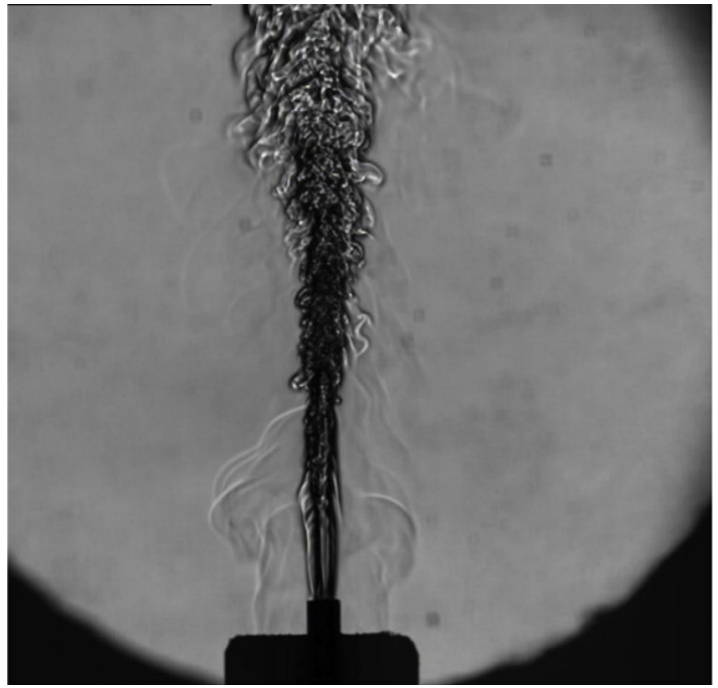
REMTEC & EMERGING CONTAMINANTS SUMMIT

OCTOBER 3-5, 2023

Validation of Supercritical Water Oxidation to Destroy Perfluoroalkyl Acids



Hicks et al., 2019

Collaborators:

- John Kirby
- Chris Bellona
- John Follin
- Ken Liberty

Overview

Challenge

- PFAS-concentrated waste actively being generated
- Reliable/practical solutions urgently needed

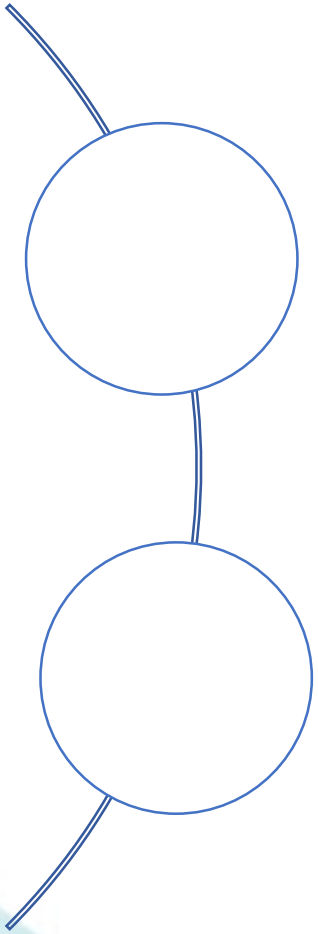
Plan

- SCWO has decades application in waste disposal; applicable to PFAS
- Can SCWO destroy PFAS-concentrated waste w/no detectable PFAS in emissions?

Result

- >99.999% reduction of detectable PFAS in **liquid** and **gaseous** emissions
- *Limited* defluorination ratio 62.6%

Field Validation Test Objectives

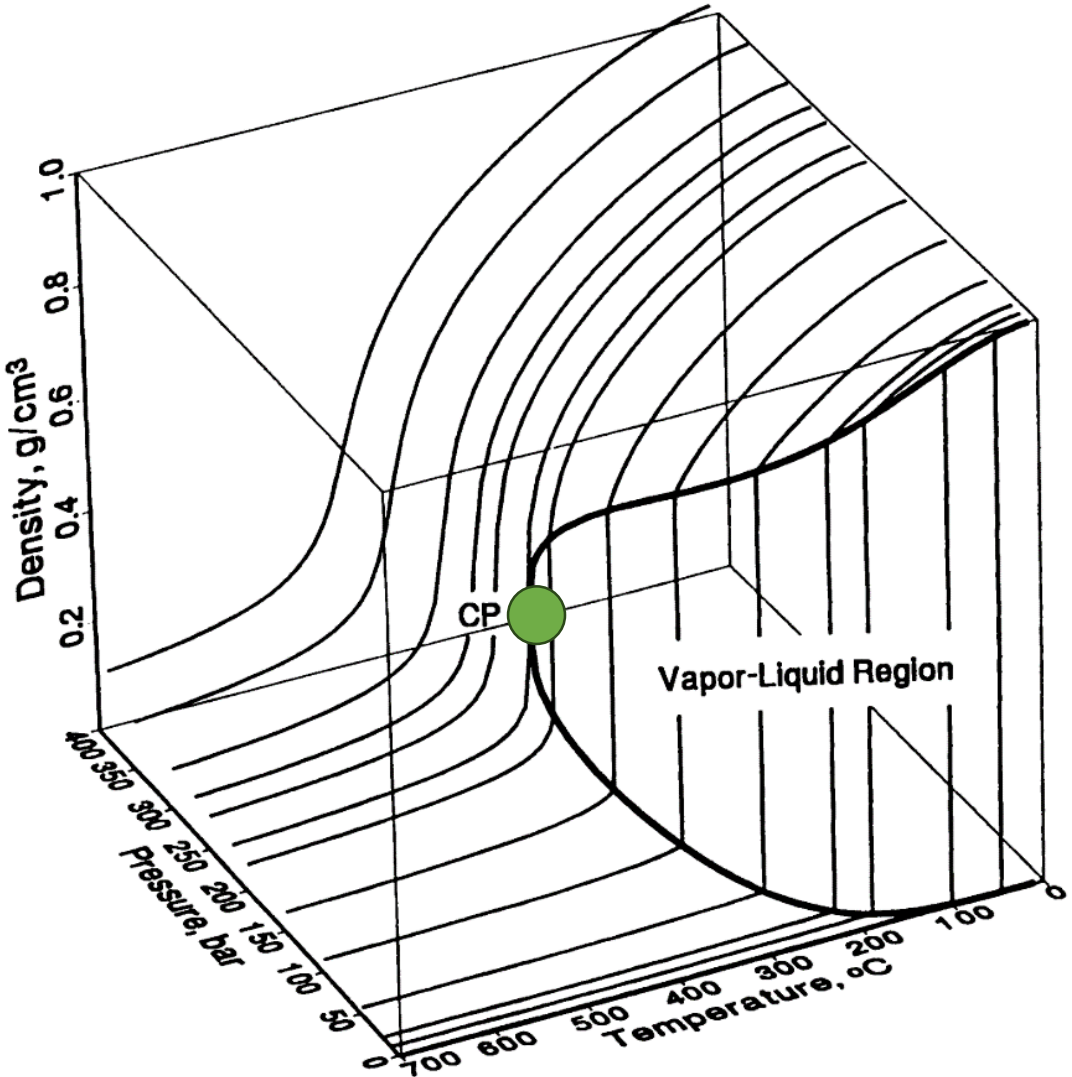


Effectiveness of SCWO for aqueous & gaseous discharge (gpm flow rate)

Attempt a fluoride mass balance

Get to Know SCWO

- Water critical point:
  374.14°C and ~220 bar
- Single-fluid phase
- No incomplete combustion products
- Influent must be pumpable to high pressure (this includes slurries[1])

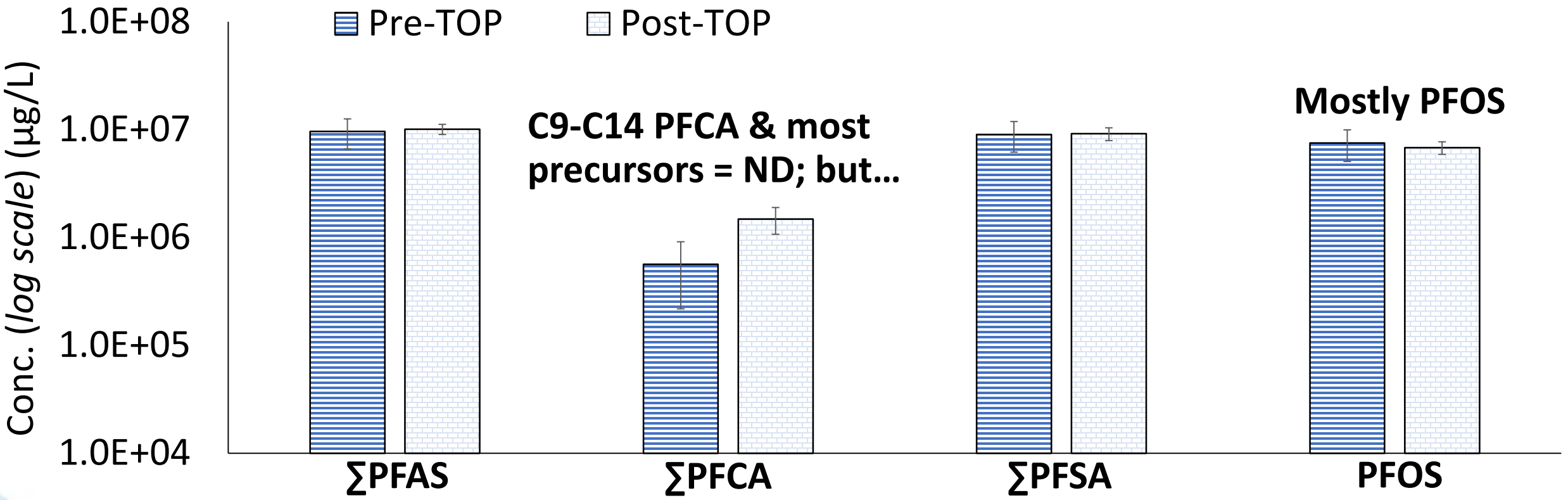


Tester et al., 1993

[1]*Chiang et al 2023*

PFAS-Concentrate Selection (Literature Data*)

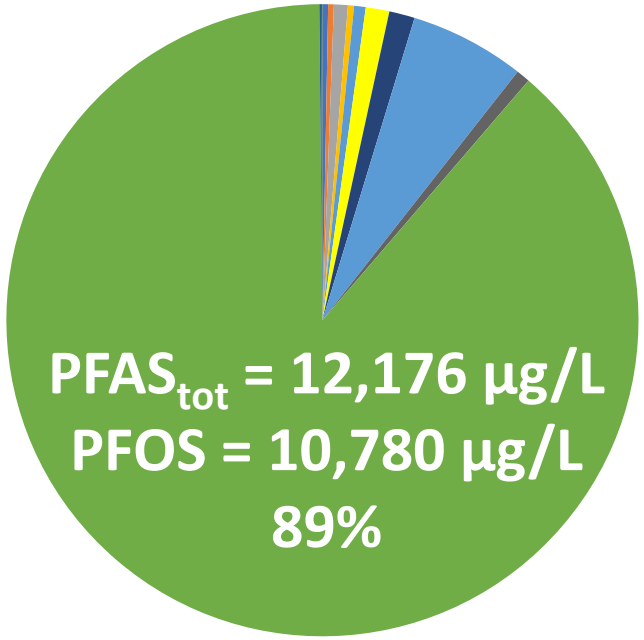
Electrochemical fluorination Aqueous Film Forming Foam (AFFF)



*Houtz 2013; Backe et al 2013; Lang and Divine 2020

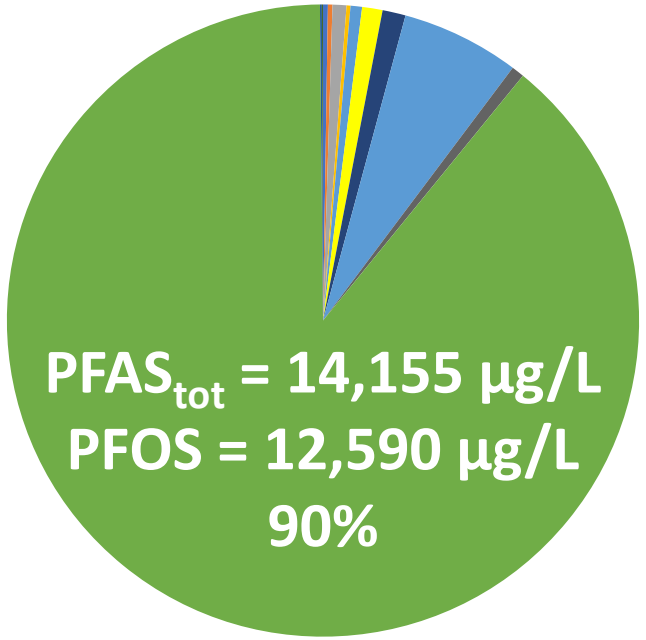
PFAS-Concentrate Selection (Actual)

Influent 1



Diluted
1,000 X

Influent 2



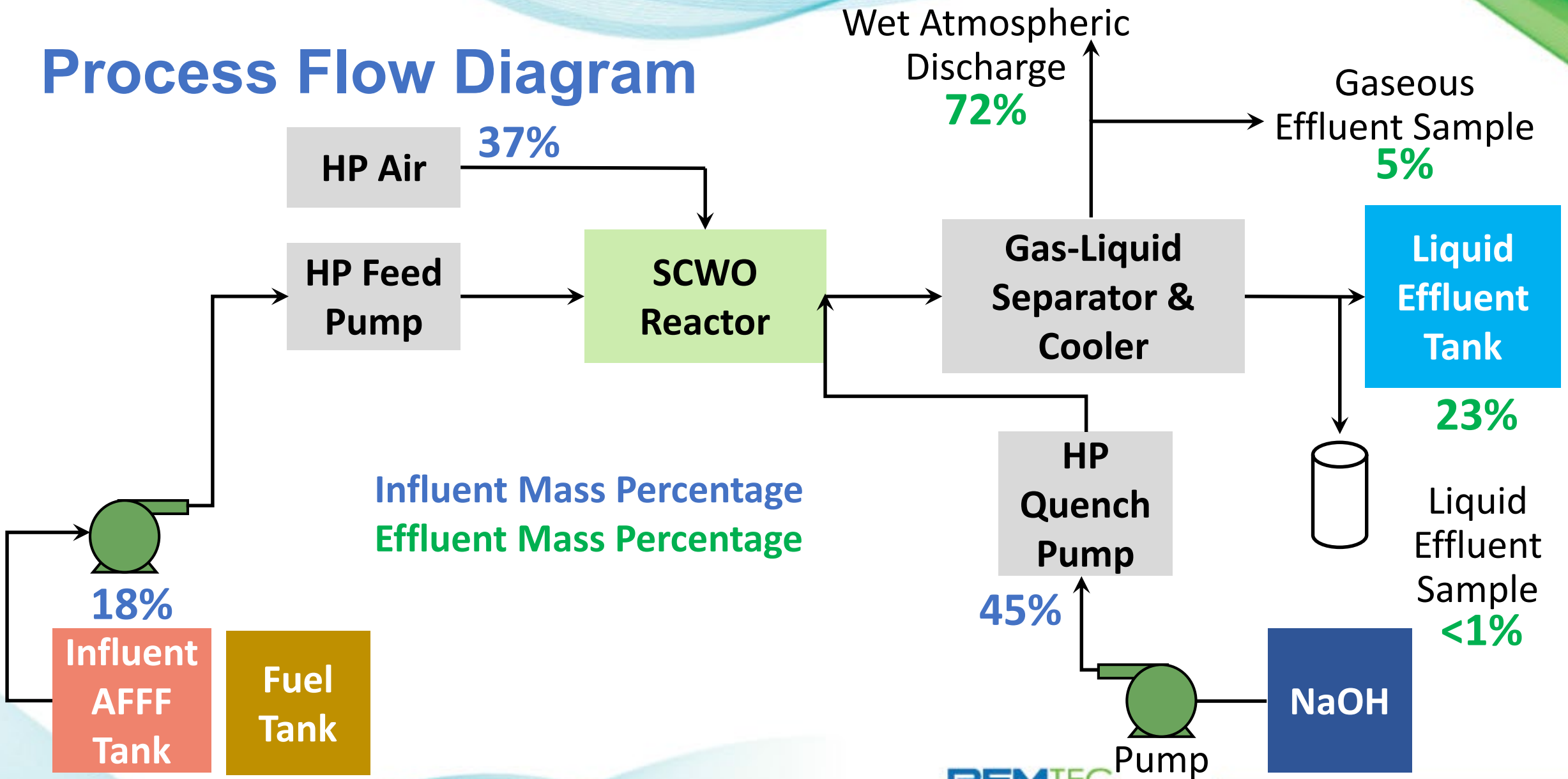
PFBA PFPeA PFHxA PFHpA
PFOA PFBS PFPeS PFHxS
PFHpS PFOS PFNS PFDS

Field Validation Test Details – San Diego, CA

SCWO skid used for validation testing
(General Atomics 2021)

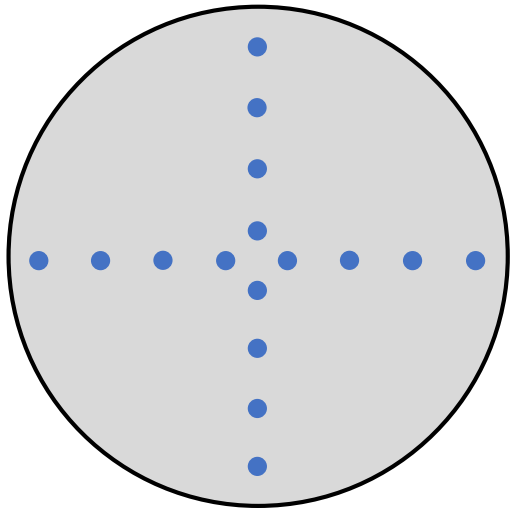
Two stage air compressor skids
(General Atomics 2021)

Process Flow Diagram



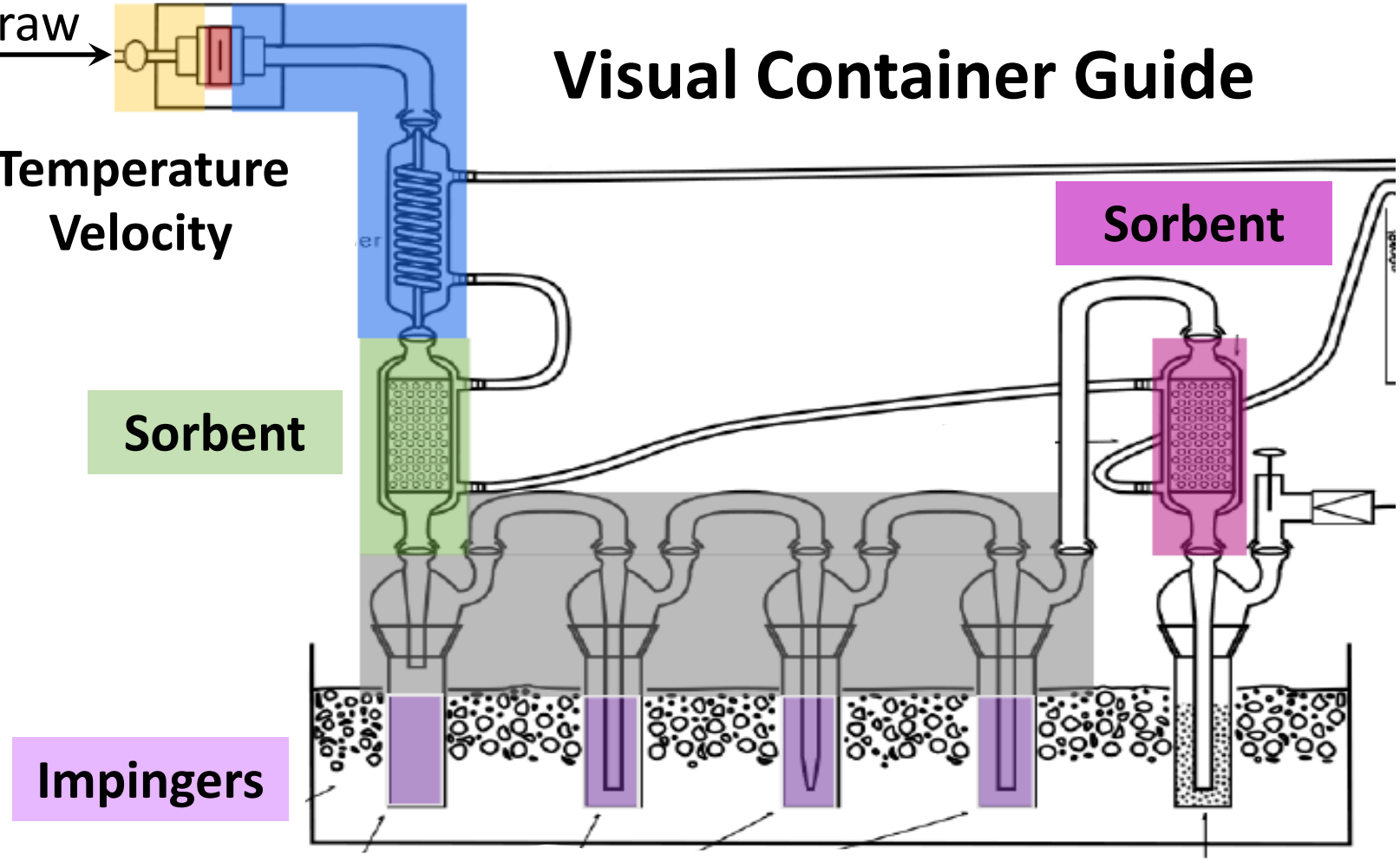
OTM-45

16-point traverse



Stack

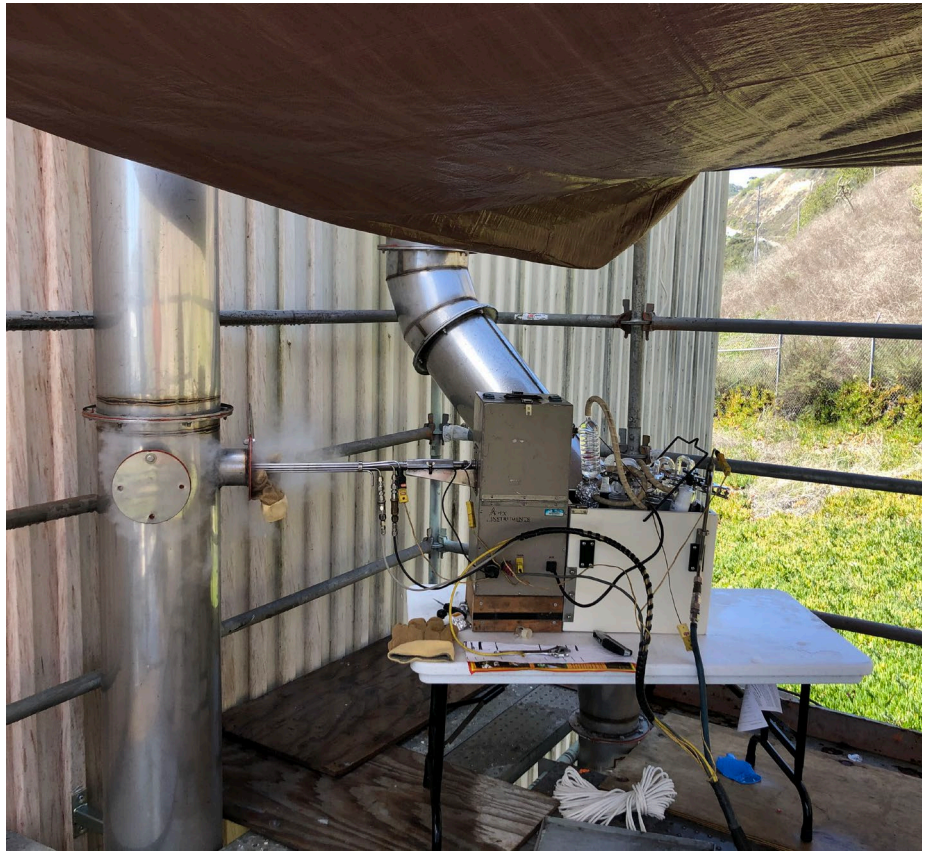
Visual Container Guide



USEPA 2021 (Version 0)

Field Validation Test Details – Stack Sampling

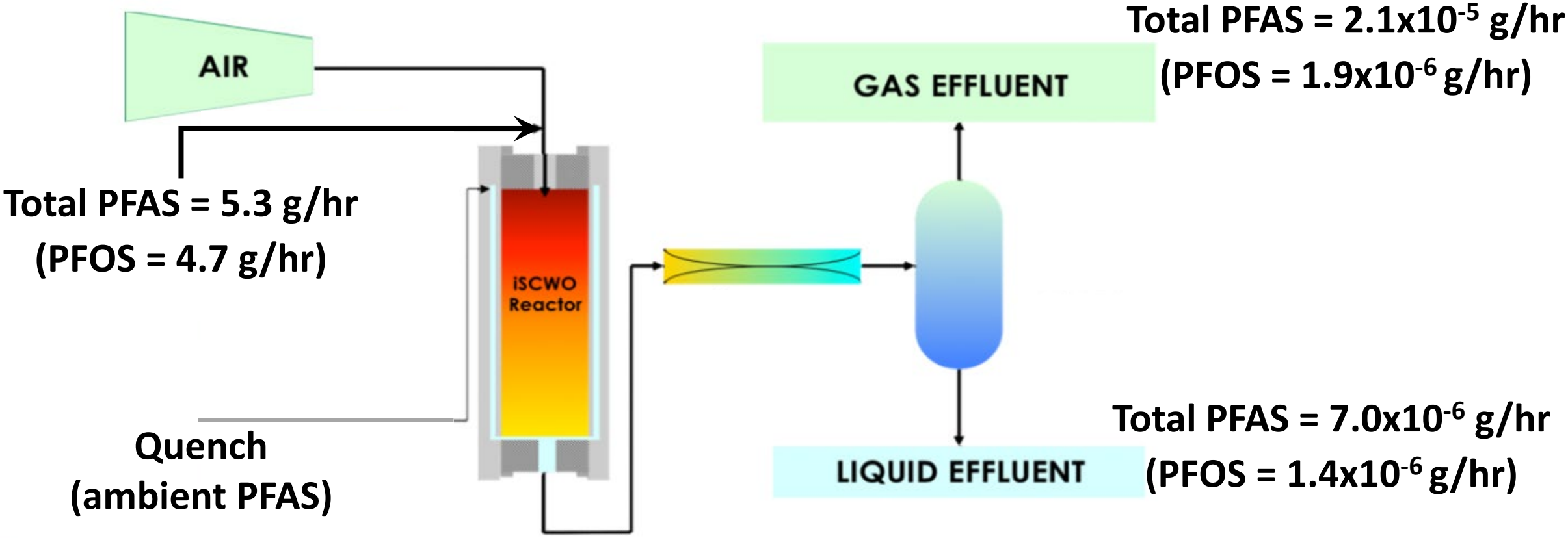
Gaseous sampling platform
(General Atomics 2021)



OTM-45 sampling train
(General Atomics 2021)

Results: Influent, Effluent, Gaseous Flow Rates

Total DRE_{PFOS} (μ; n=2) 99.9999%

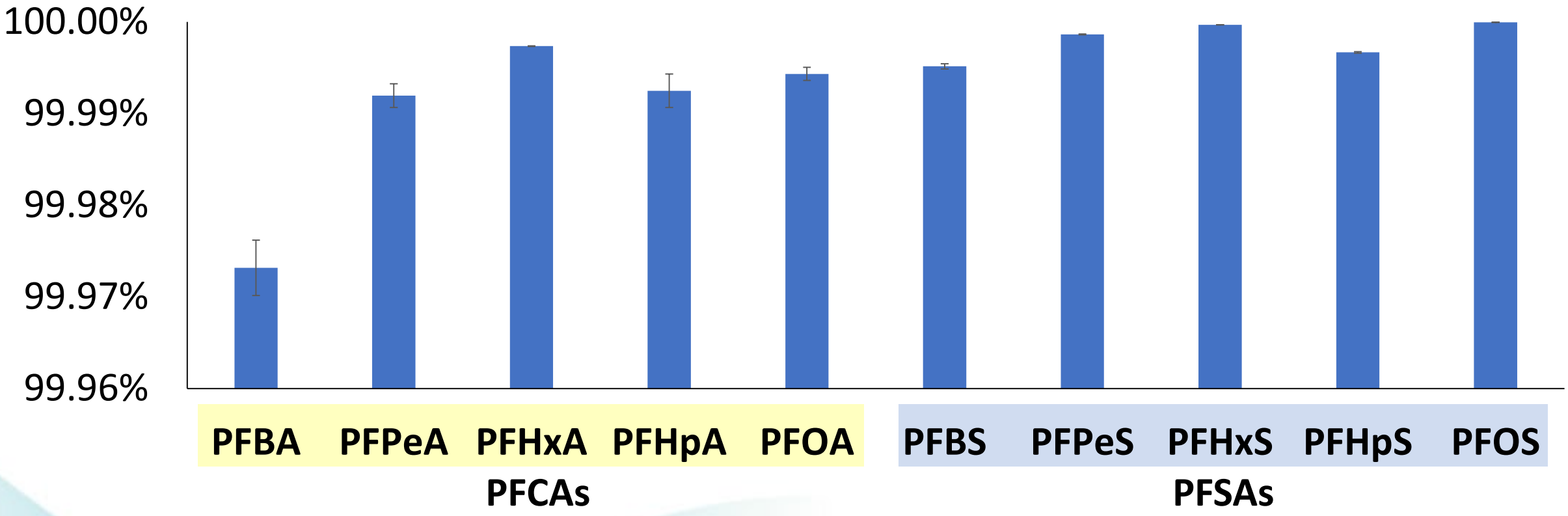


General Atomics Graphic

Results: Destruction & Removal Efficiency (DRE)

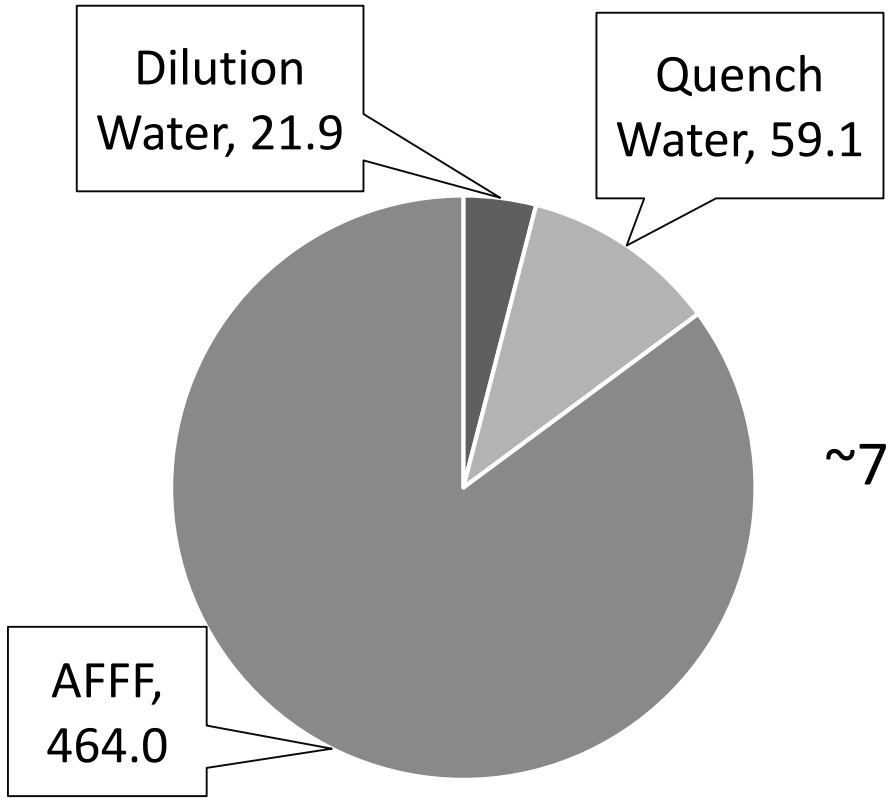
Precursor transformation?
Long to short chain PFAA conversion?

Reporting limits?
Quench water PFAS?



Results: Fluoride Considerations

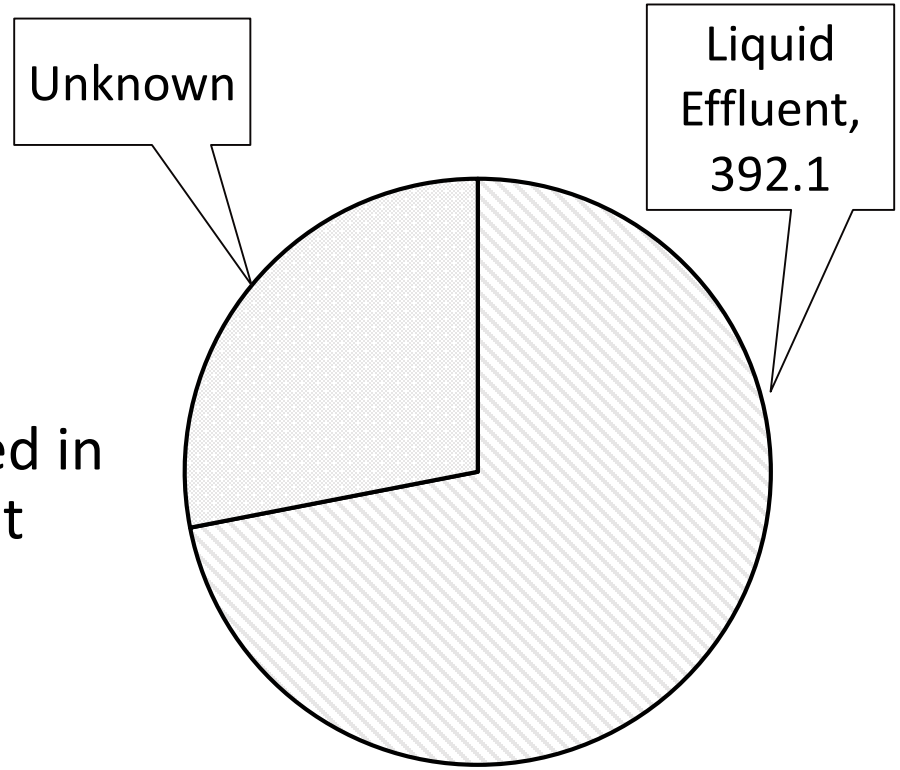
Influent mMole F



Total mMole F =545

~72% F recovered in liquid effluent

Effluent mMole F



Calculated *Limited* defluorination ratio: **62.6%**

Energy Considerations

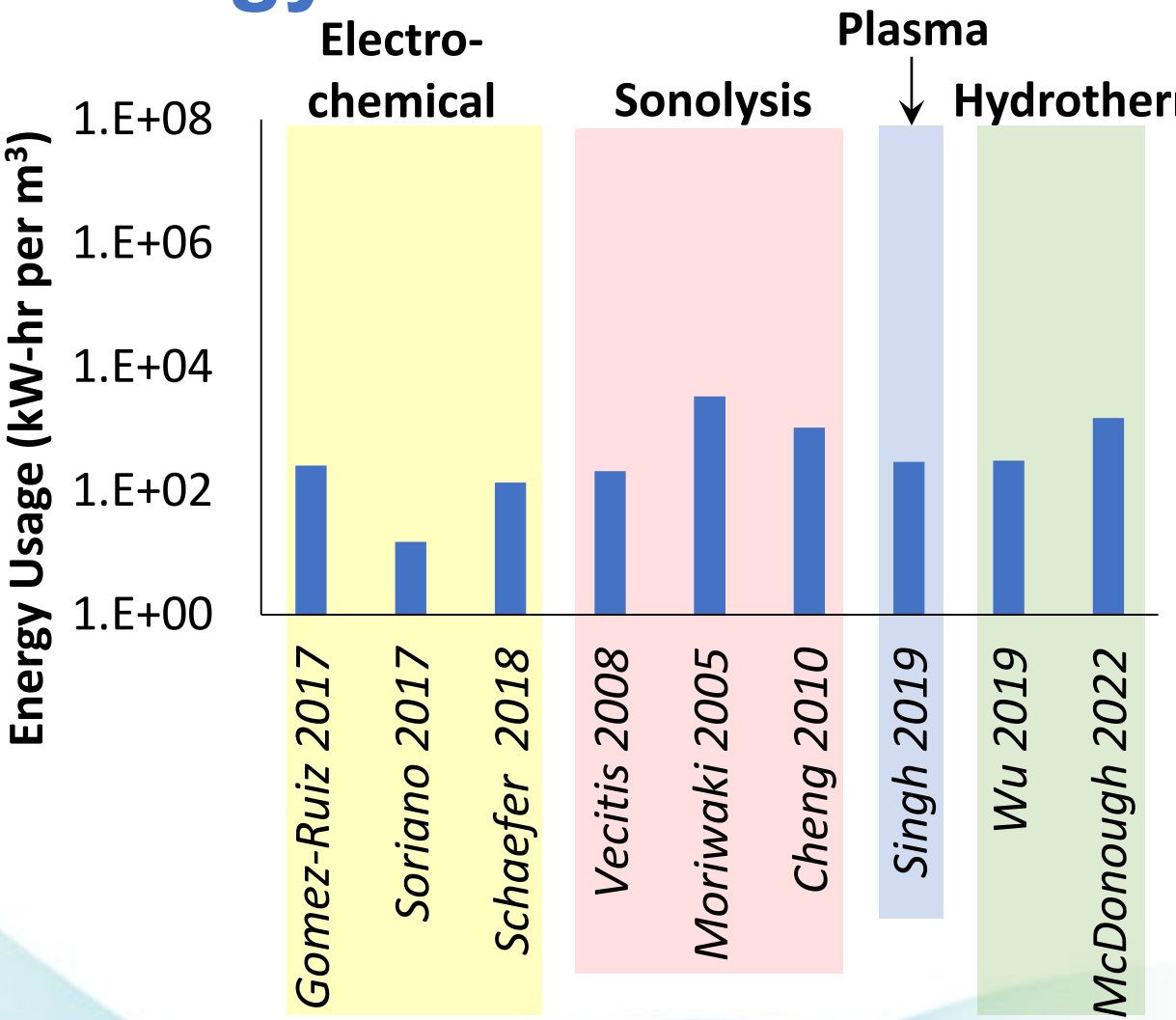
"It took a lot of energy to make PFAS, and it will take a lot of energy to destroy PFAS." anonymous

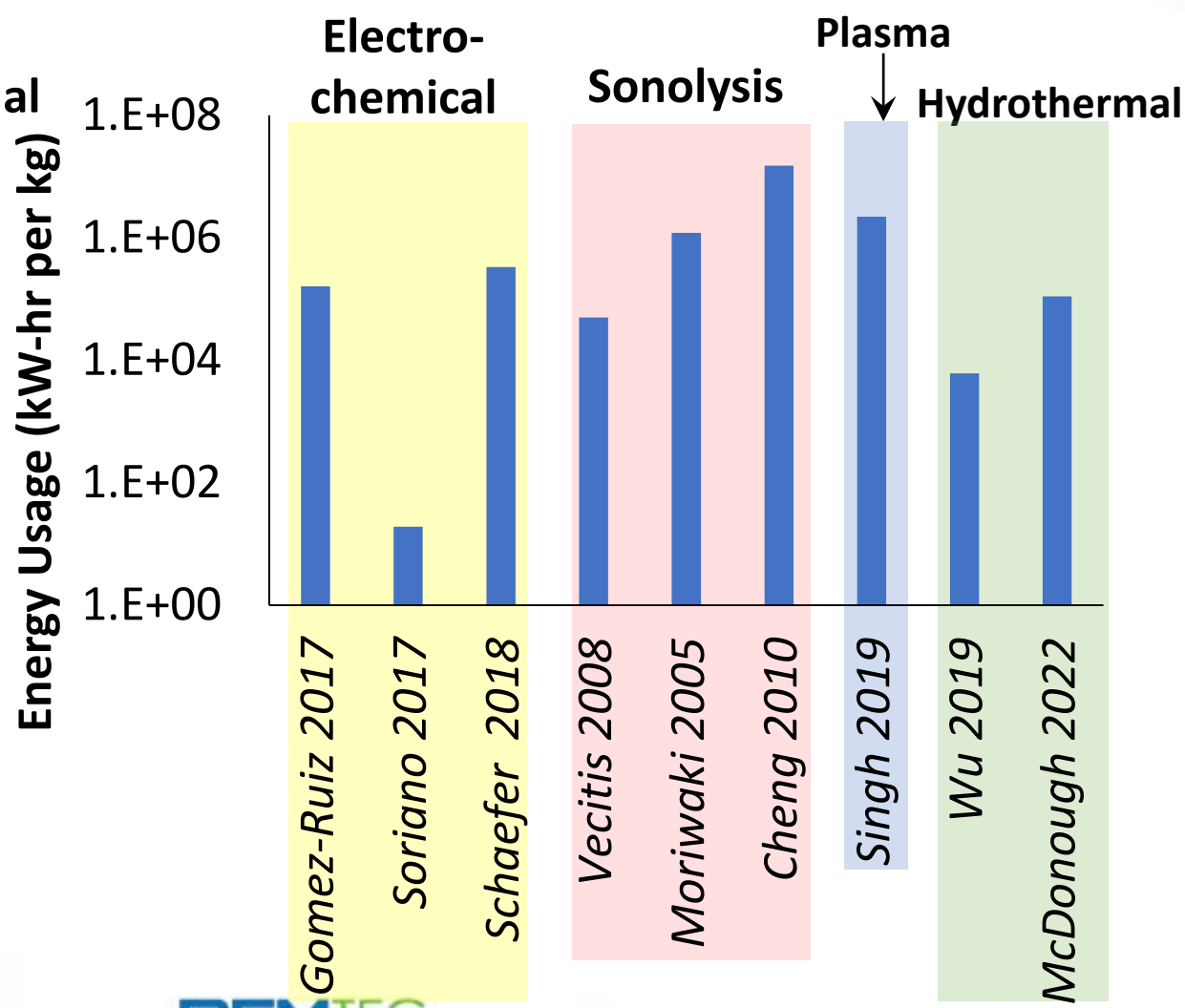
PFAS destruction technologies in the literature: ~0.1s to 1,000s kW-hr/m^3
(~$115/d to $1,150,000/d)

0.08 kW-hr/m^3
(~$100/d @ $0.15 USD/kW-hr)

PFAS-relevant destruction technologies not currently intended for dilute flow through systems

Energy Considerations





Limitations and Future Work

Non-target analysis*,**
(*Weber et al., 2022 & 2023; Krug et al., 2022
**USEPA 2022)

Fluoride in gaseous emission

1,000x dilution of concentrate**
(**USEPA 2022)

Conclusions

- Aqueous & gaseous effluent from SCWO suggest DRE >99.999%
- USEPA OTM-45 implemented to validate SCWO
- Fluorine mass balance incomplete; inorganic fluoride lost in the steam?

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Full Scale Operation of SCWO for Landfill Leachate, Industrial Wastewater and AFFF

Rick Gillespie

Chief Commercial Officer

Revive Environmental

Columbus, OH

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OCTOBER 3-5, 2023

Revive Environmental: Overview

- Water Technology company created in December 2022
- Structure: Founded by Battelle and Viking Global Investors
- Technology: Global Patents on PFAS Annihilator® and GAC Renew™
- Headquarters: Columbus, OH / CEO: David Trueba
- https://revive-environmental.com/

THE WALL STREET JOURNAL.

CBS EVENING NEWS

The forever chemicals are forever gone with the new PFAS Annihilator technology

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Learning Objectives

Review the capabilities and commercial readiness of SCWO

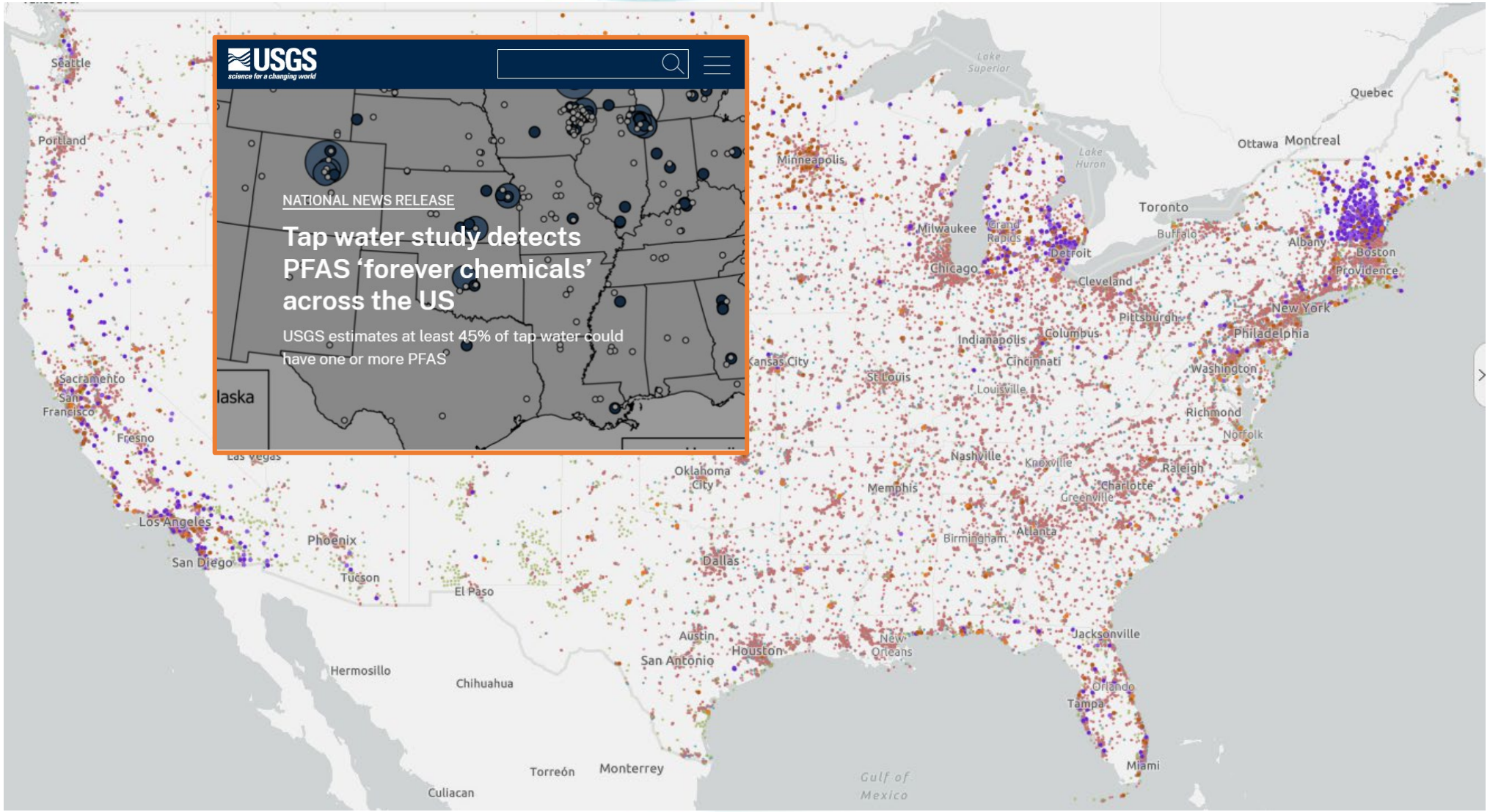
Provide an overview of the regulatory process - Transparency.

Lessons learned in the deployment, commissioning, and ongoing operation and optimization of a SCWO unit.

The PFAS Predicament

- Persistent
- Accumulative
- Toxic

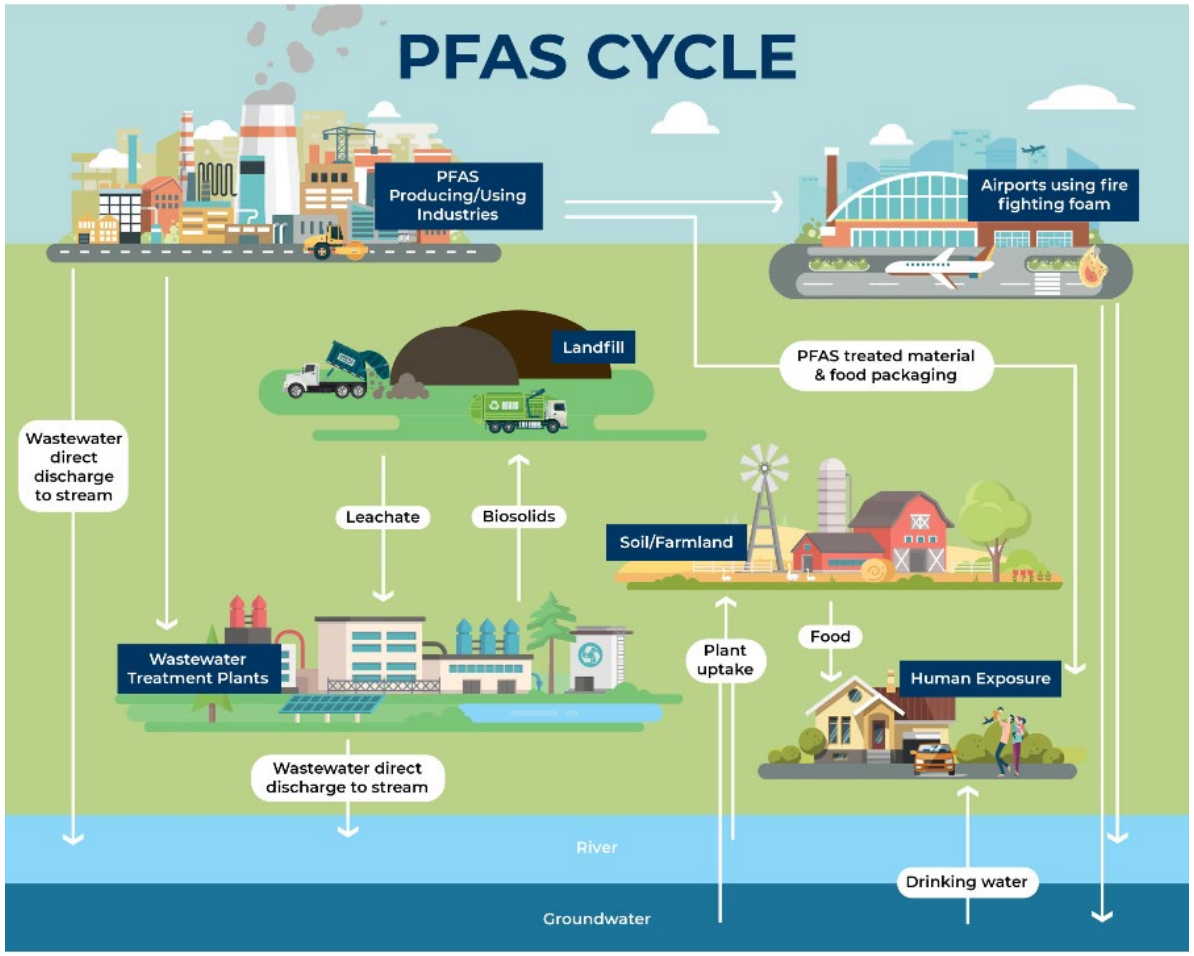
Not just ‘forever’ but ‘everywhere’ chemicals



Source: Presumptive Contamination Sites from [PFAS Sites and Community Resources map]

Application Scenarios – Overview of different waste streams

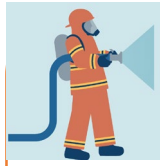
Challenges will differ by application/source



Source: Walnut Valley Water District, https://walnutvalleywater.gov/your-water/your-drinking-water/water-quality/

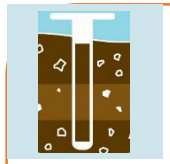
Landfill Leachate

- High Volume
- Recurring - Continuous
- High amount of co-contaminants



AFFF

- Lower Volume
- Very High PFAS (ppm)
- Concentrate vs Rinsewater



Soil / Ground Water Remediation

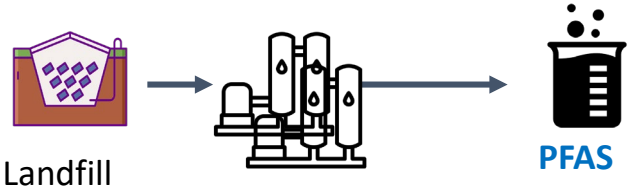
- High Volume
- Lower PFAS Concentrations
- In-Situ vs Ex-Situ

Drinking Water

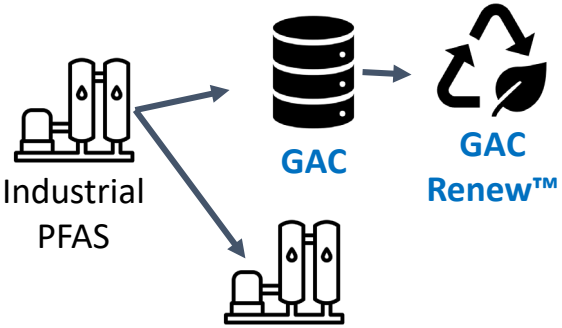
- Very High Volume
- Recurring - Continuous
- Low PFAS Conc
- Removal via GAC, RO

Current Commercial Application of SCWO

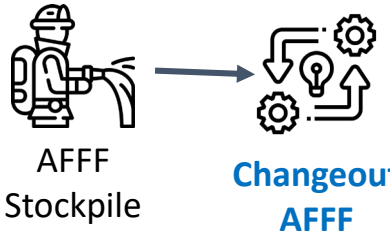
Landfill Leachate



Industrial Wastewater

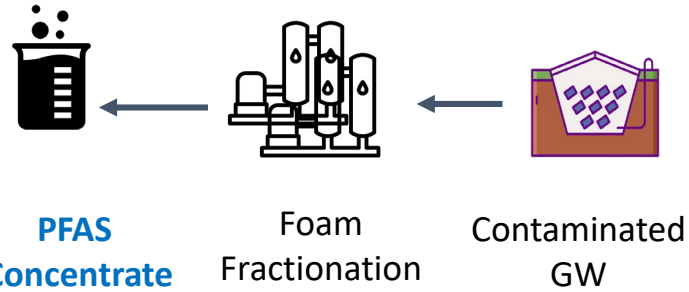


AFFF



Branch Network

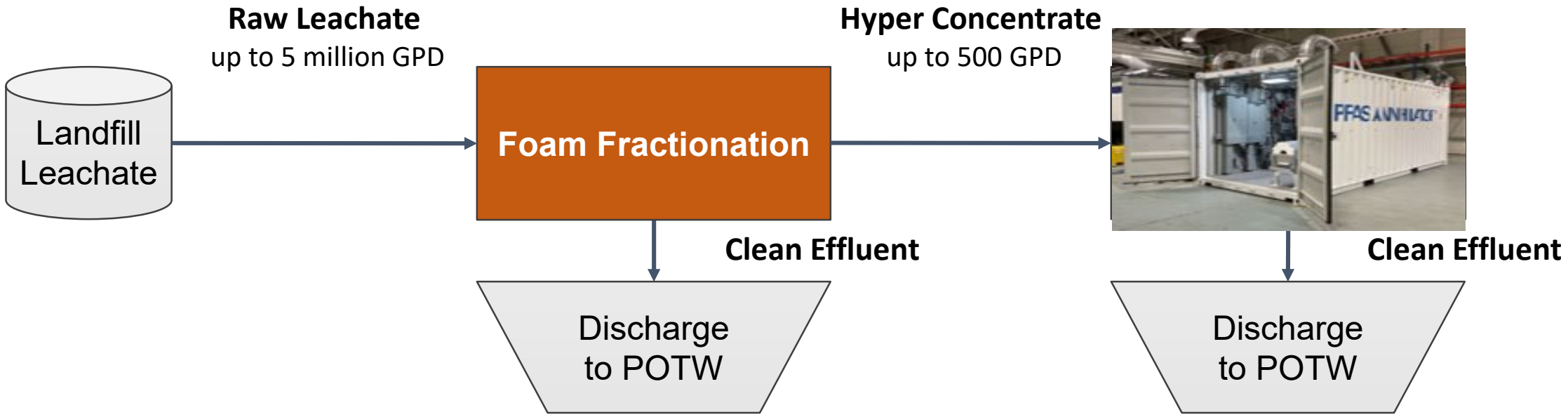
PFAS in Groundwater



Technologies Deployable by Revive

Technology Overview

Process Flow: Landfill Leachate via FF then SCWO



PFAS Separation + Concentration

Meet POTW Discharge Requirements

PFAS Destruction

Eliminate Liability

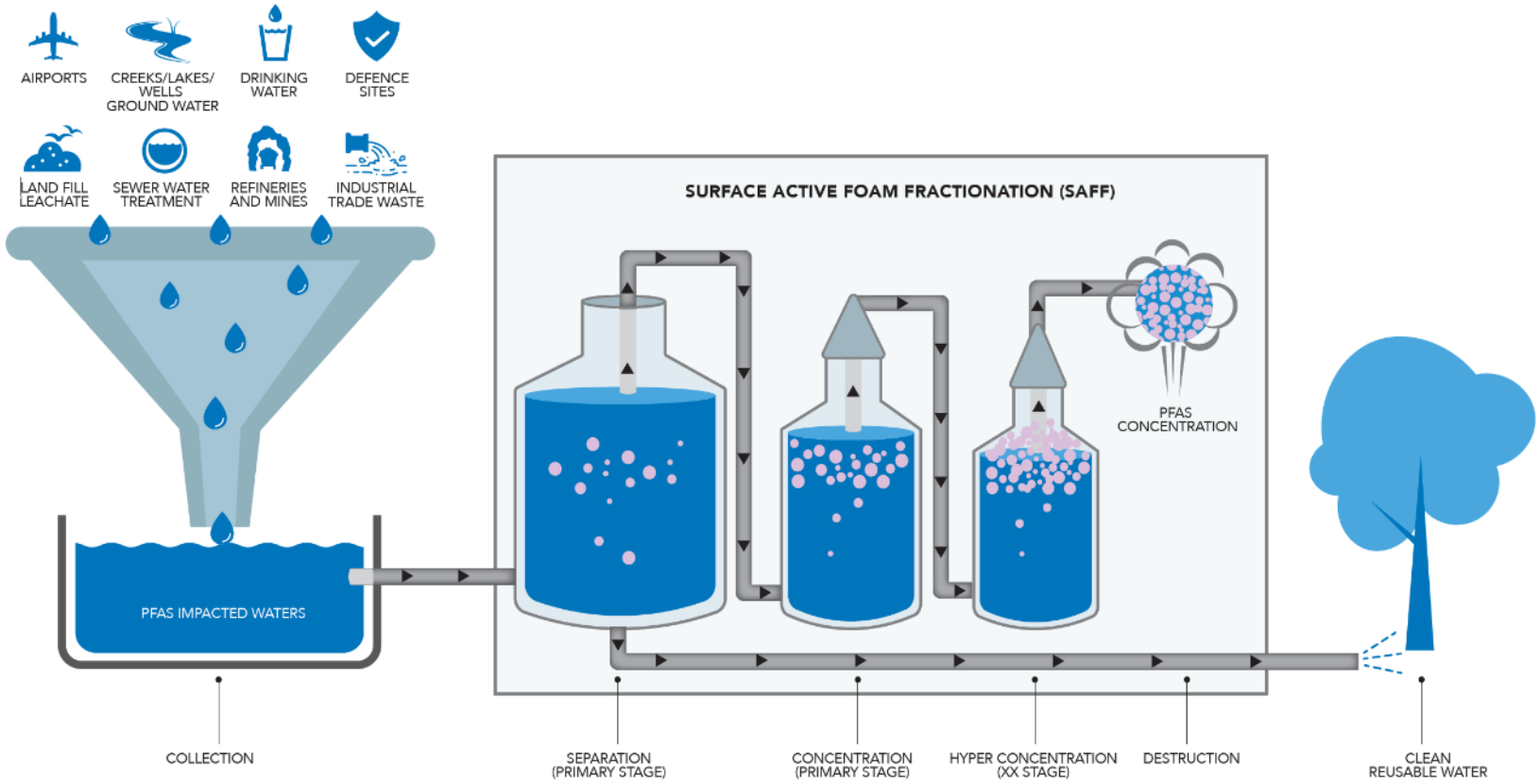
Chain of Custody
Batch receipt tied to analytical data and operating parameters

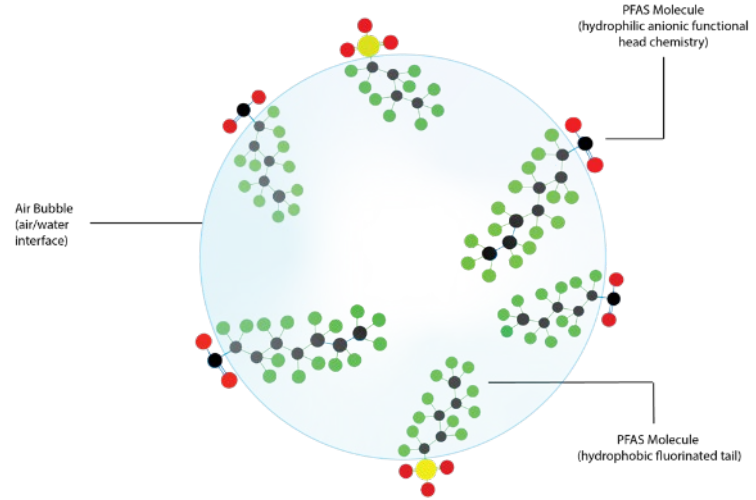
Influent, Effluent Testing
Regular sampling of all aqueous and vapor streams to ensure full destruction

PFAS destruction
Full combustion of all organic compounds incl. all PFAS analytes

No Harmful Byproducts
SCWO reaction results in clean water, nominal CO_2, and inert salts (e.g., NaF)

Foam Fractionation



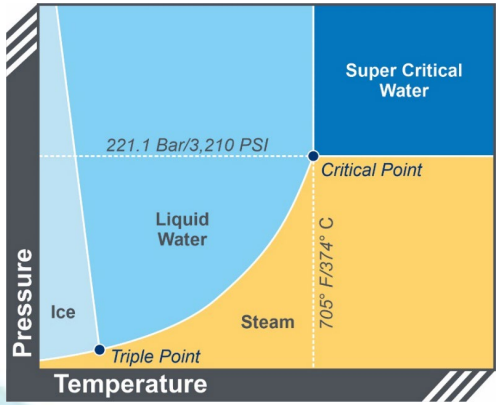


PFAS hydrophilic head and hydrophobic tail naturally adhere to air/water interface

Source: Allonnia

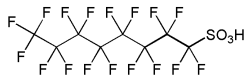
Supercritical Water Oxidation - PFAS Annihilator®

- **Fully permitted, commercial operations** in Wyoming, MI since March 2023
- **50K-150K gallons per day of raw leachate from 3 landfills**, then ran through Foam Fractionation with resulting concentrate destroyed via SCWO
- **Destroyed AFFF concentrate, AFFF rinsate** and other concentrated streams from other sources and applications



>99.99% Destruction: Long, Short, Ultra-Short analytes

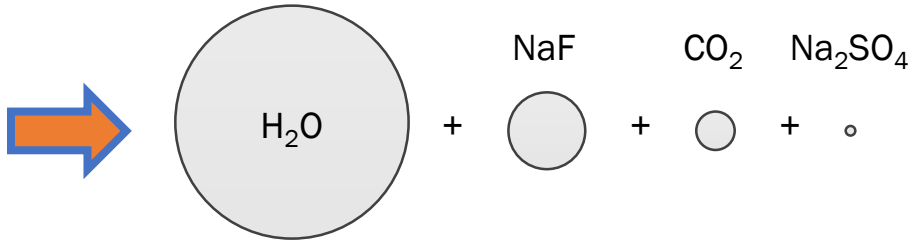
PFOA 

PFOS 

+ H_2O_2 (oxygen source)

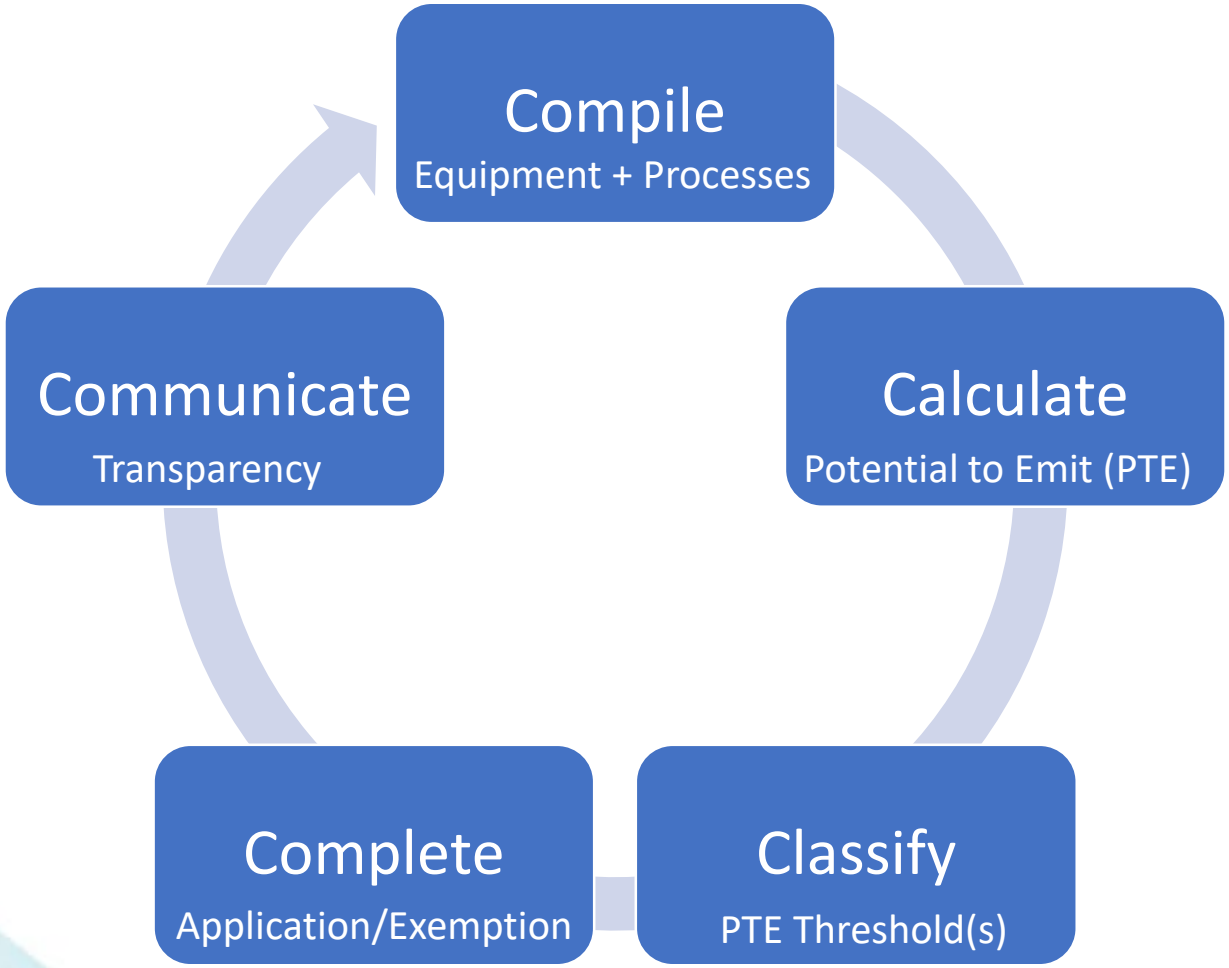
+ NaOH (Neutralization)

No harmful byproducts



Field Results and Lessons Learned from a Full-Scale Operation

Air Permitting



- EGLE (MI) exemption for air permit
  - PFAS Annihilator emits <5 lbs/day PTE's
- Transparent Monitoring
  - Initial Audit
  - Frequent proactive monitoring and reporting
- Innovation needed to sample air with low flow
- Most important = Execute the monitoring plan
- Communicate diligently

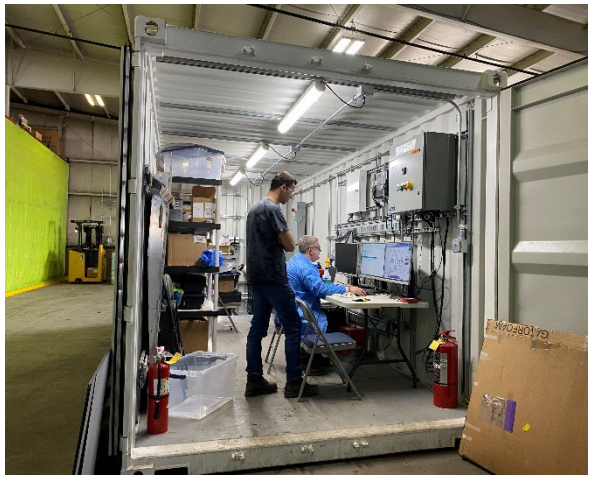
SCWO: Batch tracking, treatment and annihilation

Chain of Custody
Batch receipt tied to analytical data and operating parameters

PFAS Destruction
Full mineralization of all organic compounds incl. all PFAS analytes

Influent, Effluent Testing
Regular sampling of all aqueous and vapor streams to ensure full destruction

No Harmful Byproducts
SCWO reaction results in clean water, nominal CO_2, and inert salts (e.g., NaF)



- Power
- Water
- Shelter
- Footprint

Footprint: 40’ x 40’ for 2 CONEX boxes + equipment

Annihilator Operational Requirements

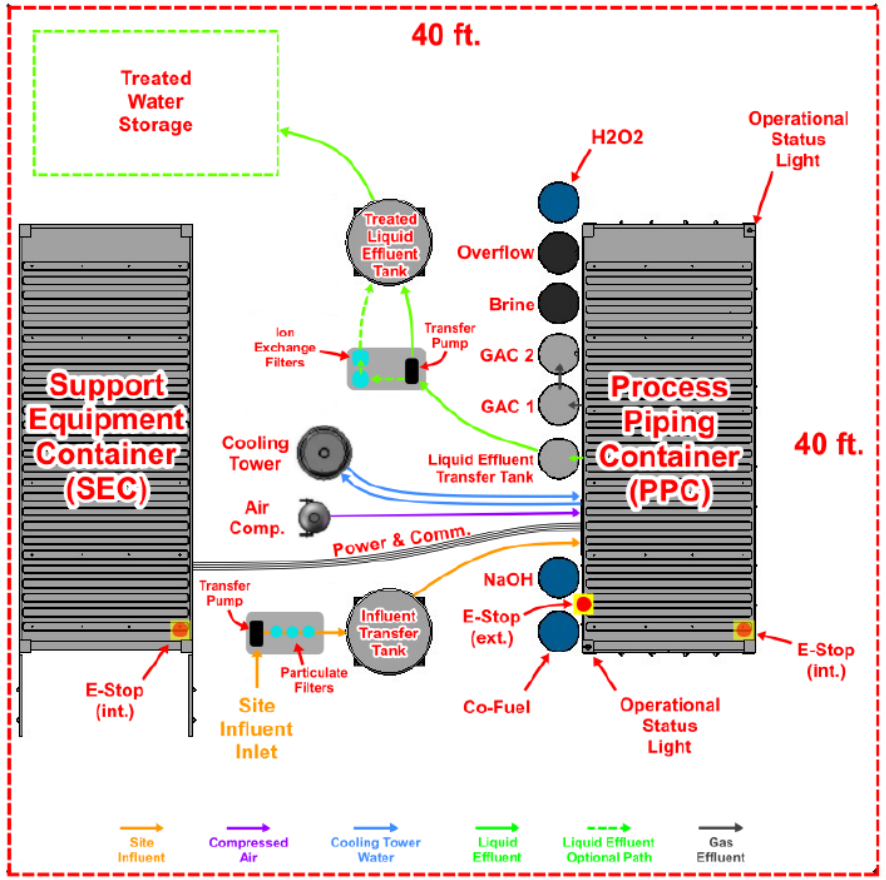


Figure 3. Typical M2 System Operational Configuration

- 40 ft x 40 ft x 12 ft
- Electrical – 480V, 3-phase, 100 A Service
- On-Site Water – 30 gph, >40 psi
- Operational Temp > 35 deg F
- Will require air and liquid discharge permit.
- Pad: Concrete or rock
- Winterization ready

Lessons Learned from Scaling Technology…

Lead with Safety

- Coordination critical with onsite partners
- Safe handling / Chain of custody

Quality Processes / Scale

- Batch tracking
- Local regulations compliance
- 500 GPD operational capability

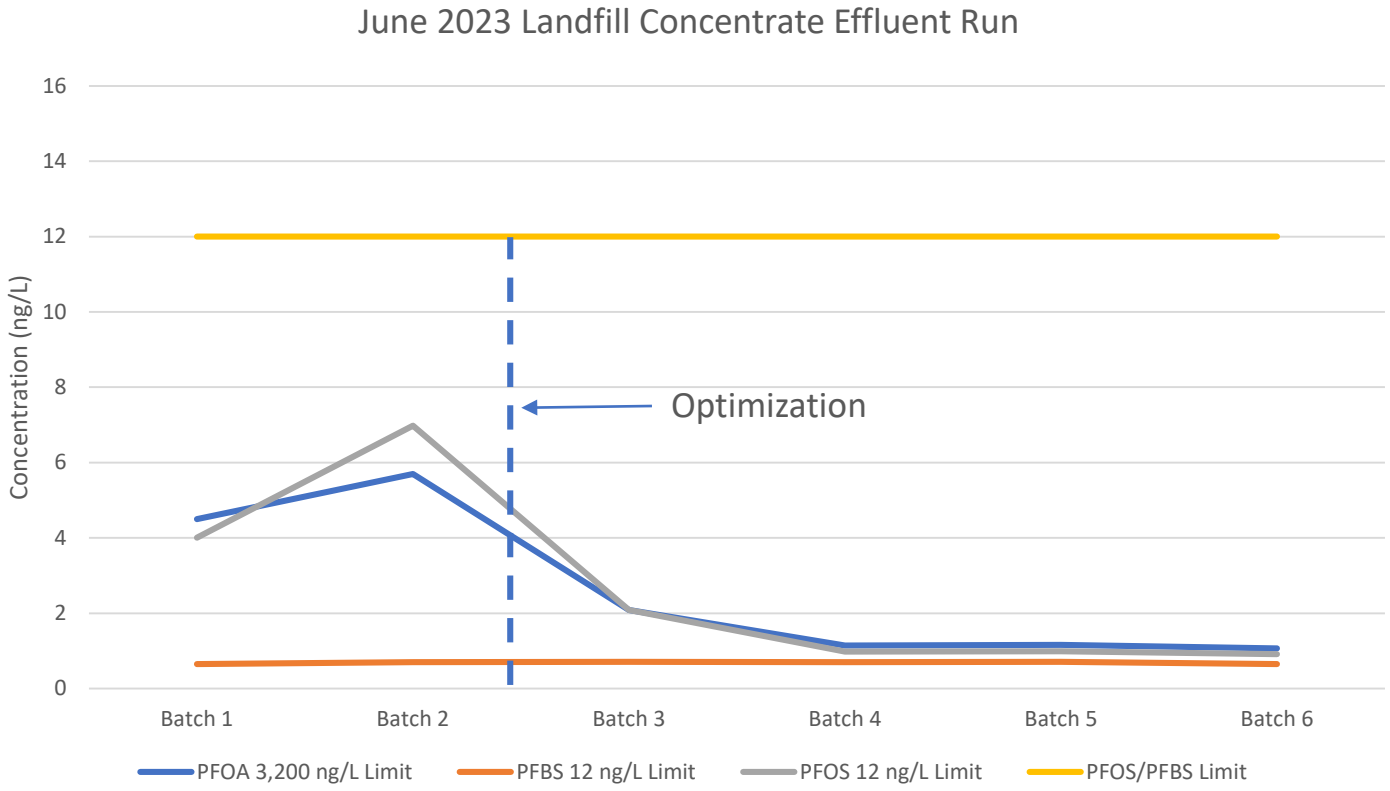
Regulatory Transparency

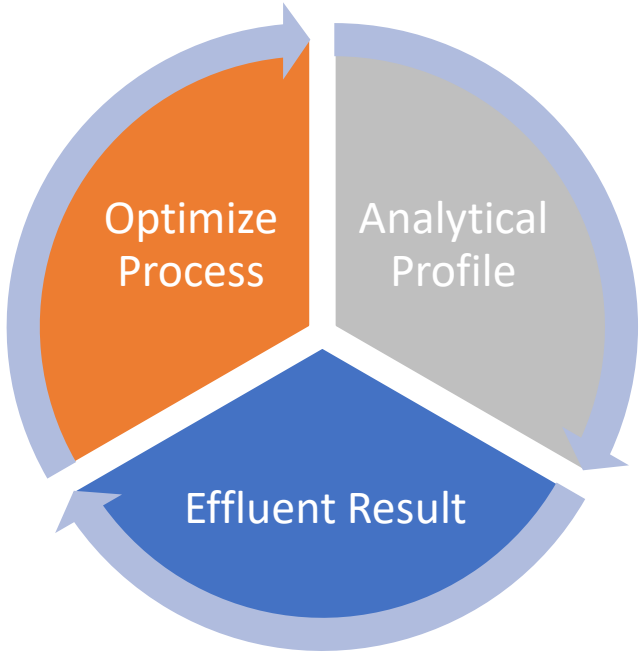
- Pre-deployment coordination
- Physical audit
- Ongoing sampling
- Water discharge limits

Infrastructure

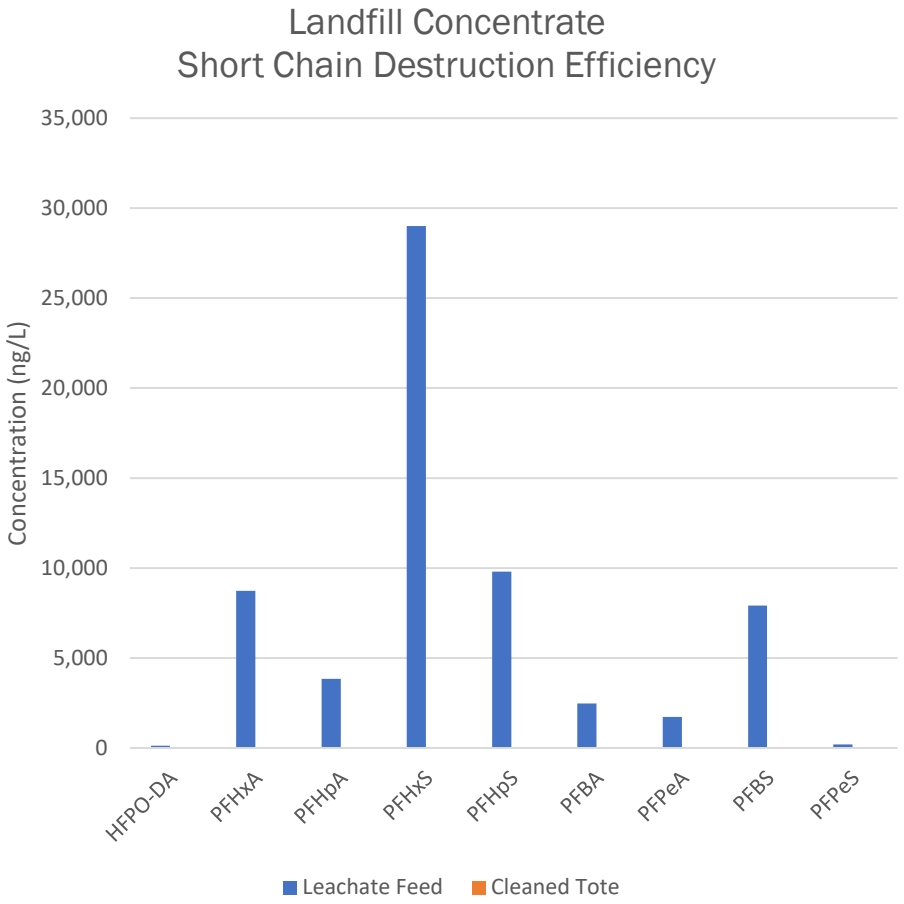
- People
- Supply Chain / Manufacturing
- Analytical Support Ecosystem

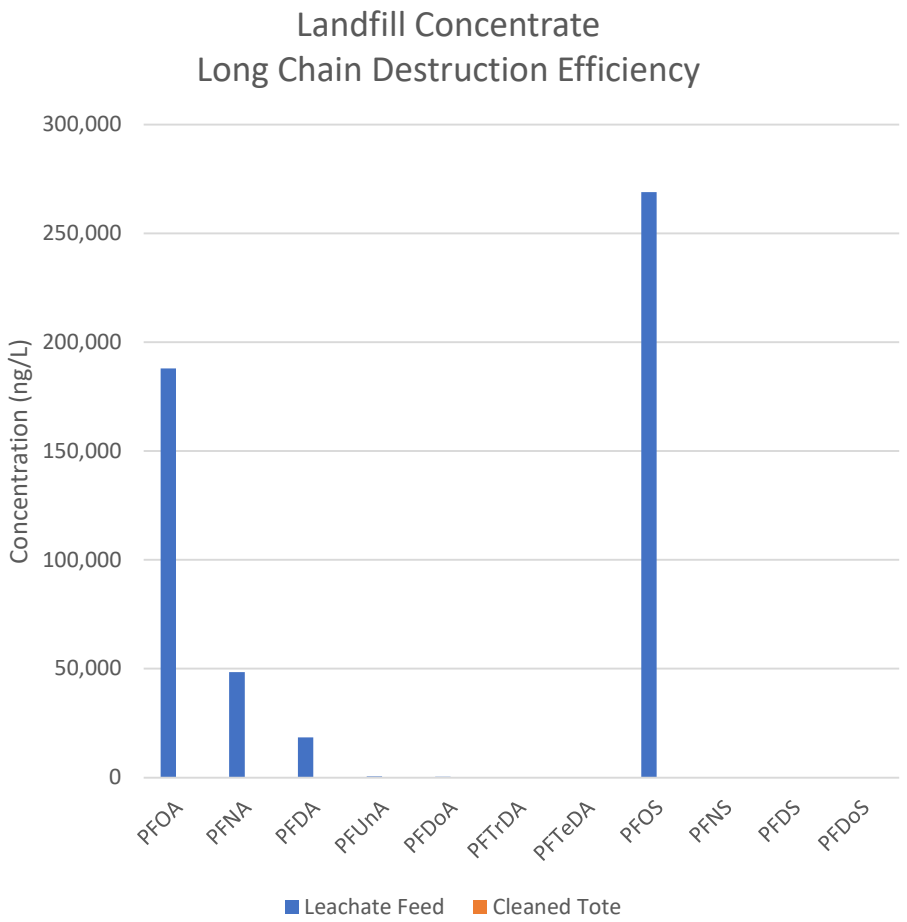
Dialing in the Operation





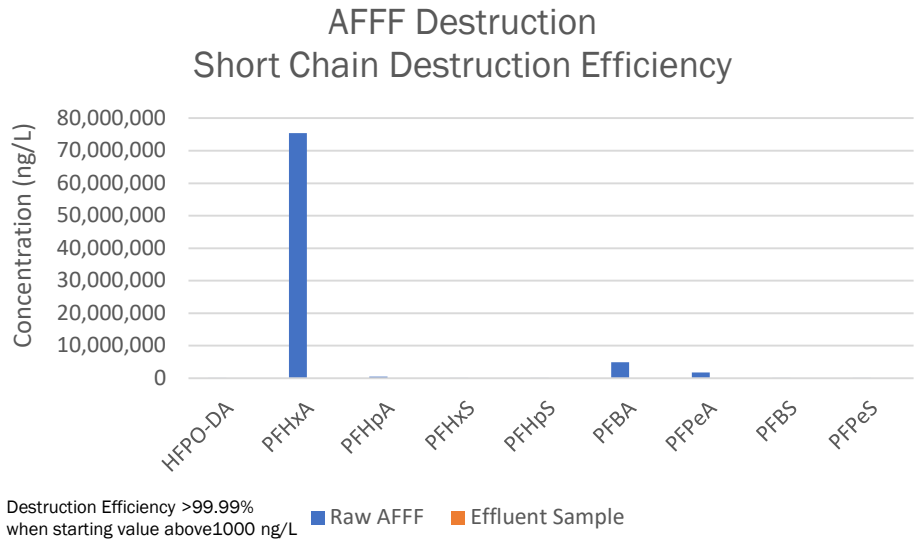
Landfill Leacahate – Short and Long Chain





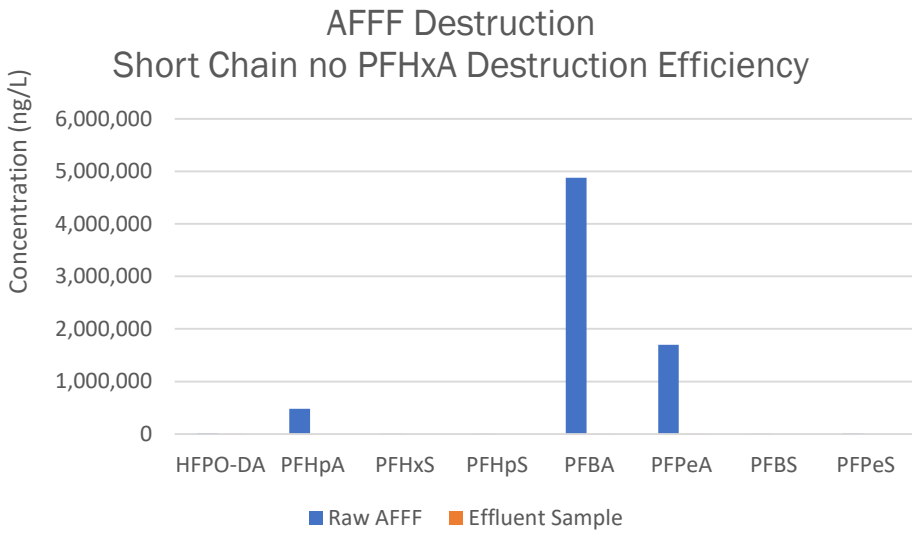
Destruction Efficiency >99.99%
when starting value above 2000 ng/L

AFF Destruction – Short and Long Chain



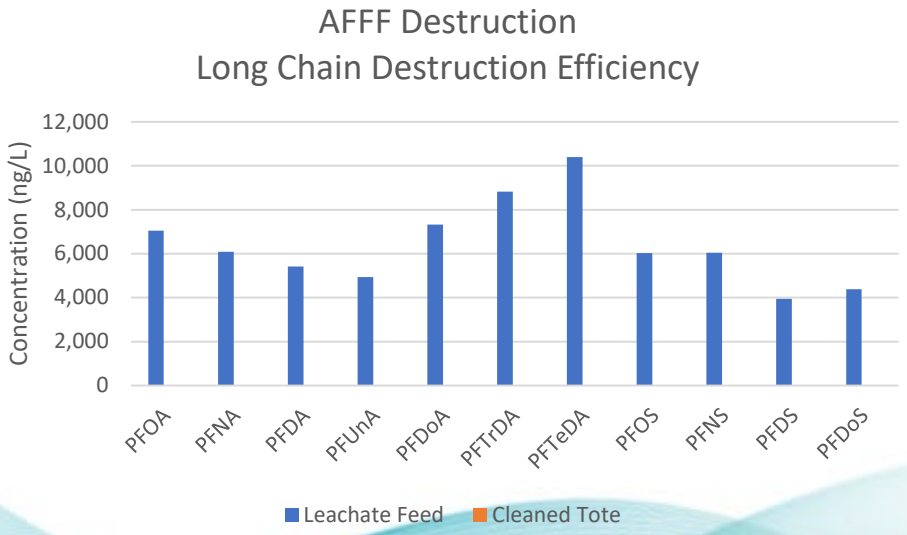
Destruction Efficiency >99.99%
when starting value above1000 ng/L

ANSULITE 6% AR-AFFF



Destruction Efficiency >99.99%
when starting value above1000 ng/L

ANSULITE 6% AR-AFFF



Destruction Efficiency >99.99%
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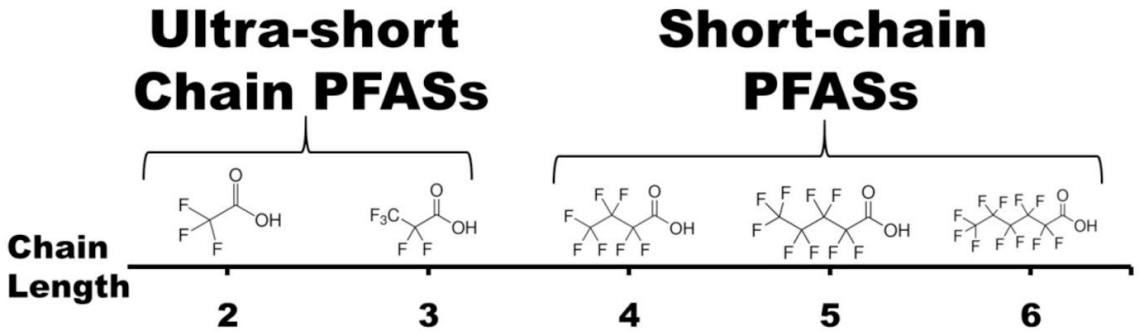

Destroys PFAS Regardless of Chain Length or Functional Groups

ANSULITE 6% AR-AFFF

			AFFF Production (ng/L)		
	Classification	More Information	Raw AFFF	Effluent Sample	% Destruction
PFBA	Carboxylic Acid	Short Chain	4,880,000	2.41	99.999%
PFPeA	Carboxylic Acid	Short Chain	1,700,000	2.27	99.997%
PFHxA	Carboxylic Acid	Short Chain	75,400,000	3.14	99.9999%
PFHpA	Carboxylic Acid	Short Chain	482,000	0.698	99.997%
PFOA	Carboxylic Acid	Long Chain	7,050	1.17	99.668%
PFNA	Carboxylic Acid	Long Chain	6,080	1.01	99.668%
PFDA	Carboxylic Acid	Long Chain	5,420	0.899	99.668%
PFUnA	Carboxylic Acid	Long Chain	4,930	0.819	99.668%
PFDoA	Carboxylic Acid	Long Chain	7,320	1.21	99.669%
PFBS	Sulfonic Acid	Short Chain	4,300	0.714	99.668%
PFPeS	Sulfonic Acid	Short Chain	13,100	0.52	99.921%
PFHxS	Sulfonic Acid	Short Chain	7,070	1.17	99.669%
PFHpS	Sulfonic Acid	Short Chain	4,960	0.823	99.668%
PFOS	Sulfonic Acid	Long Chain	6,030	1	99.668%
PFNS	Sulfonic Acid	Long Chain	6,050	1	99.669%
8:2FTS	Fluorotelomer	Fluorotelomer	22,300	3.69	99.669%
PFDS	Sulfonic Acid	Long Chain	3,940	0.653	99.669%
PFDoS	Sulfonic Acid	Long Chain	4,380	0.726	99.668%
4:2FTS	Fluorotelomer	Fluorotelomer	1,680,000	5.32	99.994%
6:2FTS	Fluorotelomer	Fluorotelomer	188,000,000	22.4	100.000%
PFTrDA	Carboxylic Acid	Long Chain	8,820	1.46	99.669%
PFTeDA	Carboxylic Acid	Long Chain	10,400	1.73	99.667%
PFOSA	Carboxylic Acid	Fluorotelomer	4,570	0.758	99.668%

- PFAS Annihilator™is the first to market for PFAS treatment.
  - Multiple landfill leachate projects
  - Multiple DoD Projects
  - AFFF State-Take-Back Programs
  - AFFF Foam Transition Projects
    - Oil and Gas
    - Chemical/Mfg Facilities
- Revive’s platform delivers consistent, industry leading PFAS Destruction
- Recognize Battelle, Allonnia, HCC, Michigan EGLE, and the City of Wyoming


PFAS ANNIHILATOR™
Questions