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Zap Lead Problem: Cost-effective and Immediate Electrochemical Pipe Scale Accelerator

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Abstract: The Electrochemical Pipe Scale Accelerator (EPSA) rapidly reduces lead (Pb) concentration in water by up to 99% by electroplating an insoluble and non-conductive lead phosphate or aluminum oxide scale. Twenty-Two million Americans, 120 million Europeans, and 500,000 Canadian households are at risk of lead-contaminated water. Unfortunately, traditional scale passivation can take up to years to form and deteriorate under a chemical change in water (Flint, Michigan, 2014). Replacing pipes can be expensive, costing $250/foot, and the U.S. government up to 47 billion dollars to replace all pipes. The objective was to engineer a low-cost and rapid device that could reduce Pb concentration below the “Lead and Copper rule." Furthermore, the relationship between varying PO_4 concentrations and Pb concentration, Al, concentration, and electricity variables were studied under a chemical change in water. The EPSA consisted of an integrated multimeter, a pre-existing Pb scale anode, an Al cathode wire, and a 1v battery. A 40cm Pb pipe was cut into four pieces, with PO_4 concentration 118-29 mg/L. An 8ml water sample was tested for four weeks using an ICP-OES and pH kit to study Pb leaching. The EPSA reduced Pb concentration by up to 99.14289 % with a concentration of 58 mg/L, taking just under 3 hours. The total cost of the EPSA is 111 times more affordable ($250 vs. $2.25 per foot), providing an affordable solution for low-income residents and immediate protection for vulnerable water systems.

Keywords: Chemistry, Water, Electrolysis, Lead pipe, Passivation

1. Introduction

1.1 Lead Problem

On April 25, 2014, Flint, Michigan, the U.S. experienced one of the worst manmade public health crises: the contamination of lead (Pb) in water. Eventually, it was declared a federal emergency by President Barack Obama on January 16, 2016. When the city switched its water source from Lake Huron to the Flint River, corrosion chemicals were not added to the water system, even though it was more acidic than Lake Huron. As a result, more than 100,000 residents were exposed to dangerous levels of Pb. Outside of Flint, an estimated 6-10 million Pb service lines exist in the U.S., accounting for 7% of households served by the U.S. water system. The “Lead and Copper” rule, which states that Pb concentration should be below 0.015 mg/L or 15 ppb (parts per billion), is broken in 5300 water systems in the United States and 22 million Americans have Pb pipes. In a global context, 25% of Europe’s domestic dwellings and 120 million EU people have Pb pipes, and 500,000 Canadians have Pb service lines.

Crucially, there is no safe level of Pb exposure. Pb can cause widespread brain damage, kidney failure, anemia, reduced fertility rates, convulsion, and even death. Furthermore, elevated Pb levels can lead to permanent behavioral and developmental problems in children. Pb contamination occurs when Pb ions leach into the water. To prevent this problem, governments add artificial inorganic corrosion chemicals, which create an insoluble scale inside the pipes, protecting the water from the corrosive metal. These corrosion chemicals are phosphates (PO_4), which react with Pb ions, creating a thin mineral scale. However, this may take months to several years and must be added continuously. In addition, Flint, Michigan is a key example of how Pb pipe scaling can react negatively to changes in the chemical composition of water. Lastly, Pb pipe replacement can range from $1,200-$12,300 per line and up to $250/foot, which is unaffordable for people below the poverty line. In the U.S. alone, replacing Pb pipes could cost up to 47 billion dollars.

However, it is theoretically possible to rapidly accelerate the passivation process in Pb pipes by inserting an aluminum (Al) wire and PO_4 electrolyte, resulting in the electrodeposition of an insoluble aluminum oxide layer. Pb pipes would be turned into electrochemical shells, which can quicken the passivation process, act as an economically feasible option, and become a non-invasive temporary solution until a Pb pipe is replaced.

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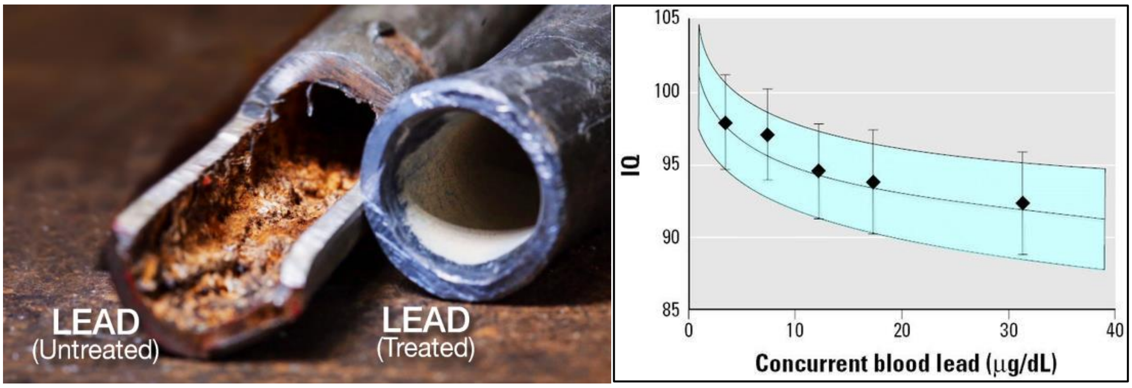


Figure 1. Untreated Corrosive vs. Passivated (Left) Pb Level vs. Child Intellectual Function (Right)

1.2 Engineering Objectives

1) Engineer a cost-effective and immediate device that reduces Pb concentration below the "Lead and Copper" rule.
2) Determine the feasibility of the device under a chemical change in water composition with non-uniform corrosive Pb scaling.
3) Investigate the effect of sodium phosphate dibasic (Na_2HPO_4) concentration on lead (Pb) concentration, aluminum (Al) concentration, and electricity variables (voltage, resistance, and current).

1.3 EPSA Prototype

To fulfill the Engineering Objectives, the Electrochemical Pipe Scale Accelerator (EPSA) was developed, which transforms the Pb pipe into a circuit using a conductive phosphate (PO_4) electrolyte solution inside the Pb pipe, a reducing cathode Al wire, an oxidizing anode Pb pipe scale (thin pre-existing crust inside the pipe) anode, copper wires, and a voltmeter. The application of EPSA in a natural setting is a five-step process.

1) Lead Pipe Location: Private service lines are located using a "scratch test" or lead kit.
2) Water Stagnation: The main water supply is shut off through the water meter.
3) Electrolyte Introduction: Small PO_4 amounts are fed inside the pipe through the water meter.
4) EPSA introduction: An Al wire is inserted inside the pipe through the water meter, with rubber insulating spacers in between to prevent short-circuiting. A conductive wire is connected to the inner scaling of the Pb pipe, and the other is connected to the Al wire. Finally, a 1-2 volts circuit is introduced, replicating the pipe as an electrochemical shell.
5) EPSA disassembly: The EPSA is removed once the current reaches 0 (using an integrated multimeter), and the water continues flowing.

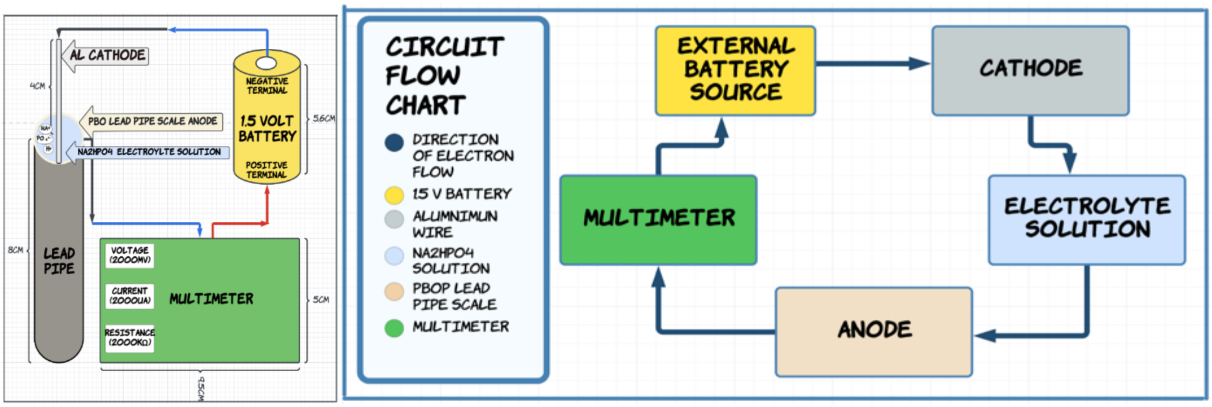


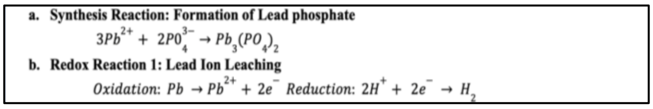
Figure 2. EPSA Prototype (Left) Circuit Flow Chart (Right)

1.4 Research Questions and Hypothesis

1.4.1 How does Na_2HPO_4 concentration affect lead (Pb) concentration after EPSA?

- Rationale: EPSA aims to reduce Pb concentration below the "Lead and Copper" rule (15 ppb).
- Background: Once the (Sodium phosphate dibasic) Na_2HPO_4 is part of the water solution, the compound will break into $2Na^{2+}$, H^+, and $(PO_4)^{3-}$. The EPSA creates an oxidation-reduction (redox) reaction where Pb ions would leach rapidly from the scale anode and bind with the phosphate ions to precipitate lead (II) phosphates on the pre-existing scale.
- Hypothesis: As Na_2HPO_4 concentration increases, the Pb concentration after the electrochemical treatment should decrease. A

higher Na_2HPO_4 concentration increases the frequency of successful particle collision and forms insoluble passivation layers.



a. Synthesis Reaction: Formation of Lead phosphate

$$3Pb^{2+} + 2P0_4^{3-} \rightarrow Pb_3(PO_4)_2$$

b. Redox Reaction 1: Lead Ion Leaching

$$Oxidation:\ Pb \rightarrow Pb^{2+} + 2e^- \quad Reduction:\ 2H^+ + 2e^- \rightarrow H_2$$

Figure 3. Balanced Redox Equation of Formation of Lead Phosphate

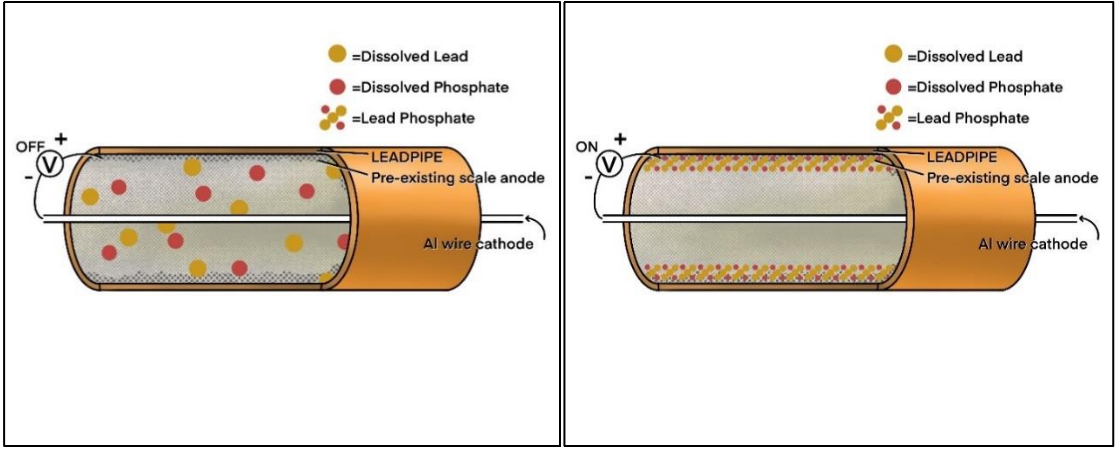
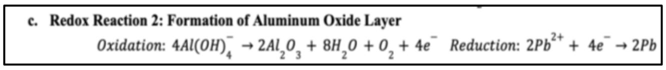


Figure 4. Introduction of Phosphate Electrolyte (Left), Formation of Lead Phosphate (Right)

1.4.2 How does Na_2HPO_4Na2HPO4 concentration affect Aluminum (Al) concentration after EPSA?

- Rationale: The presence of Al indicates the formation of the Aluminum oxide layer.
- Background: Once the Na_2HPO_4 is part of the water solution, aluminum hydroxide ions may be spontaneously released before the current, given that the solution is within the dissolution range of Al (pH >11). The power supply would then drive the electrodeposition of an aluminum oxide layer on top of the Pb pipe's pre-existing scale.
- Hypothesis: As Na_2HPO_4 concentration increases, the Al concentration after the electrochemical treatment should decrease. A higher Na_2HPO_4 concentration increases the solution conductivity, forming aluminum oxide.



c. Redox Reaction 2: Formation of Aluminum Oxide Layer

$$Oxidation:\ 4Al(OH)_4^- \rightarrow 2Al_2O_3 + 8H_2O + O_2 + 4e^- \quad Reduction:\ 2Pb^{2+} + 4e^- \rightarrow 2Pb$$

Figure 5. Balanced Equation of Formation of Aluminum Oxide

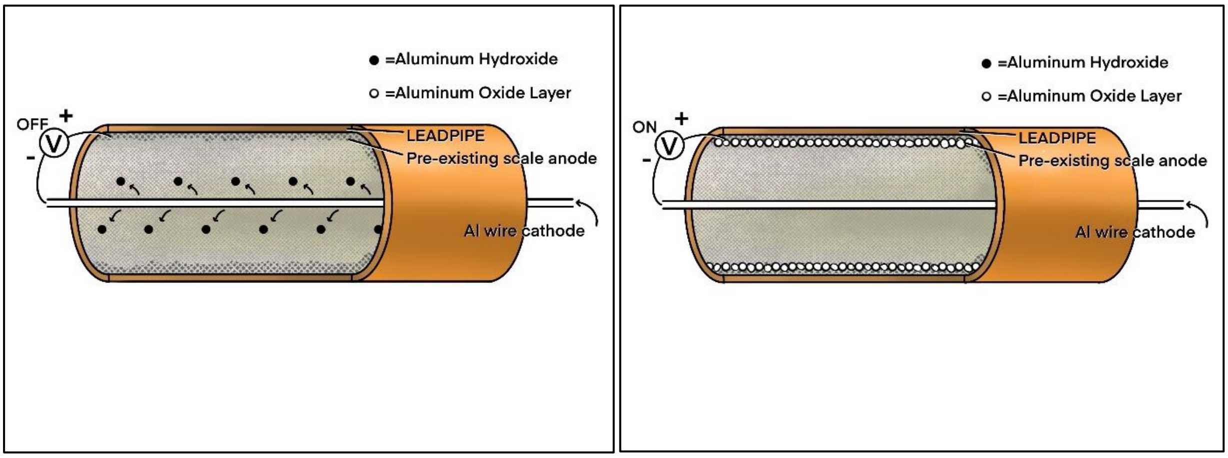


Figure 6. Release of Aluminum Hydroxide (Left) Formation of Aluminum Oxide (Right)

1.4.3 What is the relationship between Na_2HPO_4 concentration and its current, voltage, and resistance?

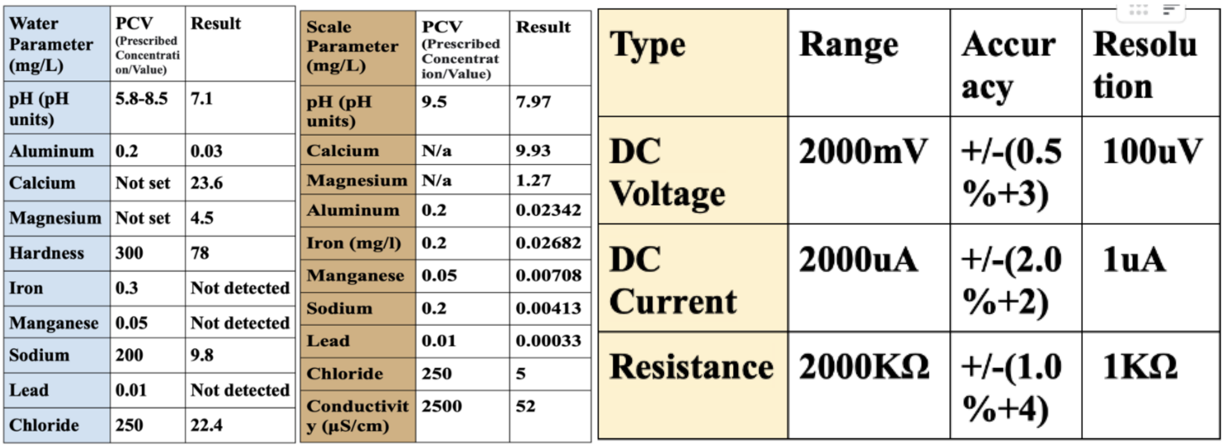
- Rationale: Identifying when the current drops close to 0 indicates that the EPSA treatment is finished.
- Background: The desired chemical products lead-phosphate and aluminum oxide are highly insoluble and non-conductive. In reference to Figure 3.1, these compounds would gradually cover the pre-existing Pb scale anode, which is conductive, indicating a slow decline in current and eventually leading to 0.
- Hypothesis: A higher Na_2HPO_4 concentration will begin in a higher current due to a higher flow of electrons but will decrease at a faster rate. Moreover, this indicates that the resistance (opposition to the current flow) will increase

faster, whereas the voltage (difference in 2 points of a current) would remain constant.

2. Methods

2.1 Controlled variables

- Lead pipe: The Pb pipe was salvaged from a home in Edinburgh, Scotland. This pipe had a non-uniform corrosive Pb scale with a scaling thickness of approximately 0.2mm, formed over at least 60 years. Crucially, Scotland's water is "soft" (low in minerals of magnesium and calcium), "pulling in" minerals from the scale, increasing the likelihood of Pb leaching. The pipe with inner/outer diameter of 1.1cm/2.2cm was cut into four 8cm pieces (A, B, C and D) using a metallic razor in the Sewoon market, Seoul, South Korea.
- Water: The solvent water was obtained from a tap in Gangnam District, Seoul, South Korea. See Water Parameters in Figure 2.2. The difference in water chemical composition (pH, chlorine, and alkalinity) replicated the event in Flint, Michigan, deteriorating the existing Pb scale.
- Phosphate: The electrolyte solution consisted of sodium phosphate dibasic (Na_2HPO_4) solute. The corresponding electrolyte solutions of 118 mg/L, 87 mg/L, 58 mg/L, and 29 mg/L were used for each pipe segment. 116 mg/L was the maximum soluble concentration, and the rest were found using logistic distribution. All concentrations were then controlled and tested with a pH kit.
- Circuit: A conductive Al wire (50ft long and 3mm in diameter) was cut into five pieces (12cm each) to act as the cathode. See Multimeter Parameters in Figure 7 for DC voltage, current, and resistance error margins.



Water Parameter (mg/L)	PCV (Prescribed Concentration/Value)	Result
pH (pH units)	5.8-8.5	7.1
Aluminum	0.2	0.03
Calcium	Not set	23.6
Magnesium	Not set	4.5
Hardness	300	78
Iron	0.3	Not detected
Manganese	0.05	Not detected
Sodium	200	9.8
Lead	0.01	Not detected
Chloride	250	22.4

Scale Parameter (mg/L)	PCV (Prescribed Concentration/Value)	Result
pH (pH units)	9.5	7.97
Calcium	N/a	9.93
Magnesium	N/a	1.27
Aluminum	0.2	0.02342
Iron (mg/l)	0.2	0.02682
Manganese	0.05	0.00708
Sodium	0.2	0.00413
Lead	0.01	0.00033
Chloride	250	5
Conductivity (µS/cm)	2500	52

Type	Range	Accuracy	Resolution
DC Voltage	2000mV	+/-(0.5%+3)	100uV
DC Current	2000uA	+/-(2.0%+2)	1uA
Resistance	2000KΩ	+/-(1.0%+4)	1KΩ

Figure 7. Water Parameters (Blue), Lead Pipe Water Parameters (Brown), Multimeter Variables (Yellow)

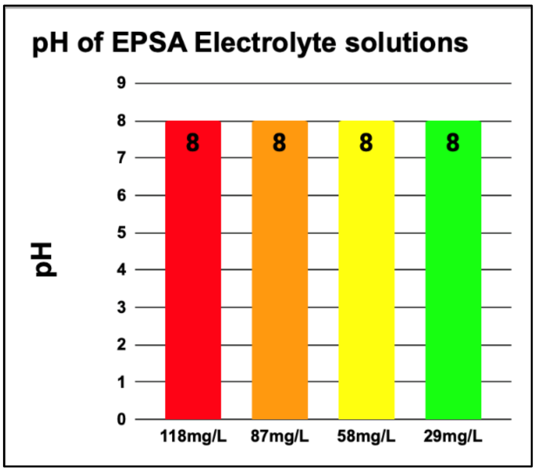


Figure 8. pH Control

2.2 Procedure

In our lab setting, the pipe was sealed on one side using glue and horizontally placed in a glass container. Afterward, 10 ml of given Na_2 HPO_4electrolyte solution (pH and Pb sampled) was introduced into the pipe using a pipette and plastic funnel. The clip shouldn't contact the solution, as it creates a short circuit. Finally, an open circuit (including the 1.5-volt battery and multimeter) was attached to the Al cathode and Pb pipe scale anode to form a closed circuit.

Figure 9. EPSA Prototype (Left), Pipe Segments A, B, C, and D (Right)

2.3 Data Collection

The data analysis below will be repeated five times for five Pb pipes with different electrolyte concentrations: 118 mg/L, 87 mg/L, 58 mg/L, and 29 mg/L.

2.3.1 Lead, Aluminum, and pH

1) Lead Control: First, an 8ml water sample in the Pb pipe was taken using a pipette before the EPSA treatment.
2) Short-term Reduction: After the EPSA treatment, the Pb pipe will be “flushed” (drained and refilled with local water three times) to mimic water circulation. Afterward, another 8ml sample will be taken.
3) Long-term Reduction: To test the effect of EPSA over a long duration, each pipe will be sampled bi-weekly for four weeks after the experiment. Each Pb pipe will be “flushed” every day at 9:00 am. The total four samples are then analyzed through the ICP-OES, known as inductively coupled plasma atomic emission spectroscopy (a technique in which the composition of element samples can be determined using plasma and a spectrometer) at Vancouver Elements Laboratory.

The ICP-OES is set to total Pb testing, including particulate and dissolved Pb. Further, Al would also be tested for signs of aluminum oxide formation. The following formula will find the final concentration of Pb and Al (mg/L):

$$Conc\ (mg/L) = \frac{[Conc\ (mg/L)] \times [Dilution\ Factor] \times [Final\ Digest\ Volume\ (mL)]}{[Subsample\ Volume\ (mL)]}$$

Figure 10. ICP-OES Mineral Concentration (mg/L) Formula

2.3.2 Integrated Multimeter

The current of the electrochemical circuit will be connected to a multi-meter between the external battery source and anode in Figure 3.0. Every 5 minutes, the voltage (mV) and current (uA) of the circuit will be recorded on a database, while the resistance (kΩ) will be found using Ohm’s Law: voltage =current × resistance.

3. Results and Discussion

3.1 Lead (Pb) Concentration and Aluminum (Al) Concentration

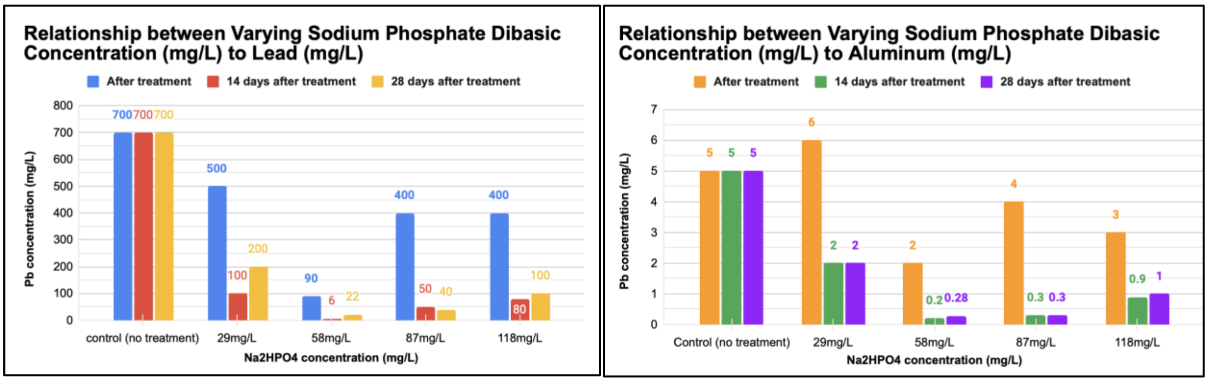


Figure 11. Relationship between Varying Sodium Phosphate Dibasic Concentration to Lead (Left), Aluminum (Right)

3.2 Electricity Variables

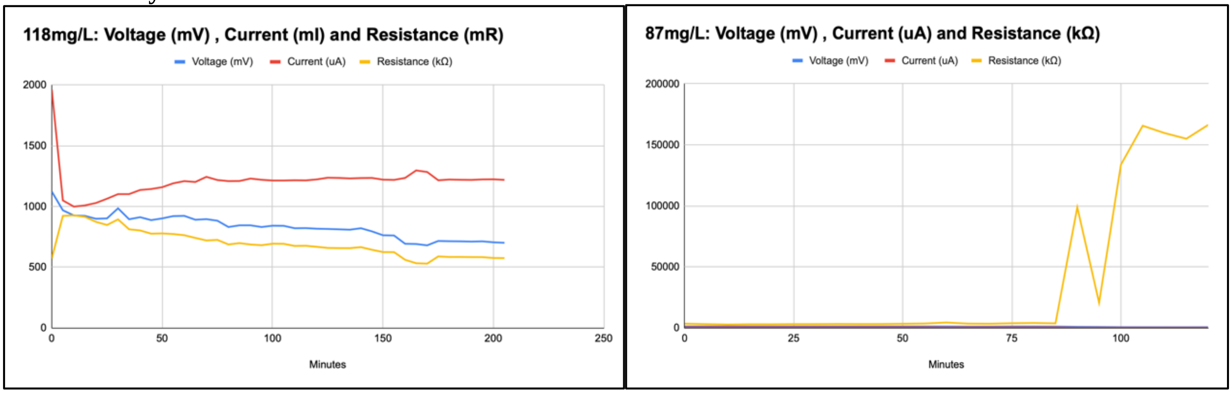


Figure 13. 118 mg/L Electricity Variables (Left), 87 mg/L Electricity Variables (Right)

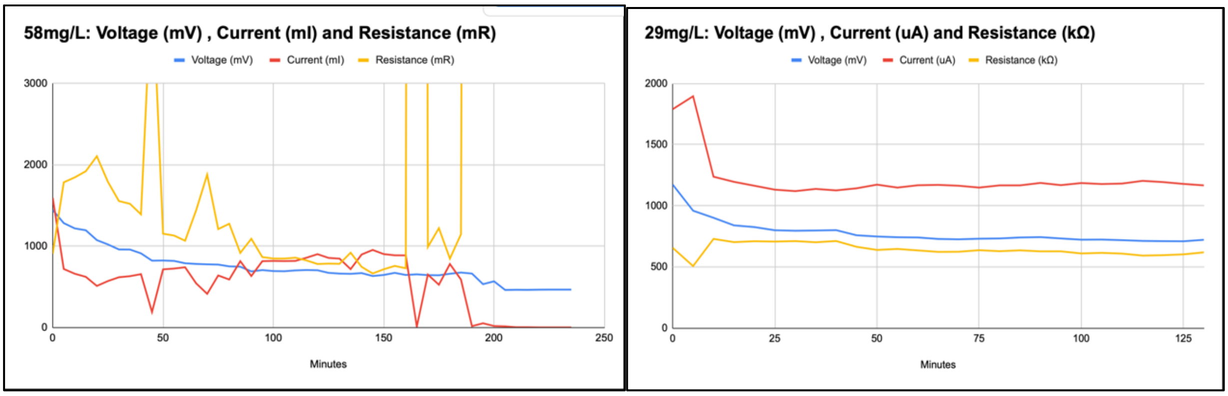


Figure 14. 58 mg/L Electricity Variables (Left), 29 mg/L Electricity Variables (Right)

3.3 Discussion

3.3.1 Key Findings

With PO_4 concentration 58 mg/L, the EPSA reduced Pb concentration by up to 99.1429%, with the treatment taking under 3 hours. However, despite the substantial decrease in Pb concentration, the Pb pipe did not comply with the "Lead and Copper rule" of concentration below 15 ppb. Moreover, the total estimated cost of the EPSA is 111 times more affordable than Pb pipe replacement ($250/foot vs. $2.25/foot).

3.3.2 Systematic and Random Errors

The main human error comes from water sampling. First, the Pb pipes did not have a functioning water cycle system, replicating the stagnant and flowing water as it would in a real-life setting. Second, short-circuiting during the experiment may have occurred if the Al cathode contacted the Pb scale anode. Third, financial constraints limited ICP-OES sampling to just four samples per pipe. As a result, Pb or Al concentration changes may have occurred between gaps in bi-weekly water sampling. Moreover, each phosphate electrolyte solution was prepared using a 100mL-graduated cylinder. The margin of error would be ± 0.5mL, given that the smallest terminal was 1mL. For the current, the range of accuracy of the electricity variables was DC voltage (2000mV) ± (0.5% + 3), DC current (2000uA) ￼ ± (2.0% + 2), and resistance (2000K￼) ± (1.0% + 4). However, this has minimal impact on measuring the EPSA electricity variables.

3.3.3 Limitations

Although the EPSA effectively decreases total concentration and forms a protective insoluble layer, it is still being determined whether the EPSA works for all Pb scales and water compositions. Further, this experiment doesn't measure how long the lead-phosphate/aluminum-oxide insoluble scale can last beyond four weeks. However, when the insoluble protective scale gradually wears out (supported by the slight increase of Pb concentration in Figure 11), municipalities can utilize a combined approach of adding small amounts of PO_4 or yearly EPSA treatment. Finally, inserting the aluminum cathode through the water meter and electrolyte solutions can cause practical issues, such as the possibility of short-circuiting and working with complex plumbing systems.

6. Conclusion

6.1 Hypothesis and Research Question

The three hypotheses were not fully supported, as the best PO_4 concentration value was between 87 mg/L and 58 mg/L. As shown in Figure 11, 58 mg/L had the most significant decrease of Pb (99%), and 87 mg/L had the quickest treatment time (2 hours). This may have occurred due to the introduction of reactive sodium ions and the formation of sodium phosphate bonding. As the sodium phosphate dibasic concentration increased, free sodium ions may have affected the electrodeposition of lead phosphate, coagulating free Pb ions into particulate Pb. Furthermore, increased electrolyte concentration may have oxidized and leached bare Pb excessively, leading to higher levels of Pb concentration.

On the other hand, a small electrolyte concentration may have had weak conductivity and temperature, preventing fewer successful particle collisions. Crucially, the formation of an aluminum oxide layer did not occur, as all the PO_4 solutions were significantly below the active dissolution rate of Al (pH>11). Thus, aluminum hydroxide ions could not spontaneously form. The presence of free Al ions most likely was leached from the pre-existing pipe scale. Notably, there was still a substantial decrease in aluminum as shown in figure 11 (aluminum).

When analyzing electricity variables, voltage largely remained constant as the driving pressure is independent of the formation of lead phosphate scaling. In figure 13-14 PO_4 58mg/L and 87mg/L, current was inversely proportional to resistance, and gradually dropped to zero. On the other hand, the electricity variables of PO_4 concentration 118 mg/L and 29 mg/L stayed at an equilibrium, supporting that the non-conductive lead phosphate did not fully cover the inner scaling but could still decrease Pb concentration by a respective 86% (29 mg/L) and 87% (118 mg/L).

6.2 Future Application

The EPSA could be a novel approach to the world's growing Pb pipe problem. Although pipe replacement will always be the best solution, the EPSA can act as a cost-effective and rapid solution until the pipe can be fixed. Furthermore, the EPSA can protect against Pb leaching during Pb pipe replacement or chemical changes in water. Water chemistry varies greatly, and more research must be conducted to understand the potential of EPSA in different water compositions. By collaborating with water municipalities and plumbers, the EPSA could be a novel option to ensure safe drinking water for millions worldwide without access to a fundamental human right: access to safe drinking water.

7. Risk assessment

The most significant risk in this experiment is Pb poisoning due to inhaling small dust Pb particles. This issue is especially prevalent when separating the pipe into five pieces using a metallic pipe cutter. Furthermore, sodium phosphate dibasic Na_2HPO_4 can be harmful with sufficient inhalation, irritating the skin and eyes. To minimize these risks, several safety steps will be introduced.

1) Preventing Contact: The surface of the Pb pipe is encased on the surface using "WaterWeld Epoxy Putty, which avoids physical contact when working with the pipe.
2) Protective Gears: Gear such as KF94 masks, rubber gloves, and clean clothing will always be used and disposed of each session. Clothes and lab setting after each experiment will be washed/sanitized.
3) Chemical Disposal: All chemical waste produced from the EPSA will be disposed of in a plastic container, then moved to a licensed disposal company.
4) National Standards for Lead: The experiment will comply with the National Institute for Occupational Safety and Health (NIOSH) Recommended Exposure Limit (REL) for the Pb Time Weighted Average of 50 micrograms per cubic meter of air (µg/m3) over 8 hours.
5) Balances and Checks: Symptoms for Pb will be checked for days, weeks, or months following the experiment. The symptoms include but are not limited to irritability, loss of appetite, weight loss, sluggishness, abdominal pain, vomiting, constipation, hearing loss, and seizures.

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