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Influence of Permeate from Domestic Reverse Osmosis Filters on Lead Corrosion and Leaching from Plastic Pipes

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INFLUENCE OF PERMEATE FROM DOMESTIC REVERSE OSMOSIS
FILTERS ON LEAD CORROSION AND LEACHING FROM PLASTIC PIPES

by

Jyotsna Shrestha

A Thesis Submitted in
Partial Fulfillment of the
Requirements for the Degree of

Master of Science
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May 2016

ABSTRACT

INFLUENCE OF PERMEATE FROM DOMESTIC REVERSE OSMOSIS FILTERS ON LEAD CORROSION AND LEACHING FROM PLASTIC PIPES

by

Jyotsna Shrestha

The University of Wisconsin-Milwaukee, 2016
Under the Supervision of Professor Jin Li

Reverse Osmosis filters are gaining popularity nowadays, in domestic water supply system, to meet the increasing demand of pure and improved drinking water. There are various types of domestic RO filters with varying sizes, capacities, and treatment stages available. However, there exist a few concerns regarding the RO treatment system. One of the major issues in the quality and distribution of drinking water is the corrosive water that the RO system produces. Therefore, this research herein tends to focus on the corrosive effect of the permeate water on lead metal, as lead is considered a serious problematic drinking water contaminant. In addition, study of the effect of RO product water on leaching of organic carbon from common plastic plumbing materials was also conducted. Three RO filters with varying treatment stages—two-stages, five-stages and seven-stages were chosen for the tests.

The lead corrosion was evaluated using immersion corrosion test of lead coupons in water samples for a total of forty days. The two-staged filter showed the highest corrosion effect among the three filters, and the seven-staged filter showed the least. As the number of treatment stages increased, the significant decrease in pH, conductivity, hardness and alkalinity of the water samples also seemed to be less. The overall findings suggested that the impact of number of treatment stages of the filters had a substantial effect on the corrosive property of the water.

From the migration test, it was found that the PEX and PVC pipes were prone to organic carbon leaching as compared to the CPVC pipes. The two-staged filter showed the highest extraction of organic compounds in all of the three pipes, and the seven-staged filter showed the least extraction of TOC. In all the samples, including the control, the initial TOC leaching on the third day was higher than the subsequent leaching periods of six and nine days. The leaching of TOC by the RO water samples was hence successfully quantified.

To
my husband,
for his love and support.

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LIST OF ABBREVIATIONS

2,4-D	2,4-Dichlorophenoxyacetic acid
AC	Activated Carbon
CPVC	Chlorinated polyvinyl chloride
CTA	Cellulose tri-acetate
CTO	Chlorine, Taste, Odor
DI	Dissolved ion
GAC	Granular Activated Carbon
GPD	Gallons per day
GPG	Grain per gallon
GPM	Gallons per minute
ICP-MS	Inductively Coupled Plasma-Mass Spectroscopy
LCR	Lead and Copper Rule
MPY	Milli-inch per year
NSF	National Sanitation Foundation
PEX	Cross-linked Polyethylene
POU	Point-of-use
PPB	Parts per billion
PPM	Parts per million

PSI	Pound-force per square inch
PVC	Polyvinyl Chloride
RO	Reverse Osmosis
SDWA	Safe Drinking Water Act
TDS	Total Dissolved Solid
TFC	Thin Film Composite
TFM	Thin Film Material
THM	Trihalomethane
TMAFC	Tap Master Artesian Full Contact
TOC	Total Organic Carbon
USEPA	United States Environmental Protection Agency
VOC	Volatile Organic Compound

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Chapter 1

Introduction

1.1 Background

The need for safer drinking water is increasing day by day. Clean drinking water scarcity is a growing concern all over the world. 663 million or one in ten people still lack access to improved drinking water supplies.¹ Even people who have access to water supplies such as household connections, public faucets, and boreholes may not have microbiologically safe water. As a result, various solutions are implemented to purify water, the techniques getting continuously improvised by novel and more efficient researches.

To meet the growing demand for higher quality drinking water, homeowners and businesses are installing the similar technology used to process popular bottled water brands like 'Dasani' and 'Aquafina'— Reverse Osmosis Filtration. RO is considered one the finest techniques to purify water and is extensively used industrially, with recent increasing domestic use. In fact, RO is the fastest growing form of in-home water treatment in the U.S.² RO is a pressure-driven process in which a semi-permeable membrane is used to pass water, filtering out dissolved constituents. The membranes used for RO have a thick barrier layer in the polymer matrix where most separation occurs. In most cases the membrane is designed to allow only water to

pass through this thick layer while preventing the passage of contaminants such as arsenic, copper, iron, lead, chromium, fluoride, radium, cyanide, nitrates, bacteria, pesticides, PCB, and benzene. As a result, RO vastly improves water purity, color and taste.^{2,3} Especially for membrane desalination, decreasing costs and higher quality production of potable water are some of the many significant reasons why this technology continues to be a preferred water treatment option in the world.

However, with the increasing popularity there exist various issues regarding the RO treatment system. One of the major concerns in the quality of drinking water and the distribution system is the corrosive water that the RO system produces. In the drinking water industry, internal corrosion of drinking water systems has often been an issue affecting water quality, public health, and the cost of safe water provision. Through this research information about the effect on the corrosion of metal pipes (lead in this case), of the product water of the domestic RO filters that are used at homes is to be highlighted. Moreover, this research tends to shed some light on the effect of the product water in leaching of organic carbon from common plastic plumbing pipes (PVC, CPVC and PEX in this case) as the use of plastic pipes in the water distribution section is gaining immense popularity.

1.2. Objective of study

The research here is intended to find the effect of product water from domestic RO filters on lead pipe systems and organic carbon leaching from plastic pipes, and analyze the obtained results. There are many researches done regarding the product water analysis of RO desalination plants and treatment systems and their corrosion and leaching effect on various metals and plastic pipes. However, there are very limited studies on the effect of the product water from point-of-use household or undersink RO filters. As lead has always been a concern in the safety of drinking water and the distribution system, the research focuses on the corrosion effect on lead coupons. Similarly, the leaching of various chemicals and organic matter into drinking water is a rising concern because of the increasing use of plastic plumbing pipes in the water distribution system. Hence, the main objectives of this study can be listed as:

- i. To analyze the extent of corrosion effect of domestic POU/ undersink RO filters' product water in lead metal.
- ii. To conduct an immersion corrosion test with lead metal coupons, replicating the environment of the internal pipe system.
- iii. To analyze the water quality parameters of the permeate and see how they affect the results.

- iv. To investigate the effects of permeate from the RO filters on leaching of organic carbon from selective common plastic plumbing pipes, using migration test based on standard Utility Quick Test.

This thesis hereafter is organized to provide an overview of relative literature, in Chapter Two, pertaining to the general introduction and basics of RO drinking water treatment system and internal corrosion theory, and the effects of the product water on corrosion and leaching of plumbing materials based on previous studies. Chapter Three of this study provides a description of the methods and materials used during data collection and analysis. Next, the results are provided along with discussion in Chapter Four, which is finally followed by conclusion and recommendations for future studies in Chapter Five.

Chapter 2

Theory and Literature Review

2.1. Reverse Osmosis Basics

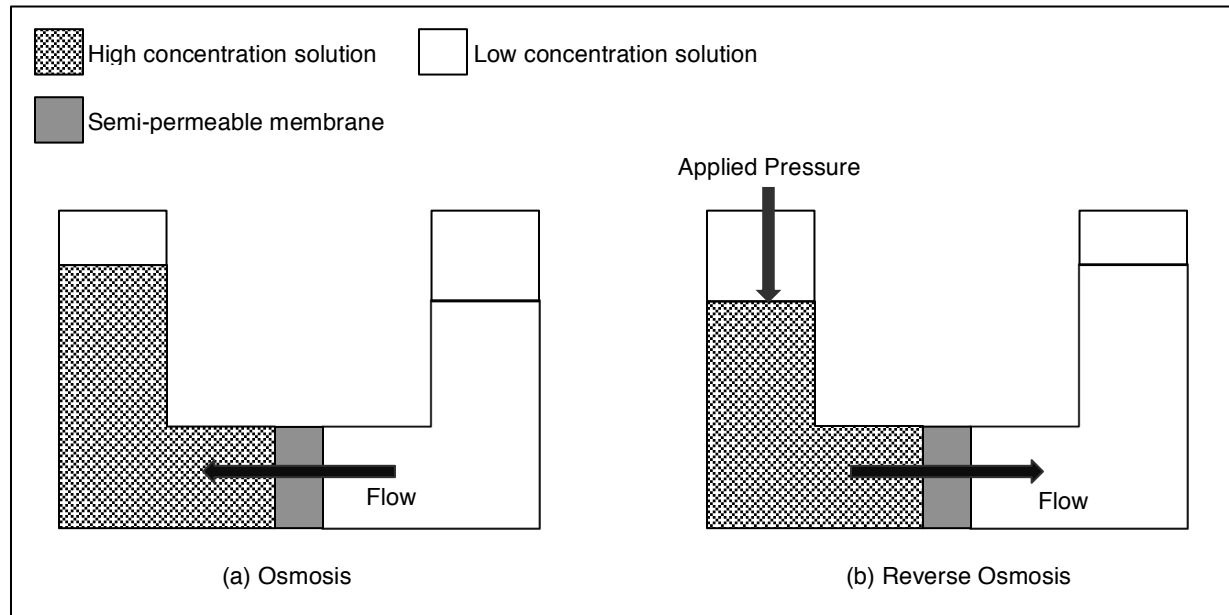


Figure 2.1. Diagram showing flow of solution in Osmosis and Reverse Osmosis phenomena.

When a semi-permeable membrane separates two solutions with different concentrations, there exists a disparity in chemical potential across the membrane. The water tends to diffuse from lower concentration (higher-potential) side to the higher concentration (lower-potential) side, until the pressure difference balances the chemical potential difference. This phenomenon shown in figure 2.1(a) is known as osmosis and the balancing pressure difference is known as osmotic pressure, which is related to

the solution's vapor pressure and temperature. If the osmotic pressure is overcome by a greater pressure gradient opposite in direction, flow occurs from the higher concentration to the lower concentration region as shown in figure 1.1(b). This phenomenon is known as reverse osmosis or hyperfiltration.⁴

2.1.1. History

After the first discovery of osmotic pressure back in 1748 by Jean-Antoine Nollet, a French physicist, the RO method was considered as a water treatment technique only in the late 1940's. Researchers began exploring this area to find a way of obtaining pure water from brackish water, as per the technology goal of saline water conversion during the Kennedy administration. In 1959, two researchers at University of California Los Angeles (UCLA), Sidney Loeb and Srinivasa Sourirajan, successfully invented a high-performance synthetic RO membrane from cellulose acetate polymer. A treatment plant was then built in Coalinga, California led by Joseph W. McCutchan, head of the Saline Water Conversion Laboratory, and the UCLA team. This plant, which was in fact the world's first RO plant, produced 6000 GPD of permeate water from brackish water. Later in 1968, Westmoreland and Bray developed the now popular spiral-wound membrane module for R.O. membranes.^{5,6} As the technology gradually flourished, its applications in municipal, industrial, military, and commercial areas increased significantly during the late 1960's and early 1970's.

2.1.2. Mechanism

Every RO system has at least four parts: a pre-filter, an RO membrane, a storage tank and a post-filter. Raw or feed water supplied from a source enters one side of the membrane, with extremely small pores, and the water that passes through the membrane gets collected in a storage tank. This obtained pure water is called the permeate water. Impurities and the remaining water is discharged from the device continuously and is called the reject water.⁷

The rate of transport of solvent through the semipermeable membrane in the reverse osmosis process is a function of the applied pressure, the differential osmotic pressure between solutions, the area and characteristics of the membrane, and the temperature of the solution. The performance of the semi-permeable membrane can be expressed through equations 1.1 and 1.2 that describe the solvent or product water flow through the membrane, and the salt flux through the membrane respectively.⁸

Water flux:

$$F_w = A (\Delta p - \Delta \pi) \dots \dots \dots (1.1)$$

where,

F_w = product water flow, g/cm²-sec

A = water permeability constant, g/cm²-sec-atm

Δp = pressure differential applied across the membrane, atm

$\Delta \pi$ = osmotic pressure differential across the membrane, atm

Salt flux:

$$F_s = B (\Delta p - \Delta \pi) \dots \dots \dots (1.2)$$

where,

F_s = salt flux, g/cm²-sec

B = salt permeability constant, cm/sec

$C_1 - C_2$ = concentration gradient across the membrane, g/cm³

In an effective RO system, the permeate water has significantly lower concentration of solutes than the feed water. The exact operating conditions for a RO system usually depends on quality of feed water, quality requirements of permeate water, and the required water flux rate.⁸

2.1.3. Applications

The areas where RO technology is applied ranges from improving drinking water, treating wastewater or brackish water, to processing food. The RO process is best known for its use in desalination with its share of about 80% in the total number of desalination plants in the world.⁹ It is also used for the production of bottled mineral water, where the water passes through a processor to remove pollutants and microorganisms. The RO technology is used to obtain purified naturally occurring water for domestic, industrial, medical, and other similar purposes. For instance, rainwater collected is purified with RO water processors and used as tap water or for landscape

irrigation and industrial cooling in Los Angeles and other cities, to resolve water shortages.¹⁰ RO is know for its uses in cleaning brackish groundwater and effluents.

In industries such as energy production, electronic, and pharmaceuticals that require production of ultrapure water, this technology is put in use. It is also used to remove minerals from boiler water. RO is used for urban and industrial water decontamination systems, although sometimes its cost-effectiveness can be a concern. RO system is significantly used to remove arsenic as well. For instance, many residents of Lahontan Valley, Nevada have installed household RO systems to produce drinking water. A study done on performance of RO systems and factors associated with arsenic removal efficiency in 59 households in Lahontan Valley indicated that the systems removed an average of 80.2% of arsenic from well water.¹¹ RO is used in the dairy industry as well for processing different concentration of milk and to produce whey protein powders.

2.2. Domestic Reverse Osmosis System

Domestic RO system functions similar to large-scale RO desalination plants; the main process behind water treatment is the same. When a moderately less volume of water, about 0-10 GPD approximately, needs to be treated, RO is usually the most flexible and cost efficient treatment process available for residential use.⁷ General RO systems use roughly three times as much water as they produce, but they are very

efficient in removing pathogenic organisms and most of the unwanted chemical contaminants.¹² The most common type of RO system used for household purposes is a point-of-use system, i.e., the system is attached to the main water source, like a kitchen sink.

2.2.1. Treatment Technique and Basic features

In a typical POU or an undersink RO system as shown in figure 2.2, tap water from faucet pipe enters the pre-filter. The most commonly used pre-filters are sediment filters that remove sediments like sand, silt, and dirt. Carbon filters may also be used to remove chlorine, which has adverse effects on TFC or TFM membranes. Carbon pre-filters, however, are not used if the RO system contains a CTA membrane. Water then passes through the RO membrane—the heart of the system. It screens out contaminants and pathogens. The water is separated into two streams after passing through the membrane. The first stream called the brine or concentrate, containing rejected concentrated minerals and metals. The reject water goes out the drain. The second stream called permeate, which is the product water, is collected in a flexible bladder inside the storage tank and is pushed out by air pressure when there is water demand. A standard RO storage tank holds up to 2.5 gallons of water. Before the water comes out of the RO faucet, water passes through a post-filter from the tank.

Post-filters are usually made up of GAC or AC components, and they remove any remaining chemical traces and polish the taste of the final product water.^{13,14}

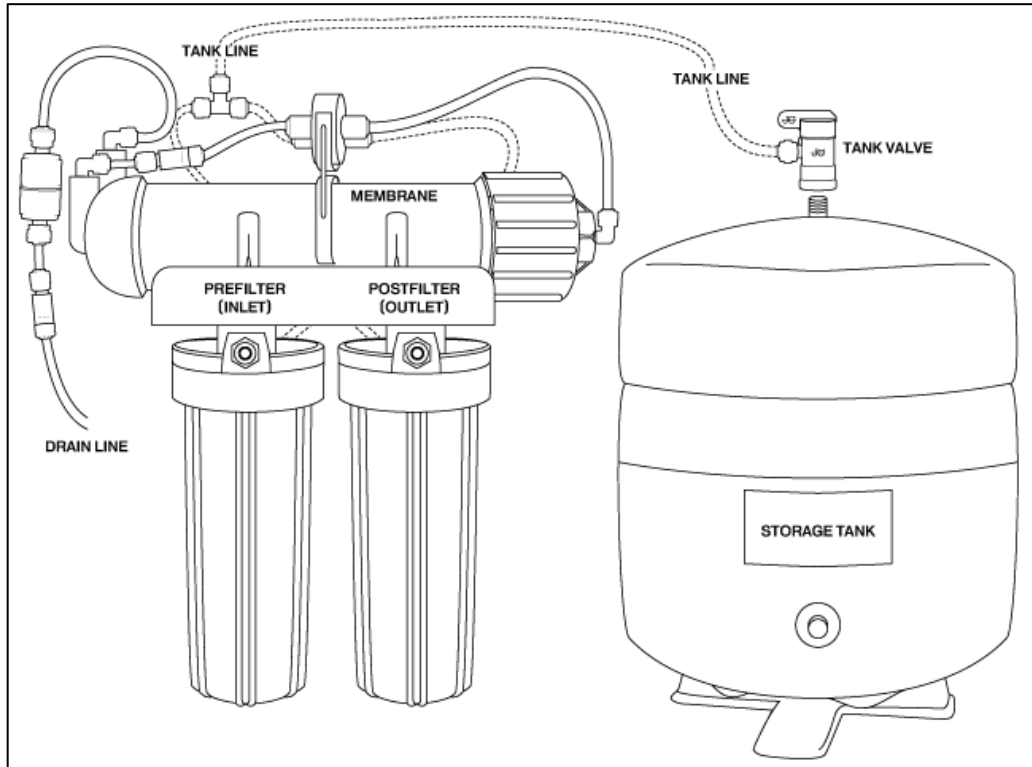


Figure 2.2. A standard 3-staged POU/Undersink RO unit¹³

The two basic RO membrane types used in the water treatment industry are cellulose acetate and thin-film composite membranes. Most of the RO filters available in the present market consist of TFC membrane, shown in figure 2.3. The popularity of this membrane over CTA is primarily due to higher rejection characteristics (salt rejection > 99.5%) and lower operating pressures.¹⁵ There are various RO membrane structures manufactured based on their applications. However, the most common physical configuration of the membrane used for RO systems in municipal treatment

applications is spiral wound¹⁵ as shown in figure 2.4, either CTA form, which is chlorine tolerant, or the TFC/TFM form, which is chlorine intolerant.

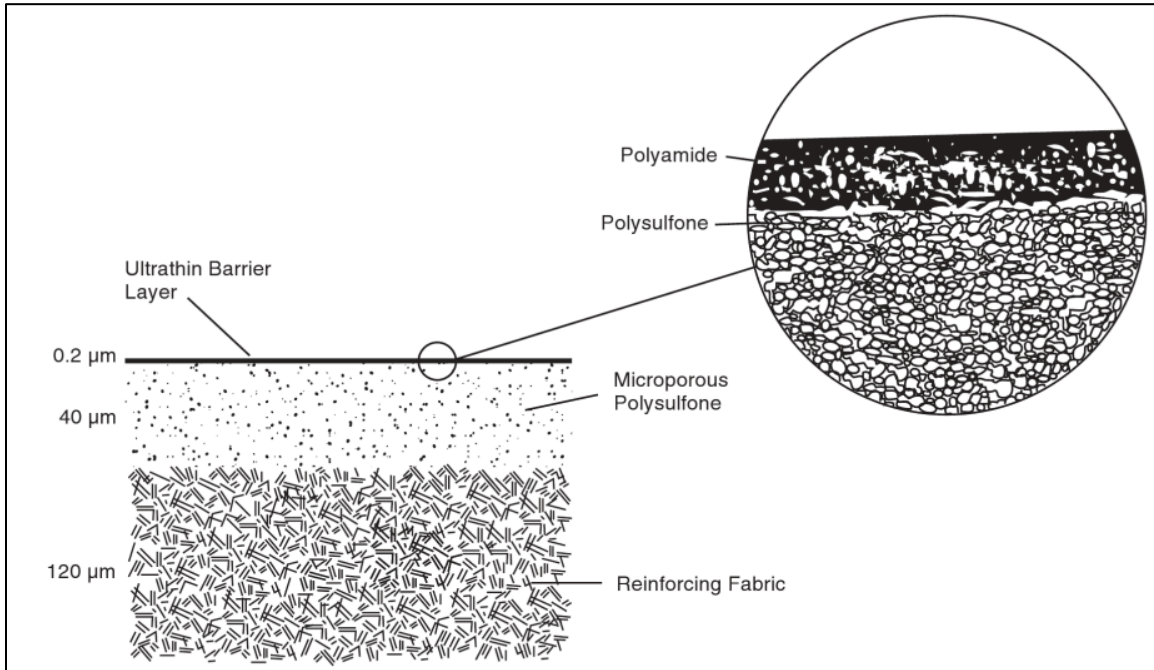


Figure 2.3. Cross-sectional schematic of TFC RO membrane

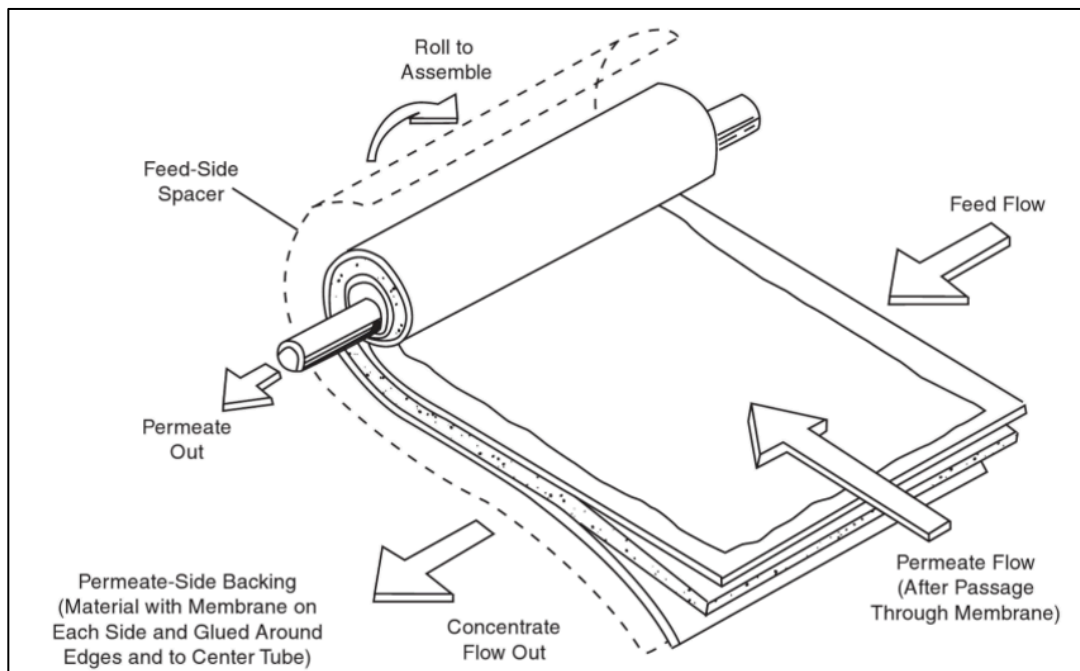


Figure 2.4. Spiral-wound Module¹⁵

2.2.2. Contaminants Appropriate for Treatment

RO membranes are capable of removing most of the chemical and organic components present in water, to produce potable water. Figure 2.5 shows the range of pore size of various membranes and examples of contaminants suitable for removal. The USEPA has identified RO as the best available technology for removing most inorganic compounds regulated under the SDWA. Table 2.1 shows some of the major contaminants that are removed by this system and their respective general rejection percentages. Studies have shown that RO membranes provide about 4 to 5-log (i.e., 99.99 to 99.999 percent) removal of viruses associated with waterborne diseases.¹⁵ Studies show that RO membranes are also effective in removing trihalomethanes (at least 80 percent of removal).¹⁷ RO is known for effective removal of nitrates and fluorides from the groundwater supplies. Thus, RO membrane is suitable for removing most of the inorganic and organic contaminants, pesticides, detergents, and improving taste, color and odor of water.

RO membranes, however, are not that effective against dissolved gases, most volatile and semi-volatile organic compounds.¹⁸ For the removal of bacteria and other microscopic organisms, sole RO units are not recommended for the treatment; it usually is more effective in conjunction with other pre- and post- treatment units.

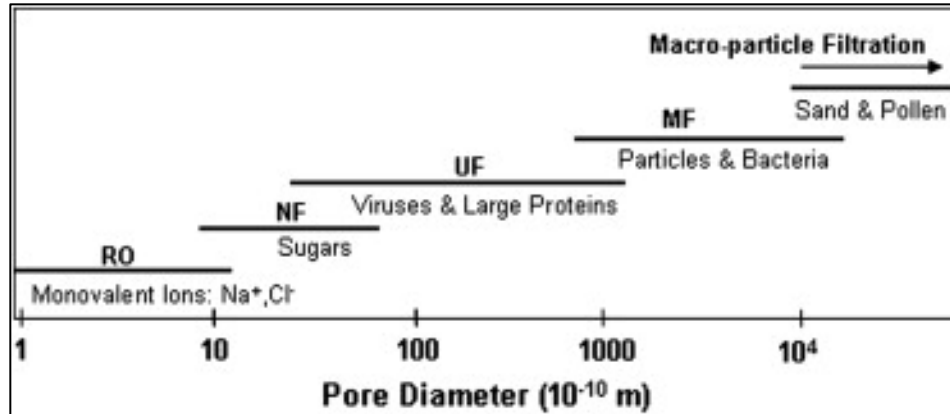


Figure 2.5. Range of pore diameters for commercially available membranes⁹

Table 2.1. Typical Rejection* Characteristics of RO Membranes¹⁶

Contaminant	% Reduction	Contaminant	% Reduction
Algae	99.9%	Mercury	93–98%
Aluminum	96–99%	Mold	99.9%
Amoebic Cysts	>99%	Nickel	93–98%
Arsenic	93–98%	Nitrate	85–90%
Asbestos	>99%	Phosphate	93–98%
Atrazine	95%	Potassium	94–97%
Bacteria	>99%	Protozoa	>99%
Barium	93–98%	Radioactivity	93–98%
Calcium	93–98%	Sediment	>99%
Chloride	95–98%	Selenium	94–96%
Chlorine	99.5%	Silicate	85–90%
Chromate	90–95%	Silver	93–98%
Copper	93–98%	Sodium	90–95%
Cryptosporidium Cysts	99.9%	Strontium	96–98%
Cyanide	90–95%	Sulfate	93–98%
Fluoride	95–98%	Thiosulfate	96–99%
Giardia Lamblia Cysts	99.9%	THM	98%
Lead	93–98%	Total Volatile Organics	95%
Manganese	93–98%	Zinc	93–98%
Magnesium	93–98%	2,4-D	95%

*Percentage rejection may vary based on manufacturer, membrane type, water pressure, temperature, routine maintenance, and TDS.

2.2.3. Pre- and Post- Treatment Units

For an RO membrane to function effectively, the permeate water needs to be treated prior to entering the membrane unit. The RO membranes are quite expensive and sensitive to various water constituents, and pre-treatment helps to protect the membrane from premature damages. Mostly all water sources in which RO technique is applied requires a certain level of pre-treatment unit like cartridge filtration (5 to 20 μm) to avoid particulate fouling.¹⁵ City water units, for instance, often require carbon filtration to remove chlorine or chemicals that clog the membrane. If the permeate water has hardness greater than the workable limit, a water softener or hardness sequestering system is required. For well water units, pre-treatment is most usually required for iron, manganese, and hardness, which all cause scaling of the membranes. Therefore, devices like water softeners, iron filters, and chemical feeders to inject sequestering chemicals may be required.

A domestic RO system may or may not have a post-filter. Usually for those systems with post-treatment, carbon filters are added to the unit to remove remaining contaminants and to improve the aesthetical properties of drinking water. Post-treatment unit serves the purpose of improvising product water by features like pH adjustment, remineralization, decarbonation, alkalinity recovery, corrosion inhibitor addition, or disinfection¹⁵. The most common post-treatment is a calcite filter, which is installed to increase pH of treated water. In the absence of a post-treatment unit, the

aggressive product water further enhances corrosion problem in plumbing materials. Permeate water out of a RO system is usually low in pH and low mineral content, and a simple calcite filter that adds calcium carbonate to the water is often used to bring the pH to neutral. Another way to improve the low pH water is to recover alkalinity by adding caustic soda or lime to permeate. If low hardness is an issue, limestone filters (dolomite or calcite) are used in post-treatment to condition water. Various factors related to end water quality, as listed below, affects the requirement for a post-treatment unit:¹⁹

- Chemical stability,
- Microbiological stability,
- Palatability, and
- Customer acceptability

2.2.4. Types of RO system in the United States market

There are various companies and vendors that manufacture and distribute domestic RO filters. Some of the popular brands of under counter RO filter, their price quote as of February 2016, and their components are listed in table 2.2.

2.3. Problems Related with RO Treated Water

As with any other water treatment systems, RO technique also has some concerns associated to it. The chemical characteristics of the final product of water may

not be acceptable in many cases according to past researches^{20,21,22}. Permeate from RO treatment system is found to be slightly acidic, contains very low buffering capacity and is very soft. The product water is adjusted, particularly with respect to buffering capacity; content of total hardness components (Ca^{2+} and Mg^{2+}) and corrosion related parameters.²⁰ Especially from systems without post-filter unit, problems like corrosive product water, and loss of essential minerals required for health²³ have surfaced. High reject water discharge during production of drinking water is also another concern for the users of domestic RO filter. An average wastewater to clean water ratio is around 3:1, i.e. three gallons of water is discharged as wastewater to produce one gallon of pure water. Installing a pump that directs the reject water to the hot water supply line of the house, however, can minimize this issue; or the reject water can be put in use for other purposes instead of draining it. There are also some novel water filters manufactured which promise "zero-waste" production, like the Watts ZRO-4 from table 2.2. Slow filtration process is another grievance about the RO system. It takes about three to four hours to filter one gallon of water for some of the leading brands of RO filters.

Table 2.2. Top-selling Domestic POU/Undersink RO filters in USA

Model	Manufacturer	Components							Vendor	Price
		1	2	3	4	5	6	7		
Active Aqua RO System AARO312 (2-Stage)	Active Aqua	Carbon/Sediment Combo Filter	RO membrane						Amazon	\$110.71
Active Aqua 100 RO System AARO100 (3-Stage)	Active Aqua	Sediment filter	Carbon filter	RO membrane					Amazon	\$158.97
APEC - Top Tier RO-90 (5-Stage)	APEC Water Systems	Polypropylene sediment filter	Carbon block filter	Carbon block filter	RO membrane	Coconut Shell refining carbon filter	Storage tank		Home Depot	\$299.35
APEC - Top Tier ROES-50 (5-Stage)	APEC Water Systems	Sediment removal filter	Carbon block filter	Carbon block filter	RO membrane	Coconut Shell refining carbon filter	Storage tank		Home Depot	\$199.00
APEC ROES-PH75 - Essence Alkaline Mineral RO System (6-Stage)	APEC Water Systems	Sediment removal filter	Carbon block filter	Carbon block filter	RO membrane	Coconut Shell refining carbon filter	Calcite acidic water neutralizer	Storage tank	Home Depot	\$229.95
APEC RO-PERM Ultimate Premium Quality Permeate Pumped Under-sink RO system (5-Stage)	APEC Water Systems	Sediment filter	Carbon filter	Carbon filter	RO membrane	Storage tank			Home Depot	\$357.35
Apex 50 MR-5050 RO Filter System (5-Stage)	Apex Water Filters Inc.	Polypropylene sediment pre-filter	AC filter	Catalytic block filter	RO membrane	Inline GAC filter	Storage tank		Sears	\$192.00
Aquaphor DWM-101 RO Water Filtration System (7-Stage)	Aquaphor Water Filters	Sediment filter	Carbon block filter	RO membrane	AC Filter	Mineralizer	Storage Tank		Amazon	\$349.00
BNF KTROSYS RO Home Filtered Water System (4-Stage)	B & F System, Inc.	Sediment pre-filter	Carbon filter	RO membrane	Polishing post-filter	Storage tank			Walmart	\$180.98
EcoPure RO Water Filtration System ECOP309 (3-Stage)	Ecodyne Water Systems	Sediment pre-filter with AC	RO membrane	AC post-filter	Storage tank				Home Depot	\$204.60

Table 2.2 continued.

Model	Manufacturer	Components								Vendor	Price
		1	2	3	4	5	6	7	8		
Express Water Alkaline Antioxidant ROALK5BN (6-Stage)	Express Water	Melt-blown polypropylene sediment filter	GAC filter	Carbon block filter	RO membrane	Alkaline pH+ filter	Inline granular carbon filter	Storage tank		Amazon	\$184.99
Express Water RO5DX RO System (5-Stage)	Express Water	Sediment filter	GAC filter	Carbon block filter	RO membrane	Inline GAC filter	Storage tank			Amazon	\$159.95
GE GXRM10R RO System (3-stage)	GE Appliances	Carbon block pre-filter	RO membrane	Carbon block post-filter	Storage tank					Home Depot	\$146.00
HAHN AquaH2O™ RO Water Filtration System HF-RO (4-Stage)	HAHN Filtration	Sediment pre-filter with AC	RO membrane	Filtration unit	Remineralizer	Storage tank				Costco	\$199.99
Home Master TMAFC Artesian Full Contact RO System (7-Stage)	Perfect Water Technologies	Sediment filter	Coconut shell carbon filter	RO membrane	Carbon/Remineralization filter	Storage tank				Home Depot	\$349.99
ISPRING LittleWell RCC7AK-UV RO Filtration System (7-Stage)	ISPRING Water Systems	Sediment filter	GAC filter	CTO Carbon filter	RO membrane	Carbon post-filter	Alkaline filter	UV lamp	Storage tank	Home Depot	\$309.67
ISPRING LittleWell RO Filter RCC7AK (6-Stage)	ISPRING Water Systems	Sediment filter	GAC filter	CTO carbon filter	RO membrane	Carbon post-filter	Alkaline filter	Storage tank		Home Depot	\$220.78
ISPRING LittleWell RO System RCC7 (5-Stage)	ISPRING Water Systems	Sediment filter	GAC filter	Carbon block filter	RO membrane	Polishing carbon filter	Storage tank			Home Depot	\$179.00
Purenex RO-5N RO Filtration System (5-Stage)	Purenex	GAC filter	Carbon block filter	RO membrane	Carbon post-filter	Storage tank				Amazon	\$160.00
Watts Premier RO-TFM-5SV (5-Stage)	Premier	Sediment filter	Carbon block filter	Carbon block filter	RO membrane	Carbon post-filter	Storage tank			Walmart	\$229.97
Watts ZeroWaste RO System ZRO-4 (4-Stage)	Watts Water Technologies	Sediment filter	Carbon block filter	RO membrane	In-line GAC post-filter	In-line carbon filter	Storage tank			Home Depot	\$465.00

2.3.1. Metal Pipes Corrosion

One of the major problems related to RO system is the aggressive product water that the system generates.¹⁵ The final pH of the RO treated water, without appropriate post treatment or chemical addition, usually ranges between 5-6 and has no buffering capacity due to little or no alkalinity and hardness present. This poses a problem of corrosion to the piping materials through which the water passes. The main types of metal pipes used for in-house plumbing are:²⁴

Lead: Although in-house lead pipes are not too popular nowadays, some lead pipes can be found in old houses and even in some new metal alloy pipes and are highly prone to corrosion.

Copper: Copper pipes are of two varieties—"rigid" and "flexible". For long-term water supply lines, rigid copper pipes are used, and flexible copper is used for short runs of water supply.

Chromed Copper: Chromed copper pipes are used mostly for exposed water supply lines, where appearance is important.

Brass: Brass pipes are sometimes used in fittings between water supply pipes.

Galvanized Iron: Galvanized iron pipe was a popular method of plumbing water supply in the home but it is no longer commonly used.

2.3.2. Plastic Leaching

With the increasing use of plastic pipes over traditional metal plumbing pipes, a need to weigh their possible water quality impacts has been created. After the production of high quality drinking water it is important to ensure that the water quality is not compromised by recontamination or microbial regrowth. Therefore it is vital to test for leaching of organic components from these plastic pipes.

The plastic pipes are generally stable in water. However, they have issues of leaching of organic contaminants in the plastic matrix or in plastic surface binding solvents and the penetration of the pipe by organic solvents from the exterior environment.²⁵ Although there is not much research supporting the leaching effects of water from domestic RO filter in plastic pipes, leaching has been a concern among bottled drinking waters²⁶, and manufacturing by-products and chemicals migrating from plastic pipes to drinking water^{27,28,29}. The major types of plastic pipes used in house plumbing are:³⁰

Polybutylene (PB): These pipes were used extensively, as cheaper copper pipe replacements, during 1970's to 1990's. Nowadays, they're not used much as they are prone to leaks.

Polyvinyl Chloride (PVC): These pipes are inexpensive and easy to use. They are used mainly to carry high-pressure water, often in the main supply line in houses. However,

they are not suitable for hot water transfer as they can distort easily in high temperatures.

Chlorinated Polyvinyl Chloride (CPVC): These pipes share similar properties with PVC but have more resistance to high temperature and are more flexible. They are more reliable than PB, cheaper and more convenient to install than copper.

Cross Linked Polyethylene (PEX): These pipes are often used for interior house plumbing. Heat resistance of PEX is higher than most plastic pipes.

High-density Polyethylene (HDPE): These pipes are extremely corrosion-resistant, long lasting, and flexible. They are suitable for all plumbing applications because of their low resistance to many solvents.

2.4. Basic Theory of Internal Corrosion of Water Distribution System

According to USEPA, corrosion means “the deterioration of a substance or its properties due to a reaction with its environment.” It can be classified as two major types— external and internal corrosion. Internal corrosion is usually of main concern in regards to the quality and flow of the water in the distribution system. In the waterworks industry, internal corrosion refers to the deterioration of the interior surface of metal pipes or fixtures, cement lining of pipes, or asbestos-cement pipe, and the environment of concern is water.³¹ Major problems created due to internal corrosion are pipe failure, water quality degradation, loss of hydraulic conveyance, leakage due

to buildup of corrosion products on the pipe wall, and potential health and economic implications.³²

Corrosion basically is an electrochemical process as shown in figure 2.6, "Me" is the base metal. There are four necessary components of a corrosion cell: anode, cathode, conductor, and conducting electrolyte. Various reasons can create an electrical potential gradient and form anodic and cathodic sites along the surface of a metal pipe. Particle deposits, pipe fixtures, manufacturing irregularities, biofilm formation, etc. are some of the probable factors.²⁵

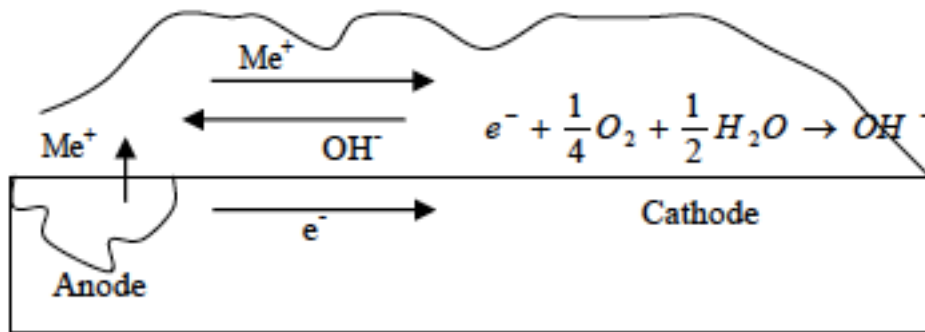


Figure 2.6. Anode and Cathode reactions for metal in contact with water³²

The oxidation of a metal takes place at the anode, generating electrons that travel to the cathode through the conductor. Electron acceptors, hydrogen ions formed by dissociation of water ($H_2O \rightleftharpoons H^+ + OH^-$), combine with the electrons and form H_2 gas at the cathode.³¹ In case of lead pipes or lead-based solders, the reactive areas of the surface like the metal-crystal grain boundaries act as anodes, where corrosion occurs. The less reactive areas like metal grains become the cathode. The most

common form of oxidized corrosion product for lead is Pb(II). Another oxidized form, Pb(IV), is produced during extremely oxidizing conditions.³²

The major types of corrosion in the water industry are: (1) galvanic corrosion, (2) pitting, (3) crevice corrosion, (4) erosion corrosion, and (5) biological corrosion. Galvanic corrosion occurs when two different metals come in contact, for instance in joints and fittings. Pitting is a non-uniform, localized corrosion that forms pits or holes in pipe surface, and occurs at surface irregularities, scratches or deposits. Crevice corrosion is localized corrosion, usually occurring at lap joints, rivets, and surface deposits, caused by acidity changes, oxygen depletion, DI and absence of an inhibitor. Erosion corrosion is caused by high flow velocity, turbulence, and change in flow direction that mechanically removes protective layers from pipes and corrodes the surface. Biological corrosion is caused by growth of organisms like bacteria, algae, and fungi on the pipe material.³¹

2.5. Effects of Lead in Drinking water

The majority of the health concerns associated with internal corrosion are related to the release of trace metal concentrations (e.g., lead, copper, cadmium, etc.) from corroding metal surfaces.³² Various regulations have been made to control lead contamination. For instance, USEPA's Lead and Copper Rule created an increased awareness and emphasis on corrosion control in distribution systems. In 2011, changes

to the Safe Drinking Water Act reduced the maximum allowable lead or “lead free” content to be a weighted average of 0.25 percent calculated across the wetted surfaces of pipes, pipe fittings, plumbing fittings, and fixture and 0.2 percent for solders and flux.³³ Although the exposure to lead is minimized by regulations like LCR and SDWA, it is not completely eradicated. Taking one of the examples of recent a case in Flint, Michigan, when the people of the city suffered from serious high levels of lead contamination (over 100 ppb) in their tap water, which was mainly caused by corrosion of old lead pipes after the city switched its water source in April, 2014.³⁴ The main sources of lead contamination are lead pipes, solders and lead-containing brass fittings, and some minor sources are PVC pipes, which contain lead stabilizers and galvanized steel pipes. Houses built before 1986 are more likely to have lead pipes, fixtures and solder.³³ As lead is comparatively inexpensive and flexible, many faucets sold are made from brass, copper, zinc and a small amount of lead. Lead is usually used to seal cracks between copper and zinc fittings, and makes brass malleable to be forged and converted into vital parts of every faucet.

One of the major concerns of drinking water with exceeding tolerable lead concentration is health. Children, especially, are affected by low levels of lead, which may cause problem in behavior and learning, resulting in lower IQ level and hyperactivity, slower growth, hearing problems, anemia, seizures, and in some rare

cases, coma or even death. In adults, there are possible cardiovascular effects, high blood pressure, hypertension, kidney failures, and reproductive problems.³³

Various studies have been conducted to test corrosion effects of product water from RO systems in water pipeline materials, especially in commercial desalination plants.^{35,36,37} For instance, in a study testing the effect of remineralization options on the stabilities of pipeline materials, corrosion rate of cast iron was highest for all remineralization methods.³⁵ There, however, are only limited references available on corrosion effects of domestic RO product water on in-house pipeline materials. Therefore, this study focuses mainly on the effects of POU RO filters' product water on the household plumbing hoping to give a better insight on this water treatment technique which is gaining increasing popularity in households nowadays.

Chapter 3

Experimental Set-Up and Procedure

3.1. Reverse Osmosis Filters Used

Three domestic RO systems, from table 2.2, were selected based on the number of stages and market popularity, for the experiment. Their general mechanisms are briefly explained below.

3.1.1. Home Master TMAFC Artesian Full Contact RO System



Figure 3.1. Home Master TMAFC Artesian Full Contact RO System³⁸

This RO water filtration system, figure 3.1, consists of five components as shown in table 2.2. The schematic diagram of the general arrangement of the system is shown

in figure 3.2, where Sediment filter (1), Carbon filter (2), RO membrane (3), Carbon/Remineralization filter (4), Storage tank (5), and a recirculation line having check valve "A" and check valve "B". The storage tank is connected to the recirculation line between the check valves.³⁹

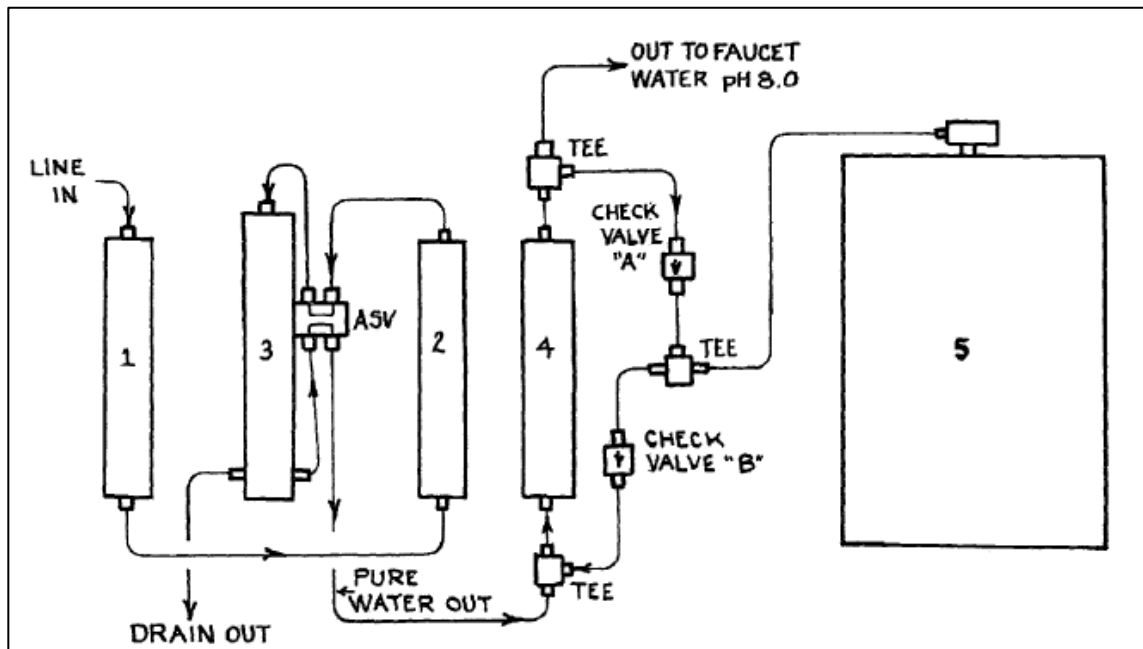


Figure 3.2. Schematic of Tap Master Artesian Full Contact system³⁹

In a seven-staged process, water from a potable municipal or well water supply firstly passes through the sediment filter. Water then flows through the coconut shell carbon filter, and next through the RO membrane that removes average of 98% of sediment, chlorine, and other common chemicals and dissolved solids. Water from the RO system with dropped pH of about 6.2-6.8 enters the Carbon/Remineralization filter then flows through Carbon/Remineralization filter, and exits filter with pH 7.0. Next the water flows through Check Valve "A" into the storage tank. When required, water flows

from the storage tank through Check Valve “B” and enters Carbon/Remineralization filter and exits with pH around 8.0.³⁹

The general system specifications for the optimum operation of Home Master TMAFC Artesian Full Contact RO System are: ⁴⁰

- Feed water pressure: 40 PSI – 95 PSI (35 PSI with permeate pump)
- Feed water temperature: 40 °F – 100°F
- Maximum TDS: 2000 ppm
- Maximum Hardness: 10 gpg
- Maximum Iron: 0.2 ppm
- pH limits: 4.0 – 10.0

3.1.2. APEC - Top Tier ROES-50 RO System

The five components of this system makes a five-staged water purification process, figure 3.3, where the tap water firstly goes to the Sediment removal filter (1), which removes dust and other particulate matter, to protect and extend the life of the RO membrane and system. Then water flows through the two Carbon block filter (2 and 3), which removes excess chlorine, VOCs, unpleasant tastes, odors, and cloudiness. In the fourth stage, water flows through the high rejection TFC RO membrane (4) where a wide variety of contaminants including arsenic, bacteria, lead, fluoride, chromium, radium, etc. are removed. The final stage is the Coconut shell

refining carbon filter (5) that removes any possible residual taste from the storage tank.⁴¹

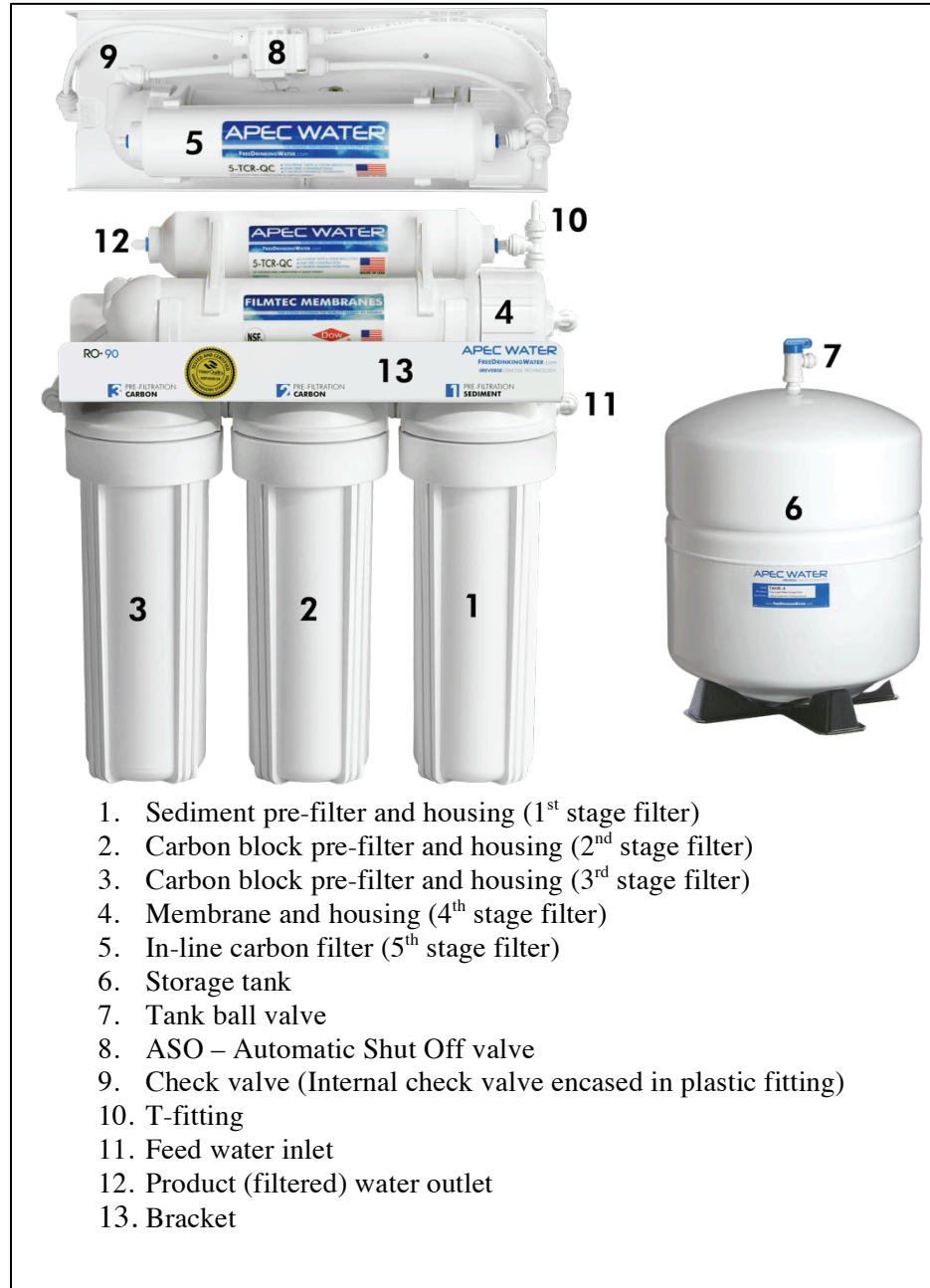


Figure 3.3. Component itemization of APEC - Top Tier ROES-50 RO System⁴²

The general specifications of this model are:⁴¹

System capacity: 50 GPD at 60 PSI, 30 GPD at 50 PSI and 77°F

Storage Tank Capacity: 4 gallons

Feed water pH: 2.0 – 11.0

Feed water pressure: 40 PSI – 85 PSI

Feed water temperature: 40 °F – 100 °F

Maximum TDS: 2000 ppm

3.1.3. Active Aqua RO System AARO312

This two-stage system consists of a RO membrane and a 10" carbon and sediment combination filter to reduce chlorine and other unwanted contaminants, to assure good membrane life. The combo filter is the first stage in the RO process, in which the sediment portion effectively removes particles and sediments like sand. The sediment filter's life depends on the amount of total particles in the water supply. The carbon portion of the filter effectively reduces VOCs from the feed water supply. It filters 2,000 gal at 1.0 GPM. The RO membrane component in the system reduces TDS like salts or calcium. A properly operating membrane usually provides a TDS reduction of at least 90%. A minimum of 40 PSI is required to properly operate the system.⁴³ The major components of this RO filtration system is shown in figure 3.4.

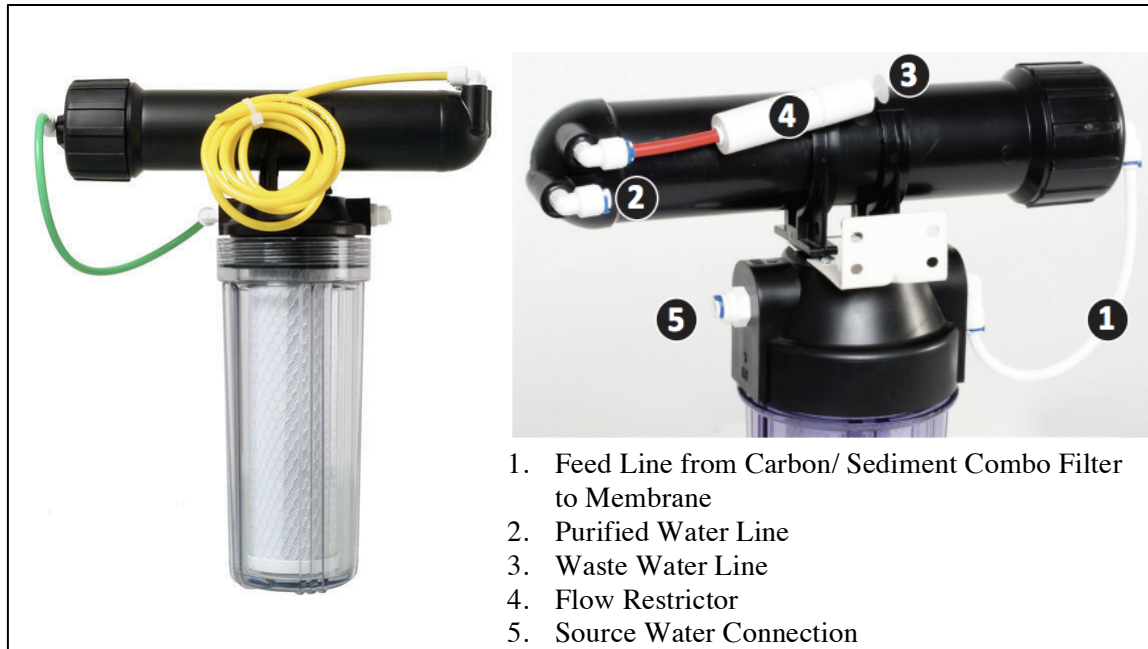


Figure 3.4. Active Aqua RO System AARO312 and its components⁴³

3.2. Immersion Corrosion Testing and Sampling Protocols

The effect of permeate from the filtration systems on corrosion of lead metal was tested using the immersion corrosion experiment and the corrosion effect was estimated through the coupon weight loss method. The three filters were set up with “Masterflex® Easy Load II” pumps (Model 77201-60) to flow feed water from a common intake water source, which was the tap water. The pumps were set at a flow of 0.08 L/min using L/S™ 16 tubing. A set of six water samples were collected from the treated permeate of each of the filtration systems. The water quality parameters such as pH, conductivity, total hardness, and total alkalinity of each of the samples were then tested based on the instruments and methods as listed in Table 3.1. The samples were then set up for corrosion testing based on the ASTM standards.^{44,45}

Table 3.1. Instruments and methodology used to test water quality parameters

Water quality parameter	Instrument	Standard Method reference number ⁴⁶
pH	VWR Symphony® B30PCI benchtop meter	
Conductivity	VWR Symphony® B30PCI benchtop meter	
Total Hardness		SM 2340 C. Hardness EDTA Titrimetric Method
Total Alkalinity		SM 2320 B. Titration Method

3.2.1. Preparation of Lead Coupons

Lead coupons were prepared from lead metal sheets with density of 11.3 g/mL, obtained from Fisher Scientific. The metal sheets were cut into dimensions of 2in x 1in x 0.03in coupons, with a small hole of about $\frac{3}{16}$ in. diameter punctured at one end. As more uniform results is expected if a considerable layer of metal is removed from the specimens to eliminate variations in condition of the original metallic surface⁴⁴, the coupons were vigorously wiped and then polished with paper towel. All coupons were then stored in a desiccator until they were ready to be immersed in the water samples. The dried lead coupons were then weighed on an analytical balance and recorded. The initial physical state of the coupons can be seen in figure 3.5.

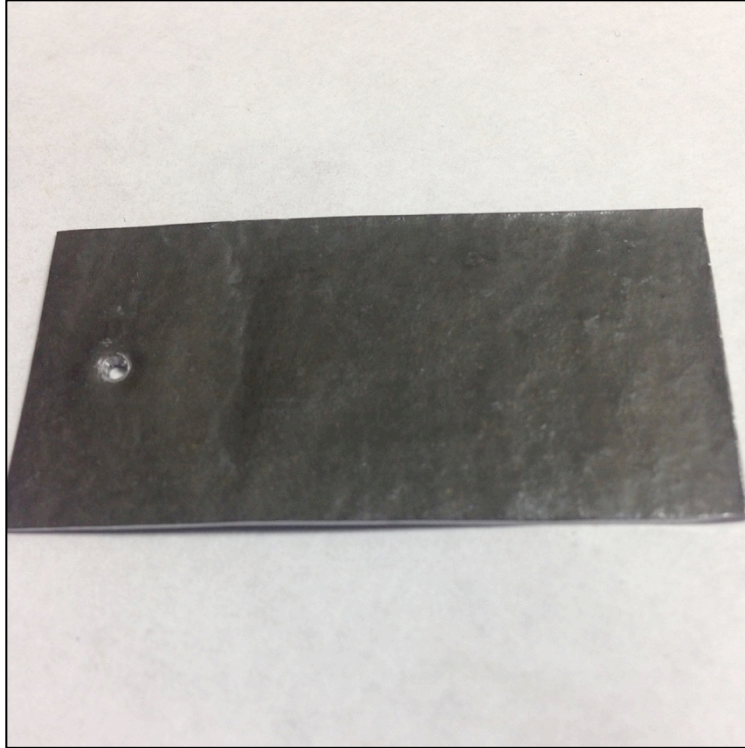


Figure 3.5. Clean and dried Lead coupon

3.2.2. Reactor Assembly

Each lead coupon was placed in 500mL plastic bottle reactors, as shown in figure 3.6, filled with the water samples for study and were conducted in replicates. Nylon strings, which were sanitized using acid bath, were placed through the hole on the coupon and attached to the cap of the reactor bottle to immerse it in the water sample such that the metal freely suspended inside the bottle. Based on ASTM G1 standard⁴⁴, the nylon string was chosen as it does not interfere with the metal and water sample, and no galvanic interactions occur. Then the reactor bottles were properly sealed and covered with aluminum foil, to protect the samples from any foreign contaminants or evaporation. Nine of the sample reactors were gently stirred

continuously and the remaining nine samples were left stagnant, to simulate a proper aspect of both the flow through pipes, and stagnant water in-between operations of the domestic filters. Each of the samples was clearly marked with unique designation. The experiment was conducted at room temperature (about 21.4°C) and was carried out for 40 days to achieve sufficient weight loss according to ASTM G31 standard⁴⁴.

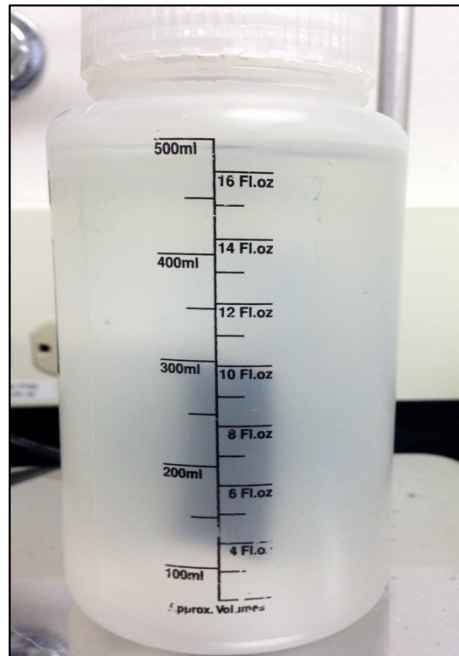


Figure 3.6. Sample reactor 500mL-bottle with immersed Lead coupon

3.2.3. Method of Cleaning Specimens

After the 40-day immersion test, the coupons were carefully taken out from the reactors and dried by hanging the coupons in empty bottles. Then they were stored in vacuum desiccators. The physical appearance of the coupons were observed and recorded as shown in figure 3.7. They were then carefully cleaned using mechanical cleaning method to remove the corrosion products. Abrasive paper towel was used to

gently scrub off the corrosion products from the surface of the coupons. The cleaning method was conducted very carefully so as not to remove sound metal. After the cleaning process, the weights of the coupons were recorded.

3.2.4. Corrosion Rate Calculation and Lead Concentration

An extra aliquot from each of the samples were filtered through a 0.45 µm filter to determine soluble lead concentrations by Inductively Coupled Plasma-Mass Spectroscopy (ICP-MS) according to EPA 200.8 method.

The average corrosion rate was then calculated by the following equation:⁴⁴

$$\text{Corrosion rate} = (K \times W) / (A \times T \times D) \dots \dots \dots (3.1)$$

where,

K = a constant (3.45×10^6 , for Corrosion rate in mpy)

T = time of exposure in hours to the nearest 0.01 h,

A = area in cm² to the nearest 0.01 cm²,

W = mass loss in g, to nearest 1 mg, and

D = density of metal in g/cm³.

3.3. Migration Experiment and TOC Test Protocol

Three varieties of plastic pipes were selected for the experiment: ½" PVC (JM Eagle Sch. 40), ½" CPVC (Charlotte FlowGuard Gold) and ½" PEX (SharkBite), for evaluation of TOC leaching, using Shimadzu Total Organic Carbon Analyzer (TOC-

L/CPH), at room temperature based on migration test using Standard Utility Quick Test⁴⁷. All pipes were certified with NSF 14 and 61 standards for use in potable water systems.

3.3.1. Sample Preparation

Each pipe was cut into a total length of three feet. The overall dimensions of the pipes are shown in table 3.2. The cut samples were then rinsed thoroughly with DI water, after removing all tapes and labels. The water samples were collected from the RO filters, and stored in clean glass bottles at 4°C. The surface area-to-volume (S/V) ratios, with the volume of water samples used are also shown in table 3.2.

Table 3.2. Overall dimensions of Plastic pipe samples

Pipe Brand	Internal Diameter (in)	External Diameter (in)	Length (feet)	Water Volume (mL)	S/V ratio (cm ² /mL)
½" PVC (JM Eagle Sch. 40)	0.609	0.84	3	170	6.24
½" CPVC (Charlotte FlowGuard Gold)	0.485	0.625	3	108	7.51
½" PEX (SharkBite)	0.475	0.625	3	110	7.73

3.3.2. Leaching/Migration Process

Each pipe types were filled with the water samples and the open ends of the pipes were covered with sealant tapes. There were a total of twelve pipes including three different pipes with tap water samples, collected for a comparison base. The leaching test was conducted for three consecutive 72-hour periods, under stagnant

conditions. After each leaching period, the leachate water was collected for TOC analysis. Then the pipes were refilled with fresh RO water samples. The initial water samples before each migration tests were also tested for TOC.

3.3.3. TOC Analysis

The initial and final water samples from each of the three periods of leaching test were collected and tested for TOC using the Shimadzu (TOC-L CPH) according to USEPA method 415.1⁴⁸). To prepare the sample vials, first the vials were soaked in 1M HCl acid bath, and rinsed with Ultrapure Milli-Q™ water. After air-drying, the top of each vials was covered with aluminum foil and then combusted in 550°C Thermolyne furnace for at least four hours to remove all trace organics. Next, the TOC-L CPH machine was calibrated using standard solutions of 0, 1.0, 2.5, 5.0, and 7.5 ppm. Each water sample was then poured into the prepared vials and 2 drops of concentrated HCl were added to maintain the pH around 2.0 for storage, before placing in the machine to get the results.

Chapter 4

Results and Discussion

4.1. Water Quality Parameters

After the 40-day wait period of the lead immersion test, changes were observed in the initial and final water quality of the permeate from the reverse osmosis filters. All the readings were observed at room temperature of about 21.4°C.

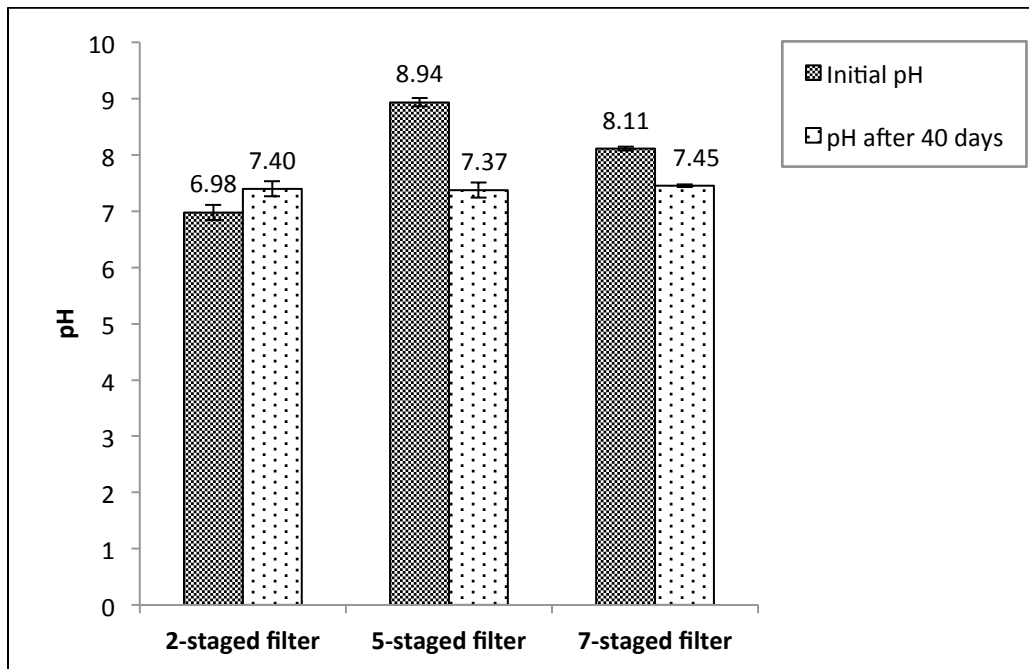


Figure 4.1. pH change of water samples with Lead coupons after 40 days; error bars show standard error of the mean.

The average initial pH of the water samples from the two-staged filter (Active Aqua AARO312), the five-staged filter (APEC ROES-50) and the seven-staged filter (Home Master TMAFC) were 6.98, 8.94 and 8.11 respectively. The pH of samples from

the five-staged filter and the seven-staged filter were comparatively higher than that of the two-staged filter, as the water in both of those systems was passed through a carbon/remineralization post-filter which added calcite that gets dissolved in the slightly acidic water to raise and neutralize the pH. Regardless of the initial pH levels, the pH levels of all the samples at the end of the experiment reached around 7.4, as shown in figure 4.1. The average final pH values of the samples from two-staged, five-staged and seven-staged filters were 7.4, 7.37 and 7.45 respectively.

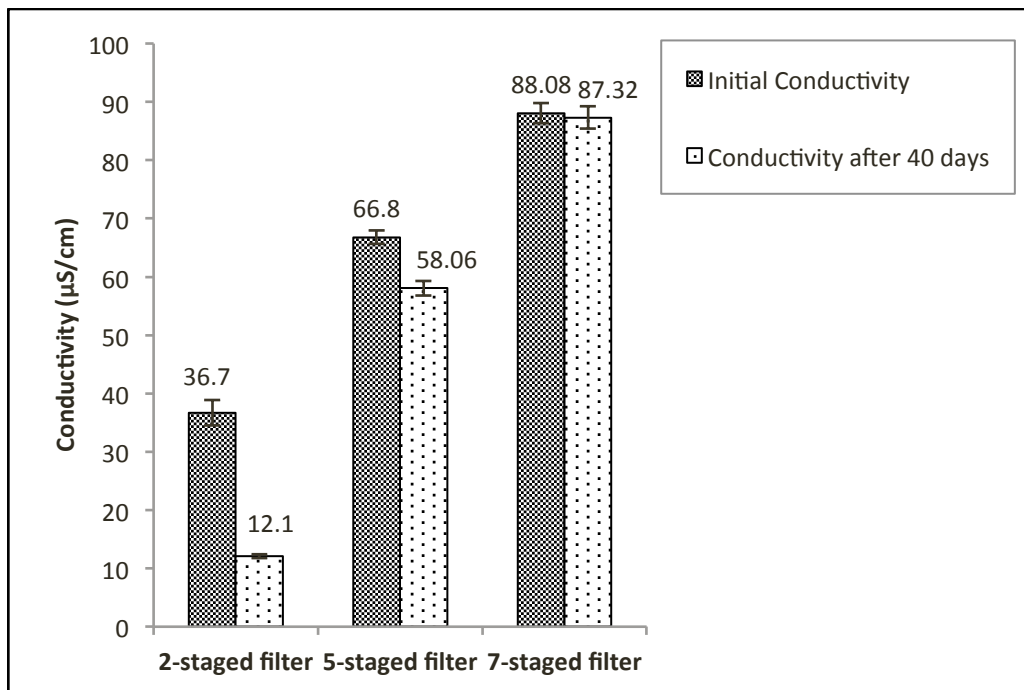


Figure 4.2. Conductivity change of water samples with Lead coupons after 40 days; error bars show standard error of the mean.

The change in conductivity is documented in figure 4.2, where it can be seen that the conductivity of all the three filters decreased after the experiment. The seven-staged filter samples had the highest initial average conductivity of about 88.08µS/cm,

which was expected as the water in this system passed through the remineralization post-filter twice and thus more amount of TDS are added back to the final water. The two-staged filter samples had the least initial conductivity of about $36.7\mu\text{S}/\text{cm}$ in average, mainly because the "pure" permeate had most of the minerals and TDS stripped from the RO membrane. The largest extent of decrease was observed in the two-staged filter samples with about 67% decrease and the smallest decrease was in the seven-staged filter samples with less than 1% decrease. The five-staged filter samples had about 13% reduction. The main reduction in the conductivity of the samples could be due to the corrosion effect, as a corroding metal forms an ionic bond with the available ions in the water solution, thus, decreasing the conducting capacity of the water.

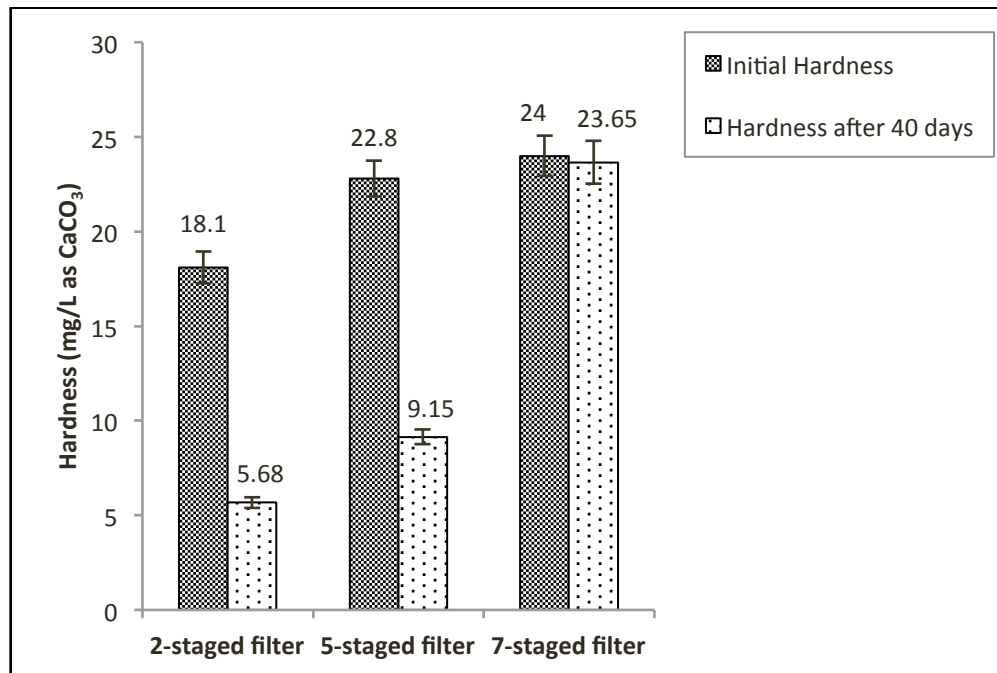


Figure 4.3. Change in hardness of water samples with Lead coupons after 40 days; error bars show standard error of the mean.

The initial water samples from the filters, as expected, were “soft” based on the degree of hardness standard developed by the USEPA (1986) as the hardness was below 75mg/L as CaCO₃. The low hardness level of the three RO permeate can be attributed to the removal of most of the initial water components that cause hardness. The hardness of the water samples, as shown in figure 4.3, was observed to have decreased after the experiment. The hardness reduction of the water samples from the seven-staged filter was quite insignificant, about 1.25%, as the initial average hardness was about 24mg/L as CaCO₃ and the final hardness was about 23.65mg/L as CaCO₃. The two-staged filter samples had the greatest reduction in hardness of about 67%, and the five-staged filter samples had about 60% decrease in hardness. The hardness of the two-staged filter was comparatively lowest because the filtration system lacked a post-filter like the other two filters, which adds back major hardness-causing minerals like calcium and magnesium.

The alkalinity of the water samples, which are documented in figure 4.4, was also observed to have decreased similarly to the hardness of the samples, especially in AARO312 and ROES-50. The alkalinity of all the samples were caused mainly by bicarbonates as the P-alkalinity of the samples was found to be zero during the titration experiment. The greatest reduction was found in the two-staged filter samples, which was about 70% and the least reduction was found in the seven-staged filter samples, which had about 9% reduction. The five-staged filter samples, which had the highest

alkalinity, underwent significant reduction after the experiment as well with around 59% decrease.

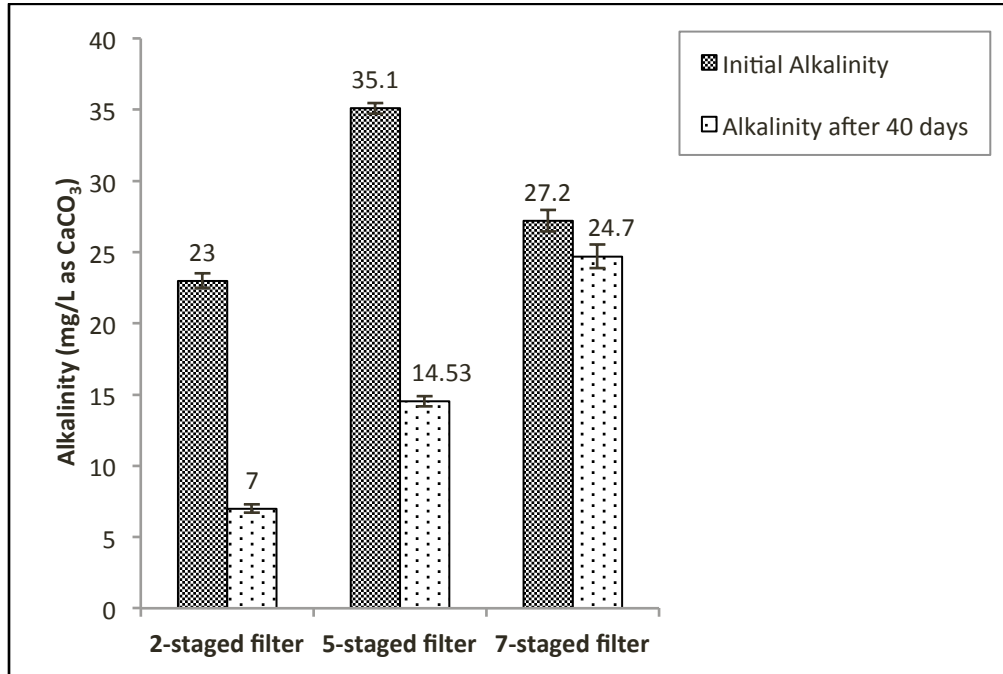


Figure 4.4. Change in alkalinity of water samples with Lead coupons after 40 days; error bars show standard error of the mean.

4.2. Lead Analysis

Most of the lead coupons that were immersed in the water samples from the two-staged filter underwent corrosion. Five out of six samples showed physical change on the surface of the coupons. Figure 4.5, pictures of some of these corroded samples, shows corrosion effect on the lead coupons from both the stirred and stagnant samples. The only major difference between the two sample types was that the coupons of the stagnant water samples had white deposits intact on the coupon surface, as shown in figure 4.5 (a), and those of the stirred water samples had corroded

surface with only slight corrosion product on, figure 4.5 (b). White precipitates were also found at the bottom of the reactors. The main reason behind the corrosion due to these water samples, as confirmed by literature review, is their water quality like the low pH level, low alkalinity, low TDS, and softness of water that are known to enhance corrosion.

There was not much corrosion products on the lead coupons that were immersed in the water samples from the five-staged filter. Three out of six samples showed slight effects of corrosion; the surfaces of these coupons, as shown in figure 4.6, were observed to have slight abrasions and white corrosion products on the surface. Some white precipitation was observed in these samples as well. Although the water quality of the samples from this filter were considered quite unfavorable for corrosion, some samples leached lead from the coupon. This could be due to the lower hardness and alkalinity that were less than the usually suitable levels of 50 mg/L as CaCO₃ or more.

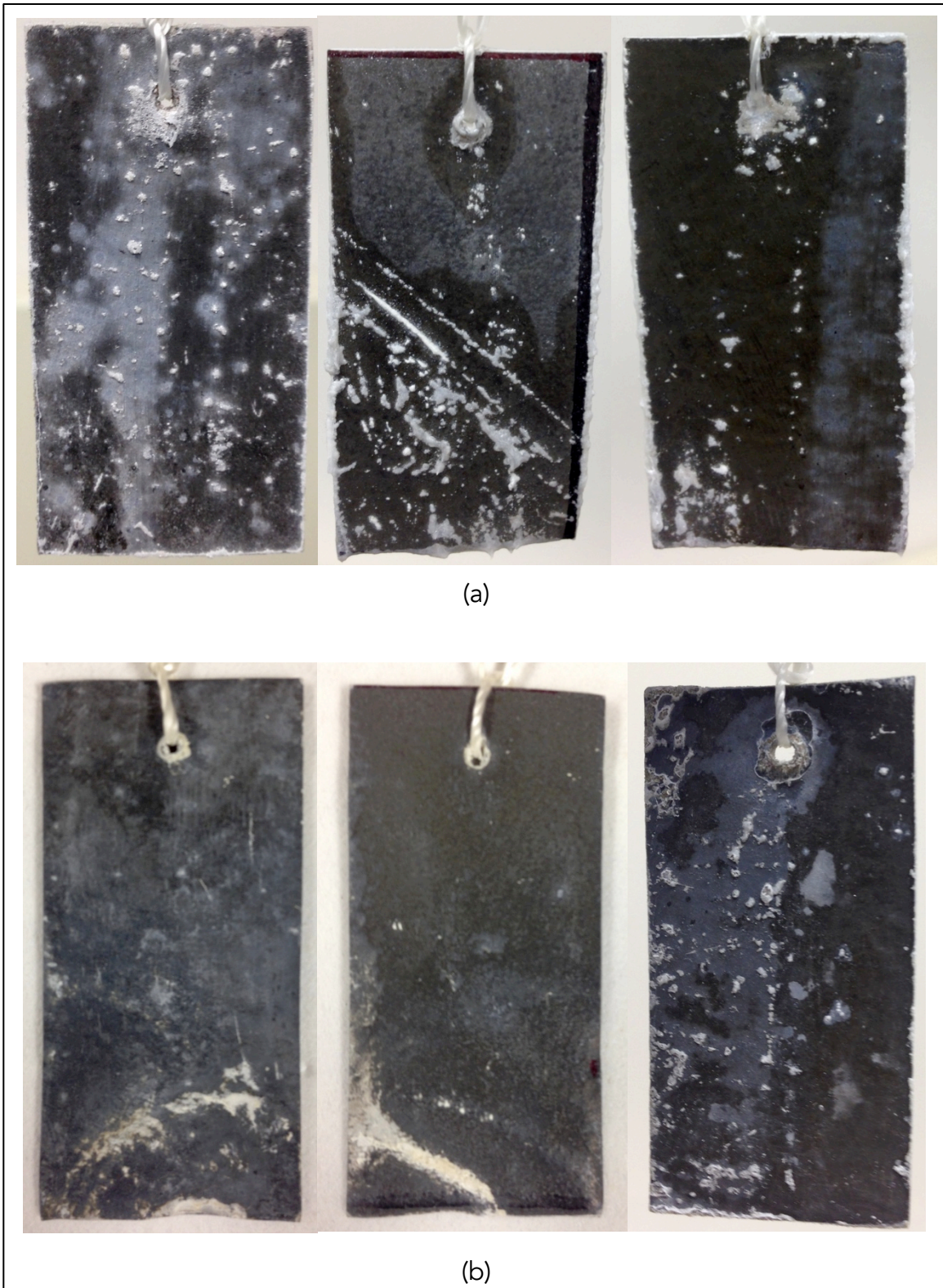


Figure 4.5. Lead coupons immersed in (a) stagnant water samples, and (b) stirred water samples from two-staged RO filter

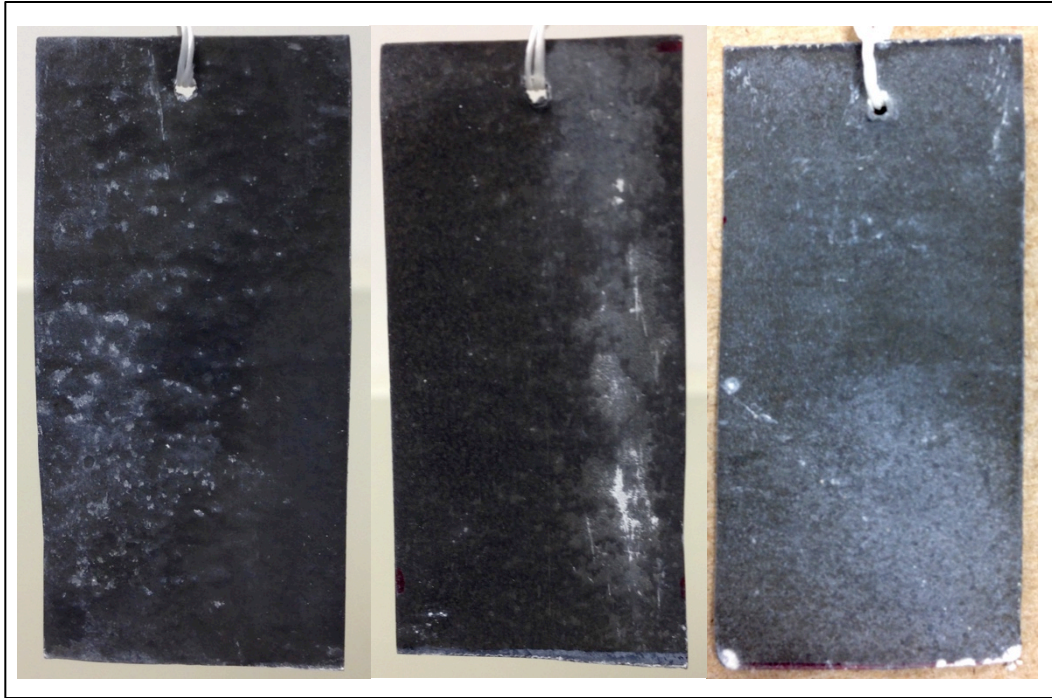


Figure 4.6. Lead coupons immersed in water samples from five-staged RO filter

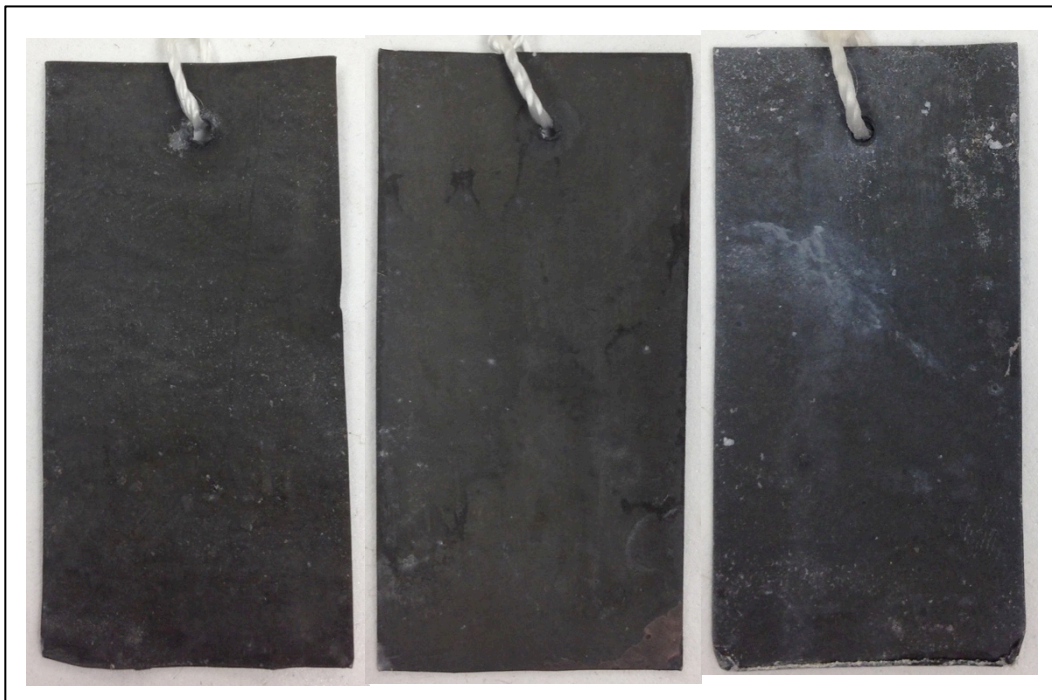


Figure 4.7. Lead coupons immersed in water samples from seven-staged RO filter

As for the coupons in the seven-staged filter water samples, in figure 4.7, negligible physical change was observed on the metal surface. Minor discoloration of

the lead surface was observed in the coupons and only one of the lead coupons underwent weight decrease. There were only slight white deposits at the bottom of the reactor holding these coupons. As the water quality of the samples from this filter was suitable for preventing corrosion, such results are quite justified.

The average lead corrosion rates of the water samples during the 40 days were calculated using equation 3.1 and the results obtained are shown in table 4.1. For this experiment, the value of 'K' was taken as 3.45×10^6 to get corrosion rate in mpy, time 'T' of exposure was 960 hours, surface area of coupon 'A' was 12.90 cm^2 , and density of the lead metal used was 11.3 g/cm^3 . Comparing the corrosion rates between different water samples, corrosion of samples from the seven-staged filter was the least. The corrosion rate for the one sample that underwent weight change was around 0.007 mpy. The most heavily corroded samples were from the two-staged filter permeate, with average corrosion rate of about 0.382 mpy. Considering the samples from the five-staged filter, which had weight loss and showed slight corrosion, had an average corrosion rate of about 0.064 mpy.

Table 4.1. Average lead corrosion rates of the water samples from the three RO filters

Water sample	Corrosion rate (mpy)
Two-staged RO filter	0.382035471*
Five-staged RO filter	0.064083369**
Seven-staged RO filter	0.007394235***

Note:* Average of six samples. ** Average of four samples. *** One sample

The lead concentrations of some of the samples were surprisingly higher, compared to the expected concentrations based on calculated corrosion rate, even in the samples from the five-staged and the seven-staged filters. The highest lead concentrations among the water samples after the experiment, which was found using ICP-MS, are shown in figure 4.8. All the values exceed the EPA limit of lead concentration, i.e. 15 ppb.⁴⁹ The lead concentration is a result of both corrosion and lead solubility processes.³² Thus, the reason of such high lead concentrations in some of the samples from five-staged and seven-staged filters could be because of the new condition of the metal coupons, which are more susceptible to leaching. Moreover, the higher lead concentration could be because of other lead products like Pb(II) carbonates that are likely to be formed in the pH range (around 8 and lower) of the water samples³².

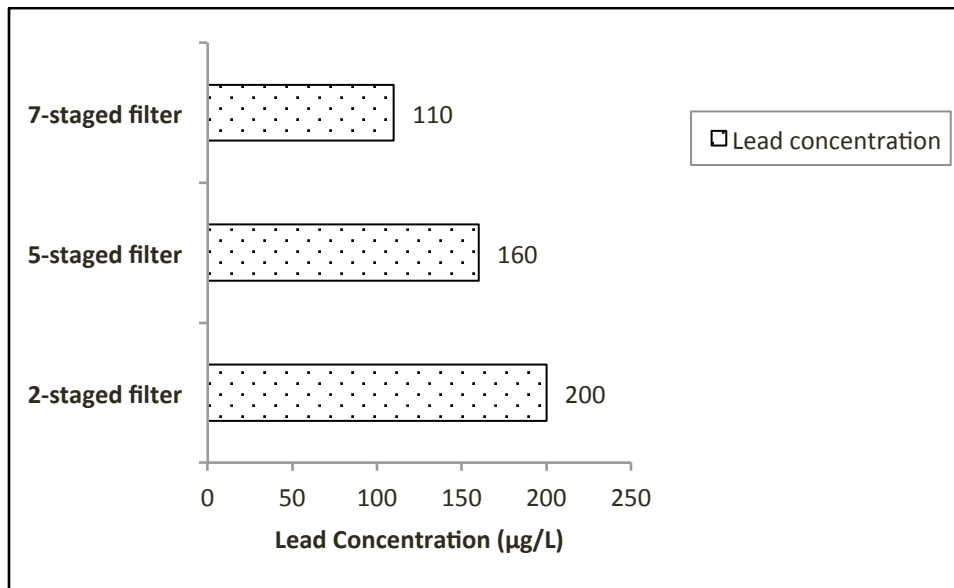


Figure 4.8. Highest lead concentration among the samples from two-staged, five-staged and seven-staged RO filters

4.3. Migration Test

The initial and final TOC concentrations of the RO filter water samples in the three different plastic pipes after three, six and nine days are shown in figures 4.9, 4.10 and 4.11, respectively. The initial and final TOC concentrations of all the samples, including tap water samples are tabulated in table 4.2. The PEX and PVC pipes showed some significant increase from the initial TOC concentrations of the water samples from the three different types of RO filters. The CPVC pipes, however, showed almost none or only slight increase in the TOC concentration. The control samples also showed similar changes in the TOC concentration in the plastic pipes.

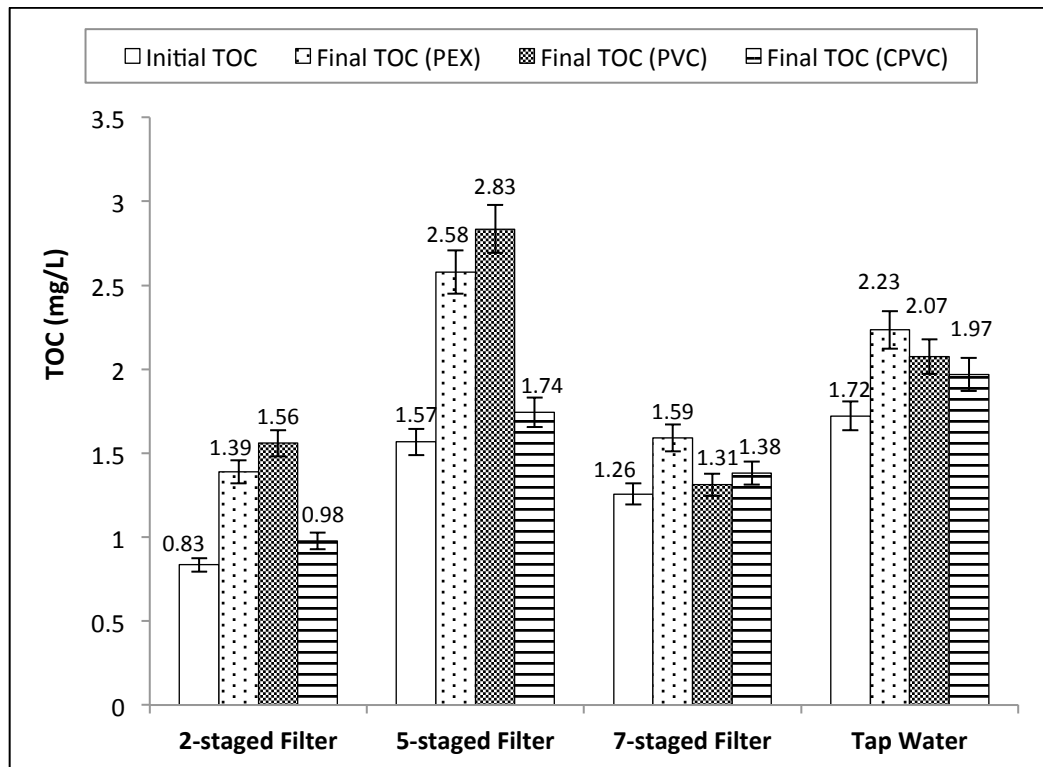


Figure 4.9. Change in TOC concentration of water samples from the RO filters after three days

Table 4.2. Initial and final TOC concentrations (in mg/L) of water samples for three leaching periods

Day 3	2-staged Filter	5-staged Filter	7-staged Filter	Tap Water
Initial TOC	0.834372	1.57	1.26	1.72
Final TOC (PEX)	1.389	2.58	1.59	2.23
Final TOC (PVC)	1.559	2.83	1.31	2.07
Final TOC (CPVC)	0.9769	1.74	1.38	1.97
Day 6	2-staged Filter	5-staged Filter	7-staged Filter	Tap Water
Initial TOC	0.65	1.76	1.25	1.72
Final TOC (PEX)	0.85	2.46	1.51	2.13
Final TOC (PVC)	1.13	2.18	1.31	2.04
Final TOC (CPVC)	0.83	1.84	1.25	1.81
Day 9	2-staged Filter	5-staged Filter	7-staged Filter	Tap Water
Initial TOC	0.59	1.36	1.16	1.731
Final TOC (PEX)	0.77	1.64	1.29	2.03
Final TOC (PVC)	0.78	1.58	1.19	2.09
Final TOC (CPVC)	0.62	1.41	1.22	1.90

Among the three filters, two-staged filter showed the most percentage increase in TOC concentrations in the water samples of PEX, PVC and CPVC pipes. Their percentage increment was highest in the third day; about 66% in PEX pipes, 87% in PVC pipes, and 17% in CPVC pipes. The seven-staged RO filter showed the lowest percentage increment, with about 26% in PEX pipes, 4% in PVC pipes, and 10% in CPVC pipes on the third day. On the sixth and ninth day, the two-staged filter again had the highest percentage increment and the seven-staged filter had the lowest.

The TOC concentration from the water samples of the five-staged filter and the seven-staged filter were found to be greater than that of the two-staged filter. The main reason behind this could be the presence of the post carbon filters, which adds back carbon components to the water.

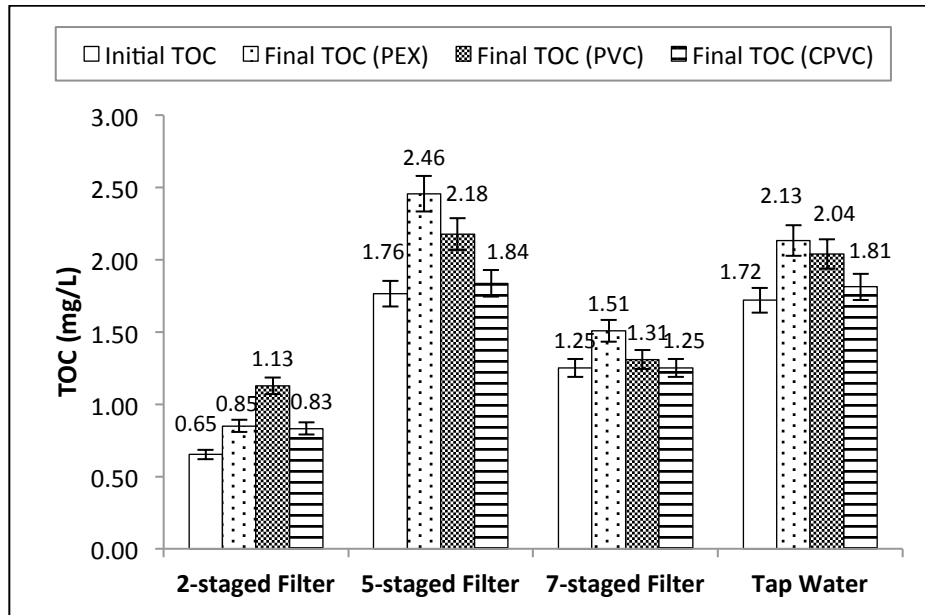


Figure 4.9. Change in TOC concentration of water samples from the RO filters after six days

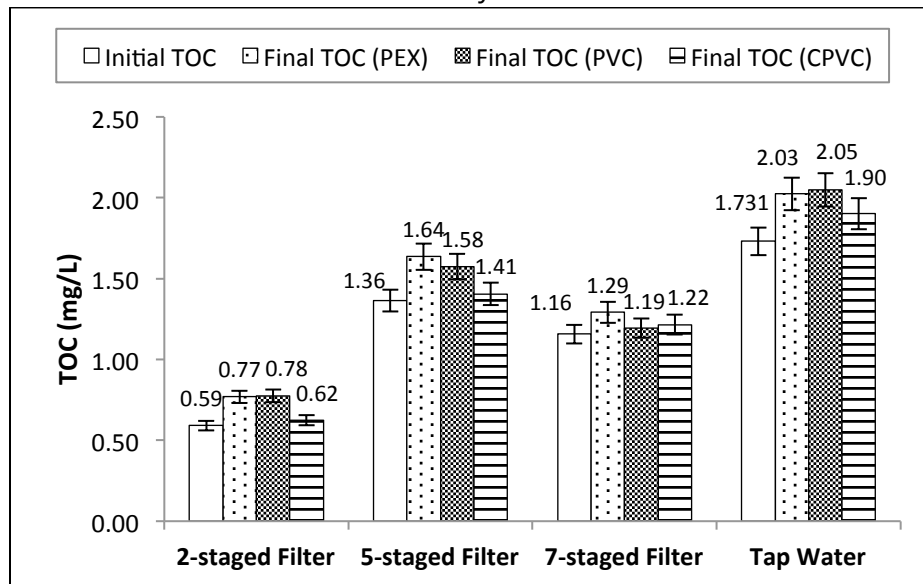


Figure 4.11. Change in TOC concentration of water samples from the RO filters after nine days

The percentage increase of TOC concentration as compared to the initial water samples of each of the leaching period, in the plastic pipes are shown in figures 4.12, 4.13 and 4.14 for the two-staged filter, five-staged filter and seven-staged filter respectively. In most of the samples, the increased percentage of the TOC concentration decreased with time. For instance, in the two-staged filter the 66% increase of TOC on the third day decreased to 30.14% on the sixth day and 30.11% on the ninth day in the PEX samples. Most of the PEX samples showed gradual decrease in the TOC percentage. Also, in all the three filter samples from the PVC pipes, there was a gradual decrease in values of TOC increment percentage from third day to ninth day. The samples from CPVC pipes, on the other hand, initially had decrease in TOC increment percentage values from the third day to the sixth day, but later they showed very slight increase in the TOC percentage on the ninth day. These reductions in TOC leaching, are similar to those described by other researchers^{50,51}. Generally, the gradual extraction of compounds from a sample material will lead to the decrease of concentration of migrates over time.

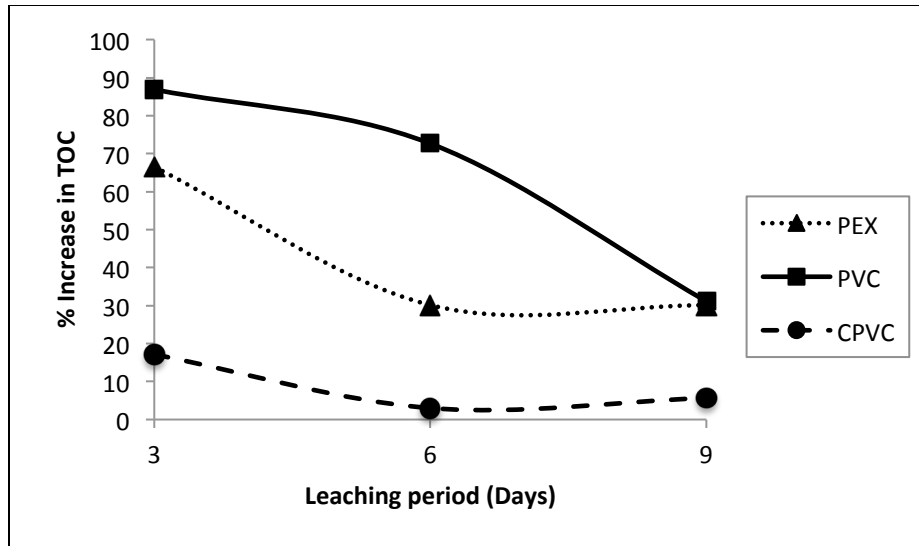


Figure 4.12. Percentage increment in TOC concentration from initial concentration after three, six and nine days in two-staged filter samples

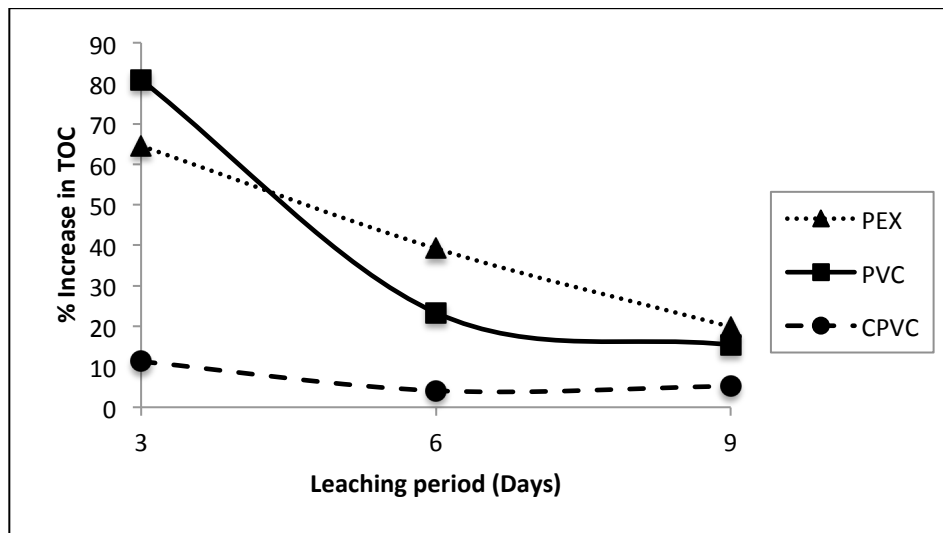


Figure 4.13. Percentage increment in TOC concentration from initial concentration after three, six and nine days in five-staged filter samples

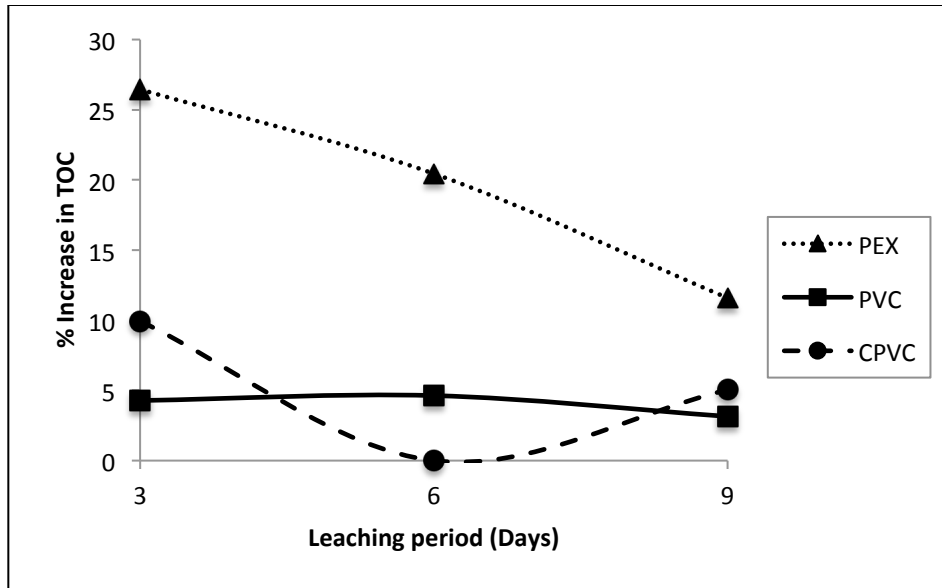


Figure 4.14. Percentage increment in TOC concentration from initial concentration after three, six and nine days in seven-staged filter samples

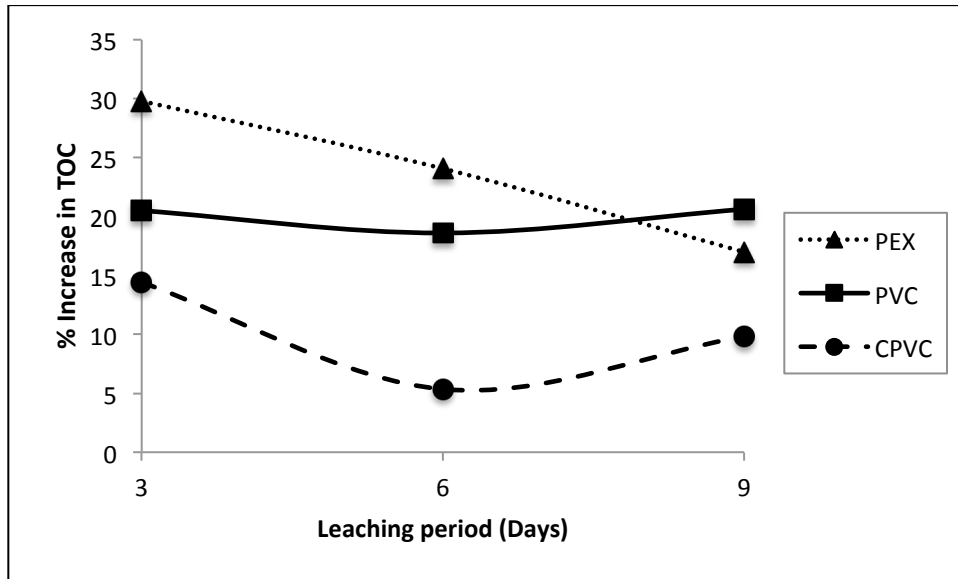


Figure 4.15. Percentage increment in TOC concentration from initial concentration after three, six and nine days in tap water samples

Chapter 5

Conclusion and Recommendation

5.1. Lead Coupon Immersion Test

5.1.1. Conclusion

The immersion corrosion test helped to quantify effects of the water quality parameters like pH, conductivity, hardness, and alkalinity on release of lead metal. This study showed that pH played an important role in lead corrosion; a lower level of pH led to an increase in lead release in the water samples. Conductivity also had a directly proportional effect on the lead release. The lower the conductivity or TDS amount, the more corrosion was observed in the lead coupons. Alkalinity and hardness had a similar effect before and after corrosion, less alkalinity and less hardness leading to more instances of corrosion.

Based on this study, the treatment stages used in the RO filtration system also had a significant effect on the corrosion of lead. The two-staged filter showed the most lead corrosion effect, and the seven-staged filter showed the least. The main reason behind the severe corrosion shown by the samples from the two-staged filter is the aggressive water quality of the samples, i.e. lower pH level, less alkalinity resulting in low buffering capacity, low conductivity and soft water. Such quality of the parameters,

as proved by other researches as well, has high chances of having a corrosion effect. The samples from the filters with a remineralization post-filter showed almost no corrosion effect (in case of seven-staged filter) or very light corrosion effect (in case of five-staged filter). The post filter increased the pH, hardness, alkalinity and conductivity significantly, making the water samples less corrosive. Therefore, the presence of a post-filter can significantly improve the water quality that inhibits corrosion of lead.

All the three filters had some extent of corrosion rate. This was somewhat expected with the use of new metal coupons as they are highly prone to corrosion. The corrosion rate of the two-staged filter samples was the highest; with the most number of lead coupon samples showing physical corrosion effect. With three out of six lead samples showing slight corrosion, the corrosion rate of the five-staged filter was less than the two-staged filter, but higher than the seven-staged filter. Only one of the samples from the seven-staged filter showed corrosion with the least corrosion rate as compared to other filters. The concentration of lead, however, was found to be greater than expected, most probably due to the vulnerable new coupons. Although new coupons were used, the results does show credibility based on the intensity and variation of corrosion among the various water qualities and treatment stages of the RO filters.

5.1.2. Recommendations for Future Research

As this experiment was conducted for forty days and with new lead coupons, there are potential improvements that can be used for better results. Some recommendations for further studies could be:

- i. Use of pre-corroded lead coupons to assess more accurate effect on old kitchen pipes.
- ii. Investigating the precipitates and deposits in the metal coupons and reactor bottles for better assessment of lead solubility and final concentrations in the water samples.
- iii. Analyzing other water quality parameters that may have properties related to corrosion effects, for better understanding of the corrosion variation caused by different water quality.

5.2. Leaching/Migration Test

5.2.1. Conclusion

The TOC release from various brands of plastic plumbing pipes was successfully quantified over the three consecutive 72-hours migration test. For the three different RO filter water, the PEX and PVC pipe samples showed substantial increase from the initial TOC concentrations, and the CPVC pipe samples showed almost none or minor increase in the TOC concentration. From this experiment, it can be concluded that the

PEX and PVC pipes are prone to organic carbon leaching as compared to the CPVC pipe. The two-staged filter showed the highest extraction of organic compounds in all of the three pipes, and the seven-staged filter showed the least extraction of TOC. In all the samples, including the control, the initial TOC leaching on the third day was higher than the subsequent leaching periods of six and nine days. Due to the steady removal of organic components from the pipe samples, the latter leachates were gradually decreasing. Consequently, the leaching of compounds in plumbing installations will be most noticeable shortly after operation.

5.2.2. Recommendations for Future Research

Although the quantification of TOC provides an idea about the leaching properties of the plastic materials, the total amount of TOC leached cannot be directly related to the amount of microbial growth supporting nutrients. Thus, analyzing other quality parameters like AOC (Assimilable Organic Carbon) is also required. Moreover, it is found that the release of organic components is higher at elevated temperature⁵⁰. Therefore, to assess for the worst-case scenario, testing could be done with stagnant samples at higher temperature. Another improvement could be by testing other varieties of the plumbing pipes as products that are made from the same polymeric material can have different migration properties because of different processes during production.

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