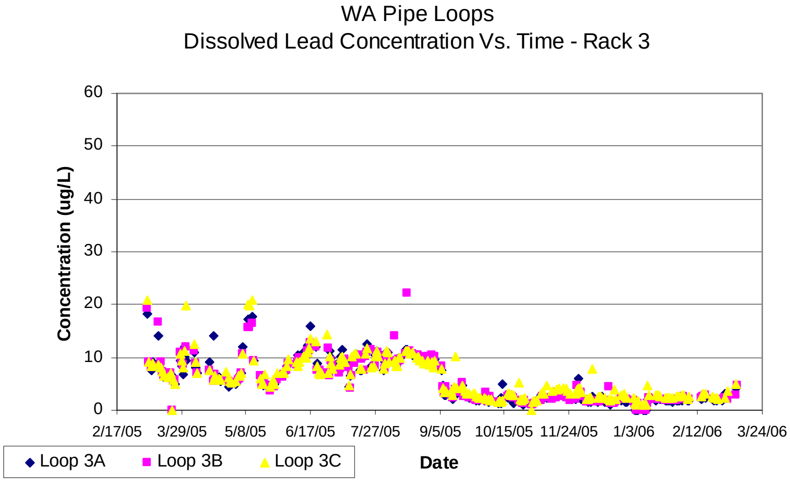
Exhibit 2.4.3b Dissolved Lead Results for Rack 2: Decrease Orthophosphate Over Time

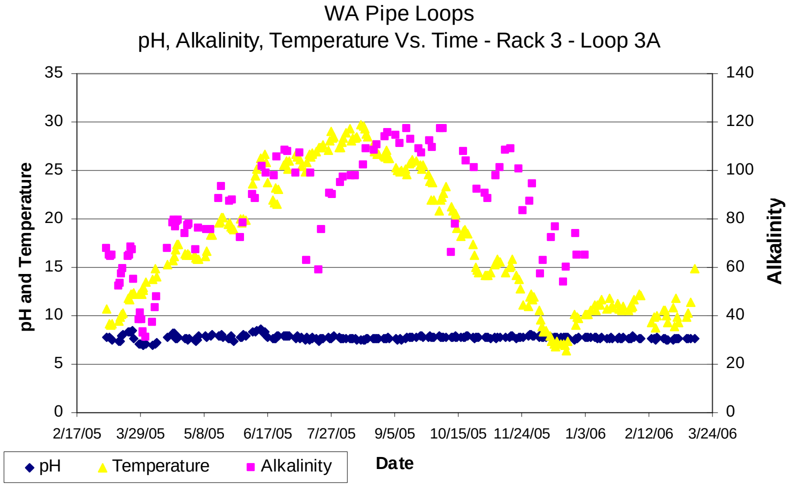


Source: Distributed to the TEWG by WA.

Exhibit 2.4.4a Results for Rack 3, Orthophosphate with Simulated Chlorine Burn

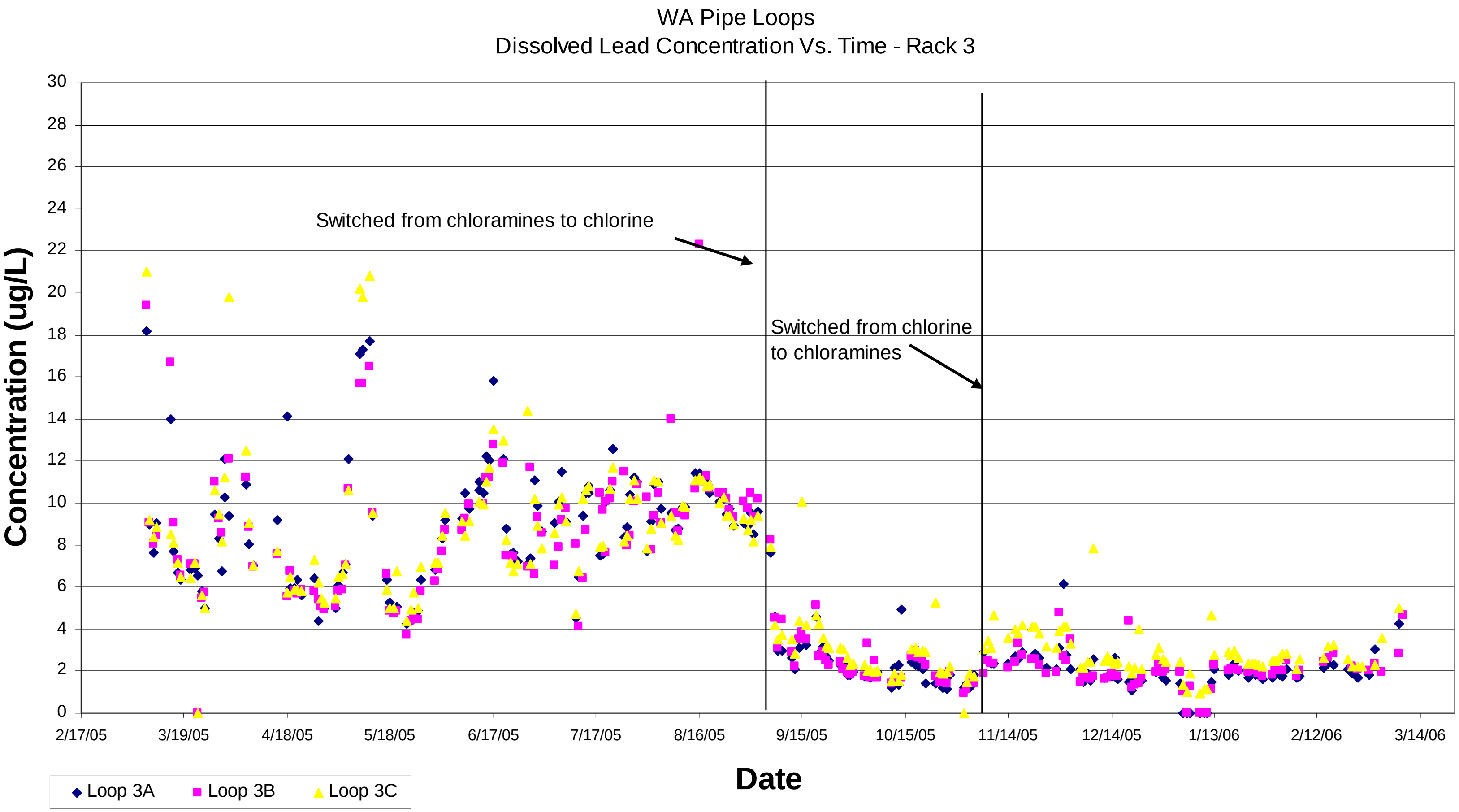






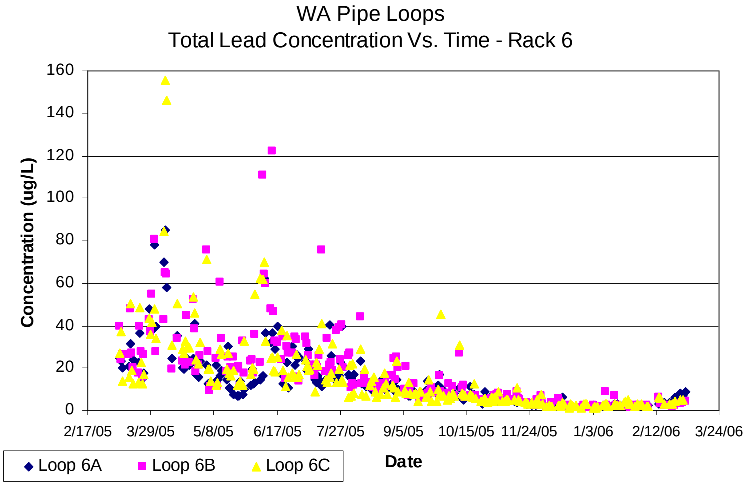
Source: Distributed to the TEWG by WA.

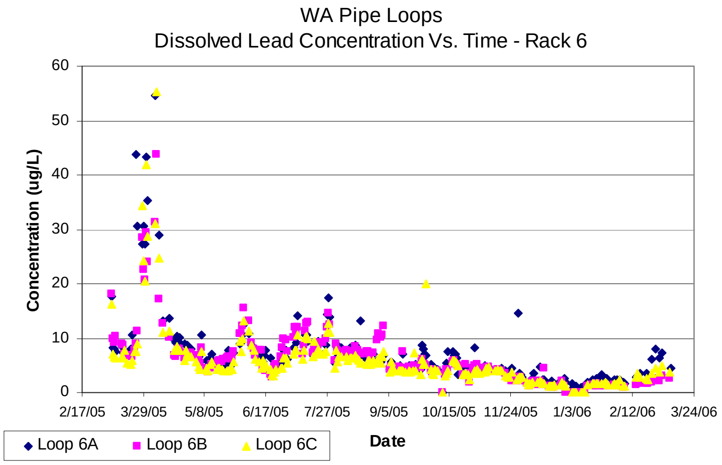
Exhibit 2.4.4b Dissolved Lead for Rack 3, Orthophosphate with Simulated Chlorine Burn

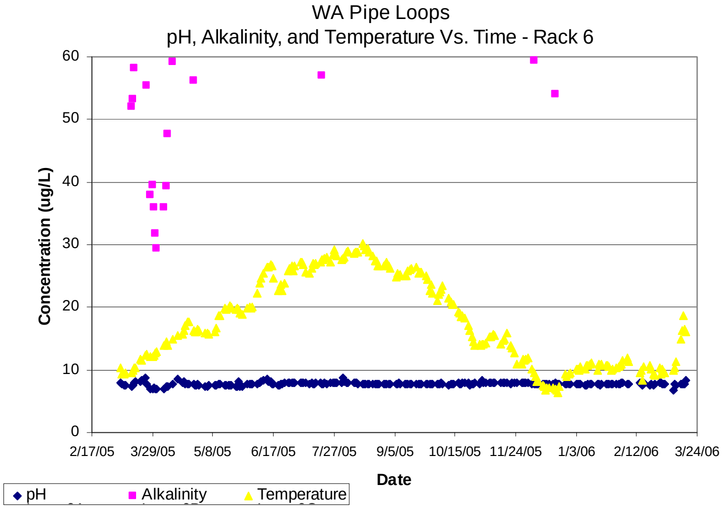


Source: Distributed to the TEWG by WA.

Exhibit 2.4.5a Results for Rack 6, High Chloramine Dose

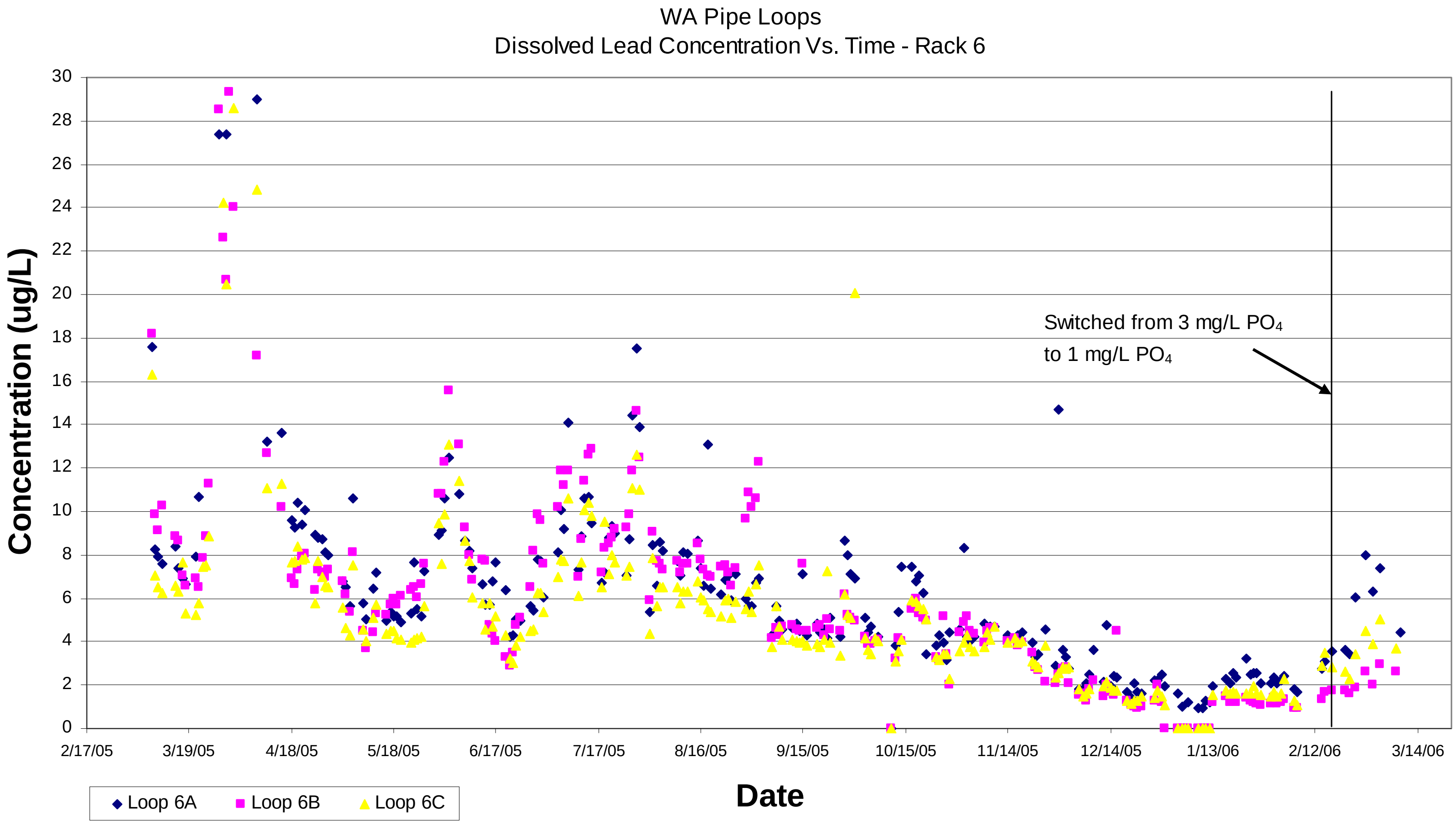

WA Pipe Loops
Total Lead Concentration Vs. Time - Rack 6


WA Pipe Loops
Dissolved Lead Concentration Vs. Time - Rack 6


WA Pipe Loops
pH, Alkalinity, and Temperature Vs. Time - Rack 6

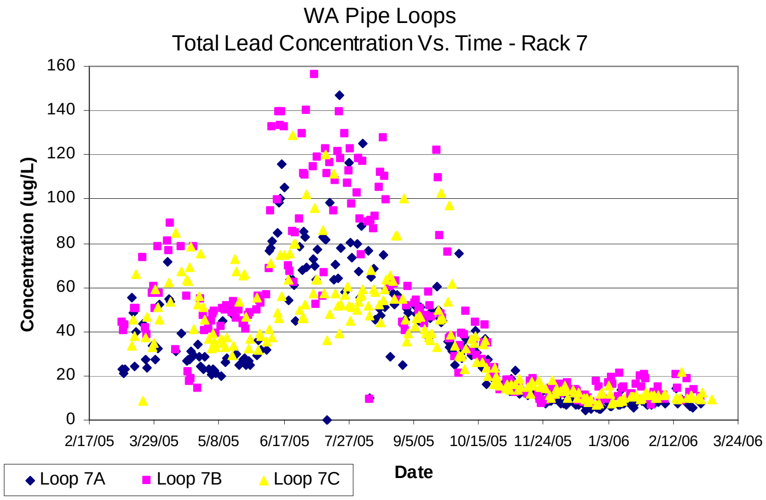
Source: Distributed to the TEWG by WA**.**

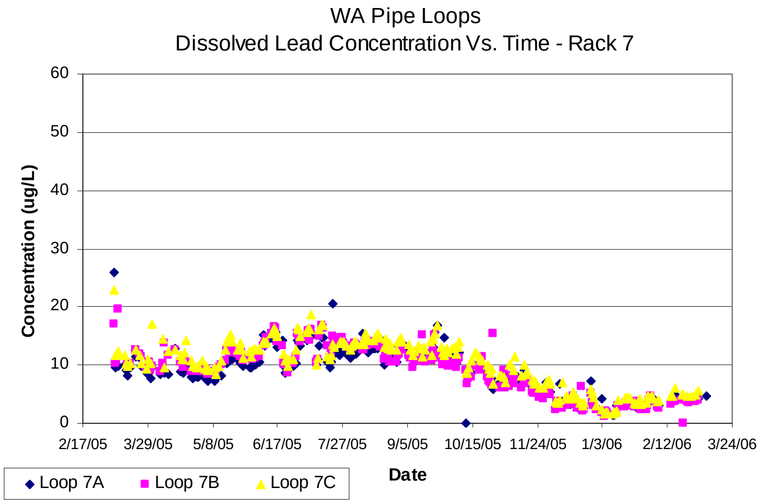
Exhibit 2.4.5b Dissolved Lead for Rack 6, High Chloramine Dose

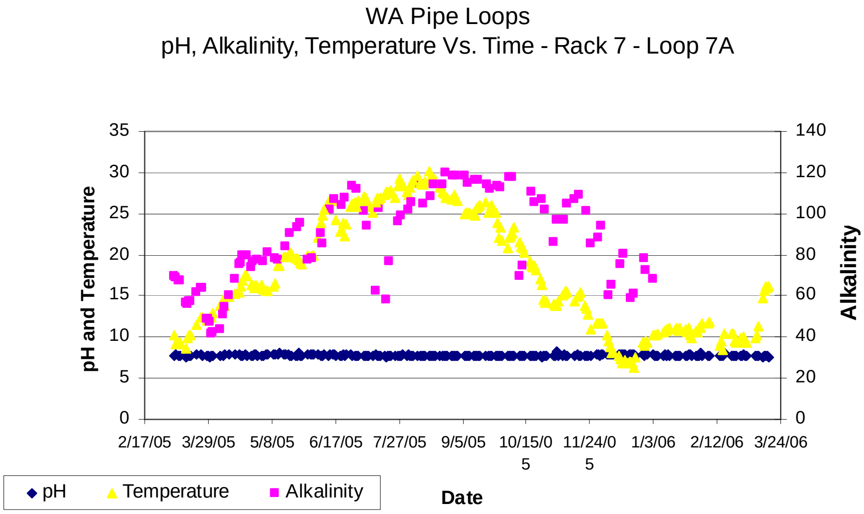


Source: Distributed to the TEWG by WA.

Exhibit 2.4.6a Results for Rack 7, Finished Water Control

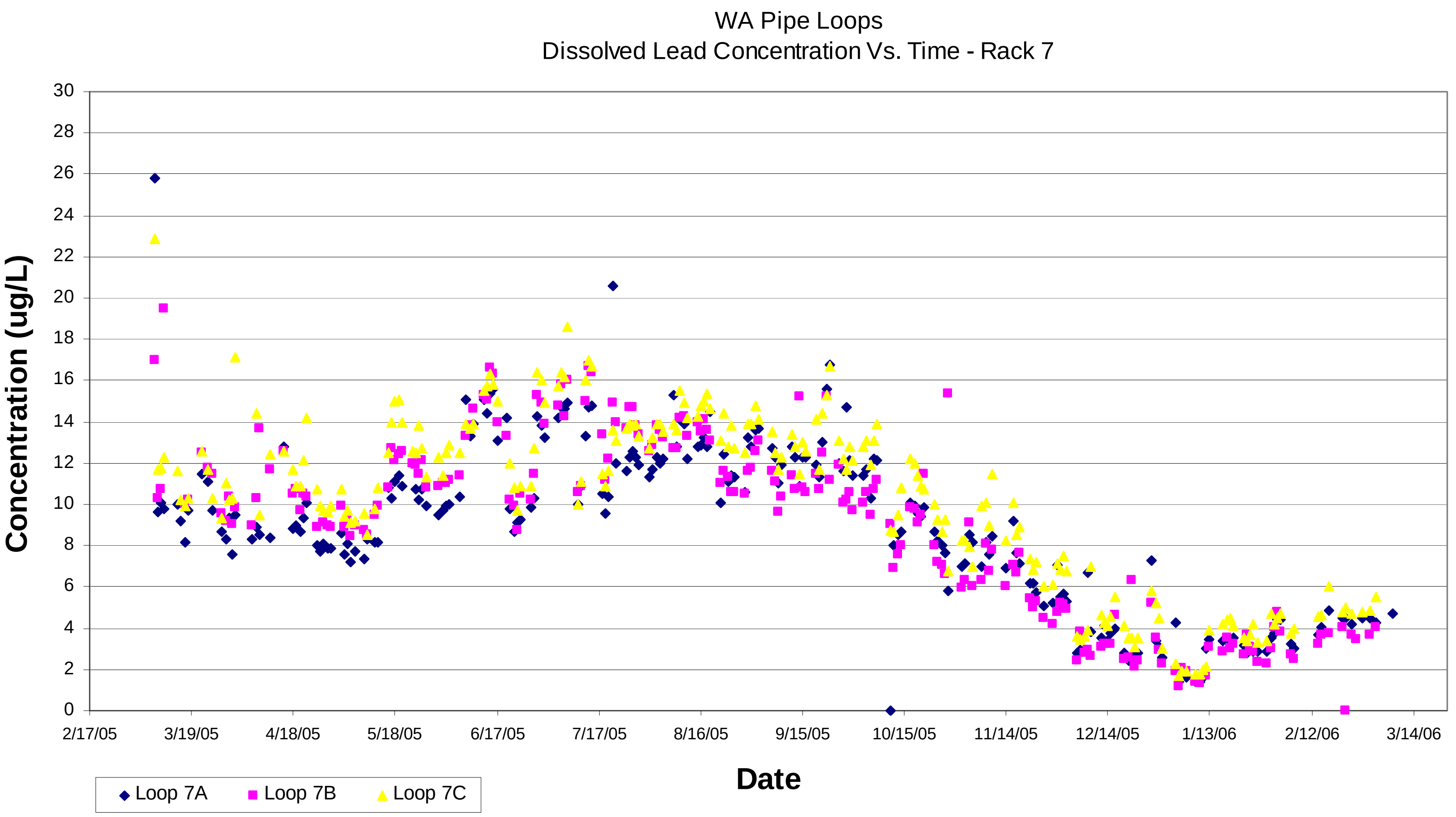






Source: Distributed to the TEWG by WA

Exhibit 2.4.6.b Dissolved Lead for Rack 7, Finished Water Control



Source: Distributed to the TEWG by WA

The results from Racks 2, 3, 6, and 7 confirm the effectiveness of orthophosphate treatment. The time needed to observe meaningful reductions in lead was longer than for the DCWASA circulation loops, although this may be attributable to the high orthophosphate dose of 10 mg/L used to accelerate results in the DCWASA loops. Total and dissolved lead both before and during orthophosphate treatment are generally lower in the WA loops compared to the DCWASA loops. However, the relative proportion of particulate lead in the WA loops was substantially greater than in the DCWASA loops. Only after substantial treatment with orthophosphate did the proportion of the particulate lead in the WA loops diminish. The presence of the higher particulate fraction may suggest a difference in loop fabrication techniques or handling of the LSL specimens prior to fabrication. Also, the pipe loops used in the WA study were allowed to dry out, while DCWASA's pipe loops remained wet. This may account for differences between the study results.

The WA data strongly suggests that there is no additional benefit associated with application of a zinc orthophosphate inhibitor as compared to the addition of a simple orthophosphate corrosion inhibitor. Moreover, the addition of the zinc component may serve to destabilize lead corrosion scales by accelerating the formation of friable lead particulates that are easily shed from the surface of the LSL.

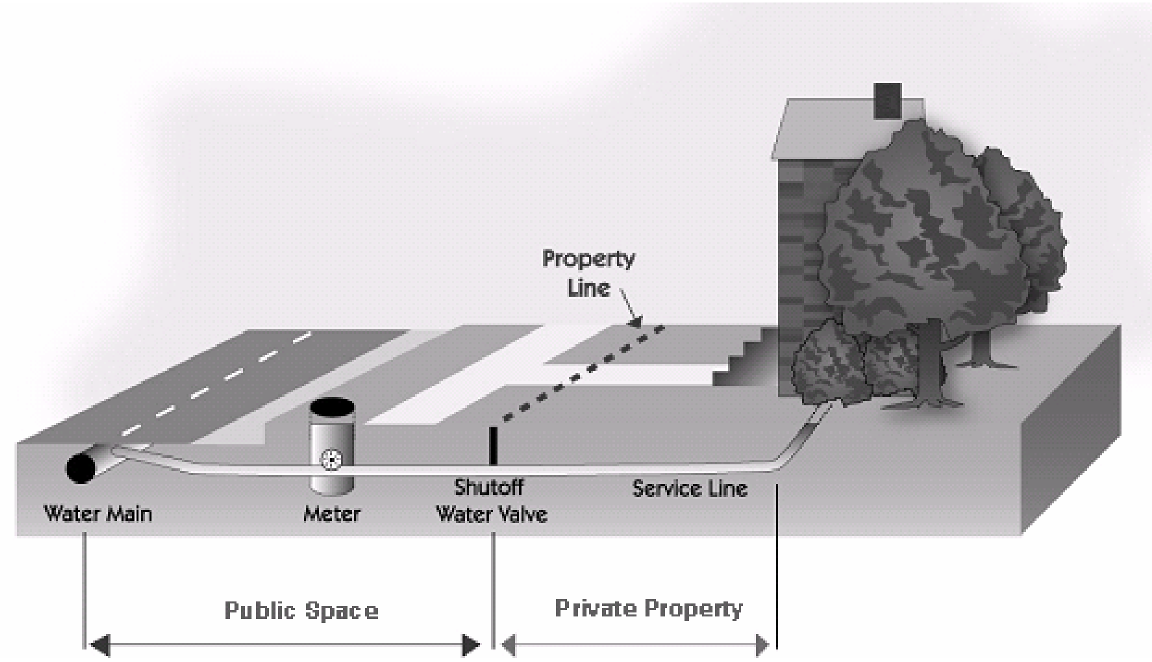
The WA testing shows that LSL lead release levels are sensitive to changing dosage levels of orthophosphate. An abrupt decrease in orthophosphate addition in early March 2006 resulted in rapid lead release. Also, results for Racks 3 and 6 show a measurable increase in lead when orthophosphate was reduced, although the dissolved lead concentrations remained below approximately 11 μg/L.

As in the case of DCWASA, Rack 3 of the WA Pipe Loop study demonstrates that a change back to chloramines after a simulated free chlorine burn can result in minor increases in lead release, although lead levels in Rack 3 stabilized fairly quickly.

2.5 Studies Related to Partial Lead Service Line Replacement

The configuration of a typical DCWASA water service line is shown in Exhibit 2.5.1. For LSL replacements, the LCR requires that DCWASA replace the public space portion and offer to replace the portion of the LSL on private property at cost. (When replacing an LSL on private property, DCWASA may only charge the property owner a price that reflects the cost of replacing the LSL, without adding any fees to the price.) Because of issues related to mechanical durability, the LSL is always replaced with a copper line. If the property owner elects not to have their portion of the LSL replaced, and DCWASA replaces all of the lead piping in the public space, the service line is considered to be a partial LSL.

Exhibit 2.5.1 Typical Water Service Line in the DCWASA System



Source: Reiber, Keefer et al. (2004).

Partial LSL replacement raises another corrosion issue, namely, the possibility that the coupling (or near coupling) of a partial LSL to the replacement copper line could create a galvanic corrosion cell that may accelerate corrosion on the remaining portion of the LSL. The concern is that coupling of the dissimilar metals may create a localized condition with the potential to elevate overall lead release rates above pre-replacement levels, which would not only defeat the intent of the replacement program but also exacerbate the situation.

2.5.1 Purpose of the Studies

Several technical questions were raised, both mechanical and EC, as to whether a partial LSL replacement may accelerate lead release from the remaining portion of the LSL, negating any benefit associated with the partial replacement. Two studies were undertaken to help address these questions:

- DCWASA performed a series of field tests that examined lead release in individual homes, both before and after partial LSL replacement.

- As subcontractor to EPA’s contractor, The Cadmus Group, Inc., HDR engineering conducted a series of laboratory based studies to examine the EC issues associated with partial LSL replacement to determine if replacing a portion of a lead pipe with copper piping might cause accelerated lead release.

2.5.2 Summary of Key Findings

- The potential mechanical disruption of lead corrosion scales on the remaining portion of the LSL is not a serious threat if reasonable care is taken in the cutting and removal process.

- Vigorous flushing alone following partial LSL replacement is sufficient to remove lead particulates generated in the cutting process.

- Well-aged DCWASA LSL specimens – including those that have been exposed to an orthophosphate inhibitor – are exceptionally well passivated and highly resistant to electrical perturbations of any kind.

- When a well-passivated LSL is coupled to a new length of copper tubing (as in a partial LSL replacement) the area of galvanic influence is very limited. The actual reach of the galvanic current is partially a function of the water quality, but is likely limited to the first inch of the LSL.

- A conventional plumbing dielectric junction removes even the minor corrosion risks associated with galvanic coupling. Any break in electrical continuity between the copper and LSLs effectively eliminates the potential for significant galvanic effect.

- A chlorine residual (free or combined) does elevate the galvanic effect on the LSL/copper couple by accelerating the cathodic current exchange process. The impact overall, however, is largely limited to the galvanic influence on the copper service line. The overall impact on the LSL surface is nearly imperceptible. Interestingly, water conductivity has a more important effect on the galvanic process than chlorine residual.

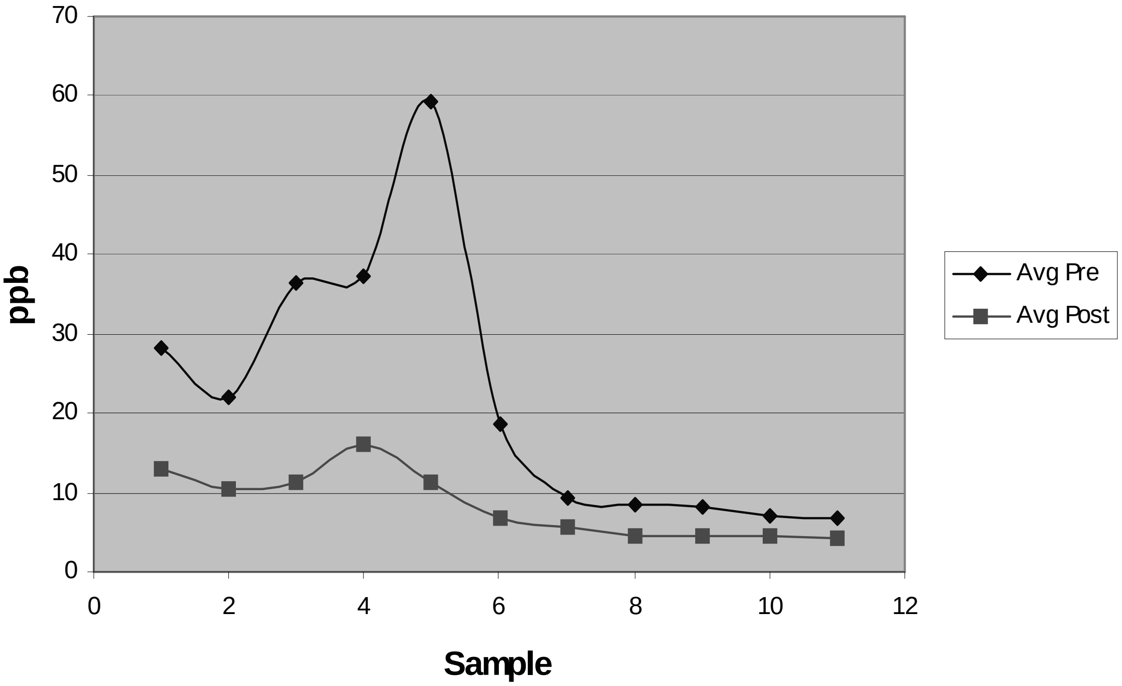
2.5.3 DCWASA Pipe Cutting Study

Early in the LSL replacement program, some homes that had undergone partial LSL replacement experienced high (>1000 ppb), albeit brief, tap water lead levels. The galvanic corrosion issue was raised as a potential cause, but it was also recognized that the method used to cut the lead pipe combined with insufficient flushing to remove lead particles derived from the installation process (the disturbance/exposure of the "cut" joint) may have contributed to the high lead levels. Out of concern over these post-partial replacement lead levels, the DOH ordered DCWASA to cease partial LSL replacements performed by cutting lead pipes, but allowed replacement of the LSL to the first threaded joint, usually to the water meter. Most of these replacements, however, did not meet the requirements of the LCR and could not be counted toward compliance with the LCR. To investigate the issue of partial LSL replacement, DCWASA put into place a program to assess lead release in a variety of homes undergoing partial LSL (Wujek, 2004).

The actual mechanics of the replacement process in this study involved a sequence of materials verification, homeowner notification and education, and lead profiling, followed by excavation and re-plumbing. Approximately 15 feet of lead service piping remained from the property line to the building face at each of the addresses. Three methods of cutting the existing service lines were used: hacksaw, tube cutter, and pipe lathe. It was also decided that as part of this study, the contractors performing the partial LSL replacement would vigorously flush the new line at for at least 15 minutes immediately following the replacement of the lead service.

Lead profiling was conducted before the partial lead service replacement, immediately after cutting and flushing, and regularly for a period of 14 days after the service lines had been replaced. As will be discussion in Section 3.3, lead profiling involves collecting and analyzing consecutive 1-liter samples from a kitchen tap following a 6-hour or longer stagnation period. Eighteen (18) pre-partial LSL replacement sampling profiles were conducted at seven addresses. Forty five (45) post-partial LSL profiles were obtained at these same addresses. A total of almost 700 individual lead measurements were conducted in this testing. Overall, the average results of the pre- and post-partial replacement sampling performed are shown in Exhibit 2.5.2.

Exhibit 2.5.2 Pre- and post-lead profiles for partial replacement sampling results



Source: Wujek, K. (2004).

The sampling results indicate that flushing immediately following a careful partial lead service replacement can reduce lead levels delivered to the household tap. The sampling also showed that the disturbance/exposure of the existing LSL where it is cut and connected to new copper piping does not necessarily increase lead levels in the delivered water. Analysis of the different cutting-method data suggests little difference in the final lead levels based on the manner in which the pipe was cut. Moreover, many of the problems previously attributed to partial LSL replacement (high transient lead levels immediately following replacement) can be avoided by vigorous flushing immediately following the replacement.

2.5.4 EPA/HDR Galvanic Corrosion Study

In theory, it is conceivable that replacing a portion of a lead line with a new copper service line could create a strong galvanic couple with an initial Cu/Pb electromotive difference in the 400 - 500 mV range (Reiber, 1991). If a significant portion of the remaining section of LSL were shifted in the anodic direction by even a fraction of this amount, there should be a substantial acceleration of the corrosion rate and associated metal release rates.

A study was initiated in late 2004 to assess the potential effects of both external currents and dissimilar metals contact on corrosion from LSLs. The final report of study findings is in Appendix C. The next several sections focus on the analysis of potential galvanic corrosion effects resulting from partial LSL replacement in D.C.

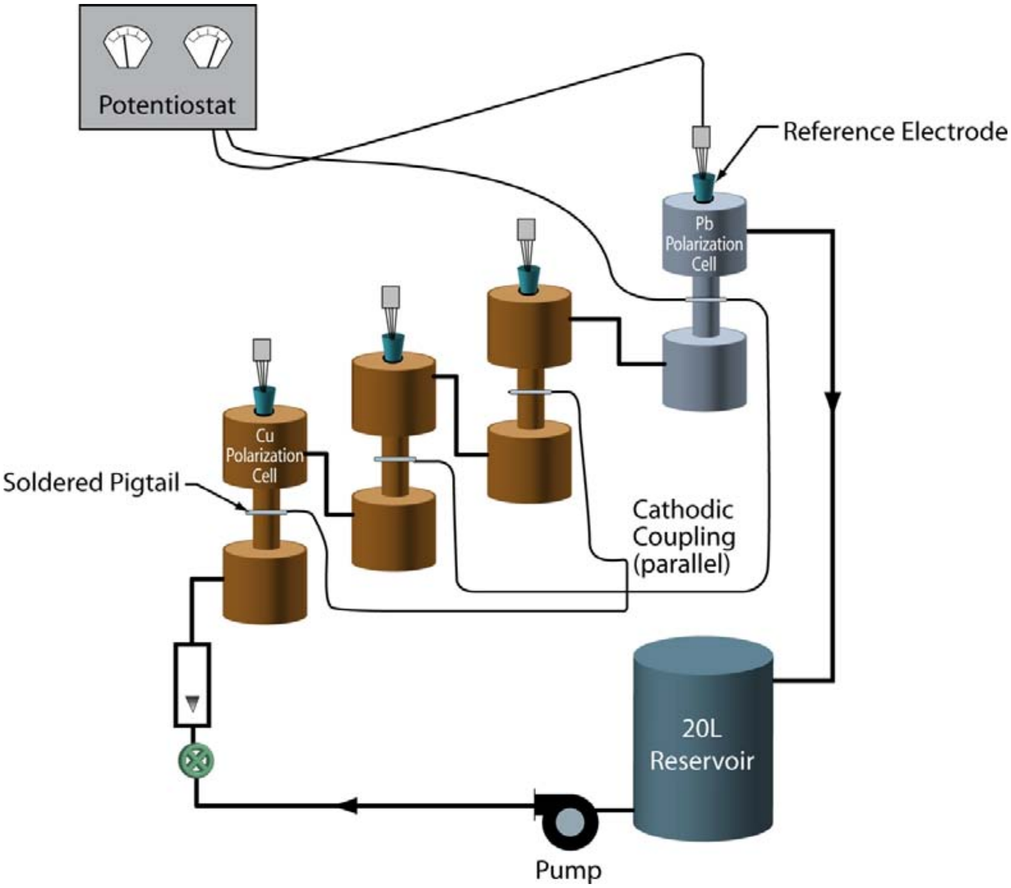
Research Protocol

At the core of this study was the search for the substantial EC impacts that, theoretically, should be associated with the galvanic and impressed currents imposed on the LSLs. The principal measure of these impacts would be a significant shift in the EC potential of the interior surface of the LSLs away from the freely corroding surface potential. This research did not attempt to create laboratory conditions that exactly replicate field conditions. Instead, the goal was to demonstrate whether or not extremes of grounding currents or galvanic coupling could affect the LSL electrochemistry. Testing was generally short-term, and designed to answer the question, “Can grounding and/or galvanic currents under a worst-case scenario meaningfully contribute to lead corrosion and metals release?”

The study used a series of EC cells which allowed the mounting of sections of LSLs under flow conditions and the placement of electrodes capable of quantifying shifts in surface potential. The surface potential measurement is sensitive, easy to use, and allows speedy measurements, but its principal advantage is that it is influenced only by the electrochemistry of the metal surface and the water in contact with that surface. It reflects the corrosion conditions of the underlying metal, which, in this case, is the factor most directly influenced by application of the galvanic and/or impressed currents in question.

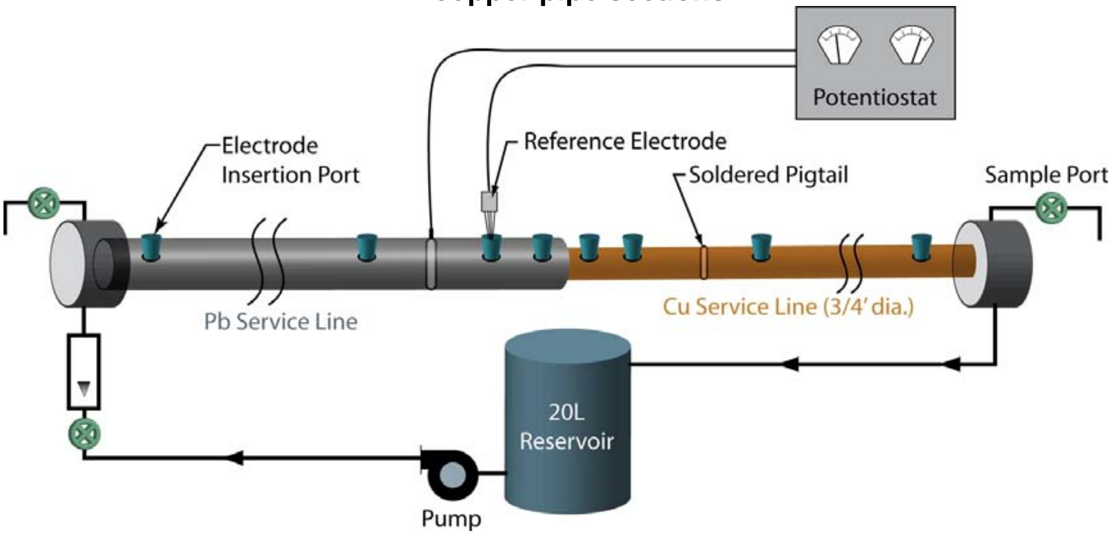
The galvanic coupling research utilized polarization cells in which individual sections of LSLs and copper tubing were mounted. These cells could be connected in a hydraulic series, with the electrical connections between the individual cells manipulated at will. Because the pipe specimens of each cell were not in direct contact, these cells were referred to as *indirectly coupled*. The importance of the indirectly coupled cells relates primarily to the ability to control cathode/anode ratios. It is critical to the appreciation of the galvanic-couple concern to understand that it is not the contact of dissimilar metals, per se, that creates the corrosion risk. Rather, corrosion risk is created by the fact that the cathodic surface (the more electropositive metal), if present in abundance, can affect a shift in the surface potential of the anodic surface, and any meaningful shift in the anodic surface in a more positive direction generates a higher corrosion rate on that surface. A second approach to galvanic testing utilized longer segments of LSLs and copper pipe coupled together in a manner similar to an actual partial LSL replacement. Because these pipe specimens are in direct contact, this type of testing is referred to as *directly coupled* pipe specimens. This form of testing yielded the most useful results about the nature of the galvanic couple formed between copper and LSL sections. The schematic presented in Exhibit 2.5.3 shows the arrangement of the individual cells, hydraulics and electrical connections for the indirectly coupled cells. Exhibit 2.5.4 presents a schematic showing the same for the directly coupled cells.

Exhibit 2.5.3 Schematic of a typical pipe rig configuration using indirectly coupled cells



Source: Galvanic Corrosion and Grounding Effects Study (Appendix C).

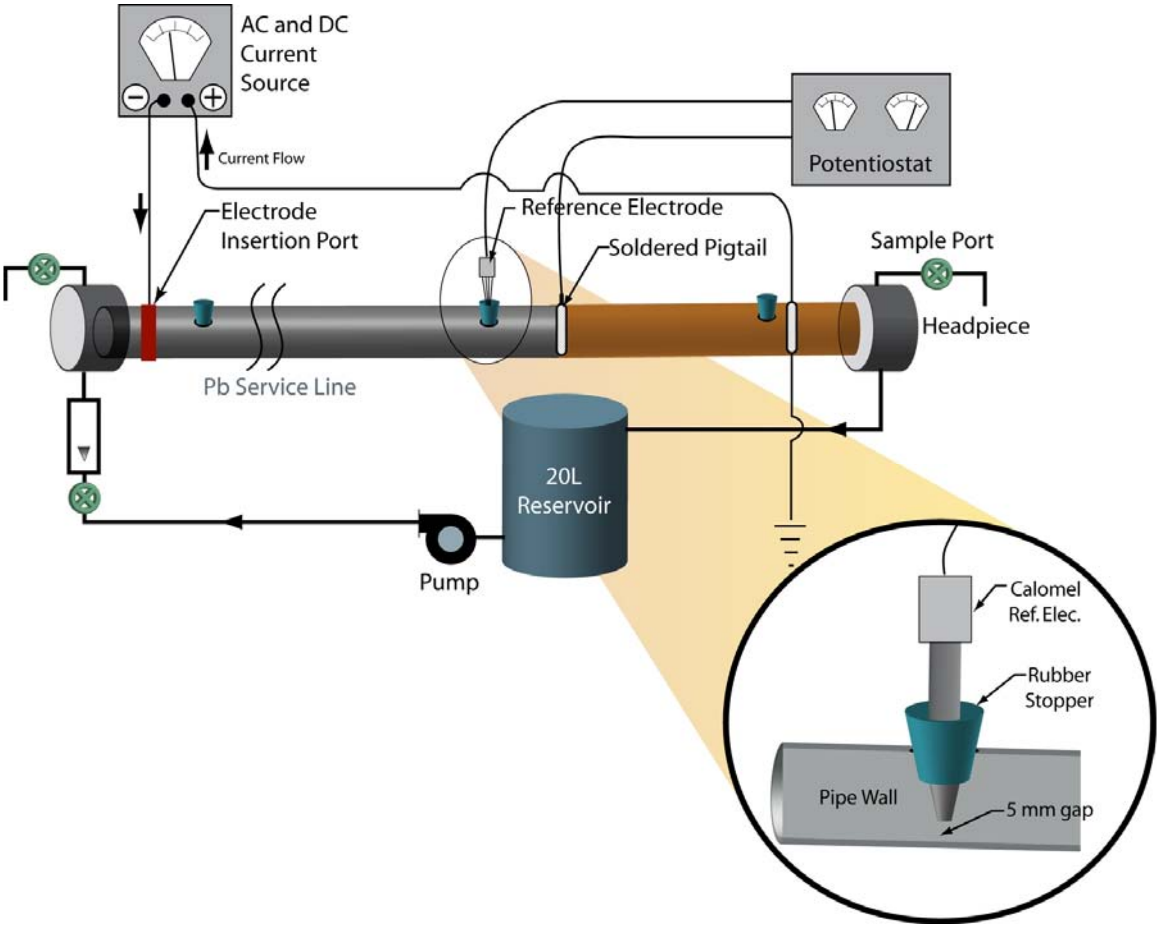
Exhibit 2.5.4 Schematic of a test rig showing the direct coupling of LSL and copper pipe sections



Source: Galvanic Corrosion and Grounding Effects Study (Appendix C).

A third type of test cell loop consisting of DCWASA LSL segments, new copper tubing, water reservoir, flow control and pumping hardware coupled to an AC/DC current generator and potentiostat was employed for the assessment of impressed currents on partial LSLs (see schematic in Exhibit 2.5.5). As in the previous cells, the LSL segments were modified to accept high impedance reference electrodes penetrating the pipe wall at multiple locations along its length. The electrodes monitor surface potential on the interior of the pipe relative to the electrolyte, yet allow for pipeline pressurization. Internal surface potential along the pipeline was monitored, while different current forms, amperages, voltages and grounding scenarios were applied to the test pipes.

Exhibit 2.5.5 Schematic illustration of impressed current test rig



Source: Galvanic Corrosion and Grounding Effects Study (Appendix C).

Using this equipment and its unique approach to simulating LSL corrosion, the study went on to investigate the impact of a variety of WQPs relative to galvanic action, including: pH, conductivity, disinfectant concentration and disinfectant type. It also looked at mechanical fabrication issues associated with partial LSLs, including the ratio of lengths of connected lead and copper pipe left in place following a partial LSL replacement, as well as the use of plumbing dielectrics to electrically isolate the lead and copper sections. Finally, the study investigated the impact of impressed currents, both alternating and direct, shunted through LSLs to ground.

Study Observations and Conclusions

In general, the study report shows that grounding and/or impressed currents moving along LSLs, and eventually leaving the pipe to ground, have no meaningful impact on internal pipeline corrosion and do not likely contribute to metals release. Secondly, while the study found that galvanic impacts can be substantial on unpassivated lead surfaces (freshly exposed surfaces), the magnitude of the impact on aged and passivated LSL surfaces (as well as on copper service lines) is so minimal as to be inconsequential. The study provides a strong basis for discounting claims and concerns relative to accelerated metal release associated with partial LSL replacement. Moreover, it shows that the long-debated controversy about the impacts of grounding currents is largely a non-issue. In short, partial LSL replacements and impressed currents are not meaningful concerns relative to optimizing distribution system corrosion control.

Specific observations presented in the final report in Appendix C are as follows.

- **Passivation**. Lead is a highly electroactive metal, and in pure form oxidizes extremely rapidly. An unscaled lead surface, even under natural environmental conditions, has an exceedingly high initial corrosion rate. Lead also passivates strongly and quickly. Observations in this study suggest that meaningful passivation on LSLs can be achieved within a matter of days. Well-aged DCWASA LSL specimens – especially those that have been exposed to an orthophosphate inhibitor – are exceptionally well passivated and highly resistant to electrical perturbations.

- **Lead Electrochemistry**. Passivated LSL specimens are highly polarization resistant – meaning that it takes an exceptional surface perturbation to affect the underlying corrosion rate. The actual degree of polarization resistance expressed as a Tafel Value 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.

- **Area of Galvanic Influence**. When coupled to a new length of copper tubing (as in a partial LSL replacement) the area of galvanic influence on a well passivated LSL is likely limited to less than the first inch of LSL pipe in the immediate vicinity of the coupling. The galvanic area of influence on an unpassivated LSL specimen is larger, but likely limited to the first few inches of pipe in the vicinity of the coupling. As the LSL passivates, the area of galvanic influence decreases rapidly. The period of transition can be as short as a few days under normal distribution system conditions. A potential reason why galvanic impacts do not generate a more significant corrosion response relates to the respective geometries of the anodic and cathodic surfaces of the pipeline couple. Because sequential pipelines (LSL to copper tubing) are connected at only a single location, 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 is relatively brief. Hence, even the meager galvanic effect is short-lived.

- **Cathodic Effect of Copper Pipe**. The cathode/anode ratio on a well passivated LSL surface is unimportant relative to the galvanic effect. This means that even an exceptionally long length of copper pipe connected to a partial LSL does not elevate the galvanic effect. (It had been argued that long lengths of copper service line connected to short LSL sections would exacerbate the galvanic effect.)

- **Water Quality and Galvanic 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. The impact overall, however, is largely limited to the galvanic influence on the copper service line. The overall impact on the LSL surface is nearly imperceptible. Interestingly, water conductivity has a more important effect on the galvanic process than chlorine residual. The area of galvanic influence on the LSL specimen is marginally expanded as the conductivity of the electrolyte (water) increases, while the area of influence on the copper service line is substantially expanded. This is because the higher conductivity lessens the resistance of the electrolyte circuit (water), expanding the "reach" of the galvanic current. DCWASA distributes a low conductivity water (< 200 microSiemens), which, in part, explains the minimal galvanic impacts observed.

- **Dielectric Effects**. While galvanic impacts relative to DCWASA partial LSL replacements 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.

- **Impressed Current Effects.** Impressed currents (AC or DC) on LSLs and copper service lines, including grounding type currents, have no impact whatsoever on the internal corrosion of the household service lines (or any other plumbing appurtenance for that matter). There is likely no acceleration of corrosion associated with the conventional practice of electrical system grounding to household water systems.

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