# Practical Application of NSF/ANSI 53 Lead Certified Filters: Investigating Lead Removal, Clogging and Consumer Experience

Jeannie M. Purchase

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Marc A. Edwards, Chair
Kelsey J. Pieper
Adrienne L. Katner
Jeffrey L. Parks
Peter J. Vikesland

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## Abstract

NSF/ANSI 53 lead-certified point-of-use filters (POUs) have been distributed to consumers in many cities facing water lead crises, including Washington D.C., Flint, MI, Newark, NJ, and University Park, IL. It is expected that these filters would reduce water lead to levels that are safe for consumption as residents wait for municipalities to provide more permanent solutions (e.g., corrosion control, lead service line replacement). These filters are certified by the National Sanitation Foundation (NSF) after meeting the challenges of treating two lab synthesized waters with 150 µg/L of soluble and particulate lead. In Flint, as in Washington, there were initial concerns that the filters would not be effective when exposed to lead levels far above the NSF/ANSI 53 150 µg/L Pb level used for certification. However, the EPA conducted a 2016 study in Flint, MI, with over 240 homes with lead up to 4080 µg/L, revealing that all POUs reduced lead levels below 1 µg/L.

Newark, NJ, in response to Lead and Copper Rule (LCR) violations, distributed over 40,000 NSF/ANSI 53 lead-certified pitcher and faucet POUs to protect consumers from high water lead levels. In the summer of 2019, preliminary tests in some homes with the highest lead in water concentrations revealed that 2 of 3 POUs used in Newark had effluent lead levels above 15 µg/L. The publication of these results caused citywide angst, distrust, and EPA mandated a switch to bottled water. However, a later and more extensive study revealed that 97.5% of homes (n=198) with properly used filters had effluent lead levels below 10 µg/L. As a result, the EPA approved Newark's request to discontinue bottled water distribution and only provide POUs to residents. Nevertheless, the experience indicated that it is vital to understand the limitations of POUs. This dissertation comprises <u>three manuscripts</u> that examine the efficacy of POUs under laboratory and field conditions.

The first manuscript sought to provide perspective into potential causes of the filter failures observed in the field. We conducted an extensive laboratory investigation that examined the performance of 10 pitcher and faucet POU brands under extreme conditions (e.g., up to 200% of rated capacity, influent lead levels ≈ 1000 µg/L). Our tests confirmed successful performance documented in some field testing and replicated underperformance observed in others. In this investigation, we observed structural failures due to poor manufacturing (i.e., leaking units, a filter with a large hole in the media) and performance failures (filtered water >10 µg/L Pb). Some of the performance failures occurred when we tested particulate lead waters, which we created, proving to be very difficult to treat relative to those used for NSF/ANSI testing. While the POUs almost always reduce consumer lead exposure, even when operated beyond their rated capacity, this study highlights instances where treated water could far exceed 10 µg/L lead.

High particulate iron (Fe) and manganese (Mn) concentrations often co-occur with high lead in many low-income, rural communities with small community water systems (CWS) or in homes with private wells. These communities are more likely to depend on POUs for protection from waterborne lead as they typically do not have the funds to maintain and upgrade infrastructure, improve corrosion control, or replace service lines. Waters with high levels of Fe and Mn could potentially impact the performance of the POU lead filters. However, such problems would not be detected in NSF/ANSI certification testing because these constituents are not included within the test water.

The second manuscript validated anecdotal reports of premature POU failure due to clogging in rural communities with high iron concentrations in their water. POU pitcher filters were tested with waters containing high lead and iron up to 100% of their rated capacity, or until they clogged as defined by a 75% reduction in initial flowrate. Iron levels above the 0.3 mg/L Secondary Maximum Contaminant Level (SMCL) resulted in rapid clogging, markedly increasing treatment costs, and decreasing consumer satisfaction. At 0.3 mg/L Fe, half of the 6 POU filters tested were clogged at between 38-68% of their rated capacity. When considering the cost of using POU filters vs. purchasing bottled water, the POU devices were often more cost-effective at iron levels at or below 0.3 mg/L. However, as iron concentrations increased, bottled water often became cost-effective depending on the circumstance. The presence of iron did not have an adverse effect on lead removal but significantly affected the cost and reduced flow rates in treating water.

The third manuscript presents a two-phase field study that sought to monitor the long-term filter performance in residential homes in New Orleans and Enterprise, LA. Previous field studies have captured POU removal efficiencies in single event (grab) samples; however, this study quantified filter performance for all the water treated up to POU practical capacity (i.e., filter life) based on consumer judgment regarding acceptable flow rate. The first phase was a rigorously controlled study that tested the POUs (100-gal capacity) at up to 200% of their rated capacity in two New Orleans unoccupied homes. Historically, the first home had consistently high lead levels (10-25 µg/L) even after flushing for > 8 min. Duplicate POUs treated that water to below 5 µg/L at up to 100% capacity, with only two exceptional samples with 12 µg/L Pb in 10-gallon batches of the treated water. The second home had a disturbed lead service line (LSL), resulting in varying concentrations of influent particulate lead ranging from 9-3000 µg/L. The duplicate POUs had difficulty producing water lead levels <10 µg/L before reaching filter capacity, with eight exceedances prior to 100% capacity. This work demonstrated that flushing alone for extended periods (>8 minutes) is not guaranteed to reduce lead levels in all homes with LSLs and highlights some limitations of POU filters in treating water with high levels of particulate lead.

The second phase of the field study monitored POU faucet filter performance in the homes of 21 residents in New Orleans (8) and Enterprise (13), LA. New Orleans is a large urban area with low to moderate water lead levels with many partial LSL replacements. Enterprise (population <300) is a rural, low-income community with an unincorporated water system with moderate to high water lead, iron, and manganese levels. Overall, the POUs consistently reduced lead to <1 µg/L, iron <171 µg/L, and manganese <180 µg/L. Enterprise's high influent concentrations of iron significantly impacted filter capacity due to reduced flow and clogging. Enterprise homes saw an average 62% flowrate reduction, and most of the homes did not reach 50% of the filter's rated capacity before consumers decided the filters were clogged. Most New Orleans residents did not experience clogging, and the homes that did saw only a 16% flow rate reduction. Overall, the New Orleans POUs were 2.3X faster in treating water by the study's end than Enterprise. There was no simple correlation between average iron concentration and days of filter life amongst residents in Enterprise as would be expected given variations in the volume of water used daily and consumer subjectivity in deciding when to end the study due to clogging. However, residents in Enterprise and similar communities would likely need to purchase 2-4 times as many filter cartridges due to clogging when compared to cities like New Orleans with lower iron concentrations. This study shows how POUs have promise for the removal of Pb and Fe in residential homes, but clogging has emerged as an important practical limitation to widespread successful POU deployment.

This dissertation highlighted the multifaceted nature of the question: "How well do POU filters work and under what conditions?" Overall, the POUs have shown their ability to reduce water lead levels effectively <5 µg/L, with a few exceptions primarily attributed to particulate lead and manufacturing quality control issues. However, when treating waters with high levels of iron and other contaminants, POU clogging can cause consumer dissatisfaction and make purchasing bottled water a more favorable solution than POU filters.

# Practical Application of NSF/ANSI 53 Lead Certified Filters: Investigating Lead Removal, Clogging and Consumer Experience

Jeannie M. Purchase

## General Audience Abstract

Lead-certified point-of-use filters (POUs) have been distributed to consumers in many cities facing water lead crises, including Washington D.C., Flint, MI, Newark, NJ, and University Park, IL. In Flint, as in Washington, there were initial concerns that the filters would not be effective when exposed to lead levels far above the 150 µg/L lead concentration used for certification. The EPA conducted a 2016 study in Flint, MI (>400 homes) that showed all POUs successfully reduced lead levels below 1 µg/L. Newark, NJ, distributed over 40,000 lead-certified pitcher and faucet POUs to protect consumers from high water lead levels. In the summer of 2019, preliminary tests in some homes with the most challenging particulate lead in water concentrations revealed that 2 of 3 POUs used in Newark had effluent lead levels above 15 µg/L. The publication of these results caused citywide angst, distrust and an EPA mandated a switch to bottled water. A few weeks later, a more extensive study revealed that over 97.5% of homes had filters that effectively reduced lead. Millions of dollars invested in the POU filters in Newark were wasted as many residents discontinued use despite positive counter-messaging of overall POU performance. Newark's filter experience illuminated how vital it is to understand the limitations of lead-certified filters as our reliance on these POUs for lead remediation increases. This dissertation comprises three manuscripts that examine the efficacy of lead-certified POUs under laboratory and field conditions.

The first manuscript provides some perspective into potential causes of the filter failures observed in the field. We conducted an extensive laboratory investigation that examined the performance of 10 pitcher and faucet POU brands under extreme conditions (i.e., used well past capacity and with high lead concentrations). Our tests confirmed successful performance documented in some field testing and replicated underperformance observed in others. In addition, this investigation observed structural failures due to poor manufacturing and performance failures (> 10 µg/L Pb) when testing particulate lead waters. While the POUs almost always reduce consumer lead exposure, even when operated beyond their rated capacity, this study highlights instances where filtered water could far exceed 10 µg/L lead.

The second manuscript validated anecdotal reports of premature POU failure due to clogging in rural communities with high iron concentrations in their water. Particulate iron (Fe) and manganese (Mn) often co-occur with high lead concentrations and cause most discoloration seen in drinking water (i.e., orange and black water). Low-income rural communities with small water systems are more likely to depend on POUs to protect them from waterborne lead as they typically

do not have the funds to maintain and upgrade infrastructure, improve corrosion control, or replace service lines.

In this study, POU pitcher filters were tested with waters containing high lead and iron up to 100% of their rated capacity, or until they clogged as defined by a 75% reduction in initial flowrate. The presence of iron did not have an adverse effect on lead removal. However, iron significantly affected POU water treatment costs and reduced flow rates. Iron levels above the 0.3 mg/L Secondary Maximum Contaminant Level (SMCL) resulted in rapid clogging prior to reaching rated capacity, resulting in increased treatment costs and decreased consumer satisfaction and convenience. When considering the cost of using POU filters vs. purchasing bottled water, the POU devices were often more cost-effective at iron levels 0.3 mg/L. However, as iron concentrations increased, bottled water often became cost-effective depending on the circumstance.

The third manuscript presents a two-phase field study that sought to monitor the long-term filter performance in residential homes in New Orleans and Enterprise, LA. Previous field studies have captured POU removal efficiencies in single event (grab) samples. However, this study captures filter performance for all the water treated up to POU practical capacity (i.e., filter life) based on consumer judgment regarding acceptable flow rate. The first phase was a controlled rig study that tested the POUs filters (100-gal capacity) up to 200% capacity in two New Orleans unoccupied homes. Historically, the first home had consistently high lead levels (10-25 μg/L) even after flushing for > 8 min. Throughout the 20-day study, the duplicate POUs in this home supplied filtered water with <5 μg/L Pb up to 100% capacity, with only two exceptions (each sample had 12 μg/L Pb). The second home had a disturbed lead service line (LSL), resulting in varying concentrations of influent particulate lead ranging from 9-3000 μg/L. The duplicate POUs in this home did not consistently produce filtered water with <10 μg/L Pb, as they had eight exceedances before reaching 100% capacity. This work demonstrated that flushing the tap is not guaranteed to reduce lead levels in all homes with LSLs, even when flushing >8 minutes. It also highlighted some limitations of POU filters in treating water with high levels of particulate lead.

The second phase of the field study monitored POU faucet filter performance in the homes of 21 residents in New Orleans (8) and Enterprise (13), LA. New Orleans is a large urban area with low to moderate water lead levels with many partial LSL replacements. Enterprise (population <300) is a rural, low-income community with an unincorporated water system with moderate to high water lead, iron, and manganese levels. Overall, the POUs consistently reduced lead to <1 μg/L, iron <171 μg/L, and manganese <180 μg/L. Enterprise's high influent concentrations of iron significantly impacted filter capacity due to reduced flow and clogging. Most of the homes in Enterprise did not reach 50% of the filter's rated capacity before consumers decided the filters were clogged. The New Orleans residents did not experience POU clogging, and many filters reached capacity. The New Orleans filters were also 2.3X faster in treating water by the study's end than Enterprise. There was no statistical correlation between iron concentration and filter life; however, residents in Enterprise and similar communities would likely need to purchase 2-4 times as many filter cartridges due to clogging compared to cities like New Orleans with lower iron concentrations. This study shows how POUs have promise for the removal of Pb and Fe in residential homes. However, clogging has emerged as an important practical limitation to successful POU deployment.

This dissertation highlighted the multifaceted nature of the question: "How well do POU filters work and under what conditions?" Overall, the POUs have shown their ability to reduce water lead levels effectively <5 µg/L, with a few exceptions primarily attributed to particulate lead and manufacturing quality control issues. However, when treating waters with high levels of iron and other contaminants, POU clogging can cause consumer dissatisfaction and make purchasing bottled water a more favorable solution than POU filters.

# Dedication

I dedicate this Doctoral Degree in Civil Engineering to my grandfather Orville Willard Purchase. Thank you for being my grandpa. You raised me and taught me hard work, determination, and the resolve needed to finish what I start. The opportunity to get a full ride, plus assistantship, to graduate school for both master's and doctorate degrees at a school like Virginia Tech was beyond what anyone in our family could have dreamed of before I started college at Clemson. But it was a mountain top that you equipped me to climb, whether through your words or the admirable example of my mother, Karen B. Purchase. You are my favorite person in the world, the one who taught me unconditional love and how to be there for the people you love. I needed YOU, and I am eternally grateful that you fought to hang on for a few more days. You gave me the will and strength to defend that morning and FINISH IT! I was even able to proudly tell you I kept my promise and fulfilled my I.O.U. of Two Degrees –

Master of Science and Doctor of Philosophy in Civil Engineering
in honor of
Orville W. Purchase
May 10, 1935 – December 24, 2021

I love you, grandpa,
*Dr. Jeannie Marie Purchase*

I dedicate this Research and Contribution to Knowledge to Pauline Ray Brown and Eugene Smith, my "Mom and Pop," from Denmark, SC. It is because of you I took on this project. You had been fighting for safe water in Denmark for over ten years when we met. You were looking for someone who would listen and help. I heard your call. For you, the citizens of Denmark, Flint, and all the communities fighting for safe water around the country, I hope this work on POU filters can provide you with information to use to protect yourselves. I will continue to use my work to find and provide solutions and tell your stories to all who will listen.

I dedicate this Work to my undergraduate students: Rebekah Broyles, Ailene Edwards, Joseph Hector, Leila Husain, Isabella Lerer, Sarah Loomis, Jesika McDaniel, Abby Simonpietri, Natalie Stone, Paighton Vanzant, and Rusty Rouillier (my mentee and partner). One of the greatest joys of my life was being your mentor throughout your tenure at Virginia Tech. I finished our mission! Your hard work is woven between this >80-page document, and it does not even scratch the surface of your contribution. There are so many things that are not written, way more than just data. There is not enough time and space to encapsulate the stories, the bonding, the scientific and not scientific things you have learned, and the positive impact your work will have on communities because of the information you produced. Thank you for trusting me to lead you and for allowing me to grow with you. I love and miss you dearly, but I know the world will be better because you all are bold enough to change it.

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Most Importantly, I dedicate my <u>LIFE</u> to my Savior and Lord, Jesus Christ of Nazareth. This journey was hard, with many moments where I was so broken, I couldn't see the other side. However, you kept me and provided me with the most incredible friends, family, mentors, counselors, and support system. I had everything I needed to not only survive but thrive. My graduate school testimony has blessed and encouraged many, and I know it will continue to inspire more. As a reflection of you, I have loved and cared for those around me to the best of my ability. Thank you for always saving me, challenging my faith, and giving me the courage to walk on water again, again…and again.

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# Chapter 1: Introduction

Recent highly publicized incidents of elevated lead levels in potable water of Washington D.C, Flint, MI, University Park, IL, and Newark, NJ were partly addressed by the distribution of hundreds of thousands of point of use (POU) filters certified by the National Sanitation Foundation (NSF) for lead removal.[1–4] The general expectation is that these low-cost pitcher and faucet POUs protect the public from lead, while consumers wait for improvements from corrosion control and/or lead pipe replacement to allow safe direct consumption of water from the tap.

In Flint as in Washington D.C., there were initial concerns that the filters would not perform adequately when exposed to lead levels above the NSF/ANSI 53 150 μg/L level used for the certification testing.[5,6] However, in Flint the U.S. Environmental Protection Agency (EPA) conducted an impressive field study, that eventually demonstrated that even in homes with lead as high as 4080 μg/L and an average of 40.3 μg/L (n=299), the filtered samples were always below 2.9 μg/L for used filters (n=210) and below 1.1 μg/L for new filters (n=242). The average filtered lead levels for the used and new filters were below 0.26 and 0.21 μg/L, respectively. On this basis the filters could be recommended with confidence to Flint residents during the water crisis and to the present day.

However, the New Jersey Department of Environmental Protection (NJDEP) requested that the City of Newark (Newark) also test POU filter effectiveness at three homes expected to represent a worst-case scenario.[7] Using samples that were believed representative of water after stagnation in the lead service line, filters in two out of the three homes did not perform as expected. Specifically, one pitcher filter had an influent Pb concentration of 112 μg/L and effluent of 50 μg/L, and one faucet filter had an influent Pb concentration of 1670 μg/L and effluent of 83 μg/L. A more comprehensive filter study in Newark, revealed 97.5% of homes (n=198) with properly used filters had effluent lead levels below 10 μg/L. Only 5 out of 198 filters had lead levels above 10 μg/L, and these filters had Pb removal percentages of 37.9 - 89.4 % relative to influent values. However, the city of Newark published the concerning results from the preliminary study and made a premature abrupt switch to the distribution of bottled water. This created widespread panic and distrust amongst consumers and caused many residents to discontinue use of the filters.[8] Thus, while POU performance was not perfect, the filters nearly always removed a high percentage of the water lead.

The mixed messaging in Newark illustrates that it is important to manage performance expectations for these devices with regulators, disaster relief organizations, media, building managers, and consumers. The widespread application of these filters in communities across the country for lead remediation requires a better understanding of the POU filter performance in a range of situations including waters with higher lead, iron and manganese than are tested during NSF/ANSI certification.

## RESEARCH OBJECTIVES

This dissertation seeks to evaluate the efficacy of lead certified POU filters from a technical (contaminant removal) and practical (end user) perspective. By challenging the filters with difficult to treat water with various concentrations and types of particulate lead and iron, we sought to document the range of factors that can affect filter efficacy in lead removal and practical capacity. The specific objectives are as follows:

1. To understand why NSF/ANSI 53 lead certified POUs occasionally produce effluent water with >10 µg/L lead
2. To evaluate limitations of POU filter performance when iron and lead co-occur in drinking water, including possible impacts on lead removal efficiency and premature clogging.
3. To consider how clogging impacts the relative costs of POU filters versus bottled water.
4. To monitor the long-term performance POU filters deployed in a range of homes in Louisiana in terms of lead removal, clogging, and practical use.
5. To demonstrate the benefits and limitations of flushing when compared to POU use.

## DISSERTATION OUTLINE AND ATTRIBUTIONS

Chapter 2: Understanding Failure Modes of NSF/ANSI 53 Lead-certified Point-of-use Pitcher and Faucet Filters

This chapter documented a range of performance issues for POU filters. Phase 1 examined how the POUs worked under the same conditions used for NSF/ANSI 53 lead certification testing. Tests using the NSF/ANSI 53 soluble lead concentration (150 µg/L) revealed some unexpected performance issues. All but one brand of POU consistently reduced lead levels <5 µg/L even when tested beyond their rated capacity, but 4 out of 10 brands of POUs had failures attributed to poor manufacturing QA/QC rather than the capabilities of the filter technology. Our tests with the NSF/ANSI 53 Particulate Lead water revealed that the size distribution of particles could be altered by changing mixing methods used during its preparation. When tested with this new Particulate lead (150 µg/L) water 4 faucet filter brands had elevated lead levels >10 µg/L when tested up to 200% of their rated capacity. Phase 2 of this study investigated the poor lead removal by 2 pitcher POUs (Brand A) from a utility in the midwestern region of the US. The utility sent shipments of water and two of the problematic filter cartridges to us for intensive testing, as their POU performance was significantly worse than that of POUs in our lab studies. We were able to rule out improper installation (user error) as a cause because the filters removed 100% of the soluble hardness ions as is expected. But when the filters were challenged with waters that had higher levels of particulate lead, with a wider size distribution and low ionic strength, we were able to replicate the failure observed in the field of 84% removal with effluent lead 122 µg/L. The problems were attributed to variability in manufactured batches of filters and waters that were more difficult to treat than in standardized NSF/ANSI testing.

This manuscript has been published:

> Purchase, J. M., Rouillier, R., Pieper, K. J., & Edwards, M. (2020). Understanding failure modes of NSF/ANSI 53 lead-certified point-of-use pitcher and faucet filters. *Environmental Science & Technology Letters*, *8*(2), 155-160.

Attributions: Jeannie Purchase (author of this dissertation) was responsible for leading the design and execution of the pitcher and faucet filter experiments over the 2 years leading up to this publication. She conducted the data analysis, data visualization, and writing of the manuscript as first author. Rusty Rouillier led the Phase 2 experiment and assisted in organizing the pitcher filter data for the Phase 1 experiment. Marc Edwards co-authored the manuscript and assisted with the data interpretation and logical flow of the manuscript. Marc Edwards, Adrienne Katner, Kelsey Pieper, and Jeffrey Parks were PI's on this project and designed the original experiment.

Chapter 3: Iron Clogging of Lead Certified Point-of-Use Pitcher Filters

Point-of-use (POU) pitcher and faucet filters are generally more cost-effective than bottled water in protecting consumers from elevated lead. However, we received anecdotal reports from residents that their POU filters were clogging well before they reached their manufactured cited capacity. It was hypothesized that waters with high particulate iron might adversely affect lead removal and cause clogging. This three-phase study examined (1) laboratory testing of POU pitcher filters with increasing iron concentrations to determine practical impacts on capacity of the units, (2) a cost-analysis comparing bottled water to POUs considering the effects of premature replacement due to clogging, (3) extrapolate predictions of laboratory data to several communities with high lead and a range of iron concentrations. The laboratory study showed neither soluble nor particulate iron impact the POUs ability to remove lead. When exposed to iron levels over 0.3 mg/L half of the POUs clogged prematurely, and all were clogged prematurely when the influent iron concentration was raised to 20 mg/L. There was a roughly linear relationship between the cost of POU treated water and iron-concentration. POUs were often more cost-effective than bottled water, but above threshold levels of iron dependent on the filter brand, bottled water can be cheaper than filtered water. Field data from iron sampling in small rural-low-income communities such as Enterprise, LA and St. Joseph, LA confirmed consumer experiences that filters could clog prematurely and predicted that in some cases bottled water was a less costly alternative to filters.

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> Rouillier, R.; Purchase, J. M.; Pieper, K. J.; Katner, A.; Edwards, M. A. Iron Clogging of Lead Certified Point-of-Use Pitcher Filters. *Environmental Engineering Science* (2022) [In Preparation]

Attributions: The first author, Rusty Rouillier, wrote the first draft, conducted all the formal analysis, and data visualization of this manuscript. As second author, I, Jeannie Purchase co-led, with Rouillier, the study investigation and execution of the filter performance experiments in Phase 1 and restructured the manuscript for publication. Co-authors, Adrienne Katner and Kelsey Pieper, provided data from previous sampling campaigns for the community analysis and contributed to revision of the manuscript. Edwards co-authored the manuscript and assisted with the data interpretation and logical flow of the manuscript. Marc Edwards, Adrienne Katner, Kelsey Pieper, and Jeffrey Parks were PI's on this project and designed the original experiment.

Chapter 4: Long Term performance of Faucet Mount Point-of-Use Filters in Louisiana Households

The long-term performance of lead certified POU filters was tested in a range of conditions in two Louisiana communities. The first Phase of research tested POU performance in a controlled study (e.g., >6 hr. stagnation, extended use) in 2 unoccupied homes where we evaluated lead removal by capturing all filtered water up to 200% capacity using automated flow control and sampling. The challenging treatment conditions in these homes were verified. Flushing alone did not always reduce lead to acceptable levels in the one home (Home with Sustained Lead) or in a second a Home with a Disturbed Lead Service Line (LSL) with very high (>3000 μg/L) and variable levels of particulate lead release. The POUs were effective at reducing lead levels <15 μg/L even up to 200% capacity for the Home with Sustained Lead, however the POUs in the Home with Disturbed LSL removed on average 57% of the lead, and the filtered water exceeded 15 μg/L on 8 occasions prior to 100% capacity. Phase 2 of the research monitored the performance of the same faucet filter POU brand in 21 homes in Enterprise and New Orleans, LA. The POUs always had good removal for lead and iron in treated water. However, the manganese levels in the treated water were occasionally (10%, n=88) higher than the SMCL (50 µg/L). All filtered Mn samples with >180 µg/L and the POUs reduced an average removal of 79% throughout the duration of the study. In a study conducted by Carrière et al. (2011), this type of POU was ineffective when removing soluble Mn and showed drastic decreases in Mn percent removals over time.[9] This limitation with Mn did not appear to impact lead removal by the POUs in our residential homes, however, should be monitored as studies are showing the potential adverse health effects of excess Mn. [9] The POU filter flowrates trended differently in the 2 communities. The Enterprise, LA homes had higher concentrations of iron and manganese which resulted in lower flowrates and a filter capacity <50% due to clogging, whereas most filters in New Orleans, LA did not significantly clog. There was a weak correlation between iron accumulation and filter life among Enterprise homes. The reduced capacity observed in Enterprise homes was reproduced in a controlled laboratory experiment, but the variability in duplicate filters would not allow for the prediction of filter failure. Clogging as seen in previous research can significantly increase treatment costs. This study illustrated that Enterprise residents would need 2-4X as many filter replacement cartridges when compared to New Orleans.

This manuscript is in preparation to be submitted to TBD.

> Purchase, J. M., Katner, A., Pieper, K. J., & Edwards, M. (2022). Long Term performance of Faucet Mount Point-of-Use Filters in Louisiana Households.

Attributions: As the first author on this paper, Jeannie Purchase designed and prepared the unoccupied home rigs and residential sampling kits and co-led the execution of the experiments and conducted all the data analysis and visualization for this manuscript. Adrienne Katner co-led the execution the study by recruiting participants for the unoccupied and residential homes in the Enterprise and New Orleans communities. Katner installed POUs in residential homes and conducted pre-and post-surveys, and she operated the unoccupied home study rigs (i.e., sampling, day to day maintenance). Katner and Kelsey Pieper corresponded with community organizations to recruit participants for the residential study. Marc Edwards co-authored the manuscript and assisted with the data interpretation and writing of the draft manuscript. Marc Edwards, Adrienne Katner, Kelsey Pieper, and Jeffrey Parks were PI's on this project and designed the original experiment.

### Chapter 5: Conclusions and Future Work

This chapter provides a summary of key conclusions from each chapter in this dissertation and proposes future work to fill knowledge gaps.

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# Chapter 2: Understanding Failure Modes of NSF/ANSI 53 Lead-certified Point-of-use Pitcher and Faucet Filters

Jeannie M Purchase, Rusty Rouillier, Kelsey J. Pieper, Marc Edwards

## ABSTRACT

NSF/ANSI 53 lead-certified point-of-use filters (POUs) have been distributed to consumers in many cities facing lead in water crises including Washington D.C., Flint, MI, Newark, NJ, and University Park, IL. After questions repeatedly arose about POU effectiveness in treating samples with relatively high lead, we examined 10 pitcher and faucet POU brands under extreme conditions (e.g., up to 200% of rated capacity, influent lead levels ≈ 1000 μg/L). Our tests sought to validate successful performance documented in some field testing and replicate underperformance observed in others. While verifying very good performance (i.e., <10 μg/L effluent lead) across most brands and situations, we encountered a few failures, including leaking units, premature clogging, and a filter with a large hole in the media. We also synthesized waters with colloidal lead that proved to be especially difficult to treat, as evidenced by 50% of influent lead passing through some replicate POUs that would have passed NSF/ANSI 53 lead-certification testing. While the POUs almost always dramatically reduce consumer lead exposure, even when operated beyond their rated capacity, this study highlights instances where treated water exceeded thresholds of 5, 10, and even 15 μg/L lead.

## INTRODUCTION

Hundreds of thousands of point-of-use filters (POUs) have been distributed to consumers during lead-in-water crises to provide safe potable water and protect public health.[1–5] These POUs were lead-certified under the NSF/ANSI 53 standards to reduce the influent lead of standardized challenge waters from 150 μg/L to <10 μg/L until 2019, and to a threshold <5 μg/L effective in 2020.[6,7] Previous lab and field studies have demonstrated that POUs treating water contaminated with >1,000 μg/L lead, usually produced water with lead <5 μg/L.[8–10] However, in field validation testing of water samples from Newark, NJ and elsewhere with up to 1670 μg/L lead, POUs had effluent lead >15 μg/L and in a few cases > 100 μg/L.[10,11] Follow-up investigations in Newark indicated that 97.5% of properly installed and operated POUs were producing effluent with <10 μg/L lead, but the sporadic failures nonetheless caused citywide angst, distrust, and a switch to bottled water.[10–12] To understand why NSF/ANSI 53 lead-certified POUs occasionally produce effluent water with >10 μg/L lead, we explored POU failure modes due to manufacturing issues, operation beyond rated capacity, and challenge waters with higher particulate lead concentrations.

## MATERIALS AND METHODS

### Phase 1: Laboratory testing of POUs

*POU Testing:* In April 2018, we reviewed POUs certified by NSF/ANSI 53 for lead removal in the Water Quality Association database and selected twelve POUs with unique filter cartridges (Table A1). All devices were tested in duplicate, except for one brand which was not available for purchase. Testing included four pitcher (Brands A-C, L) and seven faucet POUs (Brands D-

H, J-K). Brand L filters were excluded from further testing due to what we considered to be unacceptably low flowrate (<0.02 LPM; Table 2-1) during preliminary flow rate testing.

Table 2- 1: Filter test overview

| **Phase 1: Laboratory Testing of POUs** | | | | | |
|---|---|---|---|---|---|
| Steps | Water Condition | Lead (µg/L) | Procedure | Brands Tested | Brands Removed |
| 1 | Tap Water | <MRL | Flow rate trials | 11 Brands (A-L) | Brand L |
| 2 | Soluble Pb | 95.5±43.6 – F<br>149.3±15.5 – P | Tested up to 200% capacity | 10 Brands (A-K) | Brand G, H, J |
| 3 | Particulate Pb | 175.5±34.9 – F<br>189.6±92.1 – P | Tested up to 200% capacity | 7 Brands (A- F, K) | - |
| **Phase 2: An In-Depth Examination of Filter Underperformance** | | | | | |
| Steps | Water Condition | Lead (µg/L) | Volume Filtered | Effluent Sampling | Brands Tested |
| 1 | Particulate Pb | 179.4±0.5 | 3.78 L | 250 mL | CD and new POU |
| 2 | High Particulate Pb | 1,011.5± 16.8 | 2 L individual | 250 mL after each L | CD and new POU |
| 3 | High Particulate Pb | 1,011.5± 16.8 | 1 L | 10 mL | CD and new POU |
| 4 | Re-filtered High Particulate Pb effluent | - | 1L (Step 3 effluent) | 1 L | CD and new POU |
| 5 | LIS | 991.4 ± 54.7 | 1 L | 1 L | CD and new POU |
| 6 | LIS | 991.4 ± 54.7 | 1 L | 10 mL | CD |
| 7 | Re-Filtered LIS effluent | - | 1L (Step 6 effluent) | 1 L | CD |

CD: Community Deployed Filters
F: Faucet testing
P: Pitcher testing

All filter cartridges were conditioned with lead-free challenge waters. Pitcher POUs were soaked for 15 minutes and then flushed for 10 seconds, and faucet POUs were installed and flushed for 5 minutes. Our performance testing was designed to stress POUs when pushed beyond the NSF/ANSI 53 protocol limits.[6] Specifically, up to eight 3.8 L challenge water batches were treated by pitcher filters in an 8-10 hour day, with a minimum 30-minute rest period between batches (Figure A2). Faucet filters were tested on a 40-minute on and 40-minute off-cycle (Section A1). A total of 16-17, 250 mL samples were taken at regular intervals up to 200% of the POUs rated capacity (Figure S1). Flow rate, conductivity, and ion concentrations were monitored during the testing (Section A2).[13] POU failures were categorized as related to performance (i.e., effluent lead >10 µg/L), structural (i.e., loss of POU integrity or function), or clogging (i.e., reduction in flow by more than 75% from its initial rate).

*Lead Challenge Waters:* “Soluble” and “Particulate” challenge waters were adapted from the NSF/ANSI 53 protocol.[6] In all cases, the inherent variability of the influent lead water due to settling and losses to the apparatus were accounted for by measuring paired influent and effluent samples. The Soluble water at pH 6.5 with 20 mg/L alkalinity as calcium carbonate (CaCO3) had an average influent lead concentration of 149.3 ± 15.5 µg/L and 95.5 ± 43.6 µg/L (100% soluble) for pitcher and faucet filter testing, respectively (Table A2). The Particulate water with 100 mg/L alkalinity as CaCO3 at pH 8.5 had an average influent lead concentration of 189.6 ± 92.1 µg/L (36% particulate) for pitcher filters and 175.5 ± 34.9 µg/L (30% particulate) for faucet filters (Table A2). Particle size distributions were operationally defined by filtration through 0.1, 0.45, 1.2, or 5 µm pore size filters. The Particulate water deviated from the NSF/ANSI 53 protocol during particulate preparation by purposefully shaking the oversaturated lead solution instead of stirring it (Section A3), which created a higher fraction of 1.2-5 μm size particles predicted to have a lower removal efficiency according to granular media filtration theory (Section A3).[6,14]

### Phase 2: An In-Depth Examination of Filter Underperformance

Brand A pitcher filters with granulated activated carbon, cation, and anion exchange resin had the best removal throughout Phase 1, with effluent lead levels always <2.7 μg/L. Brand A POUs were distributed in a city, masked herein for confidentiality, that was experiencing high water lead levels. During a field investigation with consumer tap samples up to 706 μg/L, newly opened Brand A filters had effluent lead levels as high as 122 μg/L. Despite very significant reduction of influent lead in all tested cases, samples with effluent lead >15 μg/L are perceived as POU underperformance by many stakeholders as was the case in Newark, NJ.

Further analysis of these field samples determined that the new POUs had completely removed soluble anions and cations such as $Na^+$, $Ca^{+2}$, and $Cl^-$, but were not removing all the Pb and Sn, which tended to be almost entirely particulate in this water. We then used a sequence of challenge waters to better understand the nature of the Brand A filter underperformance in the laboratory. Two of the new field-tested Community Deployed (CD) POUs were lab tested alongside two newly purchased POUs of the same brand (Brand A). By the end of the study, all filters tested were at less than 52% of their rated capacity.

*Challenge Waters:* The highest influent lead levels in the Flint, MI, and Newark, NJ field studies were 4080 μg/L and 1680 μg/L, respectively, and virtually none of this lead was soluble.[5,10,11] Samples with lead over 1000 μg/L inevitably become a focal point of media attention and filter performance testing.[5,10,11,15,16] In this testing phase, the POUs were exposed to the Particulate water and two newly created particulate challenge waters (Table A2). The "High Particulate" water had 1000 μg/L of suspended lead phosphate (>99.9% particulate), with a pH of 8.5 and alkalinity of 100 mg/L as CaCO3. The "Low Ionic Strength" (LIS) water was the same as High Particulate water, but without the sodium bicarbonate, magnesium sulfate, or calcium chloride (Table A2). The excess of orthophosphate (27 mg/L as P) added to these waters, caused soluble lead to drop below 6% of the total lead after one hour, compared to ≈ 20% soluble lead if a more typical 1 mg/L as P dose of orthophosphate was used. The higher dose of phosphate was used because the fresh lead precipitates had the exact same zeta potential of -21 mV as those formed at the 1 mg/L dose, but it also created a broader and more even particle size distribution (Figure A3).

*POU Filter Testing Series:* The POU filtered batches of challenge waters in a series of 7 steps (Table 2-1). Step 1: 3.8 L of Particulate water, Step 2: two individual 1 L batches of High Particulate water; Step 3: 1 L of High Particulate water, with effluent collected; Step 4: re-filtering Step 3 effluent; Step 5: 1 L of LIS water; Step 6: 1 L of LIS, with effluent collected; and Step 7: re-filtering the Step 6 effluent as detailed in Table 2-1 and Section A2.

## RESULTS AND DISCUSSION

**Phase 1: Overall testing summary**

*POUs removed dissolved lead:* Nine of the 10 POU brands reduced the influent lead to below the NSF/ANSI 53 certification thresholds of 5 and 10 µg/L level for the Soluble challenge water when tested at up to 200% capacity (Figure 2-1A; Table A1). All 288 effluent samples from these 9 POU brands were <3.7 µg/L, and the average lead removal was 99.87%. One Brand B duplicate (discussed later in "Structural problems with POUs") failed to consistently reduce lead <10 µg/L (Figure 2-1D).

*POUs struggled to remove particulate lead:* Lead removal performance for the Particulate water was more variable. Only 3 of 7 filter brands (A, B, D; Figure 2-1B; Table A1) had all effluent lead levels <10 µg/L for up to 200% capacity, with 99 of 100 samples with effluent lead <5 µg/L and average lead of 0.3-1.3 µg/L for each brand. The Brand C (pitcher) had high lead in the first effluent batch for both duplicates (14.6 and 15.4 µg/L; Figure 2-1C), but after that, effluent levels were <10 µg/L, and 76% of the 34 samples were <5 µg/L. Brands E, F, and K (faucet) had at least one sample with effluent lead >10 µg/L (Figure 2-1E).

One duplicate filter tested of Brand E, E-F2, remained below 5 µg/L at all points up to 200% capacity, while the other duplicate E-F1 exceeded 10 µg/L between 65-104% of the rated capacity. Both Brand F duplicates produced water exceeding the limit of 15 µg/L at 173% or higher of capacity. The Brand K duplicate filters had the highest effluent lead levels for treating Particulate water, with values up to 34.6 and 54.7 µg/L for the duplicates. Both duplicate filters exceeded 10 µg/L upon reaching 50% and 88% capacity. These failures suggest that our efforts to make particulate lead sizes that were more difficult to treat than standard NSF/ANSI 53 testing may have been successful because effluent lead levels must remain below 10 µg/L for certification when exposed to the NSF 53 version of this water.

*Structural problems with POUs:* Several POU brands experienced structural problems during testing. Brand L duplicates required 200+ minutes to filter 3.8 L (<0.02 LPM), which was considered an unrealistically low initial flow rate, compared to the average of 44 minutes required for pitchers Brand A, B, and C to filter the same volume. When faucet filtering the Soluble water, Brand J had an extremely low flow rate of 0.58 liters/minute (LPM). A 30% reduction from its initial flow rate and less than half the average flowrate of other faucet filter brands for this condition (1.24 LPM; Table A5). The filter housing of Brands G and H duplicates leaked from multiple points when attached to the faucet (Figure A4).

The flow rate and removal efficacy of Brand B deviated markedly between duplicates (Figure 2-1D). B-P1 had effluent lead of <1.5 µg/L (98.9-100% reduction) but clogged at 81% rated capacity, as the flow rate dropped from 189.3 to 47.3 mL per minute (Table A4). In contrast, the flow rate of B-P2 increased with time and only removed 5-48% of lead. At the end of the experiment, we carefully cut away the outer wall of both filter cartridges to better understand the differing trends, revealing a large hole through the media of B-P2 but not B-P1 (Figure A5). Consistent with our discovery, online consumer reviews of this brand sometimes reported very fast flow rates co-occurring with inadequate removal of color, taste, and odors, indicating our results were not isolated. There are inconsistencies in POU manufacturing and quality control, which may not be detected in the standard NSF/ANSI 53 certification testing of one or two devices that are selected by the manufacturer.

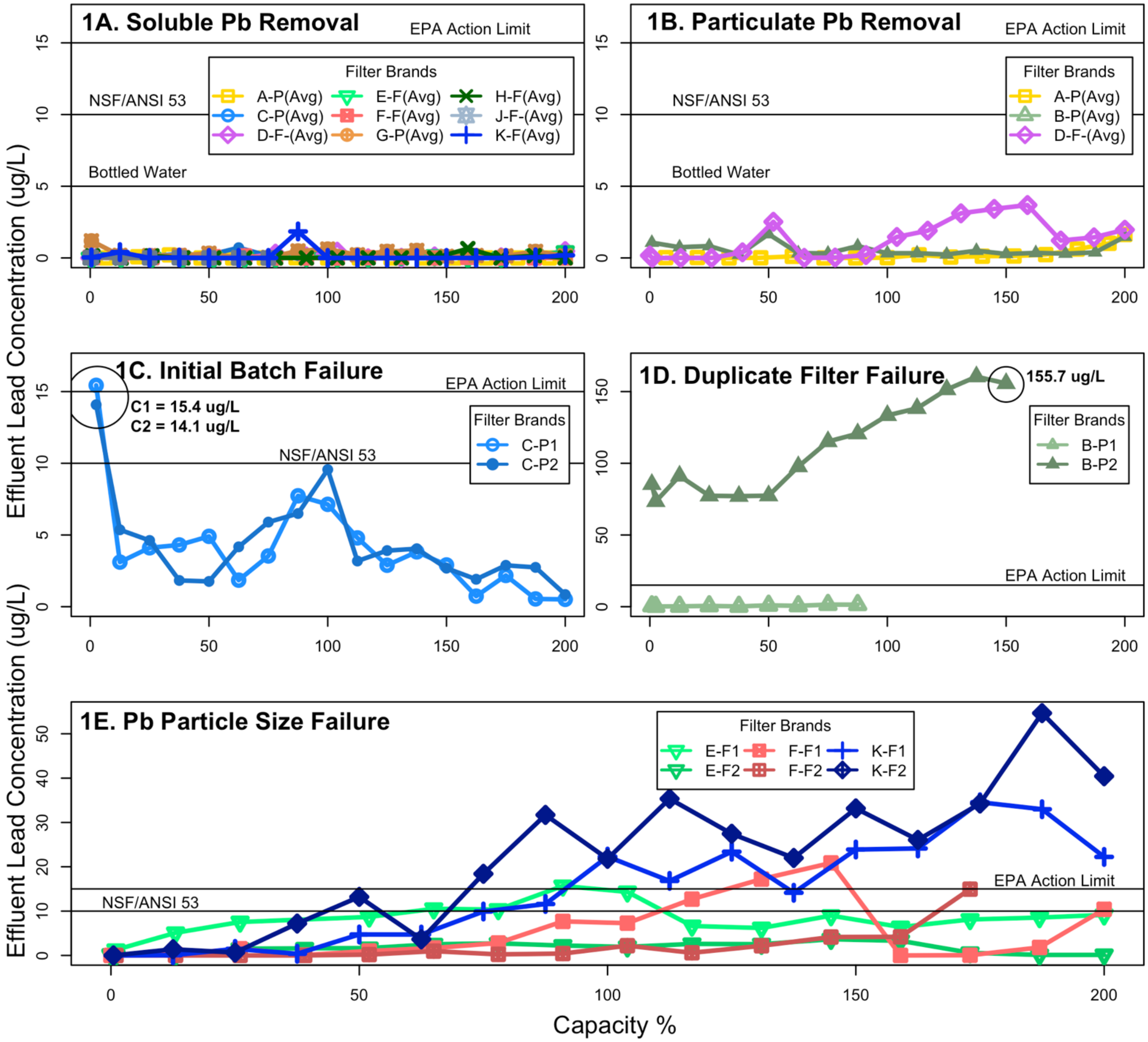

Figure 2- 1: Effluent Lead Concentration versus Filter Capacity. (A) Average effluent lead levels of 9 brands for Soluble Pb challenge. (B) Average lead levels of 3 brands for Particulate Pb challenge. (C) Elevated lead levels in the first sample for Brand C pitcher filter. (D) Brand B pitcher filter failures for Soluble Pb challenge, for both duplicates. (E) Six faucet filters across 3 brands, effluent lead levels above 10 µg/L for the Particulate Pb challenge.

*Public health impact of exceeding rated POU capacity or NSF/ANSI 53 influent lead levels:*
Concerns have been expressed about potential dangers to consumers if POUs are used beyond their rated capacity. Some of these concerns are based on prior experiences with POU treatment of arsenic with anion exchange media. Exceeding the capacity can cause treated water arsenic to be higher than the influent arsenic due to a chromatographic effect from sulfate competition.[17]

While POU performance for lead did deteriorate with increased use as expected, a relatively high percentage of lead removal (>71%) was almost always maintained even when used up to 200% of rated capacity. There was no evidence of chromatographic peaking, as expected given different removal mechanisms for lead versus arsenic. Likewise, treating water batches more frequently or with much higher lead levels than recommended by manufacturers in this work, still resulted in relatively high lead removal efficiencies.

**Phase 2: An In-Depth Examination of Filter Underperformance**

_All POUs removed Particulate lead:_ When exposed to our Particulate water (average influent of 179.4 ± 0.5 µg/L), all four POUs had effluent lead levels <1 µg/L, which proved that all of the Brand A filters would likely meet certification standards (Table A7).

_CD filters struggled with High Particulate water:_ When the High Particulate challenge water (average influent of 1011.5 ± 16.8 µg/L) was tested, the new POUs duplicates still met the <10 µg/L threshold, while the CD POUs exceeded 10 µg/L with effluent lead 42.1 - 66.6 µg/L (i.e., 10 times higher than the new POUs) (Table A7). Throughout all these studies, all soluble ions were completely removed by all the filters including $Na^+$ and $Cl^-$, which confirms that the filter media's capacity was never an issue and supports our hypothesis that lead particles or colloids were somehow passing through the filter.

To examine a hypothesis that particulates not removed by the POUs on the first pass through the filter represented a fraction of particulate lead that was somehow more difficult to remove, the effluents from the High Particulate test were re-filtered by each POU. After the first pass, CD1 had effluent lead of 26.6 µg/L, and when re-filtered, lead reduced to only 15.5 µg/L. The duplicate CD2 had 63.9 µg/L in the effluent first pass, and when re-filtered it was lowered to 40.3 µg/L. Thus, the removal efficiency decreased from 94-97% on the first pass down to 37-42% on the second pass for the duplicate tests, confirming that some particles in the influent had a lower removal efficiency by filtration. A similar reduction was seen in the new POUs. When the first pass effluents of 5.3-5.8 µg/L were re-filtered, the effluent lead was 1.6 µg/L. The removal efficiency of 99.4-99.7% from the first pass had been reduced to 70-72% in the second pass through these devices.

_All POUs struggled to treat LIS:_ The Newark, NJ water had relatively low ionic strength and hardness, expected to reduce particle removal efficiencies by granular media due to increased electrostatic repulsive forces between particles and the filter media.[11,18] Consistent with this expectation, effluent lead was >15 µg/L for all four POUs when exposed to the LIS water with an average influent lead of 991.4 ± 54.7 µg/L. Specifically, the new duplicate POUs had effluent lead of 19 and 29 µg/L (97-98% removal), whereas the CD filters had effluent lead of 123 and 181 µg/L (81-87% removal). The latter result was in the range of the worst performance encountered in the CD-field testing, in which influent lead was 706 µg/L and effluent of 122 µg/L (only 84% removal). In other words, the batch of CD filters had effluent lead 4.2-9.5 times higher than the new batch of POUs in treating this water.

When the LIS water was re-tested to confirm these results only for the CD POUs, the removal rates were again 86-90% (effluent levels of 102-148 µg/L). While re-filtering the LIS water effluent, the removal rate for CD1 was only 48.4% (102 µg/L to 53 µg/L), and CD2 was 45.4%

(148 µg/L to 81 µg/L). Overall, this work demonstrates that there can be fractions of particulate lead in samples that are very difficult to remove.[14]

It was hypothesized that particle size and surface charge, as controlled by water chemistry, partly contributed to the low removal efficiency, an expectation based on filtration trajectory and sieving theory.[14,18] Filter size fractionation of a representative LIS CD filter effluent sample indicated that about half of the particles evading removal in the LIS water were > 5 µm or between 1.2-5 µm (Figure 2-2). These results are not inconsistent with findings of Lytle et al. (2020), where the vast majority of lead evading POU removal in three Newark homes was removed by a 0.2 µm pore size filter— these authors did not further characterize the effective size of agglomerates in the influent or effluent water using larger filter pore sizes.[11]

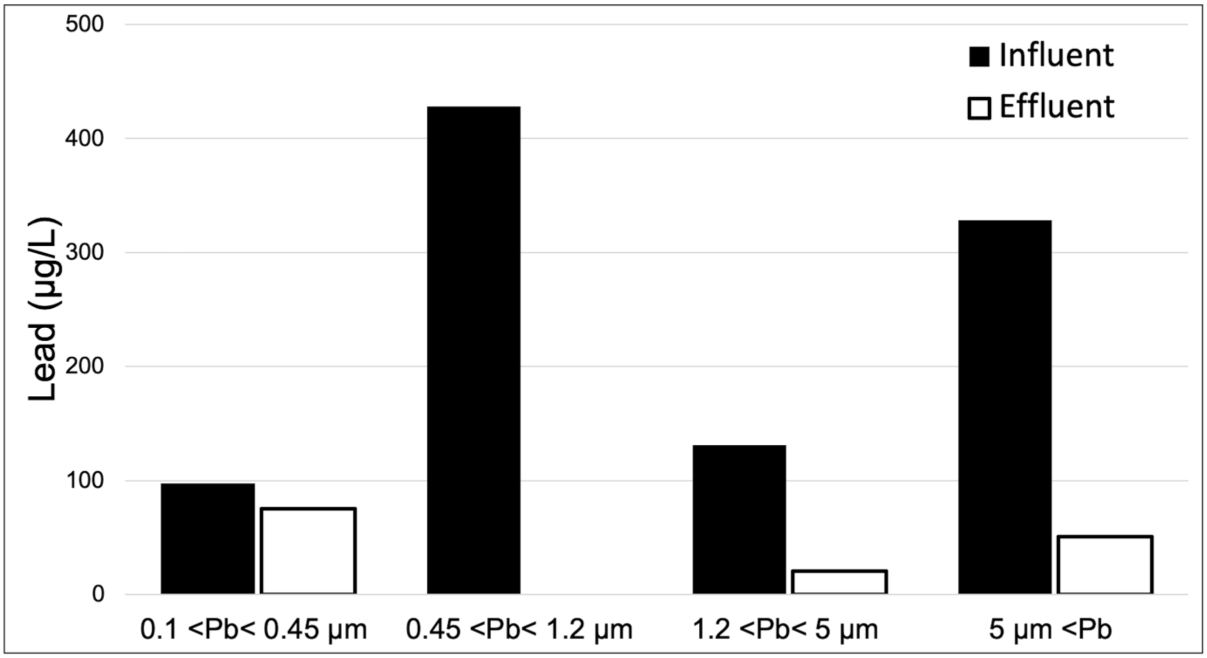

Figure 2- 2: Filtration size distribution for influent and effluent lead for a representative use of CD2

It is also clear that manufacturing deviations within a brand (i.e., the duplicate CD filters versus new duplicate filters) can produce marked variations in performance for difficult to treat waters that are not detectable in the NSF/ANSI 53 test water with only 30% particulate lead. A forensic analysis of these four filters upon completion of the study did not reveal any noteworthy differences between the two different batches (e.g., hole in the media like Brand B-P2). However, a compilation of initial flow rates for 28 of these filters over our study revealed a wide range from 62-171 mL/minute, with an average of 130 mL/minute and standard deviation 30 mL/minute, Table A8. The two CD filters did have a higher than average flow of 152 and 157 mL/minute when first received in our lab. While we did not track flow rates systematically throughout the case study and cannot definitively attribute differences in lead removal performance to this factor, the flow rate variability does reveal manufacturing deviations that could sometimes affect field performance.

Overall, while POUs usually provide important consumer protection in water lead contamination events and water crises, they occasionally have issues that can cause effluent lead to exceed desired public health thresholds. The NSF/ANSI 53 protocol committee should consider challenge waters with a higher particulate lead percentage. The current particulate lead challenge water with only 30% particulates does not reflect conditions with up to 100% particulate lead encountered in recent water crises. Considering that no safety device is foolproof or 100% effective, it is also important to manage performance expectations for these devices with regulators, disaster relief organizations, media, building managers, and consumers. [12,16,19]Finally, while the use of POUs beyond rated capacities did not ever cause effluent lead to exceed influent lead, the importance of properly maintaining the filters should continue to be emphasized.

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# APPENDIX A – SUPPORTING INFORMATION FOR CHAPTER 2

Section A1: POU testing
Section A2: Water sample analysis
Section A3: Particle size distribution difference based on laboratory methods
Table A1: Filter brand characteristics and lead levels from Phase 1
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Table A3: Role of mixing method in particle size distribution, and accounting for losses of lead to the apparatus
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Figure A3: Particle size distribution between high and low orthophosphate levels
Figure A4: Leaking unit – representation
Figure A5: Slit in media found in B-P2.

## Section A1. Faucet Filter Testing

A POU filter testing rig, based on the NSF/ANSI 53 protocol,[6] was constructed using 200-gallon tanks, a booster pump, pressure tank with a needle valve to maintain 35-45 psi, and a Chrontrol to operate duplicate filters on a pre-determined schedule (Figure S1). The rig was operated to achieve a 50% ON/ 50% OFF cycle, with each filter ON 40 minutes and then OFF 40 minutes. The tank was completely and continuously mixed in an attempt to keep most of the lead particles in suspension.

A pitcher filter rig was constructed using 50-gal tank reservoirs equipped with hoses to manually fill the pitchers (Figure S2). These tanks were also continuously mixed to maintain a relatively homogeneous suspension.

The reservoirs were cleaned after each use following the NSF/ANSI 53 (2015) protocol procedure, section 7.4.3.5.2.2.1,[6] using a 0.003 N HCl solution to acid wash materials for 2 hrs. We acid washed the tanks overnight, neutralized with sodium bicarbonate, and rinsed the equipment with DI water. Tubing was replaced between water conditions and the faucet rig components were exposed to acid no more than 2 hrs. Before testing, the surfaces of each rig were pre-conditioned following the NSF/ANSI 53 (2015) protocol procedure, section 7.4.3.5.2.2.2,[6] by filling the system up with 150 µg/L of soluble lead nitrate for a minimum of 8 hrs, for the Soluble and Particulate water conditions.

## Section A2. Water preparation

### Influent water

Water recipes were developed using the base recipe from the NSF/ANSI 53 water using Magnesium Sulfate, Sodium Bicarbonate, and Calcium Chloride, with concentrations adjusted to achieve the indicated alkalinity targets, except for the Low Ionic Strength water. pH was adjusted with 1 N Sodium Hydroxide and $CO_2$, using an Oakton pH6+ meter. Alkalinity was measured using a HACH digital titrator with 0.16 N Sulfuric Acid. Chlorine was measured using a Pocket Colorimeter II. Zeta potential for the Low Ionic Strength water was measured using the Zeta-Meter System 3.0.

### Filter effluent samples

Each filtered sample was collected in 250 mL bottles and preserved using 2% Nitric Acid. Prior to Nitric Acid, TDS and conductivity were measured. Pitcher filters were sampled with an aliquot of each 3.785 L batch, and the faucet filter samples were taken in paired samples directly from the filter unit tap as the influent and filtered effluent. It was necessary to take an influent sample every time we collected an effluent sample to account for the inherent variability in solutions with particulate lead. Filter flow rates were measured manually based on the time required to filter fixed volume containers. Conductivity and TDS readings were measured using an Oakton CTSTestr™ 50P.

### All samples

To determine the size distribution of lead particulates, total samples were taken along with aliquots passed through 0.1 µm, 0.2 µm, 0.45 µm, 1.2 µm, and 5 µm pore size syringe filters described in Tables A2 and A3. For multi-element analysis, all samples were digested with 2% nitric acid by volume for at least 16 hours prior to analysis using a Thermo Electron iCAP-RQ inductively coupled plasma mass spectrometer (ICP-MS) per Standard Method 3125-B.[12] Blanks and spikes of known metal concentrations were measured every 10–15 samples.

## Section A3. Role of mixing method in particle size distribution, and accounting for losses of lead to the apparatus

One-liter batches of the NSF/ANSI 53 pH 8.5 Particulate lead challenge water were made using two different methods. The NSF/ANSI 53 method requires the oversaturated solution to be mixing using a stir plate (found in section 7.4.3.5.2.3.2.)[6] for 60 seconds before it is diluted in the large tank for experiments. In this study we shook the solution in a capped plastic container for 60 seconds before diluting the mixture in the large tank. The differences in particle size distribution between the two methods are reported in Table A3.

Challenge water recipes were made with 15% higher lead concentrations than desired for the influent, to partly compensate for inevitable particles losses due to settling. Testing indicated that particle sizes were stable for the first 8 hours, at which point they started to significantly increase in size.

To account for unavoidable changes of ± 20 % in the influent water due to losses and gains caused by settling, sorption, adhesion, and coagulation, we collected paired samples of influent and effluent for each test of filter performance.

Table A1: Filter brand characteristics and lead levels from Phase 1

| Brand | Type | Filter Technology* | Capacity (Gal) | Capacity (L) | Soluble Lead Test Water | | Particulate Lead Test Water | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Average Influent (µg/L) | Effluent (µg/L) | Average Influent (µg/L) | Effluent (µg/L) |
| A | Pitcher | GAC, IX | 15 | 57 | 166.1 ± 5.1 | <0.1 - 0.4 | 150.1 ± 5.3 | <0.1 - 2.7 |
| B | Pitcher | GAC, IX | 120 | 454 | 143.1 ± 16.0 | 0.2 - 160.4 | 208.5 ± 105.9 | 0.1 - 2.6 |
| C | Pitcher | AC | 40 | 151 | 154.0 ± 9.8 | <0.1 - 0.9 | 147.7 ± 7.8 | 0.5 - 15.4 |
| D | Faucet | SBAC, IX, NM | 100 | 379 | 82.0 ± 1.1 | <0.1 - 0.8 | 186.7 ± 20.5 | <0.1 - 5.2 |
| E | Faucet | SBAC, IX | 100 | 379 | 81.4 ± 3.3 | <0.1 - 0.5 | 196.5 ± 20.8 | <0.1 - 15.7 |
| F | Faucet | SBAC | 100 | 379 | 129.2 ± 58.8 | <0.1 - 0.3 | 156.7 ± 57.2 | <0.1 - 20.9 |
| G | Faucet | SBAC | 200 | 757 | 99.8 ± 40.9 | <0.1 - 1.4 | - | - |
| H | Faucet | SBAC | 100 | 379 | 109.0 ± 74.1 | <0.1 - 1.3 | - | - |
| J | Faucet | SBAC | 200 | 757 | 83.9 ± 20.1 | <0.1 - 0.1 | - | - |
| K | Faucet | SBAC | 200 | 757 | 83.5 ± 9.9 | <0.1 - 3.7 | 172.1 ± 11.9 | <0.1 - 54.7 |
| L | Pitcher | GAC | 40 | 151 | - | - | - | - |

* The technology descriptions are based on labeling from the filter packaging. The exact technologies are proprietary information.

GAC: Granulated activated carbon
AC: Non-granular activated carbon
SBAC: Solid block activated carbon
IX: Ion exchange
NM: Natural minerals

Table A2: Water quality for POU challenge waters

| Water chemistry parameters | NSF/ANSI 53 Particulate Pb[a] | Faucet POUs | | Pitcher POUs | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Laboratory Study | | Filter Underperformance Study | | |
| | | Soluble | Particulate | Soluble | Particulate | Particulate | High Particulate | Low Ionic Strength |
| Alkalinity (mg/L as CaCO3) | 100.0±10% | 20.0±3.3 | 106.7±14.5 | 17.6±1.9 | 100.3±8.0 | 108.0 | 108.0 | 39.6 |
| pH | 8.5 (8.30-8.60) | 6.5±0.0 | 8.5±0.1 | 6.6±0.1 | 8.5±0.0 | 8.5 | 8.5 | 7.8 |
| Temperature (°C) | 20.0±2.5 | 14.7±3.8 | 17.3±1.8 | 22.2±2.8 | 20.8±3.7 | 21.1 | - | - |
| Total Chlorine (mg/L) | 0.5±0.25 | - | 0.6±0.1 | - | 0.53±0.1 | 0.55 | - | - |
| Total Lead (µg/L) | 150.0±10% | 95.5±43.6 | 175.5±34.9 | 149.3±15.5 | 189.6±92.1 | 179.4±0.5 | 1,011.5± 16.8 | 991.4 ± 54.7 |
| Total Particulate Lead % (>0.1 µm)[b] | 30.0% ± 10% | - | 29.8% | - | 35.9% | 31.6% | >99.9% | 96.1% |
| 0.1 < Pb < 0.45 | >20.0% | - | 13.8% | - | 35.7% | 0.0% | 0.0% | 9.4% |
| 0.45 < Pb < 1.2 | | - | | - | | 18.2% | 4.5% | 39.6% |
| 1.2 < Pb < 5.0 | <80.0% | - | 86.2% | - | 64.3% | 30.8% | 3.8% | 15.3% |
| 5.0 < Pb | | - | | - | | 51.0% | 91.7% | 35.7% |

[a] NSF International. *NSF/ANSI 53 -2015: Drinking Water Treatment Units - Health Effects*; Ann Arbor, MI, 2015. (p 73-81)

[b] Filters: 0.1 µm Millipore Sigma™ Millex™; 0.2 µm Nylon Whatman™; 0.45 µm Nylon Whatman™, 1.2 µm Sartorius™ Minisart™ NML; 5 µm Sartorius™ Minisart™ NML

Pb: Lead

Table A3: Particle size distribution difference based on laboratory methods

| Water Condition | Stirred Particulate Pb (NSF/ANSI 53)[a] | Shaken Particulate Pb (This study) |
|---|---|---|
| Total Lead (µg/L) | 202.4 ± 15.0 | 204.7 ± 8.1 |
| Total Particulate Lead % (>0.1 µm)[b] | 52.5% | 47.1% |
| 0.1 < Pb < 0.45 | 0.0% | 0.0% |
| 0.45 < Pb < 1.2 | 70.2% | 45.4% |
| 1.2 < Pb < 5.0 | 15.1% | 22.6% |
| 5.0 < Pb | 14.7% | 31.9% |

[a] NSF International. *NSF/ANSI 53 -2015: Drinking Water Treatment Units - Health Effects*; Ann Arbor, MI, 2015. (p 73-81)

[b] Filters: 0.1 µm Millipore Sigma™ Millex™; 0.2 µm Nylon Whatman™; 0.45 µm Nylon Whatman™, 1.2 µm Sartorius™ Minisart™ NML; 5 µm Sartorius™ Minisart™ NML

Pb: Lead

Table A4: Flow rates of pitcher filters for Soluble and Particulate waters

| Flow rate (LPM) | Soluble Lead | | | | | | Particulate Lead | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | A | | B | | C | | A | | B | | C | |
| Sample # | P1 | P2 | P1 | P2 | P1 | P2 | P1 | P2 | P1 | P2 | P1 | P2 |
| 1 | 0.14 | 0.15 | 0.17 | 0.24 | 0.11 | 0.09 | 0.14 | 0.15 | 0.15 | 0.07 | 0.05 | 0.05 |
| 2 | 0.13 | 0.13 | 0.21 | 0.27 | 0.11 | 0.12 | 0.14 | 0.14 | 0.18 | 0.18 | 0.06 | 0.06 |
| 3 | 0.14 | 0.14 | 0.21 | 0.45 | 0.11 | 0.09 | 0.15 | 0.16 | 0.15 | 0.16 | 0.05 | 0.05 |
| 4 | 0.15 | 0.15 | 0.17 | 0.44 | 0.08 | 0.11 | 0.15 | 0.16 | 0.24 | 0.16 | 0.06 | 0.06 |
| 5 | 0.15 | 0.15 | 0.19 | 0.42 | 0.07 | 0.12 | 0.15 | 0.16 | 0.17 | 0.19 | 0.06 | 0.06 |
| 6 | 0.15 | 0.15 | 0.17 | 0.42 | 0.11 | 0.11 | 0.15 | 0.16 | 0.2 | 0.18 | 0.05 | 0.05 |
| 7 | 0.15 | 0.15 | 0.08 | 0.41 | 0.07 | 0.13 | 0.15 | 0.16 | 0.16 | 0.14 | 0.05 | 0.05 |
| 8 | 0.14 | 0.14 | 0.04 | 0.31 | 0.07 | 0.1 | 0.15 | 0.15 | 0.14 | 0.18 | 0.05 | 0.05 |
| 9 | 0.15 | 0.15 | 0.01 | 0.23 | 0.06 | 0.11 | 0.15 | 0.16 | 0.12 | 0.13 | 0.05 | 0.05 |
| 10 | 0.16 | 0.15 | X* | 0.24 | 0.07 | 0.13 | 0.16 | 0.17 | 0.17 | 0.11 | 0.04 | 0.04 |
| 11 | 0.15 | 0.12 | X | 0.2 | 0.06 | 0.1 | 0.16 | 0.16 | 0.16 | 0.15 | 0.05 | 0.04 |
| 12 | 0.15 | 0.15 | X | 0.19 | 0.05 | 0.11 | 0.16 | 0.16 | 0.11 | 0.13 | 0.05 | 0.05 |
| 13 | 0.14 | 0.13 | X | 0.19 | 0.05 | 0.13 | 0.14 | 0.14 | 0.14 | 0.13 | 0.04 | 0.04 |
| 14 | 0.14 | 0.13 | X | X | 0.05 | 0.12 | 0.15 | 0.15 | 0.14 | 0.14 | 0.04 | 0.06 |
| 15 | 0.15 | 0.15 | X | X | 0.04 | 0.14 | 0.16 | 0.16 | 0.13 | 0.15 | 0.06 | 0.06 |
| 16 | 0.15 | 0.16 | X | X | 0.05 | 0.14 | 0.15 | 0.16 | 0.08 | 0.1 | 0.04 | 0.04 |
| 17 | -* | - | X | X | 0.07 | 0.14 | - | - | 0.05 | 0.05 | 0.05 | 0.07 |
| Average | 0.14 ± 0.01 | | 0.24 ± 0.12 | | 0.09 ± 0.03 | | 0.15 ± 0.01 | | 0.14 ± 0.04 | | 0.05 ± 0.01 | |
| Median (range) | 0.15<br>(0.12 - 0.16) | | 0.21<br>(0.01 - 0.45) | | 0.10<br>(0.04 - 0.14) | | 0.15<br>(0.14 - 0.17) | | 0.14<br>(0.05 - 0.24) | | 0.05<br>(0.04 - 0.07) | |

*- means filter brand did not have samples to be taken. Due to the samples being taken at equal increments from 0-200% capacity including a sample for the first 3.78 L batch, some brands did not need a 17th sample. X means filter clogged and testing concluded.

Table A5: Flow rates of faucet filters for Soluble water

| Flow rate (LPM) | Soluble Lead | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | D | | E | | F | | G | | H | | J | | K | |
| Sample # | F1 | F2 | F1 | F2 | F1 | F2 | F1 | F2 | F1 | F2 | F1 | F2 | F1 | F2 |
| 1 | 1.15 | 1.25 | 1.15 | 0.94 | 0.63 | 0.65 | 0.94 | 0.94 | 1.50 | 1.36 | 0.94 | 0.83 | 1.25 | 1.36 |
| 2 | 1.00 | 0.94 | 0.94 | 1.07 | 1.50 | 1.67 | 1.50 | 1.07 | 1.50 | 1.36 | 0.88 | 0.83 | 1.25 | 1.50 |
| 3 | 1.07 | 1.25 | 1.07 | 1.00 | 1.50 | 1.88 | 1.36 | 1.36 | 1.50 | 1.25 | 0.71 | 0.68 | 1.25 | 1.25 |
| 4 | 1.15 | 1.25 | 1.07 | 1.00 | 1.67 | 1.88 | 1.36 | 1.25 | 1.36 | 1.25 | 1.00 | 0.94 | 1.25 | 1.25 |
| 5 | 1.25 | 1.25 | 1.07 | 1.00 | 1.67 | 1.88 | 1.36 | 1.25 | 1.50 | 1.36 | 1.25 | 0.88 | 1.36 | 1.50 |
| 6 | 1.15 | 1.00 | 1.15 | 1.00 | 1.50 | 1.67 | 1.36 | 1.36 | 1.15 | 1.15 | 1.15 | 0.68 | 1.25 | 1.50 |
| 7 | 1.15 | 1.25 | 1.15 | 1.07 | 2.14 | 1.67 | 1.50 | 1.36 | 1.15 | 1.07 | 0.88 | 0.58 | 1.36 | 1.50 |
| 8 | 1.15 | 1.00 | 1.15 | 1.00 | 1.67 | 1.67 | 1.25 | 1.36 | 1.25 | 1.07 | 0.75 | X* | 1.50 | 1.50 |
| 9 | 1.15 | 1.15 | 1.15 | 1.00 | 1.67 | 1.88 | 1.25 | 1.36 | 1.36 | 1.15 | 0.65 | X | 1.36 | 1.36 |
| 10 | 1.07 | 1.15 | 1.25 | 1.00 | 1.67 | 1.67 | 1.15 | 1.36 | 1.00 | 1.15 | X | X | 1.36 | 1.36 |
| 11 | 1.25 | 1.07 | 1.15 | 1.00 | 1.50 | 1.67 | 1.36 | 1.36 | 1.36 | 1.15 | X | X | 1.25 | 1.36 |
| 12 | 1.07 | 1.36 | 1.07 | 1.15 | 1.50 | 1.67 | 1.36 | 1.25 | 1.36 | 1.07 | X | X | 1.36 | 1.36 |
| 13 | 1.07 | 1.07 | 1.15 | 0.94 | 1.36 | 1.50 | 1.36 | 1.25 | 1.36 | 1.15 | X | X | 1.36 | 1.25 |
| 14 | 1.00 | 1.15 | 1.07 | 0.94 | 1.36 | 1.50 | 1.25 | 1.15 | 1.25 | 1.25 | X | X | 1.36 | 1.36 |
| 15 | 1.15 | 1.15 | 1.07 | 0.94 | 1.50 | 1.36 | 1.15 | 1.15 | 1.36 | 1.25 | X | X | 1.25 | 1.15 |
| 16 | 0.94 | 1.15 | 0.94 | 0.94 | 1.50 | 1.50 | 1.25 | 1.15 | 1.36 | 1.36 | X | X | 1.25 | 1.25 |
| 17 | -* | - | - | - | - | - | 1.36 | 1.25 | - | - | X | X | 1.25 | 1.25 |
| Average | 1.13 ± 0.1 | | 1.05 ± 0.09 | | 1.56 ± 0.3 | | 1.28 ± 0.13 | | 1.27 ± 0.14 | | 0.85 ± 0.18 | | 1.33 ± 0.1 | |
| Median (range) | 1.15<br>(0.94 - 1.36) | | 1.07<br>(0.94 - 1.25) | | 1.67<br>(0.63 - 2.14) | | 1.31<br>(0.94 - 1.5) | | 1.25<br>(1 - 1.5) | | 0.86<br>(0.58 - 1.25) | | 1.36<br>(1.15 - 1.5) | |

*- means filter brand did not have samples to be taken. Due to the samples being taken at equal increments from 0-200% capacity including a sample for the first 3.78 L batch, some brands did not need a 17th sample. X means filter clogged and testing concluded.

Table A6: Flow rates of faucet filters for Particulate water

| Flow rate (LPM) | Particulate Lead | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | D | | E | | F | | K | |
| Sample # | F1 | F2 | F1 | F2 | F1 | F2 | F1 | F2 |
| 1 | 1.25 | 1.07 | 1.25 | 1.36 | 1.32 | 1.36 | 1.36 | 1.36 |
| 2 | 1.25 | 1.07 | 1.25 | 1.36 | 1.25 | 1.36 | 1.25 | 1.36 |
| 3 | 1.36 | 1.07 | 1.25 | 1.36 | 1.25 | 1.29 | 1.25 | 1.36 |
| 4 | 1.25 | 1.07 | 1.25 | 1.15 | 1.29 | 1.29 | 1.25 | 1.25 |
| 5 | 1.15 | 0.58 | 1.36 | 1.36 | 1.29 | 1.25 | 1.25 | 1.36 |
| 6 | 0.75 | 0.52 | 1.25 | 1.25 | 1.32 | 1.29 | 1.25 | 1.25 |
| 7 | 0.60 | 0.58 | 1.36 | 1.25 | 1.29 | 1.25 | 1.25 | 1.50 |
| 8 | 0.63 | 0.71 | 1.25 | 1.25 | 1.29 | 1.29 | 1.36 | 1.36 |
| 9 | 0.63 | 0.58 | 1.25 | 1.36 | 1.25 | 1.29 | 1.36 | 1.36 |
| 10 | 0.68 | 0.63 | 1.25 | 1.25 | 1.25 | 1.32 | 1.36 | 1.25 |
| 11 | 0.75 | 0.58 | 1.25 | 1.36 | 1.22 | 1.32 | 1.36 | 1.36 |
| 12 | 1.15 | 1.15 | 1.15 | 1.36 | 1.22 | 1.29 | 1.25 | 1.25 |
| 13 | 1.15 | 1.15 | 1.25 | 1.15 | 1.18 | 1.25 | 1.36 | 1.15 |
| 14 | 1.67 | 1.07 | 1.15 | 1.25 | 1.22 | 1.25 | 1.50 | 1.25 |
| 15 | 1.15 | 1.15 | 1.25 | 1.36 | 1.15 | 1.29 | 1.36 | 1.15 |
| 16 | 1.36 | 1.00 | 1.07 | 1.25 | 1.25 | 1.05 | 1.15 | 1.07 |
| 17 | -* | - | - | - | - | - | 1.50 | 1.25 |
| Average | 0.94 ± 0.26 | | 0.95 ± 0.23 | | 1.26 ± 0.06 | | 1.28 ± 0.09 | |
| Median (range) | 0.99<br>(0.56 - 1.36) | | 0.87<br>(0.67 - 1.32) | | 1.29<br>(1.05 - 1.36) | | 1.3<br>(1.05 - 1.43) | |

*- means filter brand did not have samples to be taken. Due to the samples being taken at equal increments from 0-200% capacity including a sample for the first 3.78 L batch, some brands did not need a 17th sample.

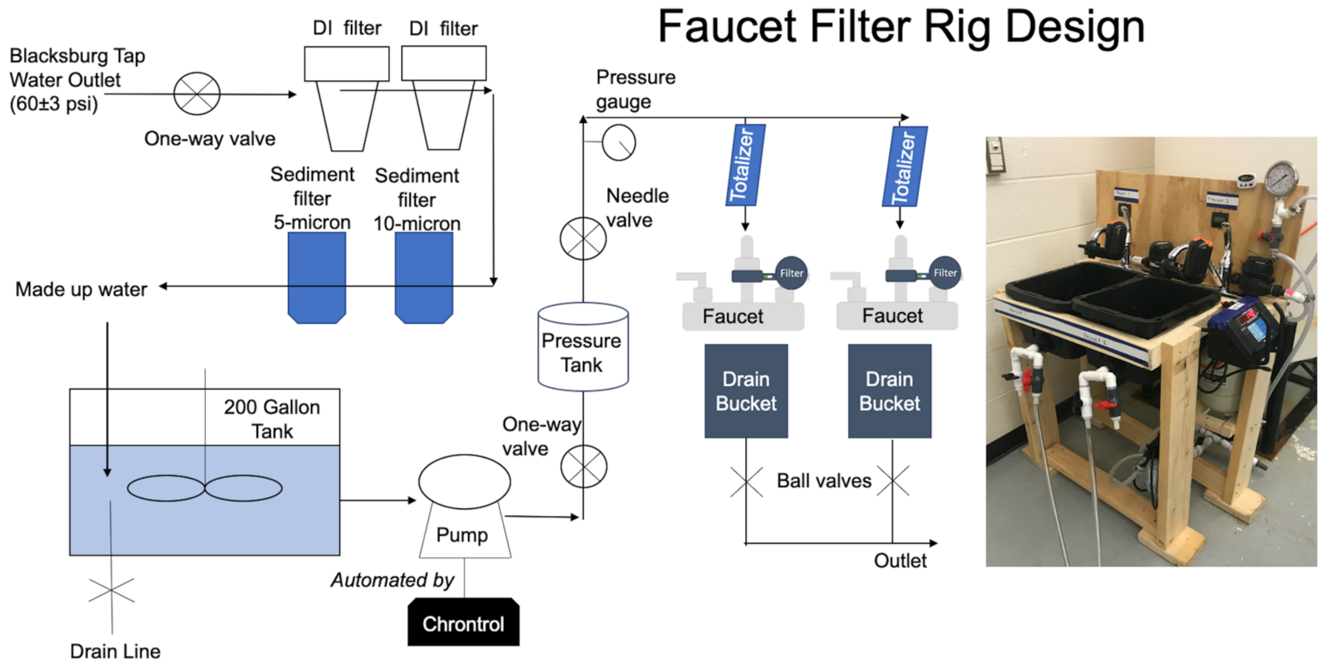
Table A7: Filter Performance of CD and new POUs

| Order | Water Condition | Filter | Influent Pb (µg/L) | Effluent Pb (µg/L) | % Removed | Filter | Influent Pb (µg/L) | Effluent Pb (µg/L) | % Removed |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Particulate | CD1 | 179.4 | 0.4 | 99.8% | New 1 | 179.4 | 0.4 | 99.8% |
| | | CD2 | 179.4 | 0.4 | 99.8% | New 2 | 179.4 | 0.7 | 99.6% |
| 2 | High Particulate | CD1 | 1011.5 | 42.1* | 95.8% | New 1 | 1011.5 | 2.4* | 99.7% |
| | | CD2 | 1011.5 | 66.6* | 93.4% | New 2 | 1011.5 | 6.4* | 99.4% |
| 3 | High Particulate | CD1 | 1011.5 | 26.6 | 97.4% | New 1 | 1011.5 | 5.3 | 99.5% |
| | | CD2 | 1011.5 | 63.9 | 93.7% | New 2 | 1011.5 | 5.8 | 99.4% |
| 4 | High Particulate, Re-filtered | CD1 | 26.6 | 15.5 | 41.7% | New 1 | 5.3 | 1.6 | 69.8% |
| | | CD2 | 63.9 | 40.3 | 36.9% | New 2 | 5.8 | 1.6 | 72.4% |
| 5 | Low Ionic Strength (LIS) | CD1 | 945.7 | 123.0 | 87.0% | New 1 | 945.7 | 18.6 | 98.0% |
| | | CD2 | 945.7 | 180.8 | 80.9% | New 2 | 945.7 | 28.8 | 97.0% |
| 6 | Low Ionic Strength (LIS) | CD1 | 1047.1 | 102.4 | 90.2% | | | | |
| | | CD2 | 1027.2 | 148.7 | 85.5% | | | | |
| 7 | LIS Re-filtered | CD1 | 102.4 | 52.8 | 48.4% | | | | |
| | | CD2 | 148.7 | 81.2 | 45.4% | | | | |

**Average values of the 2 Liters filtered for this Challenge.*

Table A8: Initial flowrates of Brand A filters from our various water conditions

| Initial Flowrates of Brand A Filter | |
|---|---|
| Pitcher Filter ID | Flowrate (LPM) |
| CD1 | 0.16 |
| CD2 | 0.16 |
| new 1 | 0.16 |
| new 2 | 0.10 |
| P1 | 0.17 |
| P2 | 0.16 |
| P3 | 0.06 |
| P4 | 0.13 |
| P5 | 0.17 |
| P6 | 0.14 |
| P7 | 0.16 |
| P8 | 0.11 |
| P9 | 0.11 |
| P10 | 0.13 |
| P11 | 0.13 |
| P12 | 0.14 |
| P13 | 0.14 |
| P14 | 0.15 |
| P15 | 0.15 |
| P16 | 0.14 |
| P17 | 0.06 |
| P18 | 0.16 |
| P19 | 0.18 |
| P20 | 0.16 |
| P21 | 0.16 |
| P22 | 0.17 |
| P23 | 0.17 |
| P24 | 0.17 |
| P25 | 0.16 |
| Average (LPM) | 0.13 ± 0.39 |
| Median (range) | 0.16 (0.06-0.18) |


Faucet Filter Rig Design

* Adapted from NSF/ANSI 53 (2015), *Figure 2 – Example test apparatus*

Figure A1: Faucet filter testing rig

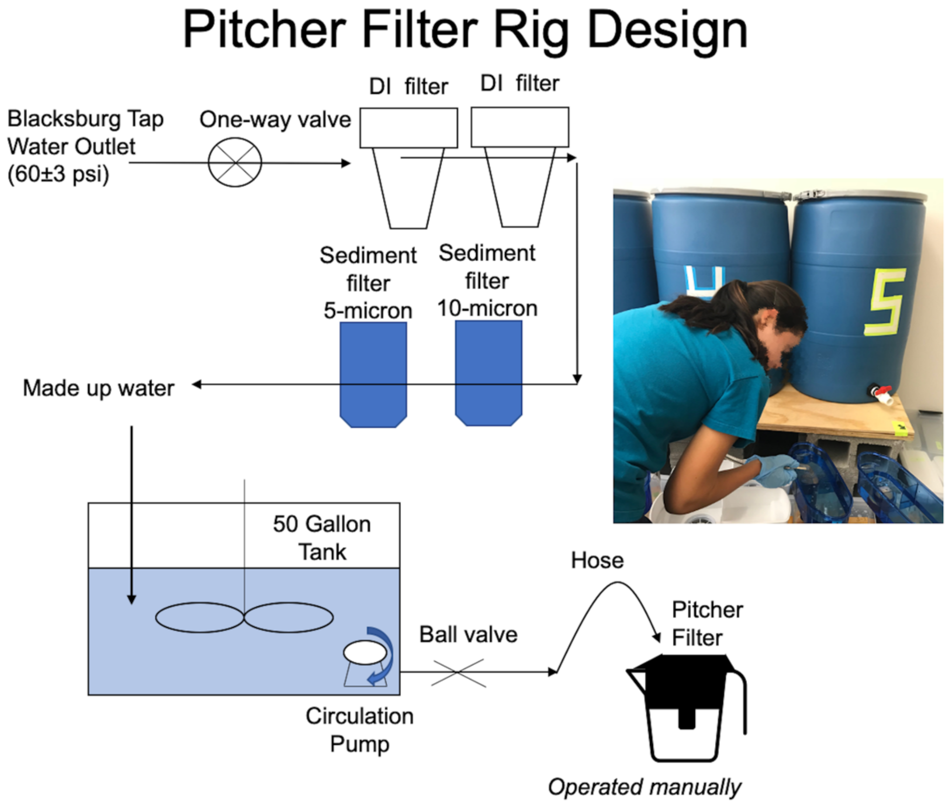


Figure A2: Pitcher filter testing rig

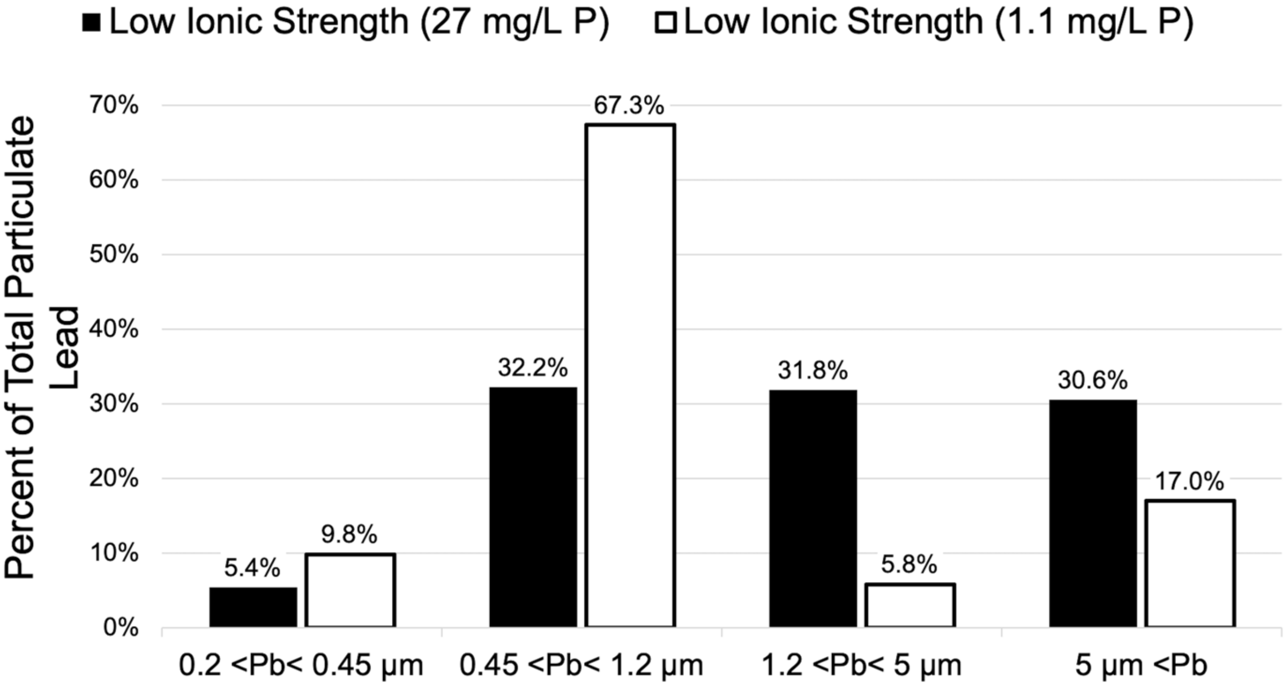


Figure A3: Particle size distribution between high and low orthophosphate levels

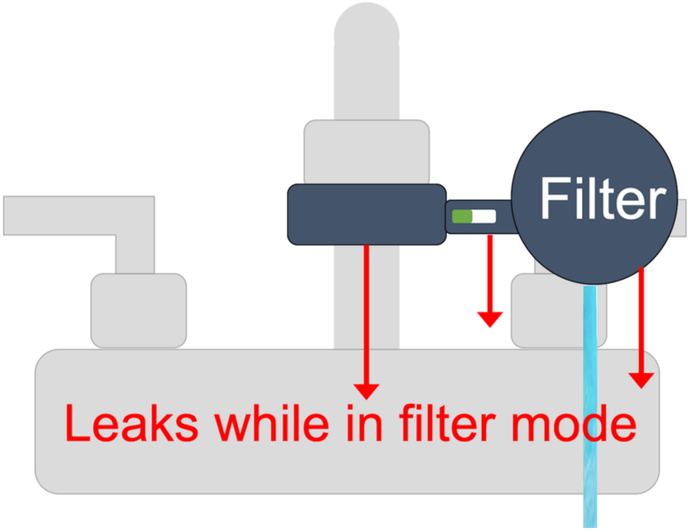


Figure A4: Leaking unit – representation

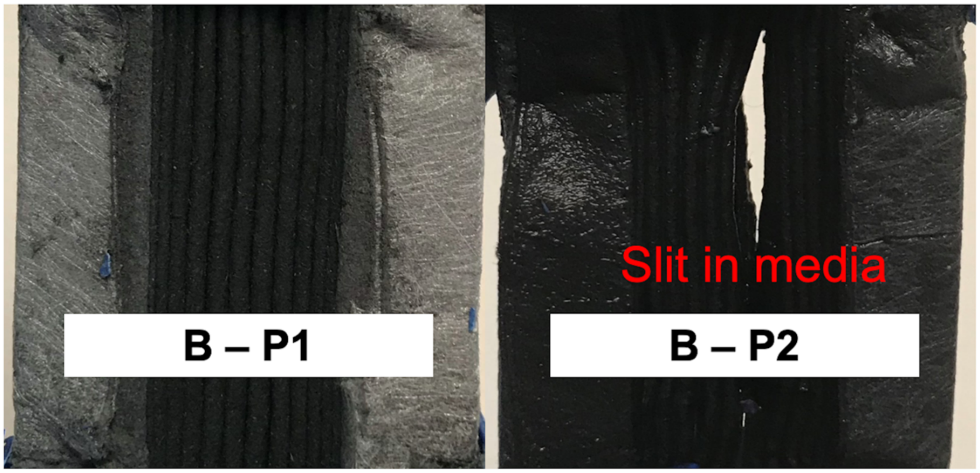


Figure A5: Slit in media found in B-P2

# Chapter 3: Iron Clogging of Lead Certified Point-of-Use Pitcher Filters

Rusty Rouillier, Jeannie M Purchase, Kelsey J Pieper, Adrienne Katner, Marc Edwards

## ABSTRACT

Point-of-use (POU) pitcher filters are increasingly used to protect consumers from lead in drinking water, but there have been anecdotal reports of premature failure due to clogging in areas with high iron in water. To evaluate this concern in relation to lead removal and treatment costs, POU pitcher filters were exposed to water conditions containing lead and/or iron and tested to 100% of their rated capacity or until they clogged. Iron levels above the 0.3 mg/L Secondary Maximum Contaminant Level (SMCL) resulted in rapid clogging, affecting both treatment costs and consumer satisfaction. At 0.3 mg/L Fe, half of 6 POU filters tested clogged prematurely between 38-68% of the rated capacity. At 1.0 mg/L Fe 4 out of 6 filters tested clogged prematurely, and all clogged prematurely at 20 mg/L. When considering the cost of using POU filters vs. purchasing bottled water, the POU devices were often more cost-effective at iron levels at or below 0.3 mg/L, while bottled water was sometimes more cost-effective at higher iron levels. The presence of iron only occasionally affected overall lead removal in this research but clogging greatly affected costs of using filters and were an understandable source of customer frustration.

## INTRODUCTION

Point-of-use (POU) household water filters have the potential to provide consumers with a cost-effective drinking water alternative to protect themselves from lead exposure (Verhougstraete et al., 2019). The percentage of consumers voluntarily purchasing such devices rose from 32% in 2002 to 43% in 2015 (Cartwright 2007; Cotruvo 2015). In addition, about 6% of bottled water consumers switched to filtration devices between 2011 and 2015 partly due to environmental concerns regarding plastic disposal (Cotruvo 2015). The NSF International/American National Standards Institute (NSF/ANSI) oversees NSF/ANSI 53 Health Effects and NSF/ANSI 42 Aesthetic Effects certification for filter performance by measuring lead (Pb) and iron (Fe) removal under prescribed protocols (NSF International 2019a, 2019b).

In recent decades, high-profile water lead contamination incidents have resulted in widespread public distribution of lead certified POU faucet and pitcher filters to protect consumers from lead exposure (Bosscher et al. 2019; Chon 2004; Koeske 2019; Tuser 2019). Following the distribution of filters during the 2015 Flint Water Crisis, public concern was expressed regarding the efficacy of POU filters. In response the U.S Environmental Protection Agency (EPA) conducted a field study with ~240 homes that determined POU filters successfully reduced water lead concentrations to below 3 μg/L even with influent Pb concentrations up to 4,080 μg/L Pb (Bosscher et al. 2019).

But in 2019, the New Jersey Department of Environmental Protection requested that the City of Newark test POU filter effectiveness at three homes expected to represent worst-case scenario lead concentrations within the city (CDM Smith 2019). Using samples that were believed representative of water after stagnation in lead service lines, filters in two out of the three homes did not produce lead levels below the 10 μg/L NSF/ANSI 53 standard requirement. A more comprehensive filter study in Newark later revealed that 97.5% of homes (n=198) with properly installed and maintained filters had effluent lead levels below 10 µg/L (CDM Smith 2019; Lytle et al. 2020). However, the publication of the preliminary results with high lead created widespread distrust and caused many residents to discontinue using their POU filters.

Recent laboratory studies have investigated and highlighted additional situations in which filters did not perform up to expectations (i.e., reducing lead levels below 10 µg/L) when tested with synthetic lead particulate waters (Deshommes et al. 2010; Doré et al. 2021; Pan, Johnson, and Giammar 2020, 2021; Purchase et al. 2020). The practical performance of these filters for consumers has also been unsatisfactory for some residents as we have anecdotal reports of premature filter clogging in waters with high iron. Masters and Edwards (2015) documented an association of particulate iron and lead in some residential homes, and it is logical to think that removal of lead might sometimes be tied to removal of iron. The current certification performance testing for lead removal does not explicitly consider the role of co-occurring iron or other contaminants in either clogging or lead removal (NSF International 2019b).

This investigation evaluated limitations of POU filter performance when iron and lead co-occur in drinking water, including possible impacts on lead removal efficiency and premature clogging. In this three-phase study we (1) conducted laboratory performance testing (lead removal efficiency and reduced capacity) for three brands of pitcher-style POU devices in the presence of iron, (2) used a cost-benefit analysis to examine the effects of reduced capacity arising from iron clogging on the relative costs of POU filters versus bottled water, and (3) extended these concepts to field data from citizen science water monitoring campaigns to further consider the scope of concerns regarding POU clogging.

## METHODS

### Phase 1: Laboratory Pitcher POU Testing

Four NSF/ANSI 53 lead certified POU pitcher filter brands were selected from the Water Quality Association database in April 2018. Three (brand A, B, and C) pitcher filters were evaluated, with the fourth brand being eliminated prior to testing due to low initial flowrates (Purchase et al., 2020). Pitcher brands A, B, and C had rated capacities of 57 L (15-gal), 454 L (120-gal), and 151 L (40-gal), respectively. The POUs were tested up to 100% of their rated capacity or until failure due to clogging occurred. The three POUs brands were tested in duplicate against three particulate iron challenge waters (Figure 3-1): (1) Moderate iron particulate at pH 6.5 (0.3 mg/L as Fe), (2) High iron particulate at pH 6.5 (1 mg/L as Fe) and (3) Very High iron particulate at pH 6.5 (20 mg/L as Fe). Two POU brands, A and B, which represent the highest and lowest capacities were challenged with the two combination waters with iron and lead. Brand A was tested in duplicate, consistent with the previous tests, while Brand B was tested in triplicate because of the duplicate failure observed in Purchase et al. (2020). The combination waters are termed, (4) Soluble Combo at pH 5 (200 µg/L Pb and 0.3 mg/L as Fe), (5) Particulate Combo at pH 6.5 (200 µg/L Pb, 2.3 mg/L $PO_4$ as P, and 0.3 mg/L as Fe), Table 1. The lower pH (i.e., pH 5) water was representative of conditions observed in Virginia private wells and tends to maximize the amount of soluble lead and iron in the water relative to higher pH municipal water supplies (Pieper et al. 2015).

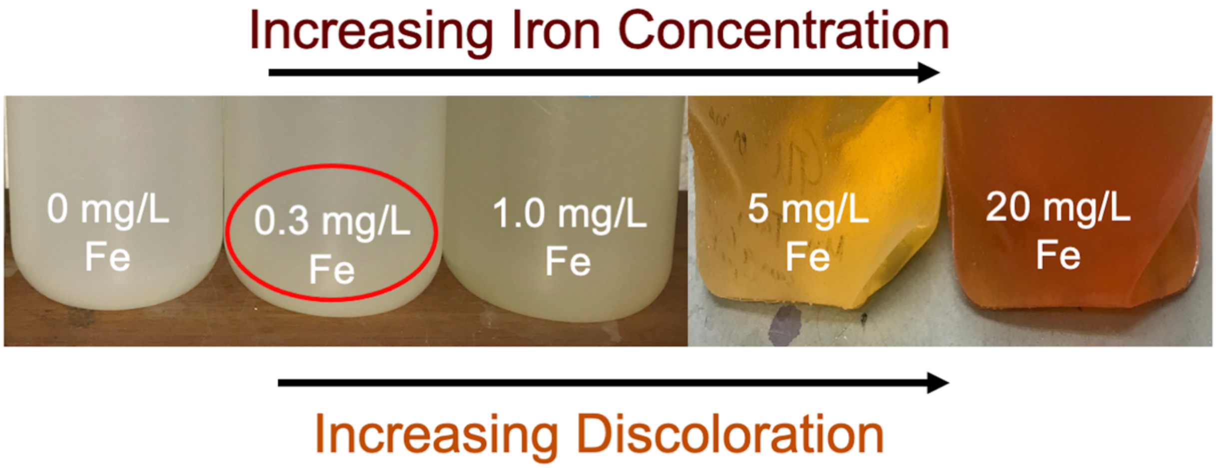


Figure 3- 1: The discoloration of increasing iron concentrations

Each filter cartridge was soaked for 15 minutes and rinsed for 10 seconds using iron and lead-free water before testing. The challenge waters were manually filtered through each POU one 3.8 L batch (1 gal) at a time, and flowrates were recorded by hand with stopwatches. The pitcher filters treated up to 12 batches of water daily, with a minimum 30-minute rest period between batches. A total of 8-9 samples (250 mL) were taken at equal intervals up to 100% of the POUs rated capacity for the particulate iron waters and 15 -18 samples for the lead-iron combination waters. This sampling scheme was followed unless filters failed due to clogging. Clogging was defined as a 75% reduction from the initial flowrate recorded for each device, and the initial flowrate was defined as the fastest flowrate measured in the first three batches treated by each device for each test.

*Water Analysis:* Influent water samples (10 mL) were taken for total and particulate metal concentration. To operationally determine particulate lead and iron concentrations in the synthesized waters, 10 mL samples were filtered through either a 0.45-micron Nylon filter or a 0.1-micron Durapore Hydrophilic Polyvinylidene Fluoride filter. All QA/QC, influent, and effluent samples were dosed with 2% nitric acid and 2% hydroxylamine hydrochloride (10% w/w) and digested for 18+ hours. The 250 mL effluent samples were then placed in an oven at 50C for 5+ hours to further assist with iron digestion. All samples were analyzed for metals concentrations using a Thermo Electron iCAP RQ Inductively Coupled Plasma Mass Spectrometer (ICP-MS) (APHA, AWWA, and WEF 2017). Blanks and spikes of known concentrations were measured every 10–15 samples for QA/QC purposes.

*Particulate Iron Waters:* To investigate the impact of particulate iron on filter clogging, POUs were challenged with waters of various particulate iron concentrations. The iron waters were made by adding the targeted amount of dry ferrous sulfate to the base water, Section B1. The water's pH was adjusted with $CO_2$ and NaOH both before and after the iron addition. Due to inherent variability, including the time to oxidize ferrous iron and the coagulation of particulates, the influent particulate concentrations often deviated from target. The average influent iron concentration for the Moderate iron particulate water was 0.4 ± 0.2 mg/L as Fe and 63±40% particulate. The High iron particulate water had an average concentration of 1.0 ± 0.3 mg/L as Fe, where 73±34% was particulate. The Very High iron particulate water had an average concentration of 19.7± 0.5 mg/L as Fe with 92±5% particulate Fe, Table 3-1. All particulate iron waters were made at a pH of 6.5 and had alkalinities between 10-30 mg/L as $CaCO_3$. pH was measured using an OAKTON water meter and a HACH digital titrator was used to measure alkalinity.

Table 3-1: Water quality for POU challenge waters

| **Water Condition** | **Total Fe (mg/L)** | **Total Particulate Iron (%)** | **Total Pb (µg/L)** | **Total Particulate Lead (%)** | **pH** | **Alkalinity (mg/L as $CaCO_3$)** |
|---|---|---|---|---|---|---|
| Moderate Iron (0.3 mg/L) | 0.4 ± 0.2 | 63.2 ± 37.0 | – | – | 6.6 ± 0.1 | 18.8 ± 4.2 |
| High Iron (1 mg/L) | 1.0 ± 0.3 | 72.8 ± 34.1 | – | – | 6.6 ± 0.1 | 14.9 ± 2.2 |
| Very High Iron (20 mg/L) | 19.7 ± 0.5 | 91.9 ± 4.9 | – | – | 6.5 ± 0.0 | 19.0 ± 4.6 |
| Soluble Combo | 0.3 ± 0.0 | 2.2 ± 3.1 | 221 ± 16.5 | 1.7 ± 1.9 | 4.9 ± 0.1 | 11.2 ± 2.7 |
| Particulate Combo* | 0.3 ± 0.0 | 89.1 ± 7.5 | 208 ± 23.0 | 97.1 ± 0.8 | 6.5 ± 0.0 | 21.3 ± 1.8 |

* Orthophosphate addition: 2.31 mg/L as phosphorous (P)

*Lead and Iron Combination Waters:* To investigate the impact of iron on lead removal, brands A and B were exposed to two waters containing both lead and iron. (1) The "Soluble Combo" water contained 221±17 µg/L as Pb and 0.3 mg/L as Fe and was designed to have virtually all soluble lead (1.7±1.9% particulate) and soluble iron (2.2±3.1% particulate) at pH 5 and alkalinity of 11.2 mg/L as $CaCO_3$ (Table 3-1). pH was adjusted to the target both before and after the metal additions were made. The iron was added in the same way it was in the particulate iron waters, and lead was added using a lead nitrate stock, Section B1.

(2) The "Particulate Combo" water had 208±23 µg/L as Pb (97.1±1% particulate), and 0.3 mg/L as Fe (89±8% particulate) at pH 6.5 and an alkalinity of 20 mg/L as $CaCO_3$, Table 3-1. The preparation of this water was designed to maximize both particulate iron and lead. Specifically, the base water was dosed with iron sulfate and the pH was then raised to 7 using NaOH to precipitate the iron. The lead phosphate particles were formed in a separate container (3.785 L) by adding lead nitrate to dissolved orthophosphate solution and shaking for 1 minute. Adding 2.31 mg/L orthophosphate as phosphorous (P) achieved less than 4% soluble lead even at pH 6.5 due to precipitation After the lead and orthophosphate particulate solution was added, the pH was re-adjusted to 6.5, Section B1.

### Phase 2: Cost Analysis

A cost estimate was conducted to evaluate the impacts of iron clogging on the relative costs of POU pitcher filters compared to bottled water. The analysis considers the cost of replacement cartridges versus various types of bottled water at major grocery stores. The initial capital cost of the reusable pitcher filter housing was excluded (which ranges from around \$17 to \$45) as this is typically a one-time purchase based on design preferences and is sometimes covered by public health agencies. The cost of POU filter replacement cartridges was determined by obtaining 6 prices from 4 different vendors. The average cost from June 2020 of one name-brand bottled water, available at four grocery and big box stores in Virginia, was used for analysis (\$1.47 per 3.785 L). The average cost of the generic or store-brand options available at the same stores was used as a representative low-cost bottled water alternative (\$0.70 per 3.785 L). It is important to note that this analysis solely focused on filter replacement and bottled water costs and did not consider other costs associated with transportation, disposal, convenience, etc.

Alternative Failure Criterion: We contemplated whether the NSF/ANSI 53 failure criterion for clogging, based on a 75% reduction of initial flowrate, was practically realistic for a typical consumer. For example, a POU pitcher with an initial filter time of 3.6 hrs per batch (3.8 L) would fail the NSF/ANSI criterion only after the POU required more than 14 hours to filter a batch of water. We rationalized that a 14-hour wait would be unsatisfactory for many consumers, so we conducted an additional cost analysis with a maximum filter time of two hours per batch.

### Phase 3: Applying the Cost Analysis to Prior Citizen Science Data

The cost analyses from Phase 2 were extended to first draw lead and iron data from prior citizen science projects to consider the practical implications of premature filter clogging. This analysis assumed that the homes in our databases were randomly selected and representative of the distribution of lead and iron across the entire community. We estimated the percentage of homes in each community where POUs were expected to be more cost-effective than purchasing bottled water. The following first draw datasets were included in this analysis: Berwyn/ Cicero, IL (n=90), Denmark, SC (n=51), Enterprise, LA (n=23), Orleans, NY (n=89), VA private wells (n=2140), and St. Joseph, LA (n=19). Data from Flint, MI, during the 2015 water crisis and post-crisis in 2017 (n=145) were also included for comparison. In addition, a set of historical samples (n=30) from the home of resident citizen scientists in Denmark, SC, were included to illustrate changes in water quality over time within a single home. This provided an opportunity for us to estimate the percent of the time from 2009 to 2017 that they could have likely benefited financially from the use of a POU filter instead of purchasing bottled water.

Statistical analysis: Correlation analysis was applied to examine the association between lead and iron in drinking water sources, occasionally observed in field data (Masters and Edwards 2015). Due to the non-normal distribution of lead and iron data (Shapiro Test, $p \leq 7.16 \times 10^{-07}$), Spearman's rank correlation was used to evaluate the association between lead and iron for each community using RStudio (Version 1.2.5001).

*Cost-analysis of POU filters versus store bottled water in each dataset*: For each community, we calculated the percentage of consumers estimated to have had lower costs using a given POU pitcher filter compared to store-brand bottled water using the prior method. This analysis was done for the entire dataset and then repeated for the sub-set of homes with elevated lead (>15 μg/L) in their first-draw samples. The first-draw iron concentrations were used to produce the cost-analysis model. Brand A results were not included, as store-brand bottled water was always a more cost-effective option than this POU pitcher filter brand.

## RESULTS

### Phase 1: Laboratory Pitcher POU Testing

*Particulate Iron Waters:* On average, the Brand A, B, and C duplicate filters removed 92.2%, 96.4%, and 99.7% of the influent iron for the Moderate, High, and Very High particulate iron waters, respectively (Table 3-2). All filtered samples for the three particulate iron waters were below the EPA SMCL of 300 µg/L, with only one exception. During the Very High particulate iron water testing, one Brand A duplicate released 370 µg/L Fe during batch 8 before clogging.

Table 3- 2: Average (± standard deviation) Lead and Iron Removal

| **Water Condition** | **Average Fe Removal (%)** | **Average Effluent Fe (µg/L)** | **Range (min - max) (µg/L)** | **Average Pb Removal (%)** | **Average Effluent Pb (µg/L)** | **Range (min - max) (µg/L)** |
|---|---|---|---|---|---|---|
| Moderate Iron (0.3 mg/L Fe) | 97.2 ± 5.6 | 9.1 ± 18.4 | <5 - 107 | -- | -- | -- |
| High Iron (1.0 mg/L Fe) | 96.4 ± 5.1 | 33.6 ± 47.1 | <5 – 190 | -- | -- | -- |
| Very High Iron (20.0 mg/L Fe) | 99.7 ± 0.5 | 63.5 ± 89 | <5 – 370 | -- | -- | -- |
| Soluble Combo (200 µg/L Pb & 0.3 mg/L Fe) | 98.9 ± 2.3 | <5 | <5 – 54.3 | 99.4 ± 2.4 | 1.2 ± 5.0 | <0.1 – 43.7 |
| Particulate Combo (200 µg/L Pb & 0.3 mg/L Fe) | 98.7 ± 2.2 | <5 | <5 – 28.8 | 98.6 ± 1.1 | 2.9 ± 2.4 | 0.6 – 11.6 |

There was a wide variation in the time required to filter the initial batches of water between POU brands and even between duplicates of the same brand (Table B1). On average, brands A and B took 26 and 24 minutes, respectively, whereas brand C took 112 minutes. One duplicate from brand C had a minimum filter time of 40 minutes for the Moderate iron particulate condition (Table B2) and a maximum initial filter time of 216 minutes for the Very High particulate iron condition (Table B3). This variability significantly impacts the flowrate threshold for clogging. For instance, using the NSF/ANSI 75% flowrate reduction criterion, the fastest brand C filter tested only had to increase from 40 to 160 minutes to treat a batch of water before it failed. In contrast, the slowest brand C filter tested had to increase from 216 to 864 minutes before it was considered clogged. Filter flowrates fluctuated throughout the filter life, which could be due to variable water transport patterns through the media, variable rest periods between batches (e.g., some flowrates increased after having >8 hr rest), and variable human response time.

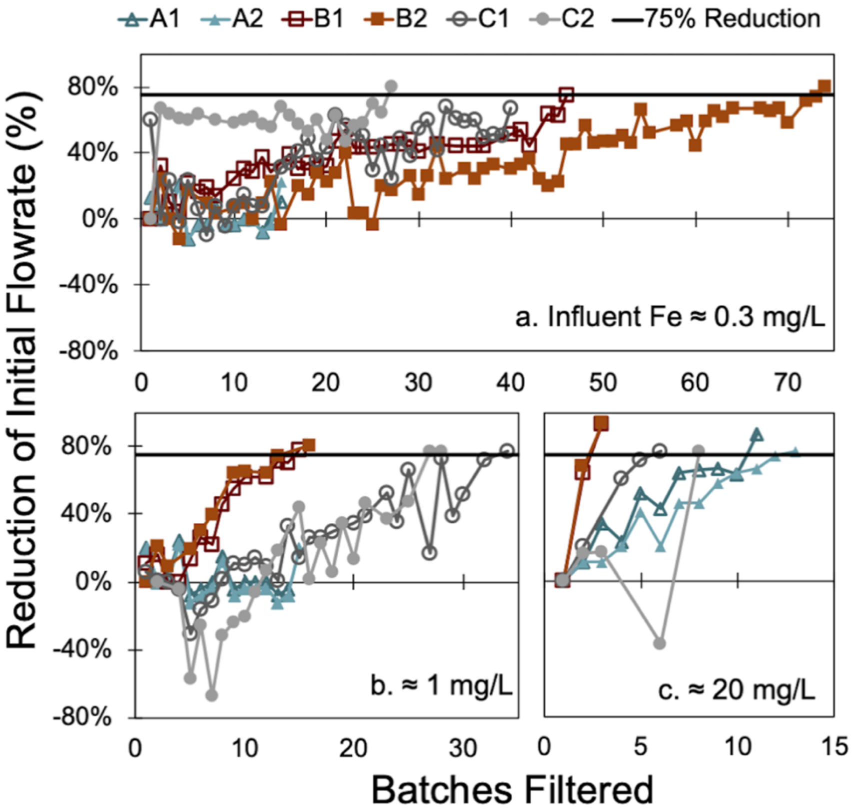


Figure 3- 2: Reduction in flowrates for POUs at various particulate iron concentrations. (a) 0.3 mg/L, (b) 1.0 mg/L, and (c) 20 mg/L.

Flowrates sometimes increased during the beginning of the filter use which resulted in a negative reduction (Figure 3-2). In addition, there were instances where the final flowrate was not recorded as the time it took to filter a single batch exceeded the hours of a normal workday. In these instances, a 77% reduction in flowrate was recorded as the point of clogging failure.

When exposed to waters containing 0.3 - 20 mg/L particulate iron, 72% (13/18) of the POU filter cartridges tested failed to meet their rated capacity due to clogging (Figure 3-2). Specifically, 3 of 6 POUs (50%) exposed to the 0.3 mg/L Moderate iron particulate water, 4 POUs (66%) for the 1.0 mg/L High iron particulate water, and 6 POUs (100%) for the 20 mg/L Very High iron particulate water had flowrates reduced by 75% before reaching capacity.

For the Moderate iron particulate water condition, one brand C duplicate and both brand B filters failed to reach 100% of their rated capacity due to premature clogging (Figure 3-2a). The brand C filter failed at 68% of its rated capacity of 151 L (40 batches), and the brand B duplicate filters failed at 38% and 62% of their 454 L (120 batches) rated capacity. When comparing the volume of treated water across brands, brand B duplicates treated the largest volume before clogging during the 46th and 74th batches (174 L and 280 L) (Figure 3-2a). Brand C duplicate 1 reached its rated capacity, treating 40 batches of water, whereas duplicate 2 only treated 27 batches before clogging. The brand A duplicates reached their 57 L (15 batches) rated capacity.

When testing the High iron particulate condition (1.0 mg/L), the duplicate filters from brands B and C clogged before reaching their rated capacity. The brand B filters failed at 15% and 13% of their rated capacity, and the brand C duplicates failed at 85% and 70% of their rated capacity. When comparing the volume of treated water across brands, brand C treated the most water, and clogged during the 34th and 28th batches (Figure 3-2b). Brand B filters treated a comparable volume of water to Brand A (15 batches), with one duplicate treating 15 batches and the other treating 16 before clogging.

The Very High iron particulate condition (20 mg/L) caused premature clogging in all three brands. The brand A filters failed at 73% and 87% of their rated capacity and treated the most water for this concentration at 11 and 13 batches (Figure 3-2c). Both brand B filters failed at <1% of their rated capacity, only treating 3 batches of water each. The brand C filters failed at 15-20% rated capacity after clogging at 6 and 8 batches.

*Lead and Iron Combination Waters:* Five POU filters were tested for the lead-iron combination conditions including two brand A and three brand B filters. When exposed to the Soluble Combo water (220 µg/L Pb and 0.3 mg/L Fe), the filters removed an average of 99.4% Pb and 98.9% Fe across all five filters when tested to 100% of their rated capacity (Table 3-2). All but two of the 81 effluent samples had lead levels below the Bottled Water Standard of 5 µg/L, with a maximum concentration of 3.2 µg/L (Figure 3-3a). One exception was a spike at 13% rated capacity of 43.7 µg/L Pb for one brand A filter. That spike in lead correlated with a spike in iron of 54 µg/L. The second observed spike of 13.7 µg/L Pb occurred in one of the brand B duplicates at 59% capacity. However, this lead spike did not co-occur with a spike in iron. Effluent iron levels remained below the SMCL across all five filters for the duration of this test condition with a maximum concentration of 54 µg/L Fe and an average below the 5 µg/L detection limit. All five filters reached 100% of their rated capacity in the Soluble Combo water.

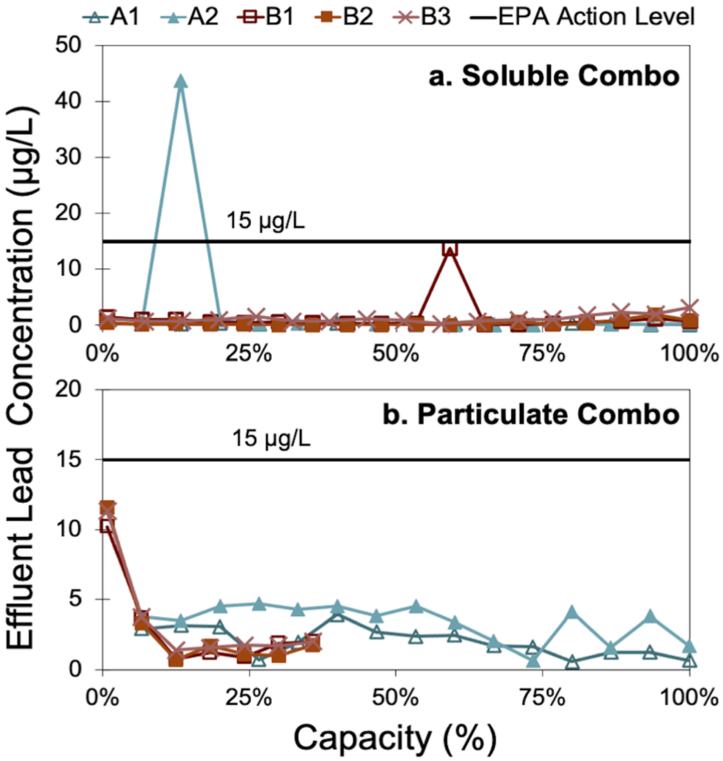


Figure 3- 3: Effluent lead as a function of percent manufacturers rated capacity. **(a.)** Effluent lead concentrations for the Soluble Combo water (220 µg/L Pb and 0.31 mg/L Fe). **(b.)** Effluent lead concentrations for the Particulate Combo water (210 µg/L Pb and 0.32 mg/L Fe).

Filter performance was relatively unaffected when exposed to the Particulate Combo water (210 µg/L Pb and 0.32 mg/L Fe), removing an average of 98.6% Pb and 98.7% Fe (Table 3-2). Except for the first batch of filtered water for each brand B filter (with 10.2, 11.6, and 11.3 µg/L of Pb), effluent lead concentrations were always <5 µg/L (Figure 3-3b). The maximum effluent iron concentration was 34 µg/L and the average <5 µg/L. In the presence of particulate lead and iron, all brand B filters failed prematurely due to clogging.

### Phase 2: Cost Analysis

The relative cost advantage of POU filters versus bottled water was a function of iron concentration. When comparing the estimated cost-per-gallon ($/3.8 L) of iron-free treated water, brand B and C POU filters ($0.14 and $0.22) were more cost-effective than both store-brand ($0.70) and name-brand ($1.47) bottled water (Table 3-3). Brands B and C remained more cost-effective then bottled water if particulate iron was near 0.3 mg/L. When iron levels increased above the SMCL, brand B became more expensive than store-brand bottled water, with an estimated cost of $1.08 at 1 mg/L and $5.58 at 20 mg/L. The estimated cost for brand C was $0.28 at 1 mg/L and $1.23 at 20 mg/L, exceeding the cost of store-brand bottled water at the higher concentration. Brand A filters ($0.97 - $1.21) were more expensive than store-brand bottled water and less expensive than name-brand bottled water over the full range of evaluated particulate iron concentrations.

Table 3- 3: Cost Analysis – Comparing POUs to Bottled Water at Different Iron Concentrations

| | Estimated Cost Per Batch ($) | | | | |
|---|---|---|---|---|---|
| | Bottled Water | | POU Costs | | |
| | Store Brand | Name Brand | Brand A | Brand B | Brand C |
| POUs Used to Rated Capacity without Iron | 0.70 | 1.47 | 0.97 | 0.14 | 0.22 |
| Moderate Particulate Iron – (0.3 mg/L) | 0.70 | 1.47 | 0.97 | 0.28 | 0.26 |
| High Particulate Iron – (1.0 mg/L) | 0.70 | 1.47 | 0.97 | 1.08 | 0.28 |
| Very High Particulate Iron – (20 mg/L) | 0.70 | 1.47 | 1.21 | 5.58 | 1.23 |

To better estimate the specific iron concentration at which the cost of POUs surpassed the cost of bottled water, the cost-per-batch ($/3.8 L) for each option was plotted as a function of iron concentration (Figure 3-4a). A linear model provided a reasonable fit to the data ($R^2 = 0.99$). However, brand B diverged from the model in a critical range of 0.3 - 1 mg/L where the increasing iron concentration begins to have a large impact on the cost-per-batch. This linear approximation is nonetheless adequate for illustrating the relative trends in cost of filtered versus bottled water that are relevant to consumer decision-making.

Brand C became more expensive than store-brand bottled water ($0.70) at around 9 mg/L Fe, whereas brand B became more expensive than store-brand bottled water at only 1.3 mg/L Fe. In addition, brand B became more expensive than name-brand bottled water ($1.47) above 4.5 mg/L Fe. The increasing iron levels did not impact the cost-advantage of brand A POUs versus bottled water. Brand A's low rated capacity (15 gallon/batches) caused the POU reach higher percent capacities than the other POUs even though it treated less water, resulting in the cost not significantly increasing with iron.

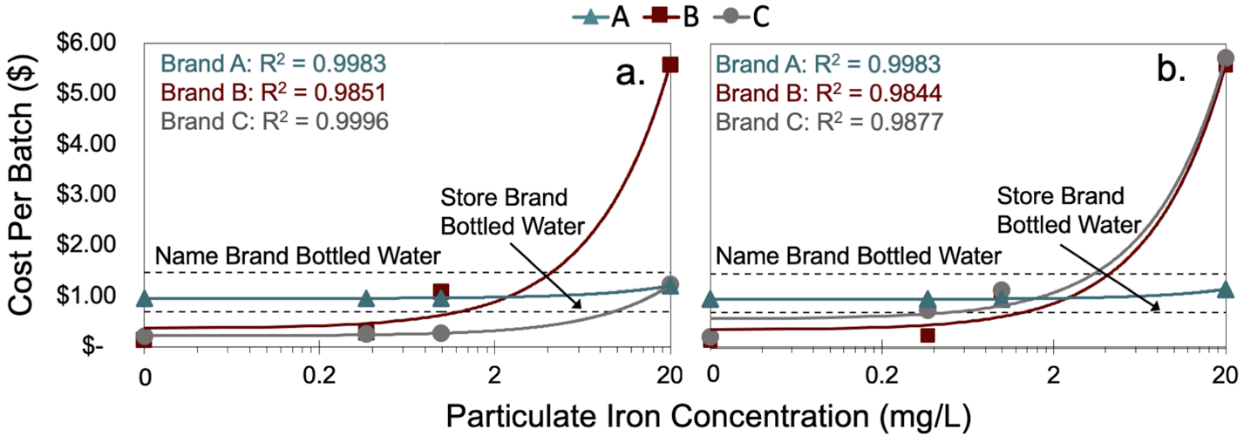


Figure 3- 4: Comparing POUs to bottled water at varying particulate iron concentrations. The calculated base cost-per-batch for each filter when the iron is not present (0 mg/L Fe) was plotted at 0 mg/L Fe for the purpose of this figure. (a) illustrates the initial cost analysis for each brand. (b) presents the cost analysis using a 2-hr max filter time failure criterion.

*Alternative Failure Criterion:* To illustrate the sensitivity of our cost analysis to the effects of consumer time invested in obtaining potable water, we repeated the analysis using an alternative failure criterion of a two-hour maximum filter time per batch. This criterion would cause slower filters to be replaced more frequently and increase costs to consumers. After applying this 2-hr limit, brand C became more expensive than store-brand bottled water ($0.70) at just 0.5 mg/L Fe and was even more expensive than name-brand bottled water ($1.47) above 3.5 mg/L Fe (Figure 3-4b).

**Phase 3: Applying the Cost Analysis to Prior Citizen Science Data**

A correlation analysis was performed to examine the possible association between high lead and high iron in several communities. The iron and lead data collected from these communities were applied to our cost analysis to investigate the potential impact of iron on POU desirability.

*Correlations between lead and iron:* The strength of the association between lead and iron varied greatly across the communities (Table 3-4). A strong correlation between lead and iron was observed across samples in St. Joseph, LA ($\rho = 0.79$, n=19) and for samples collected over a period of 9 years in the home of citizen scientists living in Denmark, SC ($\rho = 0.69$, n=30). Moderate correlations across samples were found in Enterprise, LA ($\rho = 0.45$, n=23), and Flint, MI during 2017 ($\rho = 0.55$, n=145). Most communities tested had weak correlations or no correlation across samples, Berwyn/Cicero, IL ($\rho = 0.23$, n=90); Denmark, SC ($\rho = 0.35$, n=52); Flint, MI during 2015 ($\rho = 0.39$, n=145); Orleans, NY ($\rho = 0.28$, n=89); and VA Private Wells ($\rho = 0.11$, n=2140).

Some utilities, public health agencies, or consumers might decide to deploy or implement filters only in homes with lead over the action level. When considering only the sub-set of homes tested with elevated lead >15 μg/L, the association between iron and lead increased in some communities including Berwyn/Cicero, IL ($\rho = 0.76$, n=8) and Flint, MI during 2015 ($\rho = 0.76$, n=23).

Table 3- 4: Lead and Iron correlations with cost-benefit analysis for data collected in community sampling campaigns

| Community | n | 90th Percentile | | Spearman's Correlation (Pb & Fe) | | | POU Brand | Estimated Percent of Community Anticipated to Save Money Using POUs over Store-Brand Bottled Water | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | All Samples | | >15 µg/L Pb | |
| | | Pb (µg/L) | Fe (mg/L) | All Samples | <15 µg/L Pb | >15 µg/L Pb | | NSF Criterion - 75%Reduction | Alt. Criterion <2hr filter time | NSF Criterion - 75% Reduction | Alt. Criterion <2hr filter time |
| Berwyn/Cicero, IL | 90 | 11.7 | 0.2 | 0.23 | --<br>n=82 | 0.76<br>n=8 | B | 100% | 96% | 100% | 63% |
| | | | | | | | C | 100% | 100% | 100% | 100% |
| Denmark, SC | 51 | 14.4 | 0.3 | 0.35 | 0.31<br>n=46 | --<br>n=5 | B | 98% | 94% | 80% | 80% |
| | | | | | | | C | 96% | 96% | 80% | 80% |
| Enterprise, LA | 23 | 98.9 | 1.5 | 0.45 | --<br>n=6 | --<br>n=17 | B | 96% | 57% | 83% | 33% |
| | | | | | | | C | 87% | 87% | 83% | 83% |
| Flint, MI - 2015 | 145 | 23.5 | 0.5 | 0.39 | 0.23<br>n=122 | 0.76<br>n=23 | B | 99% | 89% | 96% | 65% |
| | | | | | | | C | 95% | 95% | 78% | 78% |
| Flint, MI - 2017 | 145 | 7.9 | 0.2 | 0.55 | 0.47<br>n=136 | --<br>n=9 | B | 100% | 96% | 100% | 56% |
| | | | | | | | C | 98% | 98% | 78% | 78% |
| Orleans, NY | 89 | 17.5 | 0.7 | 0.28 | --<br>n=78 | --<br>n=11 | B | 100% | 88% | 100% | 73% |
| | | | | | | | C | 96% | 96% | 82% | 82% |
| Private Wells - VA | 2140 | 26.7 | 0.2 | 0.11 | 0.07<br>n=1742 | --<br>n=402 | B | 100% | 94% | 99% | 90% |
| | | | | | | | C | 97% | 97% | 96% | 96% |
| St. Joseph, LA | 19 | 29.5 | 1.9 | 0.79 | 0.67<br>n=16 | --<br>n=3 | B | 95% | 89% | 67% | 33% |
| | | | | | | | C | 89% | 89% | 33% | 33% |
| Denmark, SC - Resident Citizen Scientist | 30 | 64.7 | 4.2 | 0.69 | 0.59<br>n=24 | --<br>n=6 | B | 93% | 47% | 83% | 17% |
| | | | | | | | C | 60% | 60% | 17% | 17% |

**Spearman's Correlation:**

"--" indicates p-value > 0.05

For purposes of this work, Light blue represents a weak correlation ($0.3 < \rho < 0.44$), medium blue represents a moderate correlation ($0.45 < \rho < 0.55$), and dark blue represents a strong correlation ($0.56 < \rho$).

*Cost-analysis of POU filters versus store-brand bottled water in each dataset:* In conjunction with the prior laboratory testing, this analysis can be used to create a conceptual estimate of the proportion of residents in a community that could have saved money by using a POU pitcher filter (brand B and C). This analysis uses the first draw iron concentration of each home, the estimated cost of store-brand bottled water, and the cost of replacement cartridges for the POU brands in this study. The cost per batch of water for each home was dependent on their first-draw iron concentration and determined using the linear models produced in Phase 2 for each POU brand and each failure criterion (Figure 3-4a & b, Table 3-4). The number of homes with POU water costs less than store-brand bottled water ($0.70) is categorized as a home that may save money by using a POU. The percentage of the homes in each community with water costs less than store-brand bottled water is anticipated to save money by using bottled water.

The percent of a community anticipated to save money from using POU filters instead of bottled water decreases with increasing iron (Table 3-4). Communities with iron concentrations greater than the SMCL (0.3 mg/L) were predicted to have less cost savings from using a POU due to premature clogging. Additionally, when the alternative clogging criterion of a maximum 2-hour filter time was applied, the percentage of the communities expected to save money using the brand C filter decreased in comparison to the NSF/ANSI criterion (75% reduction of initial flowrate) consistent with Figure 3-4b. Brand C appeared to be the most cost-effective brand when the NSF/ANSI criterion was considered, whereas brand B often became more favorable when considering the 2-hr maximum filter time.

When examining all samples in each dataset, between 87% - 100% (average 97%) of homes would have been expected to save money using a POU filter versus bottled water under the NSF/ANSI criterion. However, an average of 91% (57% - 100%) are predicted to save money after applying the 2-hour filter time criterion. When focusing only on homes with >15 μg/L Pb, which had a slightly greater tendency to have high iron, on average, 85% (33% - 100%) would have a cost advantage using a POU over bottled water using the NSF/ANSI criterion and 70% (33% - 100%) for the 2-hour maximum filter time criterion.

In some communities with the highest Pb and iron levels, such as Enterprise, LA (98.9 μg/L Pb, 1.5 mg/L Fe) and St. Joseph, LA (29.5 μg/L Pb, 1.9 mg/L Fe), it is predicted that it would have often been more cost-effective to use store-brand bottled water over the POU filters. Based on the 2-hour criterion, in Enterprise, LA, 83% of homes with >15 μg/L Pb would have lower costs from using a brand B filter over bottled water, and only 33% would have lower costs from using a brand C filter. In St. Joseph, LA, only 33% of homes would have lower costs using a POU filter or bottled water.

When evaluating the complete set of samples collected in one home in Denmark, SC over a period of 9 years (2009 – 2017), it was estimated that the residents would have lower costs from a brand B filter 60% of the time and a brand C filter 47% of the time over purchasing bottled water. However, when evaluating only the subset of samples with elevated lead (Pb >15 μg/L), bottled water became more cost-effective than POUs due to a correlation between elevated lead and iron concentrations.

# DISCUSSION

*Certification:* The POU brands tested in this study were lead-certified in compliance with the NSF/ANSI 53 standard. Lead-certified filters are tested using synthetic soluble and particulate lead challenge waters. POU filters can also be evaluated for compliance with NSF/ANSI 42 standards for particulate removal (NSF International 2019a). Household lead certified POU faucet and pitcher filters are not typically certified under NSF/ANSI 42 for iron and manganese removal. However, many lead-certified POUs have dual certification with NSF/ANSI 42 for Nominal Particulates which might indicate improved treatment of particulate lead (Bosscher et al. 2019) and discolored waters (e.g., red water from elevated iron). POU manufacturers often seek multiple contaminant reduction certifications under NSF/ANSI 53 and 42. The lowest capacity designation determines the rated capacity for each POU device. For example, if a filter is certified to remove lead up to a capacity of 200 L, but is only certified to remove Nominal Particulate Class I (0.5 - 1 μm) up to 150 L, the published rated capacity for that POU brand would be 150 L.

*Iron and Lead Removal:* POUs were effective at removing particulate iron. In addition, POUs typically produced lead levels below 10 μg/L when tested against the lead and iron combination waters. Only five lead spikes were observed during the combination challenge water testing: three during the Particulate Combo and two during the Soluble Combo. The three lead spikes observed during the Particulate Combo testing were in the first batch of water filtered by each brand B filter (Figure 3-3). These spikes echo problems reported by Purchase et al. (2020), where it was concluded that discarding the first batch of water could help reduce exposure to elevated lead levels that may occur at the beginning of the filter life.

Only two effluent lead spikes (>10 μg/L) were observed during the Soluble Combo water testing (Figure 3-3). One spike in lead correlated with a higher release of iron (brand A) and the other did not (brand B). There was no strong correlation between lead and iron release during the remainder of the Soluble Combo testing. Specifically, even as effluent iron concentrations occasionally increased, the lead concentration remained low. Overall, as the two lead spikes were seemingly isolated occurrences, we do not believe that iron generally creates problems for lead removal.

*Reduction in Flowrate:* Increasing the particulate iron concentration resulted in more rapid clogging of POU devices. The clogging and cost-effectiveness of POU brands B and C were more adversely impacted by the presence of Moderate and High iron concentrations, even though they generally treated a larger volume of water than the brand A filters.

Brands B and C are both certified under NSF/ANSI 42 for Particulate Class I (0.5 - 1 μm), whereas Brand A is not certified to remove particulates. The ability of brand B and C POUs to remove smaller diameter particle of .5 - 1 μm could help explain the drastic reductions in flowrate that were observed for these devices. The Brand A POU cartridges may have larger pore sizes than the other POUs or utilize the larger surface area of the POU media to increase removal, reduce clogging, and maintain flowrate, as this POU is significantly larger than that of brands B and C.

The clogging effects of iron noted herein, might also apply to certain waters with high levels of turbidity and other suspended particles.

*Reduction in Rated Capacity:* For the POUs tested, the greater a filter's rated capacity, the greater the adverse impact that was observed due to particulate iron (Figure B1). Brand A had only a 20% reduction (57 L down to 45 L) in expected capacity when the particulate iron concentration increased from 0 to 20 mg/L. In contrast, brand B had a reduction in practical capacity of greater than 95% (454 L down to 11.4 L) when iron concentrations increased to 20 mg/L. Ultimately, having an 8 times higher advertised capacity for brand B (454 L) compared to brand A (57 L), practically translated to having a 4 times lower actual capacity for brand B (11.4 L, or 2.5% its rated capacity) versus brand A (45 L, or 80% its rated capacity) if Very High levels of iron were present. This dramatically impacted the expected costs to treat water with Very High iron concentrations, given that the higher capacity filter clogged much sooner than the lower capacity filter. This becomes an important factor for consumers to consider, as a higher capacity rating might influence consumers to purchase a particular filter brand, when in fact the brand with a lower capacity rating might last longer in unusual circumstances.

*Monetary and Nonmonetary Costs of POUs:* Our cost analysis sought to normalize filter performance and rated capacity to provide a practical comparison across POU brands. We validated our cost analysis results with the calculator used by Verhougstraete et al,. (2019), which proved consistent with our results when the initial filter unit cost was excluded from the calculation. Verhougstraete and colleagues (2019) found that POUs of various types were more cost-effective than purchasing the 5-gal water jugs often used in offices. Our results showed that even with reduced capacity due to Moderate and High iron concentrations, POUs were more cost-effective than name-brand bottled water and sometimes cheaper than store-brand bottled water. The iron concentrations that were evaluated as part of this analysis are generally more extreme than those typically observed in the field.

We introduced an alternative failure criterion of a two-hour filter time, to account for our belief that a typical consumer might be unwilling to wait longer to filter a batch of water. However, our calculations did not consider other operation and maintenance costs of using bottled water and POU devices in comparison to using tap water. More complex cost comparisons between POUs and bottled water can be considered in future work, as there are many nonmonetary factors known to influence a consumers' decision to use bottled water and POU devices (Katner et al., 2021). These factors could include the following considerations: (1) influent water characteristics, (2) locality, (3) family size, (4) daily water use, (5) access to transportation, (6) delivery availability, (7) disposal burden, (8) environmental concerns, (9) monetary value of time, (10) distance to the point of purchase, and (10) the consumer's trust (or distrust) the alternatives.

*Use of POUs in Communities:* Co-occurrence of iron and lead varied greatly in the communities evaluated in this study which is consistent with results found by Masters and Edwards (2015). In some communities, the association was stronger when only looking at homes with elevated lead levels. As a result, on occasion, homes with the highest lead levels also had the highest iron concentrations. These homes have an increased need for a tap water alternative due to elevated lead levels; however, there is also an increased risk of premature clogging of POUs due to the higher iron concentrations.

Our cost analysis illustrated trends in cost-effectiveness of POU devices when applied to several communities. However, applying the cost analysis to communities with varying iron concentrations further illustrated that POUs may be less attractive in communities with higher iron concentrations. Pre-flushing taps to lower the concentration of iron in water before collecting water to be used for filtration, may reduce the likelihood of clogging, and increase the attractiveness of POU filters. Consumers could be advised to run their water until it becomes clear of visible iron to extend the lifetime of their POU filters in some cases.

NSF/ANSI 53 lead certified filters have proven effective at consistently reducing lead levels, even in the presence of iron, and are often a more cost-effective alternative than purchasing bottled water. Widespread POU distribution may become more common with the recently published Lead and Copper Rule (LCR) revisions that require POU distribution to customers after lead service line replacements. The LCR revisions also allow small community water systems (serving ≤ 10,000 people) to implement POUs as a compliance alternative if a lead action level exceedance occurs.

Systems should plan to evaluate water quality throughout their distribution system before deciding on mass distribution of POU devices within their community. For instance, distributing POUs to homes with chronic discolored water, might sometimes be problematic due to consumer frustration with premature clogging and increased treatment costs. Katner et.al. (2021) conducted a POU filter field study in Enterprise, LA to monitor filter performance over time. Enterprise, LA is known for elevated iron levels and in a survey, residents indicated that their tap water had unpleasant colors, odors, and tastes. However, after participating in the study and using the provided POU faucet filter, the residents were less likely to continue using their filters because they clogged within a couple weeks or days of use and many switched to bottled water (Katner et al., 2021).

## CONCLUSION

The presence of iron only occasionally affected overall lead removal in our laboratory testing. However, premature clogging sometimes controlled the practical capacity of POU filters. Premature clogging had a major impact on the costs of POUs versus bottled water in some situations where iron levels approached or exceeded the 0.3 mg/L USEPA SMCL. In cases with sufficiently high iron levels bottled water will be more cost-effective then POU filters.

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# APPENDIX B – SUPPORTING INFORMATION FOR CHAPTER 3

Section B1: Challenge water preparation
Table B1: Variance in Initial Filter Times for each brand
Table B2: Filter Time for Moderate iron particulate water
Table B3: Filter Time for High iron particulate water
Table B4: Filter Time for Very High iron particulate water
Table B5: Filter Time for Soluble iron and lead combination water
Table B6: Filter Time for Particulate iron and lead combination water
Figure B1: Impact of particulate iron concentration on POU capacity

Section B1: Water Preparation

**Water Conditions**

The standard base water for all the water conditions consists of 8.45 mg/L Magnesium Sulfate, 20.1 mg/L Calcium Chloride, and 33.3 mg/L Sodium Bicarbonate. Sodium Hydroxide (NaOH) and/or Carbon Dioxide ($CO_2$) were added to adjust pH. Circulation pumps were utilized to keep the synthetic waters well-mixed throughout the day, and a floating cover prevented gas transfer between the water and atmosphere to maintain pH.

Particulate Iron Waters: The three iron particulate waters were (1) "moderate iron" with 0.3 mg/L Fe, (2) "high iron" with 1 mg/L Fe, and (3) "very high iron" with 20 mg/L Fe. All particulate iron waters were made at a pH 6.5 and an alkalinity of 10-30 mg/L as $CaCO_3$. Iron additions were made by first dissolving ferrous sulfate in a 2% nitric acid solution and then adding the dissolved iron into the base water before adjusting pH. Water was mixed for 30 minutes vigorously, and then the percentage of particulate iron in these waters ranged from 63-92% (Table 1).

Lead and Iron Combination Waters: There were two lead and iron combination waters. (4) The "Soluble Combo" water contained 220 µg/L Pb and 0.3 mg/L Fe, which was designed to have virtually 100% soluble lead and soluble iron at pH 5 and alkalinity of 11.2 mg/L as $CaCO_3$ (Table 1). pH was adjusted to the target before the lead and iron additions were made. The iron was added in the same way it was in the particulate iron waters, and lead was added using a diluted lead nitrate stock.

(5) The "Particulate Combo" water had 210 µg/L Pb and 0.3 mg/L Fe at pH 6.5 and alkalinity of 21.3 mg/L as $CaCO_3$, which was designed to maximize the percentage of particulate lead and iron (Table 1). The iron was added as before, and then the pH was raised to 7 using NaOH to precipitate the iron. The lead particulates were made prior to addition to the tank. The lead phosphate particulates were formed by spiking a dissolved orthophosphate solution with lead nitrate then shaking the solution for 30 seconds. The lead phosphate solution was added to the tank and the pH was re-adjusted to 6.5 to achieve 200 µg/L Lead and 2.31 mg/L orthophosphate as phosphorous (P).

Table B1: Variance in Initial Filter Times for each brand

| Brand | Minutes to Filter One Batch | | | RSD (%) |
|---|---|---|---|---|
| | Average | Minimum | Maximum | |
| A (n=6) | 26 | 23 | 28 | 8.63 |
| B (n=6) | 24 | 15 | 31 | 31.1 |
| C (n=6) | 112 | 40 | 216 | 63.5 |

Table B2: Filter Time for the duplicate samples in Moderate iron particulate water

| Moderate Particulate Iron (0.3 mg/L) | | | | | | |
|---|---|---|---|---|---|---|
| Brand | A | | B | | C | |
| Rated Capacity | 15 Gal (# batches) | 57 L | 120 Gal (# batches) | 454 L | 40 Gal (# batches) | 151 L |
| | Batch | Time (min) per duplicate | Batch | Time (min) per duplicate | Batch | Time (min) per duplicate |
| | 1 | 31 and 31 | 1 | 25 and 28 | 1 | 115 and 40 |
| | 3 | 28 and 28 | 15 | NA and 27 | 5 | 60 and 101 |
| | 5 | 24 and 24 | 30 | 42 and 33 | 10 | 50 and 95 |
| | 7 | 26 and 26 | 45 | 67 and 36 | 15 | 67 and 123 |
| | 9 | 26 and 26 | 60 | >4X and 50 | 20 | 81 and 77 |
| | 11 | 27 and 27 | 70 and 74 | >4X and 142 | 25 | 65 and 133 |
| | 13 | 25 and 25 | - | - | 30 | 102 and >4X |
| | 15 | 30 and 35 | - | - | 35 | 113 and >4X |
| | - | - | - | - | 40 | 138 and >4X |
| Average Time | 27 ± 3 | | 50 ± 37 | | 91 ± 31 | |
| Median Time (range) | 27 (24 - 35) | | 36 (25 - 142) | | 95 (40 - 138) | |

>4X: POU clogged based on failure criterion 75% reduction of initial flowrate (4X initial filter time).
NA: POU time required to a batch of water was not recorded.
Shaded rows: POU duplicate clogged when the alternative criterion was applied, 2-hr (120 min) max
-: Study concluded for that POU brand due to the POUs reaching capacity (Brand A), or both duplicate filters clogged

Table B3: Filter Time for High iron particulate water

| High Particulate Iron (1.0 mg/L) | | | | | | |
|---|---|---|---|---|---|---|
| Brand | A | | B | | C | |
| Rated Capacity | 15 Gal (# batches) | 57 L | 120 Gal (# batches) | 454 L | 40 Gal (# batches) | 151 L |
| | Batch | Time (min) per duplicate | Batch | Time (min) per duplicate | Batch | Time (min) per duplicate |
| | 1 | 34 and 35 | 1 | 35 and 29 | 1 | 100 and >180 |
| | 3 | 28 and 28 | 15 | 142 and >4X | 5 | 72 and 115 |
| | 5 | 25 and 25 | - | - | 10 | 105 and 150 |
| | 7 | 27 and 27 | - | - | 15 | 110 and 321 |
| | 9 | 26 and 26 | - | - | 20 | 144 and 208 |
| | 11 | 27 and 27 | - | - | 25 | 277 and 341 |
| | 13 | 25 and 25 | - | - | 30 and 28 | 196 and 530 |
| | 15 | 35 and 35 | - | - | - | - |
| Average Time | 28 ± 4 min | | 69 ± 64 min | | 205 ± 131 min | |
| Median Time (range) | 27 (25 - 35) min | | 35 (29 - 142) min | | 150 (72 - 530) min | |

>4X: POU clogged based on failure criterion 75% reduction of initial flowrate (4X initial filter time).
NA: POU time required to a batch of water was not recorded.
Shaded rows: POU duplicate clogged when the alternative criterion was applied, 2-hr (120 min) max
-: Study concluded for that POU brand due to the POUs reaching capacity (Brand A), or both duplicate filters clogged

Table B4: Filter Time for Very High iron particulate water

| Very High Particulate Iron (20 mg/L) | | | | | | |
|---|---|---|---|---|---|---|
| Brand | A | | B | | C | |
| Rated Capacity | 15 Gal (# batches) | 57 L | 120 Gal (# batches) | 454 L | 40 Gal (# batches) | 151 L |
| | Batch | Time (min) per duplicate | Batch | Time (min) per duplicate | Batch | Time (min) per duplicate |
| | 1 | 23 and 23 | 1 | 15 and 15 | 1 | 99 and 216 |
| | 2 | 26 and 26 | 2 | 41 and 45 | 2 | 124 and 259 |
| | 3 | 35 and 26 | 3 | 222 and 222 | 3 | NA and 261 |
| | 4 | 30 and 29 | - | - | 4 | 250 and NA |
| | 5 | 48 and 39 | - | - | 5 | 346 and NA |
| | 6 | 40 and 29 | - | - | 6 | >4X and 157 |
| | 7 | 64 and 43 | - | - | - | - |
| | 8 | 67 and 43 | - | - | - | - |
| | 9 | >4X and 55 | - | - | - | - |
| Average Time | 38 ± 14 min | | 93 ± 101 min | | 214 ± 83 min | |
| Median Time (range) | 35 (23 - 67) min | | 43 (15 - 222) min | | 233 (99 - 346) min | |

>4X: POU clogged based on failure criterion 75% reduction of initial flowrate (4X initial filter time).
NA: POU time required to a batch of water was not recorded.
Shaded rows: POU duplicate clogged when the alternative criterion was applied, 2-hr (120 min) max
-: Study concluded for that POU brand due to the POUs reaching capacity (Brand A), or both duplicate filters clogged

Table B5: Filter Time for Soluble iron and lead combination water

| Soluble Lead-Iron Combination (200 µg/L Pb, 0.3 mg/L Fe) | | | | |
|---|---|---|---|---|
| Brand | A | | B | |
| Rated Capacity | 15 Gal (# batches) | 57 L | 120 Gal (# batches) | 454 L |
| | Batch | Time (min) per duplicate | Batch | Time (min) per duplicate |
| | 1 | 27 and 61 | 1 | 17 and 17 and NA |
| | 2 | 23 and 43 | 8 | 15 and 15 and 17 |
| | 3 | 36 and 25 | 15 | 16 and 16 and 18 |
| | 4 | NA and NA | 22 | 19 and 17 and 20 |
| | 5 | 23 and 59 | 29 | 22 and 22 and 21 |
| | 6 | 57 and 48 | 36 | 21 and 20 and 21 |
| | 7 | 35 and 21 | 43 | 28 and 26 and 32 |
| | 8 | 51 and 24 | 50 | 26 and 26 and 27 |
| | 9 | 23 and 26 | 57 | 27 and 24 and 27 |
| | 10 | 21 and 32 | 64 | 27 and 27 and 29 |
| | 11 | 22 and 41 | 71 | 32 and 23 and 24 |
| | 12 | 23 and 70 | 78 | 25 and 25 and 24 |
| | 13 | 23 and 32 | 85 | 27 and 28 and 27 |
| | 14 | 23 and 30 | 92 | 26 and 29 and 35 |
| | 15 | 22 and 22 | 99 | 28 and 31 and 38 |
| | - | - | 106 | 29 and 29 and 32 |
| | - | - | 113 | 41 and 33 and 30 |
| | - | - | 120 | 44 and 32 and 30 |
| Average Time | 34 ± 14 min | | 25 ± 6 min | |
| Median Time (range) | 26 (21 - 70) min | | 26 (15 - 44) min | |

>4X: POU clogged based on failure criterion 75% reduction of initial flowrate (4X initial filter time).
NA: POU time required to a batch of water was not recorded.
Shaded rows: POU duplicate clogged when the alternative criterion was applied, 2-hr (120 min) max
-: Study concluded for that POU brand due to the POUs reaching capacity (Brand A), or both duplicate filters clogged

Table B6: Filter Time for Particulate iron and lead combination water

| Particulate Lead-Iron Combination (200 µg/L Pb, 0.3 mg/L Fe) | | | | |
|---|---|---|---|---|
| Batch | A | | B | |
| Rated Capacity | 15 Gal (# batches) | 57 L | 120 Gal (# batches) | 454 L |
| | Batch | Time (min) per duplicate | Batch | Time (min) per duplicate |
| | 1 | 24 and 24 | 1 | 15 and 15 and 14 |
| | 2 | 25 and 25 | 8 | 23 and 23 and 22 |
| | 3 | 24 and 21 | 15 | 22 and 22 and 22 |
| | 4 | 63 and NA | 22 | 29 and 30 and 30 |
| | 5 | 22 and 23 | 29 | 37 and 38 and 38 |
| | 6 | 32 and 22 | 36 | 35 and 40 and 34 |
| | 7 | 23 and 22 | 43 | 68 and 73 and 87 |
| | 8 | 23 and 21 | - | - |
| | 9 | 23 and 23 | - | - |
| | 10 | 25 and 25 | - | - |
| | 11 | 25 and 64 | - | - |
| | 12 | 33 and 23 | - | - |
| | 13 | 24 and 41 | - | - |
| | 14 | 22 and 24 | - | - |
| | 15 | 36 and 36 | - | - |
| Average Time | 28 ± 11 min | | 34 ± 19 min | |
| Median Time (range) | 24 (21 - 64) min | | 30 (14 - 87) min | |

>4X: POU clogged based on failure criterion 75% reduction of initial flowrate (4X initial filter time).
NA: POU time required to a batch of water was not recorded.
Shaded rows: POU duplicate clogged when the alternative criterion was applied, 2-hr (120 min) max
-: Study concluded for that POU brand due to the POUs reaching capacity (Brand A), or both duplicate filters clogged

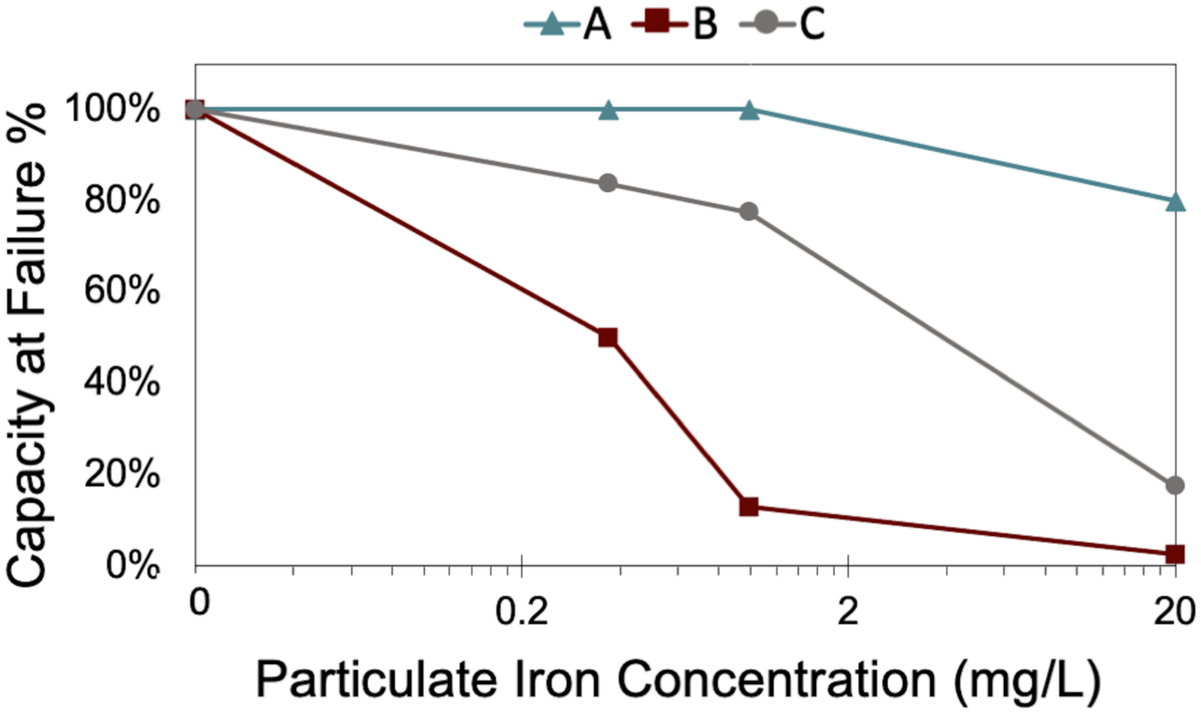

Figure B1: Impact of particulate iron concentration on POU capacity

This figure demonstrates impact of particulate iron concentration on POU capacity for duplicate brand A (57-liter capacity), brand B (454 -liter capacity), and brand C (151 -liter capacity) filters. It was assumed, based on the manufacturer's rated capacity for the brand, that filters would reach 100% capacity in the absence of iron (0 mg/L Fe). This was illustrated by plotting 100% capacity at failure for all filter brands at 0 mg/L Fe for the purpose of this figure.

# Chapter 4: Long Term Performance of Point-of-Use Water Faucet Filters in Louisiana Households

Jeannie Purchase, Adrienne Katner, Kelsey Pieper, Marc Edwards

## ABSTRACT

Lead certified point of use (POU) filters were tested in two unoccupied homes at up to 200% capacity over the course of 20 days while measuring lead concentrations in all treated water. The POUs in one home that had sustained high lead even with flushing, consistently produced water with < 5 μg/L Pb with the exception of two samples with 12 μg/L Pb. Another home with a disturbed lead service line (LSL) had erratic lead 9-3000 μg/L when profiled with sequential samples due to high levels of particulate lead. The duplicate POUs in this home did not consistently produce water with <10 μg/L Pb. This work highlights how POUs can achieve high percentage removals of lead under challenging conditions with high lead but still occasionally exceed 10 μg/L Pb. Another phase of research tested the performance of POUs deployed in 21 residential homes in New Orleans (8) and Enterprise (13) Louisiana. The POUs always reduced lead to <1 μg/L, iron <171 μg/L and manganese <180 μg/L. The high influent concentrations of iron in Enterprise had a large impact on filter capacity due to reduced flow and clogging. Enterprise homes saw an average of 62% flowrate reduction before the residents decided that the filters clogged (i.e., flow rate judged too slow for use). Most of the homes did not reach 50% of the filter's rated capacity. There was not a simple correlation between average iron concentration and days of filter life amongst residents in Enterprise, as would be expected given variations in volume of water used daily and consumer subjectivity in determination of clogging. A complementary lab experiment demonstrated that each of 4 faucet filter brands tested had differing susceptibility to clogging, and sometimes were different amongst duplicates of the same brand. This study shows how POUs are usually good in removing Pb, Fe and Mn but clogging has emerged as an important practical limitation to their use.

## INTRODUCTION

To avoid adverse health effects of lead exposure, especially for pregnant women and children, cities with elevated lead have turned to the mass distribution of bottled water and NSF/ANSI 53 lead certified point-of-use (POU) filters.[1] Their widespread use during water crises in Washington, D.C., Flint, MI, and Newark, NJ, has made their deployment more common for cities without optimal corrosion control or lead service line (LSL) replacement.[2–8] POUs are often more environmentally friendly and less expensive than bottled water.[1,9,10]

POU filters were generally very effective at reducing lead levels below <5 μg/L in field studies both in Flint (100%, n=242) homes, and in Newark, NJ (97.5%, n=198).[6,11] There were a few exceptional cases in Newark, NJ (2.5%, n=198) in which filtered water lead levels were as high as 112 μg/L.[11] Our own work examining filter failures revealed the need for better QA/QC in manufacturing because some duplicate filters dramatically outperformed others.[12] Nonetheless, POUs are proven to be effective at reducing elevated lead levels even when operated beyond capacity, although there are exceptional cases of relatively poor performance due to occasional problems removing lead particulates.[6,7,11–15]

As utilities and consumers increasingly rely on POUs to protect public health from lead exposure, there is a need to better understand factors that limit performance of these devices in the field. Prior city-wide filter sampling campaigns in Flint and Newark relied upon the collection of instantaneous grab samples and did not examine performance throughout the life of the filter. Mulhern and Gibson (2020) conducted a 6-month study on under-the-sink activated carbon filters in homes with private wells.[16] First draw unfiltered lead samples in 17 homes ranged between 0.1-34.3 µg/L Pb (median 8.2 µg/L Pb) and flushing did not always reduce lead to non-detectable levels. However, the POU filters effectively removed 98% of lead in the water and with always <1 µg/L Pb. These authors noted clogging in 3 homes after only 2-3 months of use (5-45% rated capacity).[16] Clogging in the Boyd et al (2005) study with under-the-sink filters in school water fountains was attributed to iron concentrations up to 28 mg/L at 30-40% of rated capacity. [17]

In this study, we execute a longitudinal field study of faucet mount POU filter performance in complementary testing in two unoccupied homes known to be high risk due to the presence of LSLs upstream and in 21 occupied homes with more typical lead problems. The specific goals were to (1) evaluate the relative benefits of flushing to reduce lead levels over time, (2) monitor POU filter performance in removing lead for up to 200% of each filters rated capacity for 20 days in unoccupied homes, and (3) monitor long-term filter performance in testing by consumers in New Orleans and Enterprise, Louisiana.

## METHODS

### Site Choice: New Orleans and Enterprise, Louisiana

The field experiments were executed from May – Dec 2019 using NSF-ANSI 53 lead certified filters purchased in early 2019. New Orleans was selected as a representative urban area with low to moderate water lead levels and with many partial LSL replacements previously shown to create problems with particulate lead.[18] Enterprise (pop <300) was selected as a rural community with moderate to high problems with lead, iron, and manganese. Enterprise is a good example of an unincorporated water system that might consider use of POUs instead of implementing more expensive lead corrosion control.

### Phase 1: Unoccupied Home Study

Unoccupied homes were used to conduct a scientifically rigorous field test with stringently controlled flow and stagnation events, under situations with highest risk plumbing and up to 200% of the rated POU capacity without endangering consumers. An automated rig was designed and installed in two homes in New Orleans, LA to test the long term (20 days) lead reduction by flushing and the use of duplicate POUs (Figure C1, C2). One test was in a home where elevated lead levels were sustained after long flushing (average 17 µg/L Pb) and the second was a home with a disturbed LSL installed upstream of the rig. The faucet filter used carbon-block technology and had a 100-gallon capacity, and performed well (always <15 µg/L Pb up to 200% capacity) in a prior study.[12]

*Rig Operation:* The Home with Sustained Lead levels was tested by connecting the rig directly to the kitchen tap (Figure C1, C2). The Home with the Disturbed LSL was tested by connecting the home water to a 6-ft long LSL extracted during a partial replacement in New Orleans. The solenoids, valves and timers were powered by a DC rechargeable 12 Volt 35 Amp hr. battery. The apparatus was placed within a plastic pool for secondary containment and had an emergency shut-off valve which would be triggered by leak sensors to protect the privately owned buildings.

The flow in the homes was fully automated to test 3 treatments including no filtration, and filtration through POU duplicate 1 or duplicate 2 (Figure C1, C2). Specifically, after identical 7.5-hour stagnation events 3 times per day, a solenoid would direct 10 gallons of water to flow through a tap representing one of these three conditions daily for 20 days (Section C1). The POUs were operated for 20-30 min of flow at 0.3 - 0.5 gallons per minute to achieve the target volume. Each 10-gallon flow event is equal to 10% of the filter rated capacity. In this case all of the treated water was collected and sampled as a 10-gallon composite.

*Sampling:* The reservoirs for the treated water were dosed with 50 g of Alpha Chemicals food-grade citric acid to safely drop the final pH to < 3.0, which was found to be sufficient to prevent lead losses by sorption to the walls of the plastic containers.

*Profile Sampling:* At different times the nature of lead released from each plumbing configuration during the 10-gallon flow event was characterized via sampling of discrete bottles. This "profiling" of lead release used a total of 19 bottles. Specifically, fifteen 1 Liter bottles were filled in sequence, and thereafter, 250 mL grab samples were collected after a cumulative 5, 7, and 9 gallons were flushed (Figure 4-1). A final 250 mL composite sample was collected of all the water from gallons 4-10. To determine the particulate lead concentration, 0.45 μm pore size filtered samples were taken from Bottle 1, 3, 5, 7, 11, 15, and 17. Three profiles were taken for the Home with Sustained Lead at day 0, 10, and 20. Four profiles were taken for the Home with the Disturbed LSL at Day 0, 8, 14, 20.

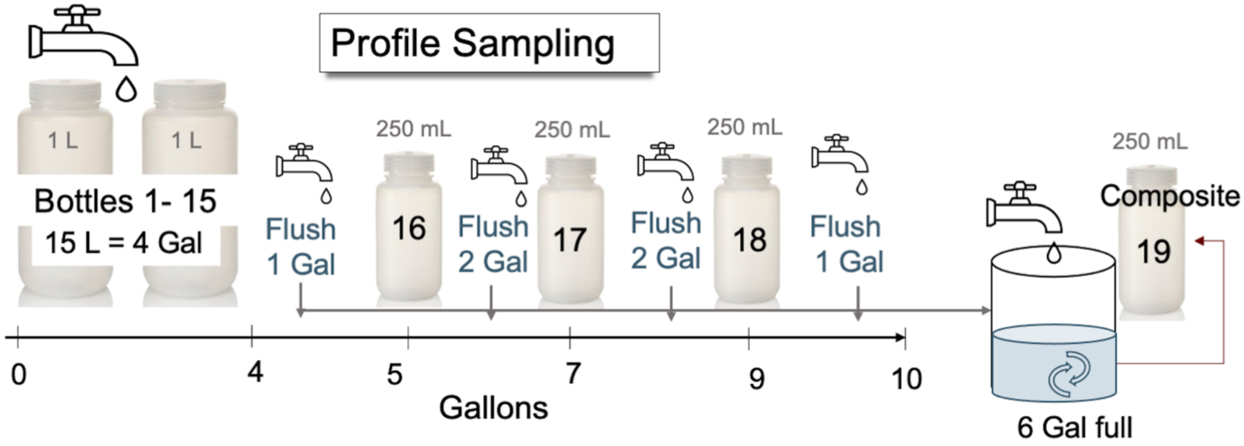

Figure 4 - 1: Profile of Influent Water

**Phase 2: Consumer Testing in Normal Field Use**
The goal of this investigation was to monitor long-term filter performance in New Orleans and Enterprise homes known to have elevated water lead levels under regular use patterns.[19]

*Consumer sampling:* This human subject experiment was reviewed and approved by the Virginia Tech IRB board (17-541). Residents qualifying for the study had > 5µg/L lead in first draw or flushed samples in our previous tap water sampling. The goal was to recruit 15 single family homes from each study area, to install and monitor a POU faucet filter used in their kitchen. Only homes with a kitchen tap design suitable for use of a POU were considered (e.g., removable aerators).

Sample collection bottles, sampling instructions, reminder cards, a stopwatch, a permanent marker, and pre-paid return postage were provided to each resident. Upon POU installation, residents were provided a free POU filter that was installed by investigators. They were trained by researchers on proper POU use (e.g., not filtering hot water, how to change cartridge), provided with the POU manual, and were encouraged to contact the authors if they needed further technical assistance. Use of the filter was routine, except for the two sampling days when residents were instructed to let the water to remain stagnant overnight for at least 6 hours prior to sample collection to monitor filter performance. After not using the water for this time, residents collected a 250-mL unfiltered first draw sample bypassing the filter to reveal the typical lead present in the untreated water. This process was repeated the next morning when residents collected the same volume of water filtered, while also measuring the number of seconds required to fill the bottle.

Residents were instructed to continue sampling weekly until one of the following three conditions occurred: 1) reach the filters 12-week max rated lifetime, 2) the built-in indicator light turned yellow/red alerting consumers that the filter was approaching the max designed volume of treatment, or 3) if the resident believed the filter was clogged (i.e., it took too long to filter the 250 mL sample). If the consumer deemed the filter to be clogged, they were asked to take one more filtered sample for this research after at least a 6-hour stagnation event. Some residents in Enterprise, LA experienced frequent premature clogging during the study, but volunteered to collect more data by testing additional filter cartridges. Residents filled out a survey pre- and post-filter testing. Pre-survey results suggested that some residents had lead pipe replacements and had other lead avoidance strategies. Two Enterprise homes had additional filters installed during the study, ELA 9 had a whole house filter and ELA 11 had an under the sink filter, but both homes had lead, iron, and manganese levels in the same range as the other Enterprise homes and it did not seem as if the filters were effective. Moreover, the POUs (from our study) in these homes still clogged prematurely at 4 and 6 weeks.

*Iron Flow Reduction Study:* Midway through the consumer study it was realized that more devices were failing due to clogging in Enterprise compared to New Orleans. A laboratory experiment was designed to verify that POU faucet filters clogged due to the elevated iron or manganese levels in the Enterprise, LA source water. Four faucet filter brands (named D, E, F, and K, designation from prior study) were tested in duplicate using and the automated faucet rig found in Purchase et al.(2020), which was powered by a booster pump and had a water pressure range between 35-45 psi.[12] The test involved filtering 3-gallon batches of water in progressively increasing concentrations of iron: 0, 150, 300, 600, 1000, 2000, 4000, and 5000 µg/L Fe. In between each iron batch the filters were flushed with 3 gallons of DI water to measure the length of time required to fill a 250 mL bottle and to monitor the clogging status of the filter using a particle free water. Tests were continued until the time it took to filter one gallon of water had doubled from when the filter was clean.

Water Analysis: The Phase 1 and Phase 2 samples were dosed with 2% nitric acid and 2% hydroxylamine hydrochloride (10% w/w) and digested for > 18 hours. The 250 mL effluent samples were then placed in an oven at 50°C for 5+ hours to further assist with iron dissolution. All samples were analyzed for metals concentrations using a Thermo Electron iCAP RQ Inductively Coupled Plasma Mass Spectrometer (ICP-MS).[20]

## RESULTS & DISCUSSION

### Phase 1: Controlled Testing in Unoccupied Homes

#### *UNOCCUPIED HOME WITH SUSTAINED LEAD*

Profile: The unoccupied Home with Sustained high-water Lead had average influent lead (10-gallon composite) of 10-24 µg/L (Figure 4-2B) during the 20-day study. When characterizing the 10-gallon flushed profiles taken on Day 0, 10, and 20 the influent lead fluctuated between 5.6-31.3 µg/L and the average percentage particulate lead was 15-21% (Figure 4-2A).

As water flowed from the tap after stagnation events, the lead concentrations peaked after flushing 20 liters in bottles 15-17, which is consistent with expectations if the lead service line is the dominant source of lead. Except for the first 6 L of the Day 0 profile, lead levels from this home were all >10 µg/L even after flushing >8 min (10-gallons). Clearly, the New Orleans public health recommendations to flush the tap 30 sec – 2 minutes to reduce lead exposure in water used for cooking or drinking, would not have been effective in this home.[21] As the study continued the lead increased slightly from Day 0 up to Day 20. This rising level of lead might reflect the relatively low water use of 30 gallons per day during this study versus 120 gallons per day of typical daily use [22] when the home was occupied.

Filter Performance: The brand E faucet filters consistently produced water with less than 5 µg/L lead except for 3 samples which were >10 µg/L (Figure 4-2B). Filter duplicate 1 had lead levels below 2 µg/L and removal efficiencies between 85.2-99.6%, except for Day 8 and 9 (composites of gallons 80-100) which both had effluent lead of 12 µg/L occurring before the filter's 100-gal capacity. The filtered lead concentrations when tested beyond the rated capacity were always <2 µg/L. Duplicate 2 always had effluent lead levels below 5 µg/L and removals of 73.8%-99.9% except for one sample with 15 µg/L on Day 11 or just 10% beyond the rated capacity.

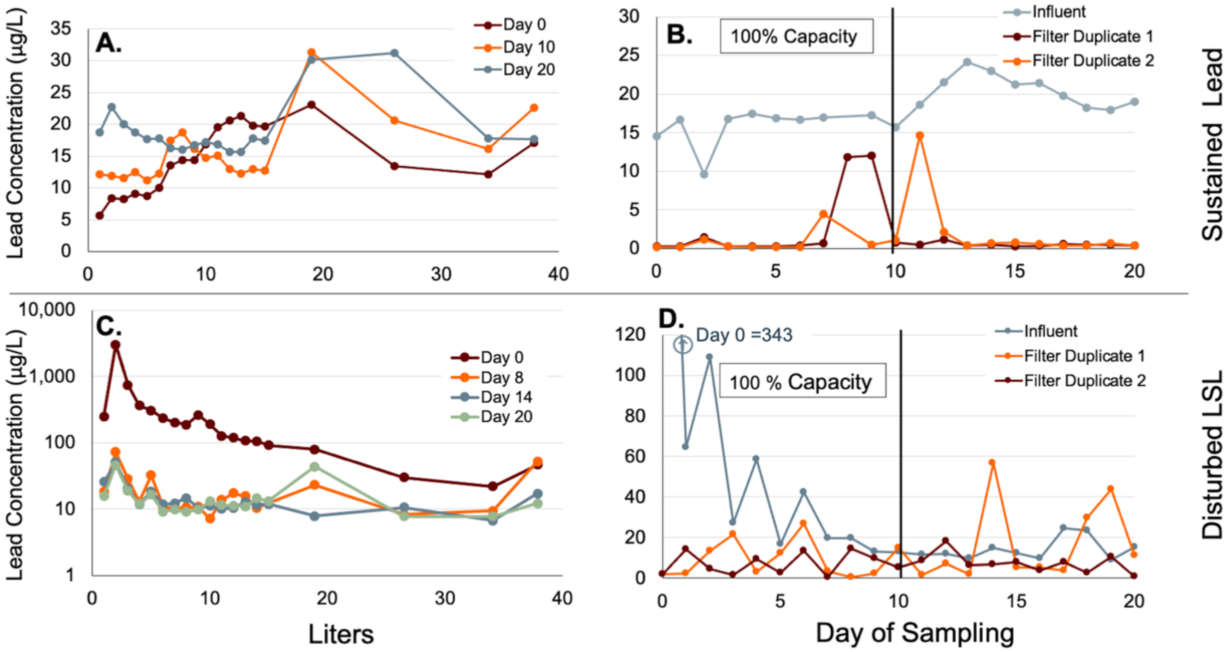

Figure 4 - 2: Unoccupied Home profile sampling and filter performance over time. (A) The lead profiles of the Home with Sustained Lead. (B)The duplicate POU filtered lead concentrations for the Home with Sustained Lead. (C) The lead profiles of the Home with Disturbed LSL. (B)The duplicate POU filtered lead concentrations for the Home with Disturbed LSL.

### *UNOCCUPIED HOME WITH DISTURBED LSL*

*Profile:* The unoccupied Home with the Disturbed LSL had average influent (10-gallon composite) lead levels between 9.2-343.7 µg/L supplied to the rig throughout the 20-day study (Figure 4-2D). LSLs often release very high lead immediately after a disturbance with declining levels thereafter.

The four 38 L (10-gallon) profiles had the highest lead concentrations in the first 4L, after which the concentrations steadily declined. The lead levels in the profiles always peaked in bottle 2 (2L), which corresponds with the water sitting stagnant in the rig's disturbed LSL (6 ft long and 1 in diameter). Day 0 had the highest lead levels with the 2 L sample at 3053 µg/L lead and an average particulate lead of 89% (Figure 4-2C, Figure C4). The lead decreased to range between 100-250 µg/L with additional flushing and eventually decreased to 50 µg/L at bottle 19. The other three profiles Days 8, 14, and 20 were similar with average particulate lead of 36-41% and concentrations fluctuating between 7-55 µg/L.

*Filter Performance:* The water in the Home with the Disturbed LSL proved to be challenging for the POUs, as they were unable to consistently treat the water to levels <10 µg/L most likely due to the very high concentrations of particulate lead. Duplicate filter 1 produced 5 grab samples with effluent lead levels >10 µg/L before reaching the rated capacity of 100 gallons. These high levels of lead occurred on Days 2, 3, 5, 6, and 10 with lead levels between 12-27 µg/L. The estimated

POU removal efficiencies ranged from 21.1-99.4%, based on the best available estimate that compared filtered and unfiltered samples with flushing collected 7.5 hrs apart. It is understood that particulate release is not perfectly reproduced from one profile to another on the same day, and that this introduces some uncertainties in the estimated percentage removal. Duplicate filter 2 had lead levels >10 µg/L in 3 samples with effluent lead of 14-15 µg/L on Days 1, 6, and 8 with removal efficiencies of 25-99.4%.

The Home with Sustained Lead levels never had filtered water lead concentrations greater than the influent lead levels. However, the Home with the Disturbed LSL had filtered lead exceed the estimated influent lead on 4 different days between Day 10 and 20. This could result from the highly variable particulate lead release patterns from partial LSLs. For instance, the Day 14 samples of untreated water had influent lead of 15 µg/L, whereas the corresponding sample for filtered water lead later was 57 µg/L taken 7.5 hours later. Due to the erratic nature of the lead release, it is possible that the actual influent to the filter when the water was treated was much higher for the treated water sample of 57 µg/L. It is also possible that previously removed lead particulates were being released from within the filter at semi-random intervals as reported previously by Deshommes et al (2010).[15] There is no perfect approach to quantifying the percentage of lead removal by filters when semi-random release of discrete particles is occurring. Even sampling the influent and effluent at the exact same time, could result in effluent lead being higher than influent lead, as 99% of the lead in a sample can be in a single particle.

### Phase 2A: Consumer Field Testing POU Performance

Water Quality of Unfiltered Water: A total of 21 residents participated in a long-term filter study conducted in the summer of 2019, including 8 residents from New Orleans (NOLA) and 13 residents from Enterprise (ELA), LA. Water quality data from both communities illustrated significant differences (Table C1 & C2; Figure 4-3). Specifically, the 8 New Orleans homes had unfiltered water with relatively low levels of lead (Pb), iron (Fe), and manganese (Mn). Unfiltered lead levels were all less than 5 µg/L, except for one sample with 22 µg/L lead. Over 75% of iron concentrations in NOLA were below 10 µg/L with a max of 57.3 µg/L and manganese levels were all <1.3 µg/L. None of the New Orleans samples exceeded the EPA Secondary Maximum Contaminant Level (SMCL) for Fe (300 µg/L) and Mn (50 µg/L). We expected higher levels of unfiltered lead in the New Orleans homes based on historical data and our intensive sampling data in the unoccupied Home with Sustained Lead in Phase 1.

In contrast, 4 out of 13 homes in Enterprise (ELA) had samples that exceeded the EPA Action Level for lead at some point in the study with a maximum value of 86 µg/L. Even though the median unfiltered Pb concentration for all Enterprise homes was only 1 µg/L (Table C2). Enterprise also had several untreated tap samples that exceeded the EPA SMCL for both Fe and Mn. The unfiltered median Fe concentration was 383 µg/L with a maximum of 19,700 µg/L and the median unfiltered Mn concentration was 106 µg/L with a maximum of 917 µg/L (Table C1).

Filter performance: All filtered lead samples were <0.8 µg/L and all iron samples were <171 µg/L, and all manganese samples were <180 µg/L. The filters performed well in reducing lead and iron levels in all homes throughout the duration of the study (Figure 4-2, Table C1 & C2). However, 10% (n=88) of all filtered samples exceeded the manganese SMCL of 50 µg/L; these samples represented 4 homes in Enterprise (Table C1, C2). The average POU removal efficiencies were 94.8% for Pb, 98% for Fe, and 79% for Mn for the Enterprise homes, NOLA homes were excluded in this analysis due to low unfiltered concentrations. Overall, the filters effectively Pb and Fe throughout the test, but the performance in removing Mn was less consistent.

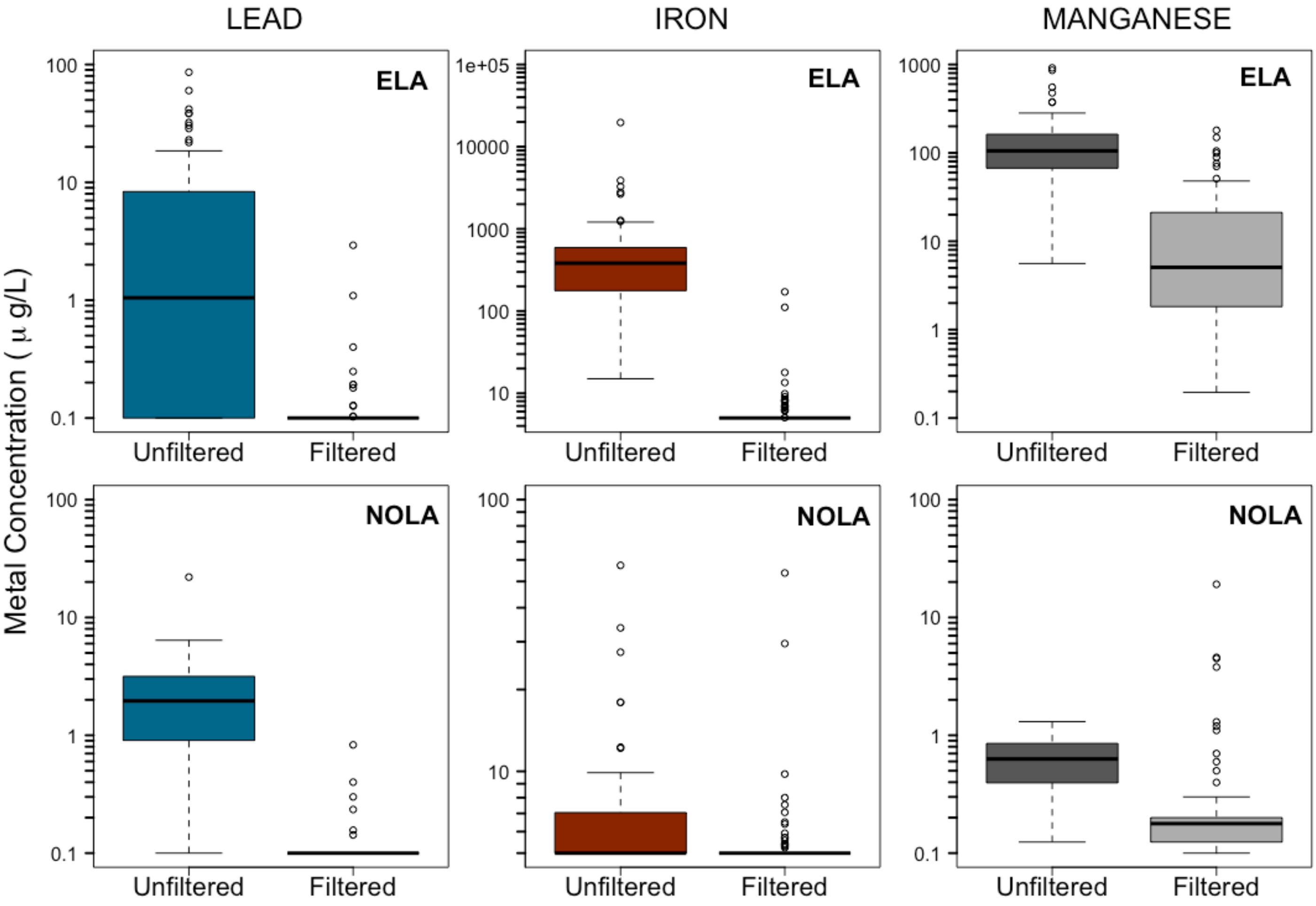

Figure 4 - 3: Influent and Effluent Metal Concentrations

### Phase 2B: Consumer Experiences with Clogging

*Comparing Flowrates in New Orleans and Enterprise:* Our field study revealed a serious problem with filter clogging. Third party certification testing under guidelines of NSF/ANSI 53 for lead and 42 for Nominal Particulates defines the point of filter clogging as the time at which the initial flowrate is reduced by 75%.[23,24] The Brand E faucet filter used in this study has a design flowrate of 1.9 lpm at 60 psi, and this initial flow rate will fluctuate with varying ambient water pressures in homes. Residents recorded the flow rate of filters throughout the study and decided when the filter was clogged based on their own judgment. One resident decided the filter was clogged after it took 30 secs to filter 250 mL (≈1-cup of water). At another extreme, one resident was more patient and did not yet consider a filter clogged even if they had to wait >3 min to filter 250 mL of water.

The average final flowrates for Enterprise homes, at the point consumers replaced the cartridges or abandoned the study, was 0.55 L/min. In the few homes where residents replaced cartridges in New Orleans the final flowrate was 1.28 L/min, which is 2.3X faster than final flowrate of the POUs in Enterprise (Figures 4-3). From another perspective, the average flowrate reduction at the point a resident declaring clogging was 62% in Enterprise, which is roughly comparable to the 75% reduction selected for this criterion in the NSF testing protocol. Due to low levels of iron and other particulates in the water, New Orleans residents only saw flowrate reductions of up to 16% on average before the end of the study.

The brand E faucet filters used in this study had a rated capacity of 100 gallons or 12 weeks. By this standard none of the filters in Enterprise reached the filter's capacity, and most were replaced before 50% of the rated capacity. As a result, these residents would likely need to replace the filter cartridges 2-4 times more frequently than expected based on the rated capacity, making POU use much more expensive than anticipated.

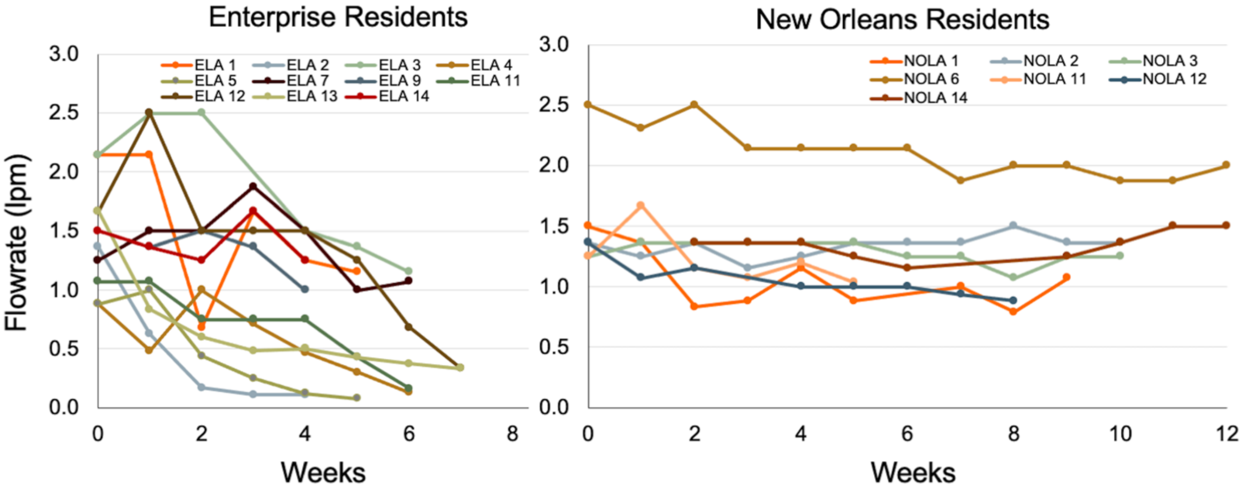

Figure 4 - 4: Filter Flowrate in NOLA and ELA over time. The POU's manufactured rated flowrate at 60 psi is 1.9 lpm.

*Quantifying the Impact of Iron on Filter Life:* In a companion laboratory study to this research, Rouillier et al. (2021) reported a direct correlation between the influent iron concentration and the length of time before clogging.[9] In the present study, there was a weak correlation between average iron concentration in the Enterprise homes and filter life based on the weeks of use (Figure 4-4A). The weak correlation is not surprising given the small number of homes (n=13), and variations in flow rates, water pressures, water use by consumers, and individual consumers criteria for clogging.

We conducted a controlled laboratory experiment that sought to estimate the amount of iron that would need to be removed to clog the filters (Figure 4-4B). When testing Brand E, duplicate filter F1 required 23 mg of Fe to reduce the initial flowrate of 1.3±0.3 lpm by 50% whereas duplicate F2 removed 46 mg iron before achieving the same reduction in flow. The large difference between the duplicates illustrates the filters variability in performance even in a lab-controlled environment. The testing of faucet filter Brands D, F, and K (Figure C5) showed less variability between duplicates in terms of the iron removed at the point of a 50% reduction in initial flow. Brand D clogged at 77-92 mg of total iron accumulation, Brand F clogged at 32-47 mg of Fe removal, and Brand K clogged at 62-92 mg of Fe removal.

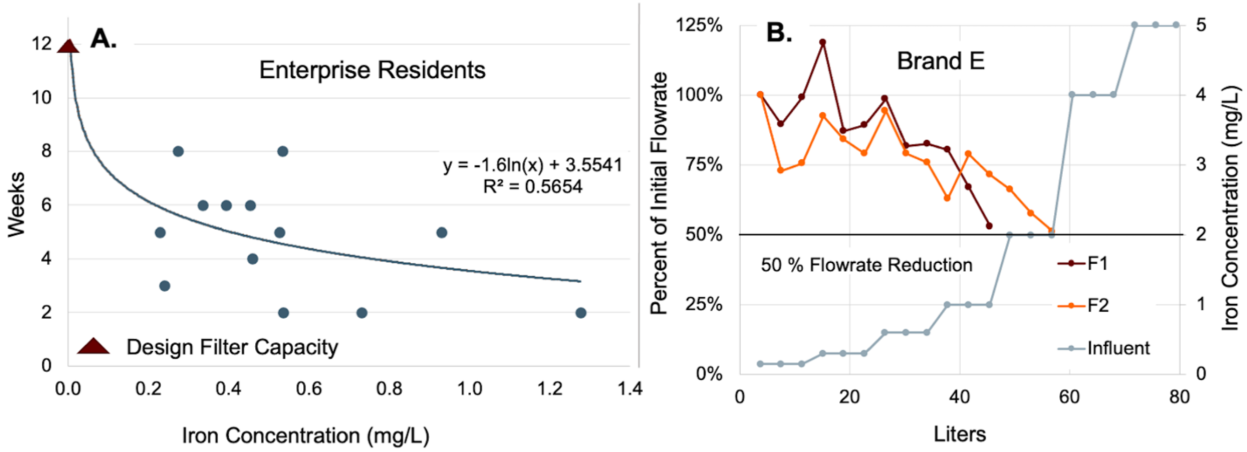

Figure 4 - 5: Iron Concentration and filter life

# DISCUSSION

*Effects of Flushing to Reduce Lead Levels:* This study confirmed prior research that the effectiveness of flushing according to available public health guidelines (for 30 secs – 2 minutes prior to filter use) is dependent on the home. In a study conducted by Katner et al. (2018) using flushing samples from New Orleans homes (Feb 2015-Nov 2016), there was no reduction in lead after 3 minutes of flushing in 81% (n=372) of homes. Lead was reduced with flushing in 13% of homes, but increased in 6% of homes.[21] We profiled the lead concentrations for up to 10 gallons (>8min flushing) in the unoccupied homes multiple times throughout the 20-day study. Out of the 3 profiles (19 bottles each) collected in the Home with Sustained Lead, the max lead concentration was 31.3 µg/L. The lowest flushed sample occurred in the first sample 5.6 µg/L and 91% (n = 57) of flushed samples were >10 µg/L. In the Home with the Disturbed LSL (4 profiles), the lowest flushed concentration was 6.7 µg/L, and 86% (n=76) of flushed samples were > 10 µg/L. There was always detectable lead in all the samples even with extended flushing.

*Filter Performance for Lead Reduction:* All the filtered samples collected by residents in New Orleans and Enterprise homes had lead levels below 1 µg/L. In the Enterprise homes, the filters removed iron well below the SMCL. However, the POU removal of manganese was inconsistent (27-100%), even though most filtered samples (75%, n=88) had < 25 µg/L Mn (Table C1). The relatively poor removal of manganese was consistent with reports of Carriere et al.[25] The occasional low removal of Mn did not correlate with the removal of Pb or Fe, consistent with prior work on pitcher filters with high removal efficiencies with co-occurring Fe/Pb waters.[9] Likewise in Flint, MI, 19% of homes had unfiltered iron above the SCML of 0.3 mg/L, but this did not affect the removal of lead by the POU.[6]

The POUs in the Home with Sustained Lead performed well in reducing lead levels up to 200% capacity as treated water in the composite samples was <5 µg/L, with only 3 samples >10 µg/L amongst both filters (400-gallons filtered). In contrast, POUs in the Home with the Disturbed LSL had inconsistent lead removals of 22-99% that decreased over time. Duplicate POUs had 8 out of 20 samples >10 µg/L prior to 100% filter capacity. The poor removal by the POUs in the Home with the Disturbed LSL (treated water >10 µg/L) is consistent with other laboratory and field studies with difficult to treat lead particulates.[7,12–14]

These results reinforce the need for remedial flushing, filter distribution, and managing expectations of consumers after partial pipe replacements.[9,26–29] There is a high risk of elevated particulate lead after disturbing lead pipes and the use of POU filters always did reduce lead exposure .

*Filter Performance from a Consumer's Perspective:* The faucet filter used in these field studies was selected because it had adapters that allowed it to fit most faucets, a by-pass valve to test the unfiltered water, and easy installation and removal by residents. Some consumers felt the filter was too big, even though it was normal for other commercially available filters. [19]

Some residents reported the filter flow rate was too slow. When installed in New Orleans and Enterprise homes the initial flow rate ranged for this POU from 0.68 – 2.5 lpm with an average of 1.35 lpm. Out of 7 filter brands tested in a prior study the clean filter flow was 1.21± 0.23 lpm at 35-45 psi. The POU brand selected for use in this study was the 2nd slowest filter with an average of 1.05 lpm and it did clog quickly in Enterprise.[12]

The EPA declared that the city of Newark, NJ should be providing bottled water immediately to residents after preliminary results of a POU performance study revealed 2 filters with elevated lead in treated water.[11,30,31] However, their follow-up comprehensive study showed lead was high after POU treatment in only 5 (n= 198) cases, which allowed the city to stop the distribution of bottled water and only provide filters.[7,11,32] The comprehensive study results may be overly optimistic because 67 of 265 homes inspected in the study were excluded from testing due to filter misuse (i.e., improper installation, incorrect cartridges, use beyond capacity, and filtering hot water).[11] Thus, the Newark performance results might be biased towards better performance than would occur if all of the homes had been sampled. Likewise, the Flint, MI EPA POU study tested fresh cartridges and took samples that represented "new" filter use in homes where filters were found to be misused or had exceeded capacity, which again can bias the results towards better performance.[6]

A total of 47% of our residents in Enterprise and New Orleans self-reported that hot water ran through the filters, even though we noted that this is not recommended by the manufacturers.[19] It is not clear what the effect of running hot water through the filter actually is. If it has no effect on performance stating that could reduce consumer angst because it seems accidental use of warm water in going to occur.

*Greater Impact of Clogging:* A significant factor that emerged in this study is that clogging can be a major problem for consumers. POU filters might not be suitable in higher turbidity or discolored waters, and their cost-effectiveness relative to bottled water is markedly reduced by rapid clogging. We recently demonstrated that in waters with high iron or high particulates, the use of POUs will be more costly than stored-brand bottled water.[9] It is hypothetically possible that flushing the water before it is applied to filters or using a whole house filter to reduce the burden of particulates, could be used to increase the time before clogging in such situations, but evaluation of this possibility would require additional research.[19,33]

## CONCLUSION

Reducing water lead levels is a complex problem that requires many different strategies to help protect public health. All remediation strategies including (1) distribution of bottled water, (2) remedial flushing to reduce lead levels, (3) installation of lead-certified point-of-use filters, and (4) replacement of leaded plumbing have strengths and limitations.

Our studies in unoccupied homes showed that flushing did not satisfactorily reduce lead levels even after >8 minutes. The Home with the Disturbed LSL had extremely high particulate lead consistent with expectations, creating a challenge in the POU faucet performance, as the lead levels frequently exceeded 10 μg/L (>50% prior to capacity) in this home.

When used in the Home with Sustained Lead levels and tested to 200% capacity, the duplicate POUs always reduced water lead levels <5 μg/L except for 3 (n=40) samples. Under regular use by consumers in the New Orleans and Enterprise residential homes, the POUs always reduced lead (<1 μg/L), iron (171 μg/L), and manganese (<180 μg/L) levels. Overall, filters are effective in the continued reduction of water lead levels throughout their filter life in the field, however they are certainly not perfect and consumer expectations should be managed.

In waters with relatively high iron the filters clogged quickly, frustrating the consumers due to low flow rates. The reduction in the practical filter capacity can significantly increase the treatment costs of POUs, potentially making bottled water more cost effective and less burdensome for lead remediation by comparison. Clogging was not a significant problem in New Orleans where iron was relatively low (median <5 μg/L, max <60 μg/L) but became a major concern in Enterprise where the median iron level concentration was 380 μg/L and some homes had iron up to 19,700 μg/L.

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# APPENDIX C – SUPPORTING INFORMATION FOR CHAPTER 4

Figure C1: Unoccupied Home Rig Schematic
Figure C2: Unoccupied Home Rig Pictures
Figure C3: Home with Sustained Lead – Particulate Lead (concentration and percentage)
Figure C4: Home with Disturbed LSL– Particulate Lead (concentration and percentage)
Figure C5: Filter Clogging for 3 faucet filter brands
Table C1: Residential Unfiltered and Filtered water data in Enterprise (ELA) and New Orleans (NOLA), LA
Table C2: Residential Sampling filter performance by home in Enterprise (ELA) and New Orleans (NOLA), LA

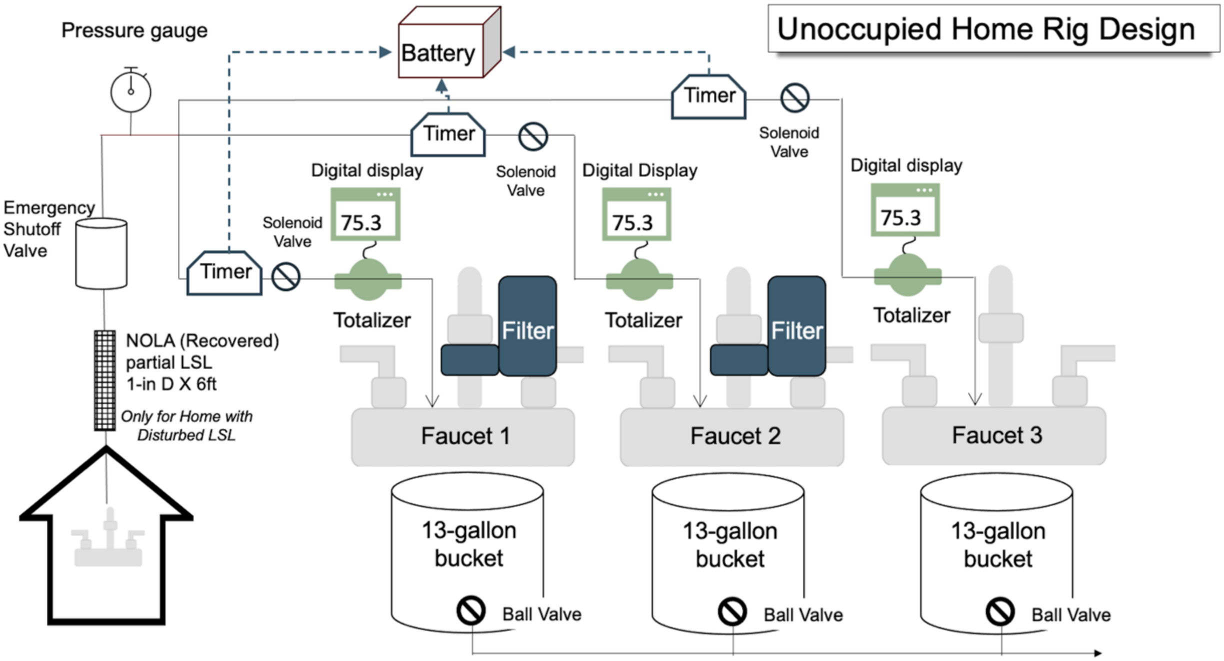

Figure C1: Unoccupied Home Rig Design

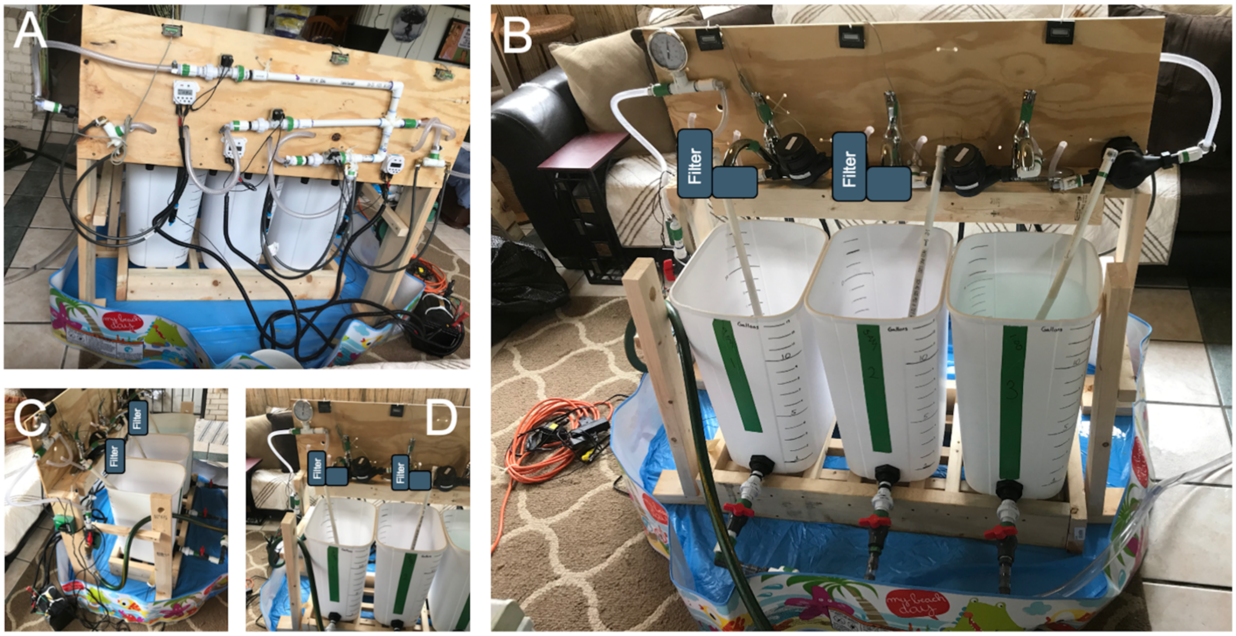

Figure C2: Unoccupied Home Rig Pictures

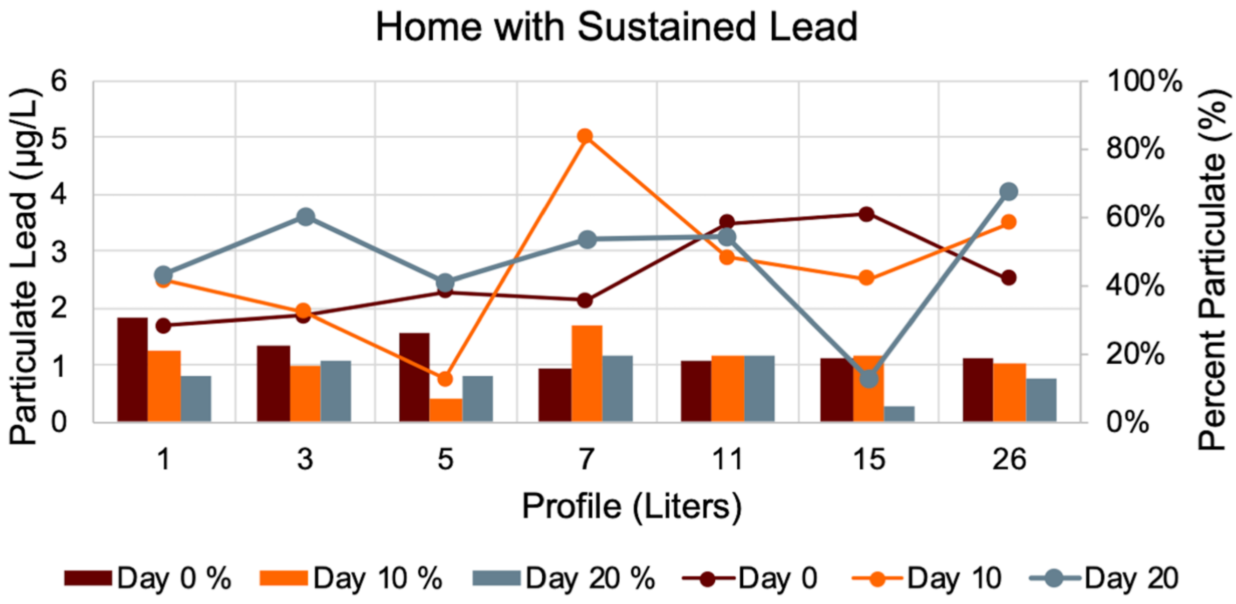

Figure C3: Home with Sustained Lead – Particulate Lead (concentration and percentage)

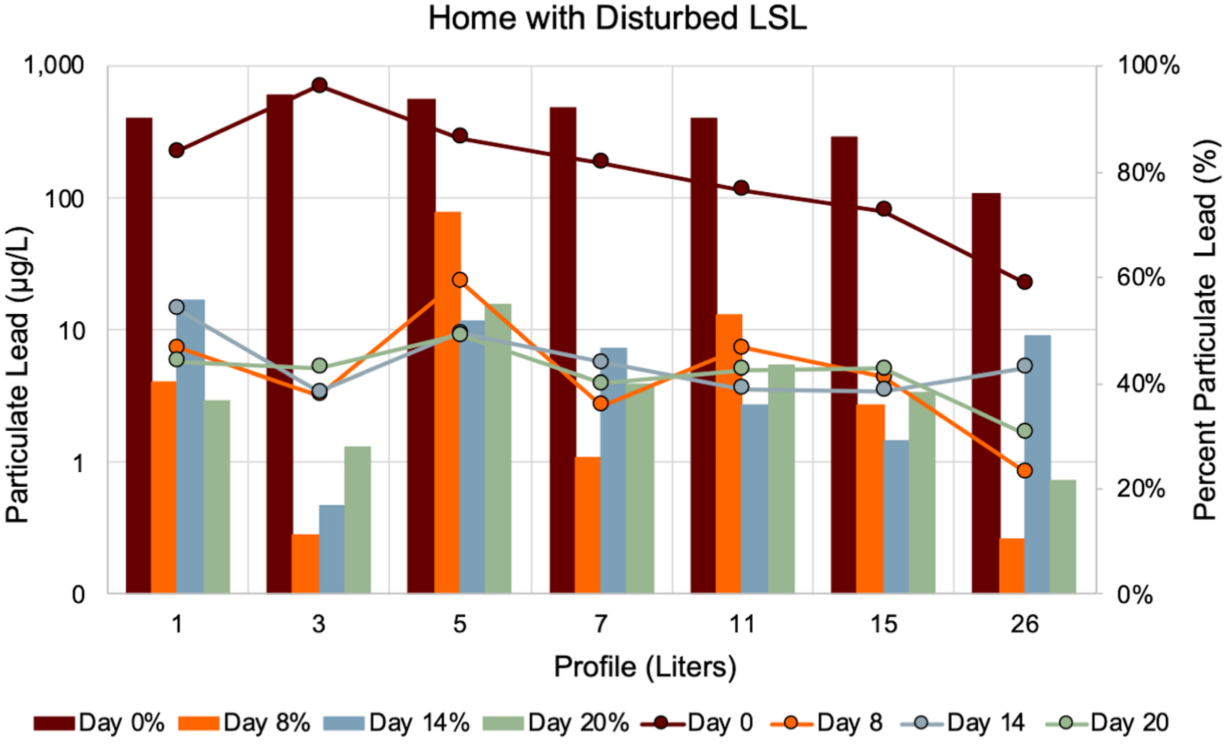

Figure C4: Home with Disturbed LSL– Particulate Lead (concentration and percentage)

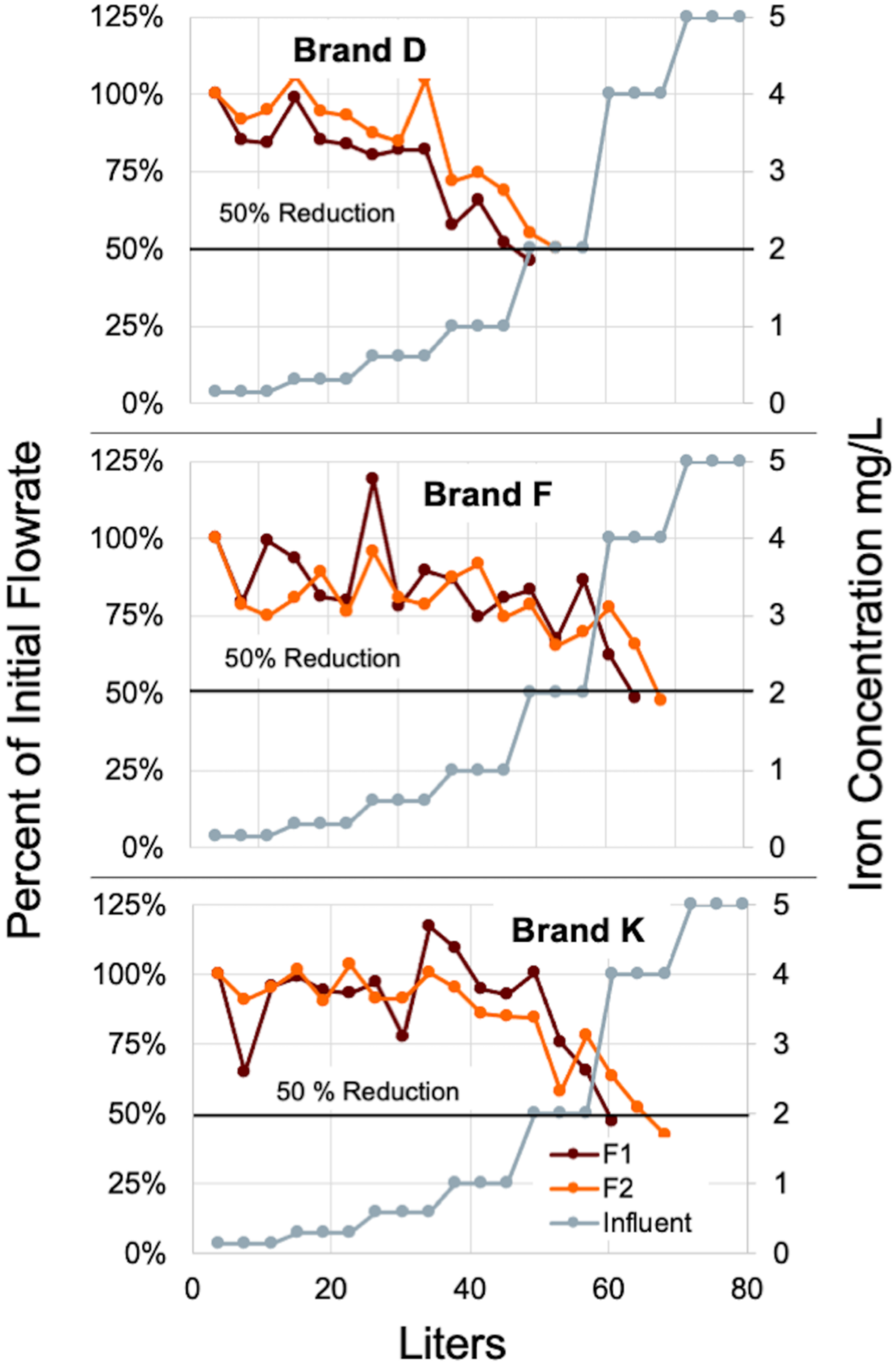

Figure C5: Filter Clogging for 3 faucet filter brands

Table C1: Residential Unfiltered and Filtered water data in Enterprise (ELA) and New Orleans (NOLA), LA

| | Metal | Min (μg/L) | 1st Qu. (μg/L) | Median (μg/L) | Mean (μg/L) | 3rd Qu. (μg/L) | Max (μg/L) | n |
|---|---|---|---|---|---|---|---|---|
| ELA | Pb – UF | 0.1 | 0.1 | 1.0 | 7.0 | 7.9 | 86.0 | 88 |
| | Pb – F | 0.1 | 0.1 | 0.1 | 0.2 | 0.1 | 2.9 | 88 |
| | Fe – UF | 15.0 | 179 | 383 | 762 | 587 | 19700 | 88 |
| | Fe – F | 5.0 | 5.0 | 5.0 | 8.8 | 5.0 | 171 | 88 |
| | Mn – UF | 5.6 | 67.2 | 106 | 142 | 162 | 917 | 87 |
| | Mn – F | 0.2 | 1.8 | 5.1 | 18.1 | 21.2 | 180 | 87 |
| NOLA | Pb – UF | 0.1 | 0.9 | 2.0 | 2.3 | 3.2 | 22.0 | 77 |
| | Pb – F | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.8 | 77 |
| | Fe – UF | 5.0 | 5.0 | 5.0 | 7.6 | 7.1 | 57.3 | 77 |
| | Fe – F | 5.0 | 5.0 | 5.0 | 6.2 | 5.0 | 53.7 | 77 |
| | Mn – UF | 0.1 | 0.4 | 0.6 | 0.6 | 0.9 | 1.3 | 77 |
| | Mn – F | 0.1 | 0.1 | 0.2 | 0.6 | 0.2 | 19.1 | 77 |

Table C2: Residential Sampling filter performance by home in Enterprise (ELA) and New Orleans (NOLA), LA

| Resident | | Lead (Pb) | | | Iron (Fe) | | | Manganese (Mn) | | | Filter Life (Weeks) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Unfiltered (µg/L) | Filtered (µg/L) | Avg Removal | Unfiltered (µg/L) | Filtered (µg/L) | Avg Removal | Unfiltered (µg/L) | Filtered (µg/L) | Avg Removal | |
| ELA | R1 | <0.1 - 1.8 | <0.1 - 0.2 | 90.9 | 33.9 - 1,150 | <0.1 - 17.9 | 92 | 5.6 - 280 | 0.3 - 70.6 | 77.3 | 2,3 |
| | R2 | 0.1 - 18.5 | <0.1 | 99.3 | 42.0 - 384 | <0.1 - 3.0 | 99.5 | 35.7 - 102 | 2.0 - 11.0 | 90.3 | 5 |
| | R3 | 0.1 - 2.3 | <0.1 - 0.2 | 79.7 | 62.3 - 1,230 | 0.5 - 6.7 | 98.6 | 25.1 - 376 | 1.6 - 11.3 | 82.3 | 6 |
| | R4 | <0.1 - 2.0 | <0.1 | 100 | 15.0 - 2,650 | <0.1 - 1.6 | 98.6 | 7.2 - 554 | 1.2 - 27.2 | 72.4 | 2,4,1 |
| | R5 | 0.5 - 41.8 | <0.1 - 0.1 | 98.3 | 89.4 - 1,210 | <0.1 - 6.3 | 99.5 | 58.3 - 204 | 0.7 - 23.6 | 93.3 | 5,2 |
| | R6 | 0.1 - 0.5 | <0.1 | 100 | 377.0 - 3,270 | 3.9 - 8.1 | 98.7 | 83.1 - 860 | 2.8 - 43.7 | 77.4 | 5 |
| | R7 | 10.6 - 38.6 | <0.1 - 0.2 | 99.6 | 151.7 - 699 | 1.3 - 9.9 | 98.8 | 72.4 - 139 | 2.3 - 8. 0 | 93.8 | 6 |
| | R8 | 0.2 - 86.0 | <0.1 - 0.1 | 91.3 | 161 - 19,700 | <0.1 - 171 | 99.2 | 28.7 - 917 | 0.2 - 25.2 | 96.2 | 1,3,2 |
| | R9 | <0.1 - 4.4 | 0.1 - 0.4 | - | 59.6 - 613 | 1.3 - 111. 1 | 91.9 | 136.0 - 260 | 99.4- 180.2 | 23.2 | 4 |
| | R11 | 0.1- 10.3 | <0.1 - 0.1 | 79.4 | 188 - 455 | <0.1 - 6.9 | 98.8 | 42.9 - 146 | 2.2 - 89.1 | 44.7 | 6 |
| | R12 | 0.1 - 1.8 | <0.1 | 100 | 311- 836 | <0.1 - 2.2 | 99.8 | 86.6 - 275 | 1.3 - 51.2 | 81.7 | 8 |
| | R13 | 0.1 - 12.2 | <0.1 - 0.2 | 99.7 | 159- 453 | <0.1 - 6.9 | 99.5 | 45.1 - 202 | 1.5 - 5.7 | 96.2 | 8 |
| | R14 | <0.1 - 4.2 | <0.1 - 0.1 | 99.7 | 155 - 632 | <0.1 - 8.5 | 98.9 | 22.8 - 161 | 0.8 - 2.7 | 98.1 | 4 |
| NOLA | R1 | 1.4 - 2.8 | <0.1 - 0.4 | 97.4 | <0.1 - 33.7 | <0.1 - 53.7 | - | 0.6 - 1.3 | 0.1 - 1.1 | 54.3 | 9 |
| | R2 | <0.1 - 6.4 | <0.1 | 100 | <0.1 - 1.9 | <0.1 - 29.5 | - | 0.2 - 0.8 | 0.1 - 0.4 | 74.9 | 10 |
| | R3 | 3.3 - 22.0 | <0.1 - 0.1 | 99.6 | <0.1 - 1.7 | <0.1 - 0.2 | 100 | 0.1 | 0.1 - 0.2 | - | 10 |
| | R6 | 0.6 - 2.7 | <0.1 - 0.3 | 97.5 | <0.1 - 57.3 | <0.1 - 2.5 | 96.2 | 0.3 - 0.7 | 0.2 - 0.5 | 55 | 12 |
| | R11 | 0.9 - 1.0 | <0.1 - 0.1 | 98.4 | 2.8 - 7.0 | 2.1 - 5.2 | 25.1 | 0.5 - 1.1 | 0.1 - 0.3 | 74.9 | 5 |
| | R12 | 1.5- 3.2 | <0.1 - 0.1 | 99.2 | 0.1 - 27.4 | 3.1 - 9.8 | 45.8 | 0.5 - 1.3 | 0.1 - 1.2 | 65.8 | 8 |
| | R13 | 0.1 - 1.9 | <0.1 | 94.2 | 6.6 - 56.4 | 4.7 - 5.7 | 28.6 | 0.4 - 2.3 | 0.2 - 0.7 | 45.5 | 5 |
| | R14 | 2.7 - 6.1 | <0.1 - 0.8 | 96.6 | 2.4 - 9.9 | 3.5 - 7.5 | 7.6 | 0.4 - 1.1 | 0.1 - 19.1 | - | 12 |

# Chapter 5: Conclusions and Future Work

This dissertation highlighted the multifaceted nature of the question: "How well do POU filters work and under what conditions?" Overall, the POUs have proven their ability to reduce water lead levels effectively <5 µg/L, with some exceptions mostly attributed to particulate lead. In this research, POU performance was not judged solely based on the filtration technology's (e.g., granular media, carbon block) ability to remove lead. The durability (e.g., manufacturing) of these filter units, cost effectiveness when compared to bottled water, and usability (e.g., flowrate) emerged as important concerns that will impact a consumer's decision to use the POUs.

Chapter 2

- Phase 1 – validated positive POU performance observed in previous lab and field studies, with exceptional cases of failures caused by manufacturing defects or influent water with particulate lead in size ranges that were difficult to treat.
- Phase 2 – investigated failures in pitcher filters deployed in a community experiencing elevated lead issues, reinforcing those variations in manufacturing and some particulate lead waters are difficult to treat and problematic.

Chapter 3

- Phase 1 – validated anecdotal reports of POU premature clogging caused by waters with high iron. While filters were effective at reducing both iron and lead simultaneously, iron did not normally adversely affect lead removal performance in achieving <5 µg/L Pb with few exceptions. Filter flowrates drastically decrease with increasing concentrations of iron which reduce the POUs practical capacity due to clogging
- Phase 2 – a cost analysis comparing bottled water and POU filters, revealed clogging can cause POUs to exceed the cost of store-brand bottled water in many circumstances, making them less desirable.
- Phase 3 – available field survey data on iron distributions in systems with water lead problems was used to predict percentages of homes in which problematic premature filter clogging may occur.

Chapter 4

- Phase 1 – Flushing did not reduce lead to safe levels in either the Home with Sustained Lead or the Home with the Disturbed LSL even after >8 min of flushing. The POUs had high removal percentages in the Home with the Sustained Lead, but the high concentrations of particulates supplied by the LSL caused the POUs to produce treated lead levels > 10 µg/L on several occasions. This validates recent research studies that demonstrate the difficulty in removing lead particles by POUs.
- Phase 2 – POUs in 21 homes always demonstrated good performance in removing lead to <1 µg/L and iron <171 µg/L). The POUs were not as effective in reducing manganese levels below the SMCL (50 µg/L); all filtered manganese levels were <180 µg/L. However, none of the filters in the Enterprise homes reached >50% rated capacity and they saw a 62% reduction in flowrate prior to clogging, whereas filters in New Orleans did not clog significantly. This study illuminated the disparities that residents with discolored water will face when provided POUs to reduce lead.

## PROPOSED FUTURE WORK

- These studies were conducted on POUs purchased in 2018 and early 2019. Partly based on our work the NSF/ANSI 53 lead certification threshold was lowered from 10 µg/L to 5 µg/L in December 2019. Lead certified POUs on the market now must meet this new requirement. It is possible that the design of filters has changed, or that the lower standard could reduce the extent of problems reported herein. Repeating these studies with newer filter models could determine if that was the case.
- Chapter 2 provided insight into the fact there are some types of lead that are difficult to treat by POU filters. More work is needed to determine what specific factors including particle size and surface charge, makes a water “difficult to treat.” This would require a detailed evaluation of how each deployed filter technology is affected by different mechanisms of lead removal.
- Because new EPA regulations and industry best practice policies advise distribution of POUs to consumers, large utilities might benefit from field testing the effectiveness of a particular brand of POU in their water under practically relevant circumstances to determine which POU would be best for them. Results can also help manage consumer expectations regarding acceptable performance.
- Consumers are advised to not use filters for hot water, but they do anyway either by accident or because they are not aware of the recommendations. Ramifications of using hot water for lead removal performance should be investigated to put the practical importance of this issue in perspective. For instance, if hot water flows through the filter for 1 second, should the filter be thrown out? Or are there only insignificant or modest issues affecting performance in terms of lead removal or clogging?