“What a Waste!” The Role of Innovative PFAS Treatment Technologies for Managing PFAS Waste from Water Treatment Systems

Wednesday June 5, 2024, Battelle Chlorinated Conference

Baxter Miatke, P.E.

Agenda

1. PFAS Water Treatment Technologies
2. Foam Fractionation PFAS Treatment
3. Foam Fractionation Testing Process
4. Foam Frac Case Study
5. “What a Waste!”

PFAS Water Treatment Technologies

ARCADIS

PFAS water treatment

PFAS IDW Management

Water Treatment Technologies

Sorbent Media

Separation Concentrates

Destruction Options

Plasma, SCWO, Thermal, etc.

Residuals?

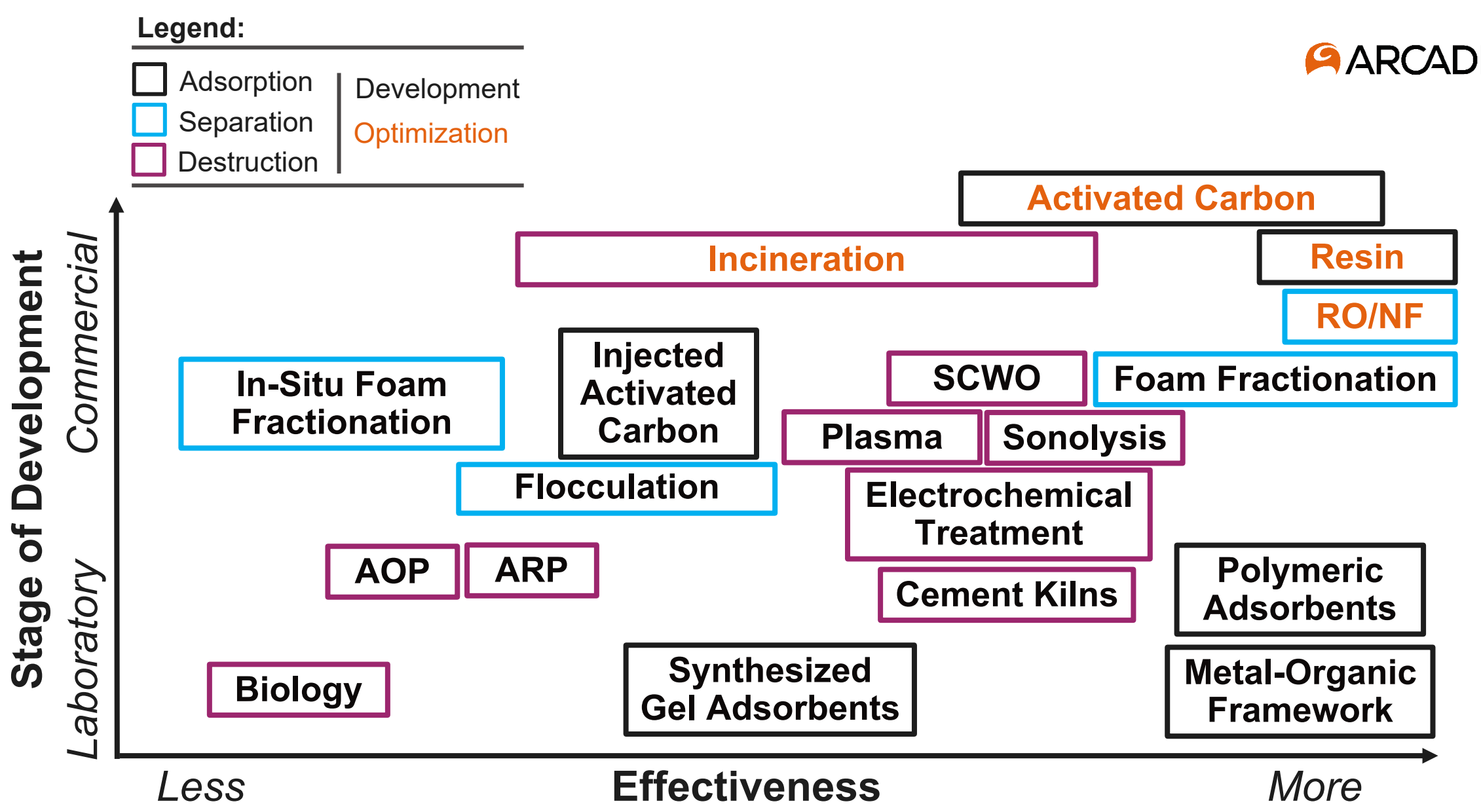
Disposal Options

Landfill, Deep Well Injection, etc.

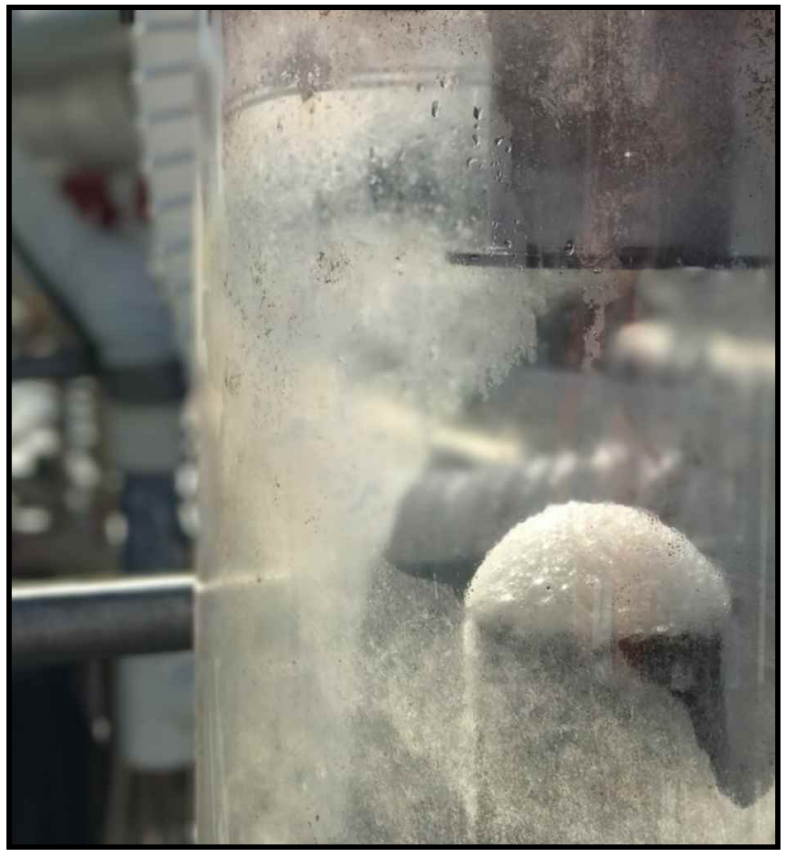
Future Risk?

PFAS Treatment Technologies for *Liquids*

Adsorption	Separation / Concentration	Destruction	
Granular Activated Carbon (GAC)	Foam Fractionation (FF)	Incineration	Cement Kilns
Anion Exchange Resin (AIX)	Reverse Osmosis (RO)	Supercritical Water Oxidation (SCWO)	Plasma
Polymeric Adsorbents	Nano Filtration (NF)	Photo/ Electrochemical	Hydrothermal Alkaline Treatment (HALT)
Metal Organic Frameworks	Flocculation	Sonolysis	Advanced Oxidation Processes (AOPs)



Foam Fractionation for PFAS Treatment



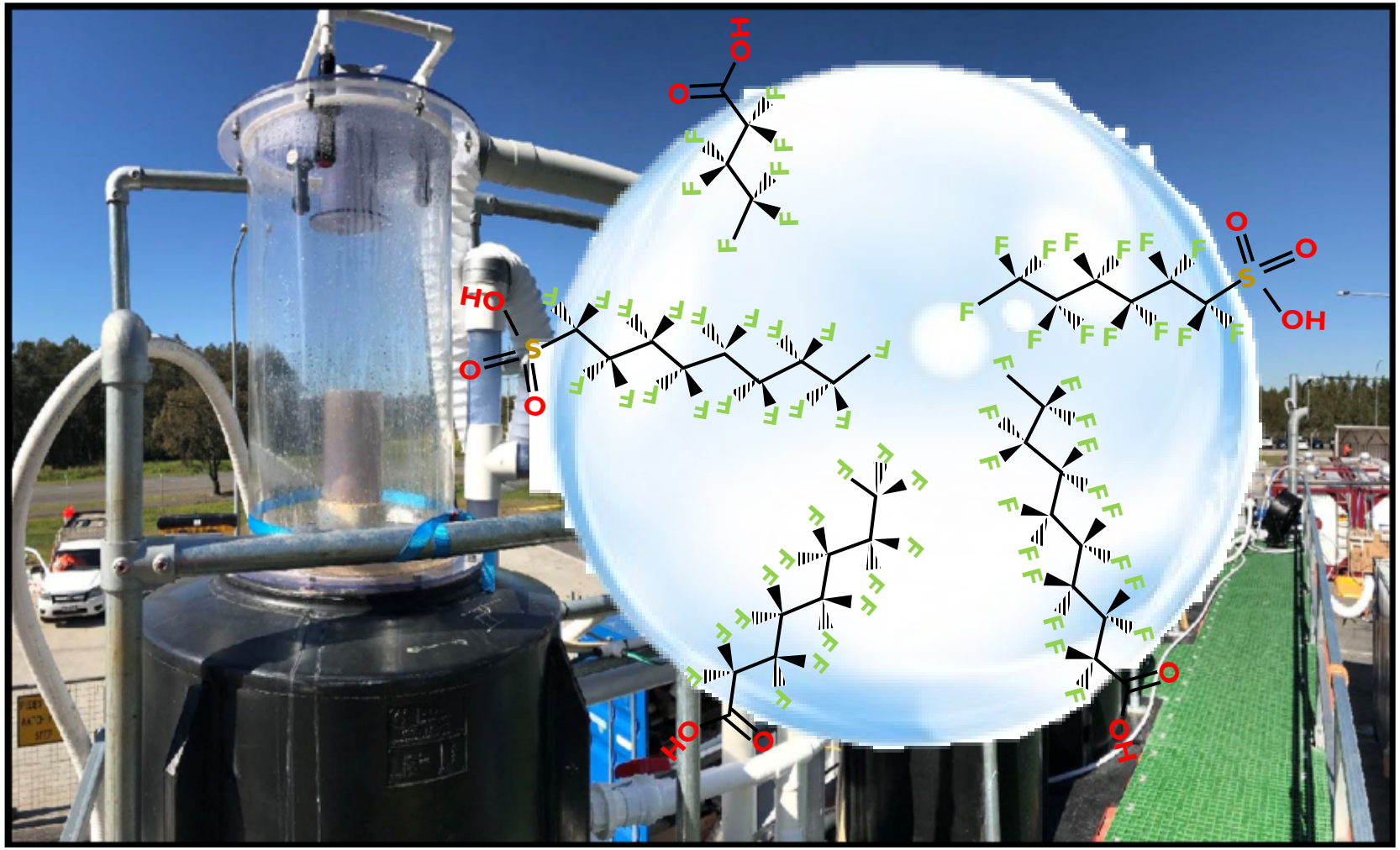
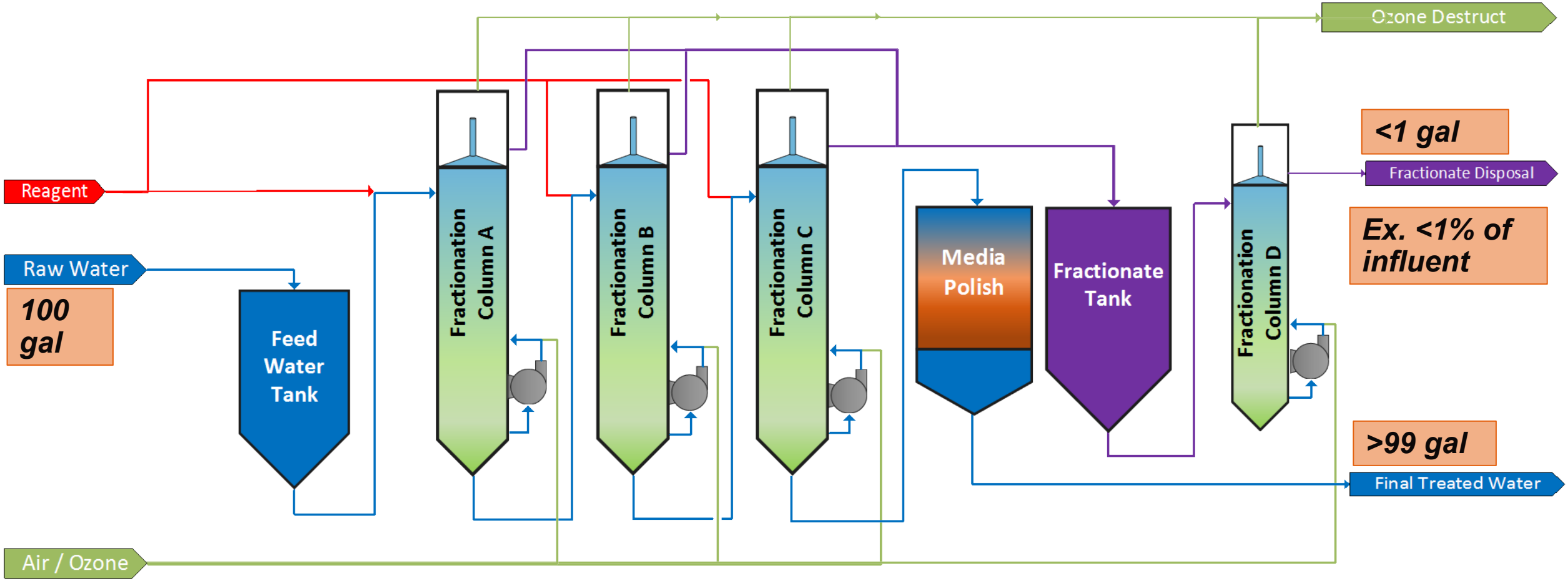


Photo Source: Evocra 2017, Australia

Foam Fractionation Treatment Process



Foam Fractionation for PFAS Treatment

- Foam Fractionation ≠ Froth Flotation
- Froth Flotation refers more to the removal of particulate materials by bubbling
- Foam fractionation indicates the foaming of dissolved materials by **adsorption** on the bubble surfaces
- Goal is to increase the available surface area for the PFAS to attract to the bubble interface
- Operating in a continuous stripper mode to minimize foam waste product and optimize operation

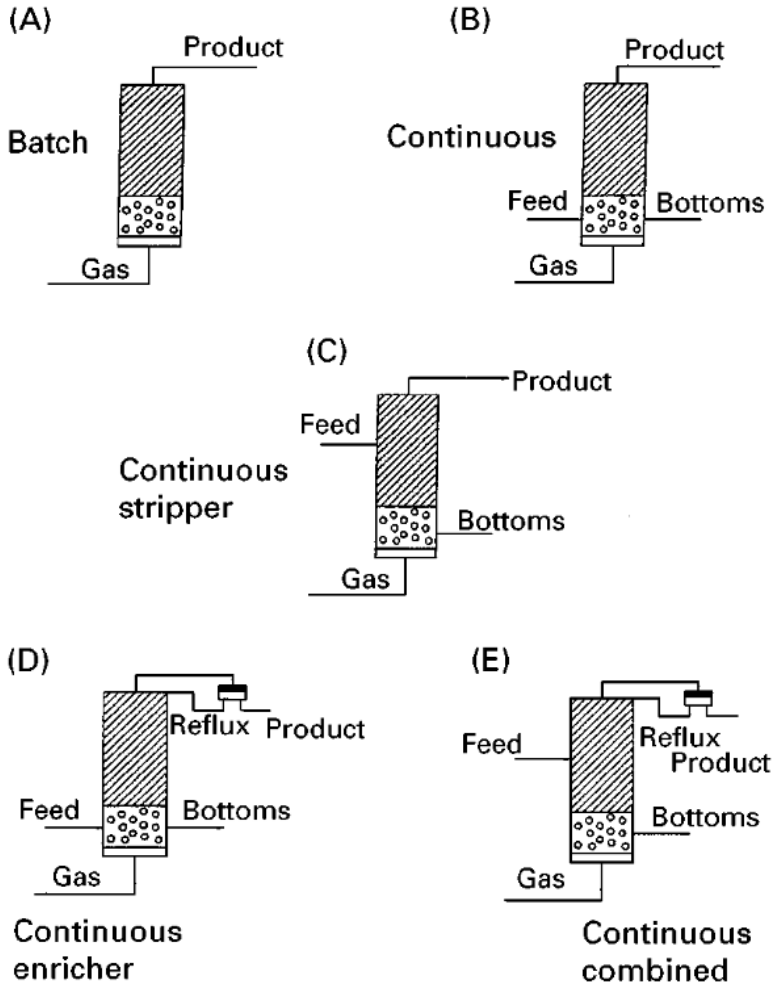


Figure 1 Different modes of operation of a foam fractionation column.

G. Narsimhan, Purdue University, West Lafayette, IN, USA

Foam Fractionation for PFAS Treatment

- Venturi inducts gas in foam fractionation
- Very high contact between gas/liquid, especially at the gas injection point on the venturi
- Formation of finer bubbles than possible from other technologies
- Vacuum- simple operation / maintenance

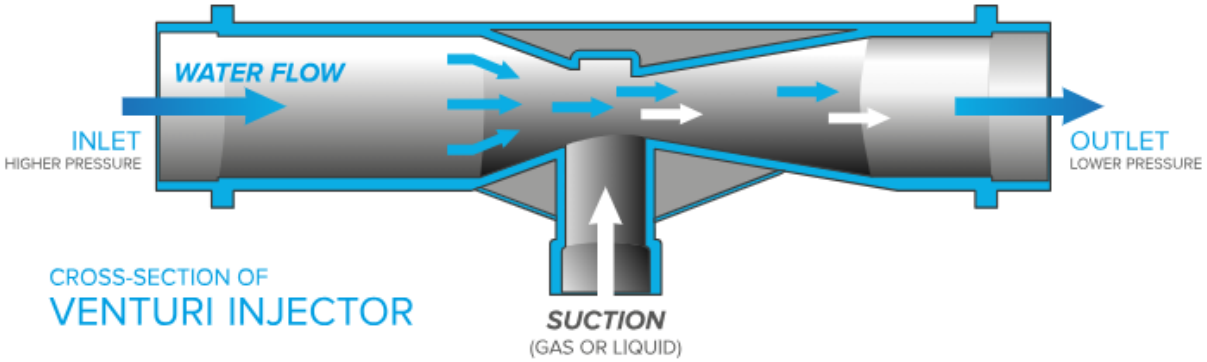
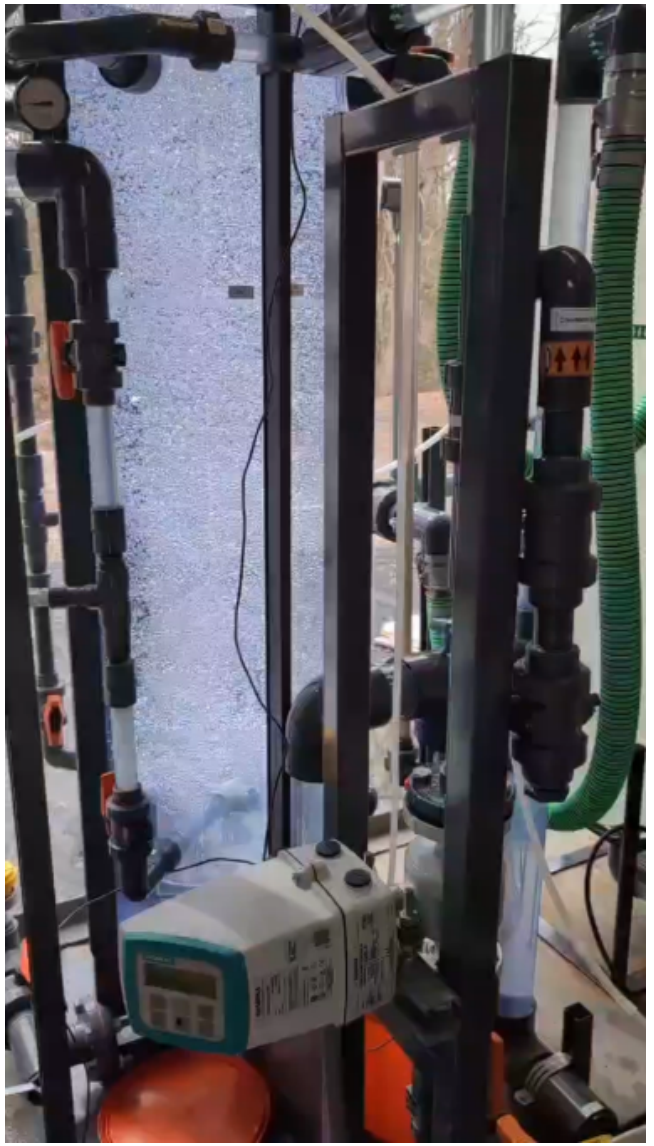


Photo Source: Mazzei Venturi

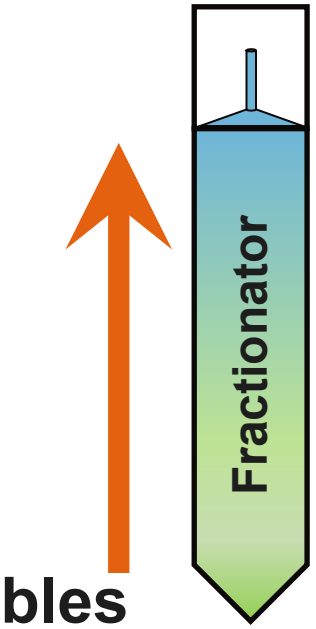


Clean Water Testing- Arcadis

Foam Fractionation Gases

- Foam fractionation uses tiny bubbles injected via a venturi to separate PFAS from the aqueous solution
- Ozone can create micro-nano-bubbles (MNBs) ranging from 10s nm to 10s µm
- MNBs can increase bubble quantity and **available surface area** for treatment
- Ozone bubbles may have a high zeta potential which lessens bubble coalescence and **improves stability**

Typical Bubbles



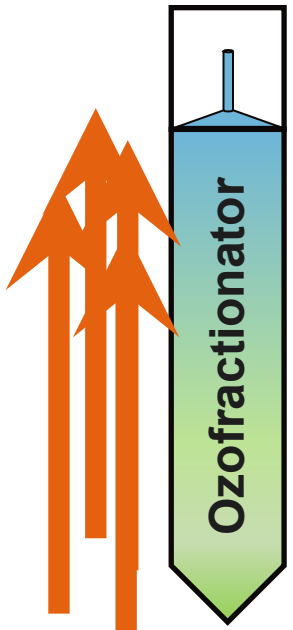
2.1×10^6 bubbles/100 gal

3,400 ft^2/100 gal

>28,000,000% surface area increase, less incidence of coalescence; more stability

247 nm

MNBs



4.8×10^{22} bubbles/100 gal

9.9×10^8 ft^2/100 gal

After (Hu and Xia 2018)

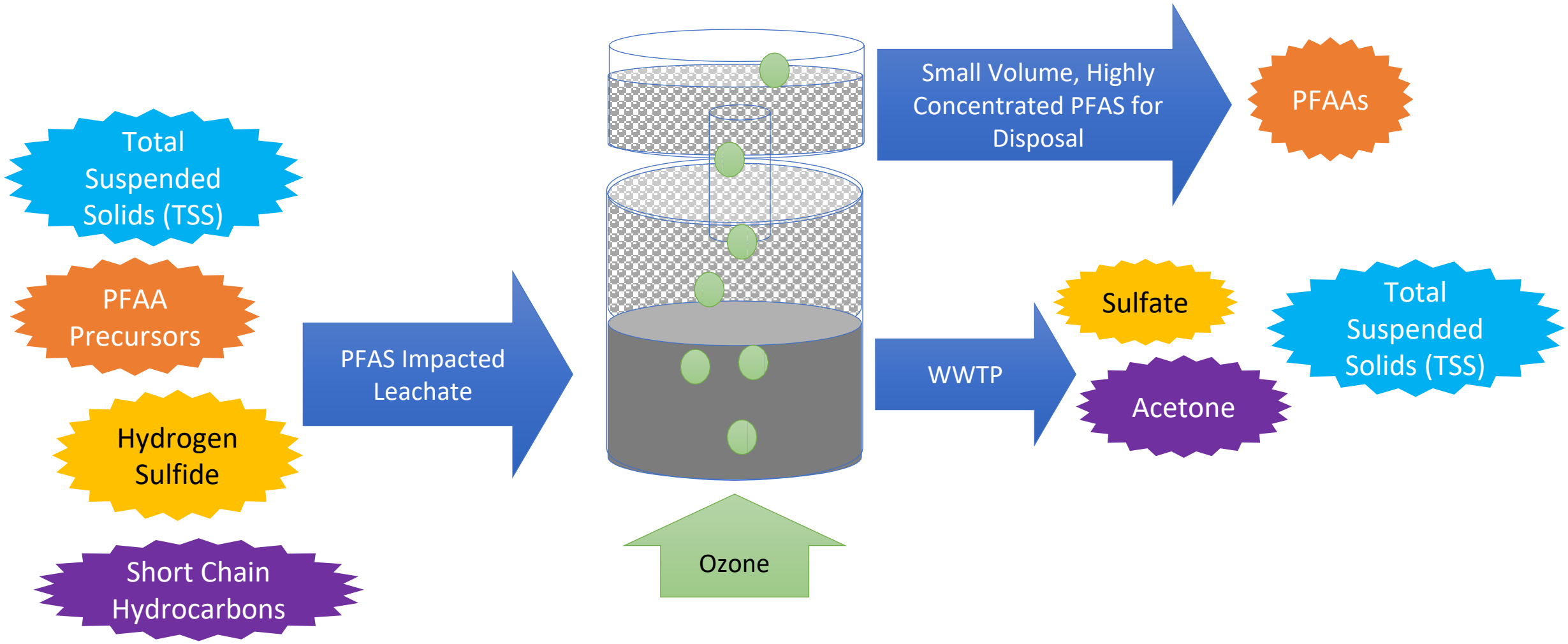
Foam Fractionation Gases

- Optimized concentrations through rigorous testing and trials
- Lower risk of ultra-short chain PFAS
- Maximize waste removal effectiveness with lower volumes

(Arcadis)

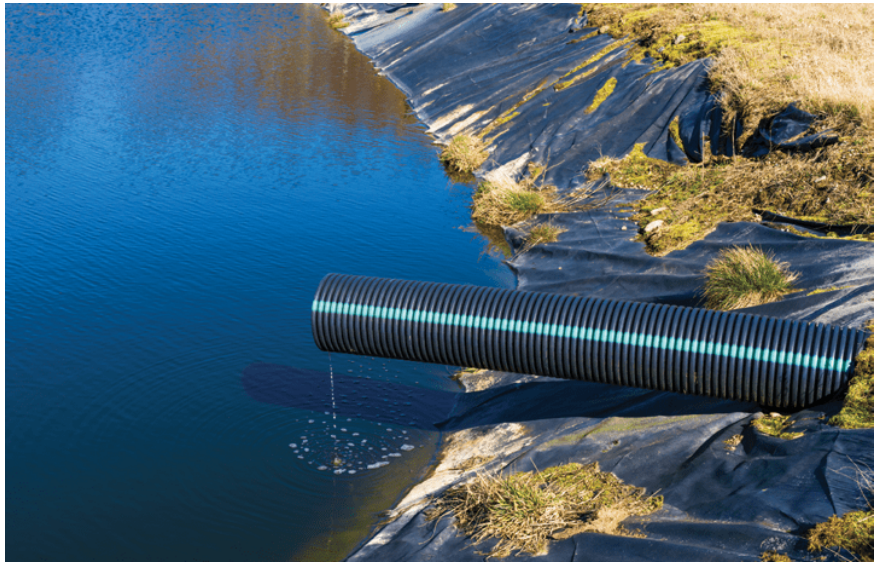
"Ozonated air fractionation showed the best PFAS removal efficiency, which was more than 95%, as a result of the enriched OH radicals in the gas bubbles." Comparative study of PFAS treatment by UV, UV/ozone, and fractionations with air and ozonated air (Dai et. al 2019)

Ozone Oxidation During Foam Fractionation



Foam Fractionation Target Sources

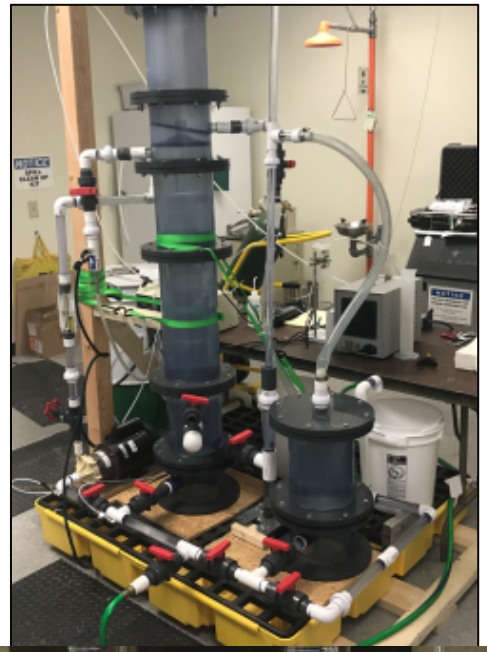
- Targeted high concentration waste with high organic co-contaminants
  - Industrial Wastewater Treatment Plants
  - Municipal Wastewater Treatment Plants
  - AFFF Impacted Source Zones (spills, groundwater)
  - Landfill Leachate (Robey et. al 2020, McCleaf et. al 2021)
  - Water treatment receiving facilities of variable sources
- Applied to groundwater with limited success requiring additional foaming agents or reagents to be added to promote foaming
- Drinking water not typically targeted, but RO reject from drinking water plants being piloted now

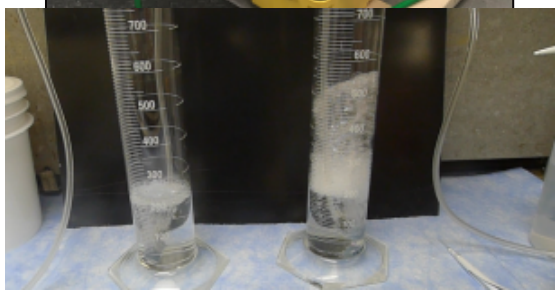


(Adobe Stock Photo)

System Design Steps

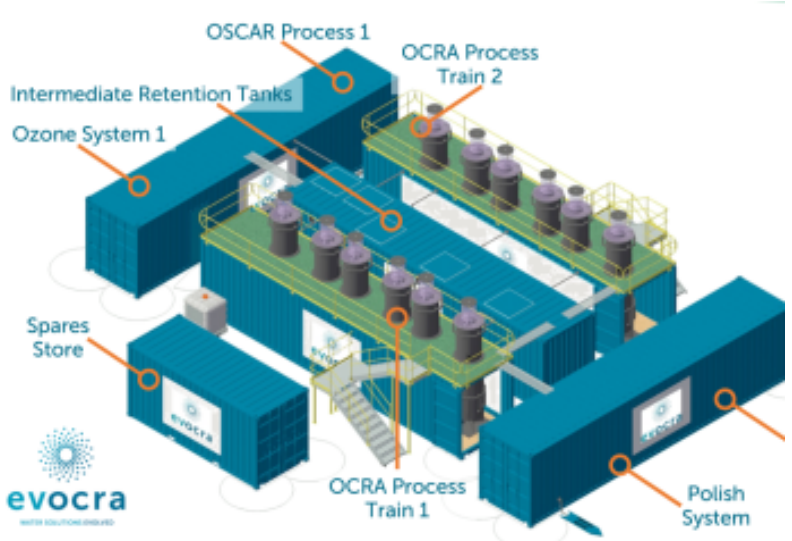
Bench Scale Testing





Pilot Scale Testing

Full System Design



Pilot-Scale Testing

Project Name	Matrix	Client and Location	Year	Type
County Wide Landfill (CWLF) Leachate Treatment Evaluation, Testing and Design	Superfund Site Landfill Leachate	Michigan EGLE Gibraltar, Michigan	2020	Bench
			2021	Pilot
			In Progress	Full Scale
Landfill Leachate Foam Fractionation Testing	Commercial Landfill Leachate	Confidential Solid Waste Company, New Hampshire	2021	Bench
Landfill Leachate Collection Facility Foam Fractionation Testing	Commercial Landfill Leachate	Confidential Solid Waste Company, Michigan	2023	Bench
			2023	Pilot
Industrial Landfill Leachate Characterization and Foam Fractionation Bench-Scale Testing	Industrial Private Landfill Leachate	Industrial Confidential Client, Alabama	2021	Bench
Industrial Wastewater with AFFF Foam Fractionation Testing	Industrial Wastewater/ AFFF	Industrial Confidential Client, Wisconsin	2019	Bench
			2020	Pilot
Industrial Wastewater RO Reject Foam Fractionation Testing	Industrial Wastewater RO Reject	Industrial Confidential Client, Illinois	2020	Bench
ESTCP Fire Decontamination Cleaning Agent Foam Fractionation Testing	PFAS Cleaning Agent	ESTCP, Pennsylvania	2022	Bench
Groundwater with AFFF Foam Fractionation Testing	AFFF Impacted Groundwater	Navy BAA, Pennsylvania	2023	Bench
			2023	Pilot
Drinking Water Plant Reverse Osmosis Reject Foam Fractionation Testing	Drinking Water RO Reject	Drinking Water Plant, Alabama	2023	Bench
			In Progress	Pilot
Arcadis Australia				
New Chum Landfill Leachate Trial	Landfill Leachate	Industrial Confidential, Queensland	2021	Pilot
			2022	Full Scale
Qantas Wastewater Treatment	Industrial Wastewater	Brisbane Airport, Queensland	2018	Full Scale
Fire Training Area Runoff Treatment	AFFF/ Sewer/ Combined Waste	Hobart Airport, Tasmania	2020	Full Scale
Campbellfield Industrial Wastewater Treatment	Industrial Wastewater	Industrial Confidential, Victoria	2021	Bench
			In Progress	Full Scale
Rutherford Sour Water Treatment Trial	Industrial Wastewater	Industrial Confidential, New South Wales	2021	Bench

Foam Fractionation Pilot Test 2023 (Landfill Leachate mixed w/ GW)

	Air 1-Air 2			Ozone 1-Air 2		
PFAS (ng/l)	Influent	Effluent	% Removal	Influent	Effluent	% Removal
PFOA	1,250	40	97%	1,564	44	97%
PFOS	38,511	288	99.3%	42,983	209	99.5%
PFNA	10,573	73	99.3%	13,689	49	99.6%
PFHxS	13,493	1,159	91%	14,909	807	95%
PFHpA	900	193	79%	875	151	83%
PFDA	438	8	98.2%	425	<5	98.8%
Sum 6	**65,165**	**1,761**	**97.3%**	**74,445**	**1,260**	**98.3%**
Volume Treated (gal)	1,708			1,668		
Foam Produced (gal)	10			5		
% Foam	0.6%			0.3%		

Foam Fractionation Expected Performance

PFAS (ng/l)	% Removal	
	Typical	Conservative
PFOA	99%	96%
PFOS	99%	96%
PFNA	98%	95%
PFHxS	97%	93%
PFHpA	81%	70%
PFDA	98%	96%
Sum6	95%	91%

*Based on Landfill Leachate mixed w/ GW 2023 pilot test performed by Arcadis (9/25-10/13). Percent removal varies significantly based on source, PFAS concentrations, surfactant load, hydraulic residence time, and foaming characteristics.

“What a Waste!”

Foam Fractionation Waste Residuals

- Low Volume
  - <1% by volume or less with subsequent processing
  - 100's of gallons per day
- High PFAS concentration
  - Influent ppt levels can concentrate into ppm level foam fractionate
- Potential for significant cost savings in disposal volumes and feasible for destruction technologies
  - E.g. Recent quote in winter 2023 was $2.24/gal to $2.92/gal for foam fractionation and destruction
- Vendors developing/offering complete destruction options coupled with FF (i.e. plasma, electrochemical, etc.)

PFAS Destruction and Disposal Options Per EPA

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Interim Storage

Underground Injection

Permitted Landfills

Thermal Treatment

As per EPA Interim Guidance on the Destruction and Disposal of Perfluoroalkyl and Polyfluoroalkyl Substances and Materials Containing Perfluoroalkyl and Polyfluoroalkyl Substances (April 2024)

Other PFAS Waste Destruction Options

- Supercritical Water Oxidation
- Photochemical
- Hydrothermal Alkaline Treatment
- Sonolysis
- Electrochemical
- Plasma

Destruction may offer lower long-term liability compared to other disposal options

CONCLUSIONS

- Foam Fractionation is an innovative PFAS treatment technology to be considered as part of a treatment train approach.
- Commercialization is increasing in the U.S. with full-scale system construction in progress.
- Ozone may improve treatment and have additional benefits in the foam fractionation PFAS treatment process.
- PFAS destruction technology advancement can provide the final step in destruction of foam fractionate concentrate waste residuals

Arcadis PFAS Solutions

PFAS?

Destruction?

Treatment?

Disposal?

PFAS Regulatory Tracking

Per- and polyfluoroalkyl substances (PFAS) a
of manufactured chemicals used in an array
commercial, and consumer products. The dy
of the PFAS regulatory environment present
for those trying to stay up to date on current
environmental regulations.

In the absence of U.S. federal numerical standards for PFAS in environmental media, many states have independently set guidance and standards, while others are just beginning the process. This has resulted in a patchwork of PFAS standards across the U.S. When taken together with evolving global regulations and numerical criteria, staying apprised of the current status of PFAS regulations requires an updated and organized tracking system.

The PFAS Regulatory Tracker

Arcadis maintains a web-based dashboard that tracks current and proposed PFAS guidance and regulations. Clients can access customized dashboards and sort information to view regulations pertaining to a specific state, PFAS compound, or environmental medium.

We are currently trac
regulations for:

- drinking water
- groundwater
- surface water
- soil

**Customizable Da
Meet Client Need**

Dashboards can be ta
specific client needs. F
dashboard customizat

- Updating at a clien
frequency (e.g., mo
- Adding regulations
international locati
- Tracking other type
(e.g., emissions inve
stewardship regula
- Developing helpful
(e.g., bar charts cor
regulations across

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Proactively Assessing Risk: The PFAS Vulnerability Tool

Poly- and Perfluorinated alkyl substanc
are a group of manufactured chemicals
an array of industrial, commercial and c
products. A growing number of state a
requiring that facilities evaluate whethe
are present, which can lead to site inves
remediation, and increased costs and t

Understanding nearby PFAS releases and impacts to drinking water supplies are important factors in understanding a site's vulnerability to upgradient impacts and regulatory scrutiny. Further, insight into a site's environmental setting can help rank sites within a broader portfolio to identify the most critical sites, in terms of risk and potential liabilities. Arcadis has developed a digital tool to assess PFAS vulnerability at individual sites/facilities and evaluate risks within a broader portfolio of sites. Forward-thinking companies are pro-actively assessing their PFAS risks to improve their ability to advocate their risk position.

compare and
of sites can g
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management
you minimize
and enforcem
your budget
geographic in
PFAS vulnera
publicly avail
specific data
framework th
prioritize sites
detailed evalu
vulnerability
which can the
prioritize sites
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environmenta

The PVT is th
development
PFAS manage
to integrate s
known or sus
sources. Data

The PFAS Vulnerability Tool

In a world where such uncertainties still exist, knowledge is power. Staying informed of the potential PFAS impacts and sensitive receptors in and around your site and having the ability to

Assessing PFAS Emissions in Ambient Air

PFAS in air emissions are receivin
attention. A range of industrial a
are being asked to assess potenti
drivers have previously focused l
groundwater and drinking water,
air quality, surface water and sed
potentially related fate and trans
now being considered as well.

Stack Testing of PFAS Emissions

Arcadis has completed PFAS emissions assessments on multiple projects and has implemented USEPA stack testing methodologies, including OTM-45, to quantify PFAS emissions from stacks. To successfully measure low-level PFAS emissions in the stack, field procedures are carefully performed to minimize background contamination and properly handle samples. In-stack reporting limits are in the nanogram per cubic meter (ng/m3) range or parts per trillion levels in gas. Mass emission rates (g/yr) are eight orders of magnitude lower than typically observed for other potential air contaminants such as pesticides and dioxins/furans.

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PFAS Cleaning for Fire Suppression Equipment & Systems

A dynamic regulatory environment has motivated foam users to transition from foams containing PFAS (C8/C6) AFFF to fluorine-free firefighting foams, now widely available and used for effective fire protection.

Contaminant Risk

Per- and polyfluoroalkyl substances (PFAS) adhere to fire suppression system surfaces in contact with aqueous film forming foams (AFFF) containing C8/C6 PFAS to form water resistant layers in foam systems. Replacing existing AFFF in foam equipment and suppression systems requires removal of residual PFAS because these compounds can rebound into replacement fluorine free firefighting (FFF) foams causing contamination and a risk of continued environmental liability.

A Successful, Biodegradable Solution

Arcadis developed an effective biodegradable cleaning agent (FluoroFighter™) to remove PFAS buildup in fire suppression systems previously containing C8/C6 AFFF. This, in conjunction with Arcadis' proven procedure for PFAS cleaning applications will remove PFAS by disrupting self-assembled layers on foam-wetted surfaces, providing assurance that PFAS impacts in newly installed foam are minimized. Using an effective cleaning agent in place of water reduces foam transition costs by reducing or eliminating time-consuming re-work, mitigating contamination of replacement foams and avoiding widespread component replacement.

Additionally, Arcadis uses innovative technologies to regenerate the biodegradable cleaning agent for reuse, minimizing disposal costs.

With water only flushes on the fire suppression system, PFAS buildup rebounded at up to 1.6 g/L in fluorine-free firefighting foams

Reducing Complications and Uncertainties

Transitioning away from firefighting foams containing C8/C6 PFAS requires a combination of engineering skills and knowledge of environmental science and policy.

Arcadis Foam Transition Services

Arcadis offers a broad scope of services for foam transition including:

- Fire system upgrade planning and permitting
- Replacement foam selection & quality assurance
- Fire system design modifications and upgrades
- Testing fire suppression system components for PFAS residual levels
- Containment system upgrades
- Piping and storage system cleaning
- Waste characterization and disposal
- Proportion testing to meet NFPA requirements
- Reporting and O&M manual updates

Thank You!

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ARCADIS

Arcadis at a Glance

Worldwide	North America
35,000 + Staff	5,000 + Staff
70+ Countries	>120 + Offices

Arcadis Generates **$4.2 Billion** in Revenues

Acknowledgements

- Corey Theriault, Principal Water Engineer, PFAS Global Team
- Bryan Bailey, Principal Water Engineer
- Andy Baumeister, Arcadis Treatability Lab
- Lauren March, Chemical Engineer
- Evocra

Arcadis. Improving quality of life.

PFAS IN PERSPECTIVE | Arcadis

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