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Design and Testing of USEPA'S Flint Pipe Rig for Corrosion Control Evaluation

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Abstract

The US Environmental Protection Agency's Office of Research and Development designed, fabricated, and installed four pipe rigs in Flint, Mich., to help the city optimize corrosion control. The lead service line (LSL) pipe loops were constructed of polyvinyl chloride pipe and fittings and welded steel channel frames. Each pipe rig consisted of four approximately 4 ft-long sections of 0.75 in. inside diameter lead pipe that were excavated from homes fed by the Flint distribution system. The rigs were operated on a set daily on/off schedule such that a specified amount of water passed through each pipe using a solenoid valve-operated timer system. Solenoid problems resulted in sporadic and enhanced daily flow volume (but no flow rate changes) that prevented restabilization of pipe scales. Lead levels were relatively sporadic and statistically different during this period. After the solenoids were replaced, the lead pipe rigs were successfully conditioned, and lead release with consistent influent water chemistry became relatively stable. Average lead levels across all 16 loops ranged between approximately 2 and 5 µg/L after the solenoid replacement. The lead results were consistent with levels measured from LSLs from homes in the city during sequential sampling efforts.

Keywords

corrosion; lead; pipe loop; rig

Lead is a toxic metal, particularly impacting young children and infants. Adverse effects of ingesting lead in drinking water are well known (Triantafyllidou et al. 2014, Triantafyllidou & Edwards 2012). Young children are especially sensitive to the effects of lead because their bodies are still developing and vulnerable to its neurotoxic effects.

Finished water leaving a drinking water treatment plant (WTP) may meet water quality standards; however, changes in the water chemistry, flow rate, and other factors can result in the release of lead from leaded plumbing materials (e.g., lead service line [LSL], leaded

SUPPORTING INFORMATION

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solder, fluxes, pipe fittings, valves, fixtures) as it passes through the distribution system. In addition, water chemistry can shift because of changes in source water or treatment, and multiple treatment plants or wells may exist in each system, causing zones of differing water chemistry that may vary over time and that may sometimes be difficult to define. These changes can lead to elevated lead and copper scale release (Schock & Lytle 2011, AwwaRF 1990).

In 2013 in Flint, Mich., as a way to reduce the city's drinking water costs, a major decision was made to change the source water from the Detroit Water & Sewerage Department (DWSD) to the Karegnondi Water Authority (KWA). However, at the time of this decision, the KWA pipeline to transport water from Lake Huron was not in place. Flint officials decided to treat their backup water source, the Flint River, using the city's existing drinking WTP and discontinue DWSD's corrosion control practice of adding orthophosphate as an interim solution in April 2014. These major source water quality and associated treatment changes to the city's finished drinking water led to a loss of corrosion control and elevated lead release (Torrice 2016). As part of the response to these events, the US Environmental Protection Agency (USEPA) provided recommendations for studies that would develop a detailed assessment of problematic lead release sources, corrosion control optimization studies for the immediate future with Great Lakes Water Authority (GLWA) water (formerly DWSD), and a potential future transition to a new water supply (Lytle 2016, Schock 2016, Schock & Lytle, 2016, USEPA Flint Task Force 2015). In 2017, the City of Flint decided to continue purchasing GLWA water for the foreseeable future.

To assess and optimize the City of Flint's corrosion control treatment, the USEPA Office of Research and Development Drinking Water Treatment and Distribution System Branch (USEPA/ORD/DWTDB) in Cincinnati, Ohio, designed, fabricated, and installed four pipe rigs, each holding LSLs to be used in Flint. These specific rigs used LSLs that were carefully removed from service within the Flint water distribution system. Each pipe rig consisted of four approximately 4 ft-long sections of 0.75 in. inside diameter (ID) lead pipe that were excavated from homes served by the Flint water distribution system. Using new lead pipes in the rigs was determined to be undesirable because the scale and deposits that built up on LSLs over decades of service in Flint could not be reproduced in a rig setting with the current water chemistry. Scale and deposit properties (e.g., porosity, structure, layers, minerals, composition) were also analyzed to understand lead release to drinking water. This report summarizes the design considerations for the pipe rig system, operational adjustments that needed to be made, and the sampling protocol. Also described are metal release results obtained for the pipe loop stabilization period and verification of performance that represents in situ conditions representative of LSLs throughout the Flint water distribution system.

BACKGROUND

Historically, several corrosion control assessment tools have been available for various kinds of drinking water internal corrosion assessment, including electrochemical methodologies, coupon testing, and weight loss assessments (AwwaRF-TZW 1996; Reiber et al. 1996, 1988; Reiber 1995; Sandvig 1995; Silverman 1995; Temkar et al. 1987; Singley et al. 1984). A

more complex approach, but one that offers an opportunity to better simulate lead release from LSLs and premise plumbing, includes the use of “pipe loops” or “pipe rigs.” Many different configurations of pipe rigs have been used in the past and have been tailored to answer specific questions (Welter et al. 2015; Kim et al. 2011; Hayes 2010; Cantor 2009; Heberling & Baron 2009; Heberling et al. 2009; Atassi et al. 2004; Hozalski et al. 2003; AwwaRF 2002, 1999, 1990; Sorg et al. 1999, 1998; MacKoul et al. 1995; Wysock et al. 1995; Yannoni et al. 1995; Kelkar et al. 1994; Wysock et al. 1991; Carruthers & Jackson 1981). An overview of pipe rig design and operational frameworks has been reported by Eisnor and Gagnon (2003).

A pipe rig approach using exhumed pipes was chosen for several reasons. Tap sampling in Flint indicated that the very serious lead release was coming from the damaged scales in the lead pipes, which were widespread in the Flint water distribution system. Therefore, repairing those scales to mitigate lead dissolution and particulate release was a high priority. To realistically achieve this simulation, exhumed LSL segments from the Flint water distribution system were used as the “pipe loops” installed in the rig, rather than using new lead pipes. Prior experience with pipe rigs in other USEPA studies suggested that when the questions revolve around scale transitioning and trying to predict the impact of water chemistry adjustments on contributions to Pb(II) levels at the tap, using already-scaled pipes representing what was actually delivering water to the residences provides the most accurate simulation. It was also known from USEPA scale analysis work, discussed later, that the dominant protection mechanism against lead release from LSLs was an amorphous multi elemental barrier deposit, rather than a true, mineralogically simple crystalline passivating film. Such layers almost certainly take extensive time to form and evolve; therefore, fresh surfaces were not believed to be a desirable starting point for comparative studies of treatment effectiveness.

In the short term (months), there were limited objectives for the pipe rigs:

- Restabilize the pipe scales to represent in situ conditions for residential LSLs
- Assess the level of improvement of the adjusted orthophosphate dose and pH control
- Help assess whether the dominant mode of lead release is soluble or particulate
- Provide a stable starting point for future corrosion control optimization testing with the selected future water source

Comparison of observed lead levels in the pipe rigs provided additional insight into the lead release mechanisms for LSLs throughout the Flint water distribution system. When stabilized, exhumed pipe loops should be confirmed to correspond well in terms of metal release to directly observed lead levels in LSLs in the distribution system determined through profile sampling; then, as treatments or water quality conditions are adjusted for experimental test purposes, much more confidence can be had in the predictive accuracy of the simulations when extrapolated system-wide.

MATERIALS AND METHODS

Pipe rig design and construction

Four Flint lead pipe rig systems were designed to enable the evaluation of several combinations of water chemistry and orthophosphate dosing scenarios, enabling the optimization of lead corrosion control conditions and evaluating the impact of source water changes on lead corrosion. The pipe rigs were named A–D, shown in Figure 1 (photograph of two rigs) and Figure 2 (schematic of one rig). Each pipe rig consisted of four approximately 4 ft-long 0.75 in. ID lead pipe sections. Lead pipe sections were extracted from four residences in Flint, and each of the four rigs was set up with lead pipe segments from the same home. Pipes from homes in different water quality zones within Flint’s distribution system were selected as differentiated by typical historical levels of free chlorine in associated distribution system water quality zones. Other major water quality parameters that were measured throughout the distribution system, including calcium, pH, or alkalinity, were observed to be generally consistent with the water quality as it entered the Flint distribution system. Specifically, two rigs were outfitted with pipes from homes believed to be supplied with water having a consistent “high” free chlorine residual, and two rigs received pipes from homes believed to receive water with “low” chlorine residual, based on city records and free chlorine field measurements, to capture differences in pipe scale behavior. The reason for this differentiation was a concern that, because elevated chlorine levels and lack of orthophosphate had occurred during the time of major water chemistry change in the Flint River source (Lytle 2016, Lytle & Schock 2016), there was at least a theoretical possibility that the oxidation–reduction potential at the pipe surfaces in these areas may have been sufficient to form patches or a layer of Pb(IV) oxides (PbO₂). If this was the case, the mineralogy of the scale and characteristics of metal release with the current or future Flint-treated water could be influenced.

The pipe rigs were constructed at USEPA’s Andrew W. Breidenbach Research Center (AWBERC) in Cincinnati, Ohio. Each rig’s pipe rack support frame was constructed using a 2 in. by 2 in. galvanized steel tube with locking casters (Figures 1 and 2). A channel¹ was installed across the length of the rig for support and mounting purposes. The pipe rigs were initially constructed by a USEPA contractor many years ago. All components of the original rigs were totally removed to avoid contamination concerns and reconstructed to include new design improvements and site-specific needs. As a result, only the original support frames constructed by a USEPA contractor were reused in the Flint rigs. The frames were reused to save time and funding concerns and to provide a rapid response to Flint’s need. Each pipe loop was constructed identically and consisted of polyvinyl chloride (PVC) pipe and fittings. All pipes and fittings were schedule 80 PVC. The installation of PVC pipe was in accordance with the manufacturer’s technical data and printed instructions. PVC pipe joints were solvent cemented or threaded. In making solvent cemented connections, the area was wiped clean, and any moisture was removed. Burrs, created by cutting the pipe, were removed. Solvent cement joints were in accordance with ASTM D2855 (ASTM 2015). All solvent cement joints were performed in a room-temperature-controlled (~22°C)

¹Unistrut™, Unistrut Midwest, Cincinnati, Ohio

manufacturing shop. In making solvent cement connections, the solvent cement was carefully applied to ensure that no spills occurred on the pipes or fittings. Any excess cement was immediately wiped from the pipe and fitting before connecting. Pipe and fittings were undisturbed for the curing time required per manufacturer specifications. In threaded connections, tape² was applied on threads, and threaded connections were not overtightened. The valves and fittings sizes necessary to construct the rigs are summarized in Table S1 (supporting information). This table does not incorporate the components for the physical rack supports or the minor fittings or PVC pipe sections needed to interconnect them.

All valves were mounted in such a position that valve position indicators were plainly visible when facing each rig. Check valves were schedule 80 PVC true union ball-with-socket or threaded ends. Each loop contained normally closed solenoid valves.³ Solenoids were slow-closing two-way forged brass bodies with National Pipe Thread end connections (model number 8221G5MO). Solenoid valves were powered to open by a National Electrical Manufacturers Association-rated enclosure, suitable to operate on a 120 V, single-phase, 60 Hz power timer relay.⁴ Solenoid valve design specifications included a 5 psi pressure differential to open and a 3 psi minimum operating pressure. Rotameters were durable, one-piece, clear acrylic construction, with easy-to-read scales graduated in gallons per minute with threaded end connections. Two types of rotameters were installed in each pipe loop rack: one influent rotameter (1 in. threaded end connection) and four individual loop rotameters (1/2 in. threaded end connection). A six-element static mixer was installed in each pipe loop to properly blend water treatment chemicals with influent water, and PVC lab cock valves were used for all sampling locations (Figures 1 and 2, parts A and B).

After fabrication, each loop was pressure tested at 65 psi. All visible leaks during the test were repaired, and the pressure test was repeated. After all repairs were completed, each rig was packaged for shipment (Figure 1). The rigs were freight-shipped to the City of Flint WTP. Upon delivery, USEPA staff members unpacked and positioned each rig in a predetermined location within the WTP. The pipe rigs were installed with lengths of 0.75 in. ID schedule 80 PVC pipe until the LSLs were available. Two plant-pressurized water taps were used to supply influent source water (GLWA water with additional orthophosphate added by Flint to bring the total level to approximately 3.6 mg PO₄/L) to each rig. A two-way garden hose plastic splitter was attached to each tap to supply each rig. A lead-free garden hose was then attached to each rig's influent ball valve. A full operational test was then performed on each rig, allowing for the identification and repair of any leaks that may have occurred during shipment. Garden hoses attached to the effluent side of solenoid valves were used to carry waste to a sanitary drain where an air gap was always maintained. After all rigs were installed and were deemed leak-free, they were ready for LSL installation.

LSL extraction

LSL segments from four homes were carefully extracted and inserted into the pipe rigs. In addition to pipes for the rigs, a section of pipe was also cut and preserved for solids and

²Teflon™, Dupont, Wilmington, Del.

³ASCO Valves 8221G5MO, Florham Park, N.J.

⁴Tork EW101B, NSI Industries, Huntersville, N.C.

surface analysis. Full LSLs were selected by USEPA from Flint's distribution system water quality records. On the basis of historical distribution system water quality records and the city's LSL removal schedule, two homes were situated in low-chlorine zones and two sites in high-chlorine areas. The sites were selected to capture potential differences in scale, representing the variability of water quality in Flint's distribution system.

LSL excavation was performed by an experienced city contractor (Figure 3). The vast majority of the overburden was removed using a backhoe through an iterative process of carefully skimming and probing earth under close supervision to ensure that the shovel did not strike the LSL. Final overburden removal/cleanup was accomplished manually with shovels. The contractor carefully removed earth from under the LSLs at approximate 4 ft intervals such that a standard manual pipe cutter could be used to cut the LSL to the target length.

Each segment of pipe was handled in a manner that permitted retention of knowledge regarding flow direction (curb to house), and segment order and was marked accordingly. LSL sections were kept level to minimize damage to the scale layers, and no water was left in the pipe. Each LSL segment end was plugged, empty, with a moistened sponge to maintain internal moisture, as experience has shown that sloshing water in a pipe can disturb pipe surfaces. The ends were then wrapped with a cloth, covered with a PVC cap, and enclosed with a plastic bag secured to the pipe with tape. Each sequential segment was then marked for flow direction and coded to identify the physical address. After all the pipes were collected, they were immediately transported by vehicle to the WTP and installed into the pipe rigs.

The LSL sections were each placed into a pipe rig at the WTP. Each rig received four pipe sections from a single site. Clear tubing⁵ was used to connect the LSL segments to the PVC fittings. The tubing was selected to fit onto the LSL and to withstand system pressure of approximately 50 psi. The other end of the tubing was then slid onto a plastic fitting, which, in turn, was sized to form a seal with the PVC coupling on the pipe rigs. Both ends of the tubing were further secured using quick-release hose clamps.⁶ Once the LSL segments were installed, the pipe rig was leak-tested and adjusted to the target flow conditions. Training of field samplers was provided for rig operation and sampling, and a logbook was kept on site for recordkeeping.

Pipe rig operation

The pipe rig was operated on a cycle that was intended to simulate periodic water demand in a "typical" household of four residents. The rigs were operated automatically using timer-controlled solenoid valves (Figure 2, part A) that opened (flow) and closed (stagnation) according to the schedule outline in Table 1.

When the solenoid valves were in the open position, the water flow rate was set to 1 gpm per pipe (or 4 gpm total per each rig) using a flow control valve (FCV-1-1) and flowmeter

⁵Tygon®, Malvern, Pa.

⁶McMaster-Carr 5322K16, Elmhurst, Ill.

immediately upstream from the lead pipe section (Figure 2, part A). One 60 min and five 30 min flow periods were established, resulting in a total flow volume of 210 gpd through each pipe (Table 1).

After LSL installation and leak testing, the rigs were run on schedule automatically, with minimal interference by USEPA personnel. This was intended to be the “recovery time” during which the existing pipe scale layers could be conditioned and recover from the disturbances associated with the exhumation. Sampling and monitoring were performed at a monthly frequency. During this time, it became apparent that the solenoid valves were opening but not consistently closing automatically. This issue resulted in total flow volumes well in excess of the target of 210 gpd/pipe. Various theories were postulated about the problem, and efforts were made to address it. It finally became apparent that the system pressure was great enough that the solenoid valves simply could not reclose against the flow pressure. A decision was made to replace all four solenoid valves with a single motorized ball valve. This was implemented and has proved effective in correcting the total daily flow volume to target values. This modification is documented in Figure 2, part B. Table S1 lists the primary plumbing components for the final design with the motorized ball valve modification.

Provisions were made in the design and construction of the pipe rigs to feed orthophosphate or other possible corrosion control treatment adjustment chemicals. This was carried out by incorporating two feed ports with check valves (Chem-X-1a/1b and Chem-X-2a/2b) to each of the four loops per pipe rig. These ports were located immediately upstream of the static mixers to provide for thorough mixing of any additions before interaction with the LSLs. This feature was not used in Flint during the stabilization period (April 2016–August 2017) described here. However, it is anticipated to be important for the later use of the pipe rig for corrosion control and water quality impact testing. If chemicals are to be injected, a peristaltic pump can be connected to each pipe via the chemical injection port (Figure 2, part B). One 20 L carboy will be required for each pipe rig (four total pipe segments), depending on experimental design. The 20 L carboys will contain a stock concentration of orthophosphate or other additions in deionized water. The stock concentration and feed rate should be determined on the basis of the desired concentration in each pipe as well as the availability of staff to refill the carboys. If staff availability is limited, the stock concentration in each carboy should be more concentrated so that the solution lasts longer. Chemical feed tubing should be installed in the chemical injection port through the pump head and into the carboy. Power for the peristaltic pump will be controlled by an electronic timer so that the pump will operate only when flow is present. A standard 120 V outlet will be required.

Water quality sampling

USEPA personnel trained in sampling techniques conducted sampling. USEPA personnel prepared field records, chains of custody, and sampling labels; conducted field measurements; and prepared samples for overnight shipment to the USEPA laboratory. Two types of water samples were collected every month from the pipe rig system. A “baseline” influent water sample consisted of a flowing or flushed tap water sample before entering the

lead pipes. The influent sample was collected from a sample port located before the lead pipes on rig B during the flow cycle. Stagnation samples consisted of water that was in contact with the lead pipe sections after the water sat stagnant in the pipes for between 6 and 12 h (average 8.5 h). During the water crisis, some stagnation samples were collected after up to 12 h of stagnation. To collect these samples, the programmed timer was bypassed on all four rigs. Stagnation samples were collected from all 16 lead pipes.

Baseline water quality

A baseline water sample was collected upstream from the lead pipe sections from a sample port on rig B. The water was collected when the solenoid valve was open (i.e., when water was flowing), and the water reflected the current Flint tap water, including enhanced orthophosphate and chlorine (and sometimes pH adjustment with sodium hydroxide) addition. Specifically, the “baseline” (influent to the pipes) water sampling port was located in the influent manifold before being routed to each loop on rig B. Before collecting the baseline sample, 100 mL of water was collected from the sampling port and discarded to ensure that the port was well flushed. Without closing the sampling port, a 1,000 mL clean, high-density polyethylene (HDPE) sample container⁷ was filled. The 1,000 mL baseline sample was split for multiple analyses discussed next.

Temperature was measured on site immediately after the sample was collected. Using a clean thermometer or thermocouple, temperature was measured in the 1,000 mL container. The pH and turbidity of the baseline water were also measured immediately on site by dispensing 25–30 mL into a clean 125 mL HDPE bottle⁷ for pH analysis and 15 mL into a sample cell for turbidity analysis. Conductivity and chlorine levels were also measured at this time.

A 125 mL water sample for orthophosphate analysis was dispensed into a 125 mL HDPE bottle,⁷ and 200 μ L of concentrated sulfuric acid (to pH 2) was added to preserve the sample. The sample was stored and transported on ice at 4 $^{\circ}$ C, and laboratory analysis was completed within 48 h. For anions and alkalinity analysis, 125 mL of sample water was collected in a 125 mL HDPE bottle,⁷ which was stored and shipped on ice. Samples for metals analysis required filling a 125 mL HDPE bottle⁷ and immediately preserving it with 90 μ L of ultrapure nitric acid (to pH 2). Laboratory metals analysis was typically completed in several weeks, well within the required six-month hold time (Table 2. USEPA Method 200.7/200.8).

Stagnation sampling from pipes

Stagnation water samples were collected directly from ports immediately downstream from each lead pipe section (Figure 2, parts A and B, “sample out” location). The valve after the sample port was closed during sampling of each pipe to isolate it from the other pipes in the rig. The samples were collected approximately twice a month after the water stood in the lead pipe for a minimum of 6 h (maximum 12 h, average 8.5 h) and were analyzed for lead and other metals. Several activities in Flint pulled USEPA staff resources away and impacted

⁷Nalgene, Thermo Fisher Scientific, Waltham, Mass.

the sampling schedule during the first few months of the rig study. During that period, stagnation times varied, but after site conditions calmed down, stagnation time was relatively steady at a targeted stagnation time of 8 h.

Similar to the procedure outlined in *Lead Control Strategies* (AwwaRF 1990), a sequential series of 30 mL samples were collected from one of the pipes shortly after the startup of rigs to optimize the sampling procedure by avoiding collecting water between the short run of plastic plumbing between the sample port and the lead pipe or from the plastic after the lead pipe. As a result of these sequential analyses, stagnant pipe samples were collected by drawing off the first 100 mL of water to waste and then collecting a 125 mL sample for lead and metals analysis. Additional water quality analyses and other operational differences, such as sampling flow rate, would likely require a longer pipe section segment and should be defined accordingly. Periodically (approximately on a monthly basis), an aliquot of the water sample was filtered to separate soluble from particulate metals. Two 30 mm syringe filters were used to remove lead particles, depending on availability. Specifically, either 0.1 μm pore-sized nylon filters,⁸ or 0.2 μm polypropylene syringe filters⁹ were used. Both types of filter units had been tested in prior studies to minimize or limit sorption losses of lead to the filter unit. Approximately 10 mL of sample was drawn from the bottle using a syringe and passed through the filter into a 60 mL HDPE sample bottle,⁷ swirled in the bottle, and then discarded to waste. Next, an additional 60 mL of water was drawn from the bottle (in 10 mL or 20 mL increments) and passed through the same filter directly into a 60 mL HDPE bottle,⁷ which had already been rinsed with 10 mL of filtrate.

Sample handling and shipment

Samples were shipped overnight or delivered to the applicable USEPA laboratory using coolers and shipping labels provided by the USEPA laboratory. When possible, overnight shipment occurred on the same day as sampling. Field sampling forms and chain-of-custody forms were placed in sealed zip-type bags inside each cooler. A hand-written, triplicate-copy, standard USEPA chain-of-custody form was used. For the shipment of sample bottles for wet chemistry analysis (including total phosphorus, anions, and alkalinity), fresh ice was used. Samples were preserved according to the analytical method (Table 2).

Analytical methods

Water samples submitted to the appropriate USEPA laboratory were analyzed in accordance with analytical methods, detection limits, and reporting limits listed in Table 2, which lists containers needed to sample water from the pipe rig. Scale analyses were performed using the same methods reported previously (DeSantis et al. 2018, Wasserstrom et al. 2017, Triantafyllidou et al. 2015, Schock et al. 2008, Welch et al. 2008).

⁸Cameo™, GVS Filter Technology, Sanford, Maine

⁹Whatman Inc.; Clifton, N.J.

RESULTS

Construction and operational costs, issues, and lessons learned

Table S1 provides an order checklist of material necessary to construct one pipe rig. The overall cost to fabricate and construct each rig (including parts and labor) was estimated to be approximately \$15,480 (based on 2018 cost estimates, Table S1). Depending on the treatment optimization process being tested, additional costs may be incurred for chemical feed pumps and associated fittings. This cost can be estimated to be \$1,400 for the addition of one peristaltic pump per feed plus other items (e.g., feed reservoir, tubing). The operation of the pipe rigs was relatively simple and automatic, with the exception of a few issues. The lessons learned are important results and worth highlighting. The pressure specifications for the tubing pipe⁵ connections that were initially installed were too closely matched to the pipe rig system pressure. When the solenoids were in the closed position during stagnation, the system pressure increased from 50 to 55 psi. Under this pressure, the tubing⁵ would noticeably “balloon.” This situation raised concerns that either the tubing would eventually fail or would force the hose clamps to loosen, both of which would result in water leakage that could be significant. This issue was addressed by purchasing a length of thicker-walled, stiffer vinyl tubing. Because this new tubing was stiffer, it could not readily be pushed onto the LSL segments. The initial installation was performed by cutting appropriate lengths and soaking the ends in hot water to soften the tubing. During the installation of LSLs in the other pipe rigs, a heat gun was used to further soften the tubing ends to more easily slip the tubing over the pipes.

After several months of operation, the slow-closing solenoids initially installed on the rigs began to fail by randomly not closing according to the set program. Although the design flow rate of 1 gpm was maintained while the valves were open, according to operating specifications, the daily total flow volume was sporadic from within a single pipe and across rigs. There was no way to predict when a valve might fail. This issue resulted in daily flow volumes that ranged from 200 to more than 1,400 gpd (Figures 4–7). On consultation with the manufacturer, various theories were postulated as to the original cause of the solenoid problem, and efforts were made to address it. Although not tested, it was believed that the water distribution system pressure was great enough that the solenoid valves could not overcome the pressure to reclose against the flow. The inconsistent flow volumes were not acceptable, and a decision was made to replace all four solenoid valves with a single motorized ball valve. Rig A was retrofitted initially (November 2016) to replace all four solenoids with four motor-actuated ball valves. This required a new timer¹⁰ (double pole, double throw) to control the valves as well as replumbing of the four separate rig waste streams to make them into a single stream. After a few months of consistent flow volumes (February 2017), rigs B–D were retrofitted with actuated ball valves. As a result of time and cost restraints, one motor-actuated ball valve was installed on each rig. Rig A, which had four motor-actuated ball valves, was once again retrofitted—this time to accommodate one valve—and the streams were combined into one single output. The removed ball valves were then installed onto rigs B–D, which required that the waste stream of all four loops per rig

¹⁰Tork DGS100A, NSI Industries, Huntersville, N.C.

be plumbed to one common drain. By tying the waste lines of all four lines on a single pipe rig together rather than leaving them separate, significant cost reductions were achieved because this reduced the total number of timer/ controllers and motorized valves from 16 to four.

Baseline water quality

Baseline water quality samples collected over time (Apr. 18, 2016 to July 18, 2017) represented the water entering the pipes at the beginning of stagnation (Table 3). It should be noted that no source of polyphosphate was used in Flint, and orthophosphate was the parameter necessary to form the desired lead–phosphate mineral, so total phosphorus was not routinely measured. The water is purchased from GLWA and is treated Lake Huron water using conventional surface water treatment. At USEPA’s recommendation, the City of Flint WTP doses additional orthophosphate to the water beyond that initially provided by the GLWA water to bring the orthophosphate level to approximately 3.6 mg PO₄/L. The augmentation to bring the total orthophosphate level to 3.5 mg/L was selected on the basis of three goals: speeding the repair of chemically and structurally damaged scales; better approximating a theoretical “point of diminishing returns” for the background pH and alkalinity, based on the Pb(II) orthophosphate solubility theory (AwwaRF 1990); and emulating dosages indicated as effective in UK practice (Cardew 2009, Hayes et al. 2008). At the onset of the return to the GLWA water from the Flint River source, there was insufficient time to conduct a new orthophosphate dosage optimization study before acting to reduce lead corrosion before the water was distributed to the pipe rigs and the community. During this initial pipe rig study period (Apr. 18, 2016 to July 18, 2017), pH, free chlorine, temperature, and conductivity averaged 7.32, 0.82 mg Cl₂/L, 22°C, and 237 µS, respectively, and some variability was observed (Figure 8). Total phosphate, total alkalinity, chloride, and sulfate averaged 3.6 mg PO₄/L, 73 mg CaCO₃/L, 10 mg/L, and 20 mg SO₄/L, respectively, and levels were relatively consistent across the study. Lead was not detected in the baseline water.

Pipe scale analysis. Flint distribution system LSLs removed from service in March/April 2016 contained three distinct scale layers that were observed consistently in all lead pipe samples received by USEPA’s Advanced Materials and Solids Analysis Research Core (AMSARC) in the same period. Figure 9, part A, shows what a halved section of LSL looked like once it was dry in the laboratory (general layer designations with arrows).

The uppermost layer (L1) in direct contact with flowing drinking water has a fine granular/sandy texture and is X-ray amorphous by powder X-ray diffraction. Elemental analysis by energy-dispersive spectroscopy (EDS) indicated that L1 is rich in iron (Fe), manganese (Mn), aluminum (Al), oxygen (O), and lead (Pb) while also containing less than 5% by weight (wt%) of silicon (Si), calcium (Ca), and phosphorus (P) (Figure 9). In a cross section under backscatter detection, this layer appears porous and has an average thickness of approximately 40 µm (Figure 9, part B). L2, the middle layer, is the thickest layer of the Flint scale, averaging about 300 µm. This layer is also X-ray amorphous; highly porous; and composed of magnesium (Mg), Al, Si, O, and carbon (C), with lesser amounts of P, Ca, and Pb. The presence of hydrogen (H), which would be a part of OH or H₂O chemical groups in

the solid phases, cannot be detected by analytical techniques used by AMSARC. These outer amorphous layers are generally poorly adhered to L3 and slough off easily when dry. The porous and poorly adherent properties suggest that the scale is potentially susceptible to lead particulate release during normal use or if disturbed hydraulically or physically.

The deepest layer of the scale (L3) is approximately 20–30 μm thick and tightly adhered to the pipe wall. This is the only layer of the Flint scale that does not contain an amorphous component. L3 primarily contains cerussite (PbCO_3) and lead phosphate as $\text{Pb}_9(\text{PO}_4)_6$ or $(\text{Ca}_x\text{Pb}_{5-x})(\text{PO}_4)_3\text{OH}$. Elemental mapping of the cross section shows that a P-rich layer is present at the surface of L3 and is approximately 7 μm thick, with localized zones extending approximately 19 μm into L3. By EDS, this layer is mainly Pb and O, with minor amounts of C, Al, P, and Ca. Other crystalline components of L3 include plattnerite (PbO_2) and litharge (PbO), with trace amounts of hydrocerussite ($\text{Pb}_3(\text{CO}_3)_2(\text{OH})_2$).

The scale analysis illustrates the complex nature of the lead scales in Flint, similar to prior general observations of phosphate treatment observed in USEPA studies (Wasserstrom et al. 2017, DeSantis & Schock 2014). Consequently, there are many factors that could impact lead release, and understanding the starting pipe scale materials before implementing treatment or source water changes is of vital importance. In the case of Flint, the uppermost layers in contact with the water are not simple, theoretically predictable crystalline Pb(II) solid phases. Rather, they contain a significant amount of amorphous material, making a priori treatment effectiveness computations and predictions essentially impossible. For example, lead solubility of amorphous materials is not predicted by thermodynamic databases currently available to geochemical solubility and speciation models. As a result, how such deposits affect drinking water quality, react to water quality changes, or respond to corrosion control is largely unknown and unpredictable by surrogate parameters, such as pH, alkalinity, or orthophosphate concentration. Furthermore, the granular L1 layer in direct contact with flowing drinking water was found to have around 20 wt% of lead distributed throughout in multiple soluble and adsorbed forms. This indicates a potential for elevated concentrations of lead when there is particulate lead release due to hydraulic disturbances or when changes in water chemistry could release particles of L1 into the water.

Lead concentration in stagnation water samples

Lead concentrations released from all lead pipe rigs and each pipe section over time are compared in Figures 4–7. There was a relatively large amount of variability in lead results during the first half of the study. The variability and inconsistency in lead levels was thought to be linked to flow issues associated with the faulty solenoid valves between May 2016 and February 2017 (November 2016 for rig A), as well as re-equilibration after the extraction and insertion into the pipe rigs. Daily flow volumes were also compared with lead levels for all rigs and pipes (Figures 4–7). As already noted, daily flow volumes were variable and, at times, randomly high because the automatic solenoid valve became stuck in the open position, allowing too much water to run through the pipes. During this operating period, maximum total lead levels ranged from 11.7 to 5,300 $\mu\text{g/L}$ (Table 4), and the average lead concentrations ranged from 4.7 to 533 $\mu\text{g/L}$. Several average lead levels, however, were overinfluenced by a single sample with a very large spike in lead concentration that was

inconsistent with other samples. For example, by removing the four water lead samples over 100 µg/L from the calculations, the average lead concentrations in pipes A1, A3, B4, and D4 dropped to 6.3, 3.7, 16, and 6.7 µg/L (compared with values reported in Table 4), respectively, and the recalculated range of average lead levels among all pipes was 3.7–15.7 µg/L. The influence of lead spikes was also apparent in the calculation of median lead levels across all pipes. Median lead levels (samples with lead spikes were included) were very similar (Table 4), ranging from 3.8 to 8.5 µg/L. Water samples with inconsistent lead concentration spikes were very likely associated with the random release of particulate lead. In two standout cases in which total lead levels were measured as 5,300 and 203 µg/L, corresponding filtered sample were also collected, and nearly 100% of the lead was particulate (i.e., did not pass through the filter) (Figures 4–7). Statistical analysis was performed to ascertain whether pipes and rigs behaved similarly with the four samples, with lead concentrations above 100 µg/L being excluded from the tests. Statistical analysis was performed using the analysis tools.¹¹ A one-way analysis of variance (ANOVA) was run with a significance value of 0.1. First, normality (Shapiro–Wilk) and equal variance (Brown–Forsythe) tests were performed. In addition to ANOVA testing being run, pairwise comparisons (Holm–Sidak method) between the mean lead concentrations of all pipes were performed.

Analysis results with a p -value < 0.1 were considered statistically different. On the basis of the ANOVA test, the averages of all data considered together were statistically different ($p = 0.032$). Six pairs of compared average lead concentrations were significantly different. Only rig A had a difference in average lead concentrations between pipes within the same rig. The average lead concentration of pipe A2 was significantly different from the other three pipes in rig A.

Lead concentrations immediately stabilized after the solenoid valves were replaced, and daily flow volumes were controlled (Figures 4–7, after February 2017). The average total lead levels among all 16 pipes ranged between 1.8 and 4.7 µg/L (Table 4). Large lead spikes in water samples were not observed, as reflected by the narrow range in relatively low maximum lead concentrations (3.5–18.5 µg/L) and standard deviations (0.7–4.4 µg/L). Median lead concentrations ranged between 1.0 and 4.2 µg/L. On the basis of the ANOVA test, the averages of all data considered together were not considered statistically different ($p = 0.109$). Four pairs of compared average lead concentrations were significantly different. Rig B demonstrated differences in average lead concentrations between pipes within the same rig. The average lead concentration of pipe B4 was significantly different from the other three pipes in rig B, and pipes D1 and D4 were considered significantly different. However, given the low mean lead concentration associated with each case, the statistical difference results are not of practical concern.

The differences in lead concentrations before and after the solenoid valve replacements were striking. Statistically, average lead concentrations before and after changing the solenoid valves were significantly different ($p < 0.001$). Before replacement, the pipes were newly installed, and some variability associated with disturbances in pipe extraction, transport, and

¹¹ SigmaPlot 13.0, Systat Software Inc., San Jose, Calif.

installation were expected as pipes “conditioned.” At the same time, the daily flow volume through each pipe was variable and unpredictable. Changes in daily flow volume, however, did not typically correspond directly to immediate changes in lead levels (Figures 4–7). After the solenoid control issue was resolved, daily flow volume was consistently on target with the study goal (Table 1) for the remainder of the study. Maintaining the target flow volume corresponded directly to the establishment of consistent lead levels for the remainder of the study. Interestingly, flow rate remained relatively unchanged throughout the study. The observation suggests that daily water flow impacted lead variability in some way.

Particulate versus soluble metals

During the period of June 2016 to March 2017, filtered samples were taken at as many sampling events as possible. The first two sampling events used 30 mm 0.2 μm pore polypropylene syringe filter disks,⁹ and subsequent sampling events used 30 mm 0.1 μm pore-sized nylon syringe filter disks⁸). Results are shown in Figures 4–7 (star symbols) and in Table 5 (all data included). It was not possible to do a side-by-side comparison of filter types, and it was not possible to do filtrations later with the initial filter units to control for changes in particulate lead speciation over time. In all cases, soluble (filtrate) lead levels were below 4 $\mu\text{g/L}$, although some sorption loss to the filters and filtration apparatus cannot be entirely ruled out. Because of the similarity of the dissolved lead results with expected analytical standard deviations, no attempt was made to evaluate trends in the lead speciation over time. These results, and additional testing of varying daily flow rates during sampling not reported here, suggest that barrier deposit scales such as these are limited in their ability to immobilize lead to minimal levels dictated by solubility alone, and lead release is dominantly and consistently in the form of very small particulates.

Pipe rig results as an approximation of Flint distribution system results

Although many sampling efforts in residences by various organizations have taken place in Flint over the past several years, none have sampled directly from LSLs. Sequential sampling (i.e., collecting a series of water samples from a faucet after stagnation) has been performed extensively by USEPA in homes across Flint’s distribution system. Successive water sample volumes can be directly associated with plumbing length and distance and plumbing material (Schock et al. 2012, Schock & Lytle, 2011, Schock & Lemieux 2010, Sandvig et al. 2008, Vaccari 1994, Britton & Richards 1981). Thus, sequential sampling can be used to identify LSLs, other lead sources, and the amount of lead they contribute to drinking water. Unlike direct sampling from LSLs like the rigs, long lengths of mixed plumbing materials likely exist between the water sampling tap and LSL. As a result, diffusion effects could potentially reduce the peak lead concentration in sequential samples compared with direct LSL sampling, where minimal distance exists between the LSL and the sampling port (AwwaRF 1990, Schock 1990). Length of LSL, distance from tap to LSL, plumbing configuration, and flow rate can impact the degree of the effect. Nonetheless, a comparison between lead levels from the rigs and from sequential sampling in a Flint home with an LSL would improve confidence in the pipe rigs of Flint’s distribution system and in the overall value in using pipe rigs to assess and improve corrosion control.

Sequential lead sampling results from a Flint home collected in June 2017 and within the same period when the rig was operated using the correct valve is shown Figure 10. The home had an 83 ft-long, ¾ in. ID LSL on the city side of the service (i.e., water main to meter, curb stop, or property line, depending on configuration). The sequential profile (Figure 10) showed a long “bump” in lead concentration between 4.25 and 9.25 L of water, which is in the location of the LSL and roughly correlates to the volume of water contained within the LSL volume. Lead concentrations ranged between 5.2 and 6.7 µg/L in the volumes where the LSL existed. Given the long pipe length, diffusion effects were not expected to be big. The lead levels associated with a home in Flint were very similar to lead levels observed from exhumed and conditioned LSLs in the pipe rigs.

SUMMARY AND CONCLUSIONS

This study showed the usefulness of a pipe rig/loop system with automated operation to provide a critical tool for the assessment of current corrosion control performance after stabilization and verification against actual field sampling data for lead pipes at homes. The design incorporates a provision for chemical feeds for water chemistry adjustment for future lead release optimization studies. In addition, while it currently uses LSLs removed from residences in Flint, Mich., the design could and should accommodate other legacy lead sources in the future because LSL pipes will be a decreasing fraction of the drinking water lead release as full LSL replacement programs progress. This design can be readily applied to other cities with LSLs and different water chemistries.

A standard pipe rig design, operation plan, and costs were developed in this project. This design consisted of a set of four pipe rigs, each holding four 4 ft-long old LSL segments removed from the same property located in Flint’s drinking water distribution system. Solenoid problems resulted in sporadic and increased flow volume (but no flow rate changes) that prevented restabilization. Lead levels were relatively sporadic and statistically different during this period. After the problematic solenoids were replaced, and design adjustments were made, the lead pipe rigs were successfully conditioned, and lead release with consistent influent water chemistry became relatively stable. Average lead levels across all 16 loops ranged between approximately 2 and 5 µg/L after the solenoid replacement and were not statistically different at the $p = 0.109$ level.

Particulate lead (defined as larger than 0.1 µm or 0.2 µm) was the dominant lead release mechanism during the test period, generally accounting for 75% to nearly 100% of the lead released. Thus, matching flow rates during rig operations and sampling to realistic field conditions is an important part of the design to obtain results predictive of field effectiveness.

Pipe scale analysis revealed the complex nature of the lead pipe scales in Flint, which contain a significant amount of amorphous material, making a priori treatment effectiveness computations and predictions essentially impossible. In addition, other potential lead sources present will remain, such as leaded brass fittings and fixtures, leaded solder, and lead accumulated in the scales of old galvanized, copper, or even plastic interior piping, even after all LSL segments are successfully removed in the future. Consequently, using a pipe rig

for future treatment optimization to balance the control of lead from all sources is highly desirable. There are many factors that could impact lead release from the many different sources, which may not respond identically to each factor. Understanding the starting pipe and fixture and fitting scale materials before implementing treatment or source water changes is very important.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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FIGURE 1.
Two LSL pipe rigs in Flint, Mich. (without LSLs) LSL-Lead Service Line

FIGURE 2.

Initial schematic of LSL pipe rig with solenoid valves (A) and final schematic of LSL pipe rig with motorized ball valve LSL pilot rig (with motorized ball valve waste) (B)

FIGURE 3.
Experienced city contractor excavating LSLs in Flint, Mich.

Figure 4.

Rig A stagnated lead concentration and daily flow volumes (stabilized after ball valve addition to control flow in November 2016 for rig A)

Figure 5.
Rig B stagnated lead concentration and daily flow volumes (stabilized after ball valve addition to control flow in February 2017)

Figure 6.
Rig C stagnated lead concentration and daily flow volumes (stabilized after ball valve addition to control flow in February 2017)

Figure 7.
Rig D stagnated lead concentration and daily flow volumes (stabilized after ball valve addition to control flow in February 2017)

Figure 8.

Flint, Mich., rig B influent water chemistry upstream of LSL (April 2016–August 2017); pH (A), temperature (B), chlorine (C), and conductivity (D)

A-macro image of scale surface, scale bar = 10 mm

B-back scatter detection electron image

^a uppermost layer, layer 1

^b quartz and calcite are likely detrital particles

^c layer 2

^d lowest layer, layer 3

Elements	L1 ^a low chlorine (STD S)	L1 high chlorine (STD S)	L2 ^a low chlorine (STD S)	L2 high chlorine (STD S)	L4 ^a low chlorine (STD S)	L3 ^a high chlorine (STD S)
C	2.42 ^c	2.34 ^c	5.89 (0.3)	5.70 (0.3)	2.30 ^c	2.09 ^c
O	39.47 (0.2)	42.11 (0.1)	51.85 (0.2)	52.67 (0.2)	15.83 (0.3)	17.02 (0.3)
Mg	2.81 (0.0)	3.17 (0.1)	10.25 (0.1)	10.70 (0.1)	—	—
Al	10.29 (0.1)	11.56 (0.1)	11.20 (0.1)	12.10 (0.1)	1.03 (0.0)	0.95 (0.1)
Si	3.86 (0.1)	3.54 (0.0)	9.24 (0.1)	9.57 (0.1)	—	—
P	3.60 (0.1)	3.79 (0.1)	2.26 (0.0)	2.59 (0.1)	1.45 (0.0)	2.07 (0.1)
S	0.14 ^c	0.08 ^c	—	—	0.13 ^c	0.08 ^c
K	0.17 (0.0)	0.14 (0.0)	—	—	—	—
Ca	2.04 (0.0)	1.95 (0.0)	1.29 (0.0)	1.36 (0.1)	0.65 (0.1)	0.94 (0.0)
Mn	7.12 (0.0)	6.39 (0.1)	0.38 (0.0)	—	—	—
Fe	6.16 (0.1)	6.13 (0.1)	0.69 (0.0)	0.55 (0.0)	—	—
Cu	0.65 (0.1)	0.79 (0.1)	1.30 (0.0)	1.44 (0.1)	—	—
Pb	21.25 (0.2)	18.03 (0.1)	5.65 (0.1)	3.31 (0.1)	78.61 (0.3)	76.86 (0.3)

^a uppermost layer, layer 1

^b standard deviation based on a sample

^c obtained by combustion and infrared absorption

^d layer 2

^e lowest layers, directly next to pipe wall. An additional intermediate layer was collected from the low chlorine sample, hence the L4 designation as the lowest layer.

— Non-detect

Figure 9.
Initial pipe scale EDS results; average percent by weight

Figure 10.
Two Flint, Mich., residential houses' lead profiles collected June 2017; (A) Home 1; (B) Home 2

Table 1.

Solenoid valve open/closed cycle

Time	Solenoid Valve Position
7:30 am	On
8:30 am	Off
4:30 pm	On
5:00 pm	Off
7:30 pm	On
8:00 pm	Off
10:30 pm	On
11:00 pm	Off
1:30 am	On
2:00 am	Targets Off
4:30 am	On
5:00 am	Off

Table 2.

Analytical methods used for pipe rig

Analyte	Analytical Method ^a	Sample Matrix	MDL ^a	Reporting Limit	Hold Time	Bottle Type	Preservative
Total lead	Based on USEPA 200.7/200.8	Drinking water	0.014 µg/L	0.5 µg/L	6 months	HDPE—125 mL or 1000-mL	HNO ₃ to pH < 2
Total metals—copper, zinc, aluminum, iron, calcium, cadmium, potassium, magnesium, manganese, sodium, nickel, chromium, iin	Based on USEPA 200.7/200.8	Drinking water	In accordance with USEPA or contract laboratory SOPs				
Additional total metals—antimony, arsenic, barium, beryllium, boron, molybdenum, selenium, silver, thallium, vanadium	Based on USEPA 200.7/200.8	Drinking water	In accordance with USEPA or contract laboratory SOPs				
Total phosphorus	Based on USEPA 365.4	Drinking water	In accordance with USEPA CRL SOPs		28 days	HDPE—125 mL	H ₂ SO ₄ to pH < 2, cool <6 C
Total alkalinity	Based on USEPA 310.1	Drinking water	In accordance with USEPA or contract laboratory SOPs		14 days	HDPE—125 mL	Cool <6 C
Water quality anions—sulfate, chloride, and fluoride	Based on USEPA 300.0	Drinking water	In accordance with USEPA or contract laboratory SOPs		28 days	HDPE—125 mL	Cool <6 C

CRL—Chicago Regional Laboratory, H₂SO₄—sulfuric acid, HDPE—high-density polyethylene, HNO₃—nitric acid, MDL—method detection limit, SOP—standard operating procedure, USEPA—US Environmental Protection Agency

^aStandard Methods 2005

Table 3.

Water quality of influent water to rig B upstream of LSL

Parameter	Rig B (Upstream of LSL)
Aluminum— <i>mg/L</i>	0.003±0.010 (13)
Calcium— <i>mg/L</i>	25.96±0.81 (13)
Copper— <i>mg/L</i>	0.008±0.020 (19)
Iron— <i>mg/L</i>	0.003±0.010 (13)
Lead— <i>µg/L</i>	0.10±0.03 (15)
Magnesium— <i>mg/L</i>	7.6±0.3 (14)
Manganese— <i>µg/L</i>	0.10±0.03 (13)
Sodium— <i>mg/L</i>	5.3±0.3 (14)
Zinc— <i>µg/L</i>	2.0±1.0 (16)
Fluoride— <i>mg/L</i>	0.8±0.1 (20)
Chloride— <i>mg/L</i>	10.1±0.6 (20)
Sulfate— <i>mg SO₄/L</i>	19.8±1.4 (20)
Total alkalinity— <i>mg CaCO₃/L</i>	73.3±3.1 (20)
Phosphate— <i>mg PO₄/L</i>	3.6±0.2 (20)
pH	7.32±0.10 (20)
Temperature—°C	22.0±3.1 (20)
Chlorine— <i>mg/L</i>	0.82±0.30 (20)
Turbidity— <i>ntu</i>	0.31±0.15 (20)
Conductivity— <i>µS</i>	236.6±5.6 (20)

CaCO₃—calcium carbonate, LSL—lead service line, PO₄—phosphate, SO₄—sulfate

Table 4.

Comparison of the stagnated lead concentrations from the pipe rigs before and after ball valve addition to control flow (in February 2017 for rigs B–D and November 2016 for rig A)

Blue: Before Valve	Rig A μg Lead				Rig B μg Lead				Rig C μg Lead				Rig D μg Lead			
	Pipe 1	Pipe 2	Pipe 3	Pipe 4	Pipe 1	Pipe 2	Pipe 3	Pipe 4	Pipe 1	Pipe 2	Pipe 3	Pipe 4	Pipe 1	Pipe 2	Pipe 3	Pipe 4
Red: After Valve																
Median— n	5.4 (10)	6.6 (10)	4.5 (10)	4.6 (10)	5.92 (14)	3.8 (14)	8.5 (14)	6.4 (14)	5.6 (14)	5.4 (14)	4.4 (14)	5.3 (14)	7.7 (14)	6.9 (14)	5.9 (14)	6.4 (14)
Average +/- standard deviation	30.0±71.5	11.5±9.1	533.3±1674	7.4±10.4	8.3±10.5	4.7±3.1	13.8±11.3	23.7±38.1	9.7±15.1	6.7±4.6	5.8±3.2	7.2±5.2	12.7±15.4	17.7±20.6	8.5±9.0	20.7±52.6
Maximum	220.0	26.0	5300.0	36.7	44.0	11.7	37.5	129.0	61.0	20.0	12.4	22.4	60.7	75.8	35.1	203.0
Minimum	2.0	3.7	1.2	2.1	2.4	1.6	3.9	1.9	1.6	2.9	2.8	2.5	0.0	2.9	1.8	2.7
Median— n	1.6 (11)	2.6 (11)	1.8 (11)	3.3 (11)	1.7 (7)	1.8 (7)	1.5 (7)	3.3 (7)	1 (7)	1.8 (7)	2.9 (7)	2.9 (7)	1.5 (7)	2.4 (7)	1.8 (7)	4.2 (7)
Average +/- standard deviation	2.6±2.7	4.1±3.9	2.6±1.5	4.6±4.4	2.3±1.45	2.7±2.3	1.8±1.0	4.7±3.2	1.9±2.3	2.5±1.7	2.9±1.0	3.1±1.0	1.9±1.7	2.6±1.7	2.1±0.7	3.9±1.8
Maximum	10.0	13.7	5.6	18.5	5.2	8.3	3.9	9.7	7.5	6.0	4.3	4.5	5.8	5.8	3.5	7.5
Minimum	0.0	1.0	1.5	2.1	0.6	1.2	0.9	2.3	0.7	1.0	1.3	1.9	0.6	0.0	1.6	1.7

Table 5.

Average solubility of lead in stagnated pipe rig sampling (all data included)

Section	Total Lead µg/L	Soluble Lead ^a µg/L	Particulate Lead µg/L	Particulate %
Rig A, pipe 1	33.8	1.0	32.8	97
Rig A, pipe 2	11.3	0.9	10.4	92
Rig A, pipe 3	665.5	0.8	664.7	100
Rig A, pipe 4	10.1	1.6	8.5	84
Rig B, pipe 1	9.8	1.0	8.8	90
Rig B, pipe 2	5.1	1.0	4.1	80
Rig B, pipe 3	16.3	1.2	15.1	93
Rig B, pipe 4	19.7	1.1	18.6	94
Rig C, pipe 1	6.0	1.9	4.1	68
Rig C, pipe 2	5.6	0.9	4.7	84
Rig C, pipe 3	5.7	1.2	4.4	77
Rig C, pipe 4	6.7	1.4	5.2	78
Rig D, pipe 1	16.1	1.7	14.3	89
Rig D, pipe 2	18.4	1.8	16.6	90
Rig D, pipe 3	8.9	1.4	7.5	84
Rig D, pipe 4	30.3	1.7	28.6	94

^aSoluble lead determined by filtering a sample through a 0.1-µm nylon syringe filter.