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OCTOBER 3-5, 2023

Synergistic Defluorination and Mineralization of Perfluoroalkyl Substances (PFAS)

Dr. Bruce E. Rittmann, Director

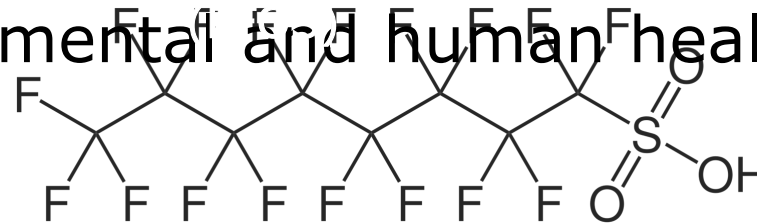
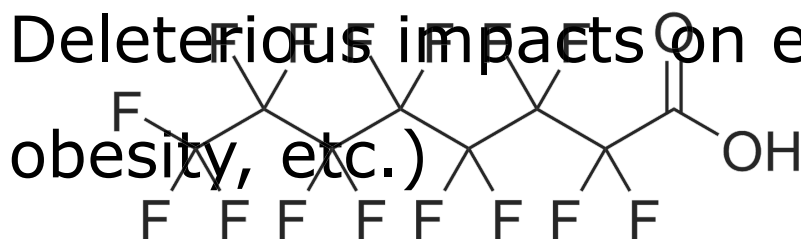
Biodesign Swette Center for Environmental Biotechnology

Arizona State University

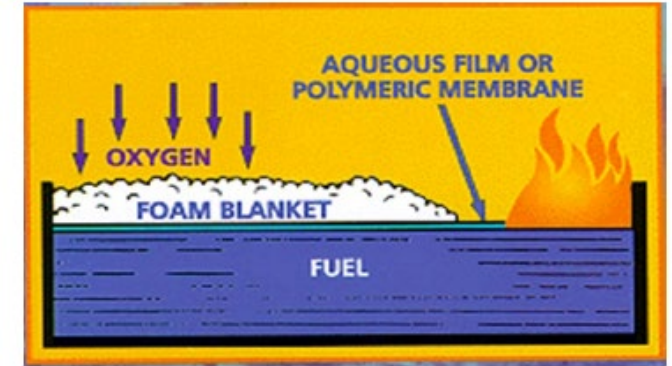
Tempe, Arizona

BRIEF INTRODUCTION TO PFAS

- Used as refrigerants and flame retardants
- In materials such as fabrics and food packaging
- Dominant agent for fighting fires at airports and military installations (**AFFF**)
- Widespread and persistent water contaminants (“forever compounds”)
- Deleterious impacts on environmental and human health (cancer, obesity, etc.)
- PFOA and PFOS are major components of AFFF



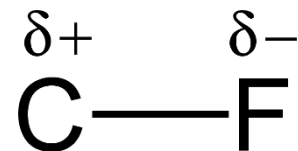
WHY IS AFFF SO USEFUL IN FIGHTING FIRES?



1. AFFF rapidly spreads across the surface of the fire and "suffocates" the combustion.
2. It does not itself combust; it is inert to reaction.

Properties of PFAS compounds

The C-F bond is the strongest in organic chemistry. Polar and short bond.



Bond dissociation energy

Bond	kcal/mol
C-F	105.4
C-H	98.8
C-O	84.0
C-C	83.1

F is very electronegative.

Table 1 Electronegativities of selected elements on the Pauling scale⁵

H (2.1)

Li 1.0	C 2.5	N 3.0	O 3.5	F 4.0
Na 0.9	Si 1.8	P 2.1	S 2.5	Cl 3.0
K 0.8				Br 2.8
Cs 0.7				I 2.5

We would love to biodegrade PFAS, but it is difficult because.....

The C-F bond is so strong
Perfluorination prevents enzyme access to target sites

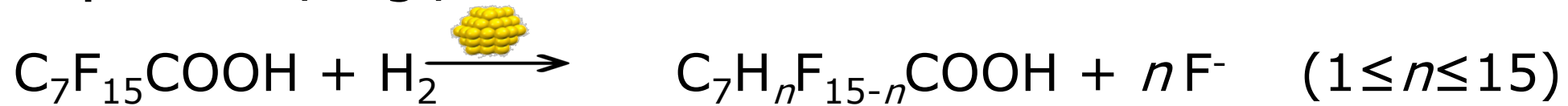
So, let's "knock off" some F substituents by taking advantage of the the strong

Reductive defluorination!

THE SYNERGISTIC PLATFORM

■ Stage 1:

H₂-induced defluorination catalyzed by precious-metal nanoparticles, e.g.,



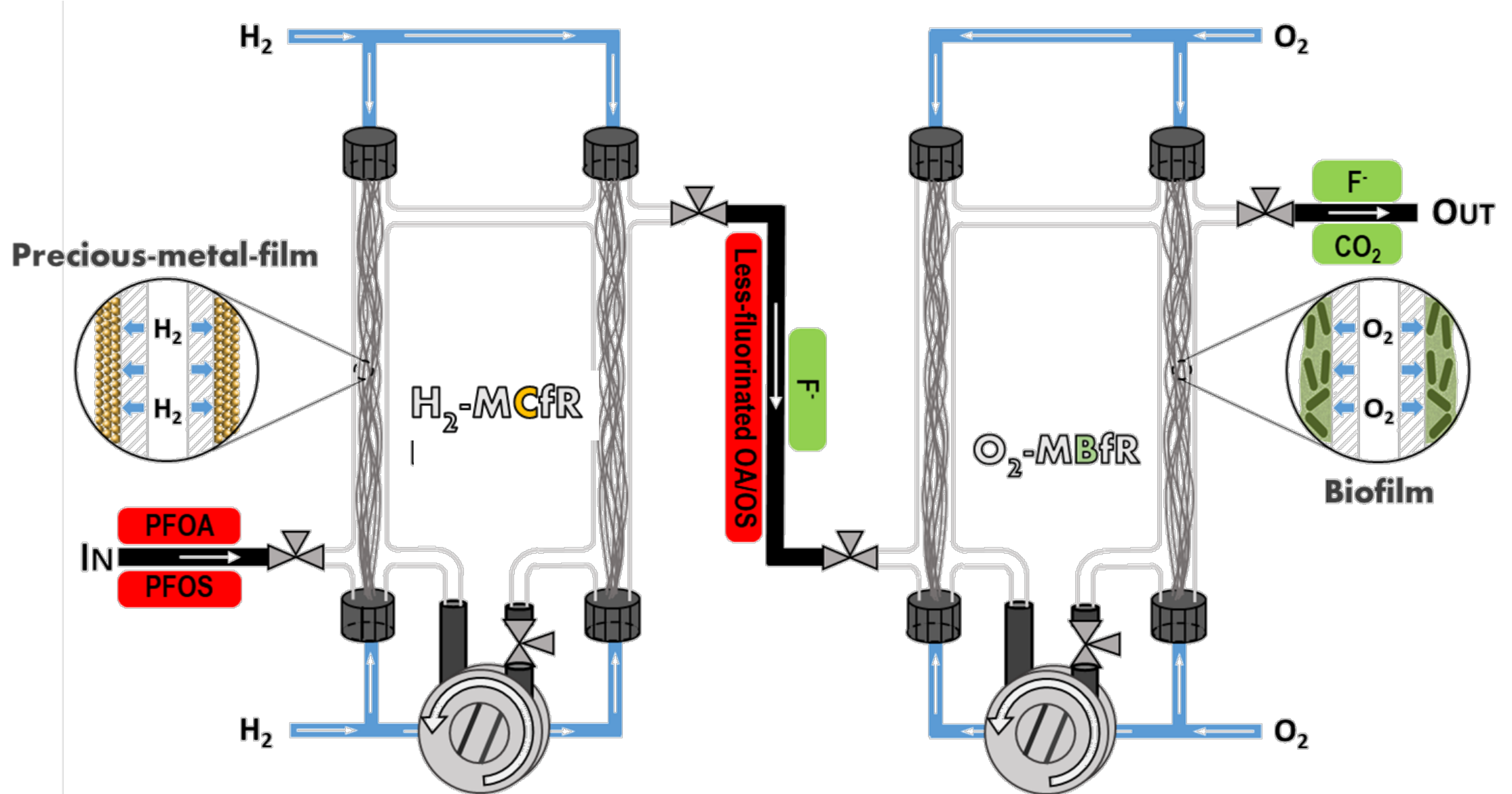
■ Stage 2:

O₂-induced mineralization mediated by microorganisms, e.g.,



THE SYNERGISTIC PLATFORM

Defluorination and mineralization of PFAS



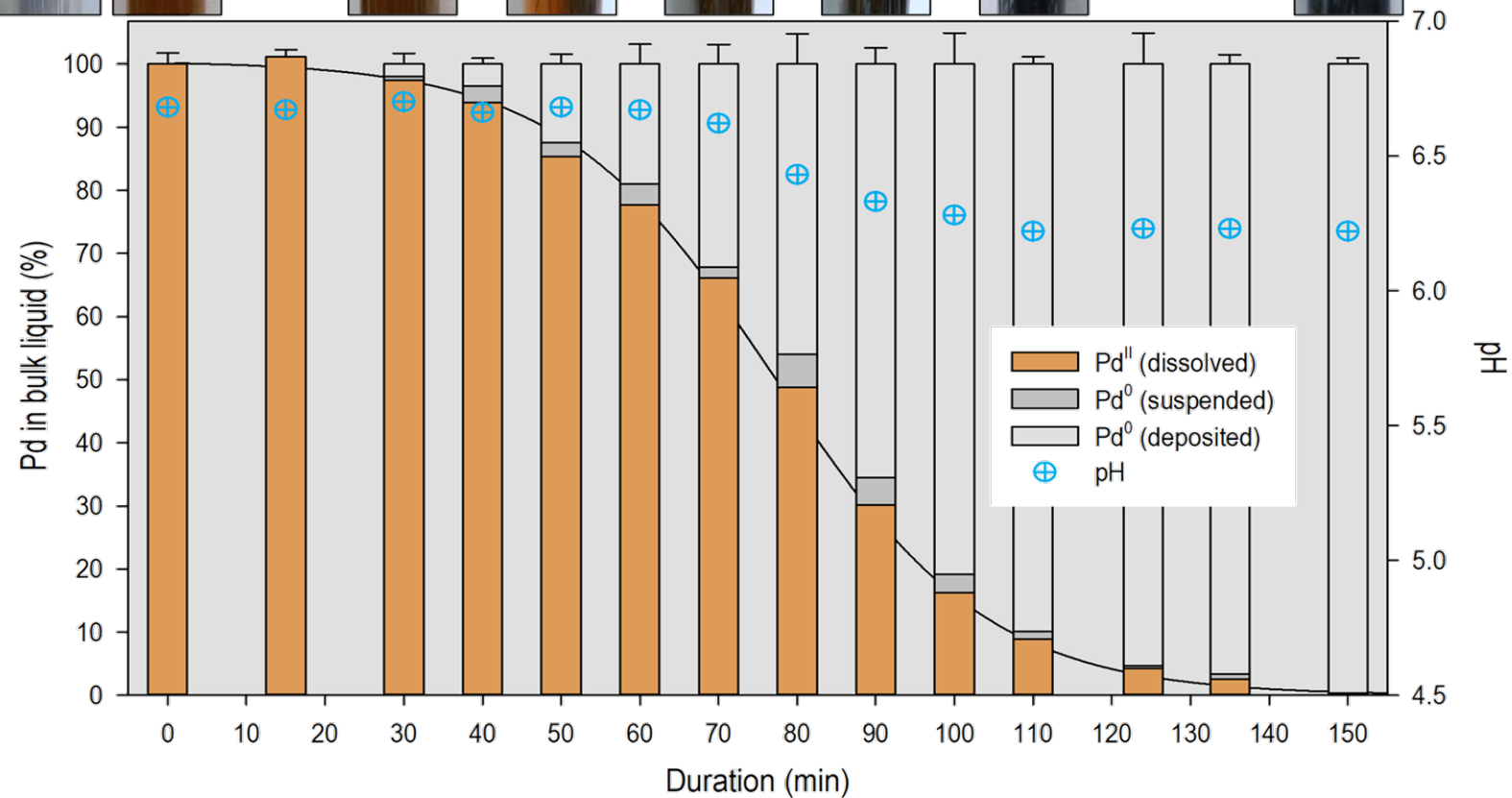
I will present extensive results for PFOA today.

We also have extensive results for PFOS, and they are similar to the results for PFOA.

Less-extensive results are likewise similar for GenX, PFBS, PFNA, and PFHXS.

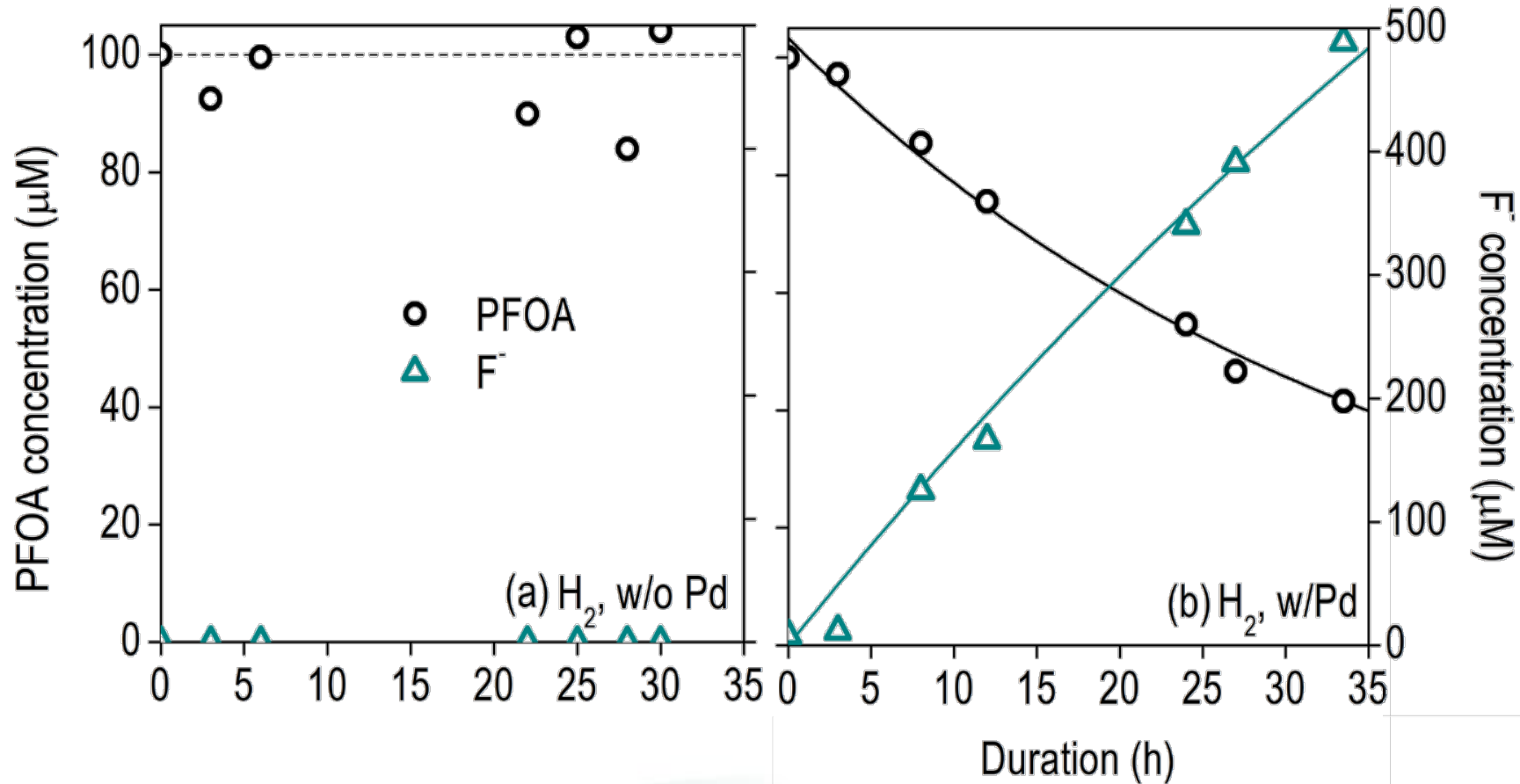
Reductive Defluorination in the H₂-based MCfR

In situ Synthesis and Deposition of Pd⁰ on gas-transfer membranes



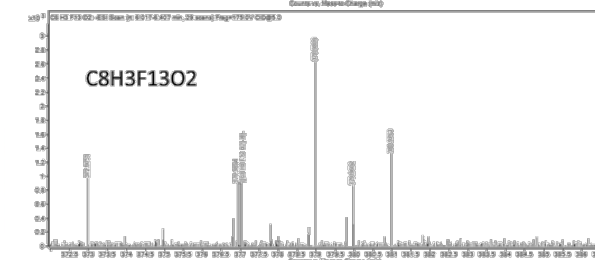
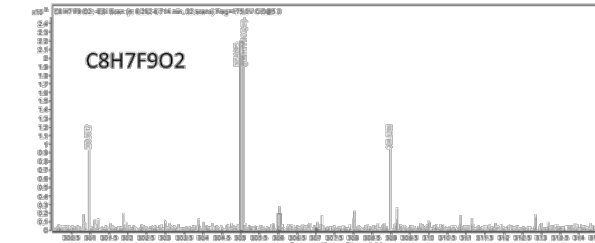
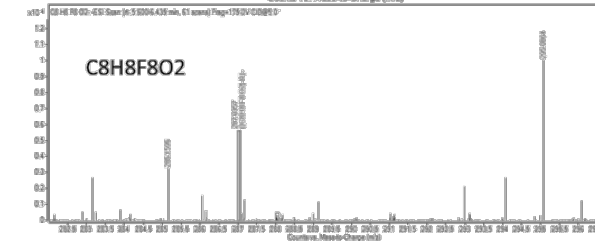
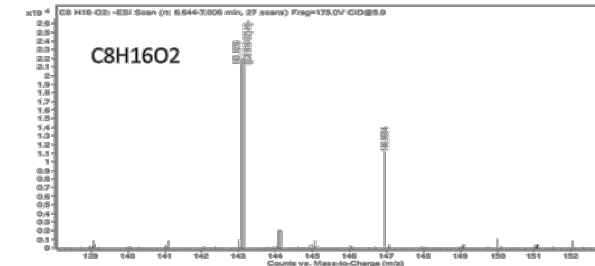
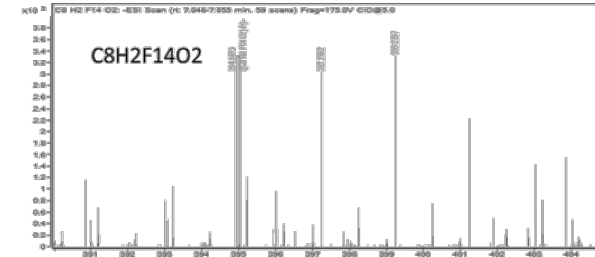
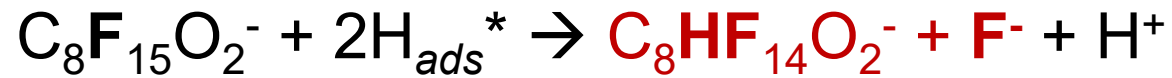
Catalytic defluorination in the H₂-MCfR (1)

Pd⁰ is capable of catalyzing reductive defluorination of PFOA



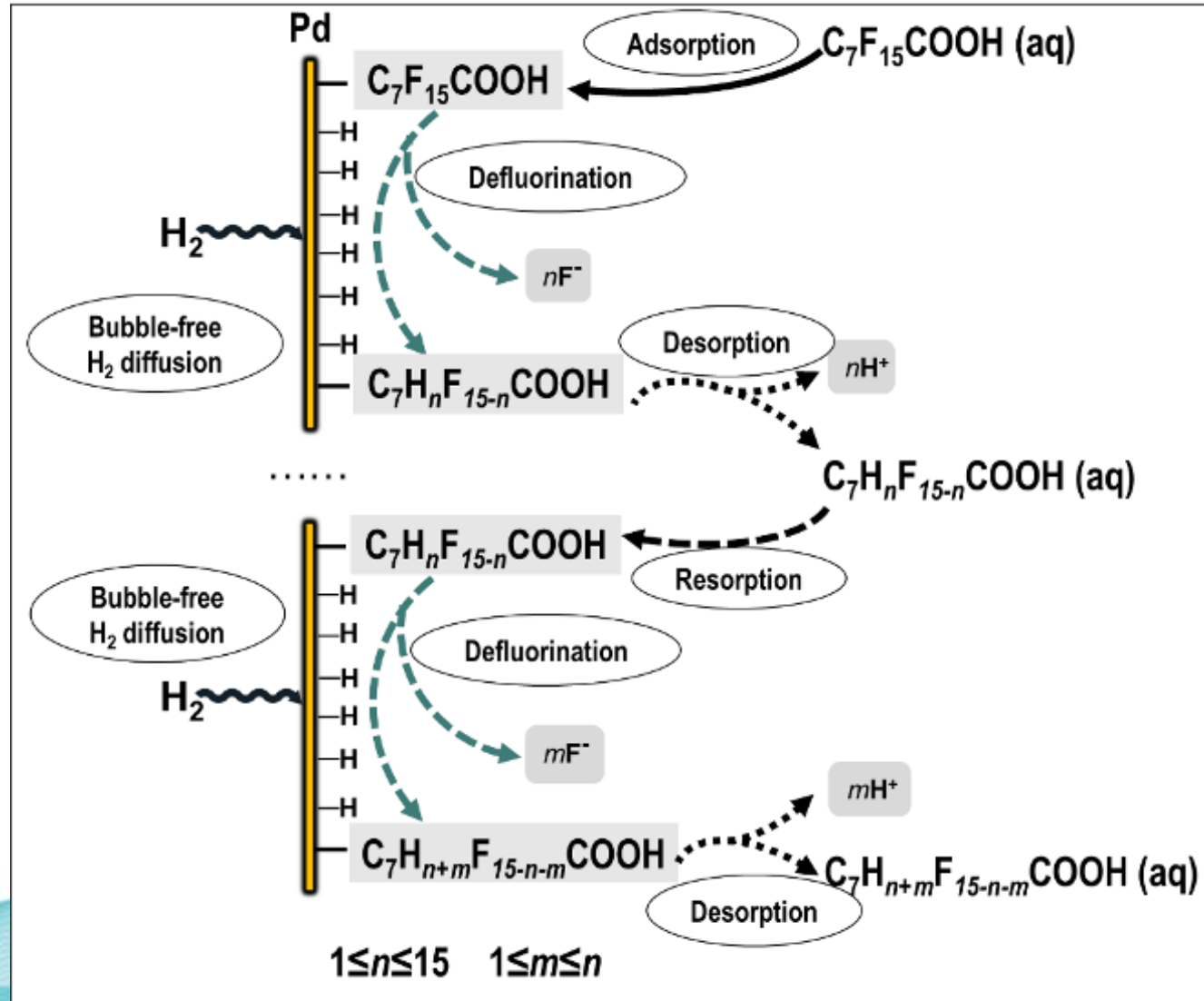
Catalytic defluorination in the H₂-MCfR (2)

Products of Pd-catalyzed defluorination:
partially to totally defluorinated OAs



Catalytic defluorination in the H₂-MCfR (3)

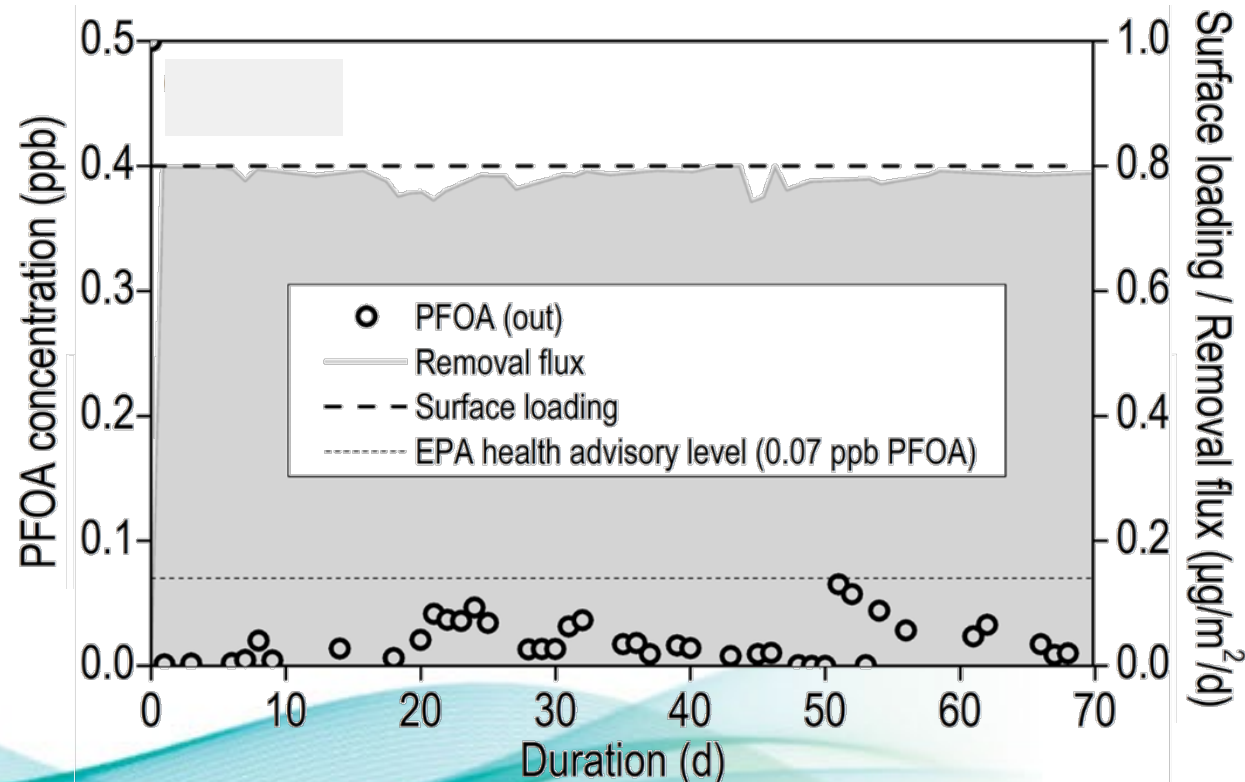
Mechanisms – Adsorption and Hydrodefluorination



Catalytic defluorination in the H₂-MCfR (4)

70-day continuous tests

- >99% PFOA removal within one day
- Effluent PFOA 20 ± 16 $\mu\text{g/L}$ (less than 1/3rd the EPA health-advisory level)

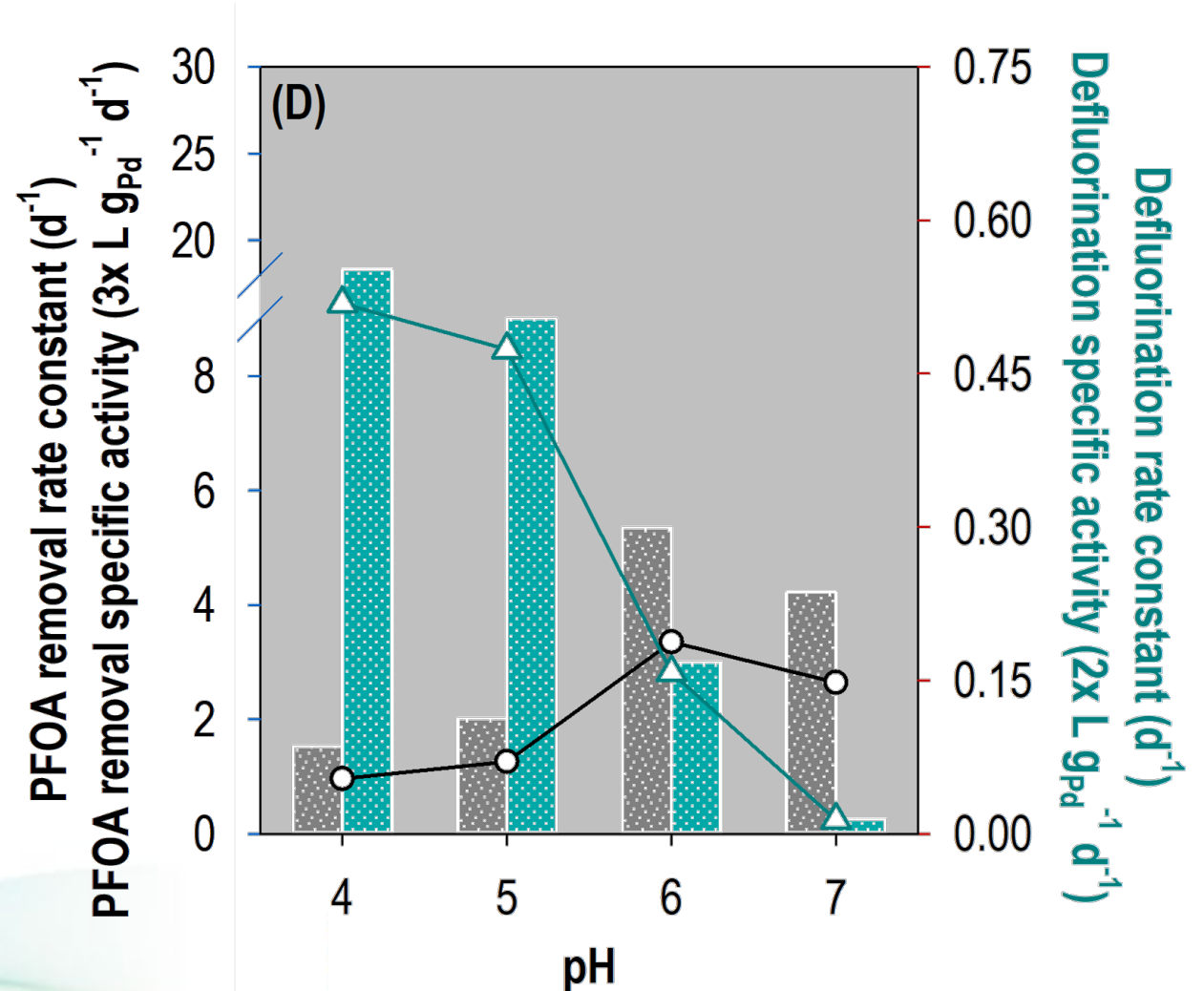


- ◆ 400 $\mu\text{g/L}$ PFOA
- ◆ 0.9 mg/m^2 Pd⁰NPs
- ◆ 2.4 atm H₂ supply
- ◆ pH 4

Catalytic defluorination in the H₂-MCfR (5)

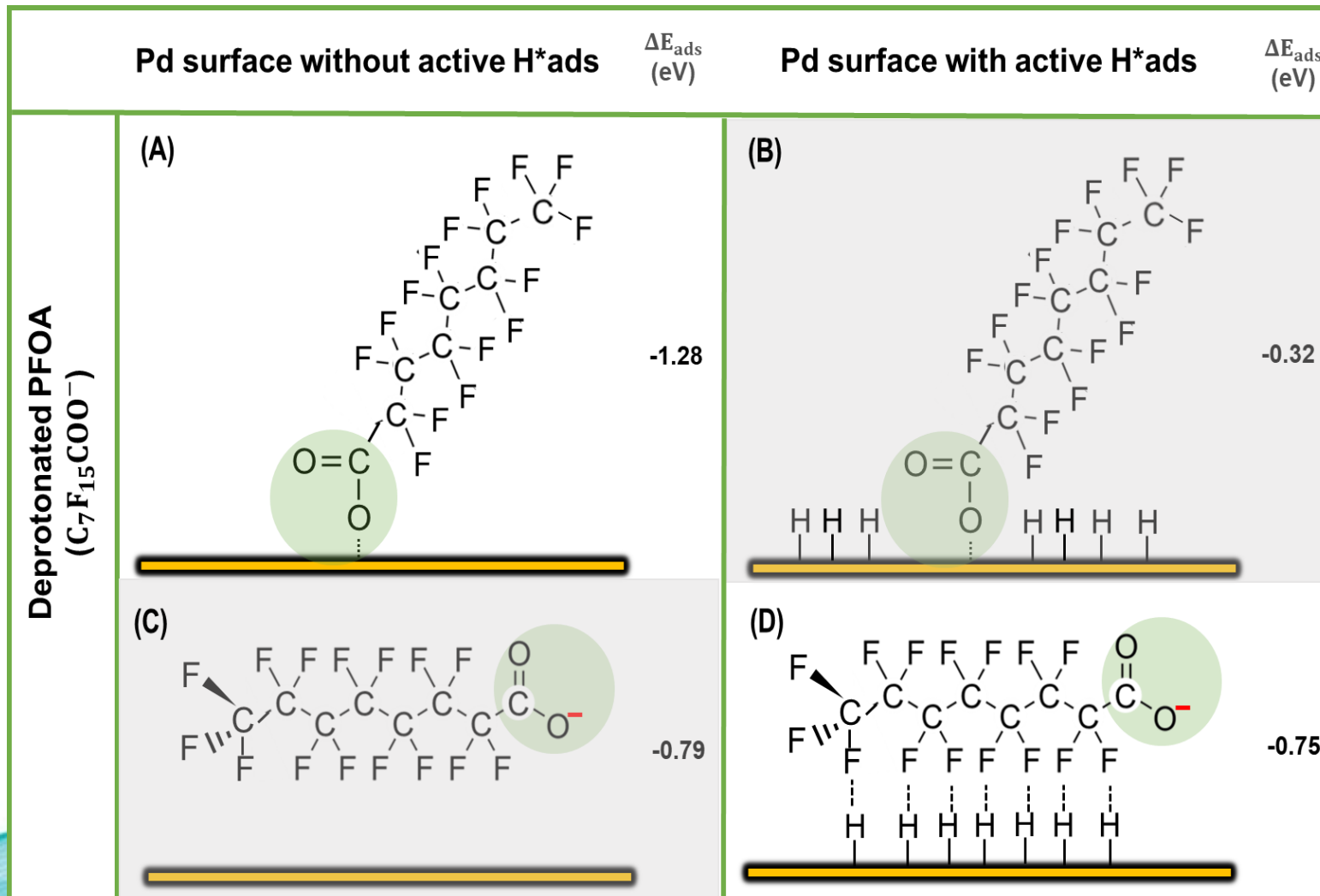
A potential pitfall of monometallic catalysts:

- Slower defluorination at increasing pH over 4
- Minimal defluorination for neutral pH



Catalytic defluorination in the H₂-MCfR (6)

Density Function Theory (DFT) tells us why the large pH effect. At higher pH, the PFOA anion outcompetes H for chemisorption. Low-pH physisorption allows adsorption of reactive H.



Catalytic defluorination in the H₂-MCfR (7)

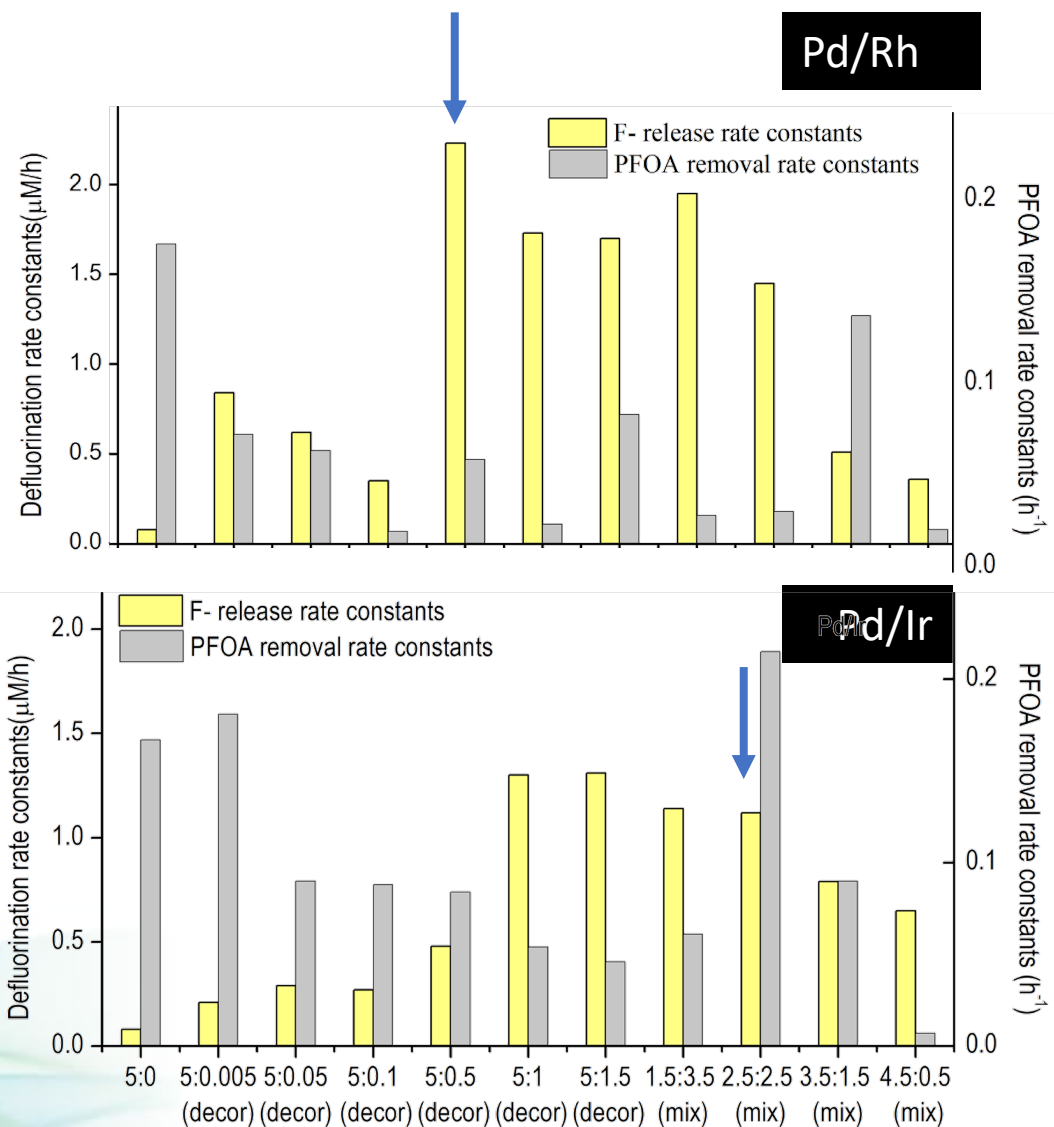
Pd-based **Bimetallic** catalysts:

- Type, coating method, and mass ratio affect defluorination efficiency

- Promising catalysts so far:

Pd/Rh (5:0.5 mol/mol decor)

Pd/Ir (2.5:2.5 mol/mol mixed)

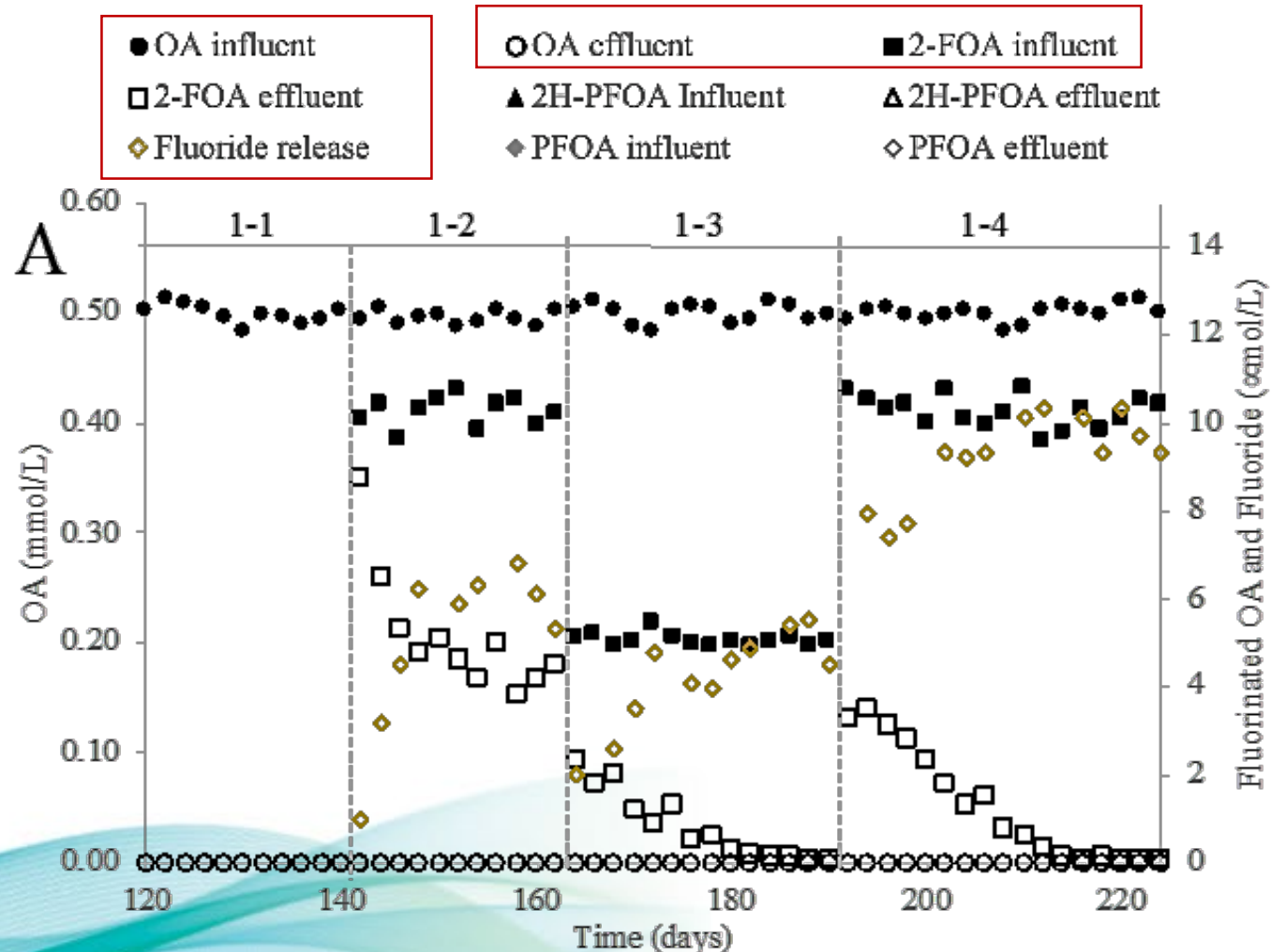


Oxidative Defluorination and Mineralization in the O₂-based MBfR

Microbial degradation in the O₂-MBfR (1)

Continuous operation:

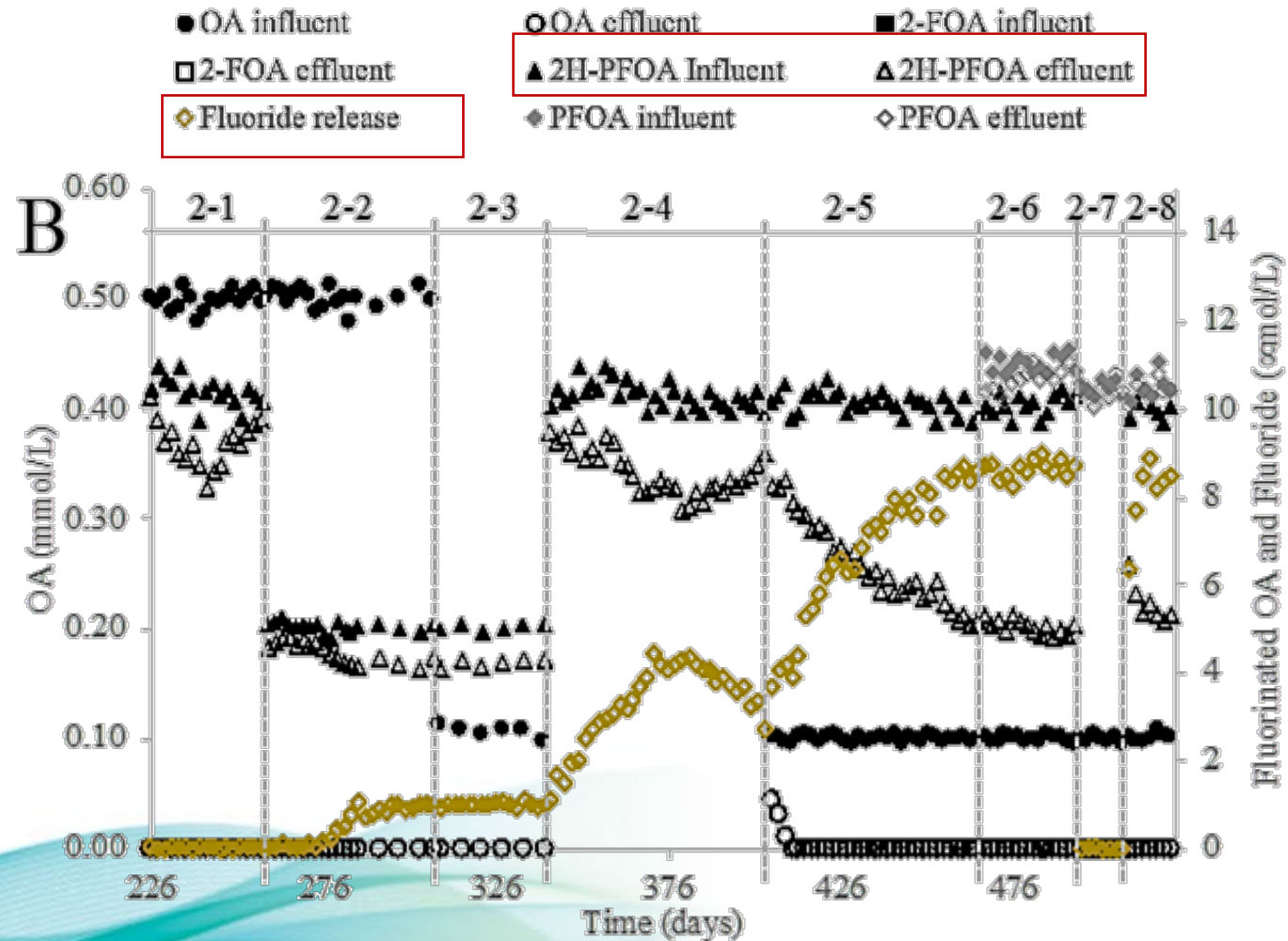
- OA-oxidizing biofilm was able to oxidatively defluorinate mono-fluoro-OA



Microbial degradation in the O₂-MBfR (2)

Continuous operation:

- OA-oxidizing biofilm was able to oxidatively defluorinate 2H-PFOA



Microbial degradation in the O₂-MBfR (4)

The heat map of relative abundances of genes related with β -oxidation shows that four had relatively higher abundances (CPM > 100, red coloration) than other genes, particularly in later stages.

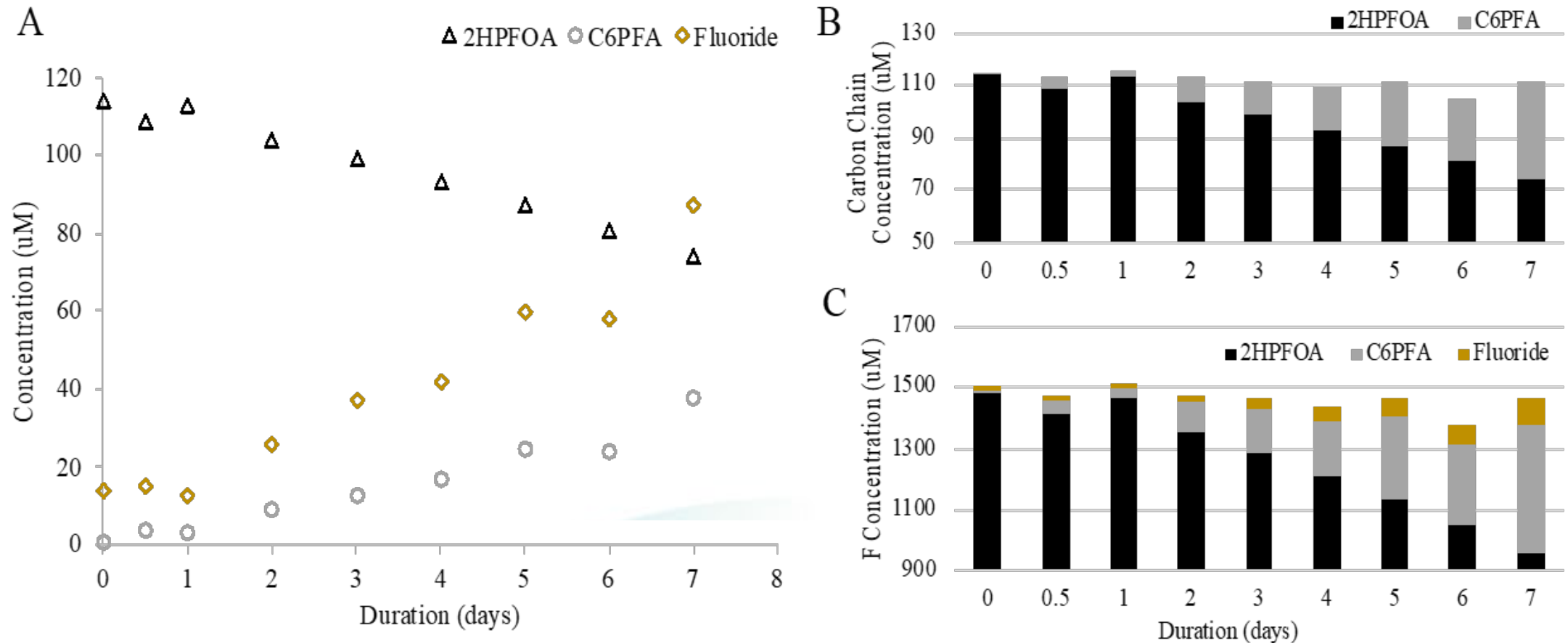
KO	Gene	Function	1-1	1-2	1-4	2-2	2-5	2-6
K00232	<i>ACOX1</i>	acyl-CoA oxidase	28.0	2.4	18.2	4.8	14.1	20.7
K00249	<i>ACADM</i>	acyl-CoA dehydrogenase	487.4	684.0	417.6	880.3	310.8	283.3
K00255	<i>ACADL</i>	ong-chain-acyl-CoA dehydrogenase	22.0	20.4	10.5	12.2	26.3	22.8
K06445	<i>fadE</i>	acyl-CoA dehydrogenase	97.9	98.4	115.2	95.7	90.9	133.2
K09479	<i>ACADVL</i>	very long chain acyl-CoA dehydrogenase	0.0	9.7	0.0	4.1	7.1	5.3
K01692	<i>paaF</i>	enoyl-CoA hydratase	311.9	419.9	249.4	575.3	175.8	169.7
K07511	<i>ECHS1</i>	enoyl-CoA hydratase	109.6	75.7	70.5	86.8	67.6	76.8
K13767	<i>fadB</i>	enoyl-CoA hydratase	0.0	0.0	0.0	0.0	4.6	0.0
K00022	<i>HADH</i>	3-hydroxyacyl-CoA dehydrogenase	3.1	0.0	10.4	0.0	0.0	0.0
K07516	<i>fadN</i>	3-hydroxyacyl-CoA dehydrogenase	155.2	254.4	194.9	275.9	129.7	167.3
K01825	<i>fadB</i>	3-hydroxyacyl-CoA dehydrogenase	11.2	9.9	9.6	13.2	7.5	6.5
K01782	<i>fadJ</i>	3-hydroxyacyl-CoA dehydrogenase	85.7	84.2	110.3	27.2	105.3	108.2
K07514	<i>EHHADH</i>	enoyl-CoA hydratase	8.2	0.0	0.0	0.0	5.1	5.7
K07515	<i>HADHA</i>	enoyl-CoA hydratase	0.0	0.0	3.2	0.0	0.0	0.0
K10527	<i>MFP2</i>	enoyl-CoA hydratase	0.0	0.0	0.0	0.0	3.7	0.0
K00632	<i>fadA</i>	acetyl-CoA acyltransferase	432.5	623.8	351.3	562.0	340.1	357.9
K07508	<i>ACAA2</i>	acetyl-CoA acyltransferase 2	1.4	0.0	0.0	9.1	3.6	0.0
K07509	<i>HADHB</i>	acetyl-CoA acyltransferase	11.1	0.0	5.6	5.7	7.2	3.6
K07513	<i>ACAA1</i>	acetyl-CoA acyltransferase 1	69.4	36.3	34.9	40.7	38.3	51.5
Unit: Counts per million (CPM); Color gradient:			0	50	100	200	400	900

Microbial degradation in the O₂-MBfR (5)

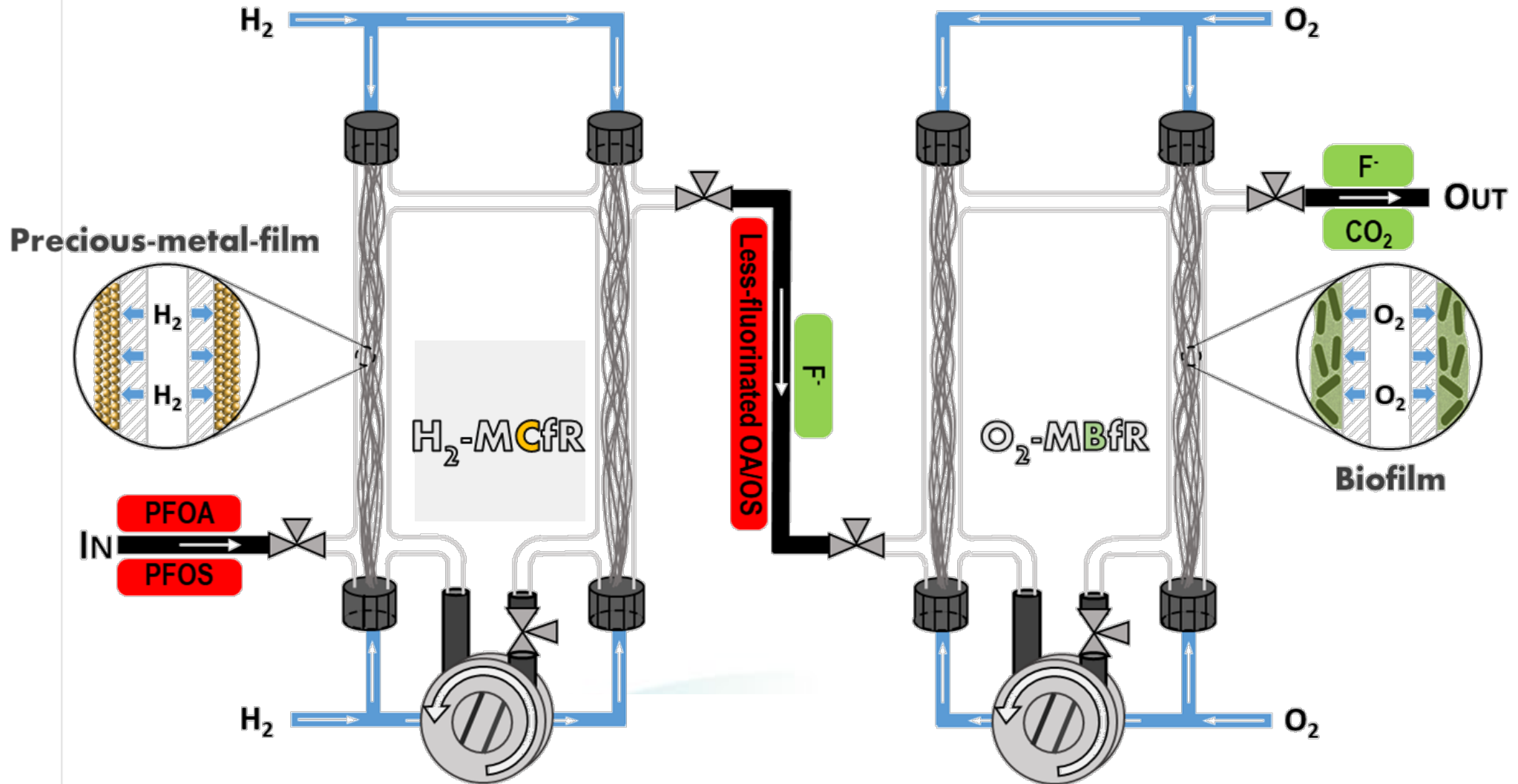
Batch studies show β -oxidation products:

- Partially fluorinated OAs were defluorinated via *beta* oxidation (shown):

e.g.,

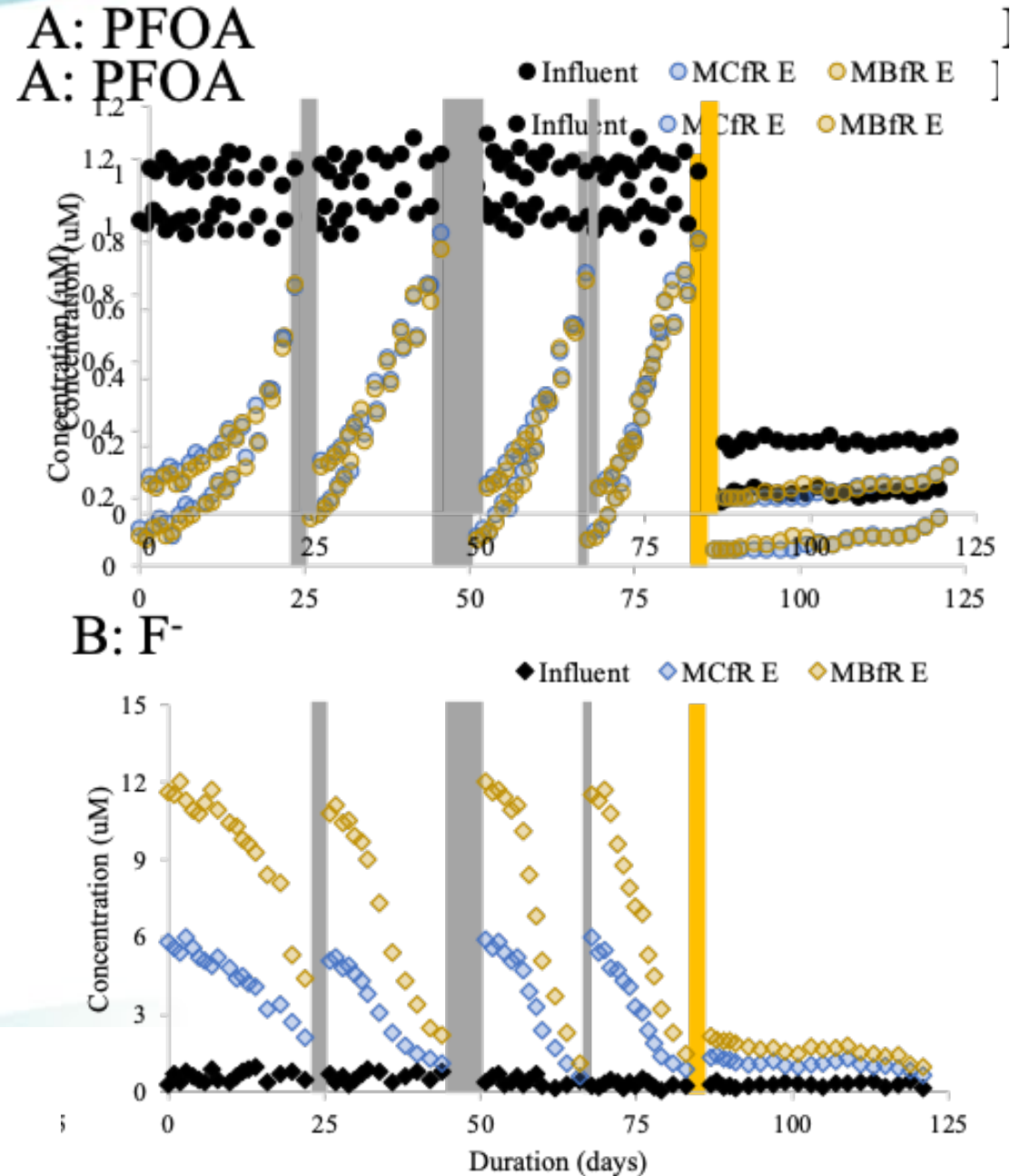


The Synergistic Platform (1)



The Synergistic Platform (2)

1. PFOA removal in the MCfR, but not in the MBfR – as expected
2. Defluorination in the MCfR and MBfR – roughly equal degrees!
3. Gradual deactivation of the Pd⁰ catalysts – due to the high PFOA input concentration (>400 ppb)
4. Reactivation with base treatment (gray bars).
5. Lower influent PFOA concentration (83 ppb) extended the activity -- what we always see.



Take-home Lessons

1. *In-situ* formation of robust Pd⁰-based catalytic films on gas-transfer membranes is simple.
2. Ours is first report of Pd⁰-catalyzed hydrodefluorination of PFOA (and PFOS and others).
3. Using bi-metallic catalysts extends the pH range of Pd⁰ catalysts. Pd/Rh is especially promising.
4. The H₂-based MCfR was able to continuously remove PFOA (and PFOS and others) below the advisory level of 70 ppt.
5. The O₂-based MBfR was able to defluorinate the partially defluorinated reduction products from the MCfR and mineralize fully defluorinated products.

Acknowledgements

- Funding: SERDP (DoD), Xylem, NEWT ERC (NSF)
- Essential ASU researchers for this work: Drs. Chen Zhou, Min Long, Yihao Luo, and Jie Cheng
- Collaborators at Rice University: Dr. Mike Wong, Dr. Thomas Senftle, Dr. Welman Elias, Juan Donosa, Kimberly Heck

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OCTOBER 3-5, 2023

Developing PFAS Source Remediation Priorities Using Predictive Groundwater Modeling

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RAMBOLL

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Challenge to Modeling PFAS

Modeling PFAS movement in groundwater is problematic

- Large population of PFAS compounds
- Transport properties unique to each PFAS
- Transformation from one PFAS to a different PFAS
- Lack of well constrained literature values for these transport properties such as distribution coefficients

Our Endpoint

- Calibrated site-specific distribution coefficients (K_d)
 - PFOS, PFOA, PFNA, PFUnA, PFTrDA
- Calibrated groundwater source concentrations
- Prioritized source remediation locations among many separate source areas
- Prioritized by magnitude of impact at the Treatment Plant

Groundwater Monitoring

- >100 Monitoring wells
 - All 4 hydrogeologic units
 - Distributed throughout the site
- > 10 Years of water level data
- 2 Extraction wells
 - Onsite treatment plant constructed for VOCs

Surface Water Monitoring

- Flow
- Elevation

History of AFFF Use

- Required Insurance testing dates
- Leaking stormwater infrastructure

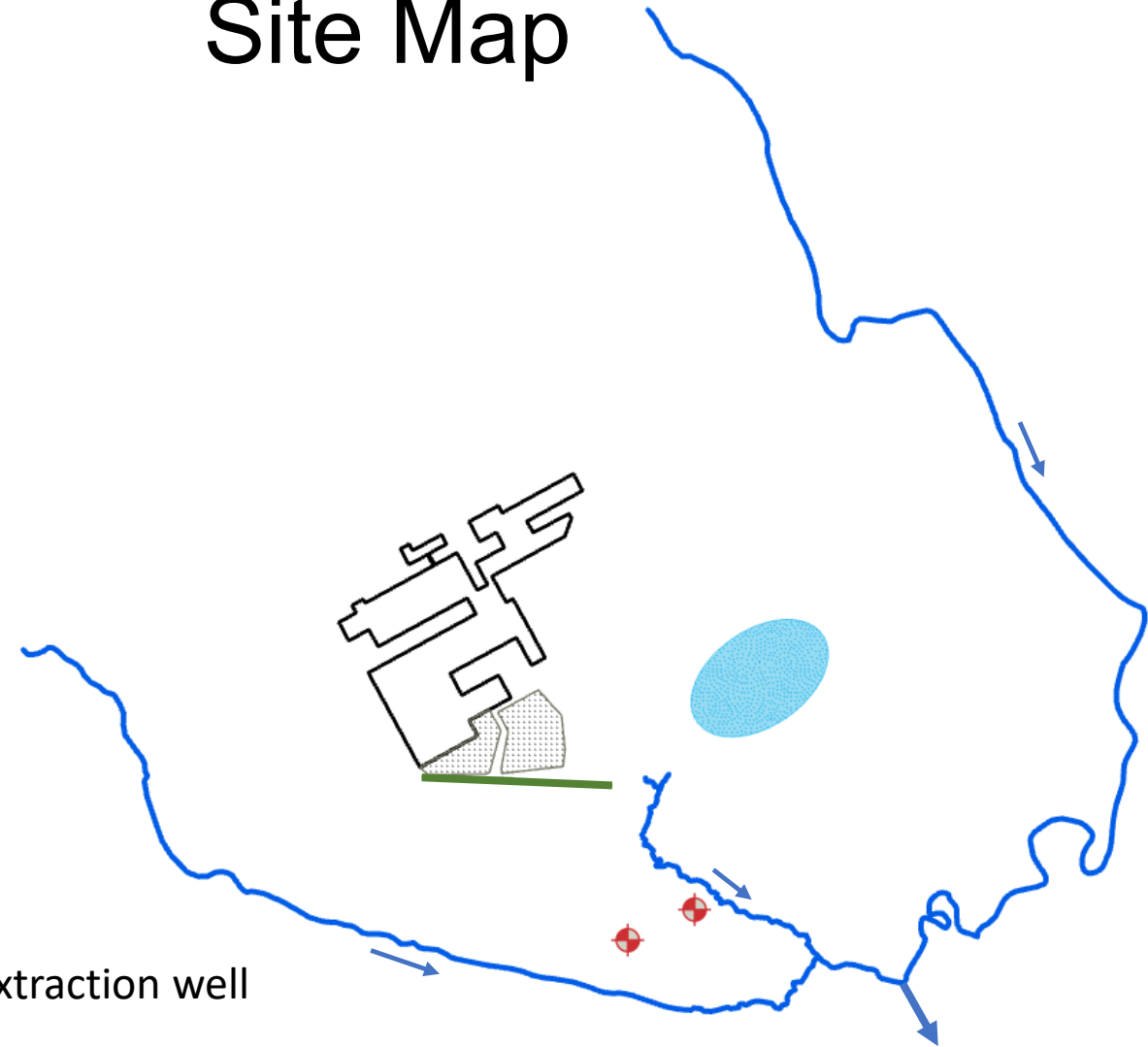
PFAS Data

- Three rounds of groundwater sampling data
- Two years of treatment plant influent and data at each extraction well
- Soil sampling events

Multiple AFFF Source Areas

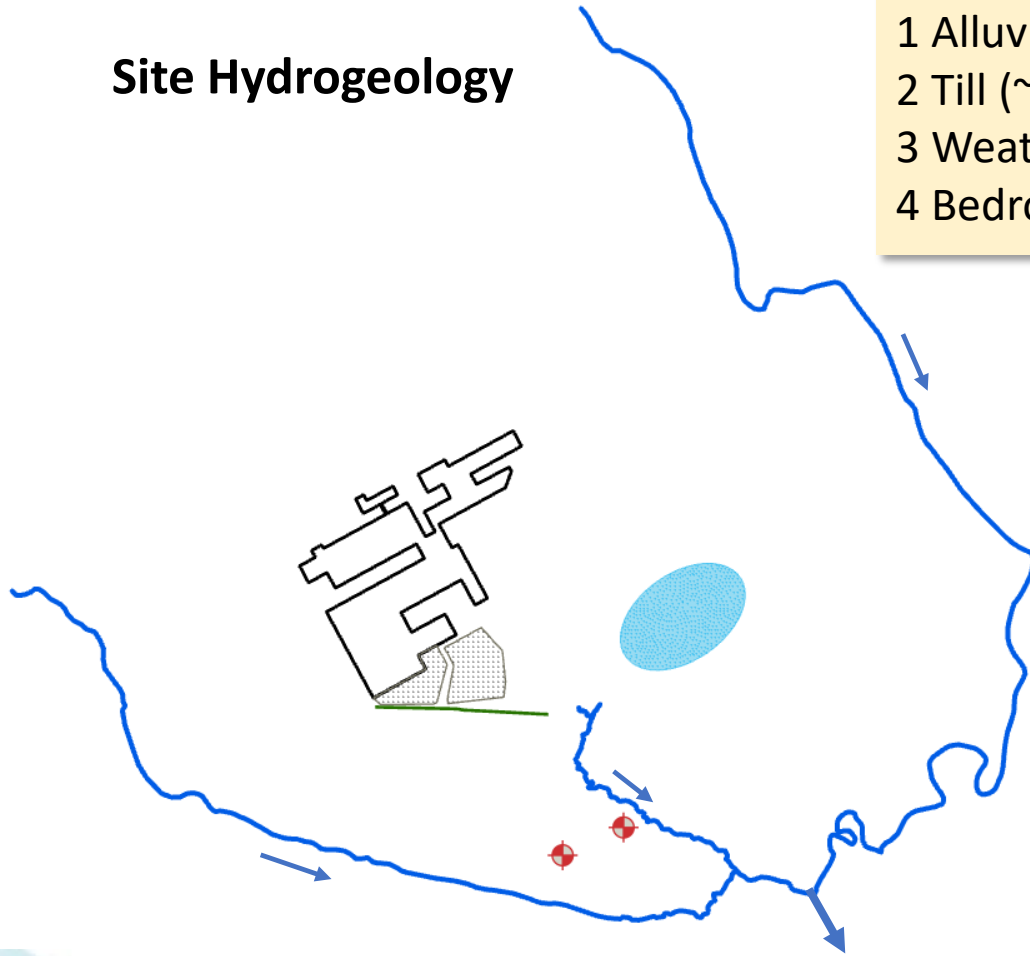
- Each with different mixture of PFAS in soil and groundwater
- Creating a commingled plume

Site Map



Model Construction

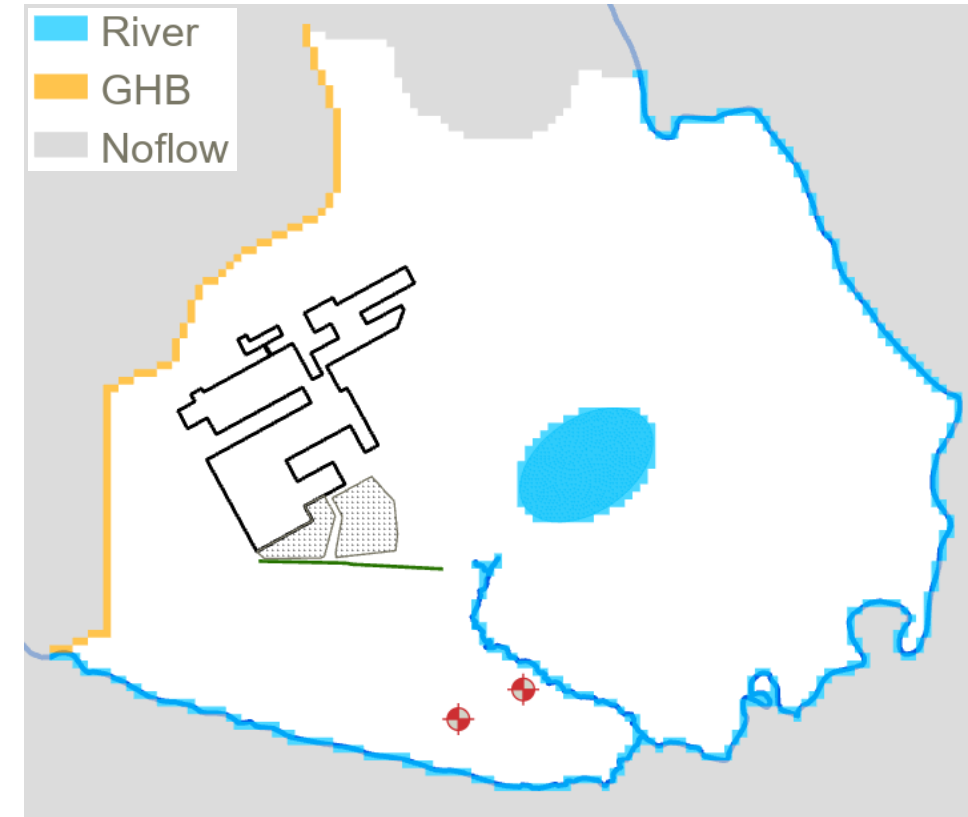
Site Hydrogeology



Layering

- 1 Alluvium (~40 ft)
- 2 Till (~30 ft)
- 3 Weathered bedrock (~5 ft)
- 4 Bedrock (>50 ft)

Boundary Conditions



Flow Model Calibration

Calibration Parameters

- Hydraulic conductivity
- River boundary
- GHB boundary

Calibration Targets

- Water level
- Streamflow

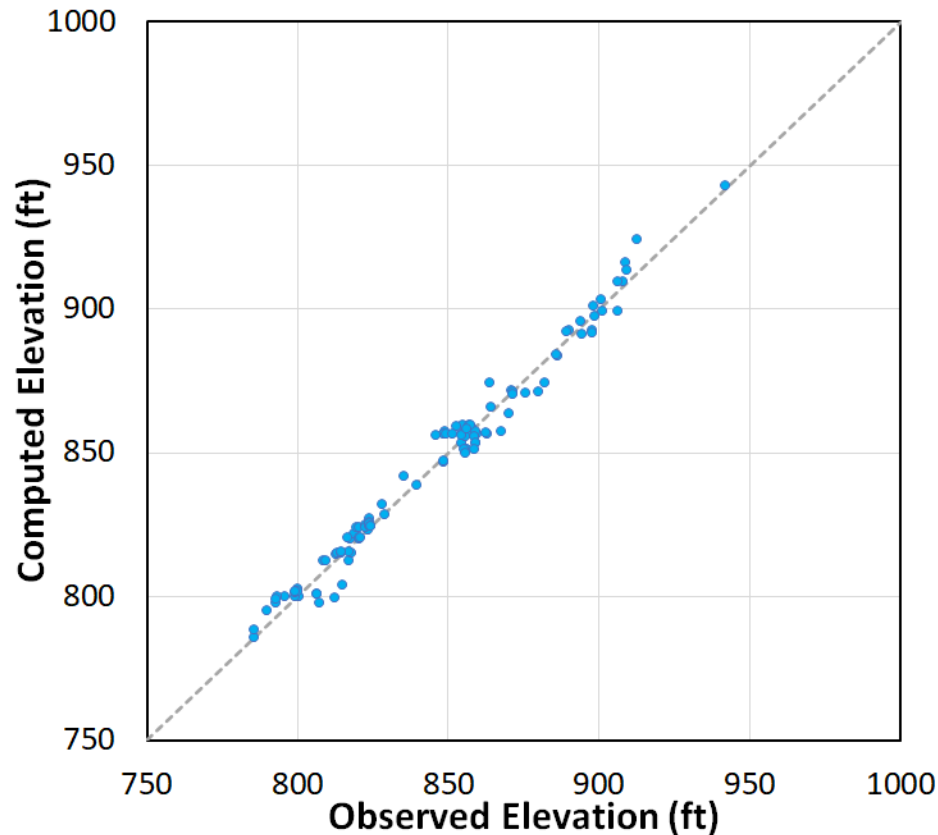
Calibration Method

- Manual
- Automated

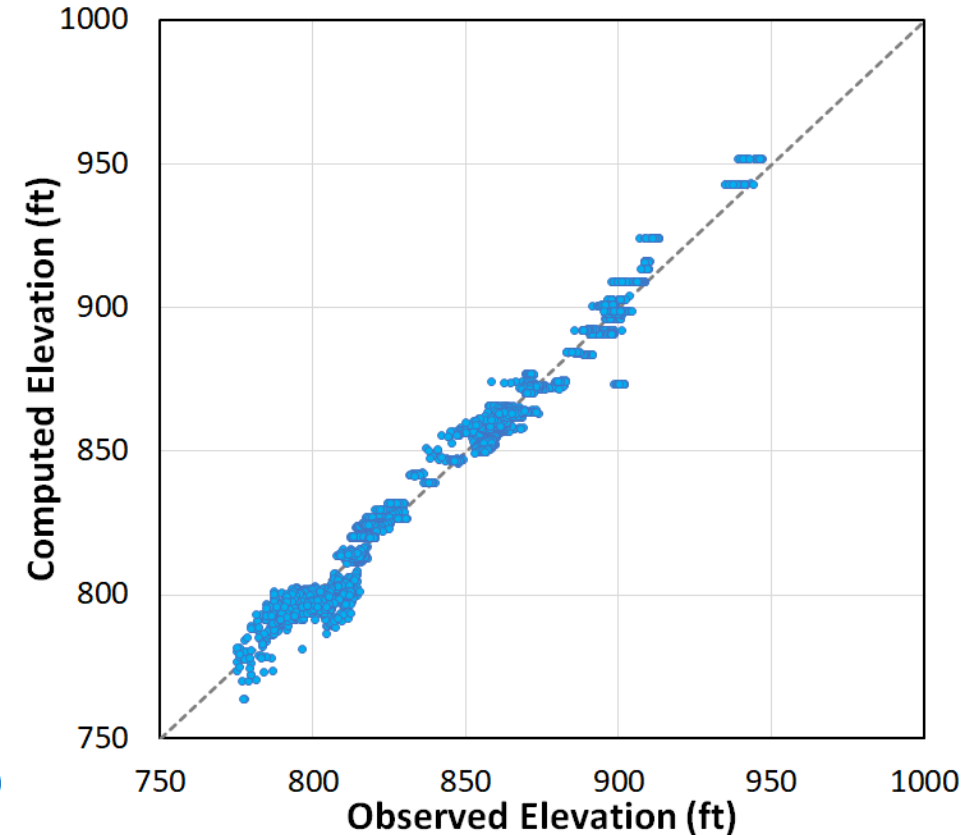
Validation

- Transient data 11 years
- Water level
- Groundwater extraction

**Steady State Calibration
Single Event Monitoring Data**



**Transient Model Validation
11 Years of Monitoring Data**



Transport Model Construction

Distribution Coefficient K_d

- PFOS, PFOA, PFNA, PFUnA, PFTrDA

Source Zone Identification

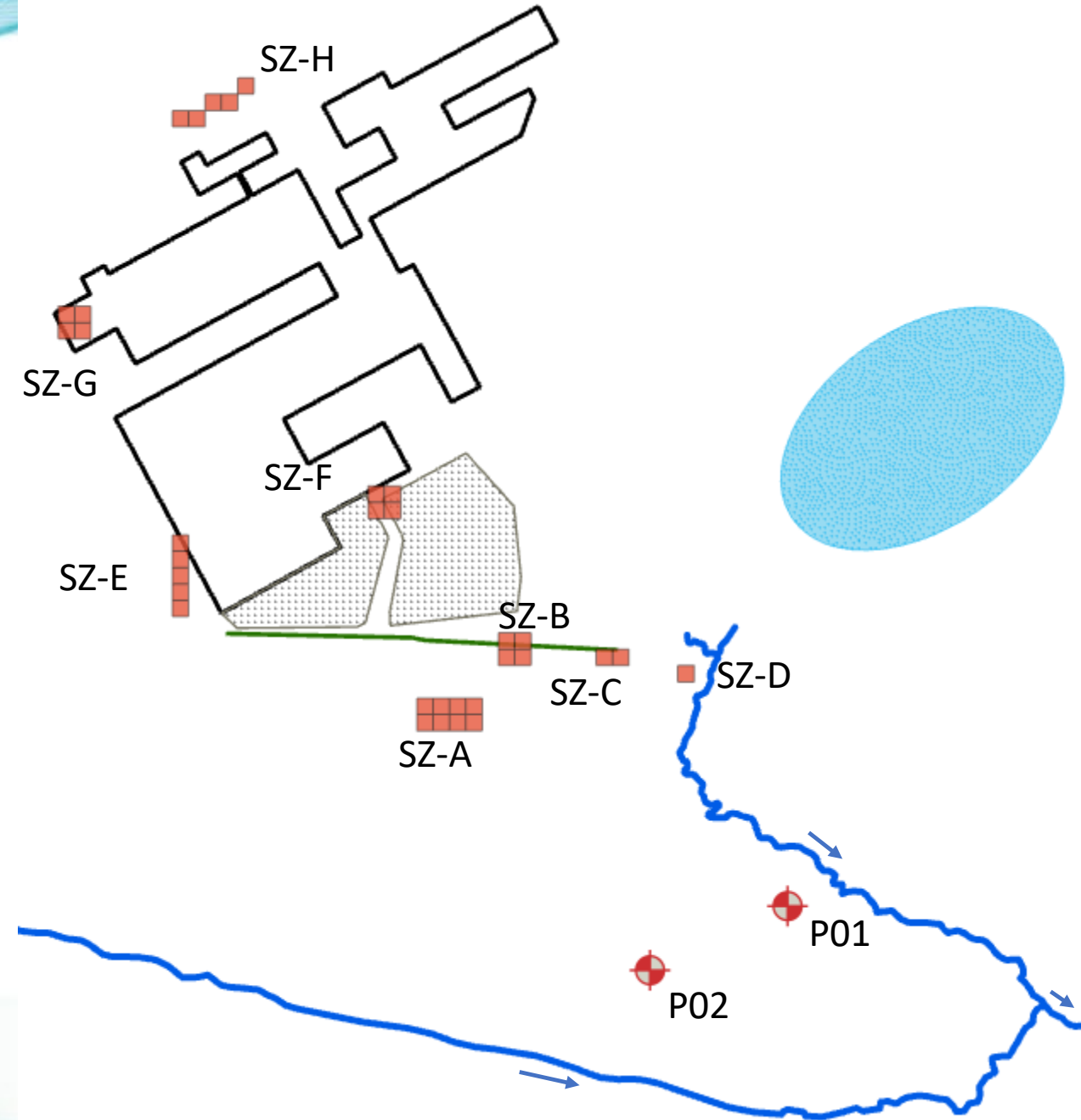
- Comingled plumes many sources
- Groundwater samples
- Soil samples
- Spatial distribution of plumes

PFAS Compounds

- Mix varied with source area

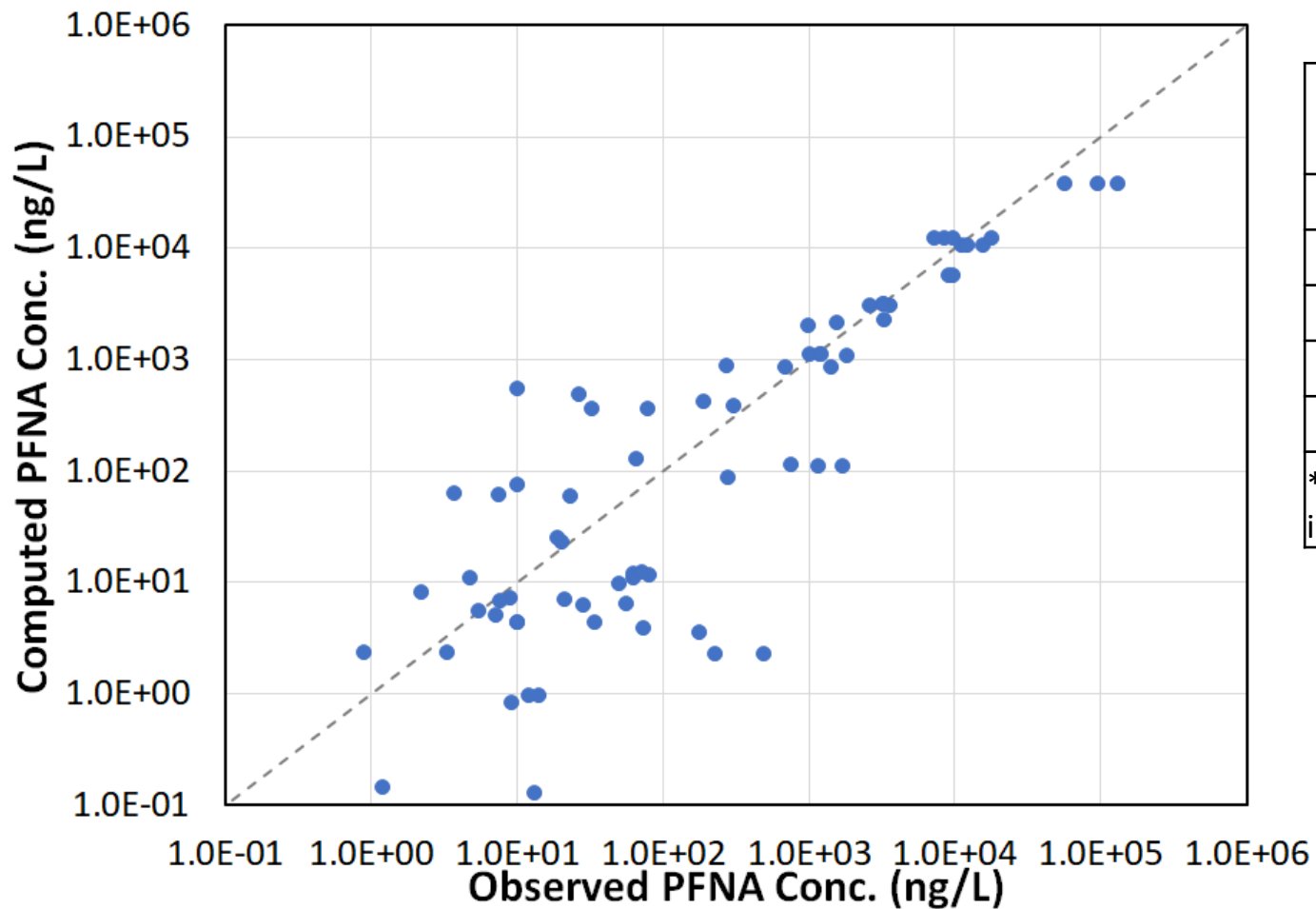
Source Strength

- Varied with source area



Transport Model Calibration

- K_d for each PFAS compound
- Source concentration for each PFAS compound at each source zone



PFAS Compound	K_d (L/kg)	
	Calibrated Value	Literature Value*
PFNA	0.43	0.23 – 7.94
PFOA	0.12	0.05 – 0.79
PFOS	0.60	0.37 – 200
PFUnA	1.98	3.63 – 630
PFTTrDA	16.25	5.13 – only value

*: K_d values calculated based on ITRC $\text{Log}(K_{oc})$ values for PFAS mixture in solution in soil assuming f_{oc} of 0.001

Predictive Simulation Baseline Condition

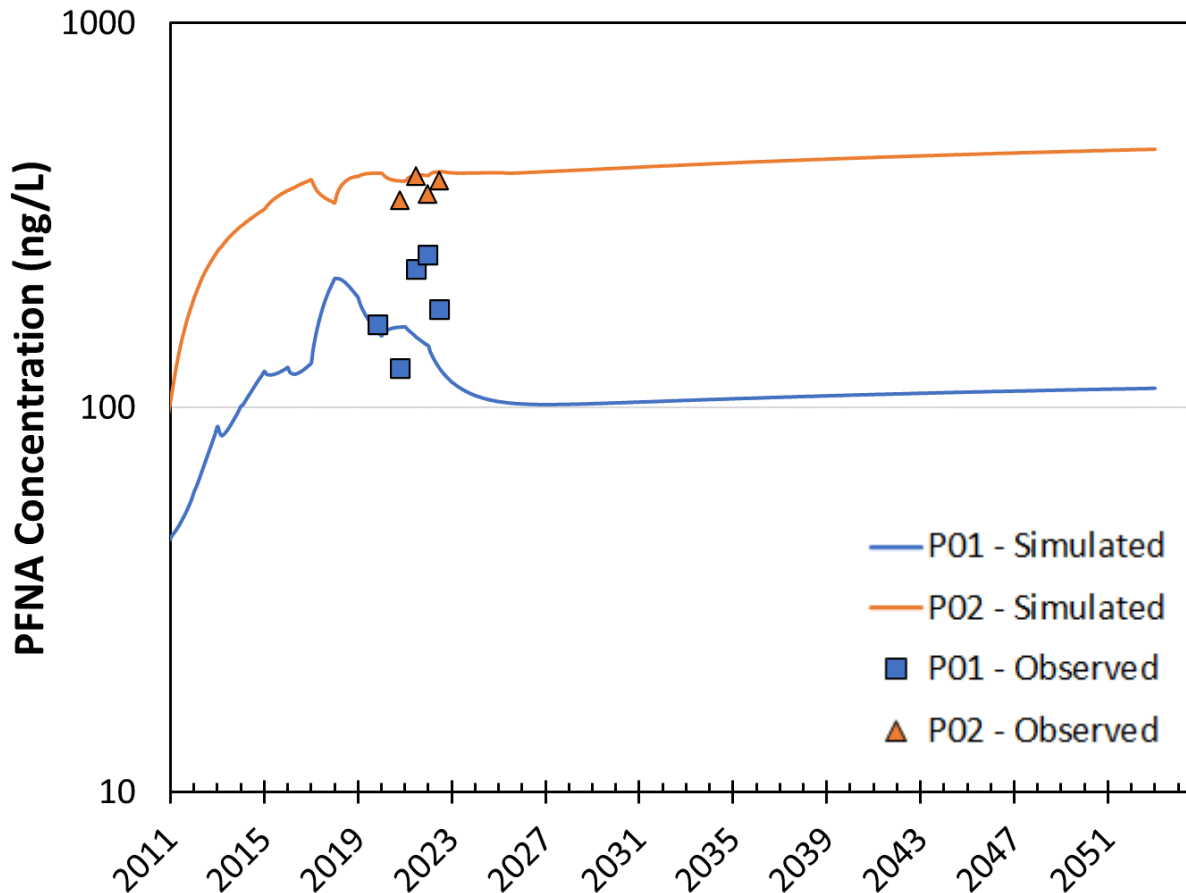
Predict influent concentration

- Individual wells
- Combined influent

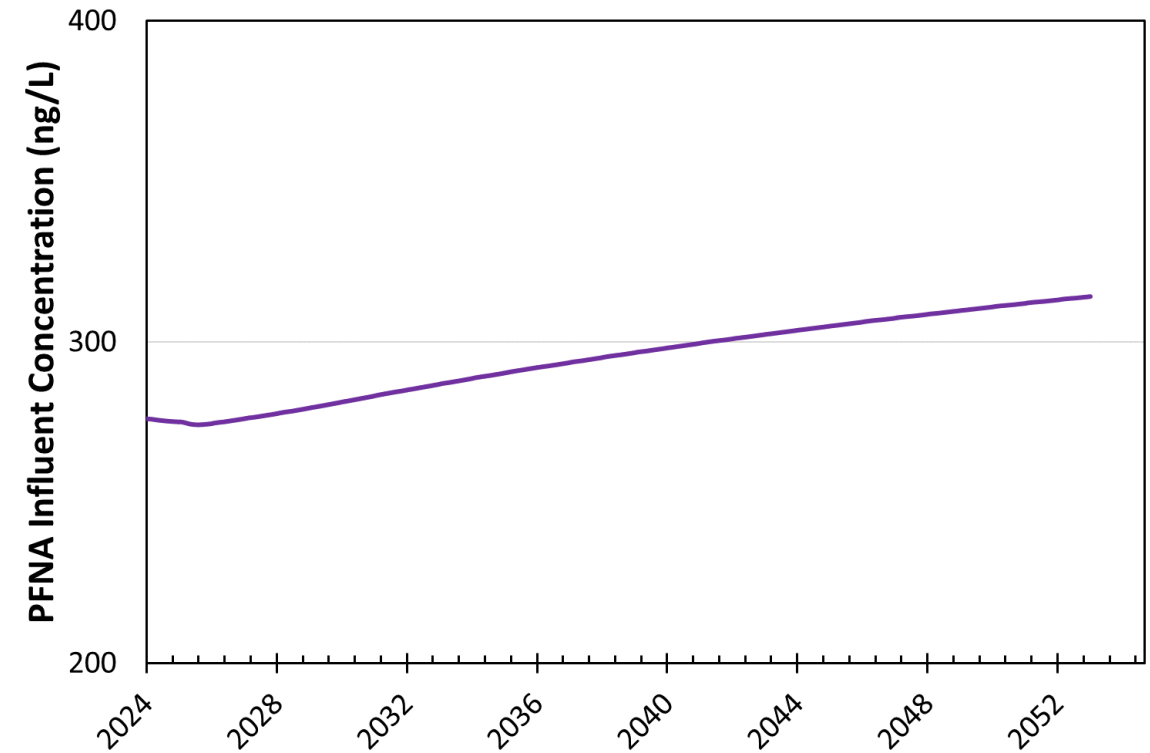
Each PFAS compound

Predict to 30 years into future

Extraction Wells Modeled and Predicted Influent



Treatment System Predicted Influent



Effect of Potential Remediation

Reduce one source's mass by 50%

- Each PFAS compound

Magnitude of change

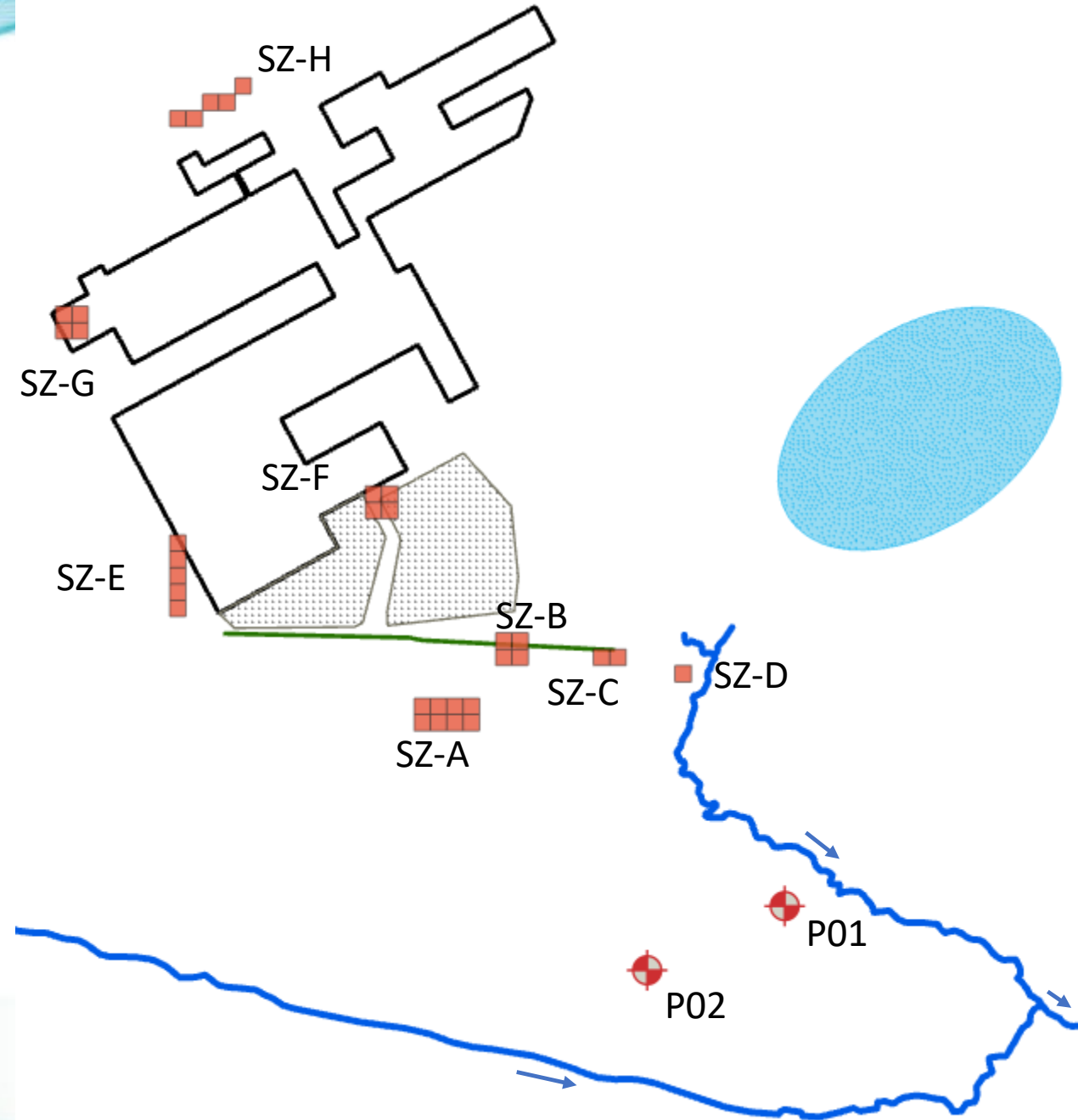
- Monitoring wells
- Extraction wells

Predict extraction well impact over 30 years

- Change in concentration over time
- Change in mass loading over time
- Change in PFAS mix over time

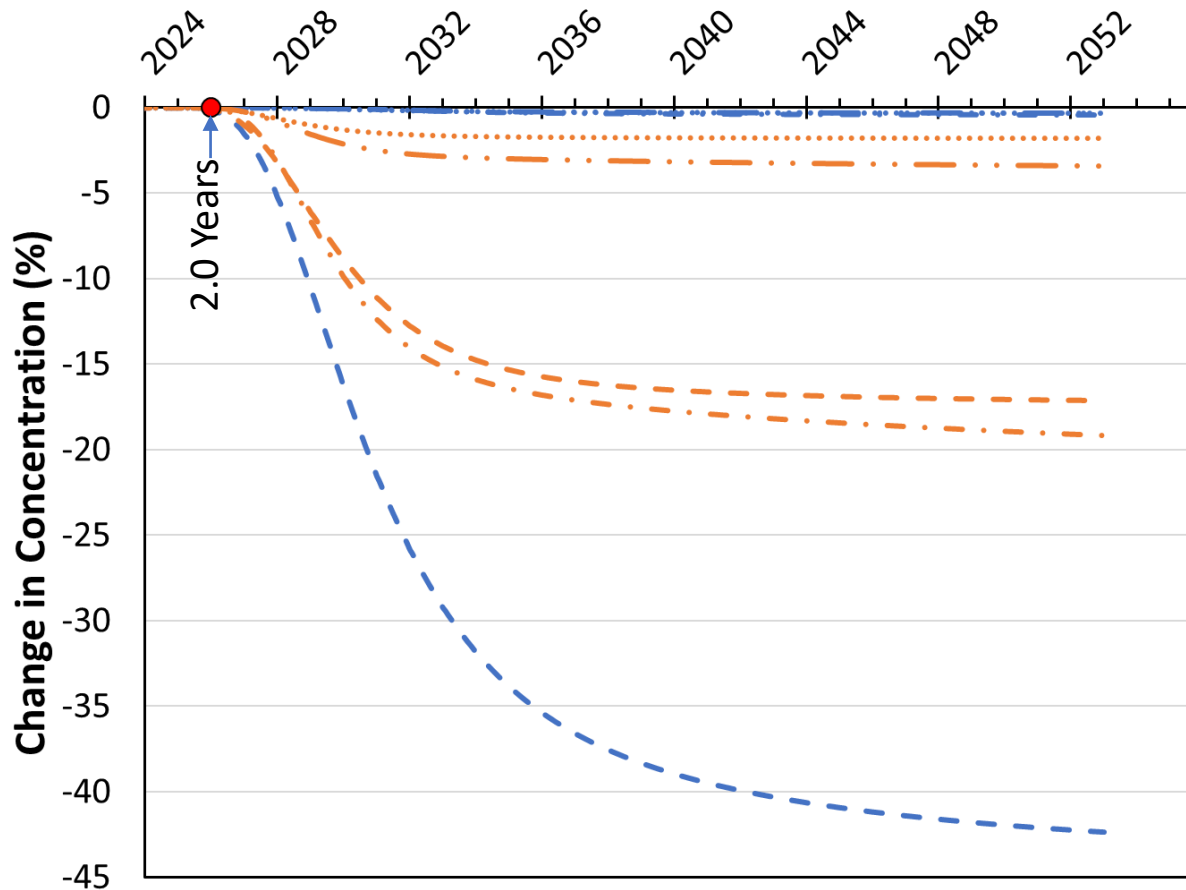
Source remediation priorities

- Which source
- Maximize effect at the treatment plant for least cost

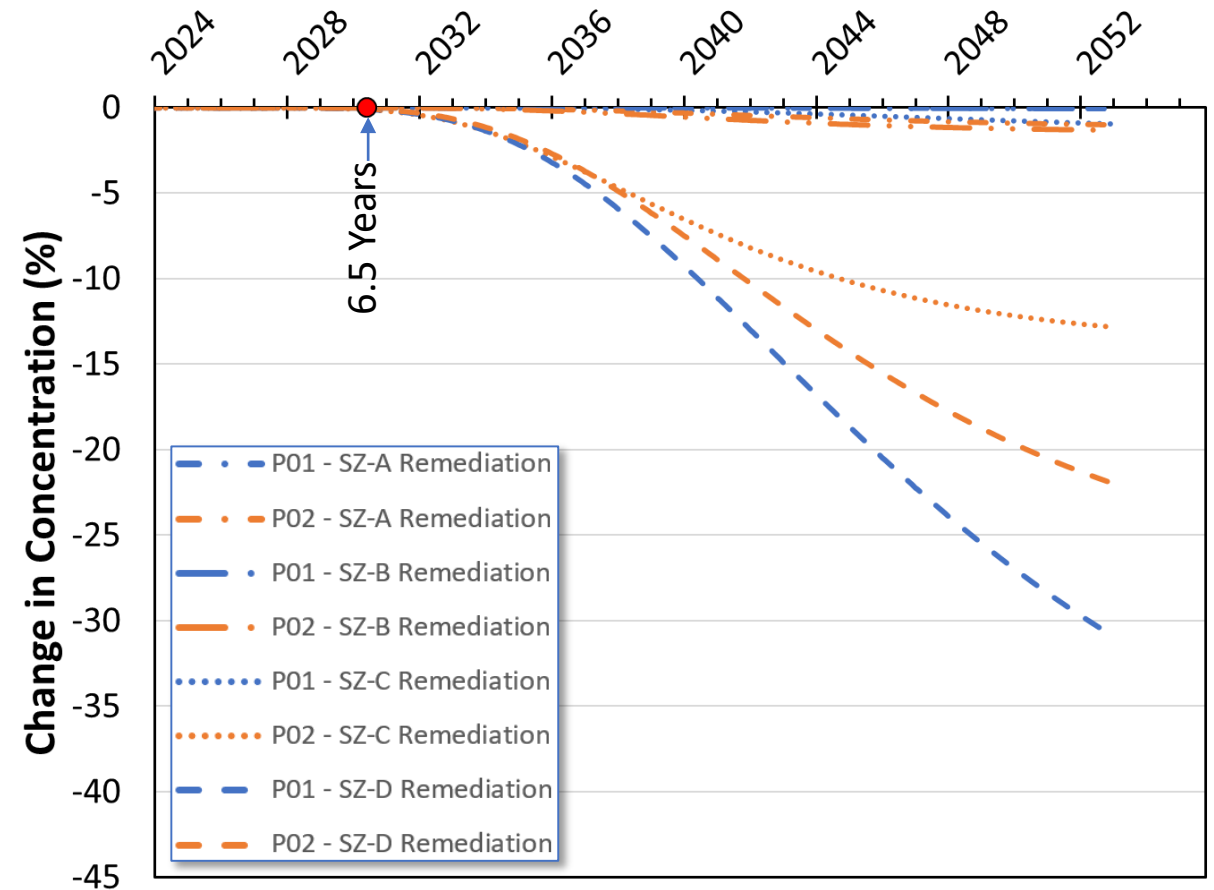


Effect of Potential Remedial Effort

Simulated PFNA Concentration Reduction In Extraction Wells



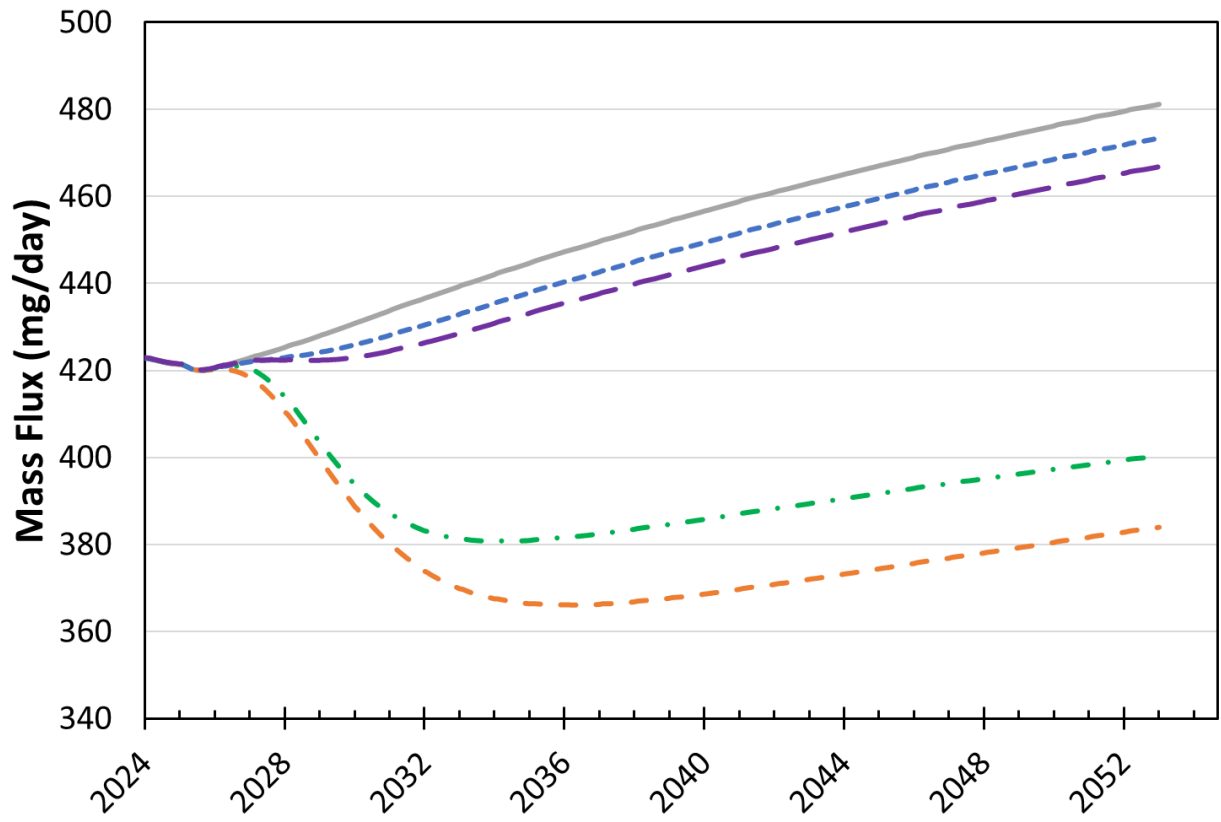
Simulated PFUnA Concentration Reduction In Extraction Wells



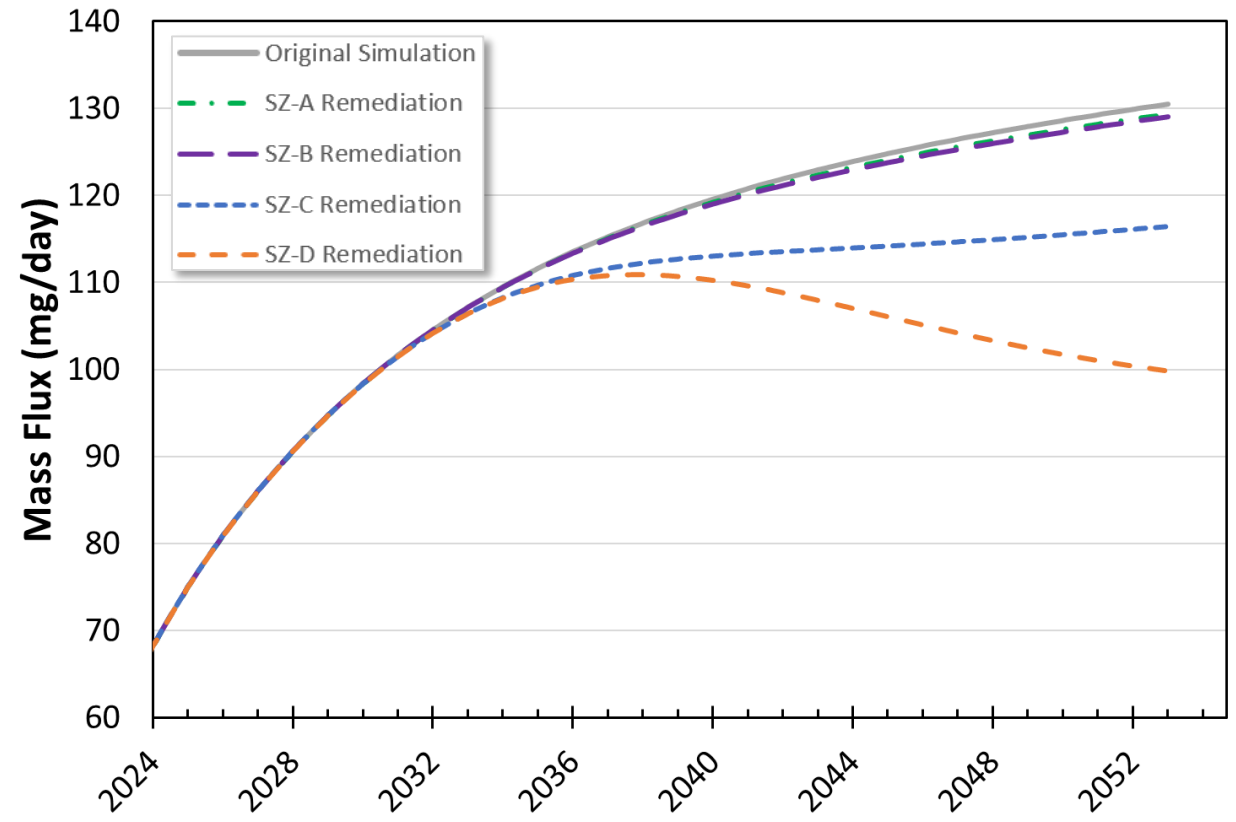
- P01 - SZ-A Remediation
- P02 - SZ-A Remediation
- P01 - SZ-B Remediation
- P02 - SZ-B Remediation
- P01 - SZ-C Remediation
- P02 - SZ-C Remediation
- P01 - SZ-D Remediation
- P02 - SZ-D Remediation

Simulated PFNA and PFUNA Mass Flux Into Treatment Plant

Simulated PFNA Mass Flux at Treatment Plant



Simulated PFUnA Mass Flux at Treatment Plant



Source Remediation Prioritization

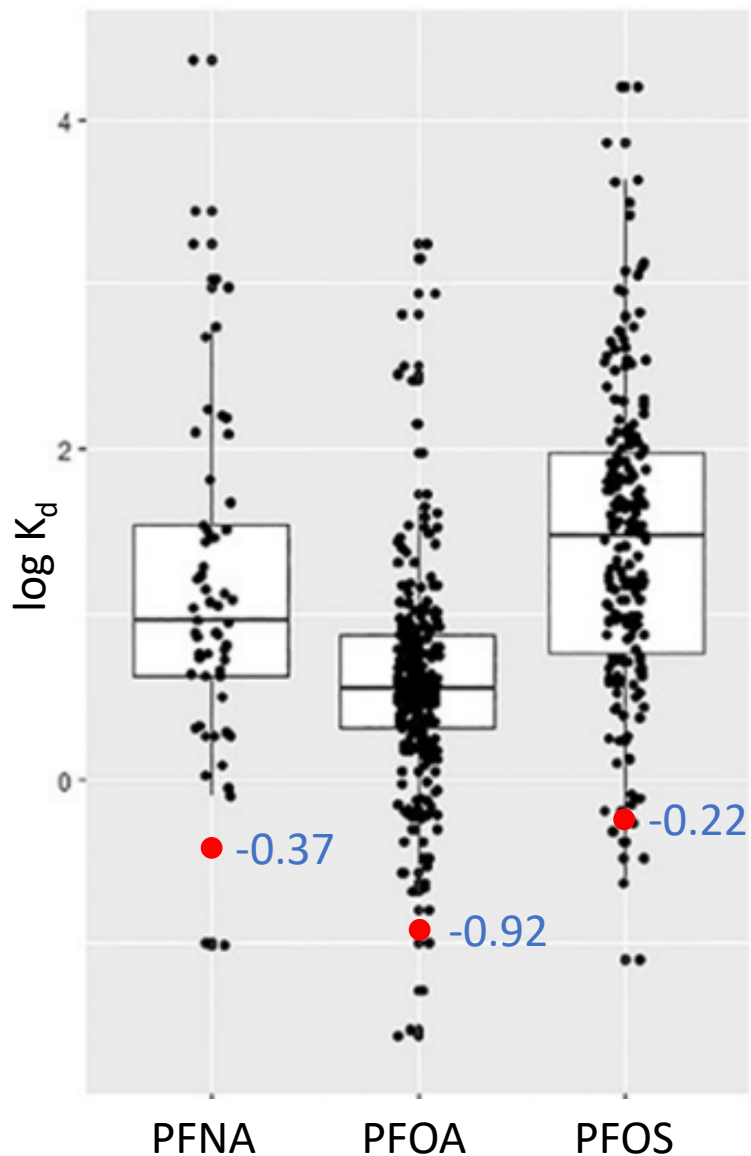
Source Zone	Ranking					
	PFNA	PFOA	PFOS	PFUnA	Sum	Overall
SZ-D	2	1	2	1	6	1
SZ-C	3	3	1	2	9	2
SZ-A	1	2	4	4	11	3
SZ-B	4	4	3	3	14	4
SZ-F	5	5	6	7	23	5
SZ-E	6	7	5	5	23	5
SZ-G	7	6	7	6	26	7
SZ-H	8	8	8	8	32	8

Impact on cost of remediation at the treatment plant

At Source Zone D remedial action would have the largest impact on total PFAS influent concentration at the treatment plant

At Source Zone H remedial action would have the least impact on total PFAS influent concentrations at the treatment plant

Calibrated Distribution Coefficients



PFAS Compound	Calibrated Value (L/kg)	
	K_d	$\log K_d$
• PFNA	0.43	-0.37
• PFOA	0.12	-0.92
• PFOS	0.60	-0.22
PFUnA	1.98	0.30
PFTTrDA	16.25	1.21

- Adsorption vs. Desorption
- Long-term field scale vs. Short-term lab scale
- Low concentration vs. High concentration

Bright
ideas.
Sustainable
change.



Jonathan Johnson, PhD
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Abstract

Adequately modeling PFAS movement in groundwater is problematic because of the large population of PFAS compounds, the transport properties unique to each PFAS, and the lack of well constrained literature values for these transport properties such as distribution coefficients. However, Ramboll calibrated site-specific distribution coefficients and groundwater source concentrations for PFOA, PFOS, PFNA, and longer chain PFAS compounds by fitting the model to several rounds of site groundwater monitoring data and data from the influent to an on-site treatment system. The calibrated site-specific distribution coefficients were found to be at the low end or below the range of literature values reviewed. This modeling approach was used to successfully prioritize source remediation at an AFFF site.

Site features included a fire-fighting training area and leaking stormwater infrastructure which resulted in multiple locations of soil and/or groundwater impacts, and relatively minor PFAS impacts at other locations at the site. Source areas were identified based on history of AFFF use and contaminant distribution. Each source modeled included a different combination of PFAS compounds based on the groundwater monitoring data. The on-site treatment system was previously constructed to address other COCs present at the site and consists of two primary extraction wells with combined discharge to a treatment plant.

Predictive contaminant transport simulations were run to simulate PFAS transport from the beginning of AFFF use to 30 years into the future as a baseline. Subsequently, each source area was assigned a 50% reduction of mass flux in the model to quantify the impact of remedial actions at individual source areas as measured by the changes observed in the influent of the treatment system.

Along the stormwater infrastructure, shorter chain PFAS sources closer to the extraction wells had the largest and earliest impact on concentration reduction at the treatment plant, however the treatment plant would not experience a measurable reduction in concentrations until a few years later. Magnitude of the impact at the treatment plant was primarily related the amount of mass reduction at the source, but the timing of the impact at the treatment plant was related to distance from the extraction well and the site-specific distribution coefficient for the PFAS compound. Sources further from the extraction wells would not result in measurable impacts at the treatment plant until several years to a decade after the remedial action.

Based on these PFAS modeling results Ramboll was able to recommend potential future remedial actions that would be expected to have the greatest material impact on operating costs and timeframes of the treatment system.



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PFAS
Solutions

A Circular PFAS Treatment System Capable of Sorption of Short and Long Chain PFASs and Aqueous Desorption, Yielding a Concentrate for Destruction

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Center for PFAS Solutions

Wilmington Delaware (www.pfasolutions.org)



Center for PFAS Solutions

Governance:

- Independent non-for-profit 501(C)(3) organization, started in 2020 with a grant from the Longwood Foundation in Delaware.

Team and Core Competencies:

- Seetha Coleman-Kammula, PhD: Polymers and Materials
- Charles Powley, PhD: PFAS Analytical Methods and Chromatography
- Stephen Lyke PhD: Chemical Engineer, Modeling
- Brian Coleman, PhD: Organic Chemist, NMR, Quality, Accreditations
- Jessica Anton, MSc: Environmental Sciences, PFAS Analysis
- Xiaohuan Qin, MSc; in Chemistry, PFAS Analysis ,Ionomer Synthesis
- Dunping Cao, PhD: PFAS Analysis, Non-targeted methods

Equipment and Capabilities:

Agilent LC-MS/MS mass spectrometre Model G6495C plus Agilent HPLC Model 1290

Agilent Technologies Gas Chromatography-Mass Spectrometer (GC-MSD) [Agilent Technologies 6890-GC 5973N-MSD]

Two PromoChrom Automated SPE

Accredited by NELAP, Certified by NJ, and DE



Activities, Partners and Funders

PFAS Analytical Services Methods 537.1, 533	Delaware Public Drinking Water Suppliers
R&D on Prevalence of PFAS Method 1633 TOP Assay	PFAS on farms treated with biosolids. 3-year study, 25 Pennsylvania farms, partner with Stroud Water Research Center; funded by USDA PFAS in wastewater; partner with Delaware Rural Water Association; funded by the US EPA
Water Treatment Solutions	PFAS treatment studies for 5 public water systems; funded by Delaware Department of Public Health Ionomer development; partner with University of Delaware; funded by SERDP



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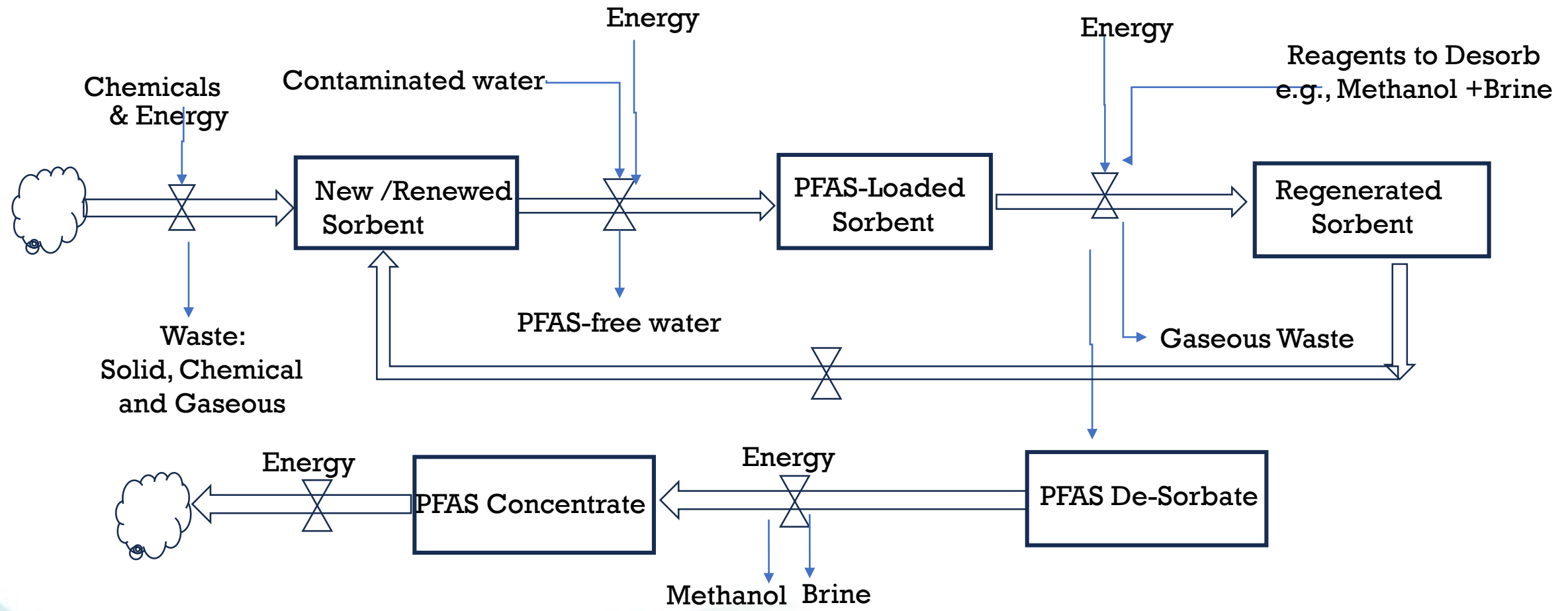
Why Yet Another PFAS Sorbent?

Because we believe there is room for sorbents with lower energy and chemical inputs and lower green house gas and hazardous waste outputs from Cradle to Cradle

Maintain the highest value of all resources used from cradle to cradle as long as possible - a definition of Circular Economy



A Simplified Stocks and Flows Map Illustrates the Challenge





Ionomers as PFAS Sorbents Have Not Been Investigated

What are Ionomers?

- Ionomers are polymers containing both electrically neutral and ionized groups.
- Polymers are macromolecules composed of a large number of repeating units called monomers.
- Depending on the type of monomers, there are different types of Ionomers
- Our Ionomers are solid water insoluble cationic polymers containing amines and cationic ammonium sites. .

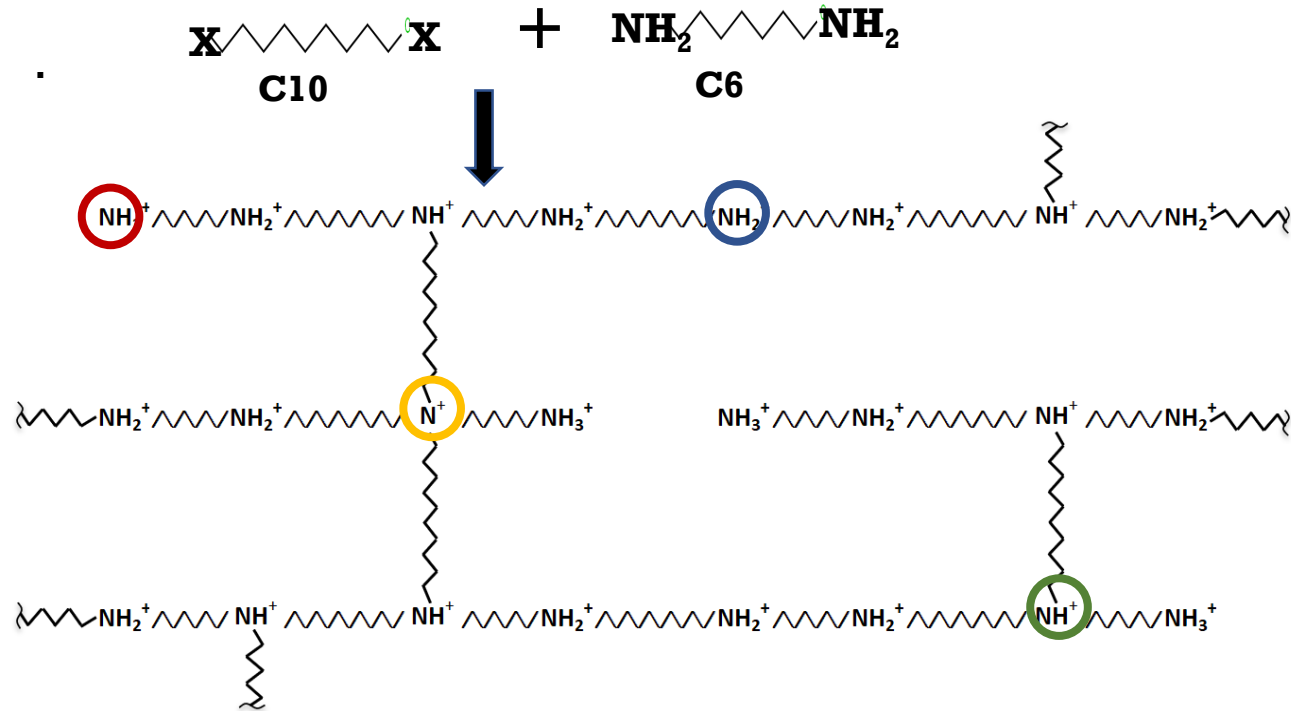


Today's Presentation

- Chemistry and Structure of our Ionomer in this study called HG-1
- SERDP Limited Scope Proposal
- Relative rates and sorption capacities of HG-1, GAC and Ion Exchange resin in deionized water with:
 - PFBA, PFBS, PFOA and PFOS individually and
 - Mix of all 4 PFAS at high and low (environmentally relevant) concentrations.
- Sorption of PFAS from well water contaminated with AFFF by HG-1
- Desorption and concentration using an all-aqueous formulation
 - Desorption data
 - Concentration factor
- Destruction of PFAS in the desorbed solution using Hydrothermal Alkaline Treatment



Ionomer labelled HG-1 Used In Current Study



Amine types % as per Magic Angle Spinning C13 Solid State NMR

Primary
17%

Secondary
55%

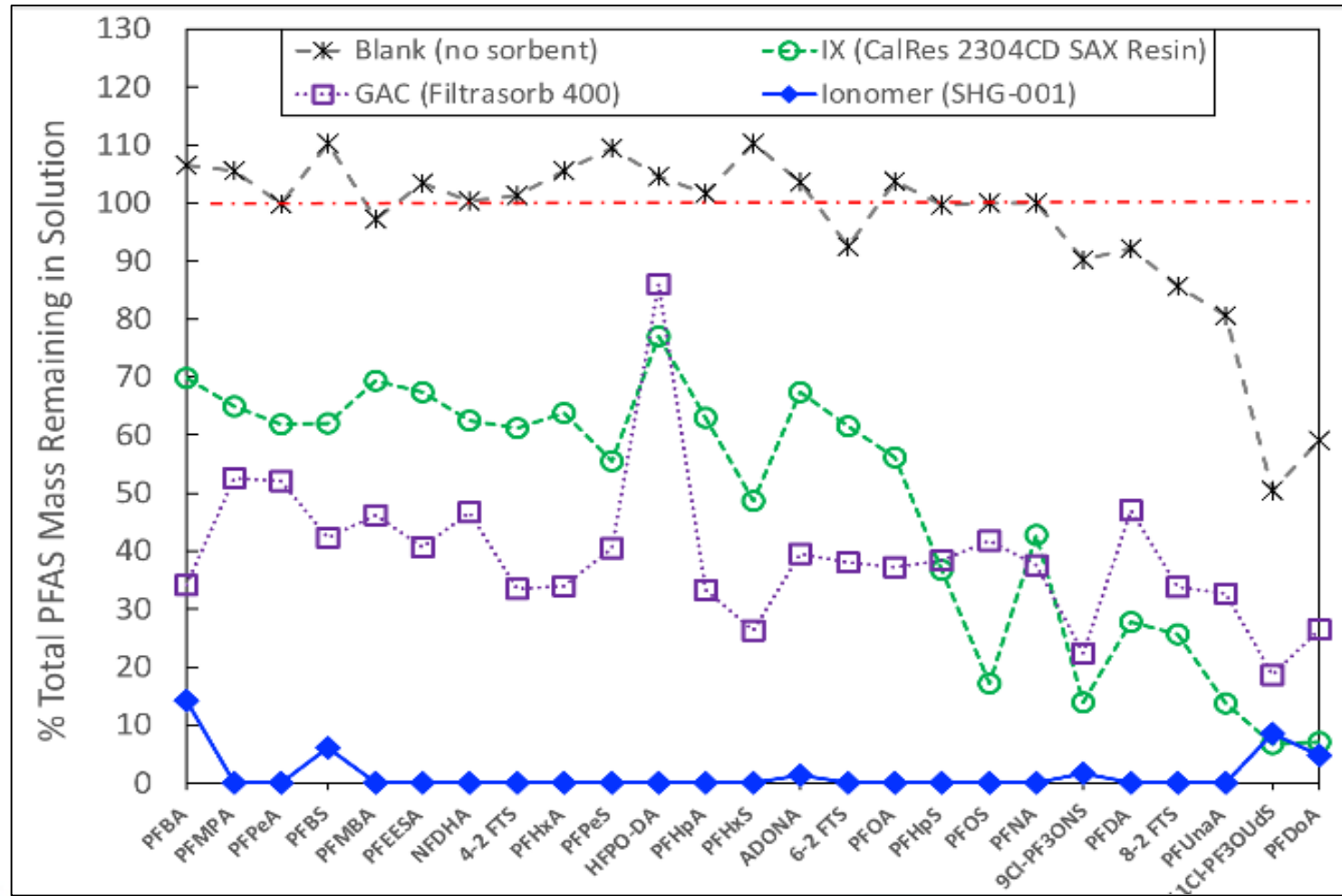
Tertiary
27%

Quaternary
1%

1. **Made in a single step** from two commercially available chemicals (monomers)
2. **Tunable for short and long chain PFAS** by varying the length of the two monomers from C5 to C12.
3. **Potential for high sorption capacity** -the entire polymer mass has amine sites distributed along and within the polymer- no resin core
4. **Potential to influence desorption** by varying amount of weak base and strong base (quaternary amine) sites.



Proof of Concept Data Used for SERDP Limited Scope Proposal



- C₄-C₁₂ PFAS (0.1 mg/L) were all removed from water by 10 mg of HG-1, compared to Filtrasorb® 400, and CalRes 2304 (10 mg each) in 1 hour
- Long-chain (>C₉) PFAS sorbed to inner walls of polypropylene vials (known as bottle effect)
- IX and GAC removed 40-80% of PFAS from water relative to blank, with GAC slightly outperforming IX for most PFAS
- Ionomer (HG-1) removed all PFAS completely except 2 C₄, 1 C₁₀ and 1 C₁₂ (all ca. 90%)

SERDP Limited Scope, One year Project, Goals etc.,

Goal: Demonstrate that Cross-linked polymeric Ionomers:

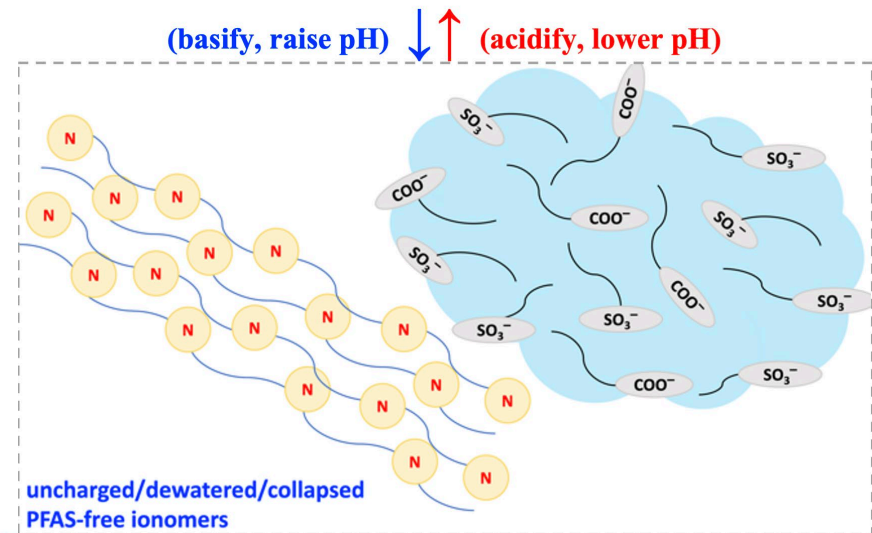
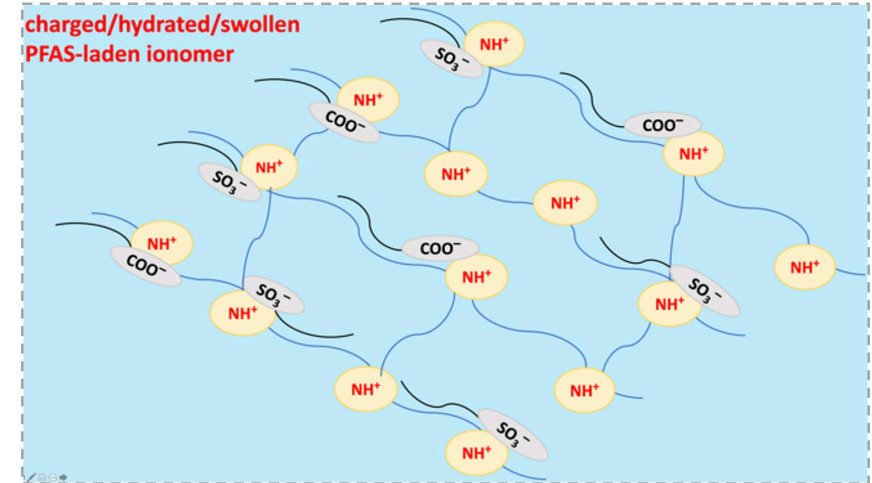
1. Sorb short and long chain PFAS faster than GAC and IX
2. PFAS can be desorbed by raising pH, without using organic solvent
3. On-site destruction of PFAS and regeneration of ionomers for reuse

Tasks: Using mix of PFBA, PFBS, PFOA, PFOS on GAC, IX and Ionomer, using batch scale tests

- Measure relative rates of sorption
- Measure relative sorption capacity
- Find aqueous desorption reagents
- Conduct Hydrothermal destruction

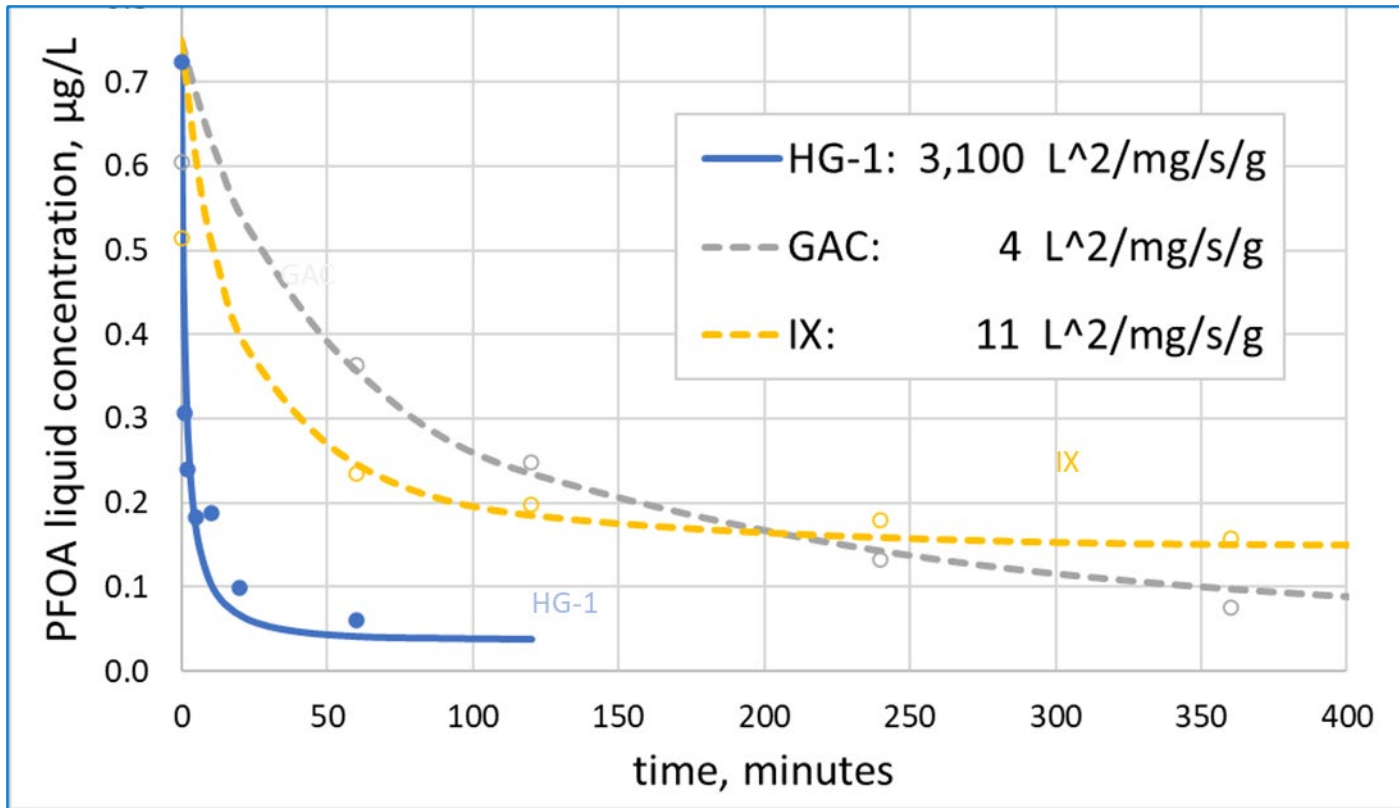
Hypothesis

- PFAS “heads” interact with amine sites via ionic (ion-exchange and in-pair) forces and the tails via Van der Waals forces.
- They swell and shrink in response to change in pH – sorb and desorb to release PFAS with change in pH





Kinetics of PFOA sorption by Ionomer HG-1, Vs GAC, IX



HG-1 kinetics orders of magnitude faster than GAC Filtrasorb 400 and IX (CalRes 2304).

We used 10x more dosing of GAC and IX to obtain more comparable rates.

Below are pseudo-2nd order rate constants fitting our data compared with published values .

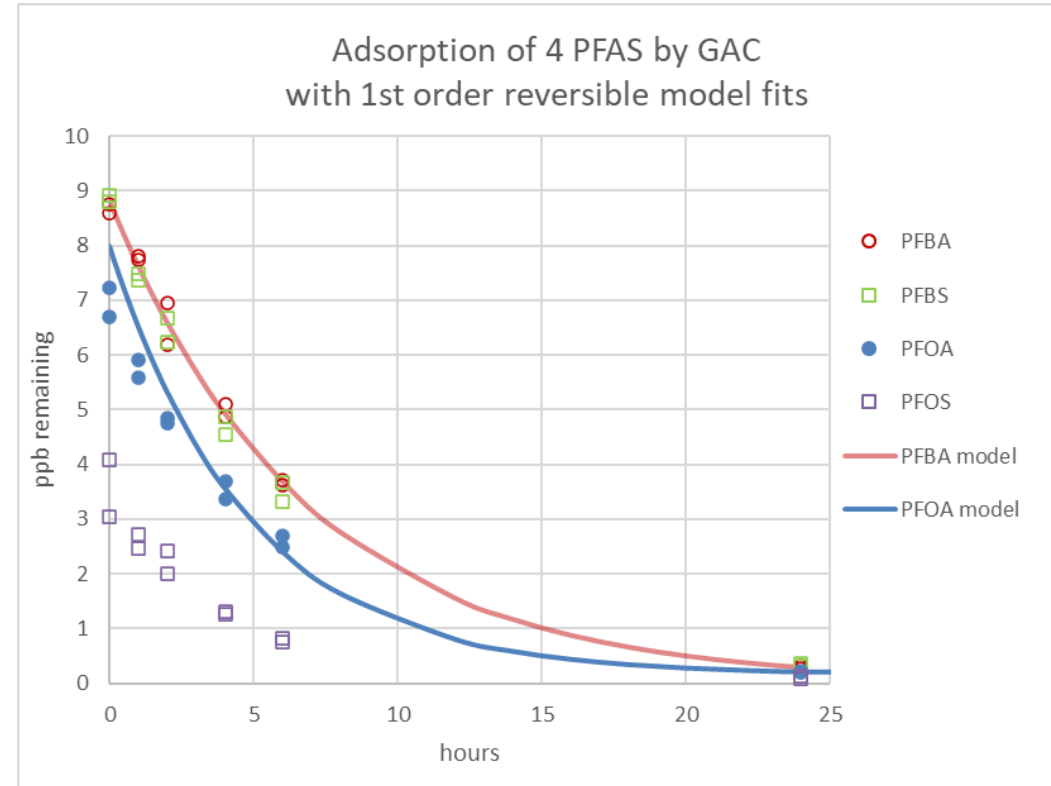
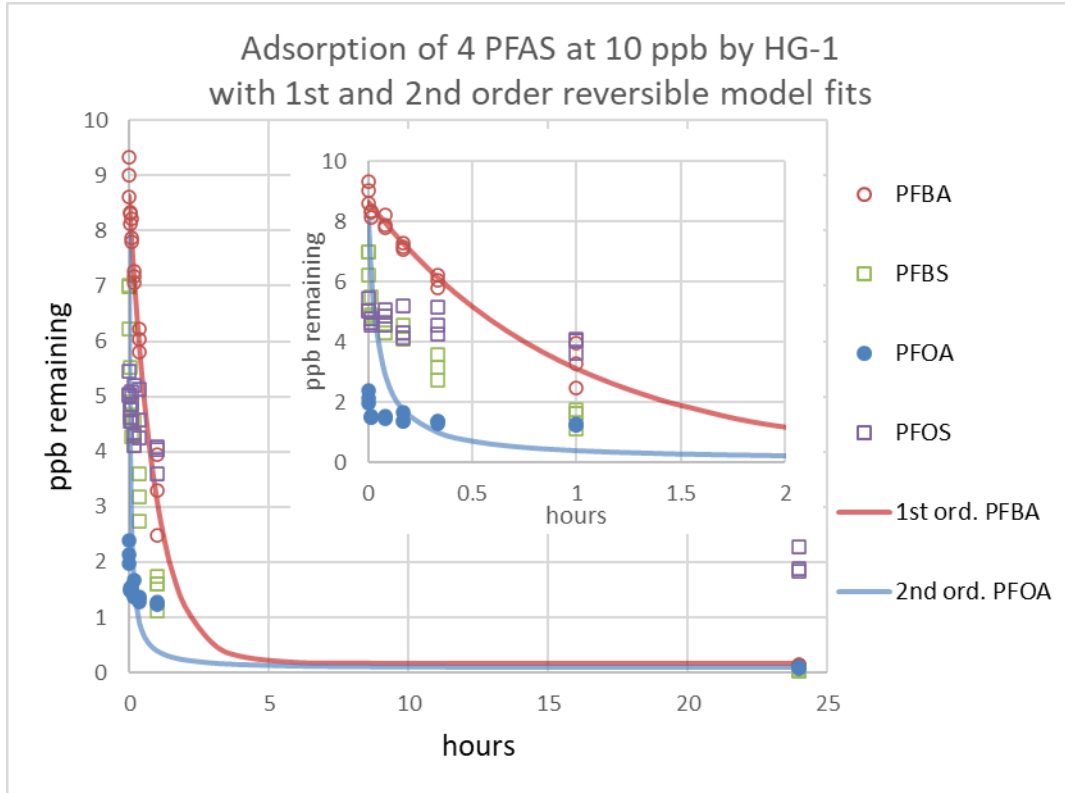
Material	k_{obs} , g/mg/hr
HG-1	1700
CCAC (Xiao, et al., 2017)	60
PEI-f-CMC (Ateia, et al., 2018)	12.8
DFB-CDP (Xiao, et al., 2017)	2.9

Testing conducted in 1 µg/L PFOA at 10 mg/L except PEI-f-CMC was tested at 20 mg/L.



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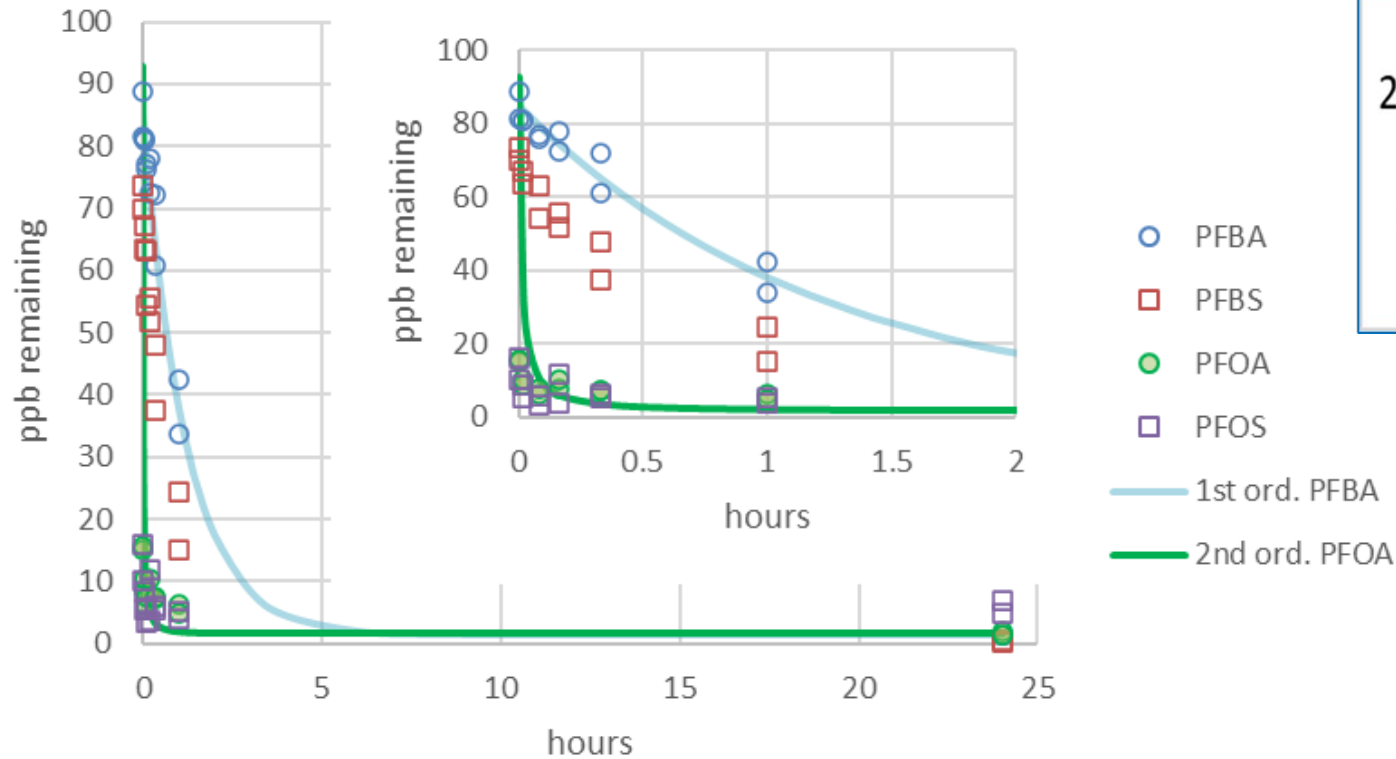
Kinetics HG-1 vs GAC at environmentally relevant concentrations 10 ppb each of PFBA, PFBS, PFOA and PFOS



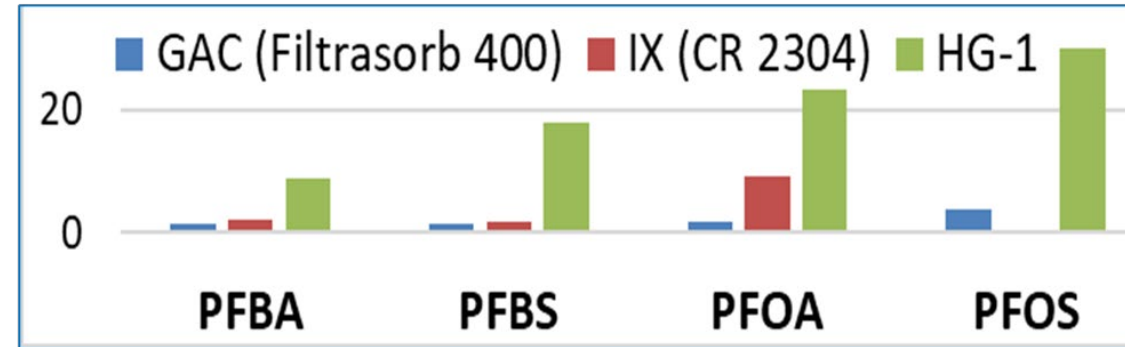
HG-1 sorbs all 4 PFAS at a faster rate than GAC in mixture of 4 PFAS at environmentally relevant concentrations

Kinetics of sorption HG-1 at high concentrations of Mix of 4 PFAS

Adsorption of 4 PFAS at 100 ppb by HG-1 with 1st and 2nd order model fits



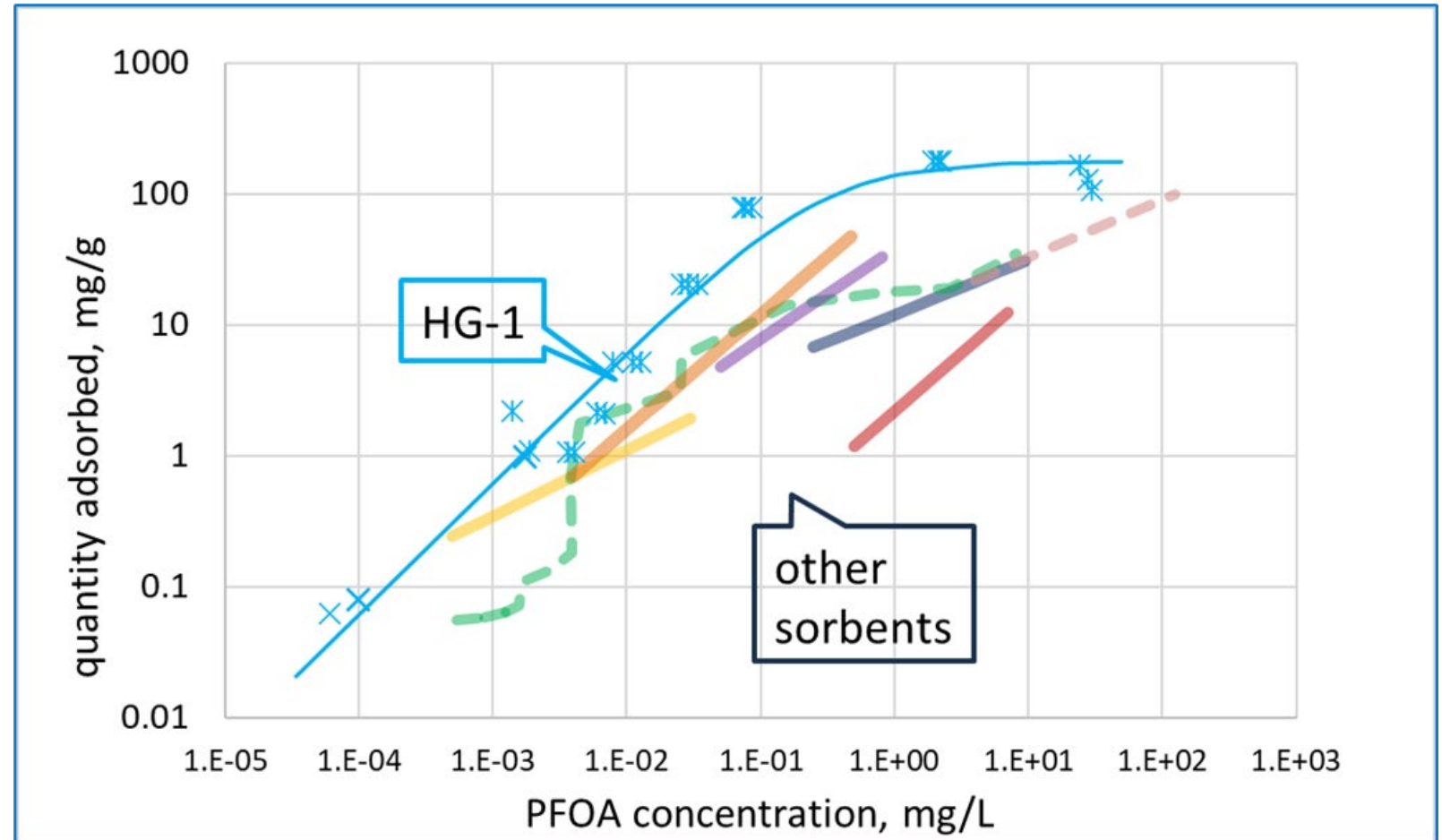
Kinetics of mix of 4 PFAS. at 10ppb by HG-1, GAC and IX. Relative rate constants First order L/g/hr



PFOA Sorption Capacity of HG-1, GAC, IX and others

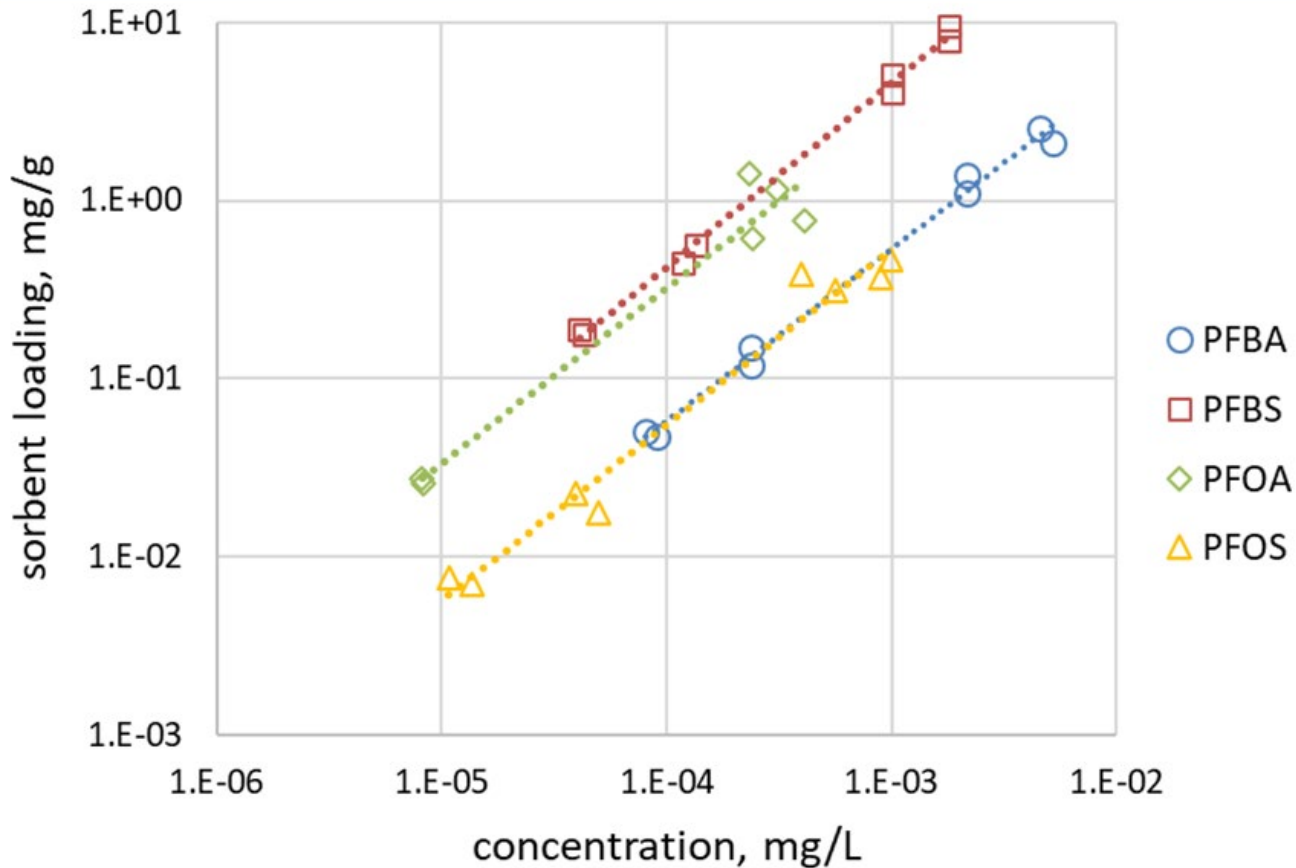
HG-1 capacity for PFOA exceeds that of GAC and IX resins.

HG-1 can sorb up to 10% its mass (100 mg/g) of PFOA, a capacity that is significantly greater than the comparison sorbents





HG-1 Isotherms in Mixture of PFBA, PFBS, PFOA, PFOS



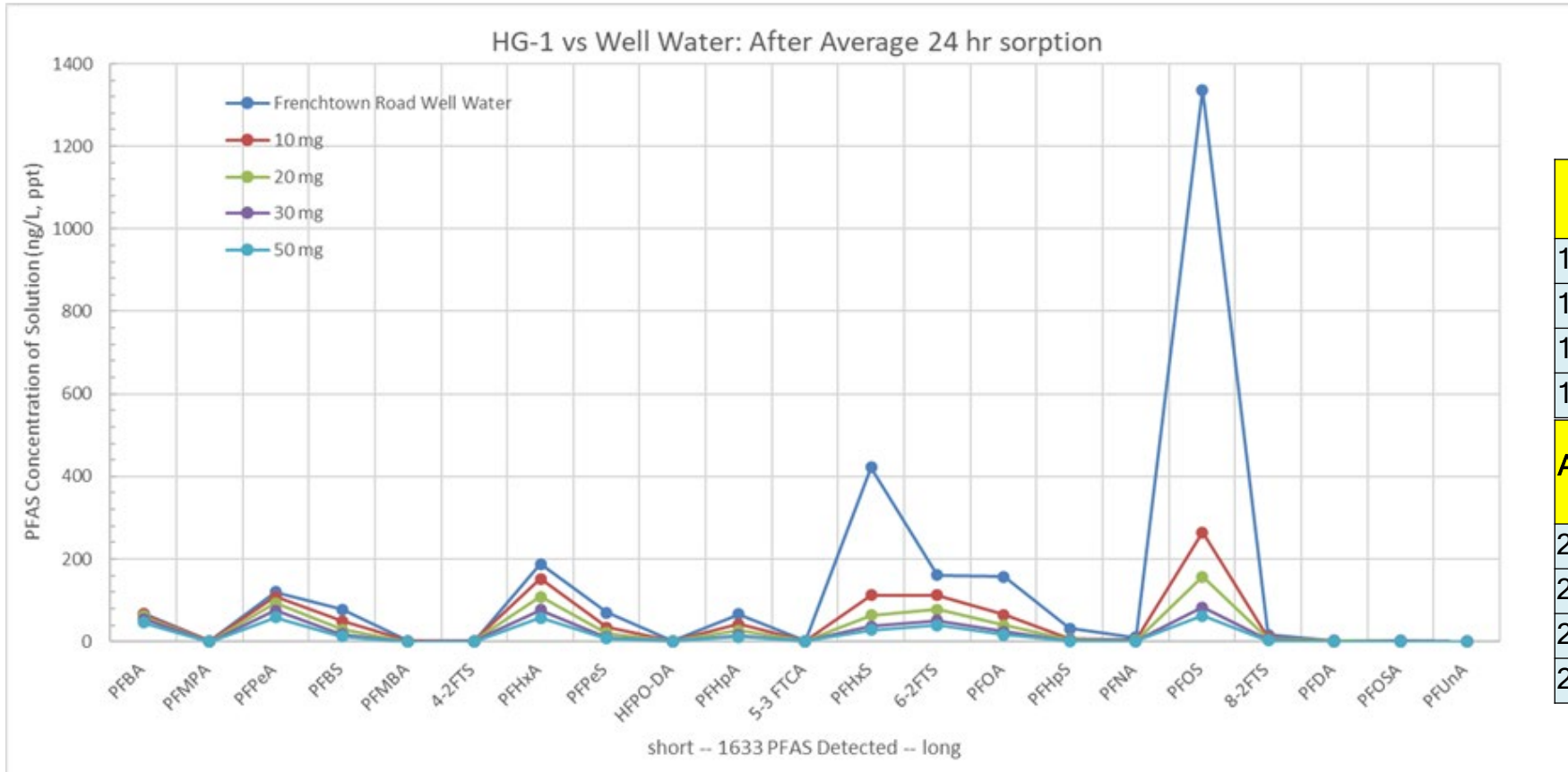
Sorption capacity of HG-1 in mg/g (measured at 1ppb) is higher than GAC for all four PFAS and higher than IX for PFOA and PFOS

	GAC F400	IX CR2304	HG-1
PFBA	0.26	2.59	0.43
PFBS	0.60	>10	5.10
PFOA	0.35	0.17	1.42
PFOS	0.23	0.02	0.47
4 PFAS	1.44	>13	7.42



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Well water contaminated with AFFF tested with HG-1 Total PFAS 2733 ppt



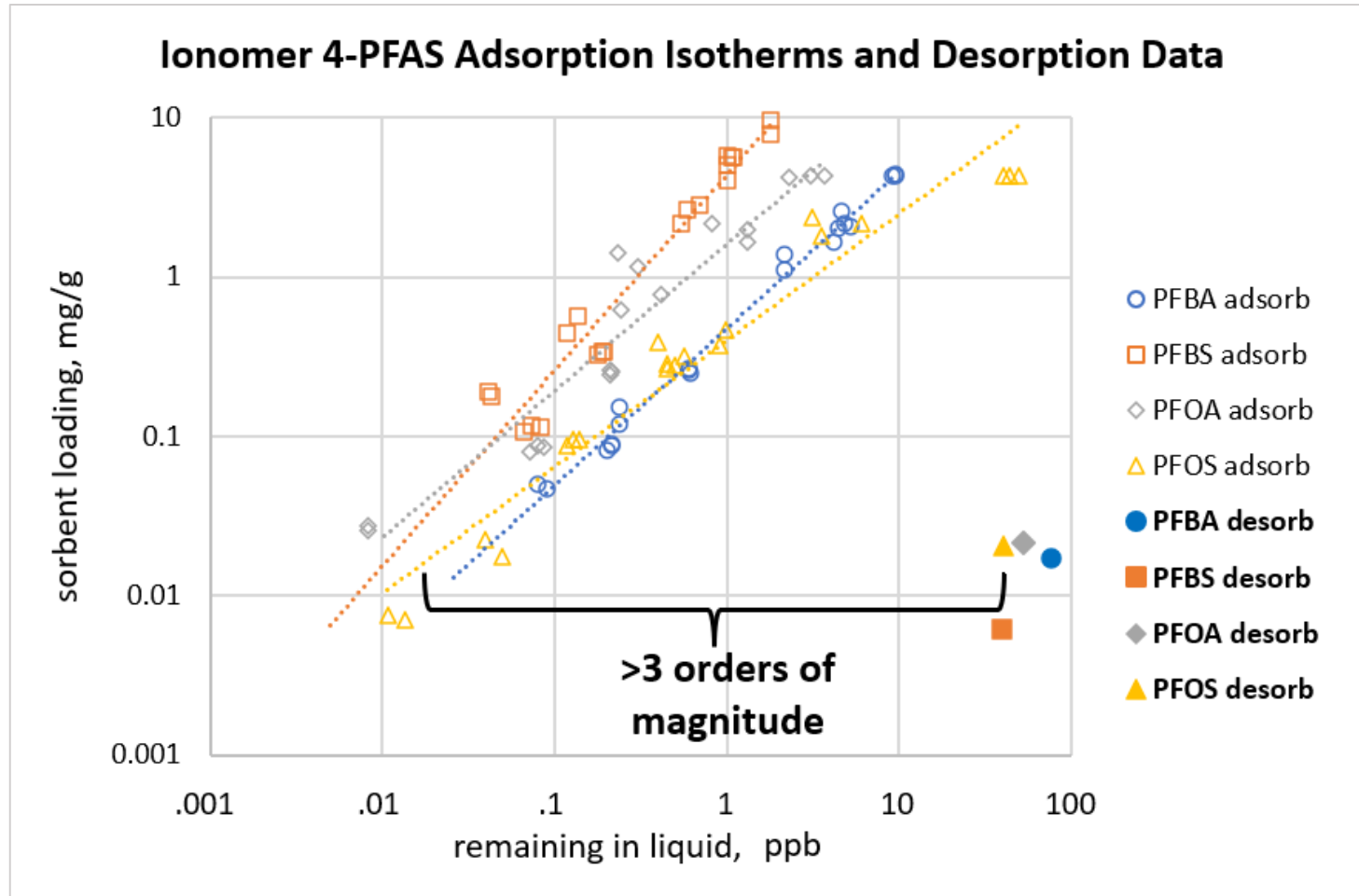
Average of A, B, C: 1 hr study		% TPFAS Removed
1 hour	10 mg	56.9
1 hour	20 mg	60.7
1 hour	30 mg	75.9
1 hour	50 mg	77.0
Average of A, B, C: 24 hr study		% TPFAS Removed
24 hours	10 mg	62.2
24 hours	20 mg	74.5
24 hours	30 mg	83.3
24 hours	50 mg	87.3

Desorption by an Aqueous Formulation Using Batch Tests

	Total % PFAS desorbed based on PFAS Sorbed	Time
IX A	23.2	1hr
	59.6	22hr
IX B	30.3	1hr
	58.5	22hr
IX C	13.9	1hr
	42.4	22hr
HG-1	92.2	1hr
	90.7	22hr



Batch Desorption Data Indicate 1000x Concentration is Possible



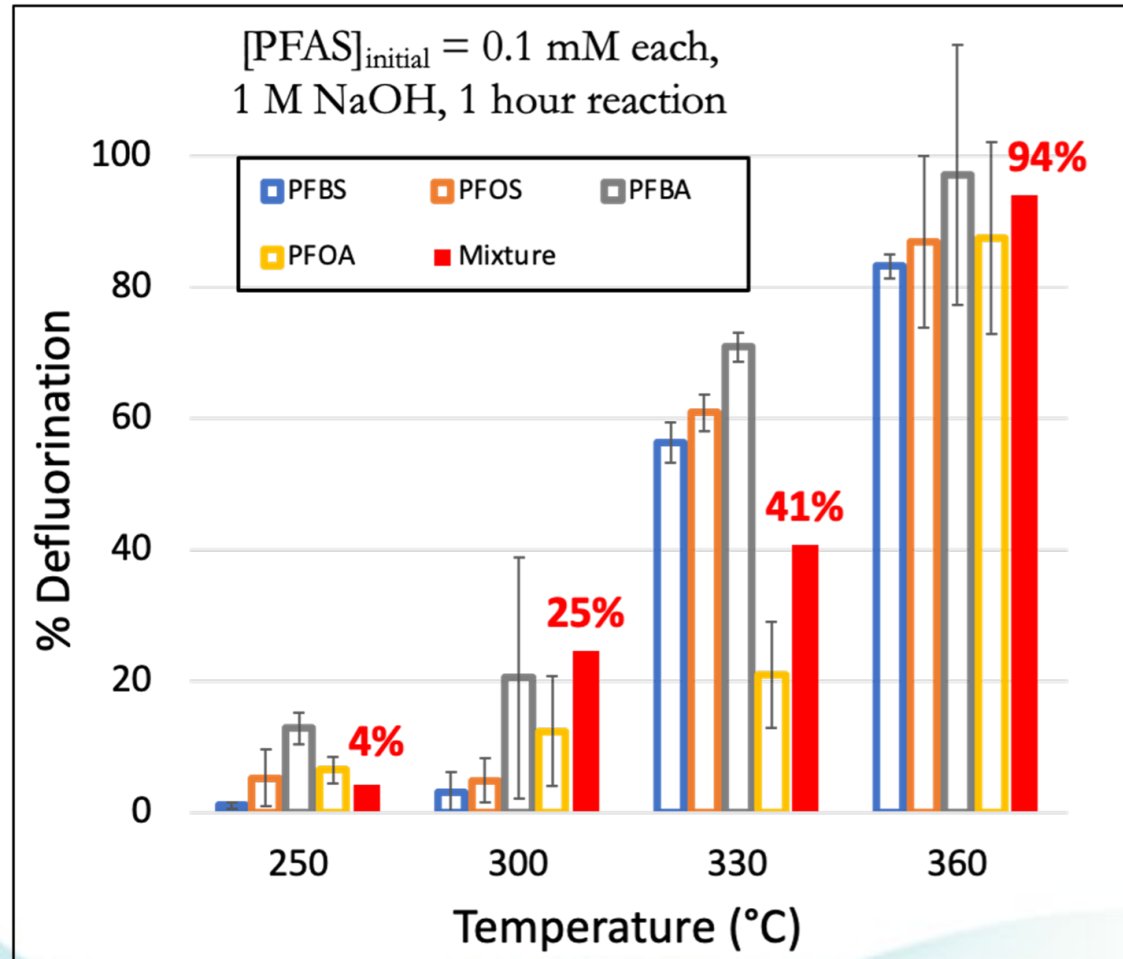
Desorption data is for one sorbent loading only.

we don't yet have data at sufficiently different sorbent loadings. But we anticipate isotherms in the desorption solution with slopes close to 1, like the adsorption isotherms.

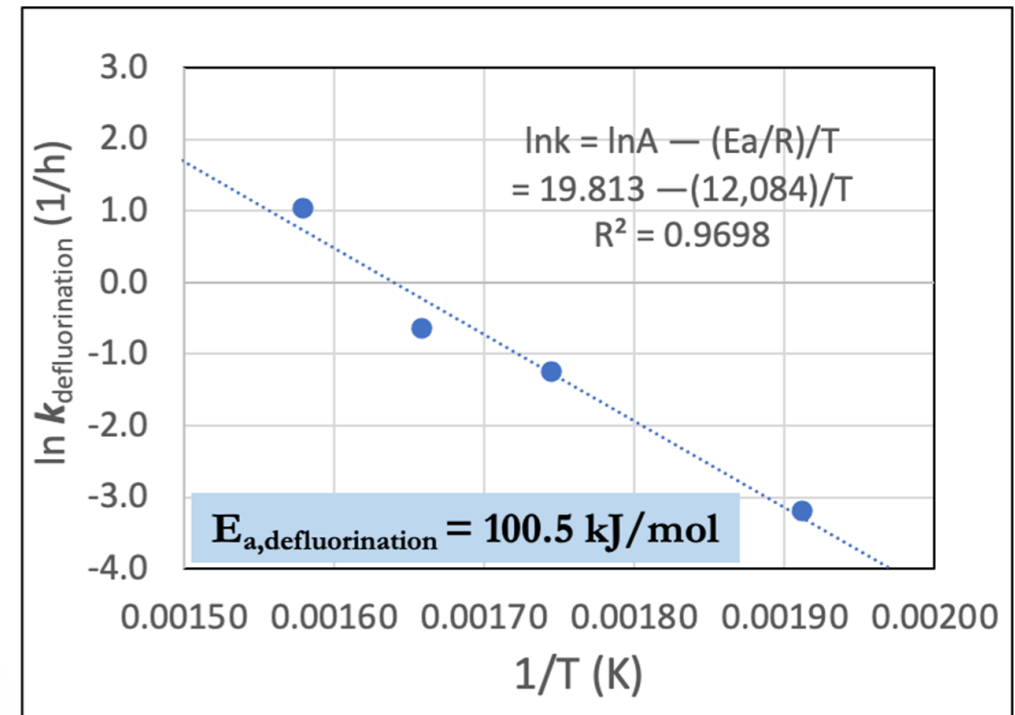


Destruction by Hydrothermal Alkaline Treatment of Desorbed PFAS in the Aqueous Formulation

Studied by Dr. Pei Chiu at University of Delaware



1. Same % defluorination for individual PFAS and mixture
2. Same % defluorination with and without 0.2% PDP
3. Activation energy (E_a) for defluorination ≈ 101 kJ/mol





Conclusions- Observations

- Ionomer labelled HG-1 sorbed mix of PFBA, PFBA, PFOA and PFOS, faster than GAC (Filtrisorb 400) and IX resin (CalRes 2304)
- Sorption capacity of HG-1 for PFOA exceeds that of other sorbents tested
- Sorption capacity of HG-1 (measured at 1ppb) is higher than GAC for all four PFAS and higher than IX for the longer chain PFAS
- Preliminary data shows an all-aqueous formulation for desorption and concentration is feasible and can be improved
- Demonstrated defluorination of PFAS in the de-sorbed liquid formulation= the additive does not interfere with destruction