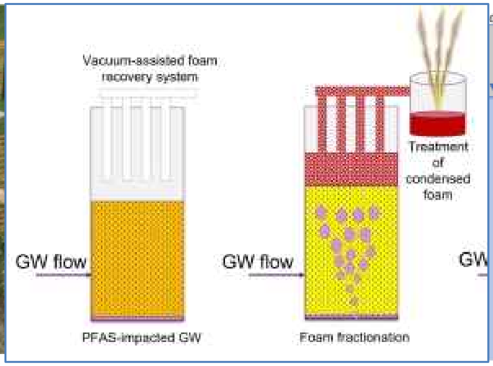
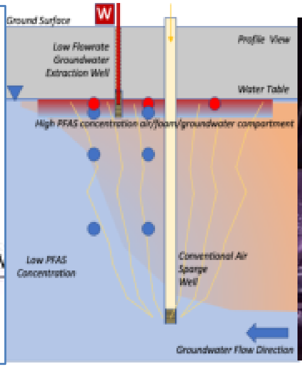
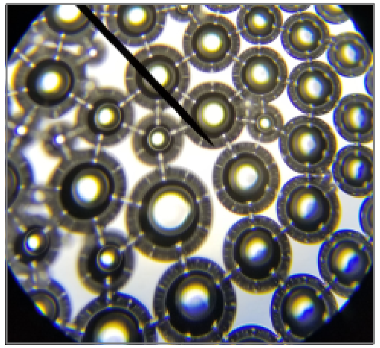
Status of Gas-Based PFAS Remediation Technologies

Charles Newell and Poonam Kulkarni
GSI Environmental

May 2023



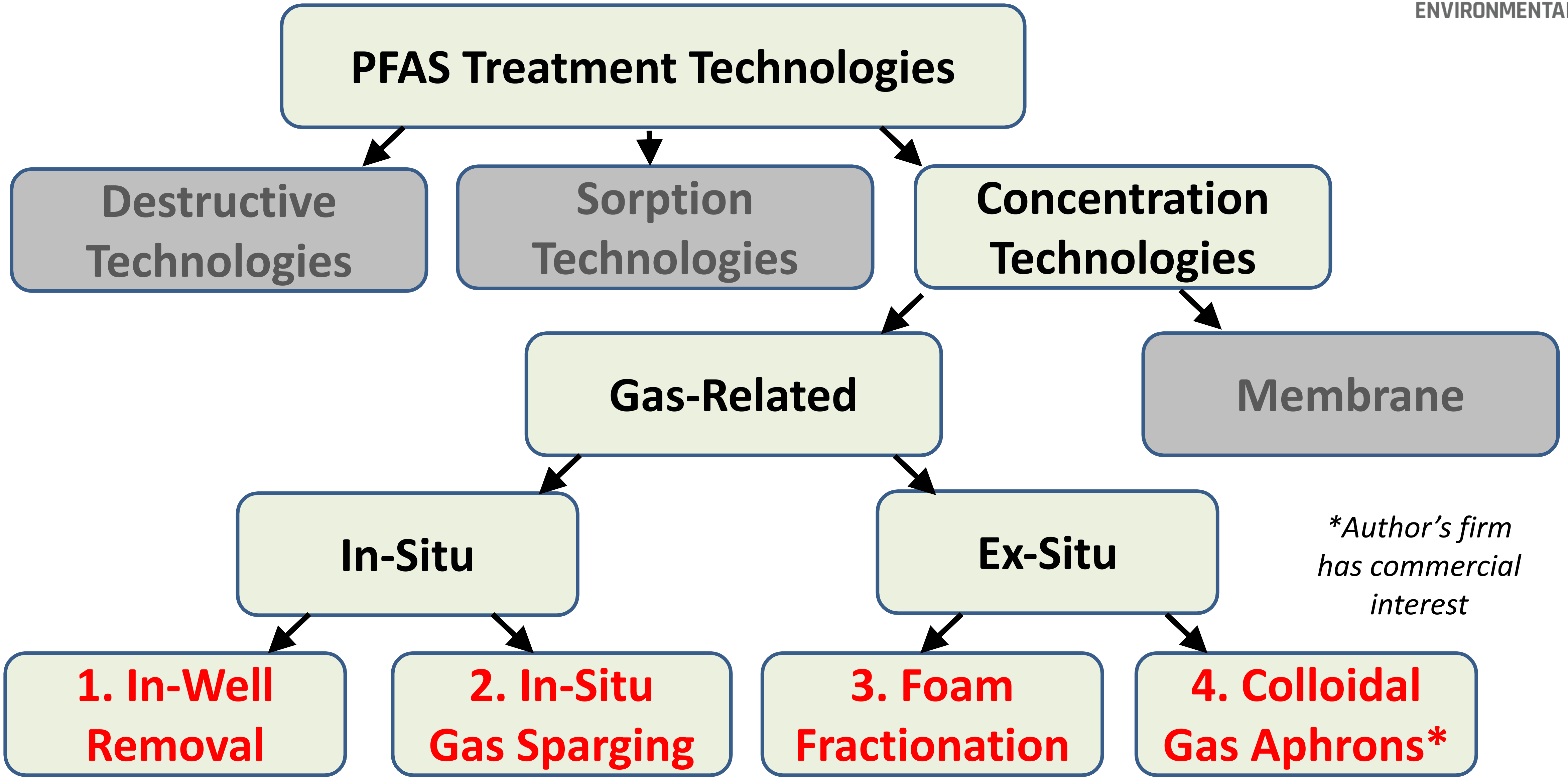




Road Map

- **Taxonomy of PFAS Treatment Technologies**
- **Key Removal Processes For Gas-Related Technologies**
- **Key Gas-Related Technologies**
  - In-Situ Gas Bubble/Gas Channel Technologies
  - Ex-Situ Gas Bubble Technologies
  - Ex-Situ Aphron Technology
- **Current State of Technology Development**

PFAS Water Treatment Taxonomy



Key PFAS Gas-Based Removal Processes

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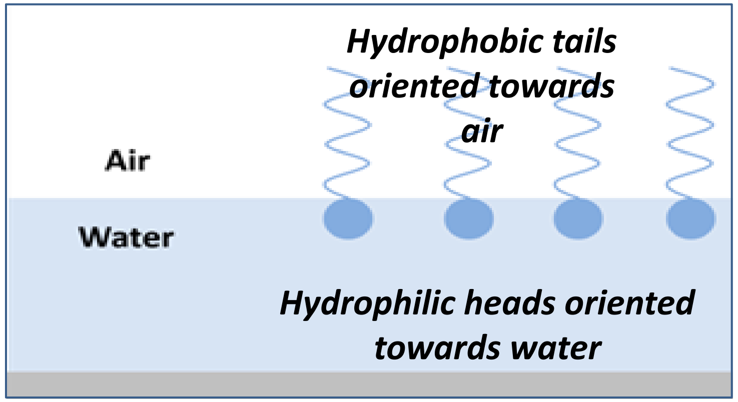
Adapted from ITRC

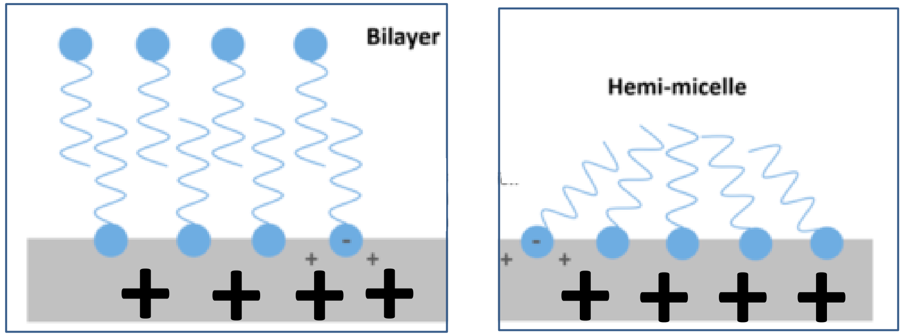
Air-Water Partitioning



PREDOMINANT MECHANISM →

Short Chained *Long Chained*

Electrostatic Attraction



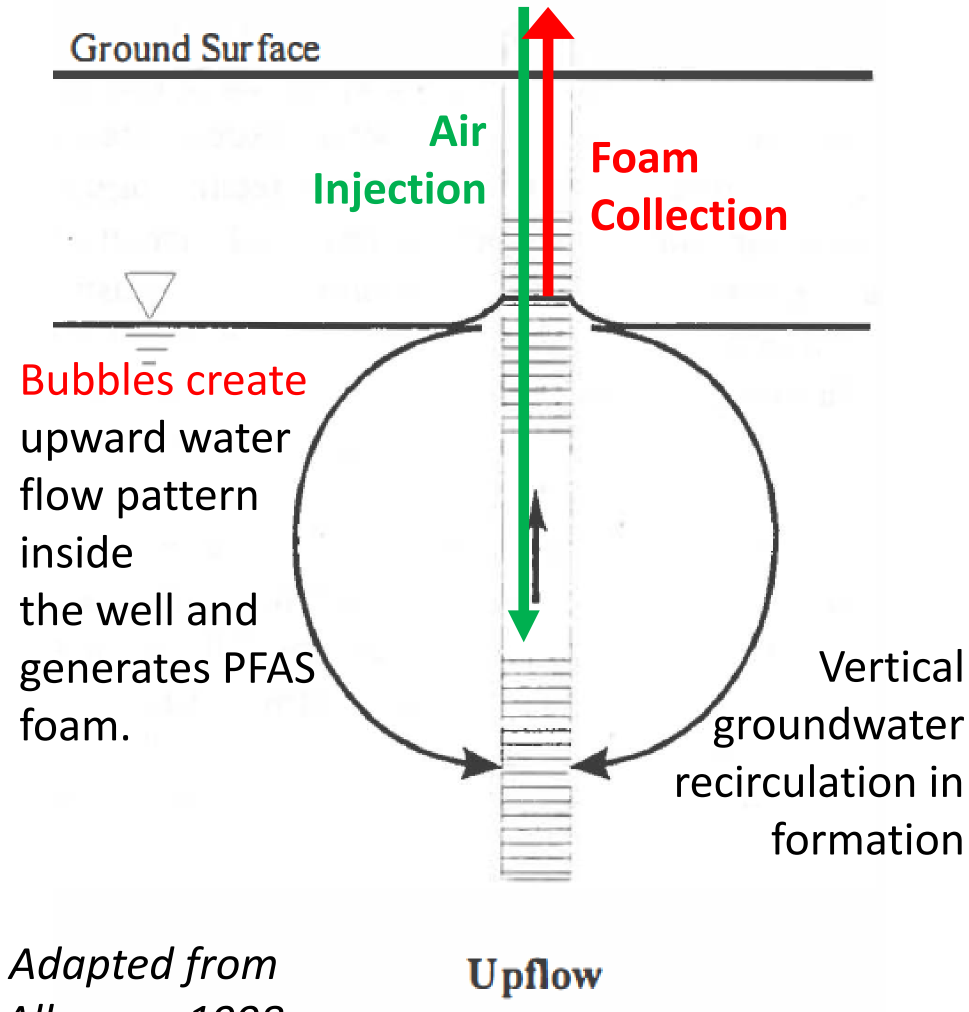
← **PREDOMINANT MECHANISM**

Short Chained *Long Chained*

In-Situ

1. In-Well Removal (D-FAS, Enviroremedy)

GSI ENVIRONMENTAL

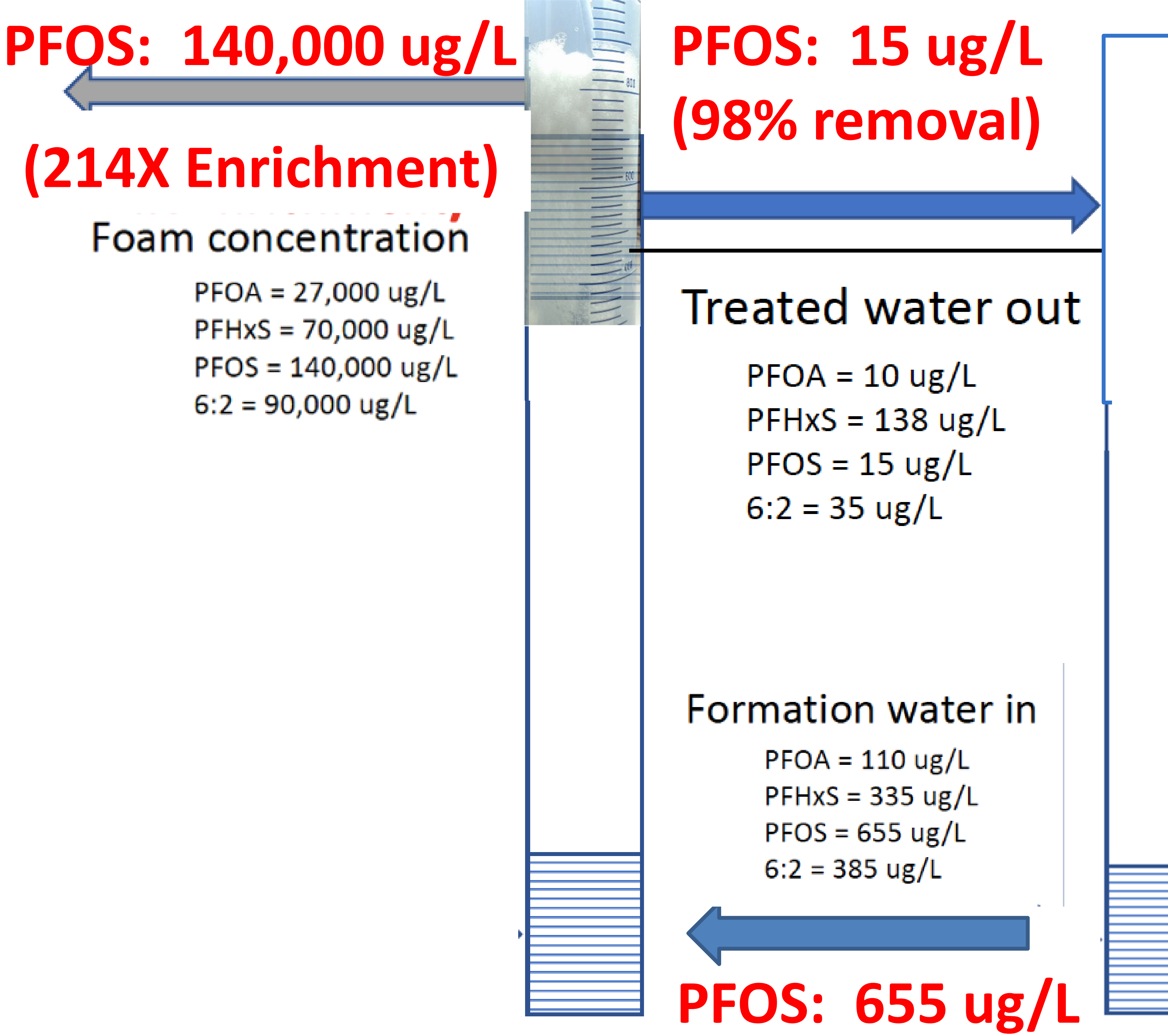


Adapted from Alleman, 1998

- PFAS Mechanism: Air/Water Partitioning
- Two Patents: Nelson 2017, Burns et al. 2017
- In-Situ Treatment of PFAS Using the D-FAS Approach (ESTCP ER19-5075, D. Reynolds)

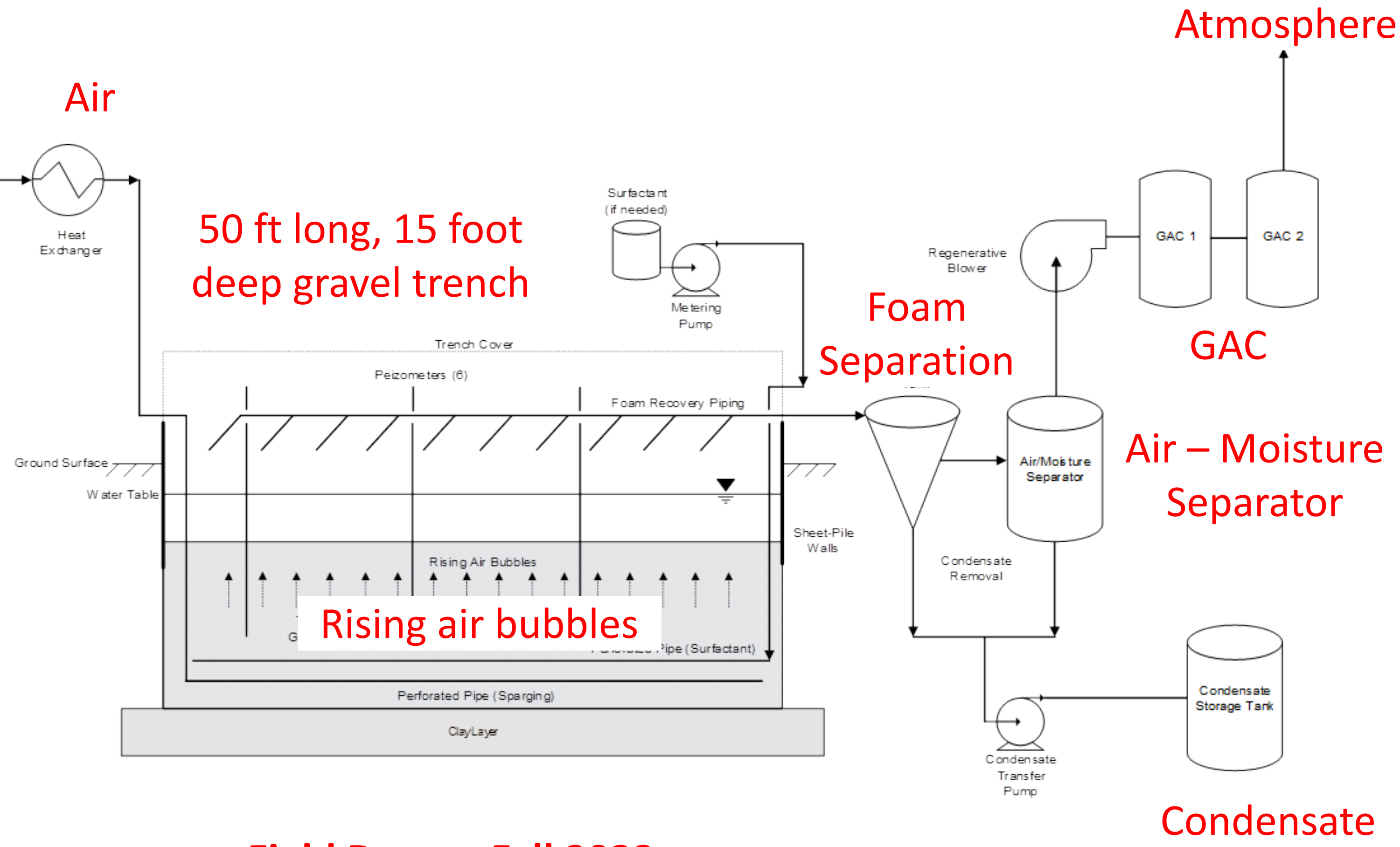
Geosyntec consultants | e⁻ LLC | ESTCP | NAVFAC | BLDI | ISOTEC

In-Situ Treatment of PFAS Using the D-FAS Approach (ESTCP ER19-5075)



Photos, graphic elements adapted from Reynolds and Nelson, 2021

2a. Low-Cost, Passive In Situ Treatment of PFAS-Impacted Groundwater Using Foam Fractionation In an Air Sparge Trench (ESTCP ER21-5124) (Dr. Zoom Nguyen)



Field Demo: Fall 2023

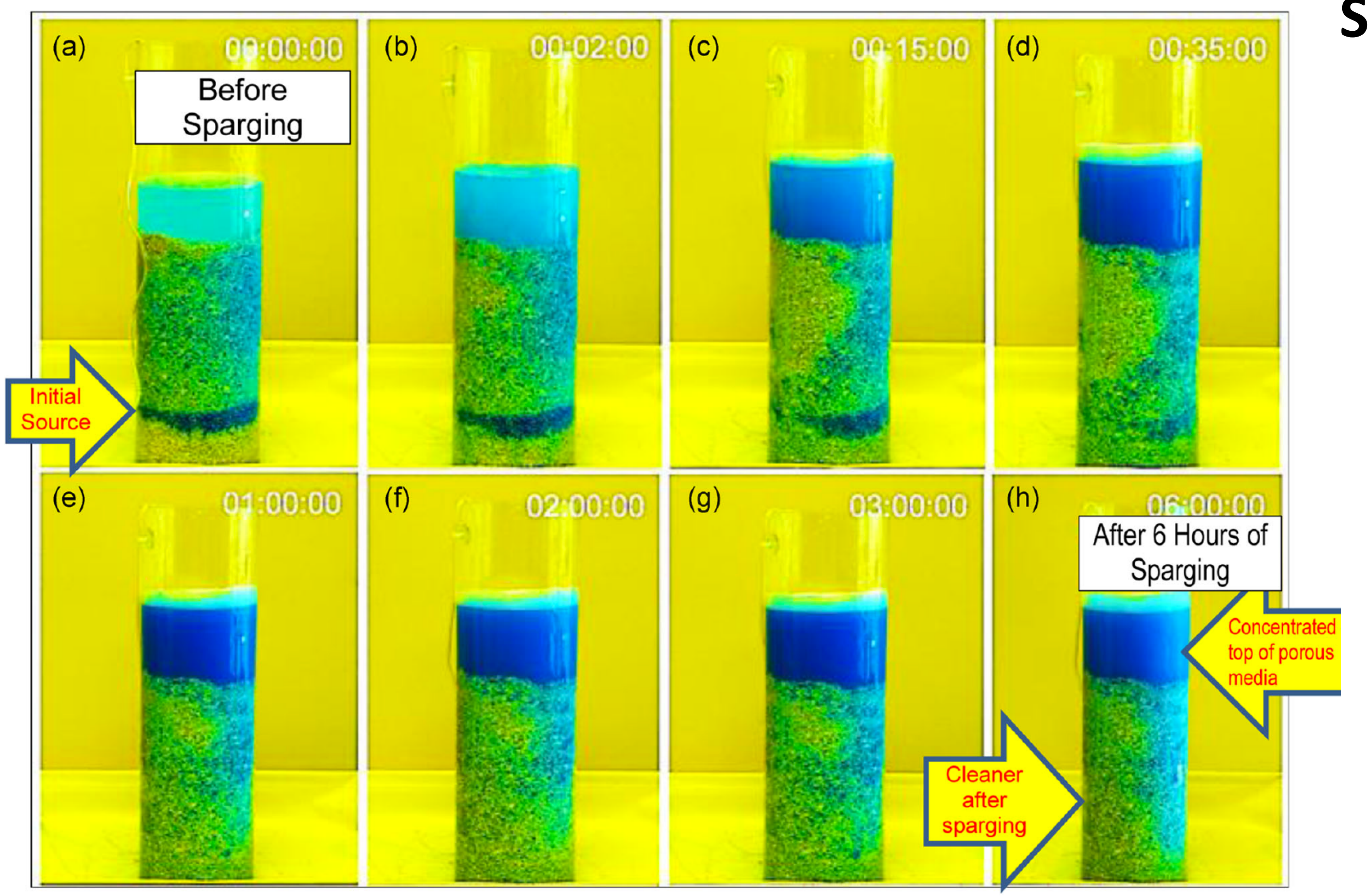
Objectives:

- Test coupled air sparge trench and in-situ foam fractionation
- Verify plume interception
- Demonstrate foam recovery
- Assess PFAS destruction; and
- Determine life cycle

2b. Gas Sparging Directly in Aquifers to Remove or Sequester PFAS (SERDP Project ER22-3221)

(GSI Environmental, Colorado State, NAVFAC, CSIRO)

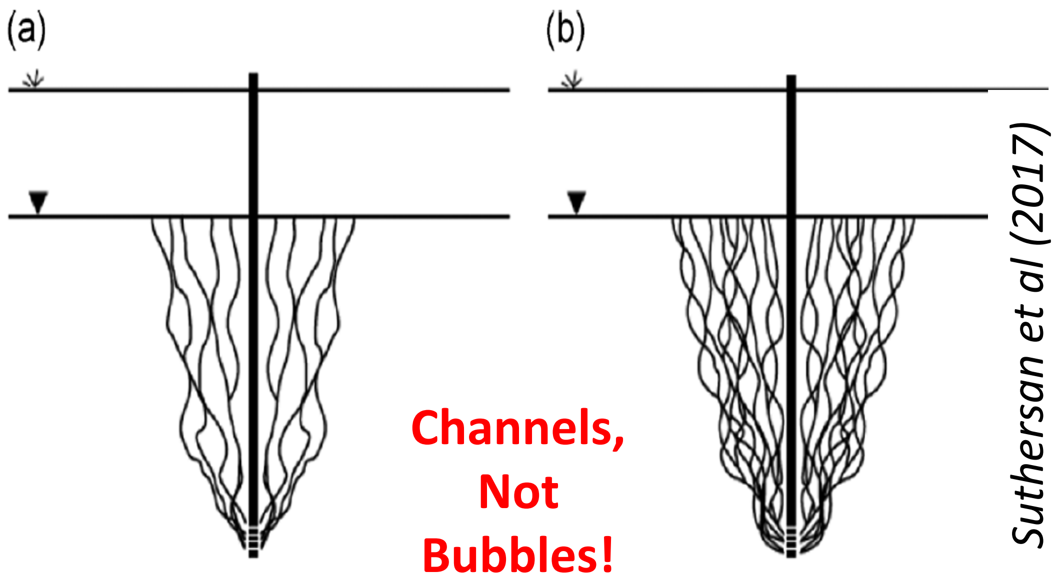
Column Test with Gravel: Bubbles Capture Surfactant and Bring to the Surface



But most of sparging sites are not gravel

Sparging in most sands creates air channels

Does sparging remove PFAS at sparge channel-dominated sites?



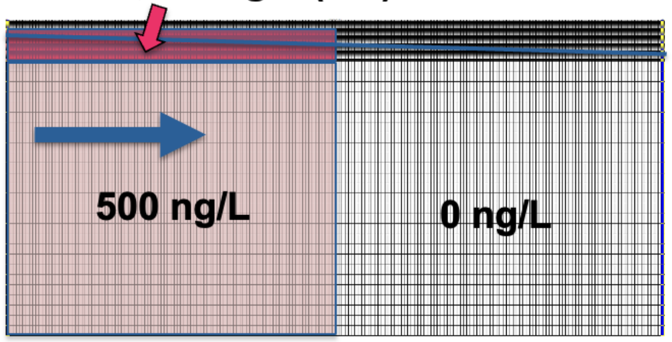
2c SERDP Project ER22-3221: Gas Sparging Directly in Aquifers to Remove or Sequester PFAS

Key Questions:

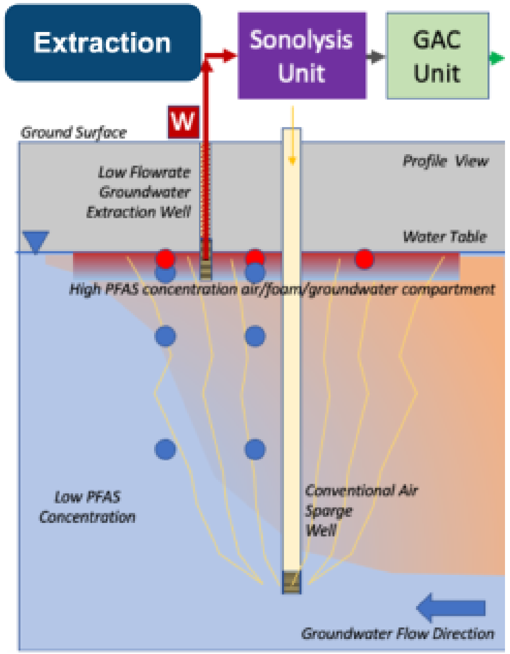
1. Does gas sparging remove PFAS?
2. Does pulsing help?
3. What is the mechanism for channels?
4. Is it easier to remove thin concentrated layer of PFAS near water table?
5. How long is the concentrated PFAS retained in the subsurface?

Approach:
Lab, Models, Field Pilot

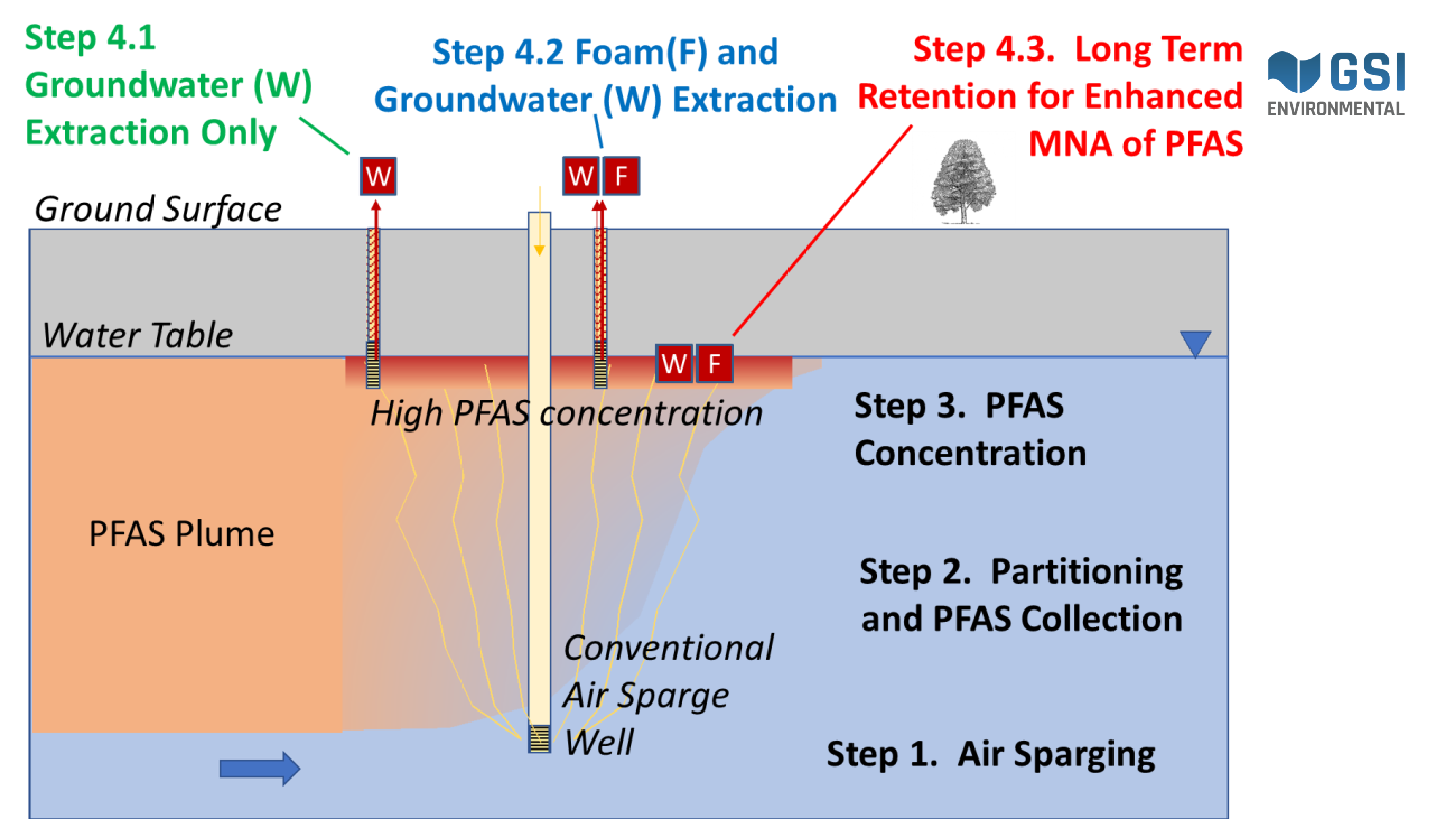
MODFLOW USG-T PFAS
(S. Panday, H. Hort E. Stockwell)



CSU Tank Exper.
(J. Scalia, J. White)



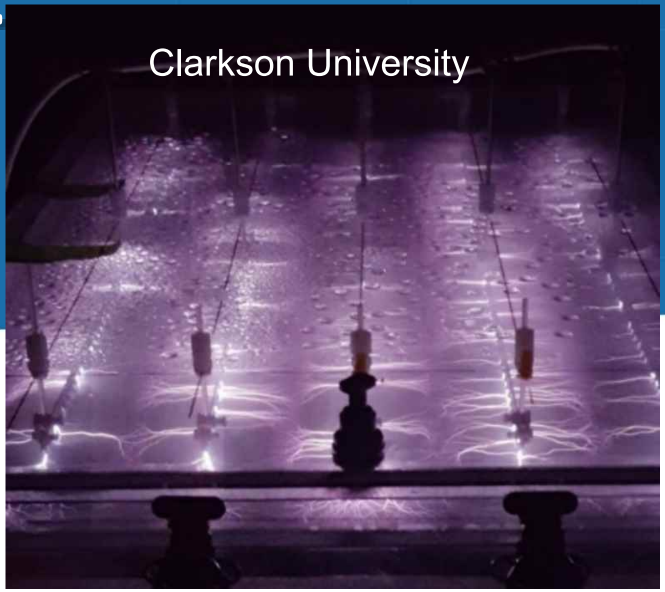
Field Trial
(P. Kulkarni)


Step 4.1
Groundwater (W)
Extraction Only
Step 4.2 Foam(F) and
Groundwater (W) Extraction
Step 4.3. Long Term
Retention for Enhanced
MNA of PFAS
GSI
ENVIRONMENTAL
W
W F
Ground Surface
Water Table
W F
High PFAS concentration
Step 3. PFAS
Concentration
PFAS Plume
Step 2. Partitioning
and PFAS Collection
Conventional
Air Sparge
Well
Step 1. Air Sparging

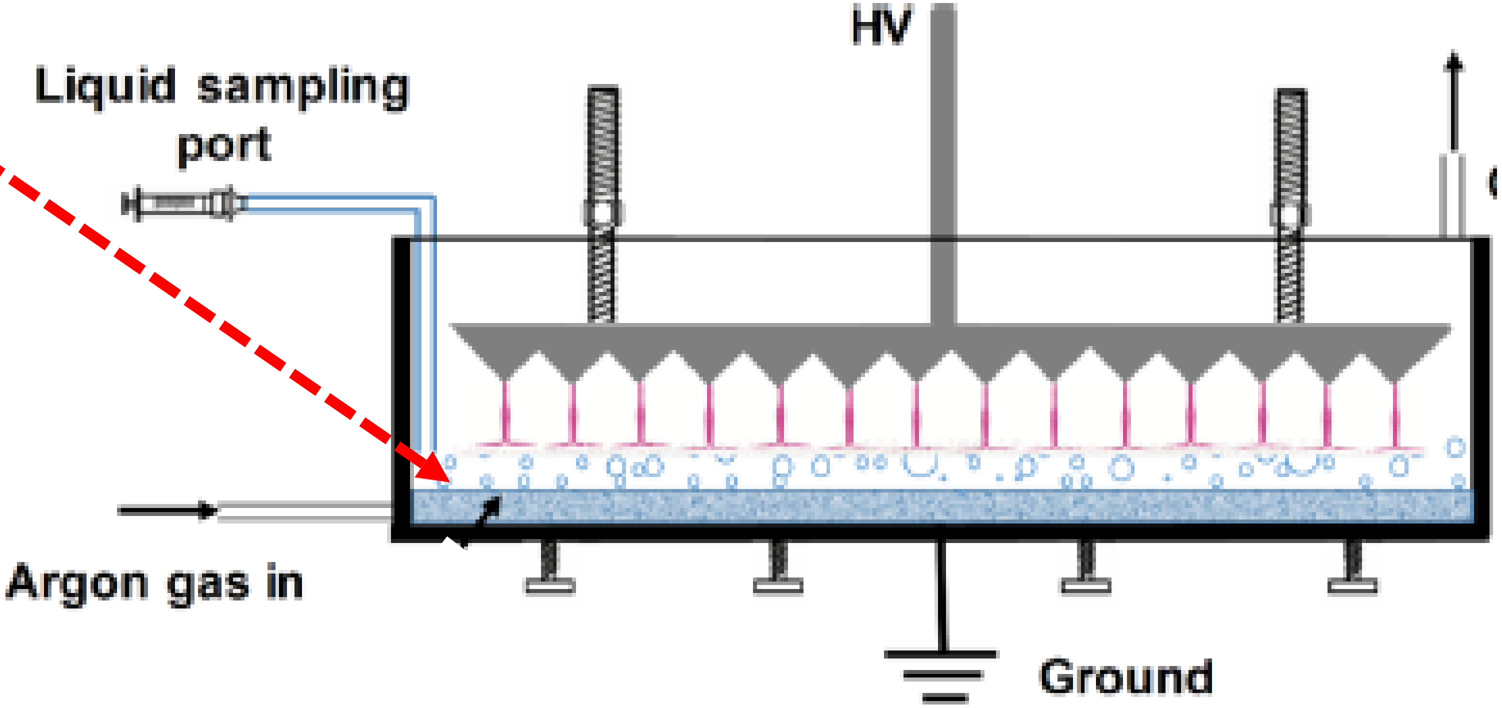
Ex-Situ

3a. PLASMA PFAS TREATMENT

Gas/Water Separation With Bubbles Then Destruction



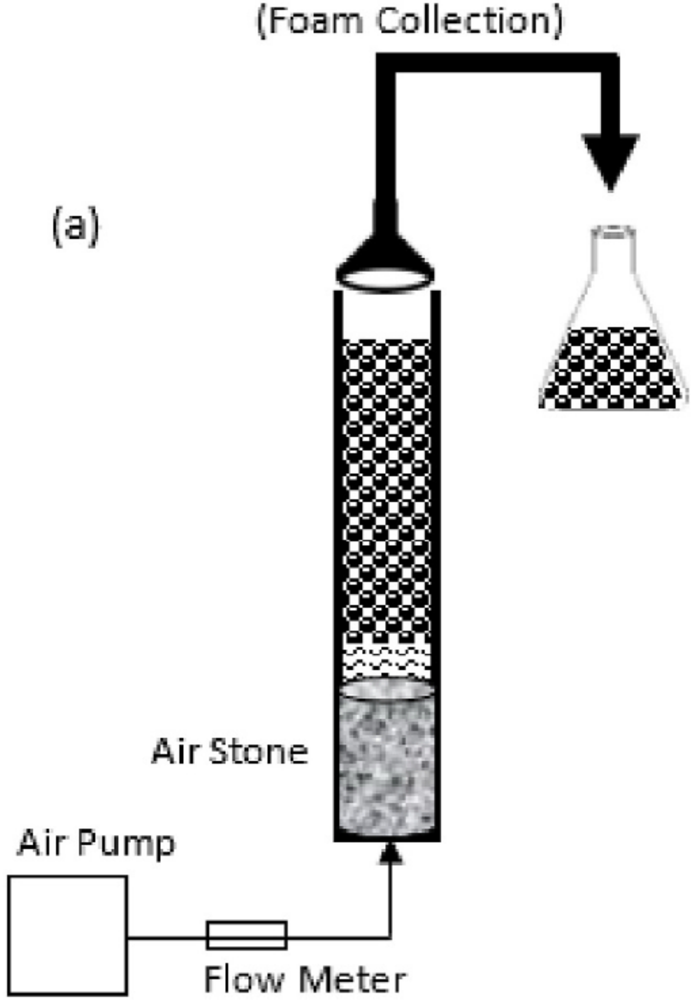
- Gas diffusers along bottom of reactor for bubble formation
- Gas/water partitioning (foam fractionation) brings PFAS to surface
- High voltage is applied between suspended (above water surface) & submerged electrodes



(Singh et al., 2019)

3b. Ex-Situ Foam Fractionation

Wang et al. (2023)



Single Stage

Average
Removal %

PFOS: 97%

PFOA: 81%

PFHxS: 97%

PFBS: 33%

PFBA: -

Commercial Technology Developers

- EPOC
  - Allonnia
  - EnvyTech
- ECT2
- SynergenMet

3c. EPOC SAFF Treatment of 80 Million Liters of Landfill Leachate

Burns et al, 2022

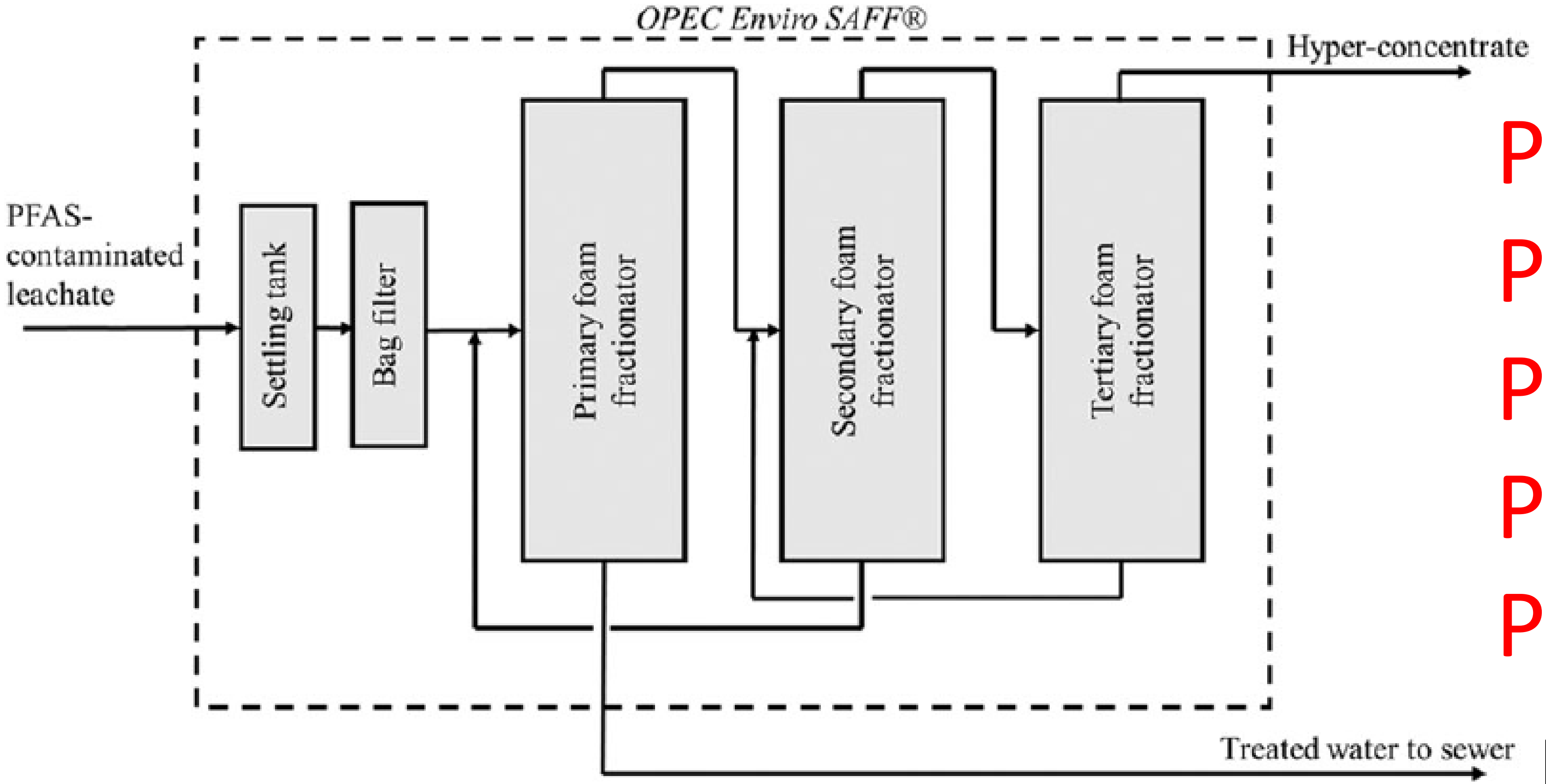


FIGURE 2 Simplified process flow diagram of the SAFF40 process installed at the Tveta landfill site.

PFOS: >98.7%

PFOA: >99.7%

PFHxS: >98.8%

PFBS: >15.7%

PFBA: -1%

Similar Results for Groundwater Treatment Application (Burns et al., 2021)

EPOC Surface Active Foam Fractionation (SAFF)

OPEC SYSTEMS

Foam Fractionation:

ITRC Proven technology category (limited applications by limited number of practitioners)

EPOC: commissioned 11 SAFF Units

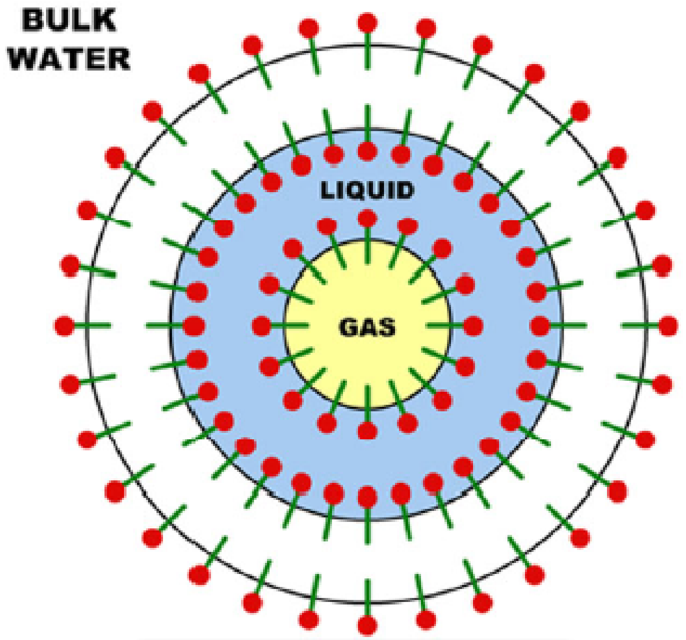
Units > 200 gallons per minute

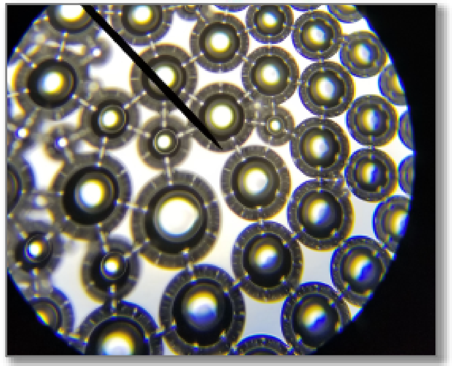
One unit teamed with Battelle Annihilator for PFAS destruction

U.S. manufacturing capability to build 150 units per year later this year

4. Colloidal Gas Aphrons

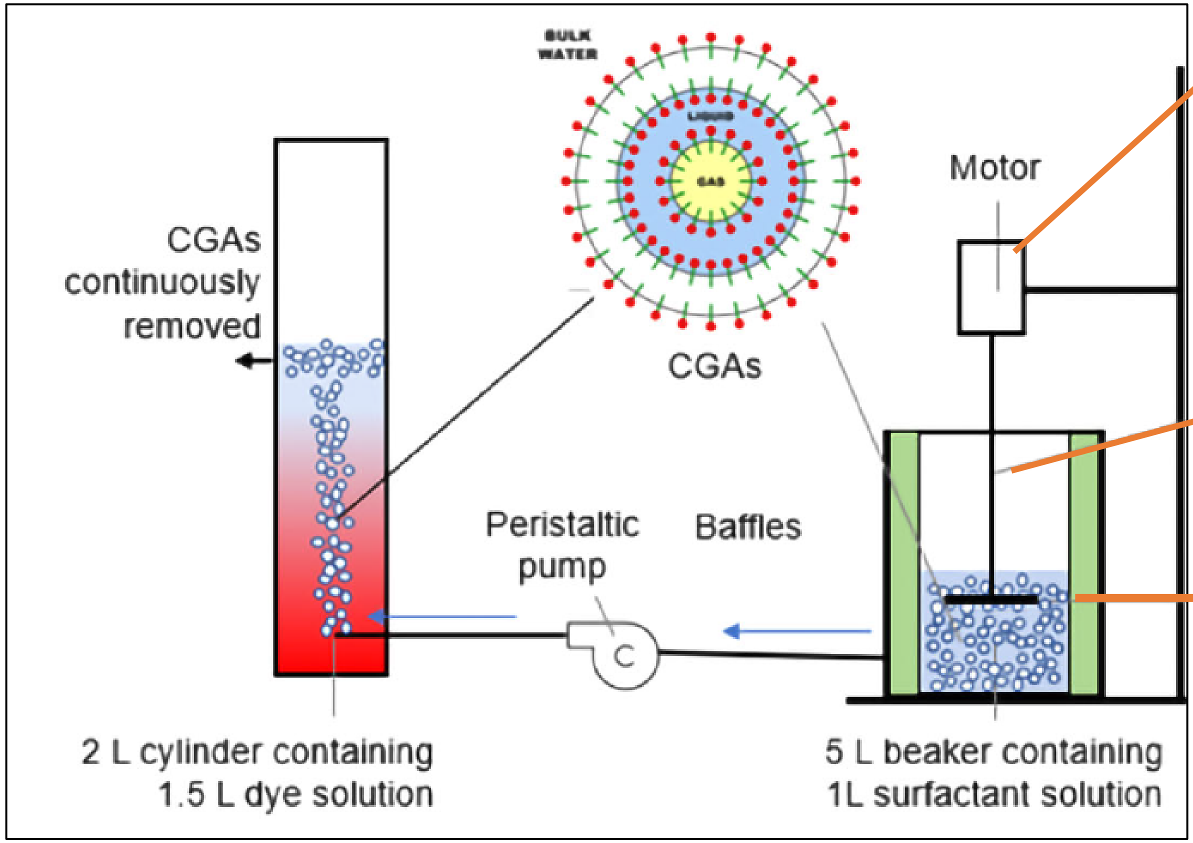
GSI Environmental Patent Pending



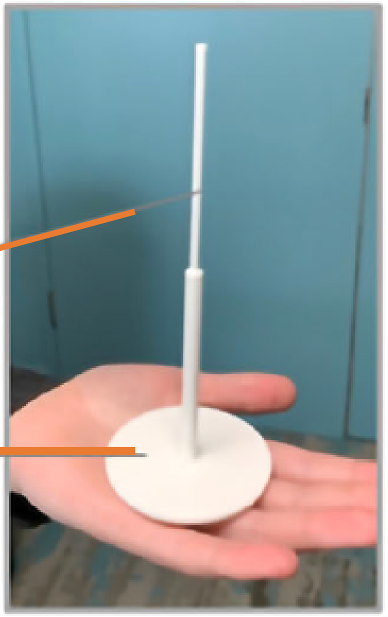


- Not bubbles but multi-layer structure
- Air + surfactant + water mix, created under high shear forces
- Separation via electrostatic processes
- Smaller than gas bubbles (10-100 um vs. 100-50,000 um) much greater contact area
- Can be mixed with either anionic or cationic surfactants

GSI/Clarkson U. Aphron Column Experiments Groundwater from Lab Mix of PFAS



Mixing speed >10,000 rpm



3-D printed rotary shaft and spinning disk

Clarkson University

Average <u>Removal %</u>

PFOS: 0% (?)

PFOA: 88%

PFHxS:(na)

PFBS: 91%

PFBA: 95%

Kulkarni et al., 2022; Newell et al., 2021 (patent pending)

GSI Batch Experiments with Aphrons – Batch Test Groundwater from AFFF Site

Average Removal %

PFOS: 66%

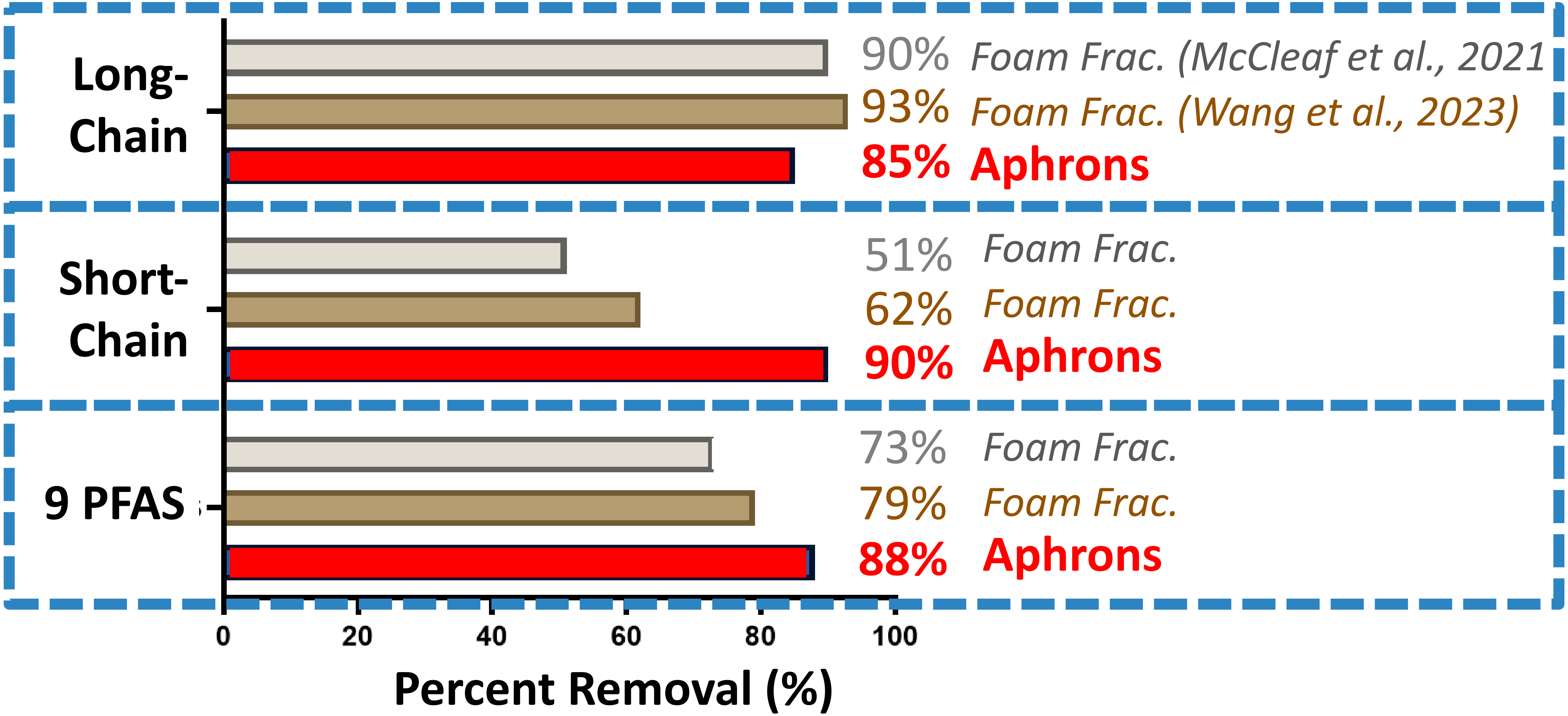
PFOA: 93%

PFHxS: 89%

PFBS: 96%

PFNA: 89%

GSI Batch Experiments with Aphrons (Aphrons Treating Groundwater from AFFF Site)



Future Development Work with Aphrons

ESTCP Project ER23-7882 (summer 2023 start)
"Separating and Destroying Short-Chained PFAS from Waste Streams by Combining Colloidal Gas Aphrons (CGAs) with Plasma"

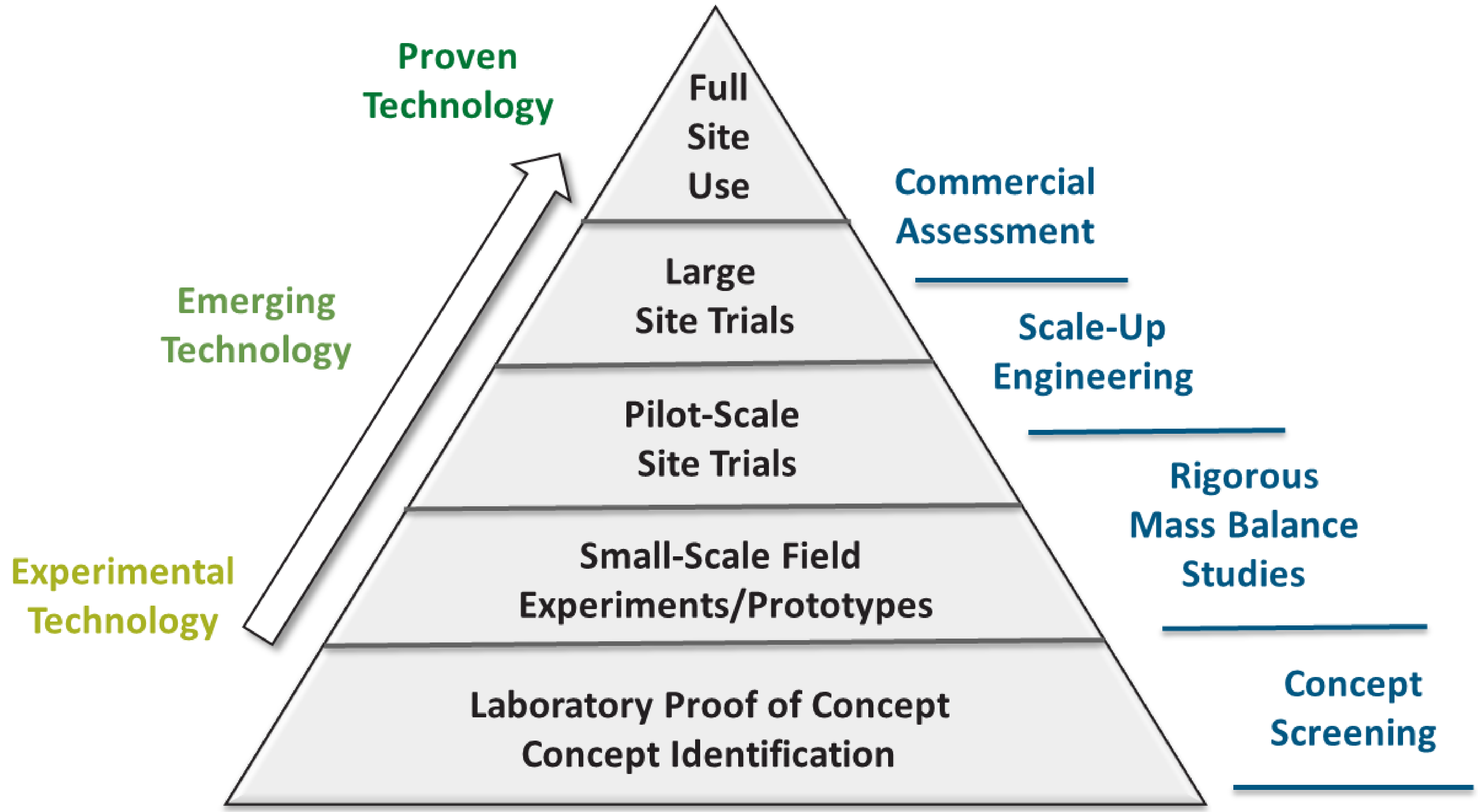
SERDP Proposal ER23-7892
"Leveraging the Unique Properties of Colloidal Gas Aphrons (CGAs) to Develop a Novel Liquid-Based Sorbent for PFAS Removal"

Commercial Development (on-going)
Continued Bench scale Testing and Design Work. Pilot tests in spring 2024

Technology Development Pyramid (Cherry et al., 1996)

Stages in the evolution of new remediation technologies

Proven Technology: *"Known Performance for a Known Price"*



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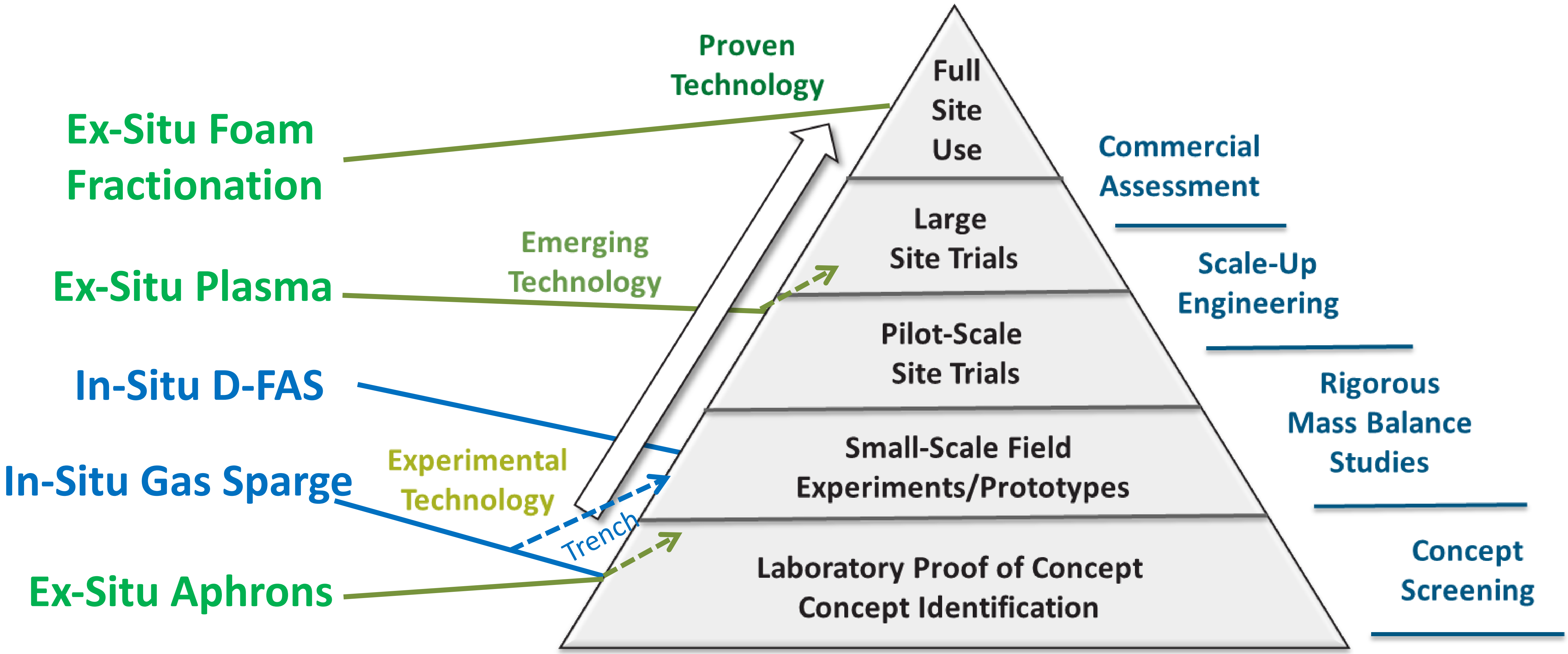
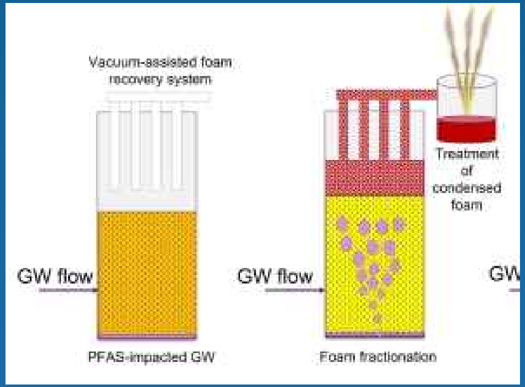
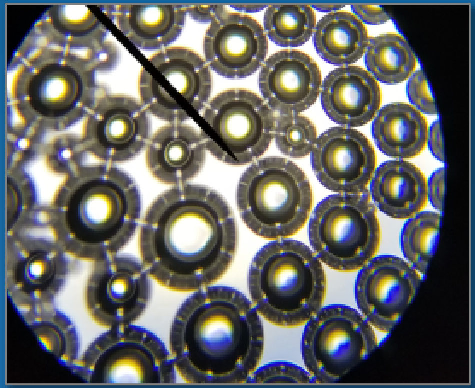
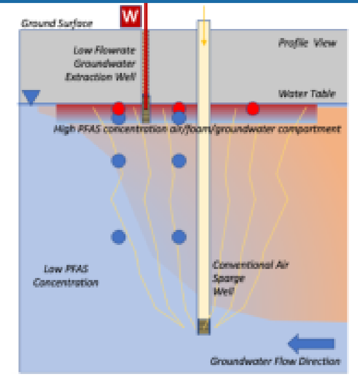


WRAP UP

- **Gas-Phase Technologies will be important for PFAS Treatment**
- **In-Situ Treatment of PFAS Plumes**
  - In-well removal
  - sparging in trenches
  - sparging in aquifers
- **Ex-Situ Treatment of PFAS Streams**
  - Plasma technology
  - Foam Fractionation
  - Colloidal Gas Aphrons







QUESTIONS

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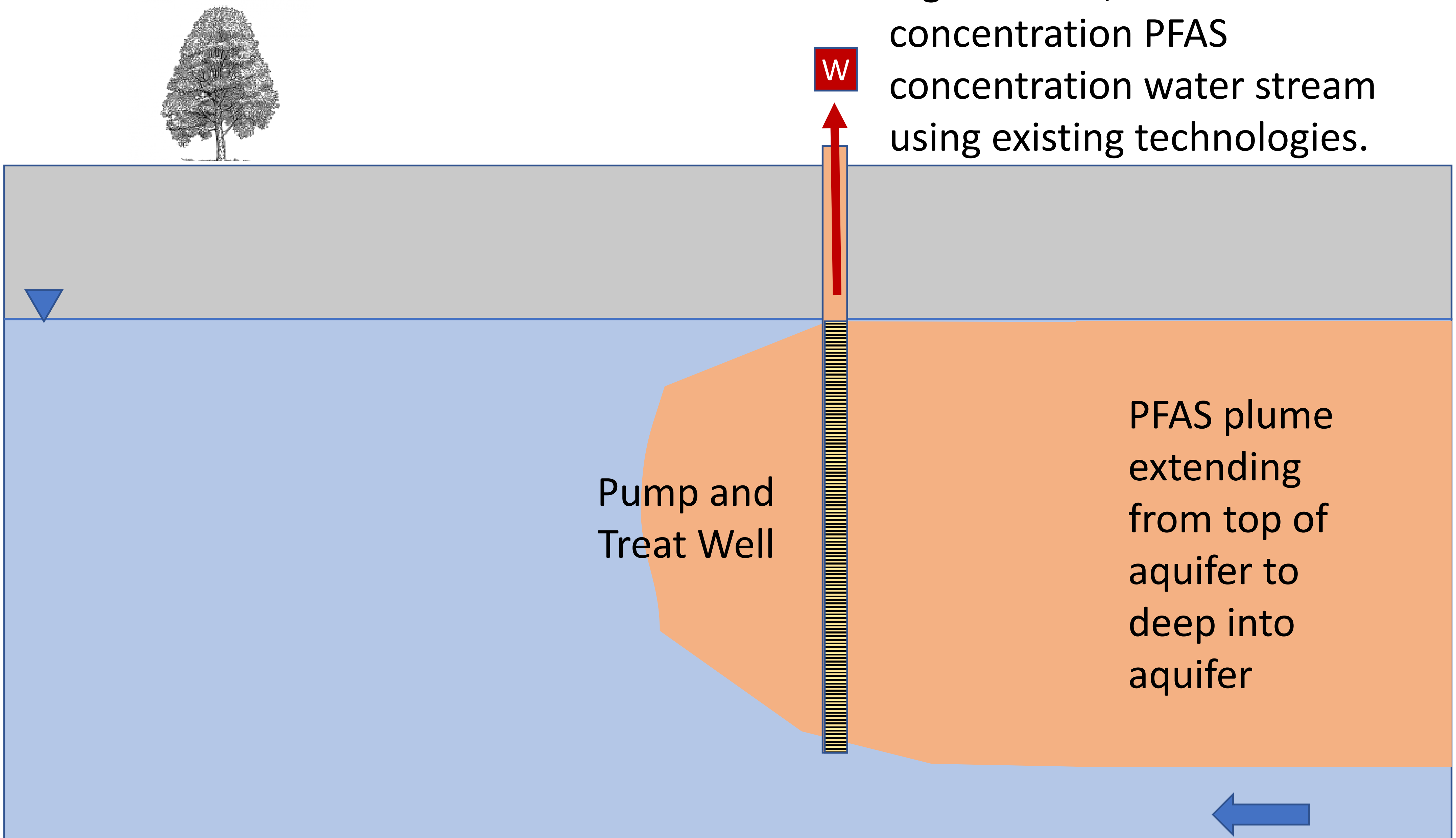
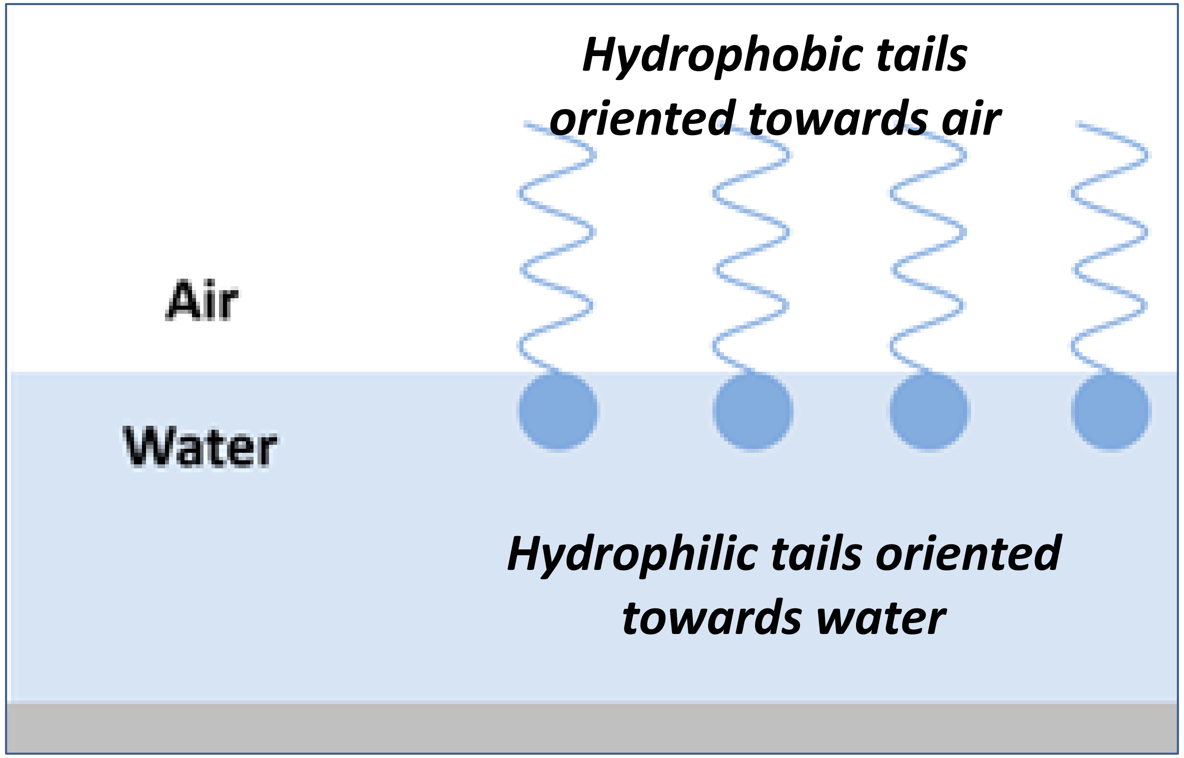
PUMP AND TREAT

W: Pumping and treatment of high volume, low concentration PFAS concentration water stream using existing technologies.



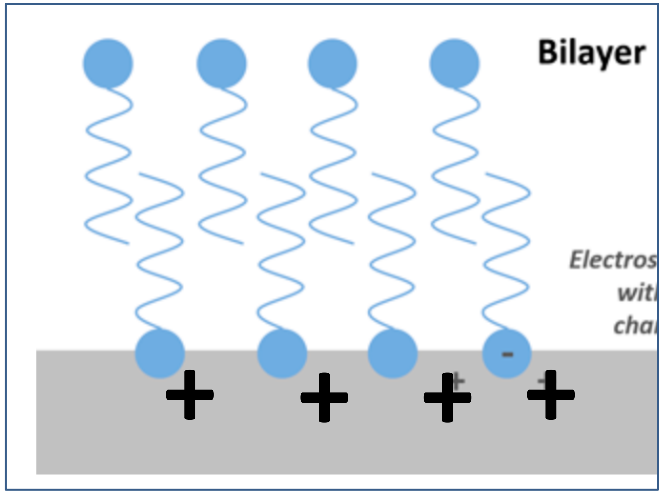
Key PFAS Removal Processes for Gas-Based Technologies

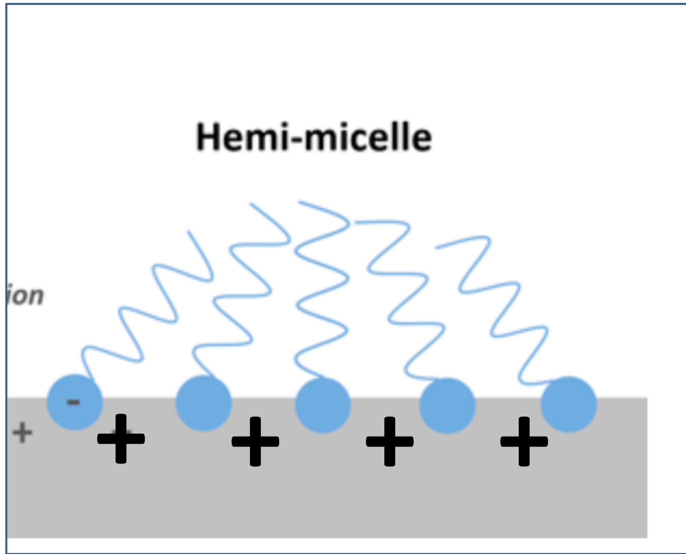
Air-Water Partitioning



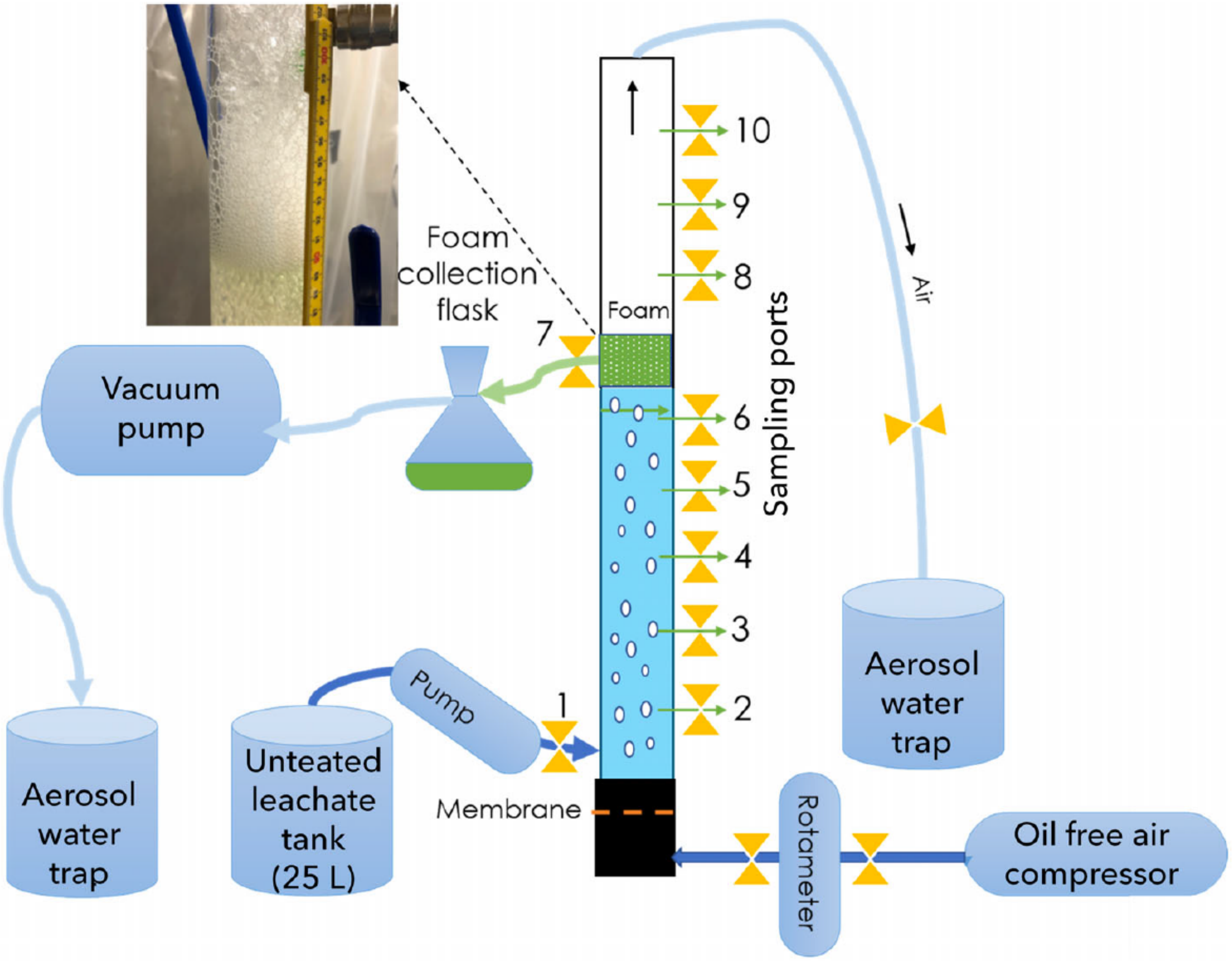
Electrostatic Attraction

Electrostatic Attraction with Positively Charged Surface





4. Foam Fractionation Single Stage Removal: McCleaf et al., 2022



Average
<u>Removal %</u>

PFOS: 98%

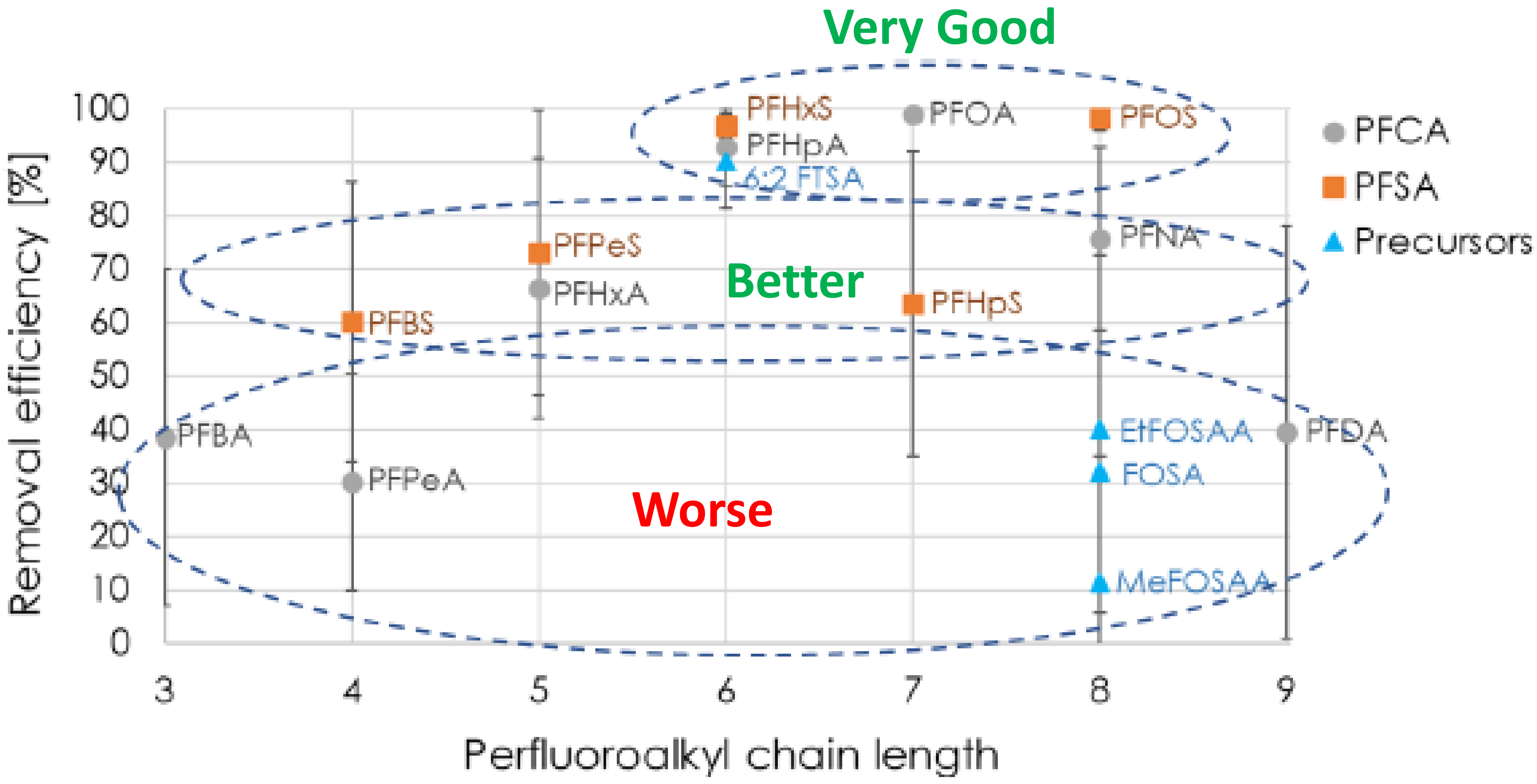
PFOA: 99%

PFHxS: 97%

PFBS: 60%

PFBA: 38%

Foam Fractionation Single Stage Removal: McCleaf et al., 2022



2. Gas Sparging Directly in Aquifers to Remove or Sequester PFAS

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In-Situ Air Sparging

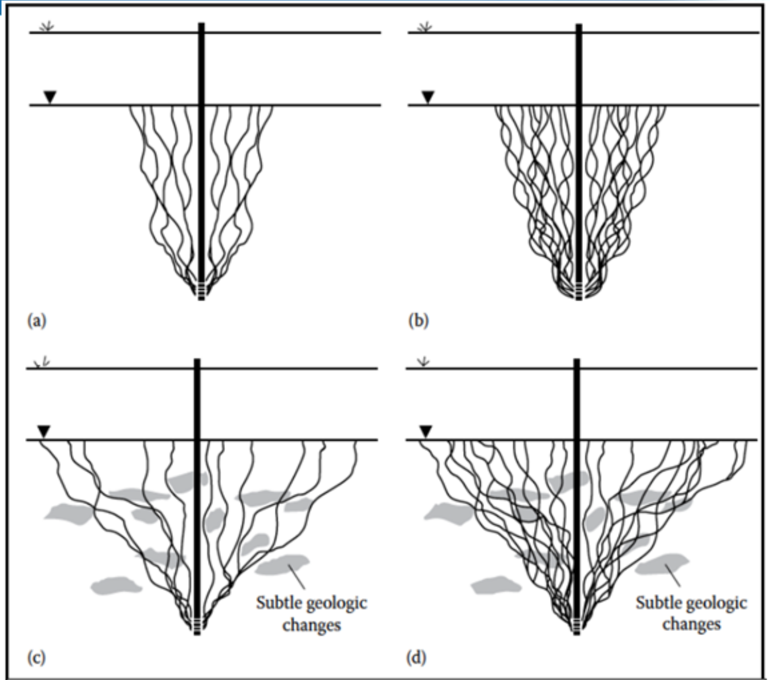
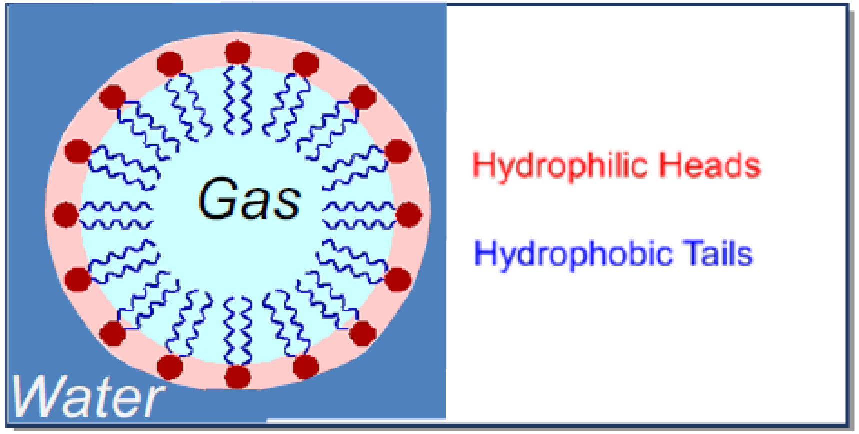
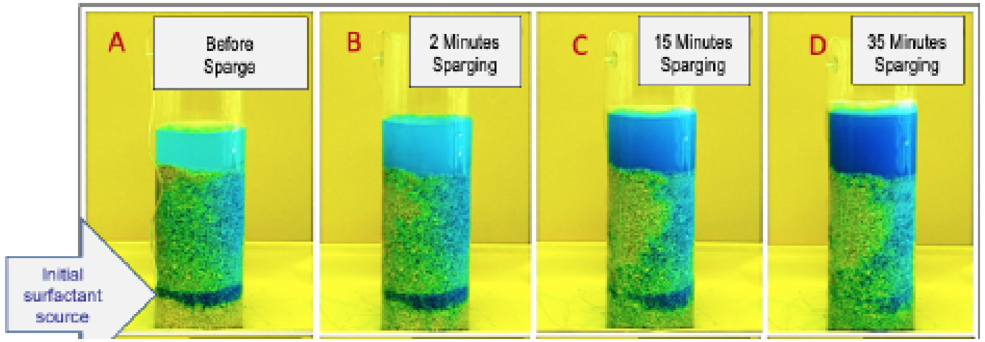


Figure 2. Zones of influence under various operating conditions. (a) Homogeneous geology, low airflow, (b) homogeneous geology, moderate to high airflow, (c) heterogeneous geology, low airflow, and (d) heterogeneous geology, moderate airflow (Suthersan et al., 2017).

Sparging to volatilize/biodegrade is one of the most commonly used in-situ remediation technologies

PFAS Surfactant Properties





Direct sparging to partition PFAS in geologic media has not been tested

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Task 1
Project Planning

Task 2a
Lab Studies
- Column Exp.
- Flow-through tanks

Go/ No go

Task 2b
Laboratory Studies
- Transformation

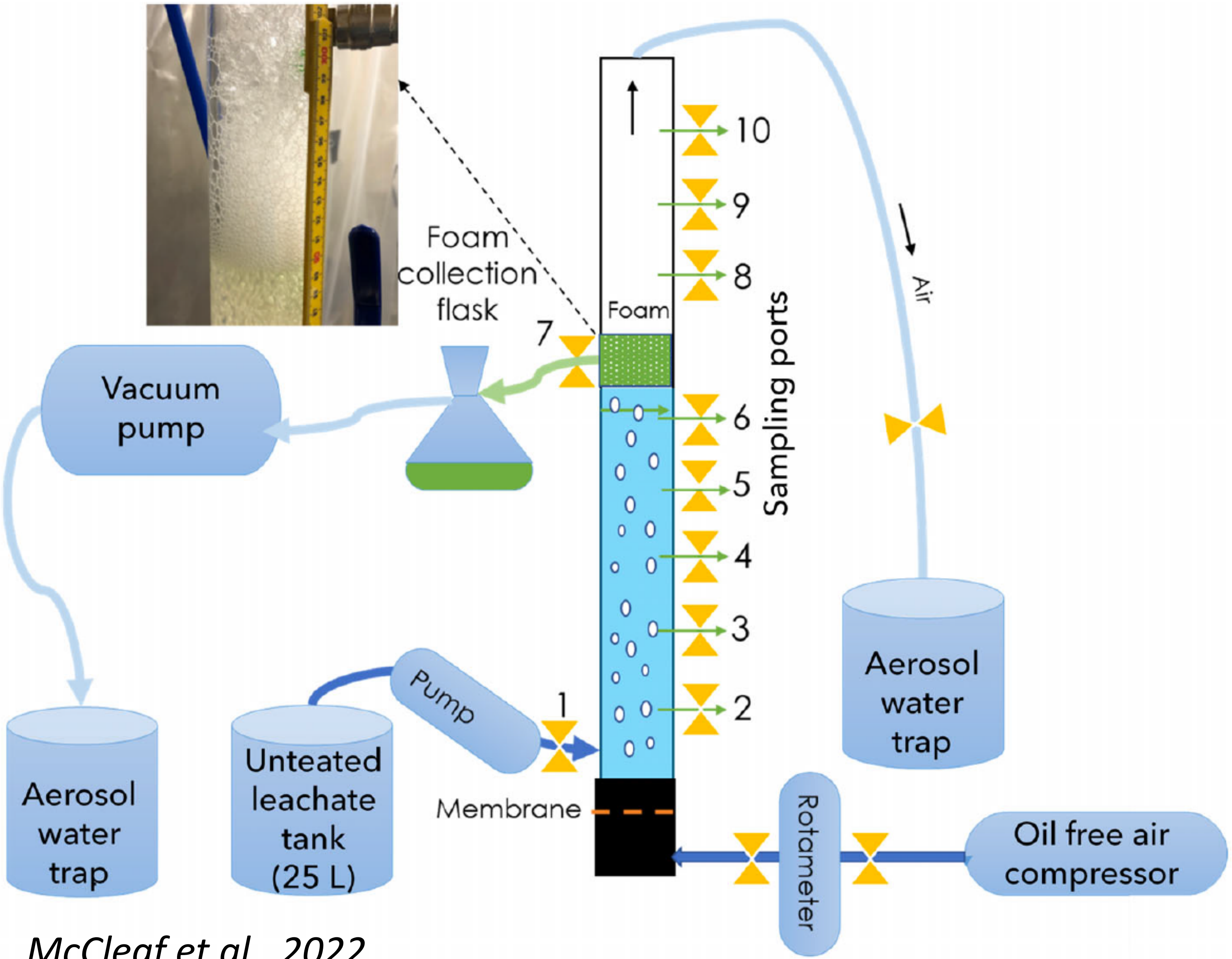
Task 4
Small-Scale Field Trial
- Sparging test well
- Extraction & Tmt.

Task 3a
Mathematical Modeling
- Mechanisms
- Retention
- Extraction -Economics

Task 3b
Math. Modeling
- Transformation

Task 5
Technology Transfer

Foam Fractionation Single Stage Removal: McCleaf et al., 2022



McCleaf et al., 2022

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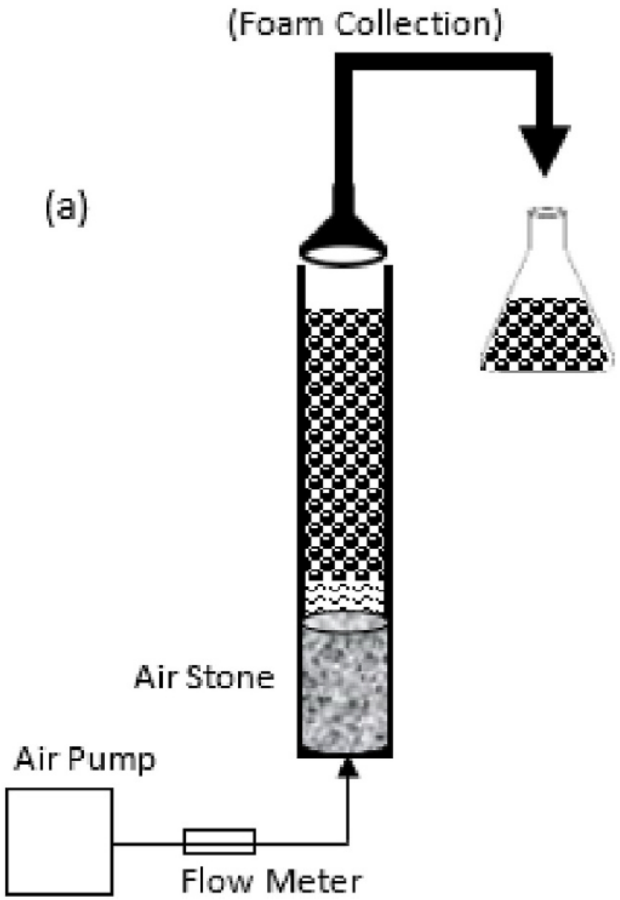
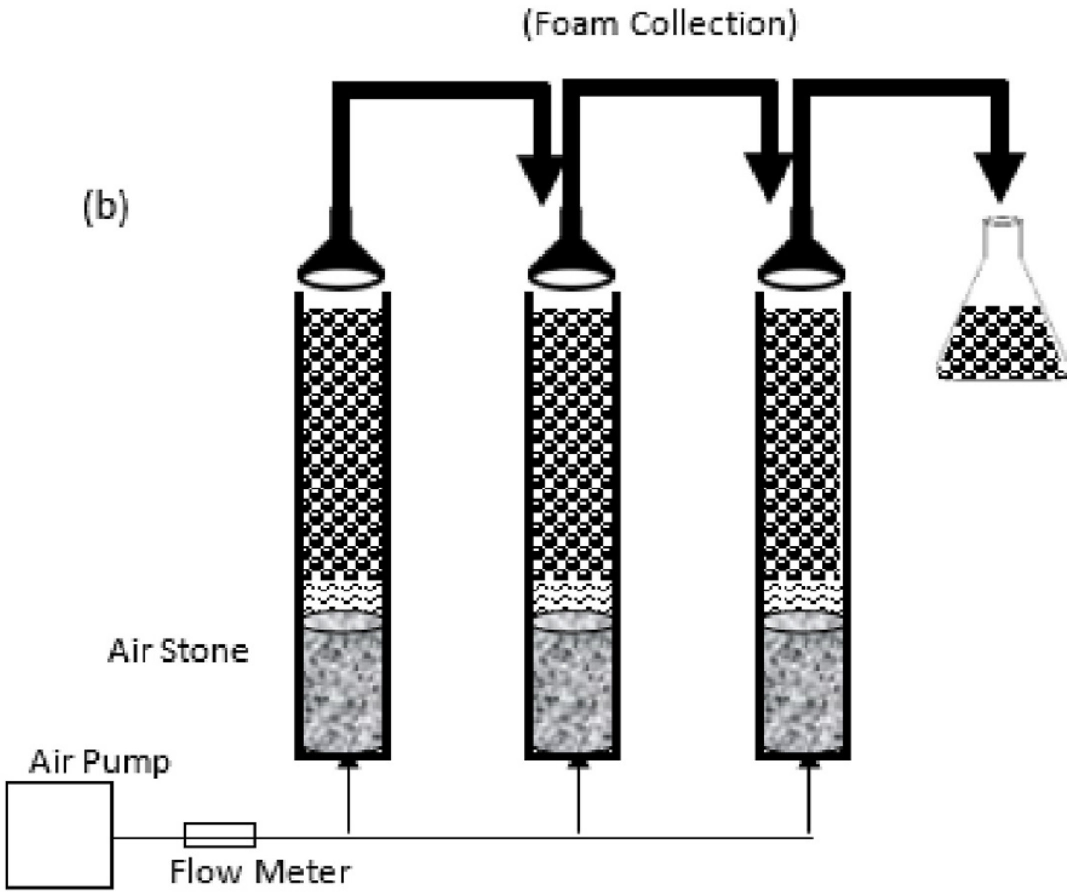
Foam Fractionation Single Stage Removal: Wang et al. (2022)



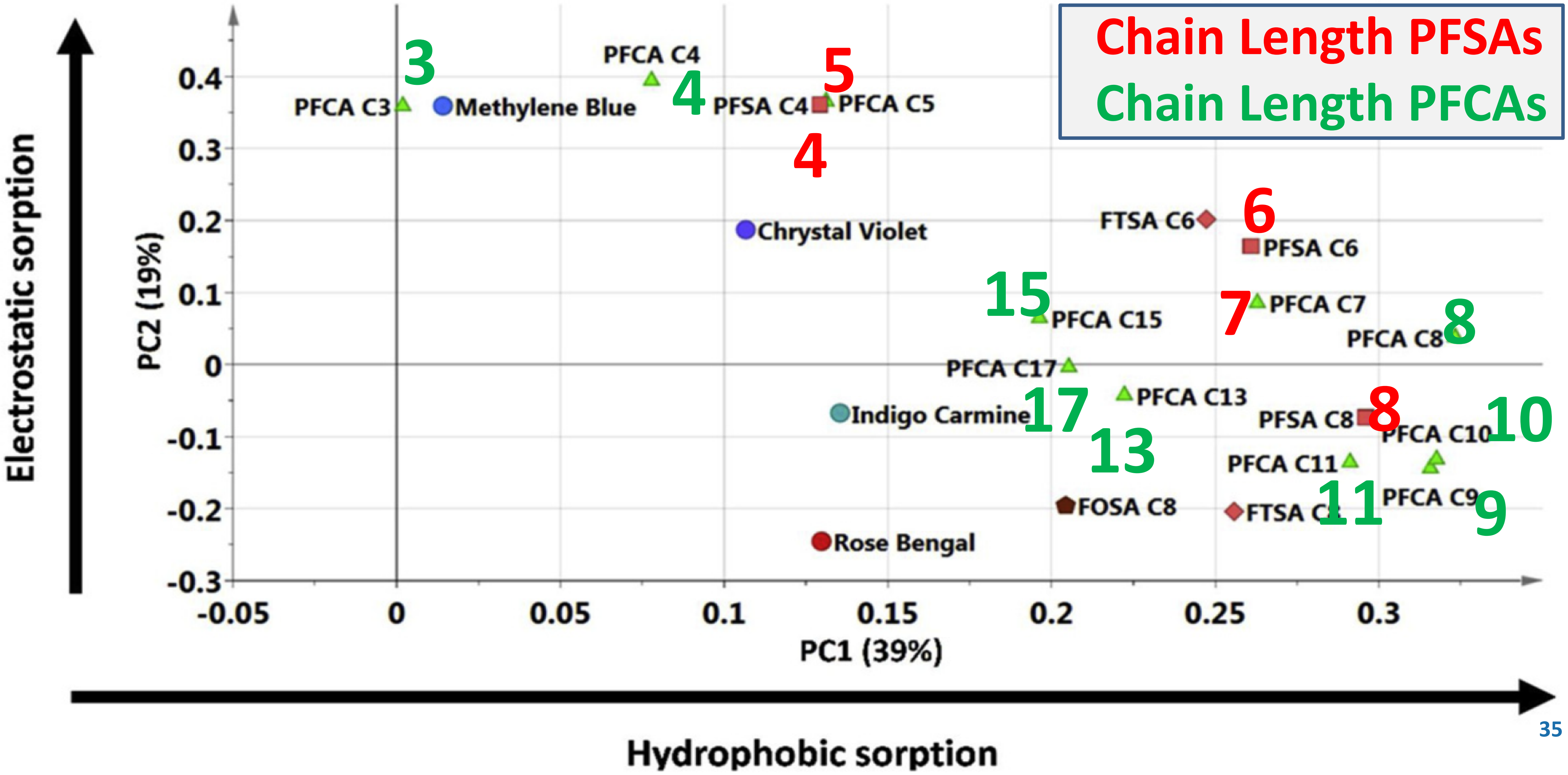
Single
Stage



Three
Stages

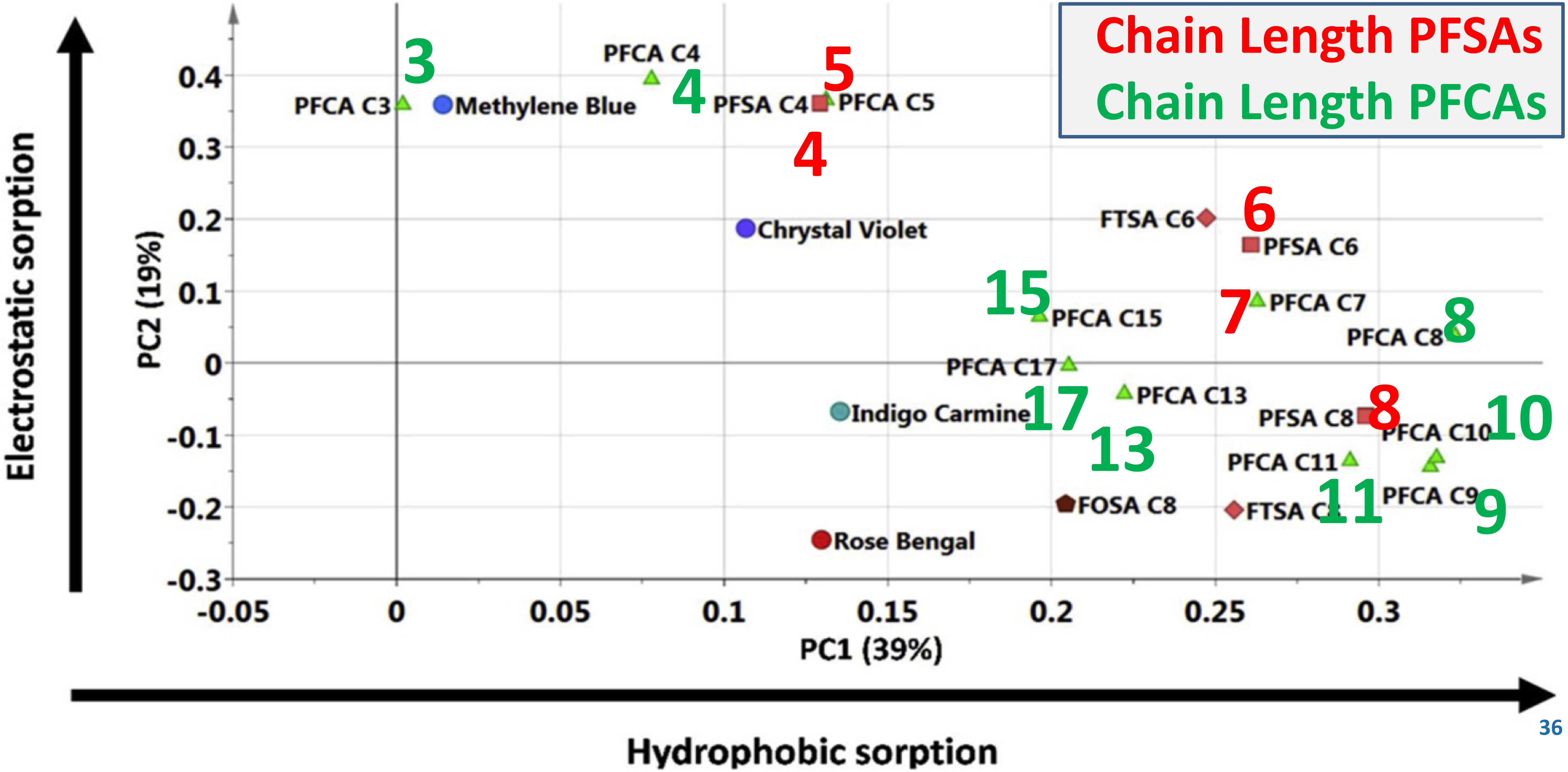
M. Sörengård, et al.

Hydrophobic vs. Electrostatic Processes (Sorengard et al., 2022)



M. Sörengård, et al.

Short-Chained: More Electrostatic
Long-Chained: More Hydrophobic



SAFF40® Container

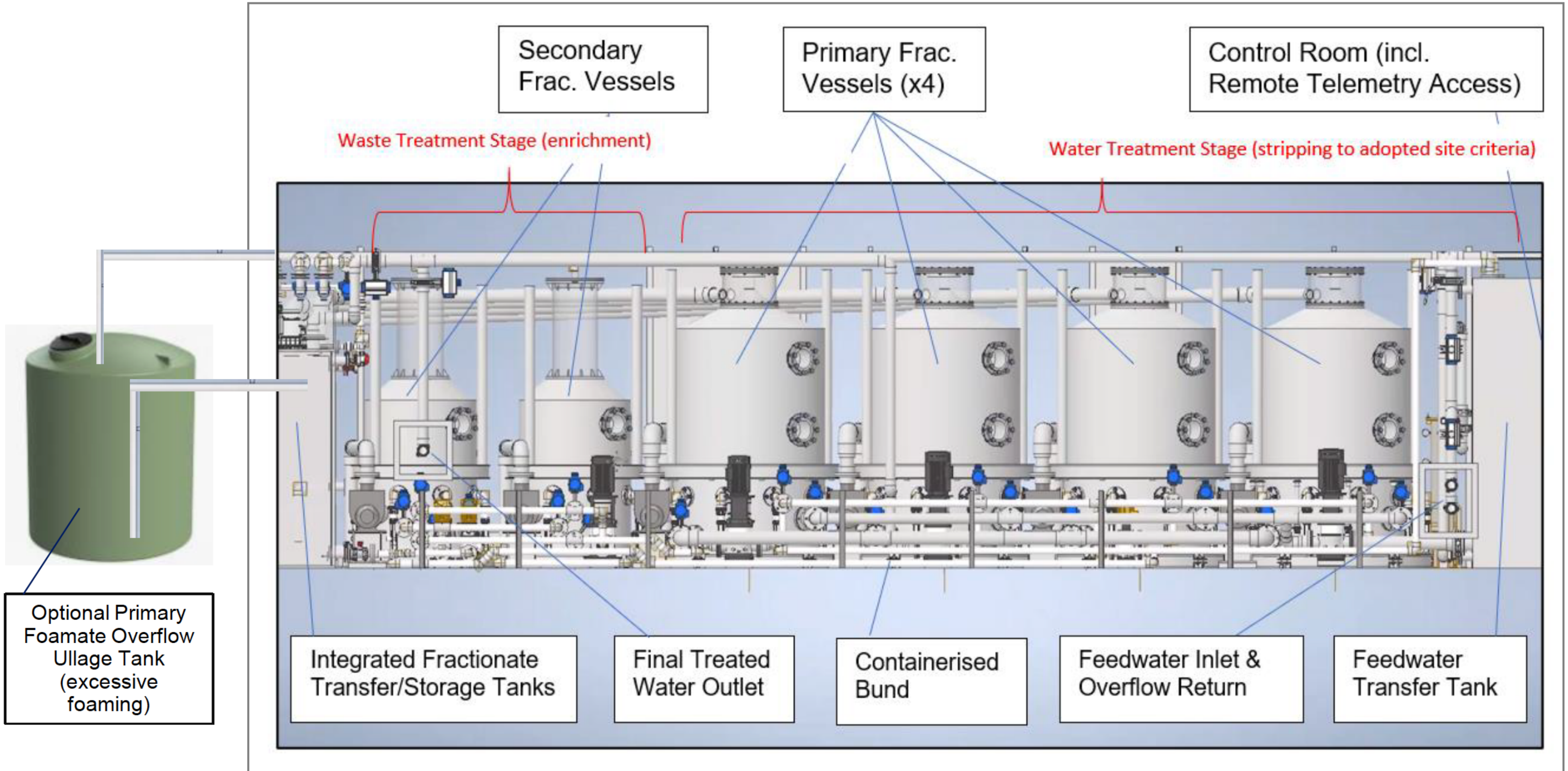


Figure-1: Schematic of containerised SAFF40™ system (elevation view showing key process stages).