

White Paper

How to Capture and Destroy PFAS

A Guide to Ending Forever Chemicals



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Introduction

Per- and polyfluoroalkyl substances (PFAS) comprise a group of over 5000 carcinogenic man-made chemicals that have been produced since the 1950s. PFAS were developed primarily to impart heat, oil, water, and stain resistance properties to products, or to reduce friction in various applications. Today hundreds of different consumer product types and industrial applications contain PFAS. Below is a partial list containing just some common PFAS applications:

- Food packaging: pizza boxes, popcorn bags, fast-food/candy wrappers, greaseproof paper.
- Food production lines
- Nonstick cook and bakeware
- Carpets
- Cosmetics
- Furniture: sofas, mattresses.
- Dental Floss
- Paints
- Aerospace
- Construction
- Waterproof Clothing
- AFFF Firefighting Foam
- Surface coatings
- Lubricants and Greases
- Pesticides
- Ski waxing
- Aerosols for fabric proofing
- Artificial grass
- Medical devices
- Electronics

PFAS is extremely persistent and does not readily degrade in our environment. Due to decades of unregulated PFAS pollution in many industrial sectors, PFAS is now a ubiquitous pollutant throughout our environment and exists at low levels in the blood of virtually every human being. Waterways and groundwater throughout the world are increasingly polluted by unregulated industrial discharge of PFAS contaminants, threatening our drinking water supply and aquatic life. Incineration plants discharge PFAS daily through their exhaust gases into the air we breathe. Landfills generate PFAS-

contaminated leachate that, unable to be properly treated using conventional techniques, is simply diluted, and discharged into receiving water bodies. Airfields and fire stations have polluted both soil and groundwater from their extensive use of PFAS-containing fire retardants during regular fire exercises.

PFAS is unfortunately so bio-accumulative that it takes many years to leave the body with half-life estimates up to 8 years or more. As such it spreads quickly through the food chain and even passes down from generation to generation via breastmilk. As PFAS remains in the body for a long time from exposure to everyday products, PFAS levels accumulate and can cause severe health problems. There is much evidence showing that PFAS exposure can lead to a host of adverse health effects, with annual health related costs estimated to be 52-84 billion EUR across Europe¹. Studies suggest that prolonged PFAS exposure is linked to:

- Increased cholesterol levels
- Lower infant birth weights
- Hormone disruption²
- Kidney, ovarian, prostate, liver, breast, and testicular cancers³
- Non-Hodgkin’s lymphoma⁴

In the United States, an estimated 2,500 industrial facilities have been identified for discharging PFAS into the air and water⁵. The table below lists current best estimate PFAS remediation costs for the Scandinavian region and the EU⁶, which attests to the vast proliferation of PFAS contamination:

	Water Treatment Cost Estimates		Soil Remediation Cost Estimates	
	Best	High	Best	High
Denmark	97	274	40	798
Norway	88	250	97	1,887
Sweden	166	472	240	4,497
EU	8,906	25,258	7,128	141,613

Table 1: Remediation costs for PFAS contaminated water and soil in million EUR.

¹ <https://www.eea.europa.eu/themes/human/chemicals/emerging-chemical-risks-in-europe>

² <https://www.epa.gov/pfas/basic-information-pfas>

³ <https://www.cancer.org/cancer/cancer-causes/teflon-and-perfluorooctanoic-acid-pfoa.html>

⁴ <http://www.ewg.org/news-insights/news-release/study-pfas-act-similar-known-cancer-causing-chemicals>

⁵ <https://www.ewg.org/news-and-analysis/2020/04/updated-thousands-industrial-facilities-likely-discharging-toxic-forever>

⁶ Nordic Council of Ministers – The Cost of Inaction: A socioeconomic analysis of environmental and health impacts linked to exposure to PFA

Current Treatment Methods

Being a highly persistent substance, PFAS is very resistant to traditional techniques like biological treatment. Even more aggressive chemical oxidation methods such as ozone or Fenton's oxidation are typically inadequate to completely breakdown PFAS to non-toxic byproducts. When it comes to onsite PFAS treatment, most conventional technologies are merely preventative, where PFAS is typically isolated but not destroyed. At many pollution sites, PFAS contaminated material such as contaminated soils and spent adsorbents are directly deposited in landfills or sent for incineration. This whitepaper however does not consider landfilling of PFAS contaminated material as a proper solution as it simply delays the problem – rainwater precipitation on the landfills generates PFAS-contaminated leachate that simply returns into our environment. Incineration on the other hand remains largely undocumented with regards to its PFAS destruction efficiency, where it is suspected that PFAS may be emitted through smokestacks or accumulate in incineration ash due to inadequate temperatures. Hence there is an urgent need to not only capture PFAS, but also identify methods that can destroy forever-chemicals. To do this, different technologies are evaluated.

PFAS Capture

Below is a list of some commercially available methods that exist today that are effective at capturing and isolating PFAS from contaminated water, as well as their respective challenges when viewed as standalone remediation techniques. These same methods can also be used to treat wastewater collected from washing of contaminated soils.

Separation Techniques:

- **Membranes:** Membrane systems such as reverse osmosis (RO) have small pores that are effective at rejecting PFAS while allowing water to pass through. However, RO retains other organics and salts in the wastewater which can quickly reduce the flux across the membrane and limit concentration factors.
 - Challenges: Membranes with larger pore sizes such as nanofiltration (NF) may risk leaking smaller PFAS compounds into the permeate stream. Membrane systems also typically require significant amounts of power for pressurizing wastewater against the membrane.
- **Foam fractionation:** Small air bubbles are passed through a water column which have an affinity for capturing PFAS compounds on their way up. The PFAS is then collected as a highly concentrated foam as it accumulates at the top of the column. Only air is consumed in the process, and no additional chemicals are added.

- Challenges: Highly effective with long-chained PFAS, but less effective with capturing short-chained PFAS.

Adsorption Techniques:

- **Activated Carbon**: Granulated activated carbon (GAC) is a common treatment method for capturing PFAS in an adsorption column, whereby PFAS adheres to the surface of the carbon.
 - Challenges: GAC has a very limited capacity for short chained PFAS. In addition, GAC is not exclusively selective to PFAS, and will be fouled by other organic compounds and ions present in the wastewater. Sustainable disposal methods for GAC need to be identified. Spent GAC is currently shipped long distances to incineration plants for destruction using significant amounts of energy and fossil fuels, where incomplete degradation due to insufficient incineration temperatures and residence times lead to the discharge of hazardous byproducts from smokestacks. The remaining incineration ash also contains PFAS and is currently sent to landfills.
- **Ion Exchange Resins (IER)**: IER have an extremely high capacity for both short and long chained PFAS, whereby PFAS adheres to the surface of the resin. IER have a higher capacity for long chained PFAS, and a moderate capacity for short chained PFAS.
 - Challenges: The performance of IER is highly sensitive to the presence of other organic compounds and ions in the water. A robust pre-treatment process train is necessary for more complex wastewaters (e.g., leachate) to prevent fouling and maintain good PFAS adsorption capacity in the IER. As with GAC, sustainable disposal or destruction methods are needed.

PFAS Destruction

As mentioned, PFAS is highly recalcitrant to conventional biological and chemical treatment processes. Hence, more advanced processes are needed to breakdown PFAS into non-toxic components and ensure complete mineralization. A list of potential PFAS destruction technologies that are shown below:

- **Pyrolysis/Gasification**: PFOS contaminated biosolids are destroyed at high temperatures in an oxygen-free or low-oxygen environment.
 - Challenges: Destruction efficiencies are still subject to investigation. However, conventional pyrolysis plants typically operate at temperatures around 800 °C that are too low to fully destroy PFAS.

- **Mechanochemical Degradation (MCD):** A milling system comprising stainless steel balls and other co-milling reagents that are used to crush PFAS in contaminated soil at high energies and temperatures.
 - Challenges: MCD technology is still under development with destruction efficiencies still subject to investigation.
- **Plasma:** Utilizes highly ionized gas to release charged radicals that can breakdown PFAS.
 - Challenges: Studies show that PFAS can be broken down but the complete defluorination of the PFAS without toxic byproducts is still questionable and subject to investigation.
- **Electrochemical Oxidation (EC):** Electrodes are submerged in wastewater to create a current to oxidize PFAS at ambient conditions and with a relatively low energy consumption. No additional oxidants are added to the process.
 - Challenges: Relative long residence times with incomplete degradation of PFAS. Electrodes can be costly and are susceptible to fouling from mineral deposits.
- **Hazardous Waste Incineration (HWI):** PFAS contaminated material is destroyed at very high temperatures requiring a 1 second residence time, though the actual destruction efficiencies are not well understood. The most difficult fluorinated compound to decompose is CF₄, requiring temperatures over 1,400 °C to destroy.⁷
 - Challenges: Unwanted fluctuations in temperatures and residence times may lead to direct discharge of incompletely degraded PFAS byproducts into the atmosphere. PFAS has been detected in soil/air surrounding incineration sites.⁸ In addition, PFAS may remain in the incineration ash, creating a new PFAS hotspot that needs to be treated.
- **Supercritical Water Oxidation (SCWO):** Use of oxidants mixed with supercritical water at temperatures above 374 °C and pressures above 22.1 MPa to break down PFAS in water.
 - Challenges: SCWO can completely break down PFAS, though it will produce corrosive mineral acids such as hydrofluoric acid and sulfuric acid. Proper acid management with base is thus required. In addition, salts created from the oxidation process are insoluble and need to be flushed out of the process to prevent fouling.
- **Subcritical Water Oxidation (subCWO):** Oxidation of wastewater below the critical temperature of water (374 °C) and pressures around 22.1 MPa to prevent the formation of steam. This maintains most salts in solution and allows easier acid management with base, hence reducing reactor fouling.
 - Challenges: Lower destruction efficiencies than SCWO. Requires very long residence times to achieve high destruction rates.

⁷ https://www.epa.gov/sites/production/files/2019-09/documents/technical_brief_pfas_incineration_ioaa_approved_final_july_2019.pdf

⁸ <https://www.ewg.org/news-insights/news/feeding-waste-cycle-how-pfas-disposal-perpetuates-contamination>

	Distillate (ug/L)
PFHpA	<0.0010
PFOA	<0.0010
PFNA	<0.0010
PFBS	<0.0010
PFHxS	<0.0010
PFOS	<0.0010
PFOSA	<0.0010
PFHxA	<0.0050
PFBA	<0.0010
PFPeA	<0.0050
PFDA	<0.0010
FTS 6:2	<0.0010
Sum of PFAS 12	<0.010

Table 2: Results after SCWO treatment of PFAS concentrate containing 100 µg/L PFAS. Analysis results are shown in µg/L.

	Feed (ug/L)	Distillate (ug/L)
PFHpA	1100	<0,0010
PFOA	2200	0,0014
PFNA	130	<0,0010
PFBS	1,4	<0,0010
PFHxS	7700	0,0093
PFOS	12500	2,8
PFOSA	25	<0,0010
PFHxA	76	<0,0050
PFBA	400	<0,0010
PFPeA	39	<0,0050
PFDA	12	<0,0010
FTS 6:2	940	<0,0010
Sum of PFAS 12	25000	2,8

Table 3: SCWO treatment of highly concentrated PFAS foamate

PFAS Treatment Trains

Treatment trains are often employed for the capture and destruction of PFAS and customized after the complexity of the wastewater. Aquarden has experience designing treatment trains including adsorbents such as IER to capture PFAS. Certain IER are highly PFAS-selective and can capture very high loads of PFAS before saturation while also capturing both short and long chain PFAS. To capture PFAS, wastewater is typically passed through two modular adsorption columns. The first adsorption column is efficient at removing organic material but has a low PFAS selectivity and lets PFAS through. The second adsorption column is highly PFAS-selective and removes PFAS below detection limits. However, IER is highly sensitive to the presence of other organics and minerals in the wastewater that can foul the IER and reduce its ability to capture PFAS. To ensure optimal performance of the PFAS adsorption columns, it is very important that proper pre-treatment processes are utilized to first remove other problematic minerals and organic compounds that may interfere or compete with the PFAS adsorption process.



Figure 1: Left – Aquarden containerized PFAS pre-treatment system comprising chemical flocculation and microfiltration. Right – Pond polluted with PFAS from firefighting activities. Note the green algae plume that can interfere with the PFAS adsorption process if not properly removed by pre-treatment systems.

Upon saturation with PFAS, the spent adsorbent is replaced with fresh adsorbent, while the PFAS-saturated adsorbent is sent to our SCWO plant for complete destruction. The diagram below illustrates an example of the complete PFAS capture and destruction process:

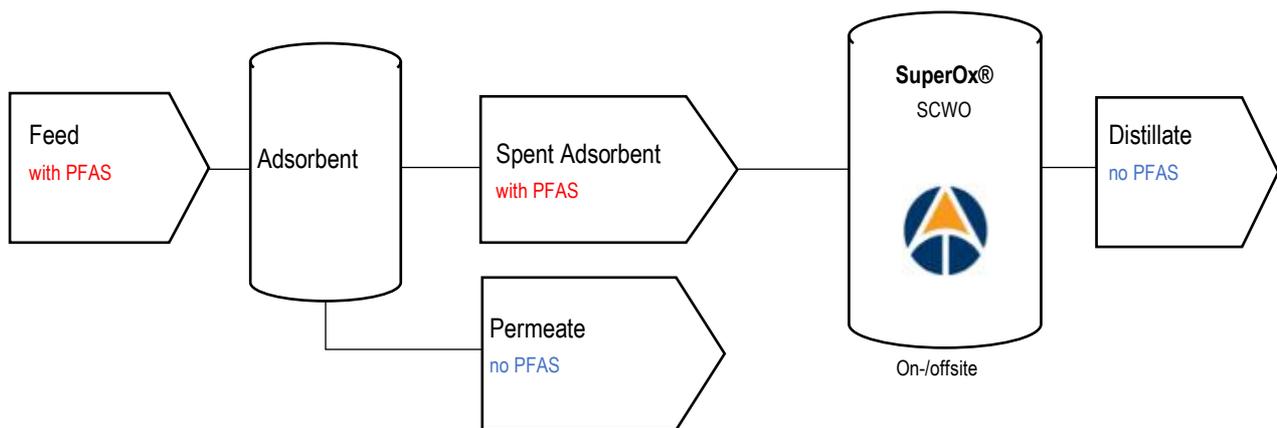


Figure 3: Example SCWO-adsorption process for PFAS treatment

Aquarden believes SCWO and subCWO to be current best available technologies for PFAS destruction, as it can ensure its destruction with minimal emissions of toxic byproducts due to the water-based treatment process. When working with very highly concentrated PFAS wastes like firefighting foam (AFFF) containing extremely high levels of PFAS (> 1g/L), trace amounts of PFAS may still be detected despite a 99,99% PFAS destruction efficiency from SCWO treatment. However, the advantage of SCWO and subCWO is that the entire process is water-based, meaning any remaining PFAS in the treated water can be simply re-polished with resins to below detection limits. All treated water can be safely analyzed prior to discharge, unlike with incineration where any unwanted emissions are immediate into our atmosphere.



Figure 2: Aquarden fullscale SuperOx® SCWO system.

For many, the treatment of PFAS is a big challenge due to the scope of the pollution. Aquarden believes in local and sustainable treatment of PFAS along with its complete destruction with SCWO and subSCWO to provide a safer environment for future generations.