AWWA WQTC, Toronto Canada
November 12, 2018

Effectiveness of Point-of-Use/Point-of-Entry Systems to Remove Select Per- and Poly- fluoroalkyl Substances from Drinking Water

Source: Denver Post

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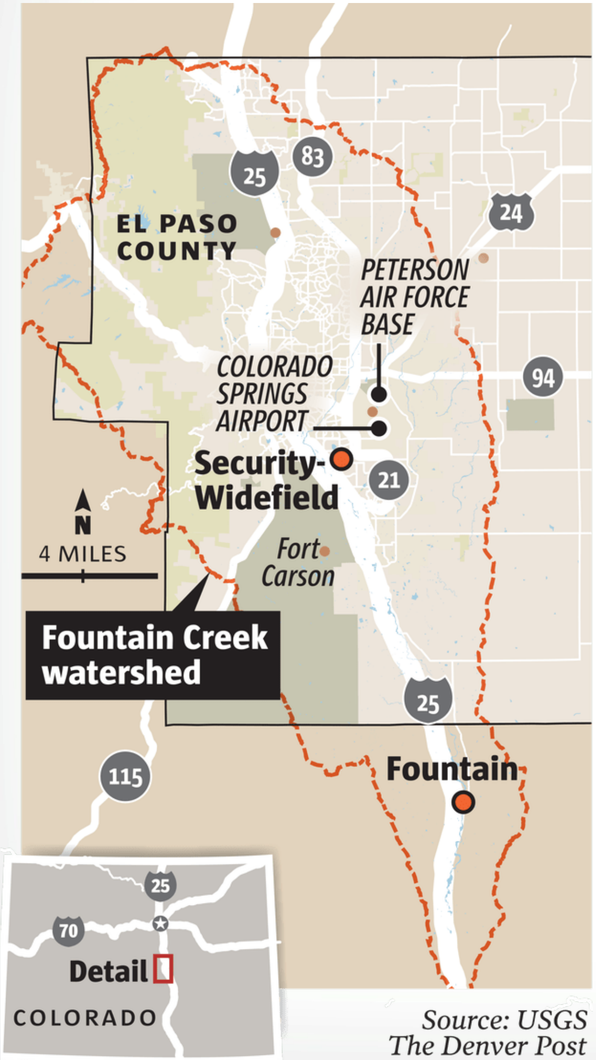
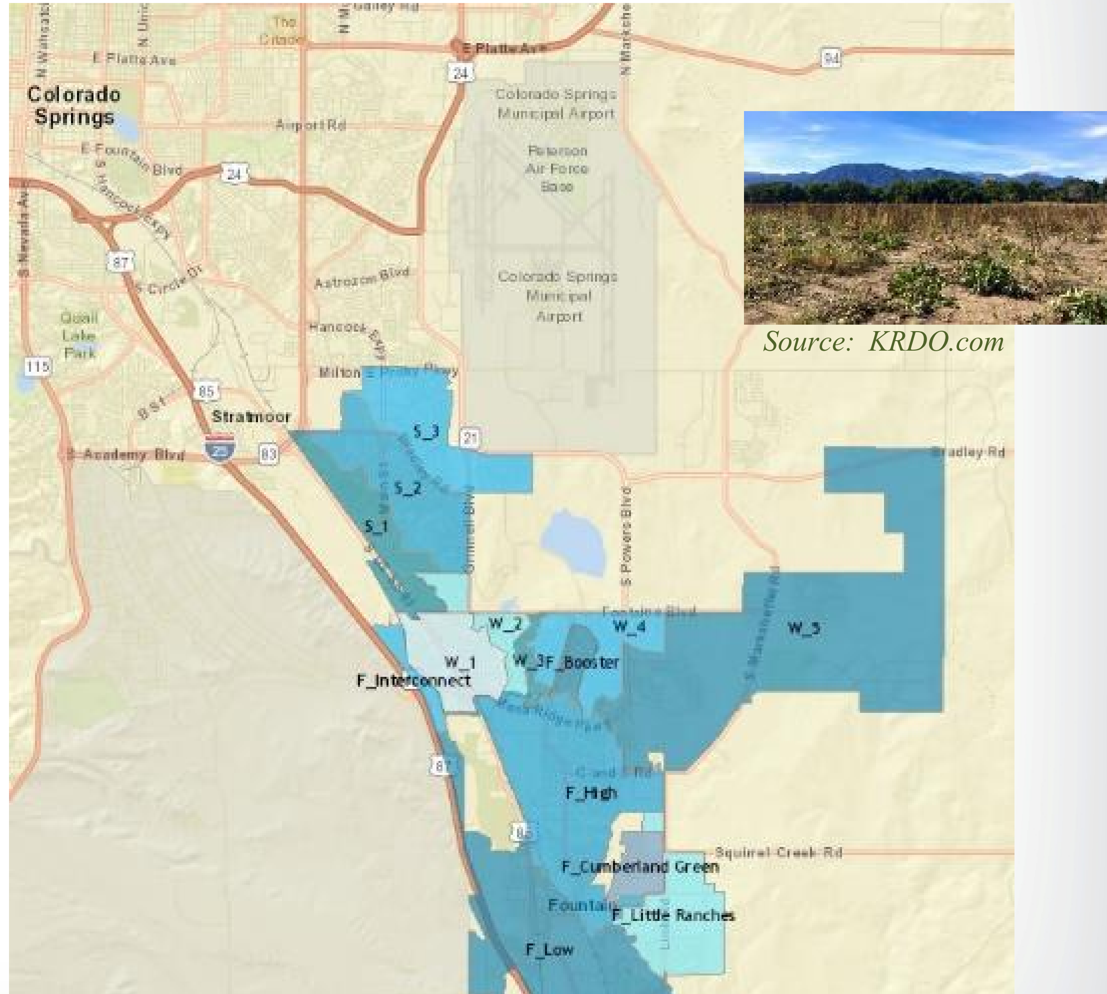
Extent of PFAS Contamination



Source: USGS
The Denver Post



Source: KRDO.com

Source: Esri, HERE, Garmin, NGA, USGS, NPS

PFAS Contaminants

Aqueous Film Forming Foam (AFFF) was used to fight fires at Peterson Air Force Base. As of August of 2016, a new product Phos-Chek 3 with shorter chain molecules is now being used.

U.S. Air National Guard photo by Airman 1st Class Amber Powell

Unregulated Contaminant Monitoring Rule 3 (UCMR3) PFAS detected in the Widefield Aquifer:

- Perfluorooctanoic Acid (PFOA)
- Perfluorooctane Sulfonate (PFOS)
- Perfluoroheptanoic Acid (PFHpA)
- Perfluorobutane Sulfonate (PFBS)
- Perfluorononanoic Acid (PFNA)
- Perfluorohexane Sulfonic Acid (PFHxS).

Potential health impacts: Cancer, liver, thyroid, pancreatic, kidney and fertility problems

Response Actions and Alternative Water Sources

- Surface water is being blended from Pueblo Reservoir to meet the PFOA/PFOS health advisory and PCE maximum contaminant levels (MCLs).
- Bottled water stations and water coolers provide alternative drinking water sources to residents living in the Widefield Aquifer region.

Source: Colorado Springs Gazette

Project Goal

To assess the removal effectiveness of target Per- and Poly- fluoroalkyl Substances (PFAS) using commercially available Point-of-Use (POU) and Point-of-Entry (POE) Reverse Osmosis (RO) treatment units and Granular Activated Carbon (GAC) adsorption systems for homes with private wells in Colorado's Widefield Aquifer. To meet this goal, the project purchased commercially available household water systems and conducted treatability studies on representative test waters.

Point-of-Use (POU)
Kitchen sink, end-of-faucet, and pour-thru devices

Point-of-Entry (POE)
Whole House; typically installed in a hot water tank room or a heated garage

R8 RARE Project Objectives

The project also documented:

- Ease of use during installation, startup, continuous and intermittent operation based on manufacturer instructions.
- Operation and maintenance schedules for replacement of RO units and GAC media based on manufacturer instructions and the representative test water quality.

Source: H2O Distributors

NSF Standard P473

NSF Standard P473 for Drinking Water Treatment Units - PFOA and PFOS is a test method for **point-of-use carbon-based and reverse osmosis treatment systems** to determine their ability to reduce perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) to below the EPA Healthy Advisory Level of 70 parts per trillion.

NSF Std P473	Individual influent sample point limits	Average influent challenge	Maximum effluent concentration
	µg/L	µg/L	µg/L
PFOS and PFOA	1.5 ± 30%	1.5 ± 10%, added as 1.0 µg/L PFOS and 0.5 µg/L PFOA	0.07

Water treatment systems, including water filters, must verify that:

- Contaminant reduction claims for PFOA and PFOS shown on the label are true
- The system does not add anything harmful to the water
- The system is structurally sound
- The product labeling, advertising and literature are not misleading

Widefield Aquifer PFAS

Maximum Widefield Aquifer PFAS Concentrations (ng/L)							
Sample Dates	PFBS	PFHxS	PFNA	PFHpA	PFOA	PFOS	PFOS+ PFOA
2013-2016	260	970	150	200	200	1600	1800

Average Widefield Aquifer PFAS Concentrations (ng/L)							
Sample Dates	PFBS	PFHxS	PFNA	PFHpA	PFOA	PFOS	PFOS+ PFOA
2013-2016	71	203	16	24	43	137	180

Source: Colorado Department of Public Health and Environment website.

Test Water
Target PFAS Composition

CAS Number	PFAS Compounds	Carbon Chain Length	Target Concentration
375-95-1	Perfluorononanoic Acid (PFNA)	**C9**	200 ng/L
335-67-1	Perfluorooctanoic Acid (PFOA)	**C8**	*800 ng/L
1763-23-1	Perfluorooctane Sulfonate (PFOS)	**C8**	1,600 ng/L
375-85-9	Perfluoroheptanoic Acid (PFHpA)	**C7**	200 ng/L
3871-99-6	Perfluorohexane Sulfonate (PFHxS)	**C6**	1,000 ng/L
375-73-5	Perfluorobutane Sulfonate (PFBS)	**C4**	300 ng/L

*To align with the NSF P473 specified 2:1 PFOS:PFOA ratio, the PFOA feed concentration was increased from 200 ng/L to 800 ng/L.

Widefield Aquifer WQ (1992-2016)

PARAMETER	MCL	MAX VALUE	UNITS
2,4,-D	0.07	0.10	mg/L
ALKALINITY TOTAL	NLE	220	mg/L as $CaCO_3$
ANTIMONY	0.006	0.00	mg/L
ARSENIC	0.01	0.06	mg/L
BARIUM	2	0.90	mg/L
BERYLLIUM	0.004	0.000	mg/L
CADMIUM	0.005	0.000	mg/L
CALCIUM	NLE	170	mg/L as $CaCO_3$
CHLORIDE	MSL = 250 MG/L	23	mg/L
CHROMIUM (TOTAL)	0.1	0.08	mg/L
COLOR (TRUE, APPARENT)	MSL=15 Color Units	<5.0	pt/Co Units
CONDUCTIVITY	NLE	470	uhm/Cm
COPPER	Action Level=1.3 mg/L	25	mg/L
CYANIDE	0.2	0.000	mg/L
DI(2-ETHYLHEXYL)PHTHALATE	0.006	0.0025	mg/L
EPICHLOROHYDRIN	NLE	3.1	mg/L
FLUORIDE	4.0	2.6	mg/L
GROSS ALPHA	15	14	pCi/L
HARDNESS CALCIUM	NLE	230	mg/L
HARDNESS TOTAL	NLE	290	mg/L as $CaCO_3$
IRON	MSL = 0.3 mg/L	BDL	mg/L
LANGLIER INDEX	NLE	-0.34 to -0.5	
LEAD	Action Level=0.015	0.012	mg/L

PARAMETER	MCL	MAX VALUE	UNITS
MAGNESIUM	MSL = 125 mg/L	18	mg/L
MANGANESE	MSL = 0.05 mg/L	BDL	mg/L
MERCURY	0.002	0.000	mg/L
MOLYBDENUM	NLE	BDL	mg/L
N_NITRATE / NITRITE	10.0 mg/L	7	mg/L
NICKEL	NLE	0.01	mg/L
NITRATE	10	9.8	mg/L
NITRITE	1	BDL	mg/L
PCE (TETRACHLOROETHYLENE)	0.005	0.033	mg/L
PENTACHLOROPHENOL	0.001	0.040	mg/L
pH	6.5-8.5	6.25 to 8.17	s.u.
PHOSPHATE, PHOSPHORUS	NLE	0.07	mg p/H
SELENIUM	0.05	0.01	mg/L
SODIUM	NLE	57	mg/L
TOTAL DISSOLVED SOLIDS (TDS)	MSL = 500 mg/L	490	mg/L
SPECIFIC CONDUCTIVITY	NLE	470	umhos
SULFATE	MSL=250 mg/L	116.00	mg/L
TEMPERATURE	NSF P473 20 ± 3 °C	13 to 15	deg. C
THALLIUM	0.002	0.000	mg/L
TOTAL ORGANIC CARBON (TOC)	NLE	1.19	mg/L
TOTAL SOLIDS	NLE	433	mg/L
TURBIDITY	1 NTU	<0	NTU
ZINC	MSL = 5.0 mg/L	BDL	mg/L

BDL= BELOW DETECTABLE LIMIT
MCL = MAXIMUM CONTAMINANT LEVEL
MSL = MAXIMUM SUGGESTED LEVEL
NLE = NO LIMITS ESTABLISHED

Test Water
Target Water Quality Characteristics

General Chemistry Water Parameters	
Temperature (°C)	RO: 25 ± 1°C, GAC: 20 ± 2.5°C
pH (pH Units)	8.2 ± 0.5
Turbidity (NTU)	<1 NTU
Free chlorine (mg/L)	<0.2 mg/L
TOC (mg/L)	RO: not specified (not adjusted) GAC: >1 mg/L (added as dehydrated NOM)
TDS (mg/L)	RO and GAC: 500 mg/L (added as NaCl)
Hardness (mg/L)	RO: 300 mg/L $CaCO_3$ (added as potassium chloride [KCl], magnesium sulfate [$MgSO_4$], sodium bicarbonate [$NaHCO_3$] and calcium sulfate [$CaSO_4 \cdot 2H_2O$]), GAC: not specified.

Sample Collection, Handling and Preservation

Analyte	Lab	Container	Preservation	Holding Time
Per-and poly-fluoroalkyl substances (PFAS)	R5	15 mL Polypropylene Container	Cool <6°C	28 days
Temperature blank	R5	One 40 mL Vial	Cool <6°C	Measure temperature upon receipt
Total Organic Carbon (TOC)	T&E	100 mL Amber Glass	Cool <6°C, No headspace H_3PO_4, pH<2;	28 days
Total Dissolved Solids (TDS)	T&E	1 L HDPE Amber	Cool <6°C	7 days
Turbidity	T&E	100 mL HDPE or glass jar or beaker	Cool <6°C	48 hours
Hardness	T&E	250 mL HDPE or glass jar	pH <2, HNO_3	6 months
Free Chlorine	T&E	40-50 mL / Glass beaker	None	Analyze Immediately
pH	T&E	40-50 mL / Glass beaker	None	Analyze Immediately
Temperature	T&E	40-50 mL / Glass beaker	None	Analyze Immediately

PFAS in Feed Water

5000 Gallon Mix Tank

RO PFAS	Target	Stability Test	RO Test 1	RO Test 2	RO Test 3
PFOA (ng/L)	800	899-967	878-1080	799-2580	800-1030
PFOS (ng/L)	1600	130-163	1370-2680	1100-6770	1290-2920
PFHpA (ng/L)	200	233-277	330-384	315-470	240-271
PFBS (ng/L)	300	Non-Detect	316-380	361-382	333-362
PFHxS (ng/L)	1000	889-1070	964-1150	844-1930	927-1130
PFNA (ng/L)	200	207-242	219-381	192-967	192-199

55 Gallon Drum

GAC PFAS	Target	Stability Test	GAC Test 1	GAC Test 2
PFOA (ng/L)	800	870-1150	926-1030	859-1070
PFOS (ng/L)	1600	139-288	1670-2740	1500-5210
PFHpA (ng/L)	200	240-296	277-332	267-287
PFBS (ng/L)	300	Non-Detect	360-405	347-379
PFHxS (ng/L)	1000	974-1180	999-1140	1020-1120
PFNA (ng/L)	200	208-304	245-310	231-448

WQ Results Summary

RO Test WQ Parameters	Target	Stability Test	RO Test 1	RO Test 2	RO Test 3
pH (s.u)	7.7-8.7	8.54-8.64	8.44-8.61	8.34-8.58	8.48-8.61
Temperature (°C)	24-26°C	24.9-29.1°C	22.0-23.1°C	21.8-23.1°C	22.0-24.4°C
TDS (mg/L)	500 mg/L	523-549 mg/L	514-576 mg/L	507-540 mg/L	446-456 mg/L
HARDNESS (mg/L)	300 mg/L	263-296 mg/L	285-323 mg/L	277-300 mg/L	240-298 mg/L

GAC Test WQ Parameters	Target	Stability Test	GAC Test 1	GAC Test 2
pH (s.u)	7.7-8.7	8.56-8.63	8.58-8.61	8.61-8.68
Temperature (°C)	17.5-22.5°C	20.9-26.5°C	20.7-22.3°C	19.6-20.3°C
FAC (mg/L)	< 0.2 mg/L	0.01 mg/L	0.02 mg/L	0.01 mg/L
TDS (mg/L)	500 mg/L	528-563 mg/L	466-466 mg/L	471-471 mg/L
TOC (mg/L)	> 1.0 mg/L	1.41-1.54 mg/L	2.35-2.52 mg/L	2.37-2.55 mg/L

Reverse Osmosis Systems

POU/POE treatment tests on three RO systems (500-1000 gal/day):

- iSpring RCS5T (0.35 gpm)
- Hydrologic Evolution (0.7 gpm)
- Flexeon LP-700 (0.5 gpm)

iSpring

Hydrologic

Flexeon

Sample Collection

Summary of RO System Specifications

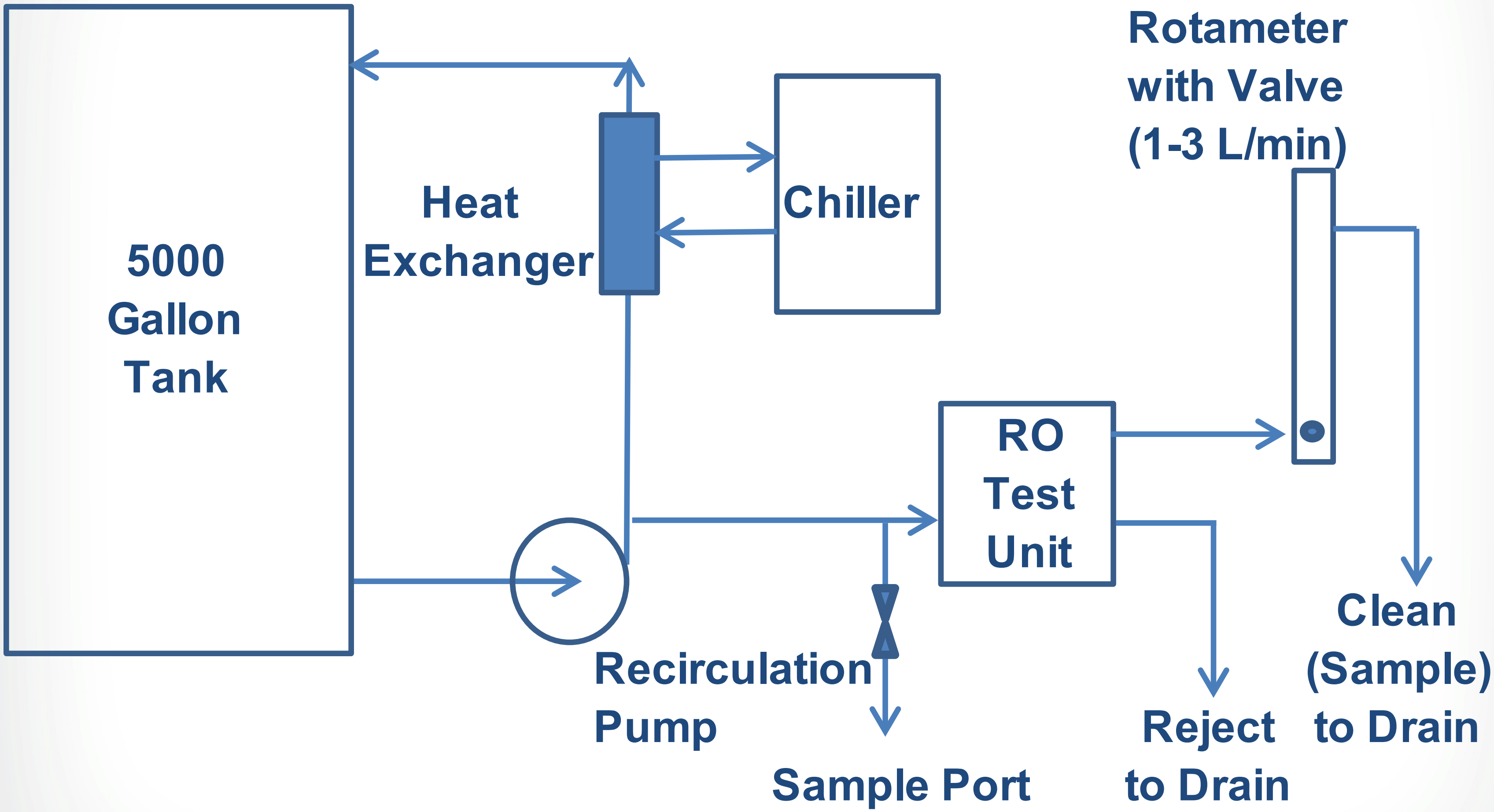
RO system	iSpring RCS5T	HydroLogic Evolution RO1000	Flexeon LP-700
Rated Capacity[A]	500 GPD (0.35 gpm)	1,000 GPD (0.7 gpm)	700 GPD (0.5 gpm)
Filters Included	Sediment filter Carbon pre-filter CTO filter RO membrane Carbon post-filter	Carbon pre-filter 2 RO membranes	Sediment filter Carbon pre-filter 2 RO membranes Carbon post-filter
System Recovery[A]	50%	50%, using 1:1 fitting	38%
Booster Pump	Yes	No	No
Connections	3/8” Inlet ¼” Outlet (tubing included)	½” Inlet 3/8” Outlet (tubing included)	3/8” Inlet and Outlet (tubing not included)
Self-Supporting	Yes	Yes	No
Size (L x W x H)	8.5” x 15” x 18.5”	20.5” x 11” x 10”	18” x 10.5” x 32”
Weight	31 lbs	16 lbs	38 lbs

[A] Pressure and efficiency depend on the temperature and pressure of the feed water.

RO System Replacement Filters and Membranes

RO system	iSpring RCS5T	HydroLogic Evolution RO1000	Flexeon LP-700
Sediment filter	#FP15 (3-6 months)	Not Part of System	#200627 (12 months)
Carbon pre-filter	#FG15 (6 months)	#22043 (2,000 gallons of purified water)	#200658 (12 months)
Carbon block filter	#FC15 (6 months)	Not Part of System	Not Part of System
RO membranes	#MS5 (24 months)	#220445 (6 – 24 months) (requires 2)	#208802 (24 months) (requires 2)
Carbon post-filter	#FT15 (12 months)	Not Part of System	#200658 (12 months)

Reverse Osmosis Test Unit



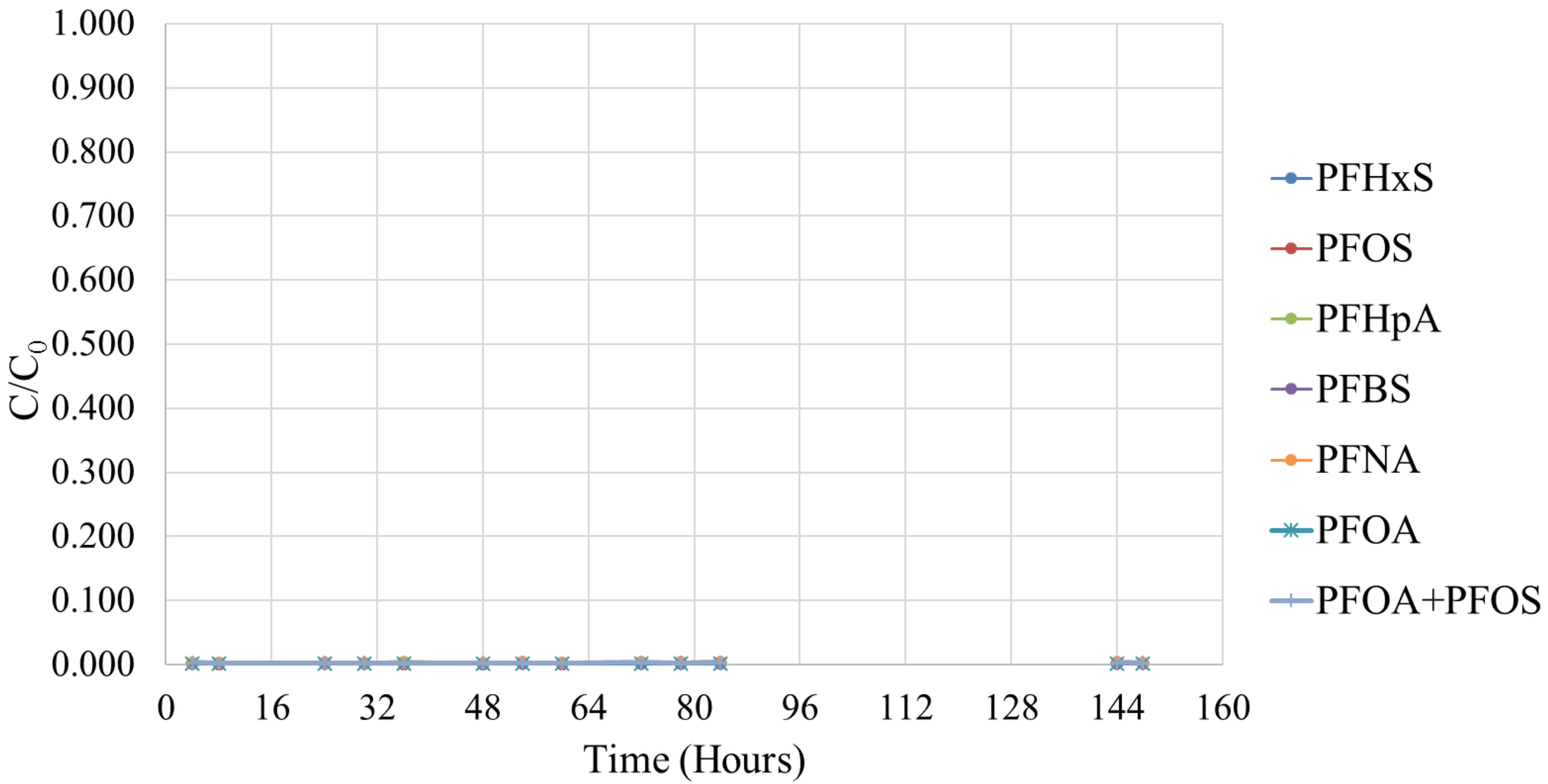
Sample Ports – Influent from 5000 gallon tank line and Effluent from RO permeate line.

RO System Sampling Plan

Day #	Day of Week	Time of Day	Sample Hour	Time of Day	Sample Hour	Time of Day	Sample Hour
Day 1	Tues	AM	Startup*	Noon	4 hr	PM	8 hr
Day 2	Wed	AM	24 hr	Noon	30 hr	PM	36 hr
Day 3	Thurs	AM	48 hr	Noon	54 hr	PM	60 hr
Day 4	Fri	AM	72 hr	Noon	78 hr	PM	84 hr
Day 5	Sat	2 Day Stagnation Period*					
Day 6	Sun						
Day 7	Mon	AM	144 hr	PM	148 hr	PM	Shutdown*
Day 8	Tues	Ship					

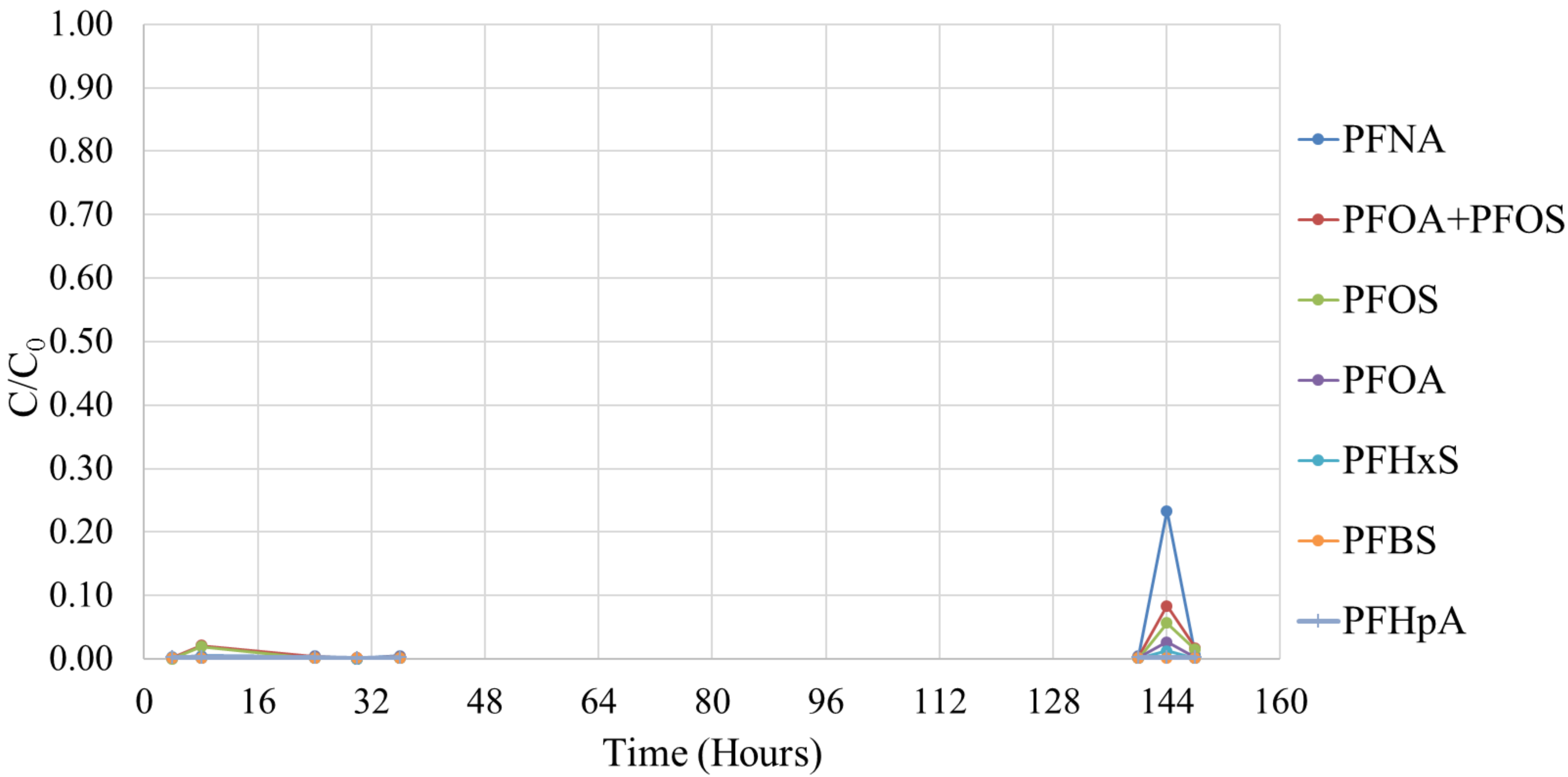
* No samples collected

PFAS Removal vs. Time
iSpring RO#1



All effluent PFAS results were non-detect

PFAS Removal vs. Time Hydrologic RO#2



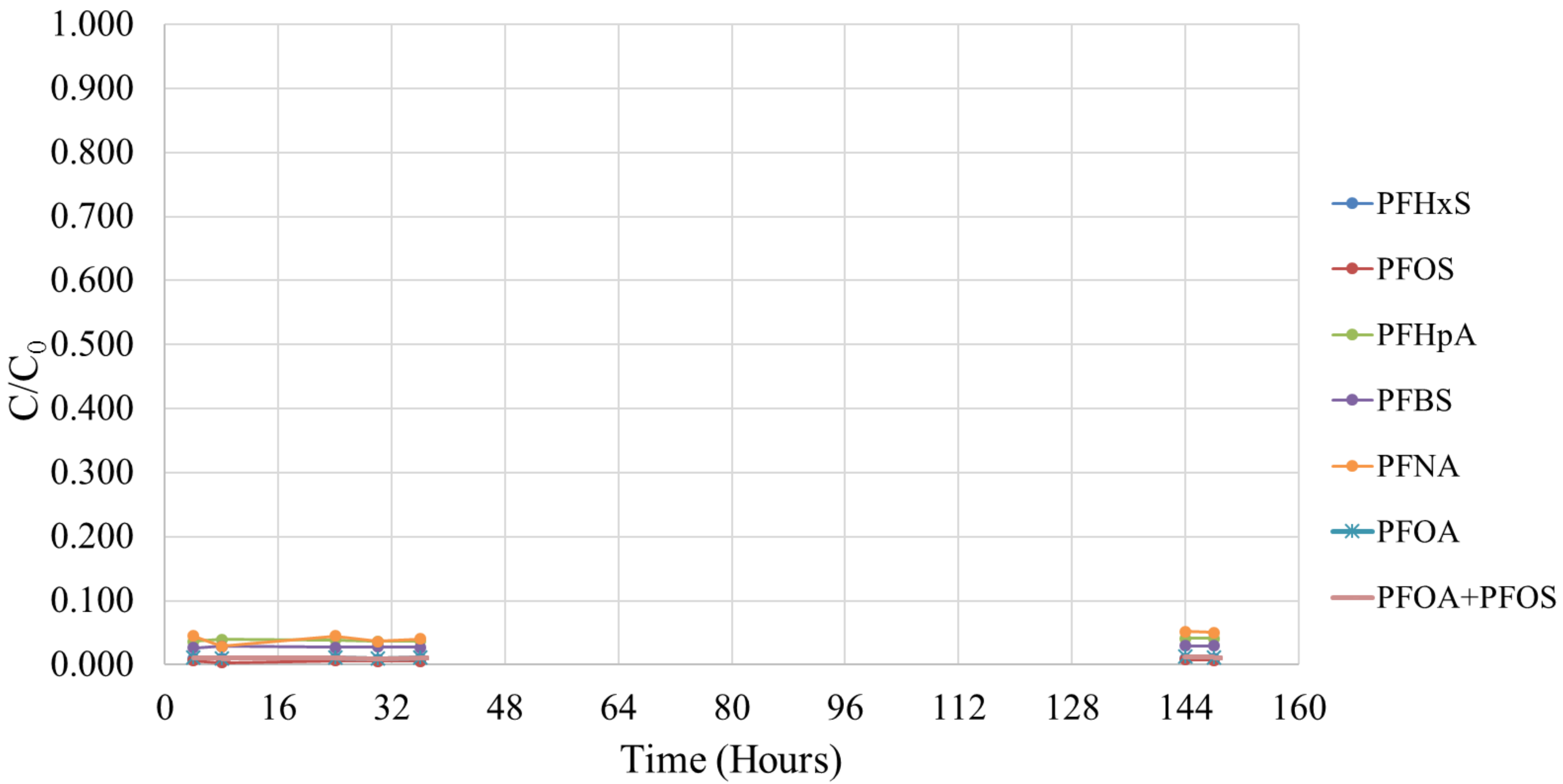
6 of 42 PFAS results were greater than non-detect

RO Test 2 PFAS Results > Non-Detect

PFC	Time (hr)	Influent Conc. (ng/L)	Effluent Conc. (ng/L)	Removal Efficiency (%)
PFOS	8	1100	22	98.0
PFOS*	144	1360	77	94.3
PFOA*	144	799	21	97.3
PFHxS	144	844	11	98.7
PFNA	144	210	49	76.7
PFOS	148	1330	20	98.5

* Exceeded the 70 ng/L PFOS+PFOA EPA Health Advisory Level

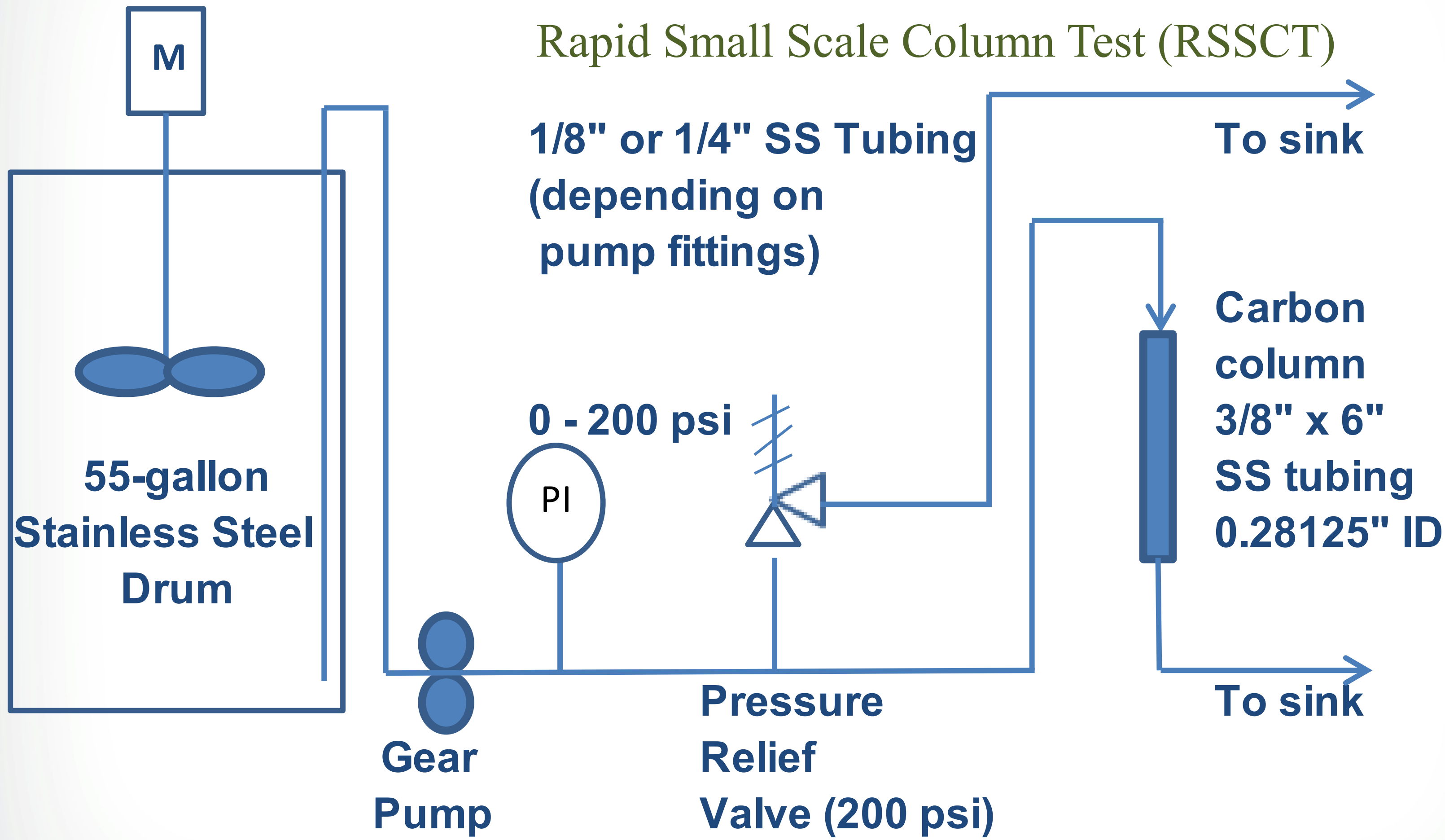
PFAS Removal vs. Time Flexeon RO#3



All effluent PFAS results were non-detect

GAC Test Unit

Rapid Small Scale Column Test (RSSCT)



Sample Ports – Influent from 55 gallon drum, Effluent from SS tubing every 30 min for 8 hrs.

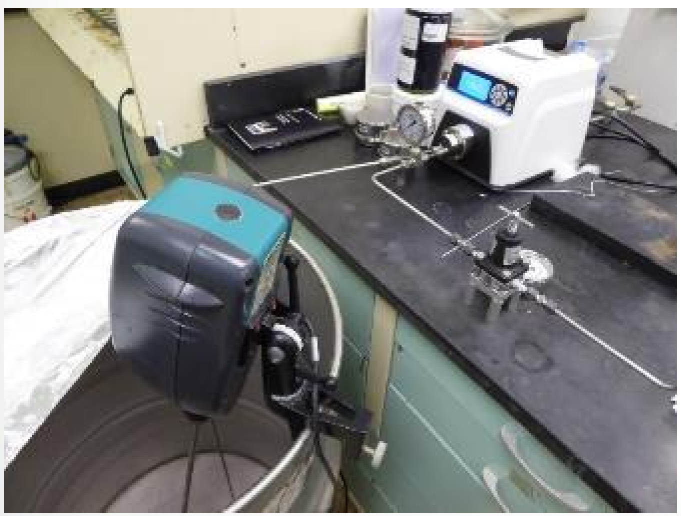
GAC Characteristics and RSSCT Design Parameters

Parameter	Test 1	Test 2
GAC	Evoqua 1230CX	Calgon Filtrasorb 600 AR+
Source	Coconut	Bituminous Coal
Density	0.45 g/cm^3	0.62 g/cm^3
Porosity	0.47	0.39
Mesh Size	12 x 30	12 x 40
$EBCT_{LC}$	10 min	10 min
$d_{p,LC}$	1.150 mm	1.063 mm
$d_{p,SC}$	0.0825 mm	0.0825 mm
Scaling Factor	194.3	165.9
Q_{SC}	10 mL/min	10 mL/min
V_{SC}	0.515 mL	0.603 mL
M_{SC}	0.2294 g	0.3742 g

GAC RSSCT Media

Commercially available GAC media tested:

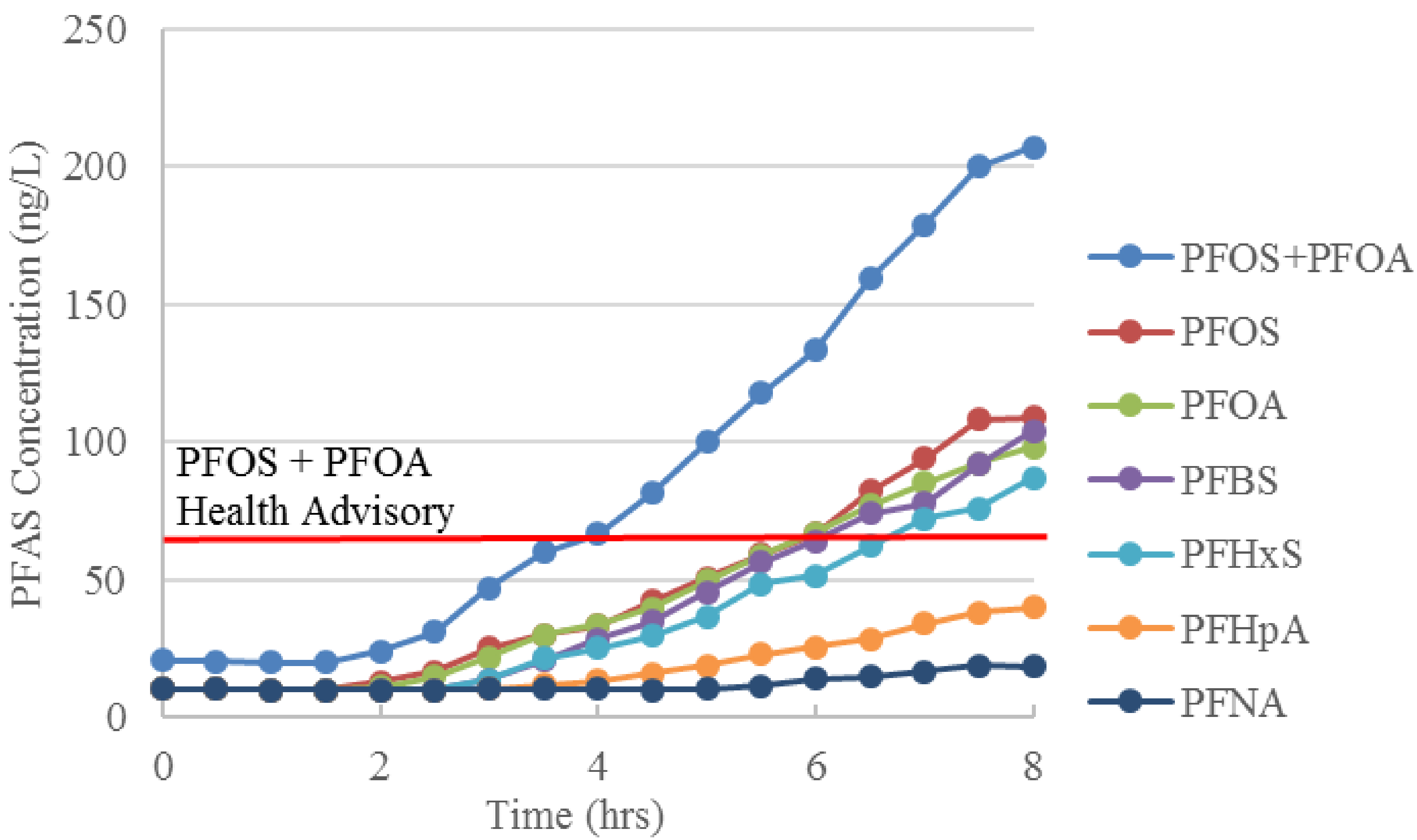
- Evoqua 12x30 Mesh RSSCT 170x200 Mesh
- Calgon 12x40 Mesh RSSCT 170x200 Mesh



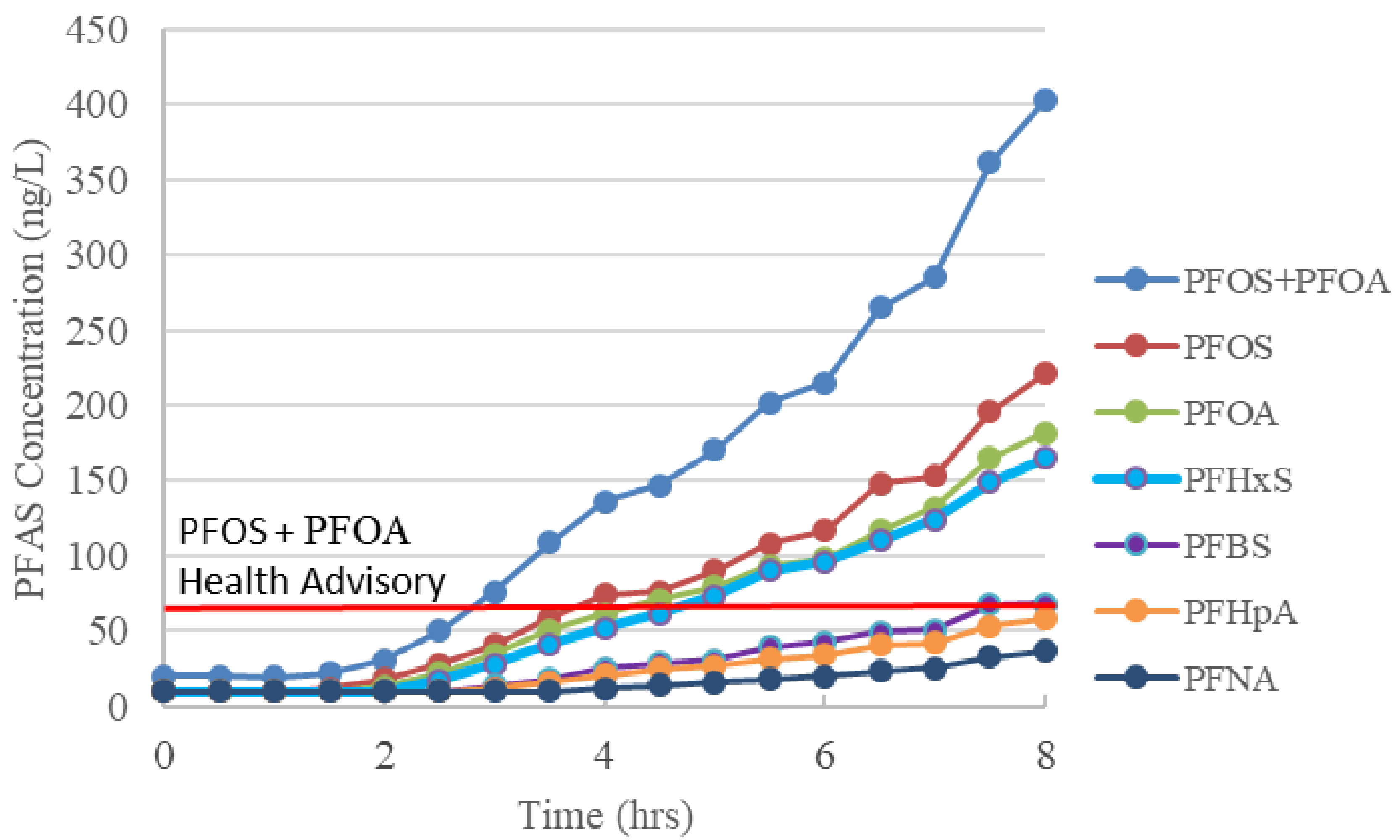
GAC

Grinding and Sieving GAC to meet RSSCT Mesh Screen Sizes

Maximum PFAS Concentrations vs. Time Evoqua GAC#1



Maximum PFAS Concentrations vs. Time Calgon GAC#2

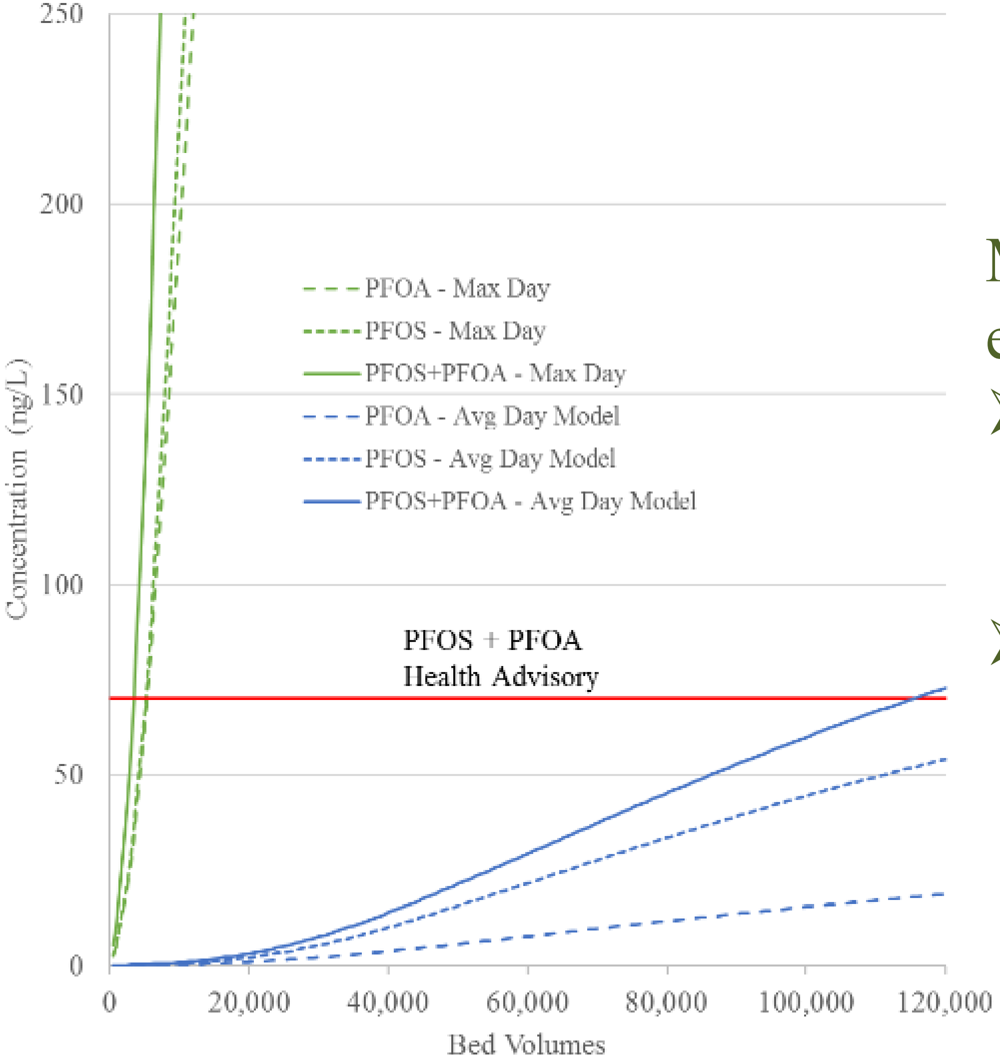


Modeling of GAC Results

- To investigate the impact of PFAS influent concentrations on GAC (bed volumes to breakthrough at 70 ng/L PFOS+PFOA), the AdDesignS™ model (Michigan Tech. Univ., v1.0, 1999) was used to predict GAC lifetime based on average PFOA (43 ng/L) and PFOS (137 ng/L) concentrations based on historic records (2013–2016) found in Widefield Aquifer region water samples.

- The PFOS+PFOA concentration in the influent was approximately 3,000 ng/L for the worst-case scenario and 180 ng/L for the average day (a 16-17x reduction). For the maximum day, the model predicted an exceedance of the PFOS+PFOA Health Advisory Level (HAL) of 70 ng/L after approximately 3,400 bed volumes for Evoqua GAC#1 and approximately 2,700 bed volumes for Calgon GAC#2, which is consistent with the experimental values.

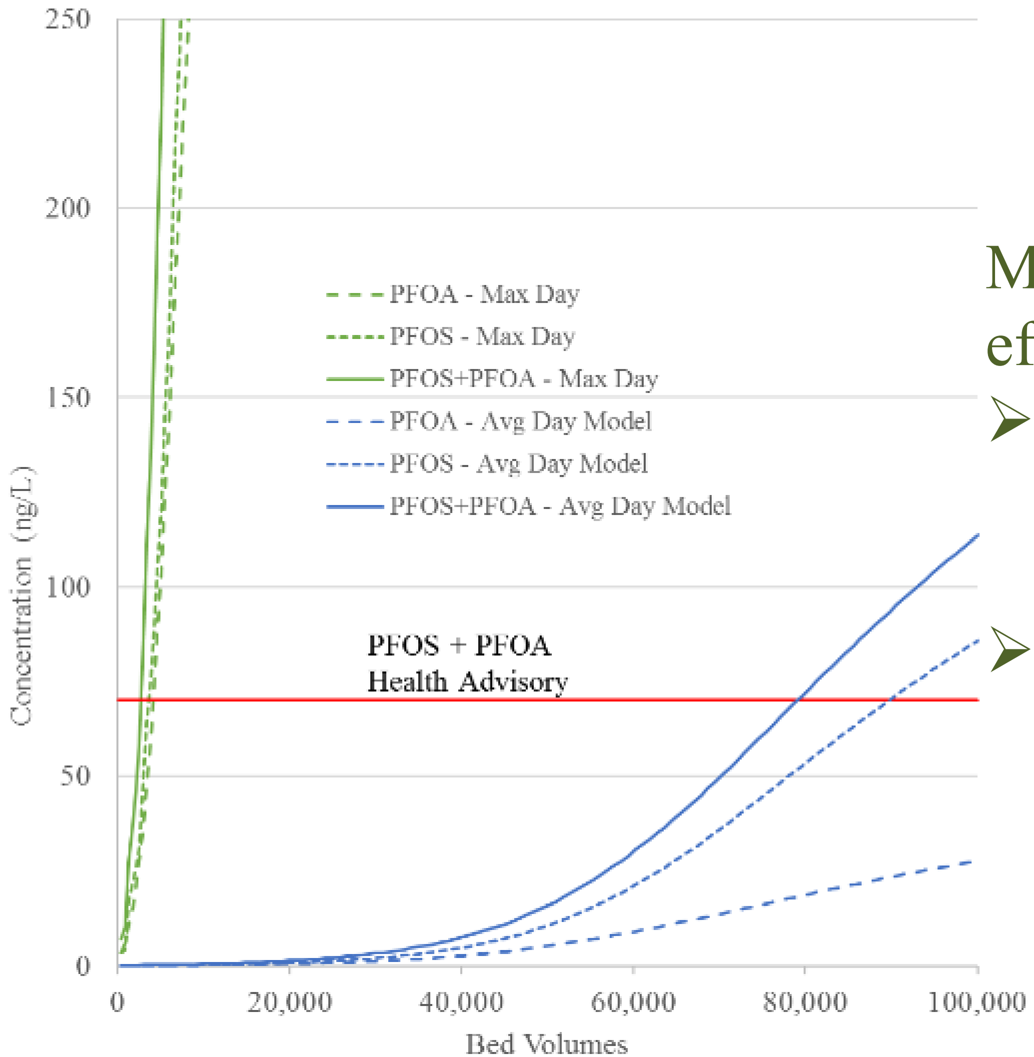
Average PFAS Conc. vs. Bed Volumes Evoqua GAC#1



Model results of PFOS and PFOA effluent concentrations

- Predicted Max. PFOS+PFOA > HAL of 70 ng/L after 3,400 BVs (24 days of operation)
- Predicted Avg. PFOS+PFOA > HAL of 70 ng/L after 115,000 BVs (2.2 years of operation)

Average PFAS Conc. vs. Bed Volumes Calgon GAC#2



Model results of PFOS and PFOA effluent concentrations

- Predicted Max. PFOS+PFOA > HAL of 70 ng/L after 2,700 BVs (19 days of operation)
- Predicted Avg. PFOS+PFOA > HAL of 70 ng/L after 79,000 BVs (1.5 years of operation)

RO Modification for Point-of-Entry Use

RO = $500

RO Booster Pump = $880

$280 67#
225
Gallons

6’2”

31”

Requires at least a 4’x4’ Room

May require a re-mineralization cartridge

28”

25”

= $2000 before installation, Weight: 150 lbs

Requires Electricity for Well, RO Booster and Water Storage Tank Pumps

Typical Household GAC System

Typical 4-5 GPM Non-Backwashing Whole House Carbon Filter with 5 and 1 micron pleated sediment cartridges (Source: H_2O Distributors)

Large Whole House Carbon Tanks Required for PFAS Removal (10 min EBCT each)

One 4-5 GPM Non-Backwashing Whole House Carbon Water Filter ($539) 35”(H) x 9”(D) tank with 30 lbs (1 cu ft) of GAC (Source: H_2O Distributors)

Two Large Whole House Backwashing Carbon Water Filter ($3990) 65”(H) x 16”(D) tank with 240 lbs (8 cu ft) of GAC (Source: H_2O Distributors)

GAC Modification for PFAS Removal

Well Water Flow must be restricted to 5 gpm

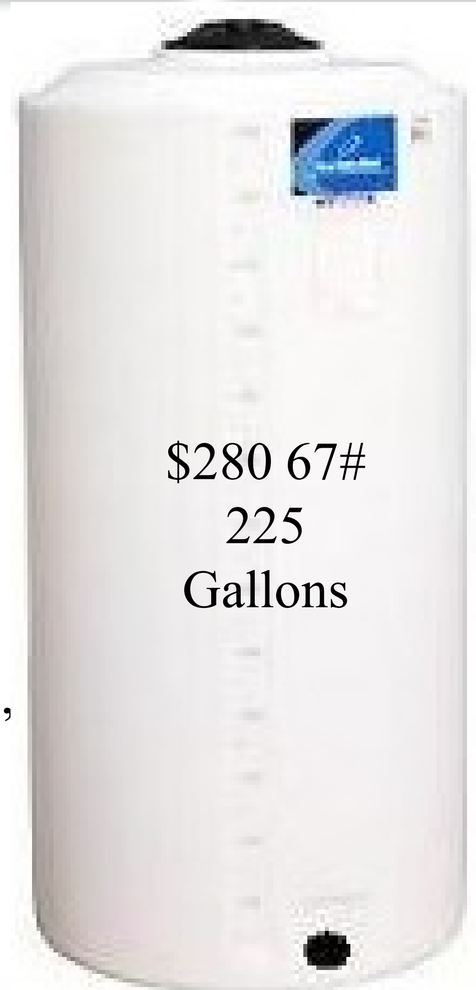
= $4000 before installation, Weight: 330 lbs

Small GAC System for PFAS Removal

Well Water Flow must be restricted to 0.5 gpm*

35’

9”



31”

Requires at least a 4’x4’ Room

6’2”

28”

25”

= $1200 before installation, Weight: 200 lbs

*Requires more frequent GAC replacement

Comparison of Household GAC and RO System Alternatives

Large GAC Adsorption System	Small GAC Adsorption System	RO System
High capital and high maintenance costs	Moderate capital and high maintenance costs	Moderate capital and maintenance costs
Large footprint and heavy components	Large footprint and awkward components	Large footprint and awkward components
Higher flow rate (4-5 gpm). No water storage tank required	Lower flow rate (0.5 gpm) requires water storage tank	Lower flow rate (0.3-0.7 gpm) requires water storage tank
Requires backwash wastewater lines and periodic carbon replacement	Fewer connections, but requires more frequent carbon replacement	Requires high system pressure, reject wastewater lines and periodic membrane replacement

Comparison of Household GAC and RO Systems

GAC Adsorption System	RO System
Issues with logistical, cost and safety of carbon replacement	Issues with sanitizing components and replacing cartridges & tubing
Cold water temperature less affected in flow through carbon tanks	Residents may complain about "cold" water at room temperature in water storage tank
May not be effective on short-chain PFAS	Treats both long- and short- chain PFAS
System could experience contaminant breakthrough if the carbon change-out schedule is not followed.	Less likely to have contaminant breakthrough even if scheduled maintenance is not performed. Corrosion control in household plumbing may be an issue for point-of-entry water treatment.

Conclusions

- The three RO systems tested successfully removed PFAS from the influent water to below analytical detection for a majority of the sampling events. However, long-term performance of the membrane systems was not tested.
- RSSCT data estimated that the coal-based Calgon F-600 GAC would have a lifetime of 20 days compared to the coconut-based Evoqua GAC lifetime of 33 days based on maximum PFAS concentrations tested before exceeding the EPA's HAL of 70 ng/L for PFOS and PFOA.
- Modeling the results for lower concentrations (average daily concentrations) gave bed lives of 1.5 years for the Calgon F-600 GAC and 2.2 years for the Evoqua Coconut carbon. However, additional pilot-tests should be performed to ensure the use of the best performing GAC for each application.

Conclusions

- If properly designed based on the source water characteristics, POU/POE water systems can provide relatively inexpensive treatment barriers for PFAS removal in the home.
- Analysis of PFAS samples is costly for homeowners and can be a major hurdle in effective removal of PFAS from household water supplies.
- Proper operation and maintenance and conservative replacement of POU/POE components and media may be one way to circumvent the high cost of monitoring treated household drinking water.

Disclaimer

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Questions?

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