PFAS Remediation Using CAC: Field Performance and Cost-Benefit Analysis

Presented by Dr. Grant Carey
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BOOTH #316

REMTEC & EMERGING CONTAMINANTS SUMMIT

OCTOBER 15-17, 2024

U.S. DoD SERDP/ESTCP Project Involvement

ESTCP ER21-3959	An Investigation of Factors Affecting *In Situ* **PFAS Immobilization by Activated Carbon**
ESTCP ER20-5182	**Validation of Colloidal Activated Carbon** for Preventing the Migration of PFAS in Groundwater
ESTCP ER21-1070	Hydraulic, Chemical, and Microbiological Effects of *In Situ* Activated **Carbon Sorptive Barrier** for PFAS Remediation in Coastal Sites
ESTCP ER24-8200	**Two PFAS Remediation Models** for Understanding and Managing PFAS in the Saturated Zone

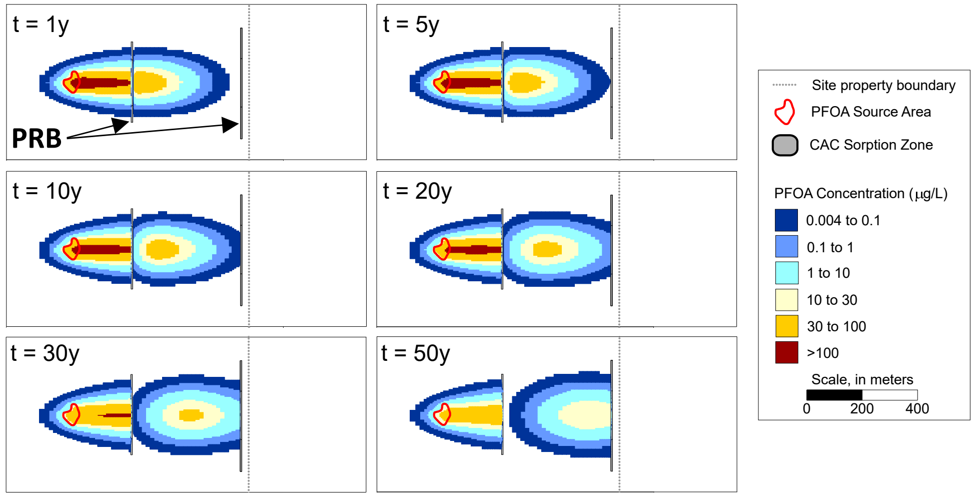
The In-Situ Remediation Model (ISR Model)

- Originally developed in 1998 as BioRedox-MT3DMS
- Field and research projects since 2017
- PFAS-related functionality
  - ✓ PFAS adsorption to CAC
  - ✓ Kinetic sorption
  - ✓ Competitive adsorption
  - ✓ CAC aging
  - ✓ Colloid transport
  - ✓ Branched decay chains

In progress

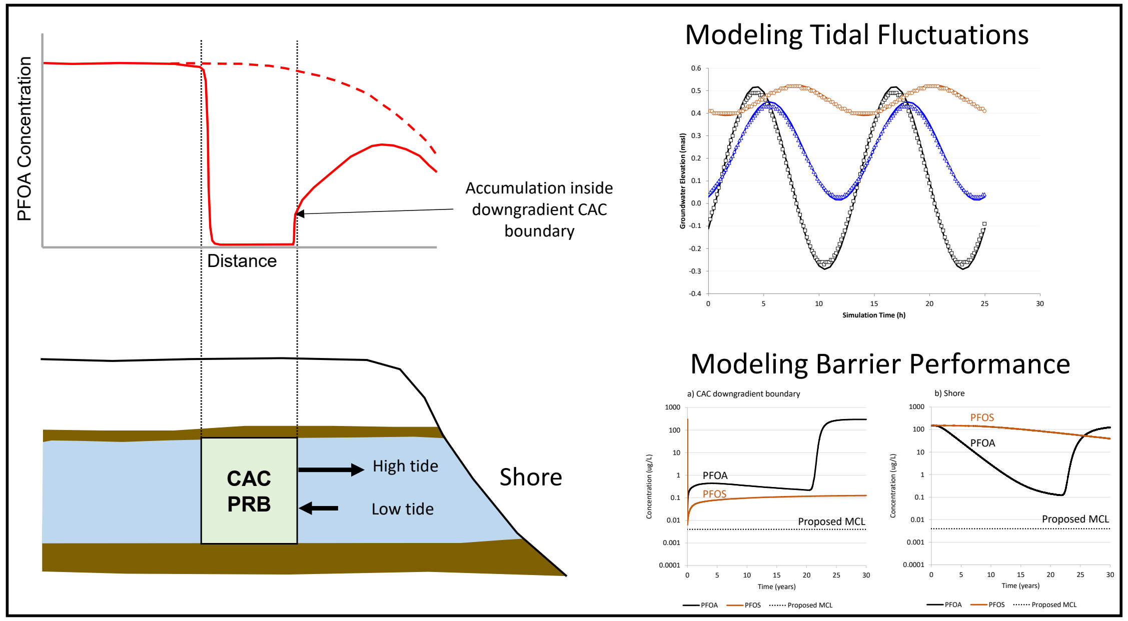
South Dakota Air Force Base

Carey et al. (2023)

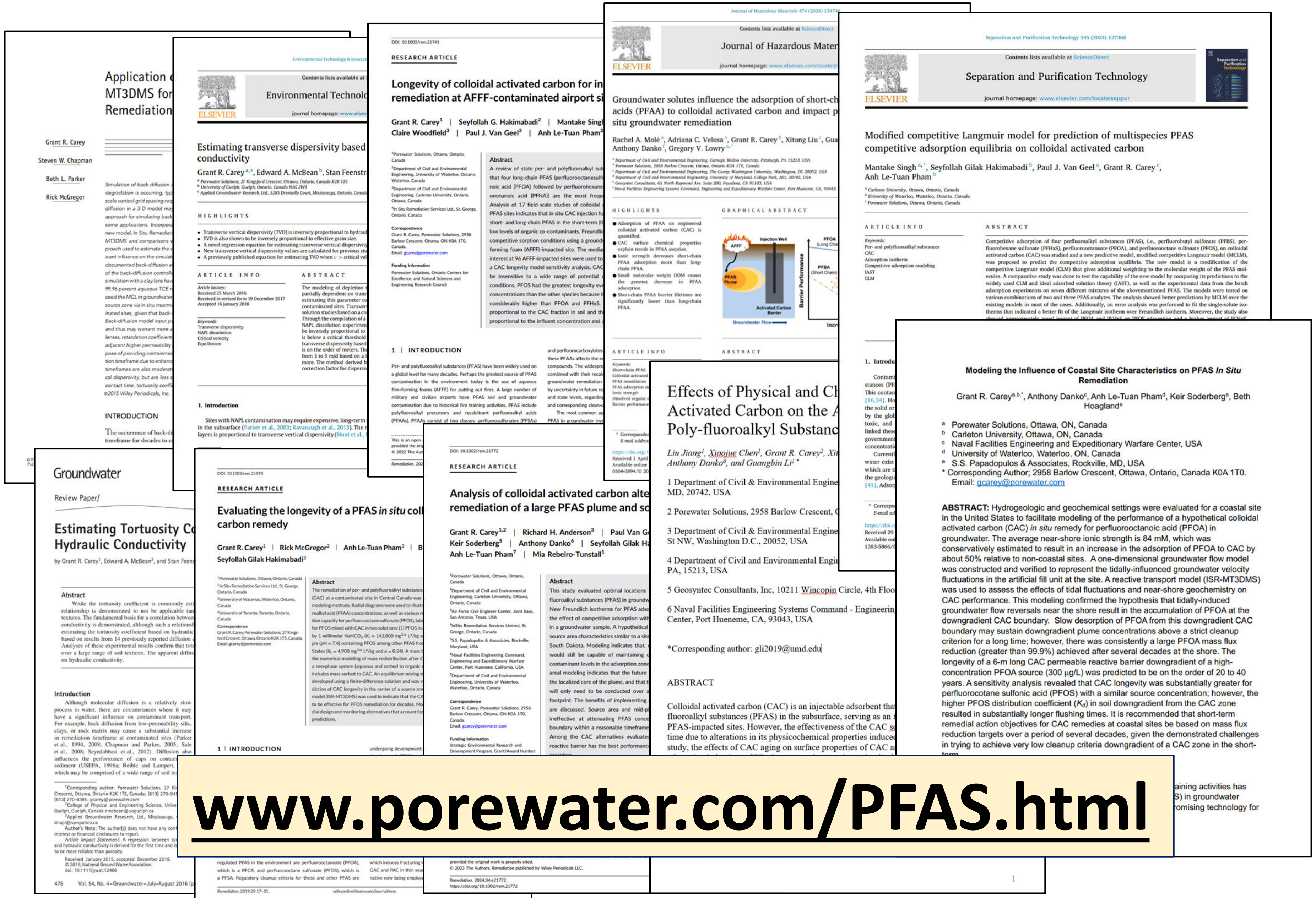


Navy Coastal Site

Carey et al. (2024)



Recent ISR Model & PFAS Publications



Application
MT3DMS for
Remediation

Grant R. Carey
Steven W. Chapman
Beth L. Parker
Rick McGregor

Environmental Technology & Innovation

Estimating transverse dispersivity based
conductivity

Grant R. Carey a,*, Edward A. McBean b, Stan Feenstra

DOI: 10.1002/rem.21741

RESEARCH ARTICLE

Longevity of colloidal activated carbon for in
remediation at AFFF-contaminated airport si

Grant R. Carey[1] | Seyfollah G. Hakimabadi[2] | Mantake Singh
Claire Woodfield[3] | Paul J. Van Geel[3] | Anh Le-Tuan Pham[2]

Journal of Hazardous Materials 474 (2024) 134746

Groundwater solutes influence the adsorption of short-ch
acids (PFAA) to colloidal activated carbon and impact p
situ groundwater remediation

Rachel A. Molé a, Adriana C. Velosa a, Grant R. Carey b, Xitong Liu c, Gua
Anthony Danko f, Gregory V. Lowry a,*

Separation and Purification Technology 345 (2024) 127368

Modified competitive Langmuir model for prediction of multispecies PFAS competitive adsorption equilibria on colloidal activated carbon

Mantake Singh a,*, Seyfollah Gilak Hakimabadi b, Paul J. Van Geel a, Grant R. Carey c,
Anh Le-Tuan Pham b

Groundwater

Review Paper/

Estimating Tortuosity C
Hydraulic Conductivity

by Grant R. Carey[1], Edward A. McBean[2], and Stan Feens

DOI: 10.1002/rem.21593

RESEARCH ARTICLE

Evaluating the longevity of a PFAS *in situ* coll
carbon remedy

Grant R. Carey[1] | Rick McGregor[2] | Anh Le-Tuan Pham[3] | B
Seyfollah Gilak Hakimabadi[3]

DOI: 10.1002/rem.21772

RESEARCH ARTICLE

Analysis of colloidal activated carbon alte
remediation of a large PFAS plume and so

Grant R. Carey[1,2] | Richard H. Anderson[3] | Paul Van G
Keir Soderberg[5] | Anthony Danko[6] | Seyfollah Gilak H
Anh Le-Tuan Pham[7] | Mia Rebeiro-Tunstall[1]

Effects of Physical and Ch
Activated Carbon on the A
Poly-fluoroalkyl Substanc

*Liu Jiang[1], Xiaojue Chen[1], Grant R. Carey[2], Xi
Anthony Danko[6], and Guangbin Li[1] **

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6 Naval Facilities Engineering Systems Command - Engineerin
Center, Port Hueneme, CA, 93043, USA

*Corresponding author: gli2019@umd.edu

ABSTRACT

Colloidal activated carbon (CAC) is an injectable adsorbent tha
fluoroalkyl substances (PFAS) in the subsurface, serving as an
PFAS-impacted sites. However, the effectiveness of the CAC s
time due to alterations in its physicochemical properties induce
study, the effects of CAC aging on surface properties of CAC a

Modeling the Influence of Coastal Site Characteristics on PFAS *In Situ* Remediation

Grant R. Carey[a,b,*], Anthony Danko[c], Anh Le-Tuan Pham[d], Keir Soderberg[e], Beth Hoagland[e]

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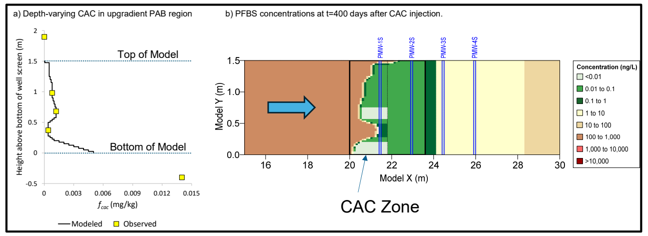
[b] Carleton University, Ottawa, ON, Canada
[c] Naval Facilities Engineering and Expeditionary Warfare Center, USA
[d] University of Waterloo, Waterloo, ON, Canada
[e] S.S. Papadopulos & Associates, Rockville, MD, USA
* Corresponding Author; 2958 Barlow Crescent, Ottawa, Ontario, Canada K0A 1T0.
Email: gcarey@porewater.com

ABSTRACT: Hydrogeologic and geochemical settings were evaluated for a coastal site in the United States to facilitate modeling of the performance of a hypothetical colloidal activated carbon (CAC) *in situ* remedy for perfluorooctanoic acid (PFOA) in groundwater. The average near-shore ionic strength is 84 mM, which was conservatively estimated to result in an increase in the adsorption of PFOA to CAC by about 50% relative to non-coastal sites. A one-dimensional groundwater flow model was constructed and verified to represent the tidally-influenced groundwater velocity fluctuations in the artificial fill unit at the site. A reactive transport model (ISR-MT3DMS) was used to assess the effects of tidal fluctuations and near-shore geochemistry on CAC performance. This modeling confirmed the hypothesis that tidally-induced groundwater flow reversals near the shore result in the accumulation of PFOA at the downgradient CAC boundary. Slow desorption of PFOA from this downgradient CAC boundary may sustain downgradient plume concentrations above a strict cleanup criterion for a long time; however, there was consistently a large PFOA mass flux reduction (greater than 99.9%) achieved after several decades at the shore. The longevity of a 6-m long CAC permeable reactive barrier downgradient of a high-concentration PFOA source (300 µg/L) was predicted to be on the order of 20 to 40 years. A sensitivity analysis revealed that CAC longevity was substantially greater for perfluorocotane sulfonic acid (PFOS) with a similar source concentration; however, the higher PFOS distribution coefficient (K_d) in soil downgradient from the CAC zone resulted in substantially longer flushing times. It is recommended that short-term remedial action objectives for CAC remedies at coastal sites be based on mass flux reduction targets over a period of several decades, given the demonstrated challenges in trying to achieve very low cleanup criteria downgradient of a CAC zone in the short-term.

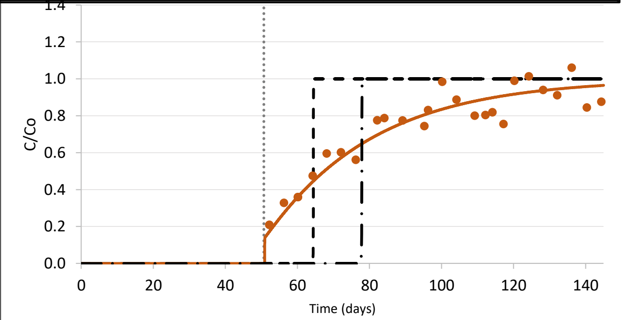
aining activities has
S) in groundwater
romising technology for

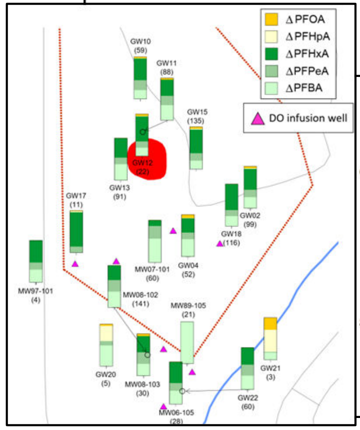
www.porewater.com/PFAS.html

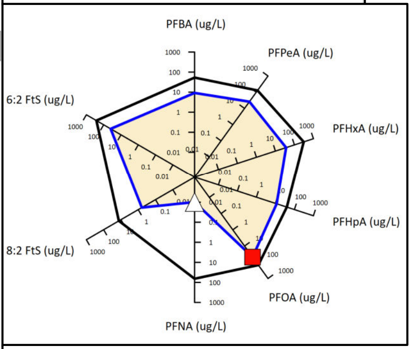
Papers in progress



Alternative	Downgradient PRB CAC Core/Fringe Concentration	Source Control	Installation Cost*	Total Cost+	Modeled PRB Longevity (y)
1.1	CAC 1000/500 mg/kg	n/a	**$1.6M**	**$4.0M**	31
1.2	CAC 2000/500 mg/kg	n/a	**$2.0M**	**$4.7M**	62
1.3	CAC 1000/500 mg/kg plus Re-injection at 15 years	n/a	**$2.4M**	**$5.4M**	n/a
2.1	CAC 1000/500 mg/kg	Cover	**$2.0M**	**$4.9M**	35 to 45 (based on 20% to 50% Md reduction)
2.2	CAC 1000/500 mg/kg	Cover + Wall	**$3.2M**	**$7.0M**	>100
2.3	CAC 1000/500 mg/kg	Soil Stabilization	**$5.6M**	**$10.3M**	>100







Outline

1 Modeling Field Performance at NESDI Site

- PFAS adsorption isotherms (short- and long-chain)
- CAC Heterogeneity

2 Cost-Benefit Analysis

- Downgradient CAC barrier
- Integrate with source control?

Field Performance at NESDI Site (Eastern USA)

Section 1

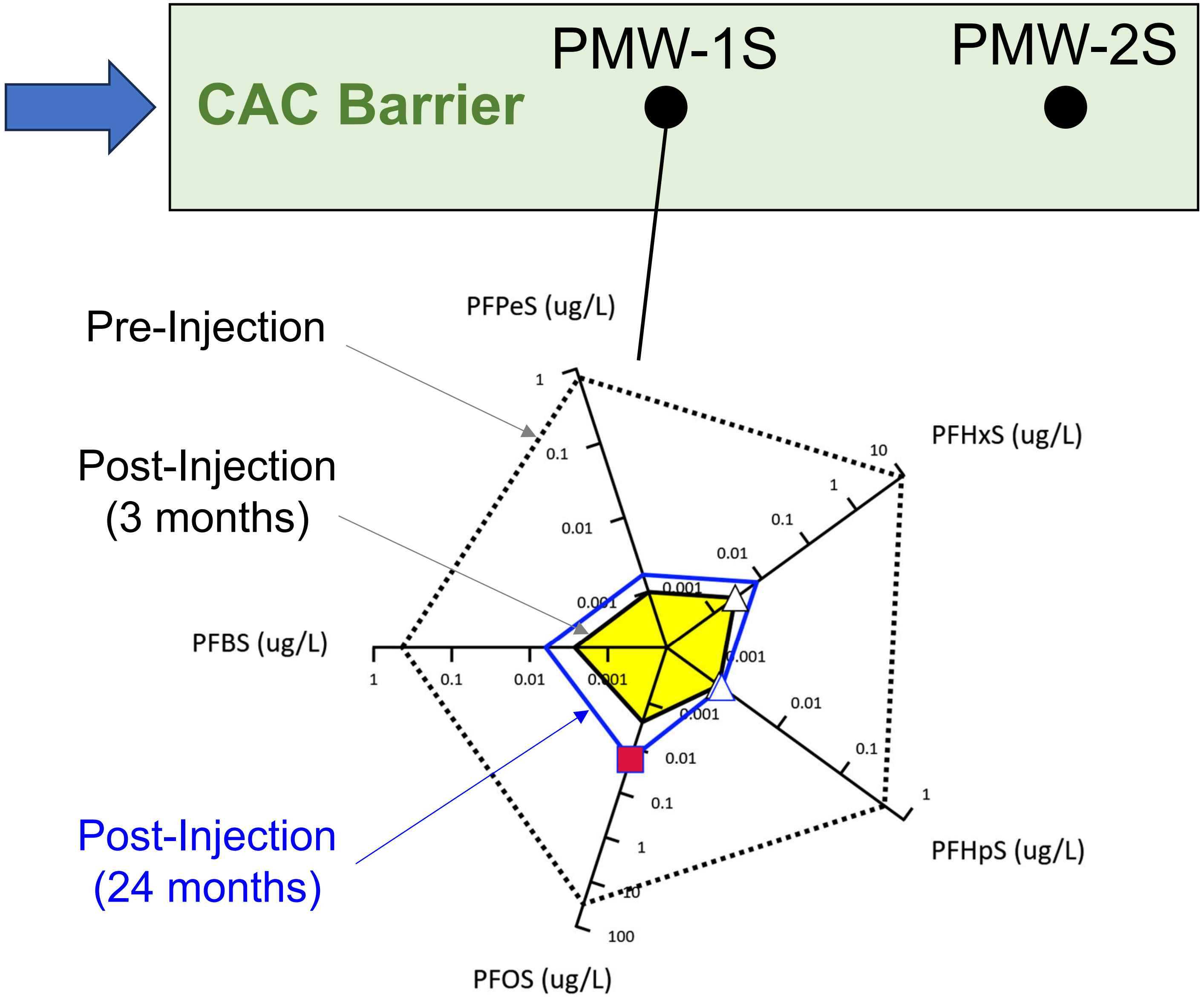
Acknowledgements

Dr. Paul Hatzinger, Graig Lavorgna, David Lippincott
APTIM

Dr. Anthony Danko
NAVFAC EXWC

Dr. Brent Sleep
University of Toronto

NESDI PRB Performance: PFSAs



CAC Barrier

PMW-1S

PMW-2S

PMW-3S

PMW-4S

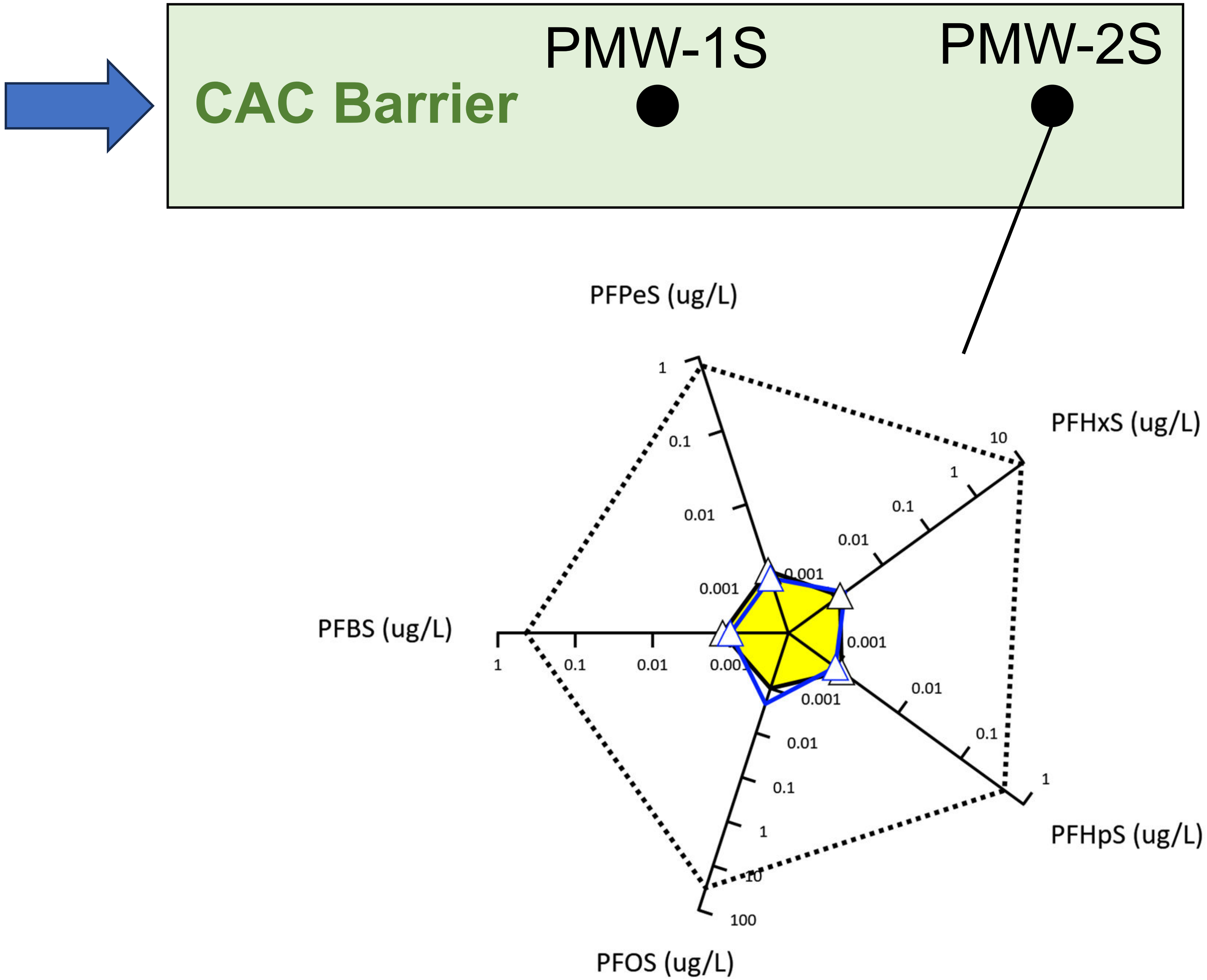
Pre-Injection

Post-Injection
(3 months)

Post-Injection
(24 months)

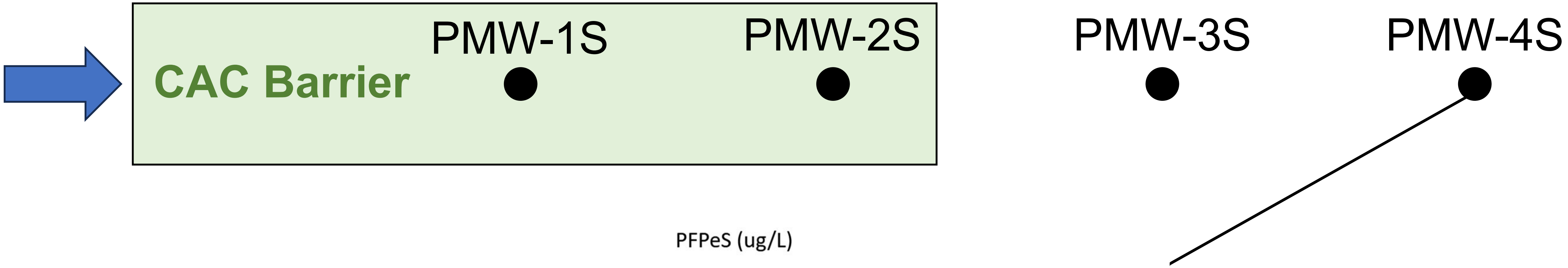
△	Non-detect
🟥	MCL exceedance
....	Pre-injection (Baseline)
▬	Post-injection (3 months)
▬	Post-injection (24 months)

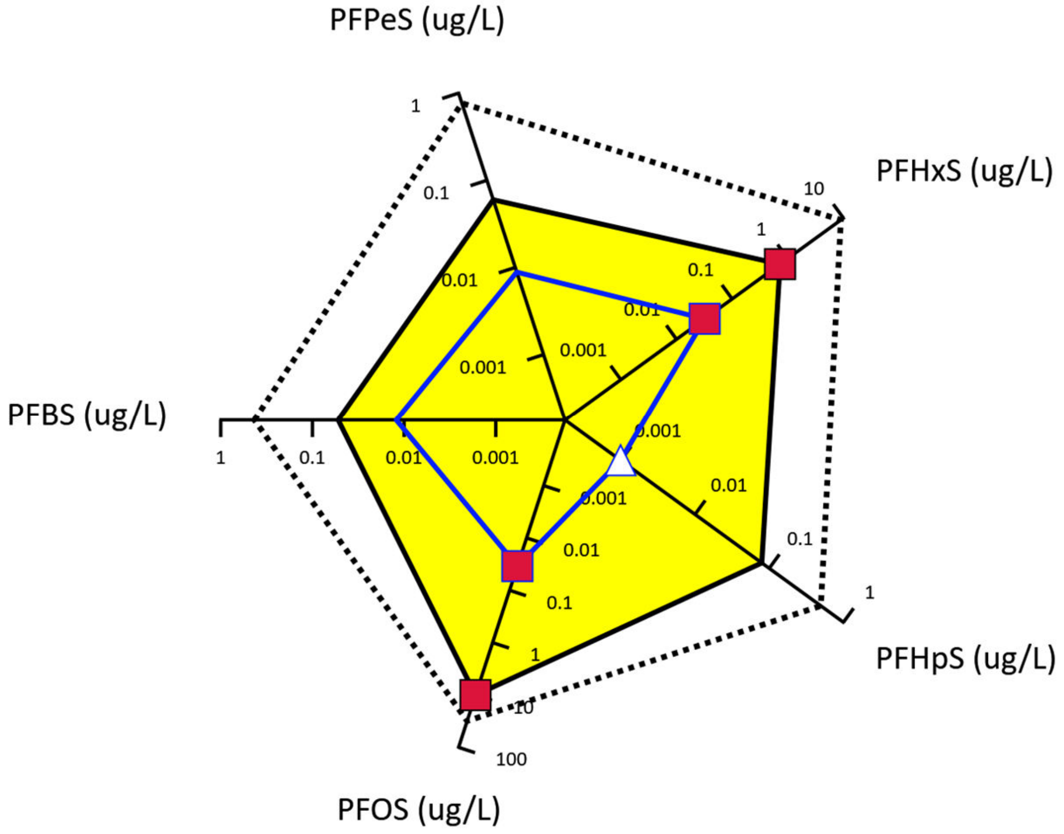
NESDI PRB Performance: PFSAs



△ Non-detect
🟥 MCL exceedance
⋯⋯ Pre-injection (Baseline)
— Post-injection (3 months)
— Post-injection (24 months)

NESDI PRB Performance: PFSAs





△ Non-detect

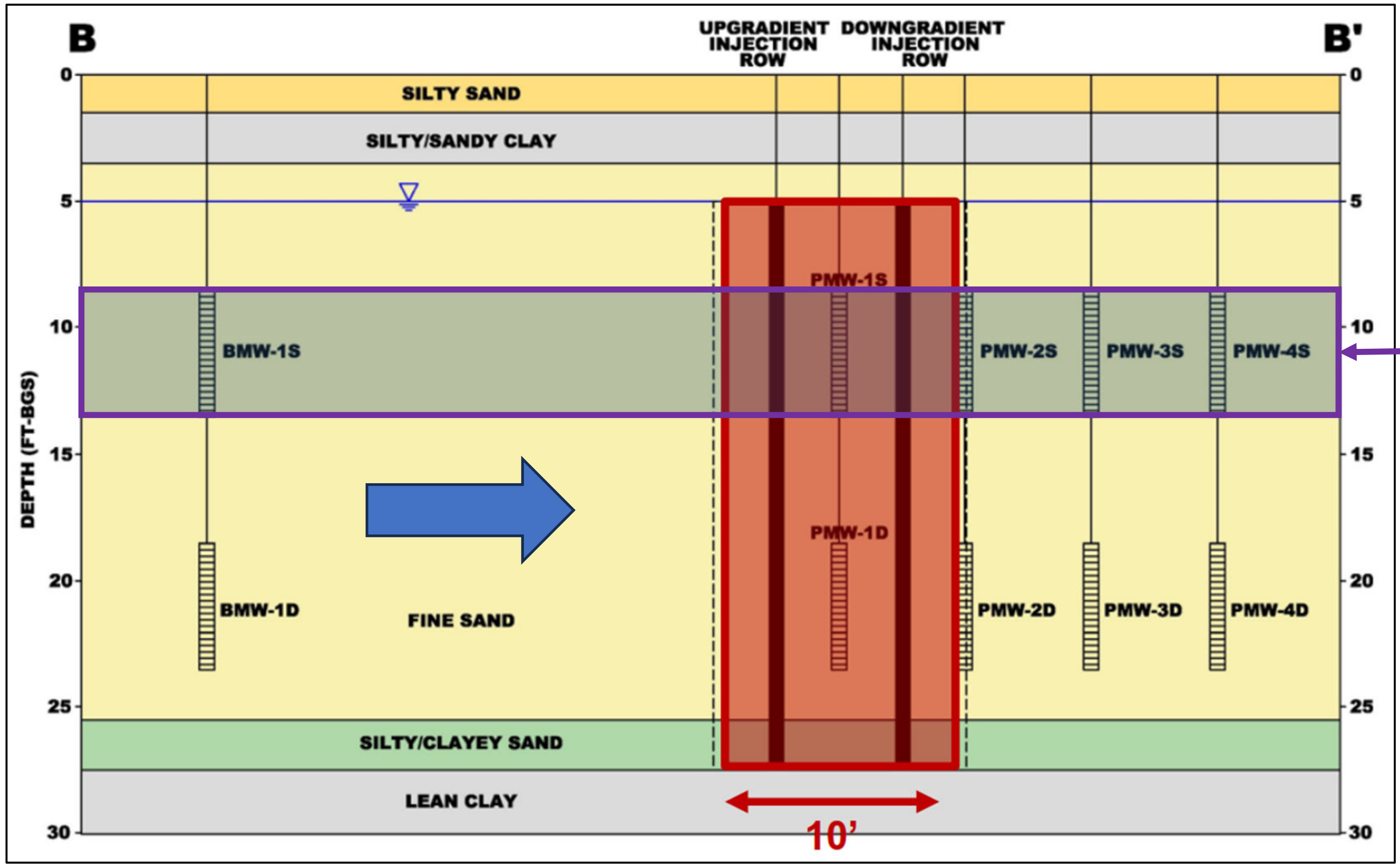
🟥 MCL exceedance

········ Pre-injection (Baseline)

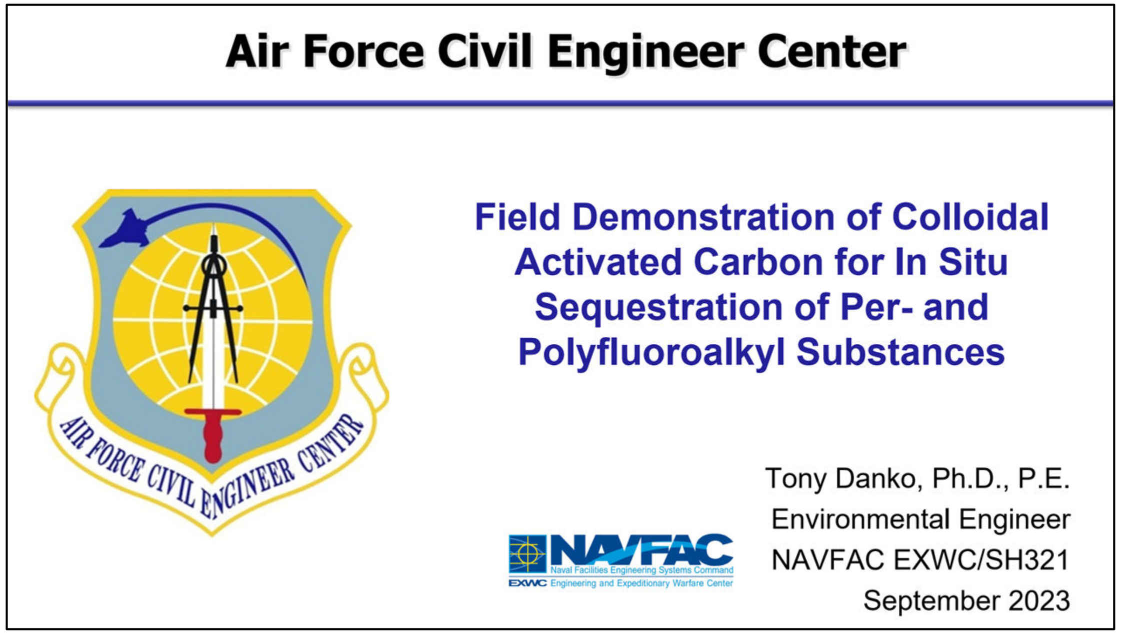
— Post-injection (3 months)

— Post-injection (24 months)

Eastern U.S. Site CAC Permeable Reactive Barrier



Modeled thickness: 5 ft

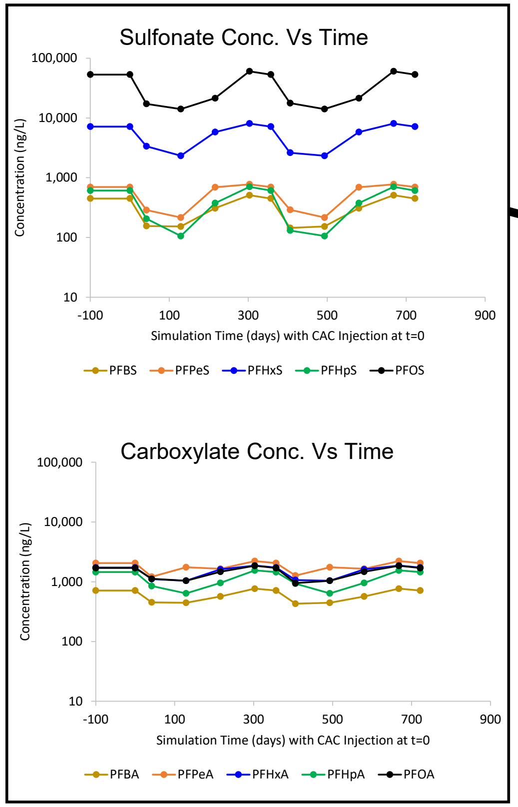


Air Force Civil Engineer Center

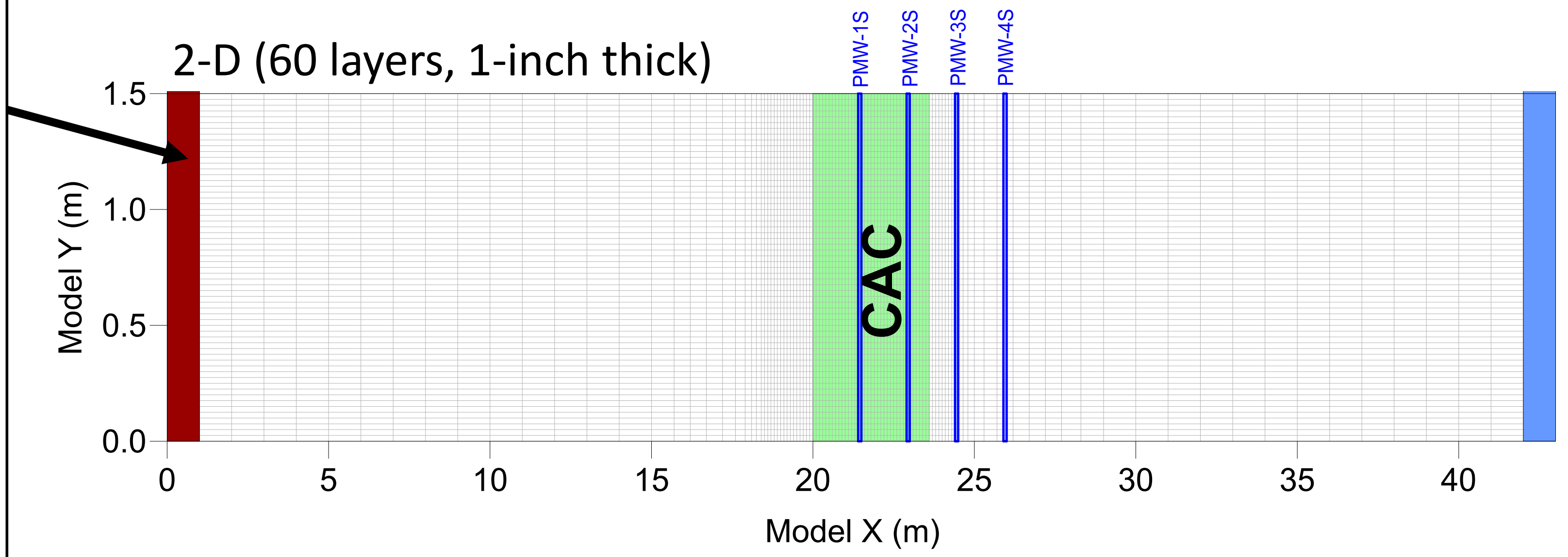
Field Demonstration of Colloidal Activated Carbon for In Situ Sequestration of Per- and Polyfluoroalkyl Substances

Tony Danko, Ph.D., P.E.
Environmental Engineer
NAVFAC EXWC/SH321
September 2023

Model Domain and Boundary Conditions



2-D (60 layers, 1-inch thick)



Carey et al. (2015)

$\alpha_z = 0.08\ K^{-0.16}$

$\alpha_z = 0.3$ mm

Note: K in m/s

K = 150 ft/y

i = 0.001 ft/ft

v = 220 ft/y

$f_{oc} = 0.2\%$

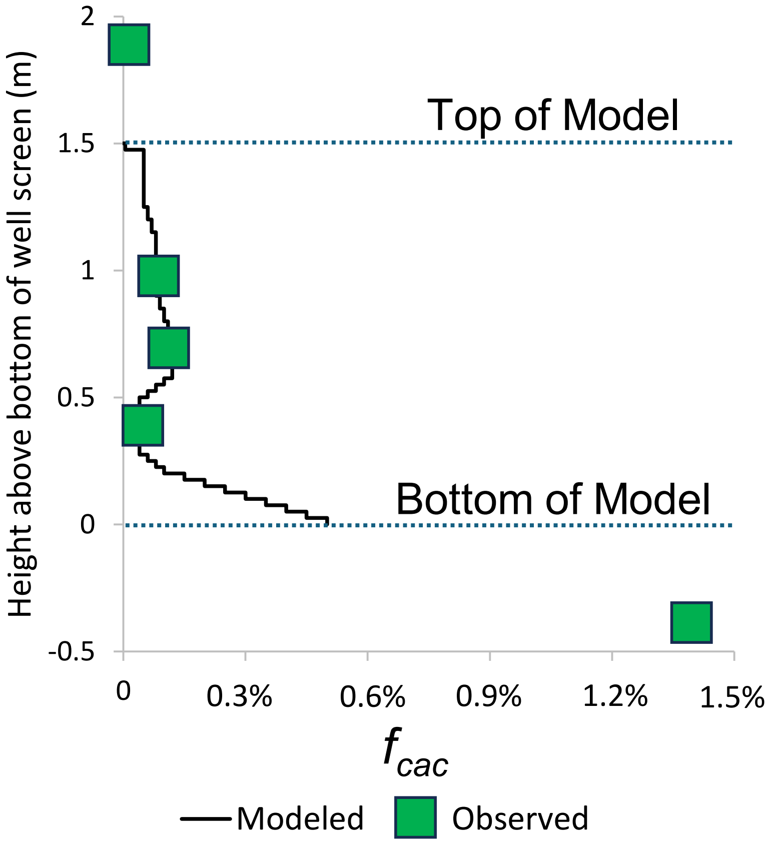
$\theta_e = 0.25$

$\rho_b = 1.6$ kg/L

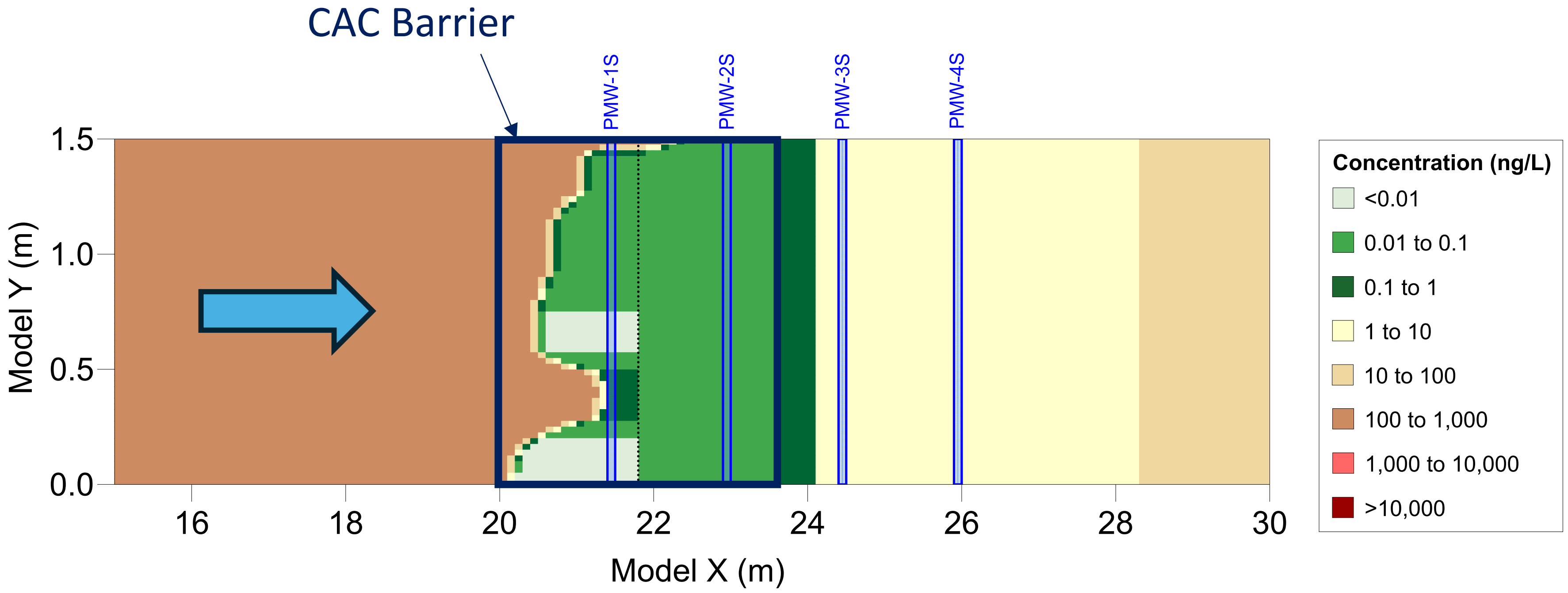
$\alpha_x = 0.03$ m

CAC Influence on PFAS Transport in Barrier

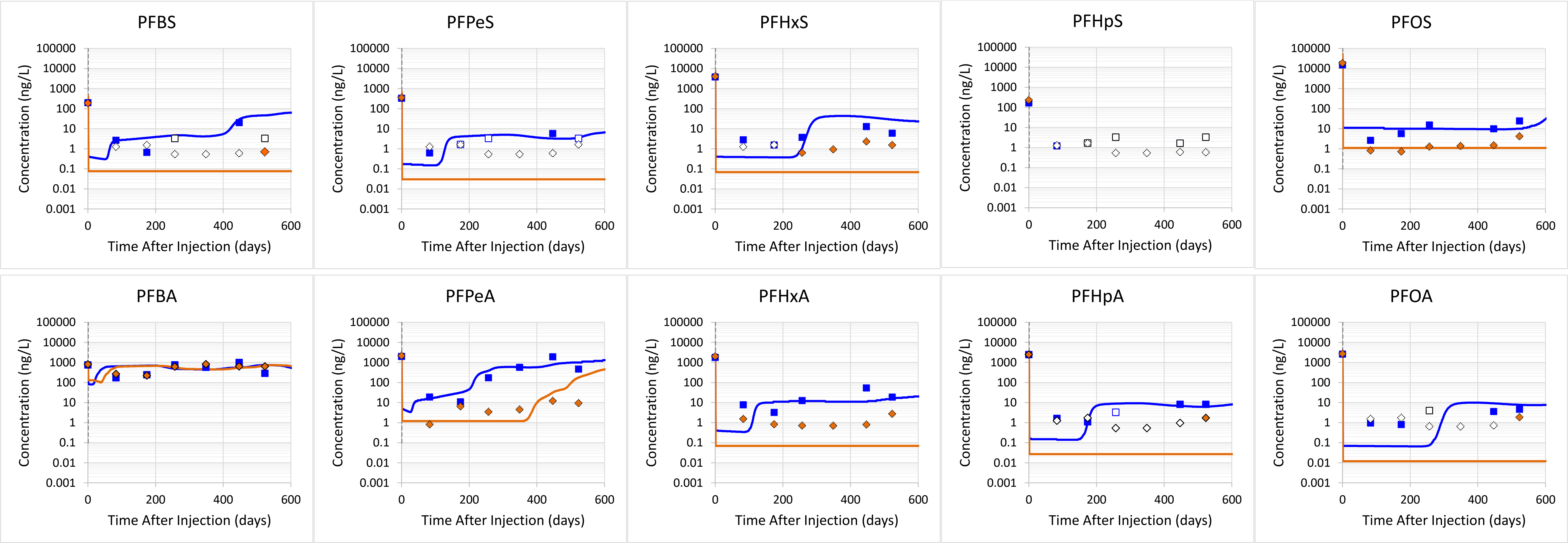
a) CAC Vertical Distribution at x = 5 ft



b) Modeled PFBS plume 400 days after CAC injection

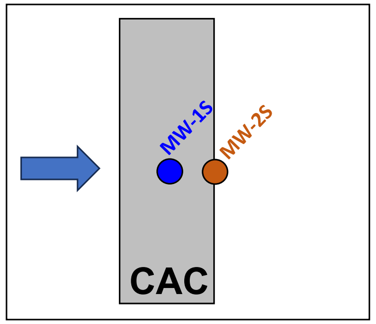


Preliminary Isotherm Calibration (First Six Quarters)



■ Observed: PMW-1S (x=5 ft)
◆ Observed: PMW-2S (x=10 ft)
— Modeled: PMW-1S (x=5 ft)
— Modeled: PMW-2S (x=10 ft)

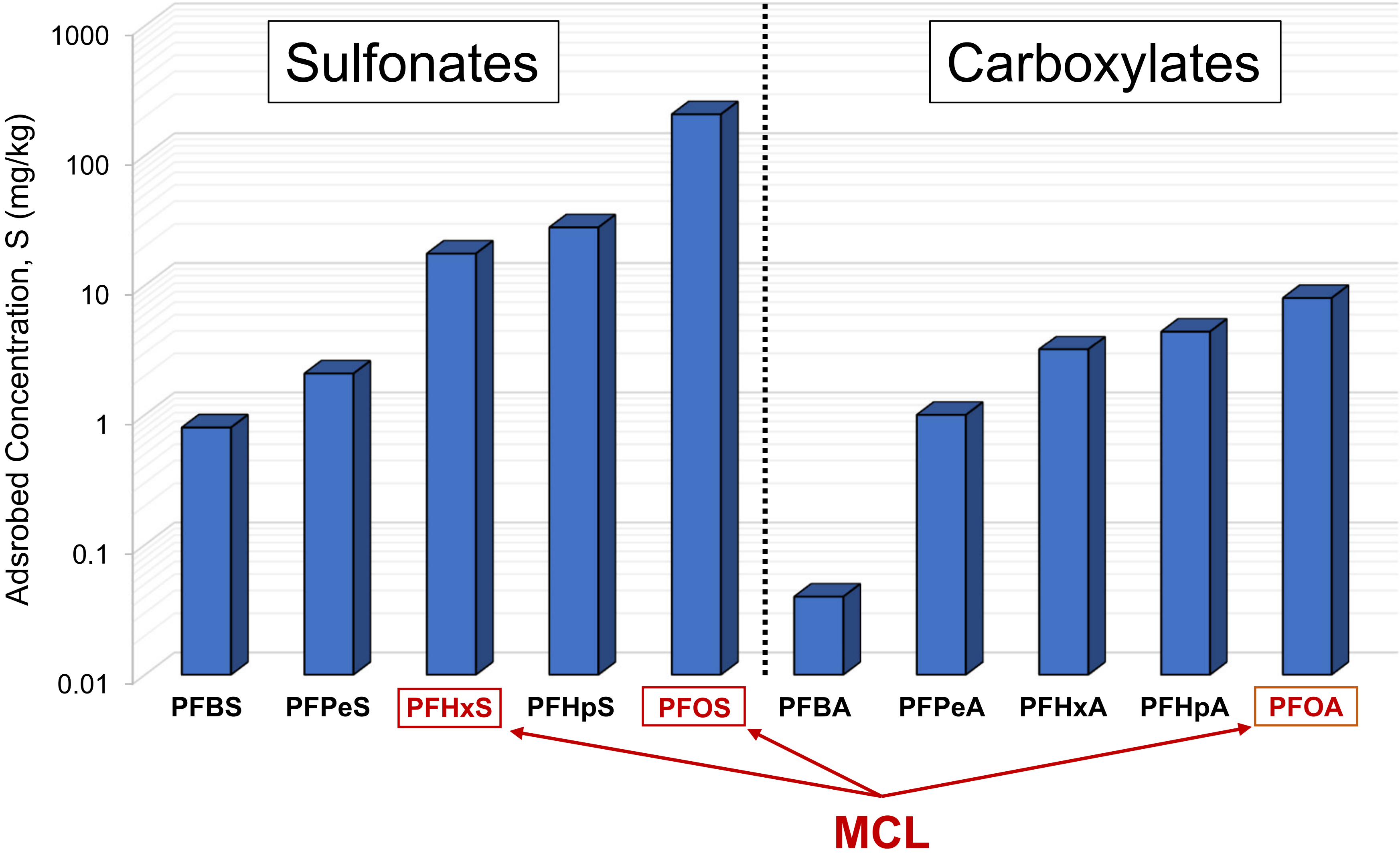
DRAFT



Adsorbed Concentration Based on Calibrated Isotherms

DRAFT

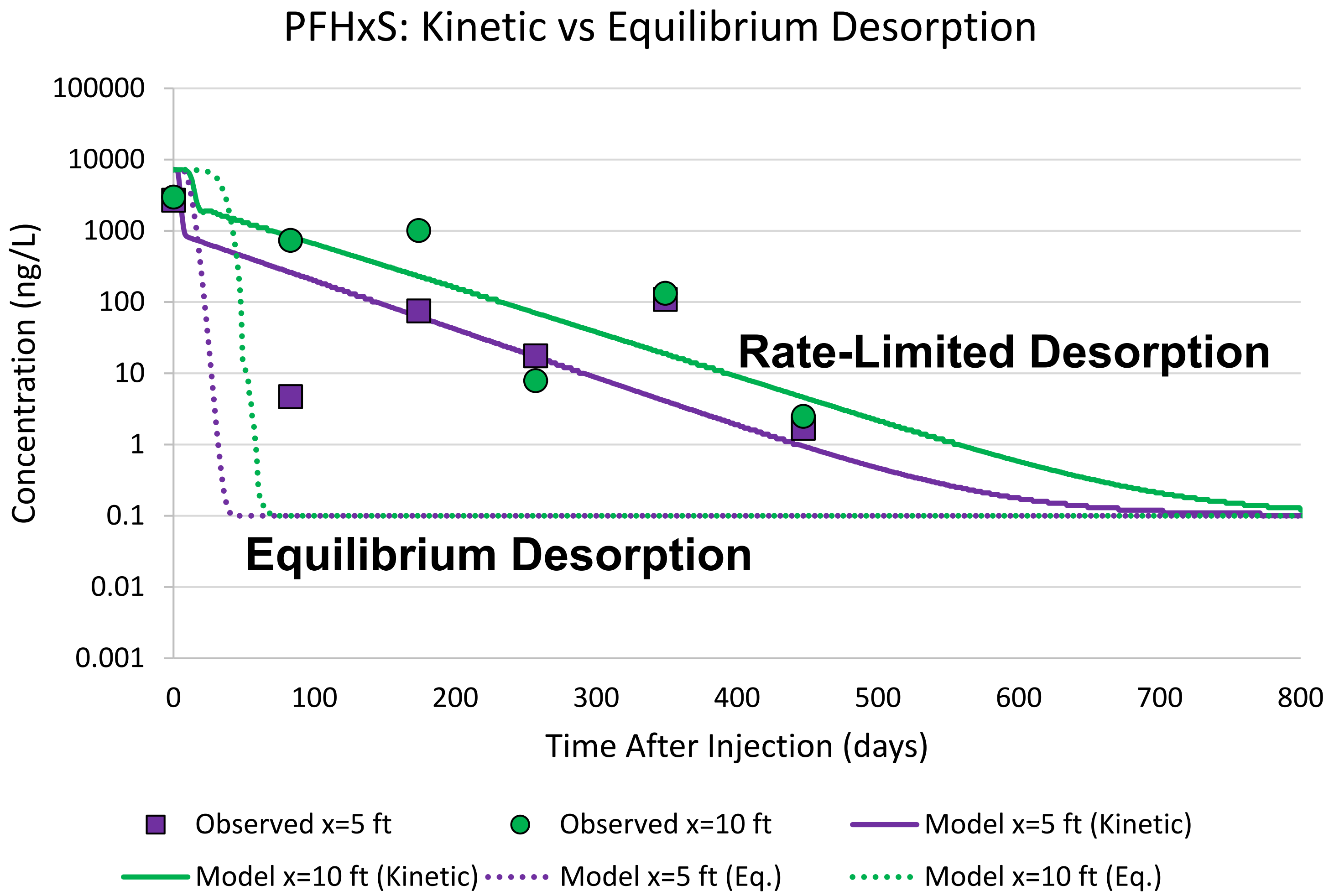
Adsorbed Concentration at Aqueous Concentration C = 1 ng/L

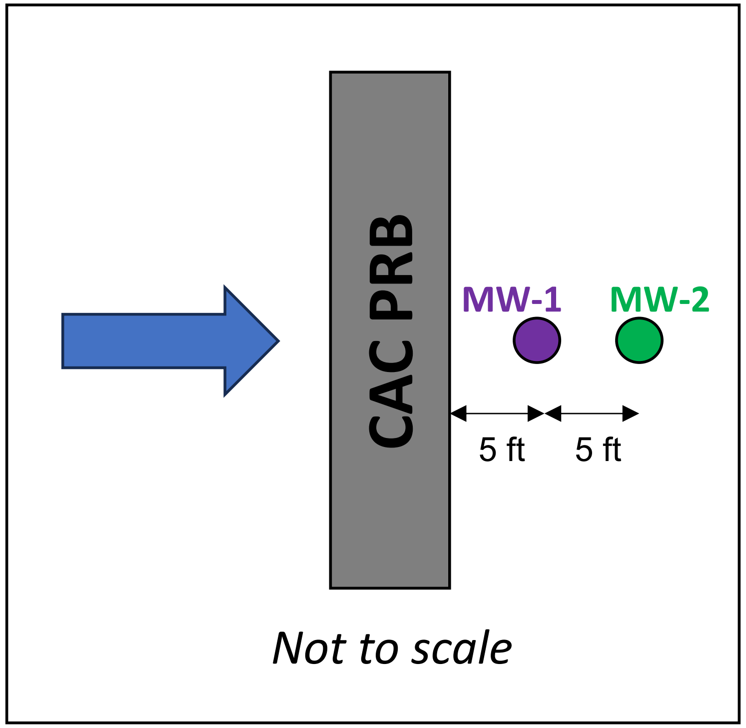


$$S = K_f \, C^a$$

East US Site: PFAS Desorption Downgradient of PRB

DRAFT





5 ft

Cost-Benefit Analysis

Section 2

Acknowledgements

Matt Vanderkooy, Adam Schneider

Geosyntec Consultants

Dr. Paul Erickson, Keith Gaskill

Regenesis

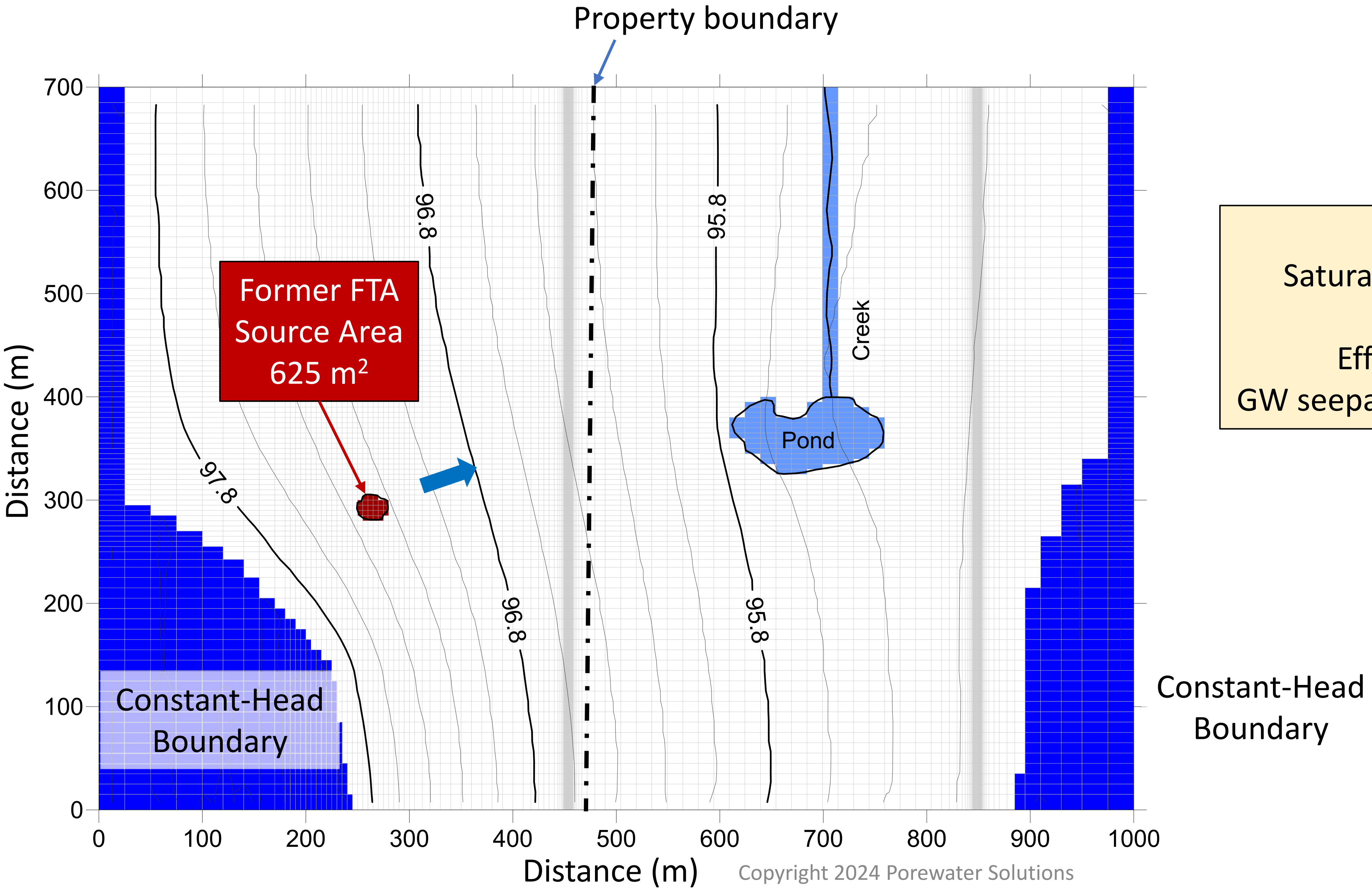
Dr. Anthony Danko

NAVFAC EXWC

Dr. Brent Sleep

University of Toronto

Hypothetical Site Setting & Model Domain

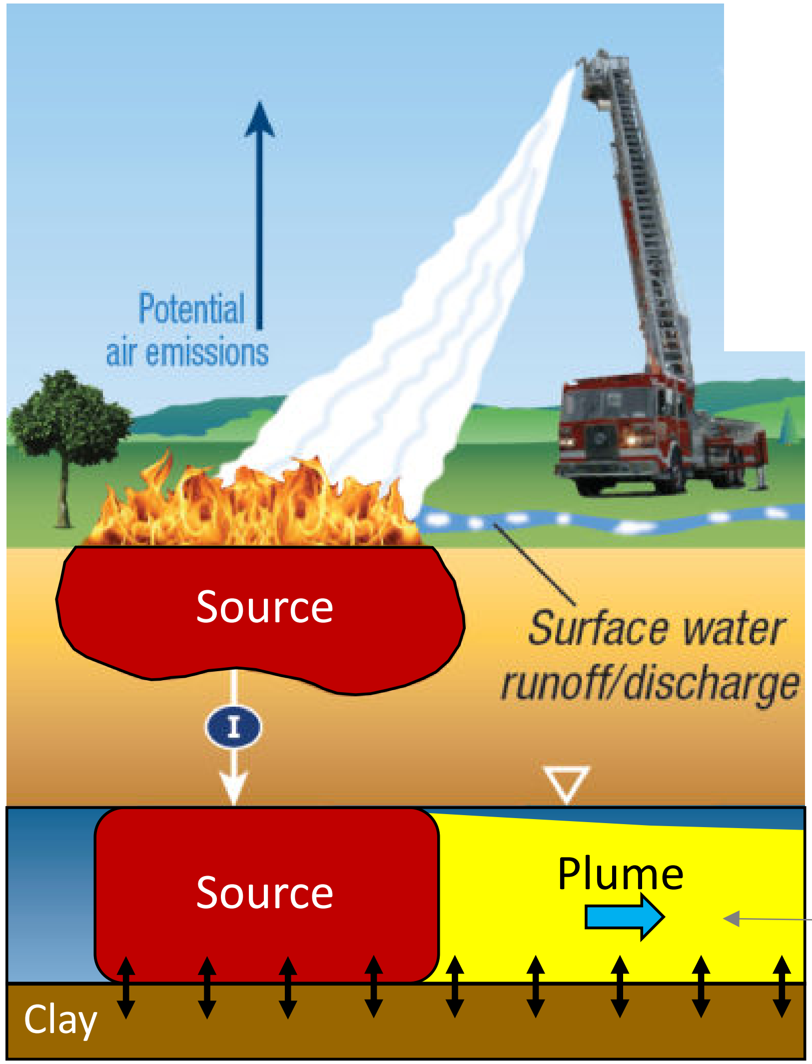


f_{oc}: 0.1%
Saturated thickness at PRB: 8 m
K = 25 ft/day
Effective porosity = 0.20
GW seepage velocity: ~175 to 200 ft/y

AFFF-Impacted Site Conceptual Model

Environmental Fate and Transport for Per- and Polyfluoroalkyl Substances

Modified from ITRC Fact Sheet, March 16, 2018 (Figure 1)



Near-Source Area

- High PFAS of Concern (POCs), precursors, etc.
- Higher CAC dose needed
- Source zones difficult to delineate

Downgradient PRB Area

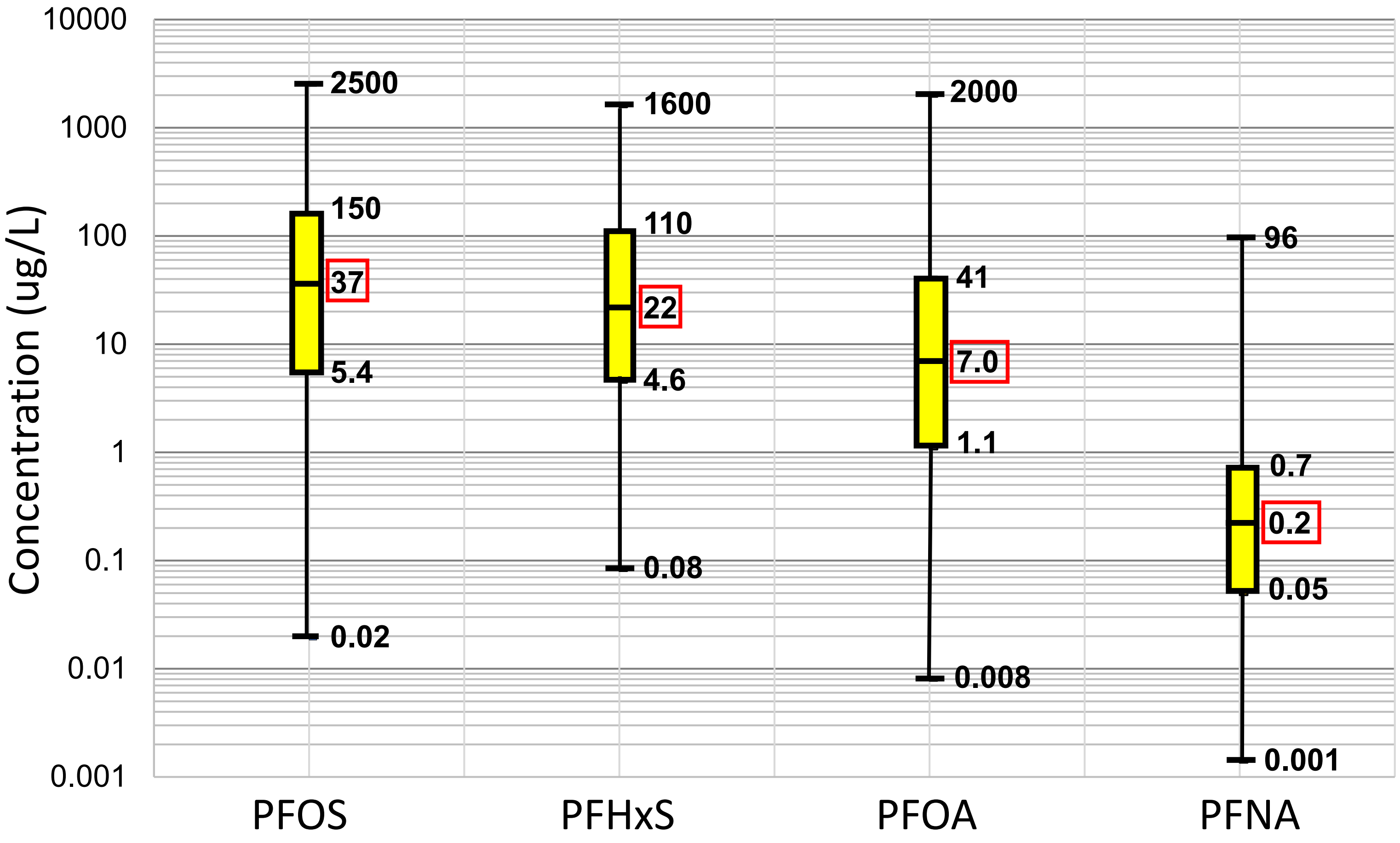
- Lower POCs, lower precursors, etc.
- Lower CAC dose needed

Source Control-Only (long distance to bdy)

- Decades to attain goals at boundary

Desorption, Back-diffusion, Infiltration

Maximum PFAS Statistics for 96 AFFF-Impacted Sites



Carey et al., 2022

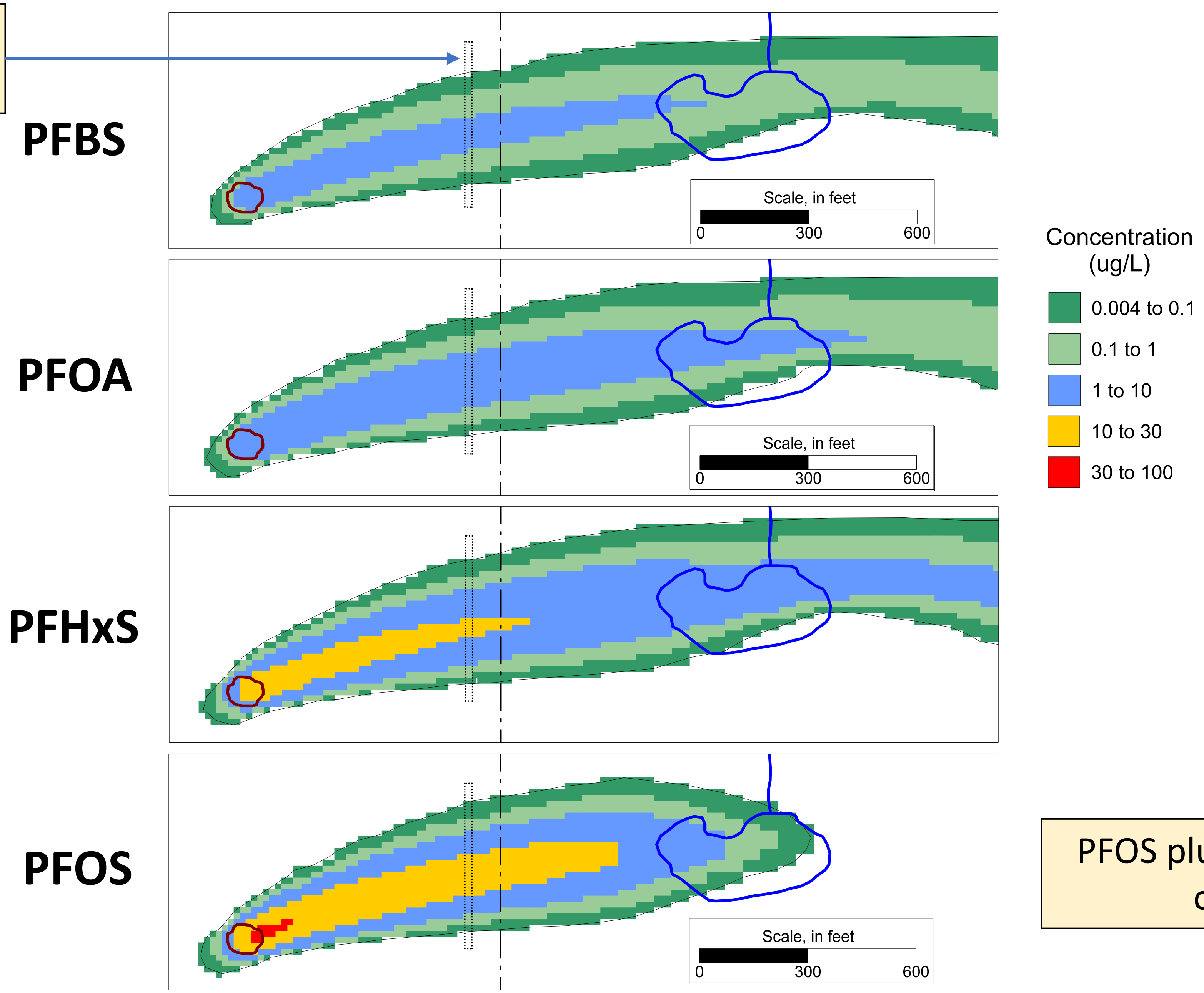
PFBS statistics are in Mole et al. (2024)

no. PFBS results:	93
Minimum (ug/L):	0.0059
Q1 (ug/L):	0.145
Median (ug/L):	3.0
Q3 (ug/L):	12
Maximum (ug/L):	230

Molé et al., 2024

Pre-Remediation Plumes (at end of 50 year simulation)

Proposed downgradient PRB location



PFOS plume is expanding over time.

Plumes at t=20 years after CAC Injection

Breakthrough Time

PFBS: 15 years

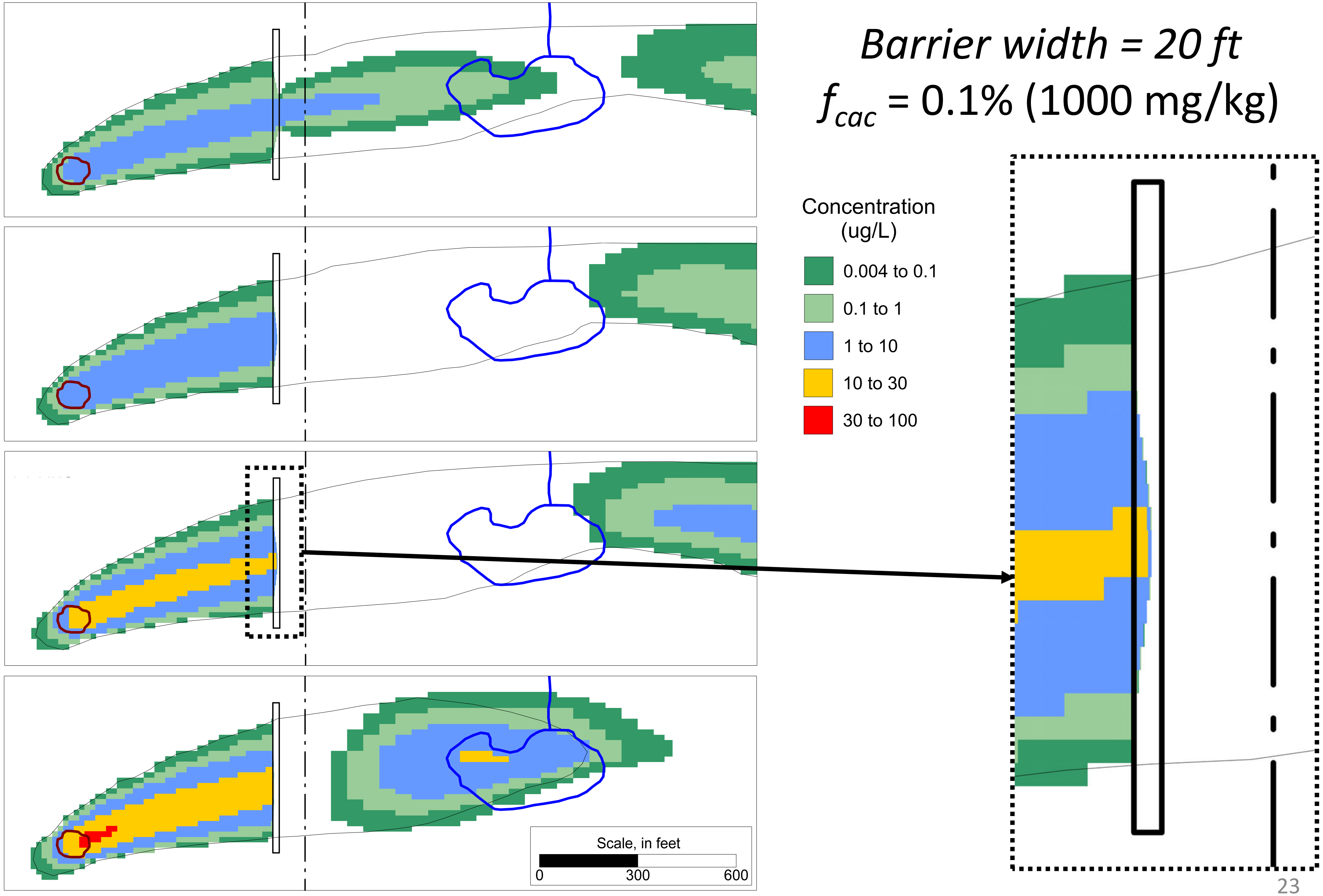
PFOA: 32 years

PFHxS: 31 years

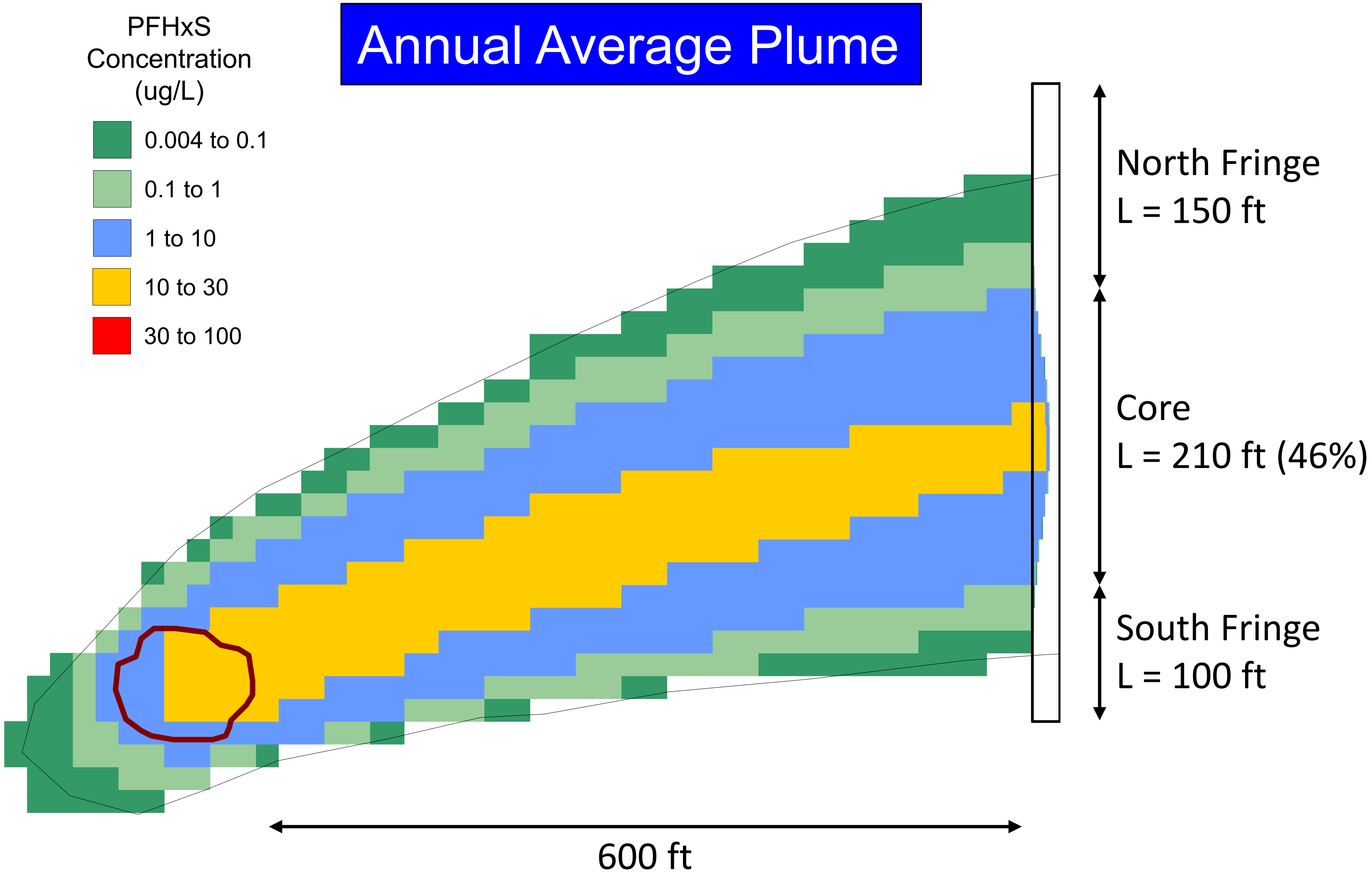
PFOS: >>50 years

Barrier width = 20 ft

f_{cac} = 0.1% (1000 mg/kg)



PRB Design with Target Longevity of 30 Years



Total depth: 40 ft

Saturated thickness: 27 ft

Total PRB Length: 460 ft

PRB Volume: 9,200 cy

PRB Component	Proportion of PRB	Target CAC (mg/kg)
Core	46%	1000
Fringes	54%	500

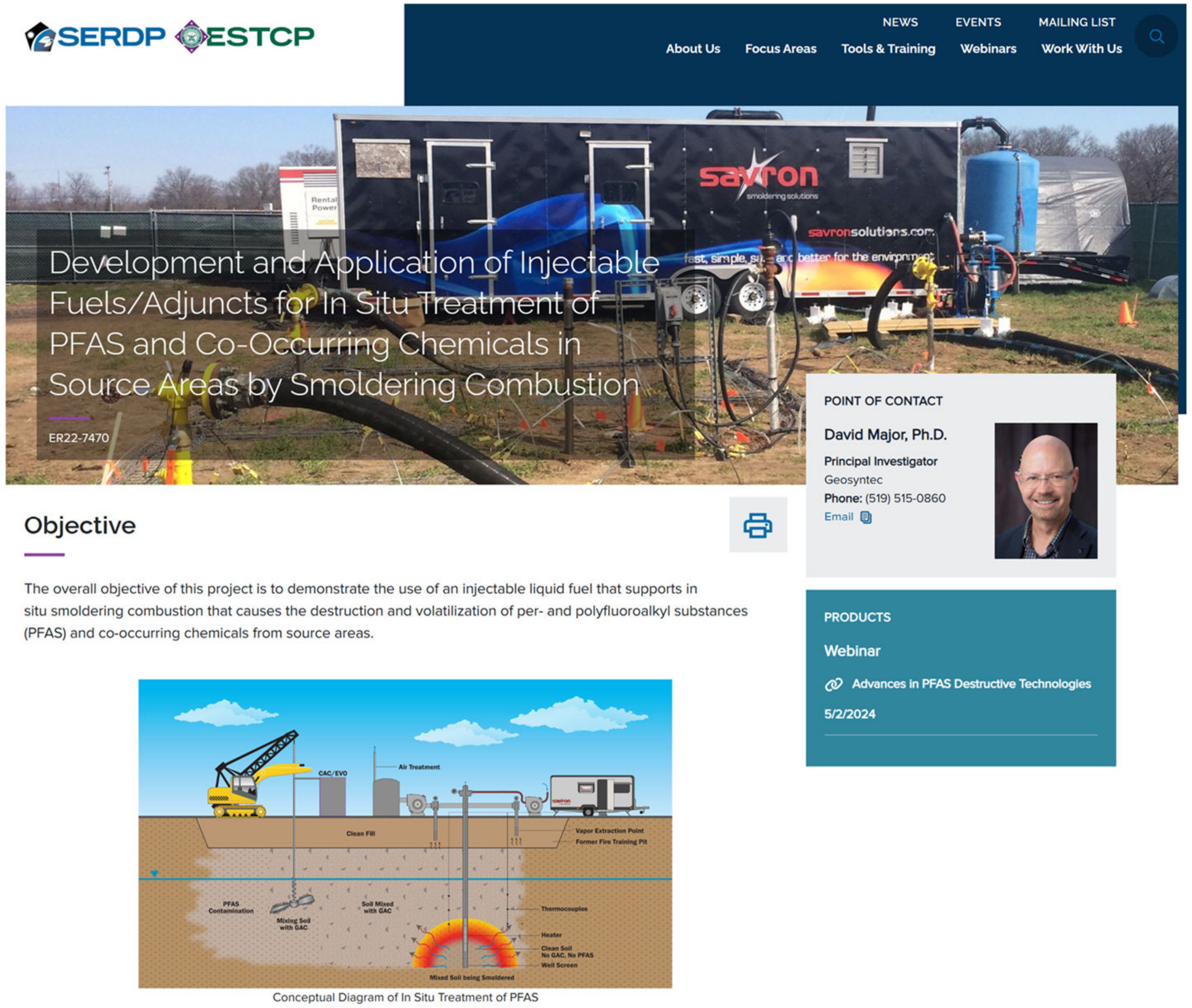
What Happens to CAC PRBs In the Long-Term?

Future options when CAC is spent:

1. Inject follow-up CAC PRB slightly downgradient
    - Low Net Present Value (NPV) cost
2. In the next decade, we may have technologies to treat PFAS-laden CAC in-situ

e.g., smoldering savron

BOOTH #211
Dave Liefl and Laura Kinsman



Development and Application of Injectable Fuels/Adjuncts for In Situ Treatment of PFAS and Co-Occurring Chemicals in Source Areas by Smoldering Combustion

ER22-7470

POINT OF CONTACT

David Major, Ph.D.
Principal Investigator
Geosyntec
Phone: (519) 515-0860
Email

Objective

The overall objective of this project is to demonstrate the use of an injectable liquid fuel that supports in situ smoldering combustion that causes the destruction and volatilization of per- and polyfluoroalkyl substances (PFAS) and co-occurring chemicals from source areas.

Conceptual Diagram of In Situ Treatment of PFAS

PRODUCTS

Webinar

Advances in PFAS Destructive Technologies

5/2/2024

Downgradient PRB Costs

INSTALLATION COST

PlumeStop® + Injection

REGENESIS®

BOOTH #112

TOTAL COST

Construction Costs

PlumeStop® + Injection

+ Well Installation

+ Professional Services (26%)

- Detailed design, work plan, H&S plan, permitting (12%)
- Construction mgt and as-built report (8%)
- Health and safety (2%)
- Project management (6%)

+ Contingency cost (30%)

Annual O&M (30 years, NPV, 4.5%)

Downgradient PRB Costs (NPV at 4.5% Discount)

Scenario 1.1: Minimum CAC dose

CAC 0.1% / 0.05% in PRB Core/Fringes

Installation: $1.6M / Total: $4.0M

Scenario 1.2: Double Dose & Longevity

CAC 0.2% / 0.05% in PRB Core/Fringes

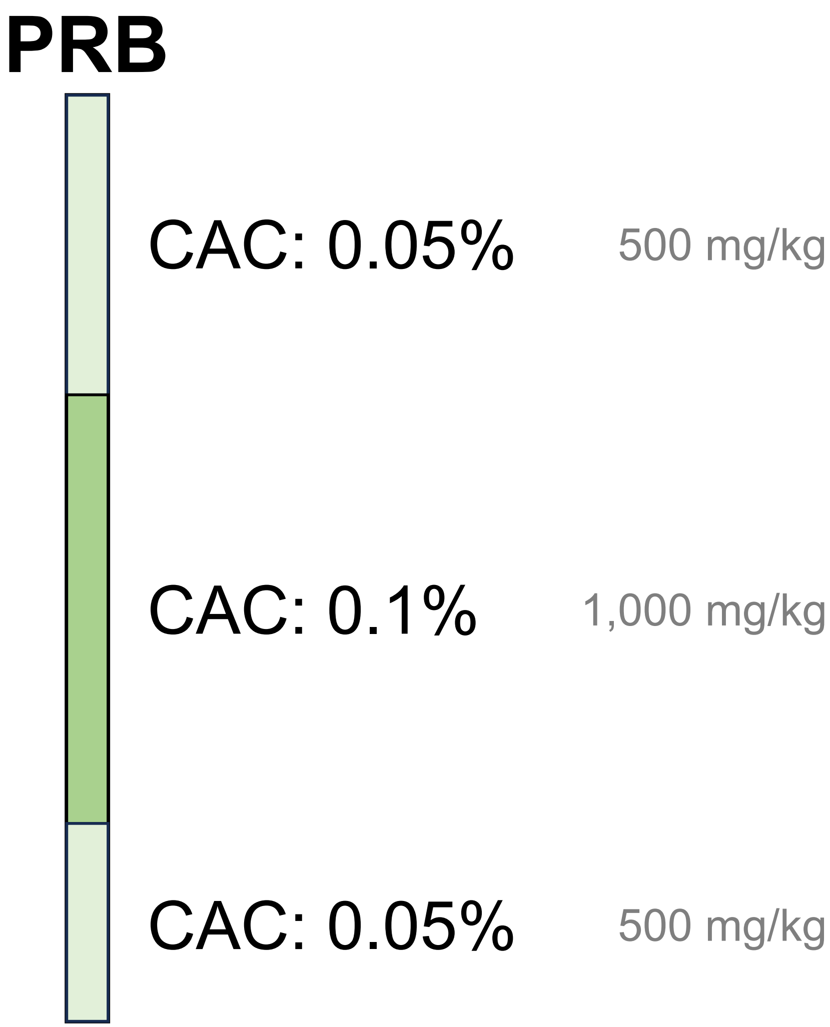
Installation: $2.0M / Total: $4.7M

Scenario 1.3: Longevity 50% of Modeled

CAC 0.1% / 0.05% in PRB Core/Fringes

Re-injection at 15 years (NPV)

Installation: $2.4M / Total: $5.4M



PRB

CAC: 0.05% 500 mg/kg

CAC: 0.1% 1,000 mg/kg

CAC: 0.05% 500 mg/kg

Site-Specific PFAS Adsorption Testing

- Site-specific chemistry will influence CAC longevity
  - Relative PFAA concentrations
  - PFAS Precursors
  - DOC
  - Other organic chemicals (e.g., DRO)
  - pH
- Site-specific isotherm testing – minor investment ($15K to $25K) to increase confidence in CAC dose and remedy longevity

SiREM

PFAS-Sorbent Isotherm Testing Services

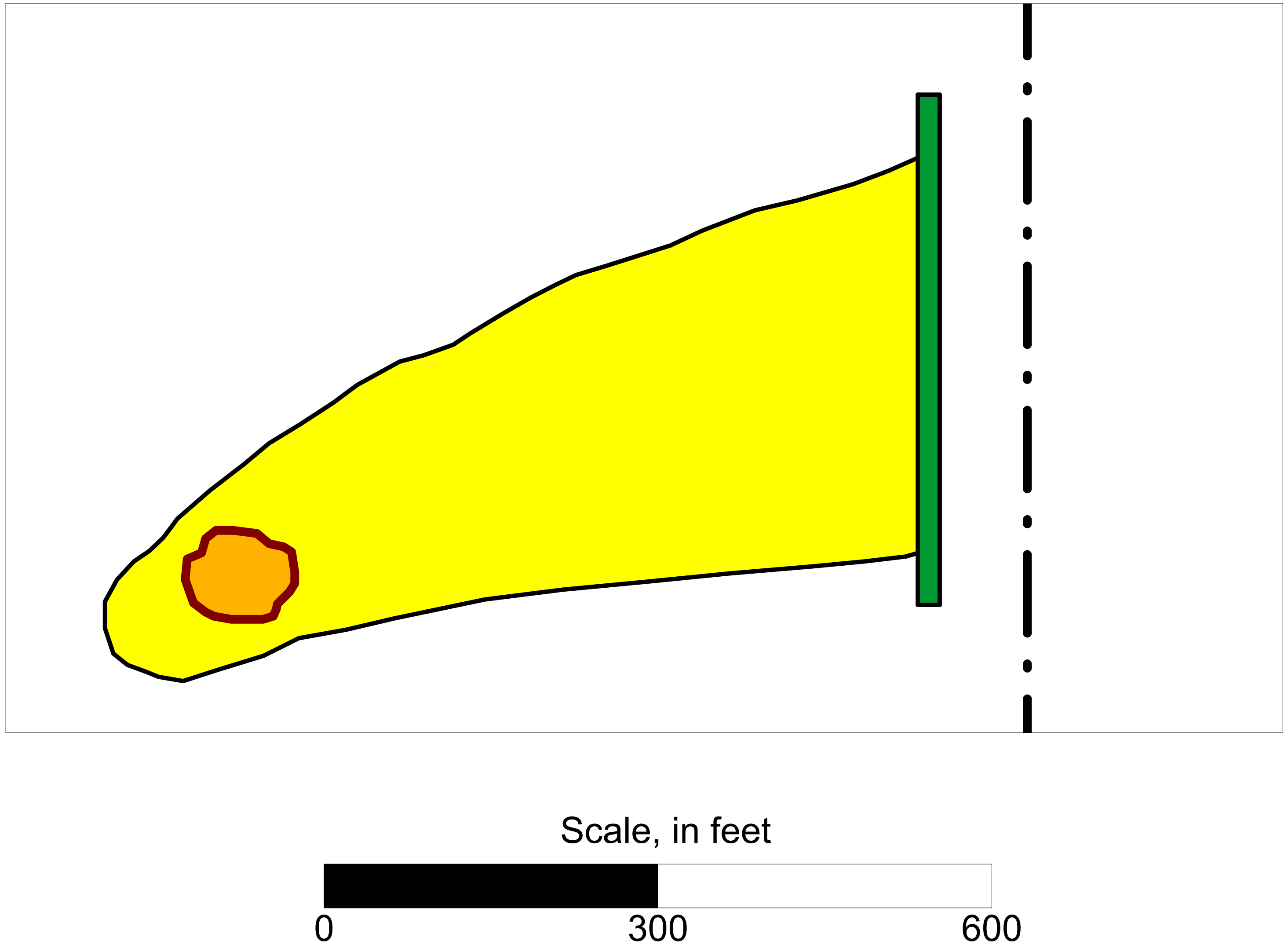
Contact: BOOTH 215
Sandra Dworatzek
519-515-0839
sdworatzek@siremlab.com

Source Control Alternatives

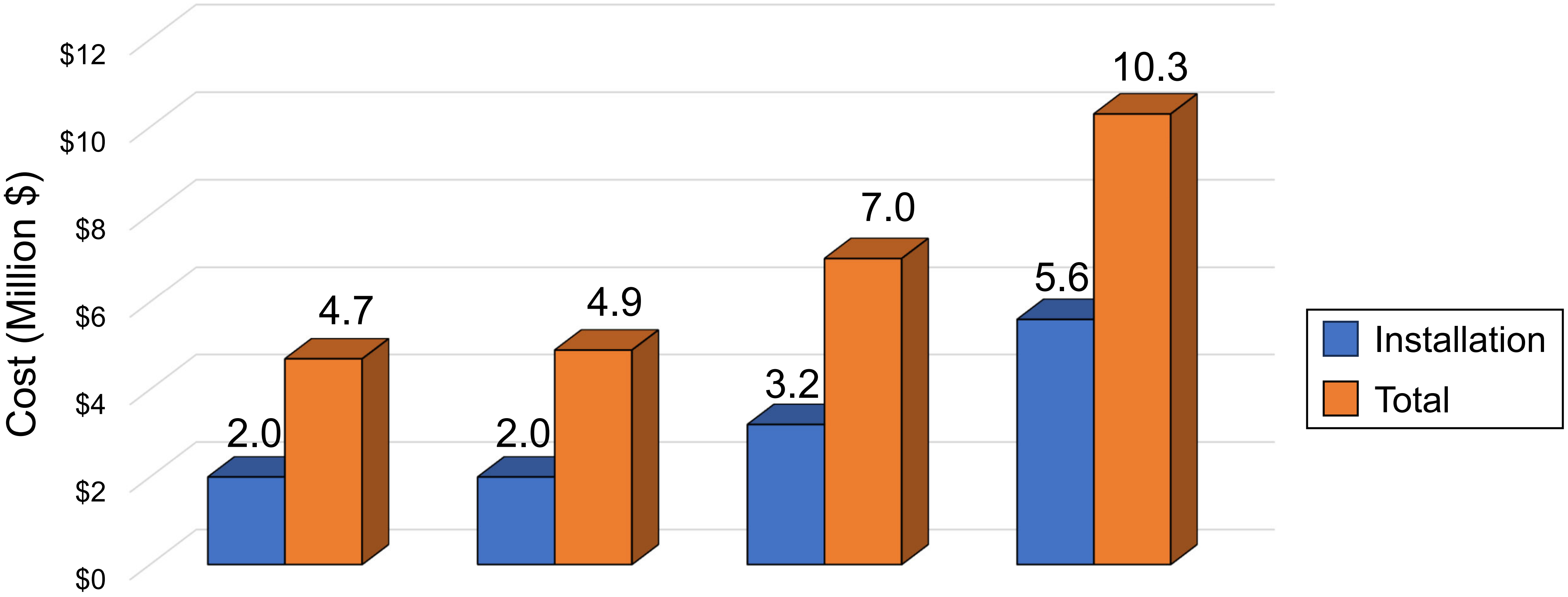
Source Control Alternatives

1. Durable cover
2. Wall + cover
3. In-situ soil stabilization (ISS)

Main benefit: Increased PRB longevity



Integrated PRB and Source Control Alternatives



PRB CAC Dose (%):	0.2 / 0.05	0.1 / 0.05	0.1 / 0.05	0.1 / 0.05
Source Control:	**n/a**	**Cover**	**Wall + Cover**	**ISS**
Longevity (y):	60	35 to 45	>100	>100

Vadose zone Md:
20% to 50% of total source

Md: Mass discharge

Questions?

Coming January 2025: Visual PFAS™ for Site Characterization and Forensics

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www.porewater.com/PFAS.html

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