Understanding Practical Limitations of Lead Certified Point of Use (POU) Filters

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ABSTRACT

There has been a recent increase in the adoption of point-of-use (POU) household water filters as an alternative to untreated tap water or bottled water. POU filters certified for lead removal have recently been distributed by the hundreds of thousands in communities amid water lead crises, as a temporary solution to protect consumers from elevated water lead levels. This thesis rigorously examines the efficacy of POU lead certified filters in removing lead under a wide range of conditions, and evaluates premature clogging due to iron and associated impacts on the cost analysis of using filters instead of bottled water.

In testing ten brands of POU devices against up to four different waters for lead removal, most devices consistently removed lead to below the 5 µg/L FDA bottled water standard. However, several failures were documented, including manufacturing flaws, premature clogging, and inconsistency between duplicate filters. When waters containing more difficult to treat lead particulates were synthesized, treated water often had lead concentrations greater than the 5 µg/L bottled water standard and sometimes were even over the 15 µg/L EPA action level. In some cases, less than 50% of the particulate lead was removed by the filter, thereby replicating some problems with these devices identified in the field. While POUs usually reduced water lead concentrations by at least 80%, a combination of manufacturing issues and difficult to treat waters can cause treated water to exceed expectations.

Consumers often purchase POU devices to remove particles and lead in waters that also contain high iron, prompting studies to examine the role of iron on filter performance. When we exposed two brands of pour-through POUs to waters with both high lead and iron, lead removal performance was generally not compromised, as treated water typically had lead concentrations less than 5 µg/L. One case was observed in which lead passed through a set of filters at high levels in association with iron, confirming expectations that in some waters iron could cause formation of lead particulates that are difficult to remove. High levels of iron sometimes rapidly clogged the POU filters, preventing them from reaching their rated capacity and increasing operational costs and time to filter water. Specifically, 50% (3/6) of the filters tested clogged prematurely at an iron concentration of 0.37 mg/L, 66% (4/6) at 1 mg/L and 100% (6/6) at 20 mg/L. A cost analysis for POUs vs. bottled water demonstrated that in waters with higher iron, store-brand bottled water was often the more cost-effective option, especially when iron levels were significantly higher than the EPA Secondary Maximum Contaminant Level (0.3 mg/L). The lower costs of bottled water in these situations was even more apparent if consumer time was factored into the analysis.

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GENERAL AUDIENCE ABSTRACT

There has been a recent increase in the use of household water filters as an alternative to tap water or bottled water. Filters that are certified for lead removal have recently been distributed by the hundreds of thousands in communities amid water lead crises, as a temporary solution to protect consumers from elevated water lead levels. This thesis rigorously examines the effectiveness of these filters under a wide range of conditions.

When tested against up to four different waters for lead removal, most filters consistently reduced lead to below the concentrations allowed in bottled water. In cases where the filters did not perform as expected, several filter failure modes were identified, including manufacturing flaws, filter clogging, and inconsistency between duplicate filters. In addition to these failures, when a water that contained particulate lead that was difficult to filter, as little as 50% of the lead was removed. While household filters often significantly reduce water lead concentrations, a combination of manufacturing issues and difficult to treat waters can cause poor performance.

In many cases, consumers purchase filters to remove particles or lead in waters that also contain iron, which caused us to investigate the effect of iron on filter performance. When two brands of pour-through filters were tested against waters with both lead and iron, lead removal performance was generally not compromised. One exceptional case was observed where both high levels of lead and iron passed through the filters, leading us to believe that iron in some waters could create conditions where lead is more difficult to remove. In many cases, the presence of iron caused filters to dramatically slow down or clog. Premature clogging due to iron prevented filters from reaching their rated capacity and, in doing so, significantly increased cost and filter times. A cost analysis for filters vs. bottled water demonstrated that in waters with higher iron, store-brand bottled water was often the more cost-effective option, especially in waters with higher levels of iron. The lower costs of bottled water in these situations was even more apparent if consumer time was factored into the analysis.

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INTRODUCTION

Point-of-use (POU) household filters can provide a cost-effective option for consumers to reduce lead exposure and avoid its adverse health impacts (Verhougstraete et al. 2019). In a recent critique of the Lead and Copper Rule (LCR), Mitchell (2018) recommended providing a refundable tax credit to individuals for purchasing and maintaining a POU device to protect themselves from lead exposure. In addition to lead removal, many consumers voluntarily purchase POUs for their households to remove other contaminants as well as taste, odor, and iron (WCP, 2007; Water Tech Online, 2015). There is also a growing number of consumers that traditionally use bottled water, who are switching to POUs as they are perceived to be more environmentally friendly (Water Tech Online, 2015).

In recent water emergencies, POUs have been distributed to affected communities by the hundreds of thousands (Washington Post, 2004; Bosscher et al.,2019; WQP, 2019; Chicago Tribune, 2019). These POU filters are certified to NSF/ANSI 53 for removal of contaminants with possible health impacts and NSF/ANSI 42 for removal of secondary contaminants (NSF, 2020). In these cases, POUs provide temporary protection to consumers as they wait for longer-term solutions such as replacing lead-bearing pipes and optimizing corrosion control.

During the 2015 water crisis in Flint, MI, after some concerns were expressed about filter performance under high water lead conditions, the U.S. EPA tested hundreds of influent and filtered samples (Bosscher et al.,2019). The treated water lead was always low (< 3 ppb), indicating that POUs perform well even with influent lead concentrations of up to 4,080 µg/L (Bosscher et al.,2019). However, when similar concerns were assessed in other communities such as Newark, NJ and University Park, IL, performance was not uniformly excellent, as treated water occasionally had over 15 ppb lead causing widespread distrust and switching to bottle water (NPR, 2019).

In addition, we have received numerous reports of slow or clogged filters in homes of communities with elevated iron in their water, causing consumers to replace their filter cartridges much more frequently than instructed. It is important to note that iron and lead can sometimes co-occur in tap water (Pieper *et al*., 2017; Masters and Edwards, 2015). This co-occurrence and the anecdotal reports of filters clogging when iron is present, caused us to re-evaluate the cost-effectiveness of POUs compared to other alternatives such as bottled water, if high levels of iron are present.

The experiments described herein examined potential limitations of POU lead filters in terms of performance and cost-effectiveness under a wide range of conditions that might be encountered in future deployments. The goal is to make sure consumer expectations for their performance are properly managed, and that the potential limitations of such filters are better understood.

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CHAPTER 1:

Understanding Failure Modes of NSF/ANSI 53 Point-of-use (POU) Pitcher and Faucet Filters

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Search words: POU, lead, performance, NSF 53

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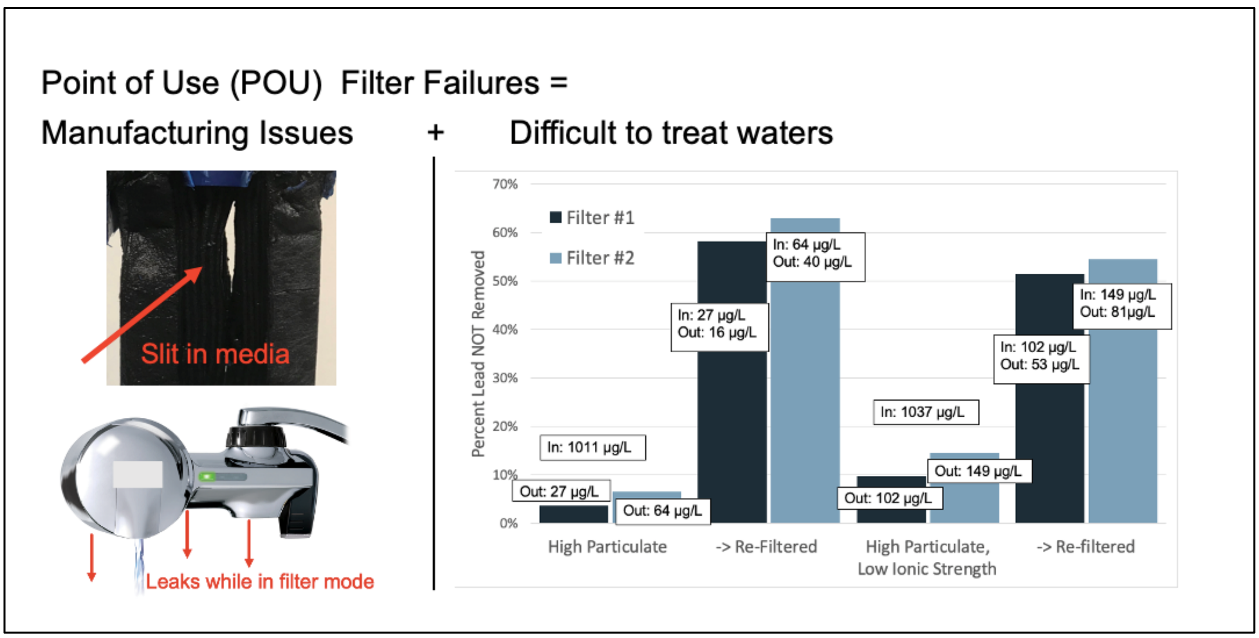
Abstract

NSF/ANSI 53 lead certified point-of-use (POU) filters were distributed to consumers experiencing elevated lead levels in Flint, MI; Newark, NJ, and University Park, IL. After questions arose about their effectiveness, we examined 10 brands of POU pitcher and faucet filters under extreme conditions (i.e., 200% of rated capacity, influent lead levels up to 1000 µg/L) that attempted to replicate field performance problems. We encountered some cases of large holes in the media, leaking devices and premature clogging. We also synthesized waters with colloidal lead that proved to be especially "difficult to treat", in which up to 50% of the influent lead could pass through some replicates of filters and not others. While the POU filters can dramatically reduce consumer lead exposure, this study highlights instances where treated water exceeded thresholds of 5, 10 and even 15 µg/L lead.



Introduction

Point-of-use filters (POUs) have been distributed during several recent lead in water crises as a means to reduce or prevent exposure (e.g., Washington, DC (2004); Flint, MI (2015-2018); University Park, IL (2019-present), and Newark, NJ (2018-present)) [1-6]. Per NSF/ANSI 53, POUs are certified to reduce lead levels below 10 µg/L when tested against challenge waters with 150 µg/L of soluble and particulate lead [7]. After their performance was question at higher water lead levels, in Flint, MI, POUs treating water up to 4080 µg/L (average of 40.3 µg/L) always produced treated water below 2.9 µg/L [5]. However, a few field tests in Newark, NJ and University Park, IL revealed some POUs that had treated water lead above 10 µg/L and a few samples over 100 µg/L. While follow-up investigations in Newark showed that 97.5% of POUs were performing as expected and producing water with <10 µg/L, a few documented failures caused citywide angst, distrust, and a switch to bottled water [8-9].

To understand why NSF/ANSI 53 lead certified filters occasionally produced effluent water with >10 µg/L lead, we conducted a comprehensive 2-year invesigation into the efficacy of pitcher and faucet POUs when exposed to waters with different types and concentrations of lead up to 1000 µg/L. The research was aimed at identifying POU filter failure modes due to manufacturing issues, operation beyond rated capacity, or presence of unusually difficult to filter colloidal lead.

Materials and Methods

Phase 1: Laboratory testing of POUs

POU Testing: In April 2018, we reviewed all available POUs listed in the Water Quality Association database of NSF/ANSI 53 lead certification. Twelve POUs that had unique cartridge technologies were identified. All but one brand (which was not available for purchase) were tested in duplicate. Our testing included 4 pitcher (A-C, L) and 7 faucet brands (D-H, J-K). Trial tests were conducted for familiarization of the filter brand technologies, including measure of initial flowrates. After trial tests, the Brand L pitcher filters were removed from further testing due to very slow flowrates (Table 1)

Prior to challenge water testing, pitcher filter cartridges were conditioned in the test water of interest without any added lead, by soaking cartridges for 15 minutes and then flushing for 10 seconds. Faucet cartridges were installed and conditioned by flushing the POUs for 5 minutes in the test water of interest without added lead. Performance testing was designed to stress the filters when pushed to the upper limits of the NSF 53 certification protocol [7]. Specifically, up to eight 3.8 L (1 gallon) batches of test water were filtered through pitcher filters in an 8 – 12 hour day, with a minimum 30-minute rest period between each batch. Faucet filters were tested on a 40-minute on and 40-minute off cycle. A total of 17 samples were taken at regular intervals up to 200% filter rated capacity. Filter flowrates, conductivity, and metal concentrations were monitored throughout. Filter failures were categorized as performance (i.e., treated effluent lead level >10 µg/L), structural (i.e., loss of filter integrity or function) and or clogging (i.e., more than a 75% reduction from the initial flowrate).

Lead Challenge Waters: A “Moderate Soluble Pb” and “Moderate Particulate Pb” concentration waters were adapted from the NSF/ANSI 53 protocol [7]. The Moderate Soluble Pb water had an average influent lead concentration of 107-149 μg/L (100% soluble) at pH 6.5 with 18-20 mg/L alkalinity as calcium carbonate ($CaCO_3$). The Moderate Particulate Pb water had an average influent of 185-190 μg/L (30-36% particulate) at pH 8.5 with 108 mg/L alkalinity as $CaCO_3$ (Table A1). The soluble and particulate lead size distribution were operationally defined by filtration through 0.1, 0.45, 1.2 or 5 μm pore size filters (Table A2). Preparation of the "Moderate Particulate Pb" water was modified from the NSF 53 pH 8.5 particulate water protocol, by shaking the over saturated lead solution instead of stirring it. This deviation created a higher fraction of particulates in the 1.2-5 μm size range that was expected to have a lower removal efficiency based on filtration theory, Table A2, Phase 1: Part 2 [7,10].

Phase 2: Examination of University Park Filter Failures

After University Park (UP) field testing revealed performance concerns in lead removal for Brand A, two of the field tested filters were shipped to our lab for follow-up testing and compared to two newly purchased filters of the same brand (Brand A pitcher filters). We then conducted a battery of tests with a range of challenge waters, attempting to replicate and understand the observed poor field performance. At the start of this testing, all filters had treated only 0-2 gallons of water and after it was completed none of the filters had exceeded 25% of their rated capacity

Particulate Lead Challenge Waters: The POUs were exposed to the Moderate Particulate Pb water and two additional particulate waters with various size distributions (Table A2: Phase 2). The "High Particulate Pb" water had a concentration of 1000 μg/L of synthesized lead phosphate particulates, with an adjusted pH of 8.5, alkalinity of 100 mg/L as $CaCO_3$, and 1 mg/L, as Phosphate, orthophosphate corrosion inhibitor. The "High Particulate Pb, Low Ionic Strength" (High Particulate Pb, LIS) water was the same water, without adding sodium bicarbonate for alkalinity but with 1 mg/L as P orthophosphate (Table A1 and A4).

POU Testing Series: The POUs were tested by treating batches of water in a sequence of 7 steps (Table 1) as follows: Step 1: 3.8 L (1 gal) of the Moderate Particulate Pb water, Step 2: 2 separate liters of High Particulate Pb water; Step 3: 1 L of the High Particulate Pb water again, but with the treated water effluent collected; Step 4: the effluent from Step 3; Step 5: 1 L of the High Particulate Pb low ionic strength water; Step 6: repeat of 5 with only the UP filters and the treated effluent was collected; and Step 7: UP filters were exposed to the effluent from Step 6.

Water Sample Analysis

Filter flowrates were measured throughout the study. Conductivity readings was measured using an Oakton CTSTestr™ 50P. Chlorine was measured using a Pocket Colorimeter II. 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.

All metal samples were digested with 2% nitric acid by volume for at least 16 hours, before analysis using a Thermo Electron iCAP-RQ inductively coupled plasma mass spectrometer (ICP-MS) per Standard Method 3125-B [11].

Results

Phase 1: Overall testing results of POUs.

POUs removed dissolved lead: Nine of the 10 POU brands reduced influent lead in water to below the NSF/ANSI 53 threshold of 10 µg/L for the Moderate Soluble Pb water. These brands always reduced lead below the bottled water standard of 5 µg/L, with all samples <3.7 µg/L and most samples (72.2%, n=288) <1 µg/L (Figure 1A and Table A5). The average lead removal across all brands was 99.87%. Brand C had effluent lead ranging from 0.2-160.4 µg/L, to be discussed in "Structural failures of POUs" (Figure 1C).

POUs struggled with particulate lead: The lead removal performance for the Moderate Particulate Pb water was more variable, as only 3 of the 7 filter brands (A, C, D) always had effluent lead levels <10 µg/L for 200% capacity. These three filters also had 99 of 100 samples below the 5 5 µg/L bottled water standard, The average effluent levels were just 0.26 µg/L [pitcher filter Brand A = , 0.6 µg/L (pitcher filter Brand C), and 1.3 µg/L (faucet filter Brand D).

The POUs that did not always perform to such a high level were Brands B, E, F, and K. Pitcher Brand B had high lead concentrations in the first batch for both duplicates (14.6 and 15.4 µg/L; Figure 1D). After this batch, all the remaining filtered water samples were <10 µg/L limit and many were below the bottled water standard (76.5%, n=34). Product literature for this brand did not include a suggestion to discard the first batch of filtered water, as is common for other brands.

The other three faucet filter brands (E, F, K) reached effluent lead levels above NSF/ANSI 53 threshold of 10 µg/L, sometimes even before reaching 100% of rated capacity (Figure 1E). Brand E had one duplicate, E-F2, that remained below 5 µg/L up to 200% capacity, while the other duplicate E-F1 exceeded 10 µg/L consistently when between 65-104% capacity with a high sample of 15.7 µg/L. 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 Moderate Particulate Pb water, with values up to 34.6 and 54.7 µg/L for the duplicates. Both duplicates filters also exceeded 10 µg/L at 50% and 88% capacity. These failures suggest that our efforts to make particulate lead sizes that were more difficult to treat when compared to NSF testing may have been successful, because lead levels must remain below 10 µg/L for certification when exposed to the NSF 53 version of this water.

Structural Failures with POUs: Three brands had what we termed "structural failures" following the trial experiments. Both duplicates of Brand L required 200+ minutes to filter 3.8 L, which to our mind meant that the POUs were clogged when purchased. Brands G and H (both duplicates) leaked from multiple points when attached to the faucet (Figure A2) during the trial phase. Because of these experiences Brand L was not tested, and Brands G and H were only tested for the Moderate Soluble water after the replacement of the filter units.

When filtering the Moderate Soluble water, two brands (C and J) experienced structural failures associated with filtering times. Brand J had an extremely low flow rate of 0.57 liters/minute (LPM), which was less than half the average flowrate in this study (1.27 LPM). As this flowrate was a 30% reduction from its initial flowrate, we discontinued testing of this POU due to premature clogging. The flowrate and resulting efficacy of Brand C deviated dramatically between duplicates (Figure 1C). C-P1 had a decreasing flowrate (e.g., initial flowrate reduced from 189.3 to 47.3 mL/minute), resulting in the filter clogging at 81% rated capacity. Despite clogging, C-P1 had effluent lead levels below 1.5 μg/L (i.e., 98.9-100% reduction with an average influent lead of 142 μg/L). In contrast, the flowrate of C-P2 increased with time, to the point where it filtered one 3.8 L batch of water in just 7 minutes (versus 20 minutes typical for this brand) and it only removed 5-48% of the lead. For example, the first batch of treated water lead was 85 μg/L, and it kept rising to 133.4 μg/L at 100% capacity. At the end of the experiment, we forensically dissected both filters, and found a large hole in the wall of the C-P2 cartridge (Figure A3). Consistent with our discovery, online consumer reviews of this brand sometimes report very fast flowrates along with poor removal of tastes and odors. On this basis our results do not appear to be an isolated incident.

Phase 2: Examination of University Park Filter Underperformance

The Brand A pitcher filters always demonstrated very good lead removal throughout the Phase 1 testing. For instance, Brand A always had effluent levels below 0.43 μg/L (P1) and 2.67 μg/L (P2) even when treating the Moderate Particulate Pb water. Compiling all Brand A data from the Moderate Soluble Pb and Moderate Particulate Pb from Phase 1, revealed that 60% (39/64) of the filtered samples were below our minimum reporting level of 0.1 μg/L. We were therefore surprised when a few samples field tested for Brand A in University Park, IL, had treated water lead as high as 100 ppb, even as the same filters were completely removing soluble anions and cations such as Na_+, Ca^{+2} and Cl^-. This prompted a sequence of tests on duplicate sets of Brand A filters field tested at University Park and another set of duplicate filters previously purchased by Virginia Tech.

All filters removed moderate levels of particulate lead: When exposed to our Moderate Particulate water, step 1, (179.4 μg/L) all four Brand A POUs (2 UP and 2 VT) performed as they had in Phase 1. Specifically, all treated water lead levels were <1 μg/L, which proved that the filters were not inherently defective.

*UP filters struggle to remove High Particulate Pb***:** When the newly developed High Particulate Pb (1011 μg/L) challenge water was filtered, the VT duplicate filters performed as expected, while both UP filters exceeded the EPA Action Level of 15 μg/L. UP1 and UP2 had average effluent lead concentrations of 37.2 and 65.7 μg/L, step 2 and 3 combined, which was roughly 6 – 19.3 times higher than the average 3.4 and 6.2 μg/L from the VT filters.

These High Particulate Pb treated waters, were then re-filtered by each POU, to help understand if the particles that were escaping treatment, were somehow especially difficult to remove. After the first pass UP1 had effluent lead of 26.6 μg/L, and when that water was passed through the filter again the treated water had 15.5 μg/L. UP2 had 63.9 μg/L in the first pass treated water, and 40.3 μg/L after the water was treated again. Thus, the removal efficiency decreased from 93.5-96.4% on pass one, down to 36.9-41.7% on pass two.

A similar decrease in performance was also observed for the VT filters. Specifically, when the first pass effluent of 5.3 or 5.8 μg/L, was retreated by passing it through the filter again, the effluent lead was 1.6 μg/L. The removal efficiency of 99.4-99.7% in the first pass, was reduced to 69.8-72.4% in the second pass.

All POUs struggled to remove High Particulate Pb, Low Ionic Strength: Particle removal efficiencies tend to be lower in low ionic strength water, if there is electrostatic repulsion between particles and the filter media. Effluent lead levels were higher than 15 μg/L for all 4 POUs when exposed to the High Particulate Pb, LIS (1037 μg/L) water, which was predicted to be more challenging than the High Particulate Pb water. The UP filters had effluent lead levels of 123 and 181 µg/L (81-87% removal). This result was in the range of the worst performance encountered in the University Park field testing, in which a water with an influent concentration of 772 µg/L lead had an effluent of 122 µg/L lead (84% removal). The same water filtered by VT POUs had 19 and 29 µg/L effluent lead (97.0-98.0% removal). Thus, the field-tested (UP) version of Brand A, consistently had effluent lead 4.2-9.5 times higher than the same filters purchased at VT for the High Particulate Pb, LIS water.

Re-testing the High Particulate Pb low ionic strength water to confirm the result, the effluent levels were 102 and 148 µg/L (85.5-90.2% removal). When those effluent waters re-treated, UP1 had influent lead of 102 µg/L and effluent lead of 53 µg/L (48.4% removal). For UP2, the influent lead was 148 µg/L and effluent lead was 81 µg/L (45.4% removal). These removal percentages were much less than the 85.5% and 90.2% removal observed in the first pass treatment, which again suggests that a fraction of the lead particulates could not be removed even by filtering the water twice.

Discussion

This study provided some insight to relatively rare problems encountered with POU filter underperformance. Testing of the filters with modified NSF challenge waters up to 100% of rated capacity rarely revealed problems with lead removal performance. The problems were due to leaks in the filter housing, a large hole identified in one filter media and premature clogging. This reflects some inconsistencies in manufacturing and quality control issues, that could go undetected in routine NSF/ANSI certification testing on two devices that are provided by the manufacturer. When we inquired about these problems with manufacturers, not revealing our identity, the customer service representatives offered to replace the filters or provide a refund.

The Phase 2 study was especially interesting, as it illustrated that replicate filters of the same brand purchased in different places at different times, sometimes did not show any problems for the easier to treat waters such as those used for certification or in Phase 1 of our research. But when encountering more difficult to treat waters, deviations amongst duplicates become apparent with relatively high levels of lead in treated water.

There are widespread concerns about potential dangers to consumers if they go beyond the rated capacity of POUs. When treating arsenic, allowing filters to go beyond capacity can have serious health implications because previously removed arsenic can be "re-released" to treated water at very high levels due to a chromatographic effect [12]. No such problems were observed for lead. While performance did deteriorate beyond rated capacity as expected, a high percentage lead removal (> 71%) was maintained. Likewise, treating batches of water more frequently than recommended by manufacturers, did not markedly reduce lead removal performance.

This work did confirm beliefs that the POUs sometimes fail to remove certain types of particulate lead [13]. In this work we created challenge waters in the laboratory with virtually 100% particulate lead for which lead removal could be lower than 50%. It is hypothesized that the poorly removed particles had diameters approaching the 1 µm size minimum removal efficiency according to rapid filtration trajectory analysis theory, and/or high levels of electrostatic repulsion between the filter media and suspended particulates. [11,14]

Overall, while POU filters provide an important consumer protection in the event of water lead contamination events, they occasionally have issues that can cause effluent lead to exceed thresholds of 5, 10, 15 and even 100 μg/L in treated water.

Table 1: Study Methods

Phase 1: Laboratory Testing of POUs				
Order	Water Condition	Procedure	Brands Tested	Brands removed following test
1	Tap Water	Trials	11 Brands (A-L)	Brand L
2	Moderate Soluble Pb	Tested up to 200% capacity	10 Brands (A-K)	Brand G, H, J
3	Moderate Particulate Pb	Tested up to 200% capacity	7 Brands (A- F, K)	-
Phase 2: Examination of University Park Filter Failures				
Steps	Water Condition	Volume Filtered	Effluent sampling	Filters Tested
1	Moderate Particulate Pb	3.78 L	250 mL composite	UP and VT
2	High Particulate Pb	Two 1L batches	250 mL composite each batch	UP and VT
3	High Particulate Pb	1 L	10 mL composite	UP and VT
4	High Particulate Pb - Re-Filtered	1L batch collected from step 3	1 L sample	UP and VT
5	High Particulate Pb, LIS	1 L	1 L sample	UP and VT
6	High Particulate Pb, LIS	1 L	10 mL composite	UP
7	High Particulate Pb, LIS Re-Filtered	1L batch collected from Step 6	1 L sample	UP

VT: Virginia Tech
UP: University Park

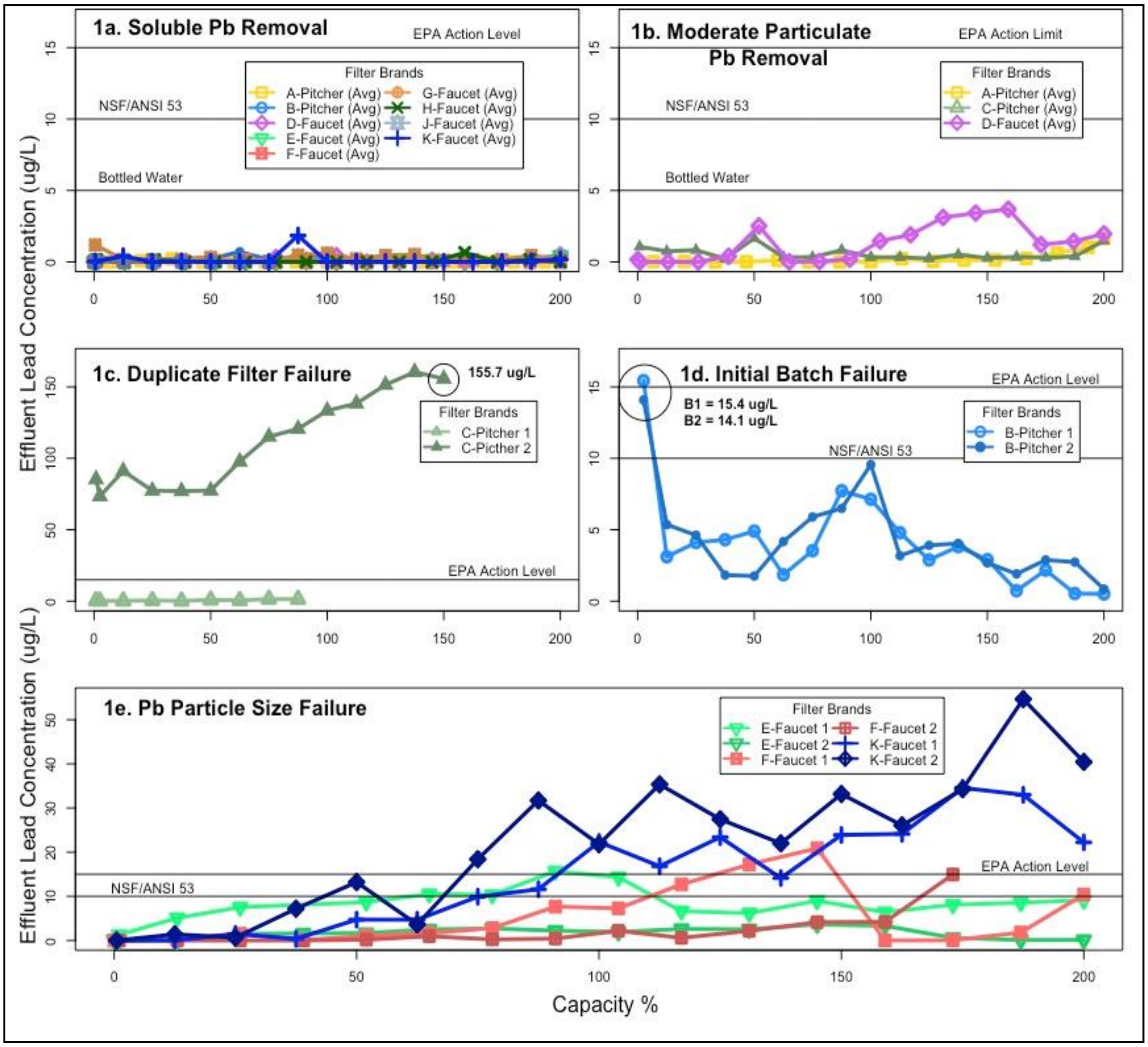


Figure 1: Effluent Lead Concentration versus Filter Capacity. **(A)** Average effluent lead levels of 9 brands for soluble lead challenge. (**B)** Average lead levels of 3 brands for particulate lead challenge. (**C)** Brand C pitcher filter failure for soluble lead, for both duplicates. (**D**) Elevated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

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CHAPTER 2:

Impact of Iron on Pitcher-Style POU Lead Removal Performance

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Abstract
Point-of-use (POU) pitcher filters are increasingly relied on to protect consumers from elevated lead in water. Anecdotal reports of premature failure due to clogging of these filters in areas with high iron raised concerns about the efficacy of these devices. To evaluate the impact of high iron waters on 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 filter failure occurred. With few exceptions, the presence of iron did not adversely affect levels of lead in the treated water. However, iron did cause premature clogging failure, which had implications for treatment costs, especially when iron was significantly above the Environmental Protection Agency (EPA) Secondary Maximum Contaminant Level (SMCL) of 0.3 mg/L. Specifically, at levels near the SMCL, 3 out of 6 POUs tested (50%) clogged prematurely; however, POUs were still more affordable than store brand bottled water in the majority of cases. When influent iron levels exceeded the SMCL, 66% (4/6) clogged prematurely when influent iron was 1.0 mg/L and 100% (6/6) clogged prematurely when influent iron was 20 mg/L. After considering the role of high levels of influent iron, bottled water often became more cost-effective than POU filters, especially if consumer convenience and time were valued.

1. Introduction

Point-of-use (POU) household water filters have the potential to provide consumers 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 (WCP, 2007; Water Tech Online, 2015). In addition, about 6% of bottled water consumers switched to a filtration method between 2011 and 2015 due to environmental concerns regarding plastics disposal (Water Tech Online, 2015). Standards for filter performance testing and certification are developed by the NSF International/American National Standards Institute (NSF/ANSI). The removal of lead (Pb) and iron (Fe) are evaluated to assess compliance with the NSF/ANSI 53, and NSF/ANSI 42 standards, respectively (NSF, 2020).

Recently, widespread water lead contamination incidents have resulted in public distribution of lead certified POU faucet and pitcher filters to protect consumers from lead exposure (Washington Post, 2004; Bosscher et al., 2019; WQP, 2019; Chicago Tribune, 2019). Following the distribution of filters during the 2015 Flint water crisis, public concern was expressed regarding the efficacy of POU filters. The U.S Environmental Protection Agency (EPA) then conducted a study in which it was concluded that POU filters successfully reduced water lead concentrations to below 3 µg/L, even with influent concentrations of up to 4,080 µg/L Pb (Bosscher et al., 2019).

Similar concerns regarding filter performance arose in Newark, NJ, where lead certified pitcher and faucet filters had been distributed to protect residents from lead exposure (CDM Smith Inc. and City of Newark Department of Water and Sewer Utilities, 2019). Out of three filters that were being monitored, two failed to reduce lead concentrations to below 10 µg/L. This result prompted a broader investigation where it was concluded that 97.5% (193/198) of the filters tested were successfully reducing lead concentrations to below 10 µg/L, suggesting that the previously observed failures were real but relatively rare.

A third case of concerns regarding filter performance arose when two of four pitcher filters that were field tested failed to reduce lead concentrations to below 10 µg/L in University Park, IL (Purchase et al., 2020). These failures prompted comprehensive laboratory testing where it was concluded that a combination of manufacturing flaws and difficult to treat waters resulted in the filter failures. Specifically, inherent flaws in the batch of filters from University Park coupled with a more difficult to treat, low-ionic strength water synthesized in the laboratory, recreated failures during laboratory testing that resembled those observed in field testing.

While existing literature suggests that POUs can often provide effective water treatment, some issues have been identified where lead levels in filtered water exceeded the NSF threshold of 10 µg/L Pb when testing protocols differed from those used in NSF/ANSI 53 (Deshommes et al., 2010, Purchase et al., 2020). A critical review of existing literature regarding POU effectiveness concluded that while most filters that are on the market have gone through testing and certification, there is a need for research to establish the practical efficacy in use (Brown et al., 2017).

In addition to addressing concerns regarding lead removal performance, it is also important to evaluate how other contaminants might impact overall POU performance. Because iron and lead can co-occur in particulates of various sizes and characteristics, it is expected that poor iron and lead removal would sometimes be related (Pieper *et al*., 2017; Masters and Edwards, 2015). In addition, anecdotal reports of filter clogging in waters with high iron suggests POU performance could be significantly impacted by additional contaminants such as iron. Current certification performance testing for lead removal does not require testing in the presence of iron (NSF, 2020).

This investigation evaluated complications to filter performance if iron and lead co-occur in drinking water, including hindered lead removal and premature clogging. Three phases of research included 1) laboratory testing of performance (lead removal efficiency and clogging) in three pitcher-style POU devices in the presence of iron, 2) using a cost-benefit analysis to examine the extending impacts of iron clogging on the relative costs of POU filters versus bottled water under various scenarios, and 3) extending these concepts to field data from citizen science water monitoring campaigns to estimate the scope of the concern about clogging.

2. Methods

Phase 1A. Laboratory Pitcher POU Testing

We identified four NSF/ANSI 53 lead certified pitcher POUs via the 'Find WQA-Certified Water Treatment Products' database published by the Water Quality Association in April 2018. Three (Brand A, B and C) of these pitcher filters were evaluated, as one brand was eliminated prior to testing due to low initial flowrates (Purchase et al., 2020). The three POUs had rated capacities of 15, 40, or 120-gallons, respectively. POUs were tested in duplicate to 100% of their rated capacity or until failure due to clogging occurred, as defined according to the NSF/ANSI 53 criteria as the time at which a 75% reduction of the initial flowrate was achieved. The time to filter each gallon of water was measured using a stopwatch and used to determine the flowrate through each device. The initial flowrate was considered the fastest recorded from the first three gallons filtered by each device tested.

Five water conditions (three iron and two lead-iron combination waters) were tested with each filter (Table 1). A standard base water was used for all of the challenge waters which consisted of 50 gallons of DI water, 8.45 mg/L magnesium sulfate, 20.1 mg/L calcium chloride, and 33.3 mg/L sodium bicarbonate. Iron and lead additions were made, as specified in the following sections. 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.

Table 1: Particulate iron and lead/iron water conditions (average ± standard deviation)

Water Condition	Total Pb (µg/L)	Total Particulate Lead (%)	Total Fe (mg/L)	Total Particulate Iron (%)
Moderate iron	–	–	0.37 ± 0.16	63.2 ± 37.0
High iron	–	–	0.99 ± 0.31	72.8 ± 34.1
Very high iron	–	–	19.70 ± 0.50	91.9 ± 4.9
Soluble combo	220.9 ± 16.5	1.7 ± 1.9	0.31 ± 0.02	2.2 ± 3.1
Particulate combo*	207.6 ± 23.0	97.1 ± 0.8	0.32 ± 0.03	89.1 ± 7.5

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

Particulate Iron Waters: To investigate the impact of particulate iron on filter clogging, all three POU brands were exposed to three waters with varying concentrations of particulate iron: (1) "moderate iron" with 0.37 mg/L Fe, (2) "high iron" with 1.0 mg/L Fe, and (3) "very high iron" with 20 mg/L Fe (Table 1). 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. At the final pH of 6.5 and alkalinity of 17 mg/L (Table B-1), the percentage of particulate iron in these waters ranged from 63-92% (Table 1)).

Lead and Iron Combination Waters: To investigate the impact that iron has on lead removal, brands A and C were exposed to two waters with both lead and iron. (1) The "Soluble combo" water contained 220 µg/L Pb and 0.31 mg/L Fe (Table 1), which was designed to have virtually 100% soluble lead and soluble iron at pH 4.9 and alkalinity of 11.2 mg/L as $CaCO_3$ (Table B-1). While this pH is not common in municipal systems, it has been documented in homes supplied by private wells (Pieper et al., 2015). 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.

(2) The "Particulate combo" water had 210 µg/L Pb and 0.32 mg/L Fe (Table 1) at pH 6.5 and alkalinity of 21.3 mg/L as $CaCO_3$ (Table B-1), which was designed to maximize the percentage of particulate lead and iron. Adding 2.31 mg/L orthophosphate as phosphorous (P), achieved less than 4% soluble lead even at pH 6.5 due to precipitation. The iron was added as before, and then the pH was raised to 7 using NaOH to precipitate the iron. After the lead and orthophosphate were added, the pH was re-adjusted to 6.5.

Brands A and C were selected for this phase of testing as our prior research showed that all three POU brands performed satisfactorily (Purchase et al., 2020), and Brands A and C have the smallest and largest capacity ratings. Brand A was evaluated in duplicate, while brand C was evaluated in triplicate due to concerns that arose around the time that this testing was performed regarding the high performance variability of this particular brand (Purchase et al., 2020).

POU Conditioning: Each filter cartridge was soaked for 15 minutes and rinsed for 10 seconds using an iron and lead-free water of the same pH and alkalinity as the synthetic water to be tested. The synthetic water was then filtered through each filter one gallon at a time until the filter met capacity or failed due to clogging. Depending on a filter's flowrate, 1 to 12 gallons of water were filtered each day.

Water Sampling: Effluent samples were taken at approximately equal increments of percent capacity, but the number of samples varied slightly based on brand and water condition. For the three iron waters, 8 samples were collected for brand A, and 9 for brands B and C. This sampling scheme was followed unless filters failed due to clogging, at which point testing was terminated. For the combination waters, 15 samples were taken for each brand A filter and 18 for each brand C filter unless failure occurred. A filter was deemed failed once a 75% reduction in flowrate was recorded for that device. In some cases, the time to filter a gallon of water was dramatically higher in the final volume filtered, surpassing the devices clogging criteria, and in such a case the result was recorded as a 77% reduction in flowrate because the exact time was so long it could not be determined in a normal business day. Testing was then terminated.

Water Analysis: To determine the percent of soluble and particulate lead and iron 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 digested with 2% nitric acid and analyzed for metals concentrations using a Thermo Electron iCAP RQ Inductively Coupled Plasma Mass Spectrometer (ICP-MS). Blanks and spikes of known concentrations were measured every 10–15 samples for QA/QC purposes.

A HACH digital titrator was used to measure alkalinity, and pH was measured using an OAKTON water meter.

Phase 1B. University Park Case Study

To further investigate the impact that the combination of manufacturing issues and difficult to treat water have when iron and lead co-occur, we synthesized the "particulate combo" water with iron, lead and phosphate, but without any added magnesium sulfate, calcium chloride, and sodium bicarbonate, resulting in a lower alkalinity of 3.4 mg/L as $CaCO_3$ after the lead and orthophosphate additions were made.

This "Low Ionic Strength - Particulate Combo" water had 210 μg/L Pb and 0.30 mg/L Fe at pH 7.5.

This testing utilized four brand A filters that had been tested in a University Park case study, where it was concluded that a combination of manufacturing variability and difficult to treat waters resulted in lead removal problems in two filters from University Park (Purchase et al., 2020). The other two filters had been purchased by Virginia Tech prior to the comprehensive laboratory testing and served as controls. Before use in this testing, the filters had only reached 35-42% of their rated capacity.

One liter of this low ionic strength – particulate combo water was passed through each filter. A 10 mL sample was then taken from each liter of filtered water and acidified before being analyzed for metals concentrations using ICP-MS.

Phase 2. Cost Analysis

An analysis was conducted to evaluate the impacts of iron clogging on the relative costs of POUs versus bottled water. We first considered only the cost of purchasing replacement cartridges or bottled water at major grocery or box 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.

The cost of POU replacement cartridges and bottled water was determined by averaging the price of replacement cartridges and store-brand water available at four grocery or box stores in Virginia in June 2020. One name brand bottled water from the same stores was also selected for comparison.

In some cases, we recognized that there was a notable time burden associated with the longer times to filter water in the presence of iron. For instance, in one case the initial gallon took 3.6 hours to filter. Using the NSF 53 failure criteria, this particular filter cartridge would fail only after it took more than 14 hours to filter a single gallon of water. Since we believed many consumers would not wait this long for a gallon of treated water, we constructed another cost analysis using a maximum tolerable filter time of two hours per gallon. In other words, if a filter took longer than two hours to filter a gallon of water, it was considered failed due to clogging for this alternative analysis.

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

To illustrate the practical implications of iron clogging, we used first-draw lead and iron datasets from prior citizen science projects in order to estimate the percentage of each community that would have had lower costs using a POU rather than a store brand bottled water. This analysis includes a comparison between Flint, MI, during the 2015 water crisis and post-crisis in 2017. We also look at a set of historical samples from the home of resident citizen scientists in Denmark, SC, to estimate the percent of time from 2009 to 2017 that they could have benefited from a POU device over bottled water. We also considered correlations between lead and iron in drinking water, to determine how the impacts would affect decisions by consumers who selected a filter if they knew they had high lead, versus those who installed it as a precautionary measure.

Correlations between lead and iron: Correlation analysis was applied to examine the association between lead and iron in drinking water sources, which is occasionally observed in field data (Masters and Edwards, 2015). Due to the non-normal distribution of lead and iron data, Spearman's rank correlation was used to evaluate the association between lead and iron for each community.

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. This analysis was done for the entire dataset, as well as for a sub-set of homes known to have elevated lead (> 15 μg/L) in their first draw water. Brand A results were not included because store-brand bottled water was always a more cost-effective option than this POU pitcher filter.

Interviews with residents experiencing varying water levels of iron and lead: To understand factors impacting POU adoption, interviews were conducted with residents from St. Joseph, Enterprise, and New Orleans, LA between Jan 2018-Dec 2019. Our preliminary investigations revealed that each town had varying water levels of iron and lead. New Orleans had low water lead and iron levels compared to the towns of St. Joseph and Enterprise. Enterprise had a maximum of 103 µg of lead per liter of water (µg/L) and 6,947 µg/L of iron (n=17 homes). St. Joseph had a maximum of 42 µg/L of lead and 84,430 µg/L of iron (n=15 homes). New Orleans had comparatively low maximum levels of lead (8 µg/L) and iron (84 µg/L) (n=18 homes). Texts were examined for reoccurring themes and to select illustrative quotes or experiences. The study protocol, informed consent procedures and data collection instruments were approved by the Louisiana State University- Health Institutional Review Board (IRB # 887 and 10069).

3. Results/Discussion

Phase 1A: Laboratory Pitcher POU Testing

Impact of Particulate Iron on POU Clogging: POUs effectively removed iron. Specifically, the POUs removed, on average, 97.2, 96.4, and 99.7% of the influent iron for the moderate, high, and very high particulate iron waters, respectively (Table 2).

There was a wide variation in the time required for different brands and duplicates of the same brand to filter the initial gallons of water when particulate iron was present (Table B-2). Brands A and C took an average of 26 and 24 minutes, respectively, whereas brand B averaged 112 minutes to filter a gallon of water. This variability ultimately impacted the flowrate threshold for clogging. For instance, using the 75% flowrate reduction criteria, the fastest brand B filter had to increase from 40 to 160 minutes before it failed, whereas the slowest brand B filter had to increase from 216 to 864 minutes to treat a gallon of water before it was considered clogged.

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

Water Condition	Average Pb Removal (%)	Average Fe Removal (%)
Moderate Iron	--	97.2 ± 5.6
High Iron	--	96.4 ± 5.1
Very High Iron	--	99.7 ± 0.5
Soluble Combo	99.4 ± 2.4	98.9 ± 2.3
Particulate Combo	98.6 ± 1.1	98.7 ± 2.2

When exposed to waters containing 0.37 - 20 mg/L particulate iron, 72% (13/18) of the POU filter cartridges tested failed to meet their rated capacity due to clogging (Figure 1). Specifically, 3 POUs (50%) exposed to moderate iron water, 4 POUs (66%) for the high iron water and 6 POUs (100%) for the very high iron water had flowrates reduced by 75% before reaching capacity. Thus increasing the particulate iron concentration resulted in premature clogging; however, even at the lowest tested iron concentration (0.37 mg/L) one of the brand B duplicates and both brand C filters had already failed to reach 100% of their rated capacity due to premature clogging. The brand B filter failed at 68% of its rated capacity, and the brand C filters failed at 38 or 62% of their rated capacity.

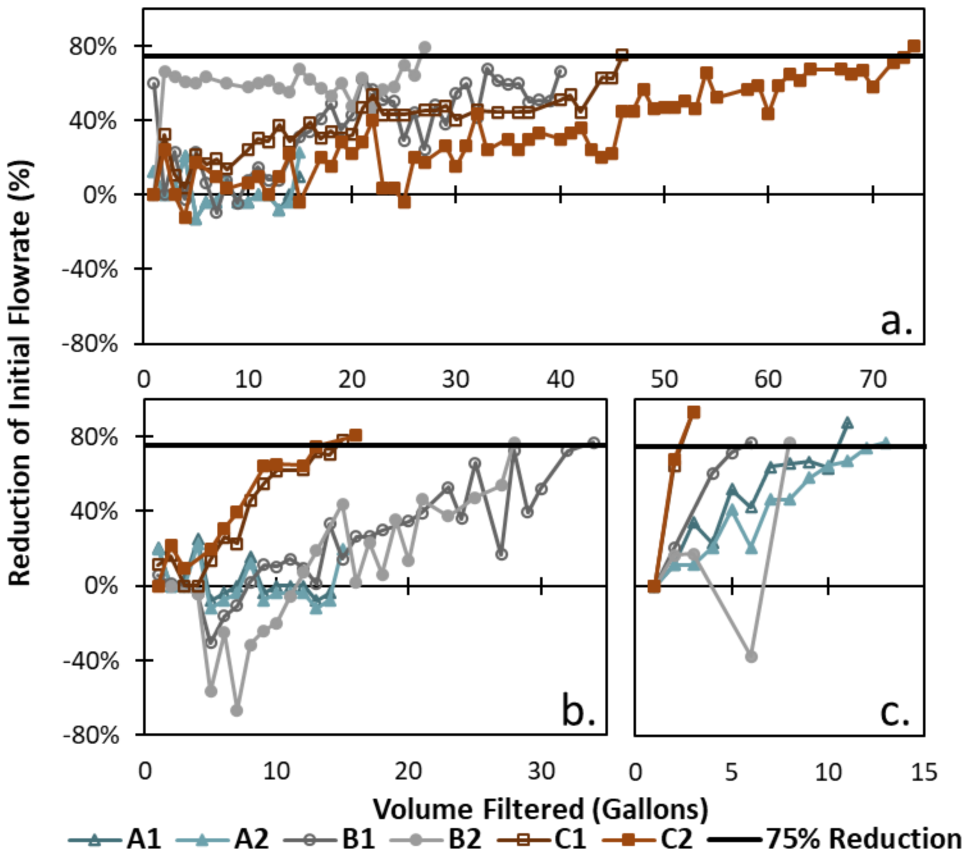

Figure 1: Reduction in flowrates for POUs different particulate iron concentrations. (a) 0.37 mg/L, (b) 1.0 mg/L, and (c) 20 mg/L.

In general, the greater a filters rated capacity, the greater the adverse impact that was observed due to particulate iron (Figure B-1). Consider that brand A, with only a 15-gallon capacity, had only a 20% reduction (15 down to 12 gallons) in expected capacity when the particulate iron concentration increased from 0 to 20 mg/L. In contrast, brand C, with a 120-gallon capacity, had a reduction in practical capacity of greater than 95% (120 down to 3 gallons). Ultimately, having an 8 times higher advertised capacity for brand C (120-gallons) versus brand A (15-gallons), practically translated to having a 4 times lower actual capacity for brand C (3-gallons, 2.5% its rated capacity) versus brand A (12-gallons, 80% its rated capacity) if very high levels of iron were present. This has a dramatic impact on the expected costs of the produced water, given that the higher capacity filter actually clogged sooner than the lower capacity filter. This is also an important factor for consumers to consider, as a higher capacity rating might influence consumers to purchase a filter brand when, in fact, a brand with a lower capacity rating may occasionally last longer.

Impact of Soluble or Particulate Iron on Lead Removal

When exposed to the soluble combo water (220 µg/L Pb and 0.31 mg/L Fe), the filters removed an average of 99% Pb and 99% Fe across all five filters when tested to 100% of their rated capacity (Table 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 2a.). The two spikes (43.7 µg/L and 13.7 µg/L) occurred at 13% (brand A), and 59% (brand C) of the filters rated capacity. Iron levels were below the SMCL, with a maximum concentration of 0.05 mg/L and an average of 0.003 mg/L Fe. All five filters reached 100% of their rated capacity.

When exposed to the particulate combo water (210 µg/L Pb and 0.32 mg/L Fe), the filters performance was relatively unaffected, still removing an average of 99% Pb and 99% Fe (Table 2). All effluent samples, except for the first gallon for each Brand C filter (10.2, 11.6, and 11.3 µg/L), had lead levels below the Bottled Water Standard of 5 µg/L, with a maximum concentration of 4.7 µg/L (Figure 2b). The maximum concentration of iron in the filtered water was 0.03 mg/L, with an average of 0.004 mg/L Fe. In the presence of particulate lead and iron, all brand C filters failed prematurely due to meeting clogging criteria and did not reach 100% of their rated capacity.

Except for one spike in lead observed during the soluble combo challenge water, the filters consistently reduced lead concentrations to below the USEPA Action Level. Thus, from the perspective of lead removal, the filters were generally not adversely affected by the presence of iron, suggesting that POU pour-through filters could provide consumers a means to decrease lead exposure when iron is present in their water.

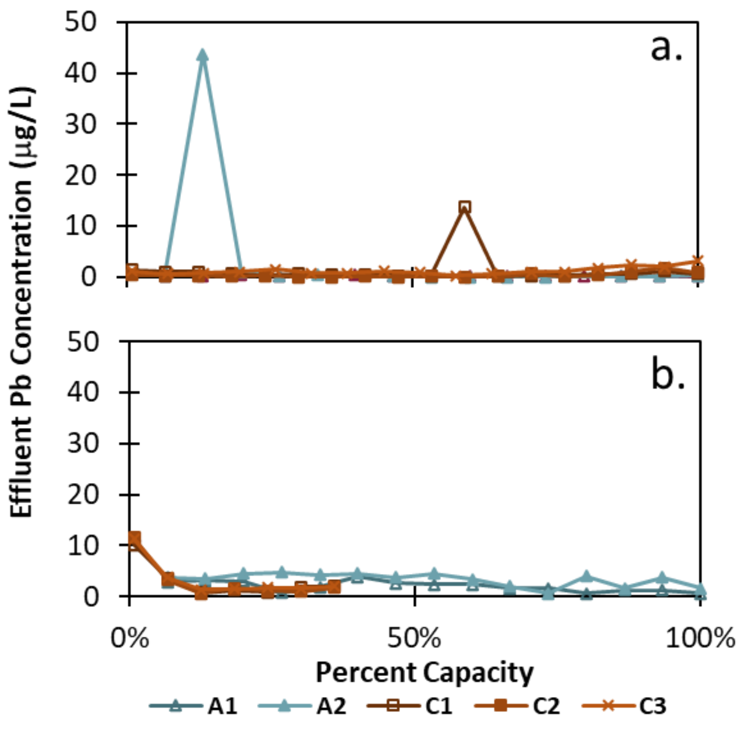

Figure 2: Effluent lead as a function of percentage manufacturers rated capacity. **(a.)** Effluent lead concentration for the soluble combo water (220 µg/L Pb and 0.31 mg/L Fe). **(b.)** Effluent lead concentration for the particulate combo water (210 µg/L Pb and 0.32 mg/L Fe).

Phase 1B: University Park Case Study

The two batches of filters used in these tests were well under their rated capacity, and their overall performance and design in removing dissolved constituents was verified by the fact that weakly exchanged Na^+ ions were removed to >99.9% in all treated samples. On this basis it is believed that lead in treated water, is in the form of a difficult to remove lead colloid or particle.

As was the case in the earlier study, we continued to observe a marked difference in filter performance between the two different batches of the same filter. When exposed to the "Low Ionic Strength - Particulate Combo" water, the two duplicates from VT removed an average of 98% of the lead and 97% of the iron, whereas the University Park filters only removed 92% of the lead and 64.6% of the lead. In addition, there was a strong linear correlation (R^2=0.99) between the amount of lead and iron that passed through the filters (Figure SI-2), suggesting that the lead particles hypothesized to be passing through the filter were attached to iron particulates. The key practical result is that the University Park filters passed 17.2-18.8 µg/L Pb (8.2-9.0%), whereas the Virginia filters allowed only 4.1-7.4 µg/L Pb (2.0-3.5%) in the treated water, which is an indication that sometimes the presence of iron could adversely affect lead removal, even if that was not the norm encountered in other challenge waters.

Phase 2: Cost Analysis

When comparing the estimated cost-per-gallon for treatments in the experiments with different levels of iron in the water, POUs were always a more cost-effective alternative than purchasing name brand bottled water when iron was not present. Yet brand A filters were always more expensive than store brand bottled water and were always somewhat less expensive than name-brand bottled water (Table 3). At particulate iron levels near the 0.3 mg/L SMCL, brands B and C were more cost-effective than both store brand and name brand bottled water, but at much higher iron levels clogging caused the name brand bottled water to became less expensive than brand C filters.

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

	Estimated Cost Per Gallon ($)				
	Bottled Water		POU Pitcher Filters		
	Store Brand	Name Brand	Brand A	Brand B	Brand C
POUs Used to Rated Capacity	0.70	1.47	0.97	0.22	0.14
Particulate Iron – (0.37 mg/L)	0.70	1.47	0.97	0.26	0.28
Particulate Iron – (1.0 mg/L)	0.70	1.47	0.97	0.28	1.08
Particulate Iron – (20 mg/L)	0.70	1.47	1.21	1.23	5.58

To better estimate the specific iron concentration at which the cost of POUs surpassed the cost of bottled water, the cost-per-gallon of each alternative was plotted as a function of iron concentration (Figure 3). Several models were applied to this data, and ultimately, a linear model proved to fit the data best. In the case of brand C, our data diverges from the model in a critical range (0.37 - 1 mg/L), where increasing iron concentrations begin to have a large impact on cost-per-gallon, but this analysis is nonetheless adequate for purposes of illustrating general trends that are relevant to decision making.

Higher levels of iron had no impact on the relative cost-advantage of brand A versus bottled water, but brand B became more expensive than store brand bottled water at around 9 mg/L Fe.

Brand C became more expensive than store brand bottled water around 1.3 mg/L Fe and more expensive than name brand bottled water above 4.5 mg/L Fe.

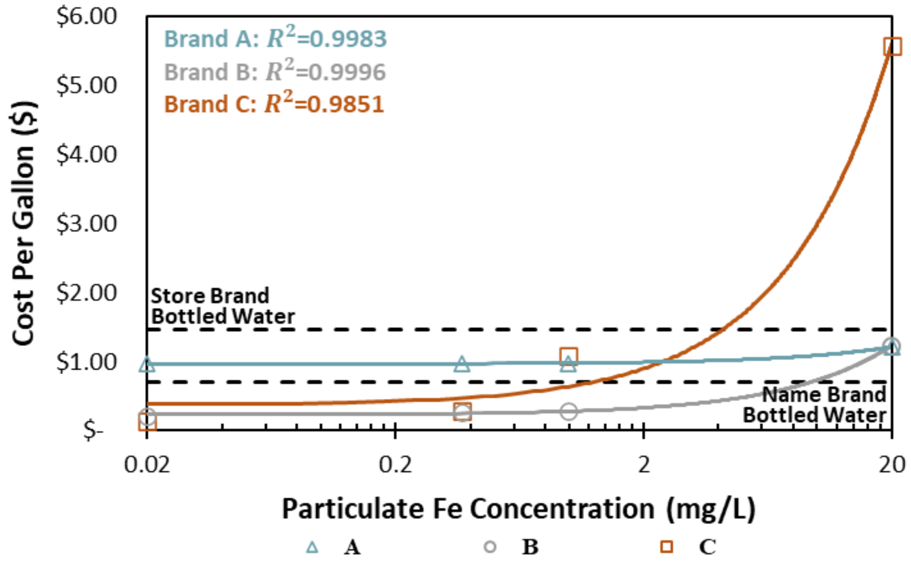

Figure 3: Break-Even Concept – Comparing POUs to Bottled Water at Varying Particulate Iron Concentrations. The calculated base cost-per-gallon for each filter when iron is not present (0 mg/L Fe) was plotted at 0.02 mg/L Fe for the purpose of this figure.

While these levels of iron would be considered extremely high for potable water, such levels of iron have relevance in some situations, including some water emergencies with interrupted corrosion control, in private well water or even some public water supplies.

Considering Alternative Failure Criteria and Consumer Preferences.

Individual consumer preference for POU filters versus bottled water, are likely affected by a wide number of specific factors beyond the simplistic cost-benefit analysis presented above, and could include many of 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) in either alternative. Moreover, both bottled water and POU devices have extra time and/or labor requirements associated with their use compared to simply using tap water, and the differential time to deal with each option will also vary. For bottled water, most of the extra time is in the purchasing and transportation of water, and the opening and disposal of the bottles. For POU pitcher filters, there is less time spent in purchasing and transporting a POU cartridge, but there is the additional task of continuously refilling your pitcher and waiting for treated water.

To illustrate the sensitivity of the cost-benefit analysis to some of these consideration, we repeated the cost-benefit analysis using an alternative failure criteria, as well as consumer perceptions of extra time and hassle to deal with one option or the other.

Alternative Failure Criteria. If a consumer set a maximum tolerable filter time of two hours as a criterion for filter cartridge replacement due to clogging, rather than waiting for filter treatment time to increase by 400% versus its initial value, affects the costs for slow filters such as brand B because the filters would be disposed of more quickly. Specifically, brand B previously became more expensive than store brand bottled water at around 9 mg/L Fe and was always a more cost-effective option than name brand bottled water. But applying a 2-hour maximum tolerable filtering time, brand B became more expensive than store brand bottled water at only 0.5 mg/L Fe, and more expensive than name brand bottled water above 3.5 mg/L Fe (Figure 4). Brand A and C were not significantly affected under this alternative criterion.

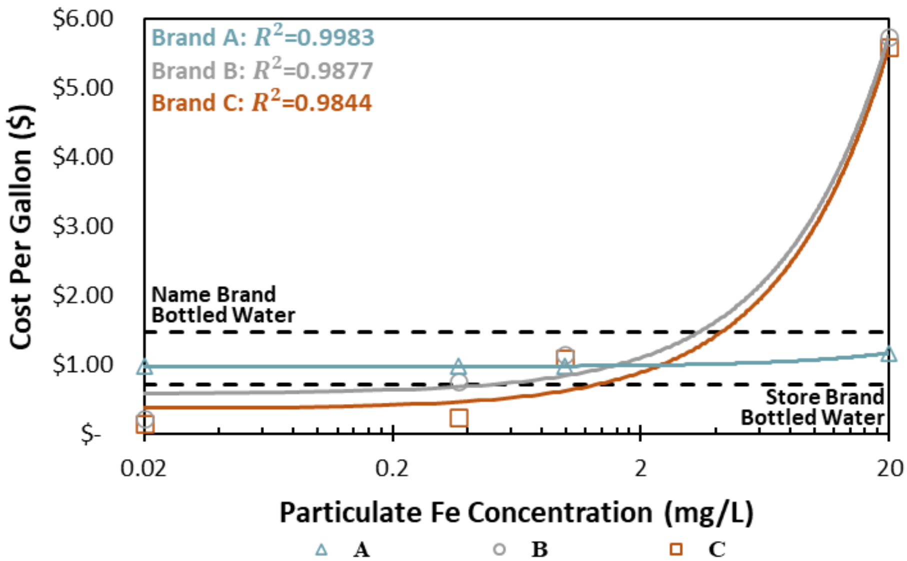

Figure 4: Alternative Cost-Benefit Analysis. The calculated base cost-per-gallon for each filter when iron is not present (0 mg/L Fe) was plotted at 0.02 mg/L Fe for the purpose of this figure.

Consumer Time Valued Due to Circumstances Favoring Bottled Water. In some cases, we have found consumers using pitcher filters, who feel it takes extra time for cooking or drinking when compared to simply purchasing and using bottled water from a nearby store during routine shopping. We decided to quantify that perception in terms of the monetary value of the consumers time. While the relative estimate of the time differential for each option would vary from consumer to consumer, we considered a case in which it takes an extra 5 minutes-per-gallon of water using a POU versus bottled water. We then considered a continuous range of hourly rates for the value of consumer time (Figure 5a).

Under these assumptions, the brand A POU filter was always more cost effective than the name brand bottled water, but store-brand bottled water would be more cost-effective if the consumer valued their time at more than $6.00 per hour. For filter brand B, the breakeven points for consumer valuation of their time were $15.00 per hour for name-brand bottled water and $6.00 per hour for store-brand bottled water. Likewise, the breakeven point was $16.00 per hour for filter C versus name-brand bottled water and $7.00 per hour for filter C versus store-brand bottled water. The point is that under this sort of decision-making criteria, bottled water may be a more cost-effective option for those who value their time at a higher rate.

Consumer Time Valued Due to Circumstances Favoring POU Devices. In other instances, a consumer's unique circumstance(s) might make use of POU devices less time-consuming than bottled water. For instance, in rural American towns far from stores, or in cases where consumers do not have personal transportation, purchasing and transporting bottled water can be a burden. As acknowledge previously, the relative estimate of the time differential for each approach would vary from consumer to consumer, but we considered a case in which the additional time it takes to use bottled water versus POU to be 10 minutes.

Under that assumptions POU devices were always less expensive than name brand bottled water. Brand B and C POUs were always more cost effective than store brand bottled water, while brand A POUs became less expensive than store brand bottled water if a consumer valued their time at greater than $2.00/hour. Clearly, POUs will become more desirable, the more difficult it is to purchase and transport bottled water.

This sensitivity analysis demonstrates how individual consumer circumstances or preferences can shift the cost analysis between POUs and bottled water. The possible presence of iron in water and its role in causing clogging of POUs, further complicates consumer decision making.

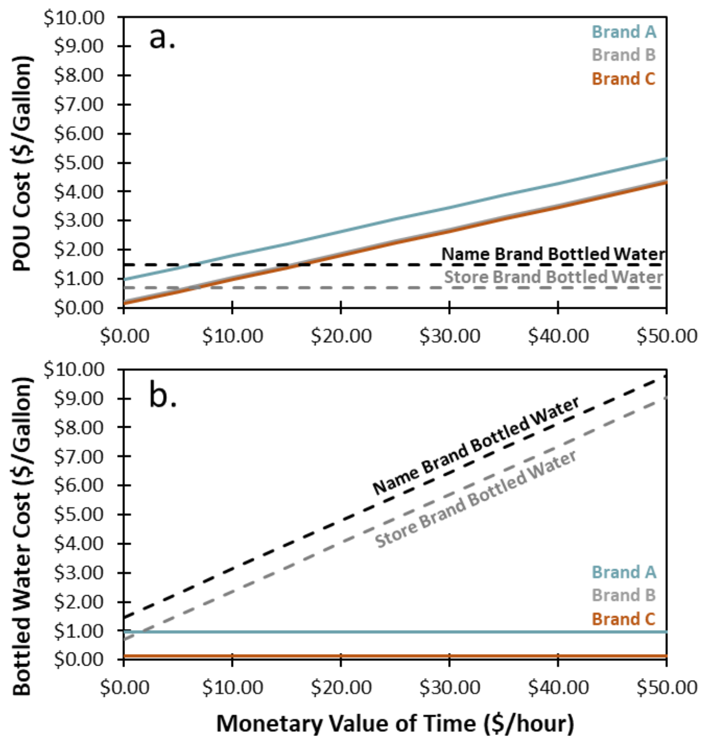

Figure 5: Consumer time valued. **(a.)** 5 minutes less time using bottled water versus POU. **(b.)** 10 minutes less time using POU than bottled water.

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

To further investigate the possible impact of iron on POU desirability, we applied our cost analysis to several communities where we collected extensive lead and iron data. In addition, we performed a correlation analysis to examine the possible association between high lead and high iron in each community.

Correlations between lead and iron: We found that the strength of the association between lead and iron varied greatly across the communities that we analyzed (Table 4). Some communities had a strong correlation between lead and iron, such as St. Joseph, LA ($\rho = 0.79$). We also observed a strong correlation between lead and iron in a home of resident citizen scientists in Denmark, SC ($\rho = 0.69$). Other communities had no or low correlations such as in VA Private Wells ($\rho = 0.11$) or consumers' homes in Berwyn/Cicero, IL ($\rho = 0.23$). If we focus on the homes that only had >15 µg/L, at which consumers have an obvious need of POU filters or bottled water, we found that the association between iron and lead sometimes increased, including in Berwyn/Cicero, IL and Flint during 2015. In other words, sometimes homes that have higher lead also are the homes that tend to have higher iron, increasing the risk of clogging if POU filters are used.

Table 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 that Could Have Benefitted from a POU			
								All Samples		>15 µg/L Pb	
		Pb (µg/L)	Fe (mg/L)	All Samples	<15 µg/L Pb	>15 µg/L Pb		NSF Criteria	Adjusted Criteria	NSF Criteria	Adjusted Criteria
Berwyn/Cicero, IL	90	11.7	0.2	0.23	--	0.76	B	100%	96%	100%	63%
					n=82	n=8	C	100%	100%	100%	100%
Denmark, SC	51	14.4	0.3	0.35	0.31	--	B	98%	94%	80%	80%
					n=46	n=5	C	96%	96%	80%	80%
Enterprise, LA	23	98.9	1.5	0.45	--	--	B	96%	57%	83%	33%
					n=6	n=17	C	87%	87%	83%	83%
Flint, MI - 2015	145	23.5	0.5	0.39	0.23	0.76	B	99%	89%	96%	65%
					n=122	n=23	C	95%	95%	78%	78%
Flint, MI - 2017	145	7.9	0.2	0.55	0.47	--	B	100%	96%	100%	56%
					n=136	n=9	C	98%	98%	78%	78%
Orleans, NY	89	17.5	0.7	0.28	--	--	B	100%	88%	100%	73%
					n=78	n=11	C	96%	96%	82%	82%
Private Wells - VA	2140	26.7	0.2	0.11	0.07	--	B	100%	94%	99%	90%
					n=1742	n=402	C	97%	97%	96%	96%
St. Joseph, LA	19	29.5	1.9	0.79	0.67	--	B	95%	89%	67%	33%
					n=16	n=3	C	89%	89%	33%	33%
Denmark, SC - Resident Citizen Scientists	30	64.7	4.2	0.69	0.59	--	B	93%	47%	83%	17%
					n=24	n=6	C	60%	60%	17%	17%

Spearman's Correlation:
"--" indicates p-value > 0.05
Light blue indicates a weak correlation
Medium blue indicates a moderate correlation
Dark blue indicates a strong correlation
White indicates trivial results (Spearman's Correlation < 0.3)

POU Benefit Analysis:
NSF Criteria: The breakeven concentrations were calculated using the NSF failure criteria (75% reduction in initial flowrate)
Adjusted Criteria: The breakeven concentrations were calculated using the adjusted failure criteria (2-hour maximum tolerable filter time)

Cost-analysis of POU filters versus store bottled water in each dataset: The percent of a community estimated to save money from a POU rather than store brand bottled water, varied depending on the amount of iron present in each community (Table 4). Communities with higher 90th percentile iron concentrations such as in St. Joseph, LA (1.9 mg/L) or Enterprise, LA (1.5

mg/L), had lower percentages of the community, yet still a majority, that are predicted to save money using a POU filter instead of store brand bottled water. In St. Joseph, we estimate that 89-95% of the community would have saved money using a brand B or C filter rather than store brand bottled water, according to our baseline cost-analysis (All Samples, NSF Failure Criteria) in comparison to other communities, such as Berwyn and Cicero, with a lower 90th percentile iron concentration (0.2 mg/L) where 100% of the community could have benefitted from a brand B or C filter according to our cost-analysis.

If the failure criteria accounting for a maximum 2-hour filter time per gallon was also applied, a decrease in the percent of each community that might have benefited from a POU over store brand bottled water occurs for brand B filters. For instance, in Enterprise, 96% of the community would have saved money from a brand B filter under our initial cost-benefit analysis. However, if we adjust this criterion to include the 2-hour constraint, only 57% of the community would have saved money from a brand B filter versus bottled water.

There is a further decrease in the percentage of a given community that would save money from a POU over store brand bottled water when considering only the portion of the homes in a community with elevated lead (>15 μg/L). When looking only at this particular subgroup, the percentage that would have a cost benefit from either POU brand in St. Joseph dropped from 89% to 33%.

These trends are also evident when we look at the comparison between Flint 2015 and Flint 2017. Our baseline cost-benefit analysis estimated that 99-100% of the community could have benefitted from a brand B filter in either year. When we adjust this analysis to include a maximum tolerable filter time, we predict that 89% of the community would have had a cost advantage versus bottled water in in 2015 when the 90th percentile iron concentration was 0.5 mg/L. In contrast, we estimate than in 2017 (post water crisis), when the 90th percentile iron concentration decreased to 0.2 mg/L, that 96% of the Flint community would have had a cost advantage from a brand B filter. But if we take this one step further and look only at the portion of the community with elevated lead levels, we estimate that only 65% of the Flint homes with elevated lead, would have had a cost advantage using brand B POU filters versus store brand bottled water.

<u>Interviews with impacted residents:</u> While all of these factors have the potential to impact the desirability and practicality of implementing POUs, the magnitude of that impact varies significantly from community to community and in individual households. For example, in New Orleans, an urban area with water conditions that make POU filter clogging negligible (low lead and iron), POUs are likely the most cost-effective solution. Whereas in St. Joseph and Enterprise, LA, which are both rural low-income towns with no public transportation, minimal internet, sparse markets, and high water iron and lead, bottled water may be the most cost-effective solution for many. While some residents tried POU filters, in the words of one resident, "*filters didn't last but a day or a week*". One Enterprise resident had to use a string filter, as well as a whole house point-of-entry (POE) charcoal filter to reduce iron levels in the water before it reached the kitchen tap, where the tap water was subsequently filtered through another charcoal POU filter. Filters continued to clog up prior to their expected lifetime expirations, thereby requiring frequent filter cartridge replacements, and back flushing of filters "*every so often*".

This intricate water treatment system amounted to a total installation cost of between $5000 and $6000. Every household is unique in terms of their barriers and needs. For example, the cost was cited as the most prohibitive factor to many low-income residents. Another problem was the lack of support for elderly and sick residents in transporting heavy loads of bottled water and ice long-distances. Isolation and lack of transportation was an ongoing issue in the rural areas of St. Joseph and Enterprise, LA. When asked what it was like having to purchase bottled water, one Enterprise resident said, *"Whenever you run out you're like, I got to go to town. I mean we're 30 minutes from anywhere so yeah it's aggravating."* Isolated areas are just as likely to have problems replacing POU filter cartridges. One Enterprise resident remarked, "*When you run out you know and you can't go get one, and it's stopped up—well, you've got to use the faucet."* Thus, the most practical and desirable solution will depend not only on the community's unique water quality characteristics, but also on other characteristics unique to each household. It is critical that households be allowed to select from a variety of different solutions that will work for each unique combination of conditions, and that each household be given enough information to understand both the short- and long-term costs and maintenance burdens for sustaining each solution.

4. Conclusions

The presence of iron only occasionally affected overall lead removal in our laboratory testing; however, premature clogging sometimes controlled the practical capacity of the filter. Almost seventy percent (16/23) of the POU filter cartridges failed to meet their rated capacity due to clogging when exposed to particulate iron in this work. Premature clogging had a major impact on the cost analysis of POUs versus bottled water in some situations. Specifically, in cases with very high iron, bottled water often became the more cost-effective option when considering only the base cost of POU filter cartridges (cost adjusted based on iron concentrations) and store brand bottled water.

POU filters can provide a safe and affordable solution for many consumers with elevated lead in water, or for consumers who are concerned about having elevated lead in water. However, waters with higher levels of iron may make bottled water a more cost-effective option in some situations. It is also important to consider that there are many other factors that might influence a particular consumers decision making regarding alternative drinking water sources. Finally, the clogging effects of iron noted herein are also likely to be observed in certain waters with high levels of other suspended particles including manganese or turbidity.

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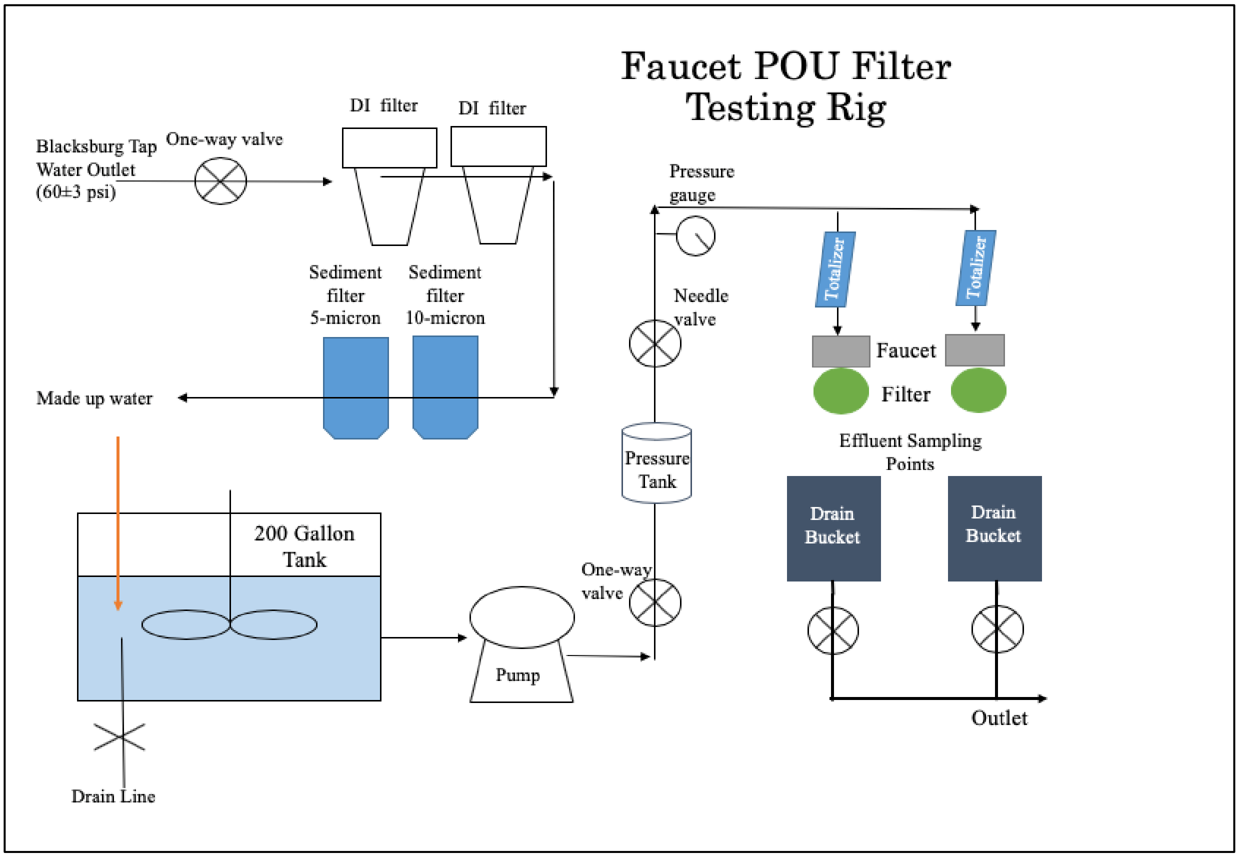
ENGINEERING SIGNIFICANCE/CONCLUSIONS

This research raised important concerns regarding the efficacy of point-of-use (POU) filters when used as a public health intervention for elevated lead in water. We have created scientifically reproducible challenge water recipes with lead particulates that are relatively difficult to remove by many POU filters compared to those present in waters used for performance certification. We also identified many circumstances in which treated water from POUs did not achieve bottled water or EPA action levels and demonstrated that in waters with high iron or turbidity that the filters could clog prematurely, dramatically decreasing their cost-effectiveness. It is clear that there will be some situations in which POUs will be less effective than bottled water, especially when consumer convenience and time spent using the devices are valued. Different homes and communities can have unique circumstances in terms of difficult to treat water lead and suspended particulates including iron, that should affect the decision to use such devices.

Further work should be done to examine the characteristics of lead particles in terms of size and surface charge, that cause them to escape removal during filtration. Such insights would be invaluable to understanding when POUs can provide a cost-effective and safe drinking water alternative.

APPENDIX A: CHAPTER 1 – SUPPLEMENTARY INFORMATION

Figure A1: Faucet Testing Rig



*For faucet filtering, a mechanical testing rig was constructed, an adaptation from the NSF/ANSI 53 protocol was constructed composed of 200-gallon batch tanks, a booster pump, pressure tank and needle valve to maintain 35-45 psi, and a Chrontrol to operate duplicate filters. This testing rig was adapted from the NSF/ANSI 53 protocol to achieve the required 50% ON/ 50% OFF cycles for a 40 min ON/Off cycle.

Table A1 – Water Chemistry table

	Moderate Soluble Pb	Moderate Particulate Pb		High Particulate Pb	High Particulate Pb, Low Ionic Strength
		NSF/ANSI 53	Virginia Tech		
Alkalinity (as CaCO3)	18.1±6.8 mg/L – Pitcher 20 ± 3.4 mg/L – Faucet	100 mg/L	109.6 ± 43 mg/L- Pitcher 107 ± 16 mg/L – Faucet	100 mg/L	-
pH	6.6± 0.1 – Pitcher 6.5± 0.03 - Faucet	8.5 ± 2.5	8.5 ± 0.03 – Pitcher 8.49 ± 0.1 – Faucet	8.5	8.3 unadjusted
Temperature	23 ± 3.5 C – Pitcher 15.1 ± 1.8 C – Faucet	20±2.5 C	21.6 ± 3.6 - Pitcher 17.2 ± 2 – Faucet	-	-
Total Chlorine	-	0.5 mg/L	0.5 ± 0.26 – Pitcher 0.62 ± 0.1 – Faucet	-	-
Orthophosphate (as P)				1 mg/L	1 mg?L
Total Lead	149.3 ±15.5 μg/L – Pitcher 107.61±38.74 μg/L - Faucet	150 μg/L	189.61 ± 92.13 μg/L – Pitcher 185.5 ± 52 μg/L – Faucet	1011 μg/L	1037 μg/L

Table A2: Particle Size distribution of all Lead Challenge Waters

Water Condition	Total Pb (μg/L)	Total Particulate Lead (%)	Particulate Size Distribution (proportion of total)				
			0.1* < Pb <0.45 μm	0.45* < Pb < 1.2 μm	1.2*< Pb <5 μm	5 μm* < Pb	Total
Phase 1, Part 1: Different Methods of Making Particles							
Moderate Particulate Pb (stirred - NSF)	219.5	48%	0.0	0.70	0.16	0.14	1
Moderate Particulate Pb (shaken - VT)	210.5	49%	0.0	0.38	0.27	0.35	1
Phase 1, Part 2: Conditions for Filtration							
Moderate Soluble Pb	149.3 μg/L – Pitcher 107.6 μg/L - Faucet	-	-	-	-	-	-
Moderate Particulate Pb	189.61 μg/L –Pitcher 185.5 μg/L – Faucet	36% - Pitcher 30% - Faucet	0.39 – Pitcher 0.14 – Faucet		0.61 – Pitcher 0.86 – Faucet		1
Phase 2: University Park Field Case Study – Influent Lead Waters							
Moderate Particulate Pb	179.4 μg/L	31.4%	0.0	0.18	0.31	0.51	1
High Particulate Pb	1011 μg/L	100%	0.0	0.045	0.038	0.917	1
High Particulate Pb, Low Ionic Strength	1037.1 μg/L	96.1%	0.096	0.396	0.153	0.357	1

**Materials of syringe filters used in study:*
0.1 μm - Polyvinylidene fluoride (PVDF) (33 mm): MilliporeSigma™ Millex™ Sterile Syringe Filters: Durapore™ PVFD Membrane (SLVV033RS)
0.45 μm – Nylon
1.2 μm - Surfactant-free Cellulose Acetate (SFCA) (28 mm): Sartorius™ Minisart™ NML Syringe Filters, Sterile (14-555-301)
5 μm – SFCA (28 mm): Sartorius™ Minisart™ NML Syringe Filters, Sterile (14-555-303)

Table A3: Steps for making Moderate Soluble Pb and Moderate Particulate Pb Waters

Moderate Soluble Lead Water	Moderate Particulate Lead Water
1. Fill Tank with DI Water 2. Mix Water 3. Add 180 Magnesium Stock 4. Add 360 mL of Calcium Stock 5. Add 360 mL of Sodium Bicarbonate 6. Record Initial pH of Water 7. Adjust pH to 6.5 using CO2 8. Record Temperature 9. Test Alkalinity 10. Add 50 mL soluble lead stock 11. Switch to circulation mixing	1. Fill Tank with 180 gallons of DI Water 2. Mix water 3. Add 960 mL Magnesium Stock 4. Add 1,965 mL Calcium Stock 5. Add 1,965 mL Bicarbonate Stock 6. Add 9 mL Bleach 6% 7. Record the Initial pH of the Water 8. Adjust the pH to 8.5 by adding 1 M NaOH 9. Record Temperature and Chlorine 10. Add 40 mL Soluble Lead Stock 11. Wait 1 minute for Lead to be mixed 12. Fill a takeout ½ gallon into 1 gal jug 13. Add 40 mL of Insoluble Lead Stock to takeout jug 14. Shake bottle vigorously (60 secs), add back into tank 15. Let water mix for an additional 10 minutes 16. Verify Alkalinity 17. Switch to circulation mixing
Magnesium Stock: Magnesium Sulfate Anhydrous– 32 g/L Calcium Stock - Calcium Chloride Dihydrate Stock – 38 g/L Bicarbonate Stock - Sodium Bicarbonate Stock – 63 g/L Soluble Lead Stock – Lead Nitrate 3.6 g/L + 2 mL of 100% Nitric Acid Insoluble Lead Stock - Lead Nitrate 1.6 g/L Take out for 50-gallon batches about ½ liter in a 1-liter bottle Circulation mixing for 50-gallon tank uses a circulation pump, for 180-gallon batch use mixer on 1 sec ON/ 10 sec OFF cycles (cycles controlled by Chrontrol)	

<u>Water Recipe Chemicals</u>

Lead Nitrate (N_2O_6Pb) – Crystalline (Fisher CAS 10099-74-8)
Sodium Bicarbonate ($NaHCO_3$) – Crystalline (Fisher CAS 144-55-8)
Magnesium Sulfate Anhydrous ($MgSO_4$) – Certified Powder (Fisher CAS 7487-88-9)
Calcium Chloride Dihydrate ($CaCl_2 \cdot 2H_2O$) – Certified ACs (Fisher CAS 10035-04-8)
Sodium Phosphate Dibasic Anhydrous (Na_2HPO_4) – Certified ACS (Fisher CAS 7558-79-4)
Sodium Hydroxide (NaOH)- Granular (Fisher CAS 1310-73-2 or CAS 497-19-8)

Table A4: Steps for making High Particulate Pb and High Particulate Pb, Low Ionic Strength waters

High Particulate Pb	High Particulate Pb, Low Ionic Strength
1. Rinse tank for to remove old particles, fill 75.7 L (20 gal) 2. Begin circulation mixing 3. Add 106 mL Magnesium Sulfate 4. Add 218 mL Calcium Chloride 5. Add 218 mL Sodium Bicarbonate 6. Adjust pH to 8.5 7. Add 9 g of Sodium Phosphate to 3.78 L (1 gal) jug of DI water. Be sure it is fully dissolved 8. Add in 0.14g Lead Nitrate into the gallon Sodium Phosphate solution 9. Shake well at least 60 sec and add in 10. Take Total and F0.45 Samples 11. Verify Alkalinity	1. Rinse tank for to remove old particles, fill 75.7 L (20 gal) 2. Begin circulation mixing 3. Add 9 g of Sodium Phosphate to 3.78 L (1 gal) jug of DI water. Be sure it is fully dissolved 4. Add in 0.14 g Lead Nitrate into the gallon of Sodium Phosphate solution 5. Shake well at least 60 sec and add in 6. Measure pH no adjustments 7. Take Total and F0.45 Samples
Magnesium Stock: Magnesium Sulfate Anhydrous– 32 g/L Calcium Stock - Calcium Chloride Dihydrate Stock – 38 g/L Bicarbonate Stock - Sodium Bicarbonate Stock – 63 g/L Sodium Phosphate Lead Nitrate All pH adjustments are done with CO_2 or NaOH Circulation mixing achieve using small tank pump – SPECS	

Table A5: Influent and Effluent lead level for Phase 1

				Moderate Soluble Pb Water		Moderate Particulate Pb Water	
Brand	Type	Capacity (Gal)	Capacity (L)	Average Influent Lead (µg/L)	Effluent Lead (µg/L)	Average Influent Lead (µg/L)	Effluent Lead (µg/L)
A	Pitcher	15	57	166.12	<0.1 - 0.43	150.14	<0.1 - 2.67
B	Pitcher	40	151	153.97	<0.1 - 0.9	147.71	0.5 - 15.4
C	Pitcher	120	454	142.69	0.2 - 160.4	208.51	0.1 - 2.6
D	Faucet	100	379	82.02	<0.1 - 0.8	220.20	<0.1 - 5.1
E	Faucet	100	379	81.43	<0.1 - 0.5	195.40	<0.1 - 15.7
F	Faucet	100	379	129.15	<0.1 - 0.3	176.14	<0.1 - 20.9
G	Faucet	200	757	99.83	<0.1 - 1.4	-	-
H	Faucet	100	379	108.98	<0.1 - 1.3	-	-
J	Faucet	200	757	83.88	<0.1 - 0.1	-	-
K	Faucet	200	757	83.49	<0.1 - 3.7	172.08	<0.1 - 54.7
L	Pitcher	40	151	-	-	-	-

Figure A2: Structural Failure Leaking Unit – Representation

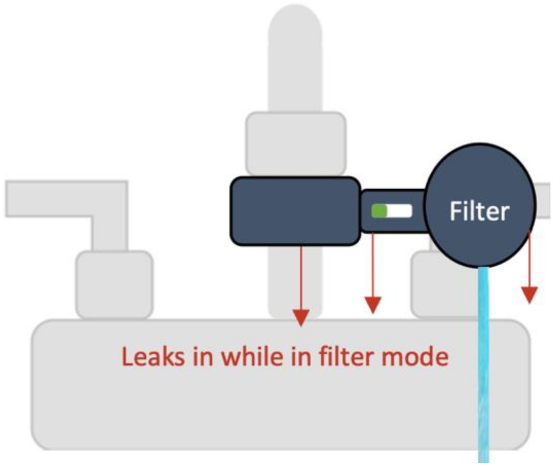


Figure A3: Slit in media found in Brand C-P2

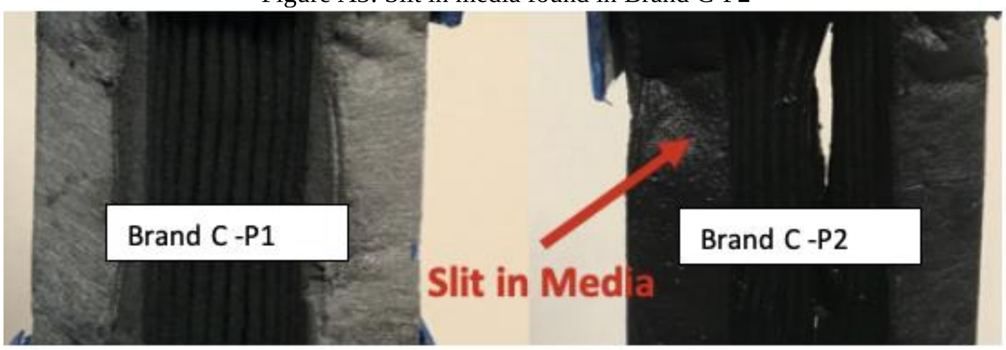


Table A6: UP and VT Filter Performance

Order		Filter	Influent (µg/L)	Effluent (µg/L)	% Removed	Filter	Influent (µg/L)	Effluent (µg/L)	% Removed
1	Moderate Particulate Pb	UP1	179.4	0.4	99.8%	VT1	179.4	0.4	99.8%
		UP2	179.4	0.4	99.8%	VT2	179.4	0.7	99.6%
2	High Particulate Pb	UP1	1011.5	42.1*	95.8%	VT1	1011.5	2.4*	99.7%
		UP2	1011.5	66.6*	93.4%	VT2	1011.5	6.4*	99.4%
3	High Particulate Pb	UP1	1011.5	26.6	97.4%	VT1	1011.5	5.3	99.5%
		UP2	1011.5	63.9	93.7%	VT2	1011.5	5.8	99.4%
4	High Particulate Pb, Re-filtered	UP1	26.6	15.5	41.7%	VT1	5.3	1.6	69.8%
		UP2	63.9	40.3	36.9%	VT2	5.8	1.6	72.4%
5	High Particulate Pb, Low Ionic Strength (LIS)	UP1	945.7	123.0	87.0%	VT1	945.7	18.6	98.0%
		UP2	945.7	180.8	80.9%	VT2	945.7	28.8	97.0%
6	High Particulate Pb, LIS	UP1	1047.1	102.4	90.2%				
		UP2	1027.2	148.7	85.5%				
7	High Particulate Pb, LIS Re-filtered	UP1	102.4	52.8	48.4%				
		UP2	148.7	81.2	45.4%				

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

APPENDIX B: CHAPTER 2 – SUPPLEMENTARY INFORMATION

Table B-1: Additional water parameters

Water Condition	pH	Alkalinity (mg/L as $CaCO_3$)	Temp. (C°)
Moderate iron	6.6 ± 0.1	18.8 ± 4.2	23.3 ± 1.7
High iron	6.6 ± 0.1	14.9 ± 2.2	25.0 ± 1.4
Very high iron	6.5 ± 0.1	19.0 ± 4.6	22.7 ± 0.5
Soluble combo	4.9 ± 0.1	11.2 ± 2.7	22.4 ± 0.9
Particulate combo*	6.5 ± 0.1	21.3 ± 1.8	21.6 ± 1.0

Table B-2: Variance in Initial Filtering Times

Brand	Minutes to Filter One Gallon			RSD (%)
	Average	Min	Max	
A (n=6)	26	23	28	8.63
B (n=6)	112	40	216	63.5
C (n=6)	24	15	31	31.1

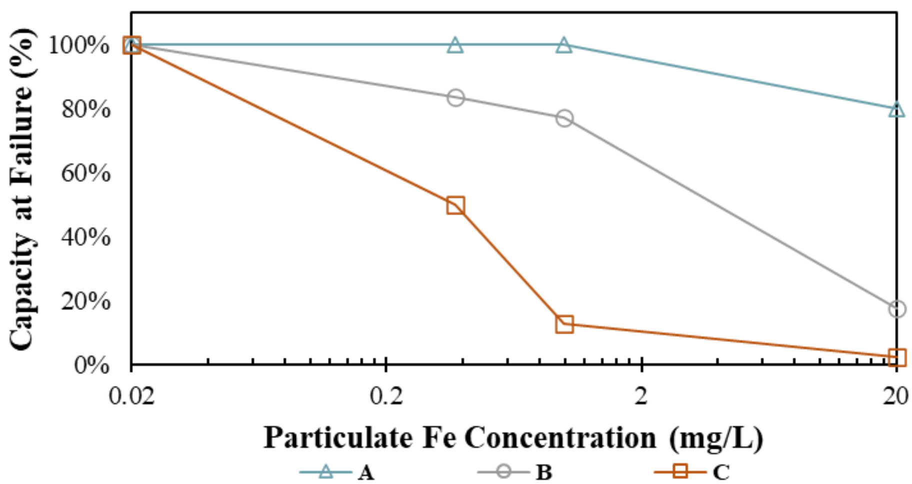


Figure B-1: Impact of particulate iron concentration on POU capacity for duplicate brand A (15-gallon capacity), brand B (40-gallon capacity), and brand C (120-gallon capacity) filters. It was assumed that filters would reach 100% capacity in the absence of iron (0 mg/L). This was illustrated by plotting 100% capacity at failure for all filter brands at 0.02 mg/L Fe for the purpose of this figure.

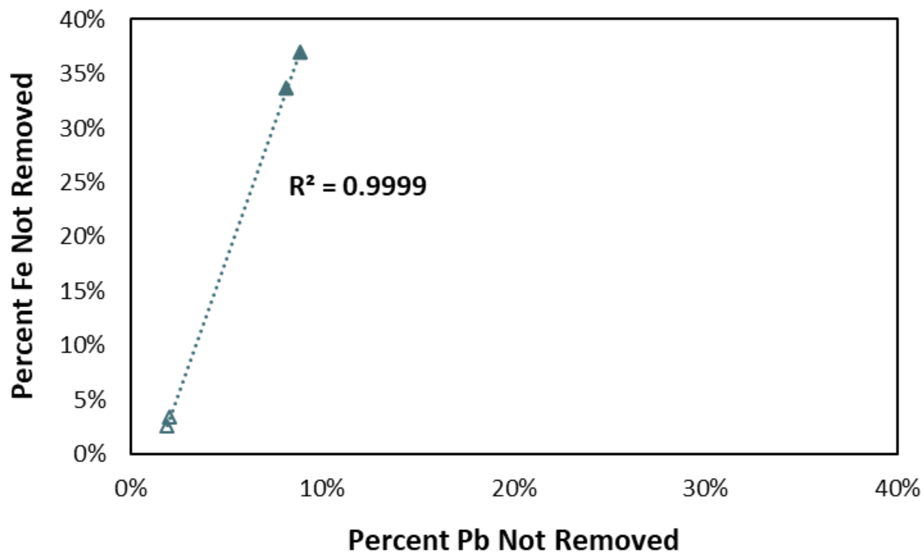


Figure B-2: Correlation between lead and iron that was not removed after filtering one liter of a difficult to treat, low alkalinity – particulate combo water (210 µg/L Pb and 0.30 mg/L Fe), through four brand A filters (15-gallon capacity). Open triangles designate the two new filters, whereas the closed triangles designate the two field-tested filters from University Park, IL.