

PFAS – A CASE STUDY OF INNOVATIVE AND EFFECTIVE TREATMENT TECHNOLOGY

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ABSTRACT

Per- and Poly-fluoroalkyl substances (PFAS) have a wide range of applications from firefighting foams and fireproofing to cookware coating, due to the unique specification of this substance. PFAS are very resistant to thermal and chemical changes and the strong carbon fluorine (C-F) covalent bond makes it a very popular commercial substance for manufacturing non-stick cookware and grease-proofing agents. To date, over 9,000 compounds in the PFAS family have been identified (NIOSH, 2021). The PFAS family and the uses of these substances have been growing ever since the initial compounds were manufactured. The unique physical and chemical properties of PFAS compounds make them highly recalcitrant and persistent, which result in non-treated PFAS being detected in various waste streams, surface water, groundwater, and drinking water. Even in small quantities, consumption of PFAS can harm human health. Such health effects can include carcinogenesis, endocrine disruption, infertility, birth defects, and neurotoxicity. The adverse health effects from PFAS have raised significant concerns worldwide which has led to various governmental guidelines and regulations (ITRC, 2022).

Common approaches for removing PFAS from water streams rely on separation (via different media, reverse osmosis or foam fractionation). Notably, many research entities are also focusing on PFAS destruction technologies that rely on advanced oxidation processes (AOPs) such as super critical water oxidation (SCWO), plasma and electrochemical oxidation (EO). More effective treatment processes including nanofiltration and reverse osmosis have been studied. However, these remediation techniques usually face other challenges such as fouling and they generate PFAS-concentrated waste that requires further treatment.

Advanced redox reactions such as electrochemical oxidation are emerging treatment methods that are the most efficient technologies in removing PFAS without leaving downstream by-products. These technologies can be energy-efficient as they can utilise renewable energy such as solar energy. AECOM, in association with Georgia University, are developing an innovative treatment technology for degrading aqueous PFAS from water and waste streams. Results of bench and pilot trials have demonstrated degradation efficiencies up to 99%.

Unlike other treatment technologies that use separation techniques, this technology aims to destroy the PFAS mass. DE-FLUORO™ has been tested in Australia on various water and wastewater streams. Research results show that this technology has the potential to successfully destroy dissolved phase PFAS mass in a cost- and energy-efficient manner on-site.

KEYWORDS

PFAS Destruction, Electrochemistry, Water Quality, Emerging Contaminant, Persistent Pollutant, Treatment, Technology, Innovation, Efficiency

PRESENTER PROFILE

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INTRODUCTION

WHAT ARE PFAS?

Per- and poly-fluoroalkyl substances (PFAS) are a group of chemical compounds that have been manufactured and used since the 1950s to make products that are highly resistant to heat, stains, grease and water. Some uses of PFAS are in making clothes, carpet and shoes that are more resistant to stains and in manufacturing non-stick cookware and firefighting foam (Aqueous Film Forming Foam [AFFF]). PFAS may be used in daily life such as paper/paperboard food packaging, grease-proofing agents in fast-food wrappers, microwave popcorn bags, take-out paperboard containers, and pet food bags to prevent oil and grease from foods from leaking through the packaging. Figure 1 shows various sources of PFAS world-wide. In previous studies conducted in the US, scientists found PFAS in the blood and urine of 97 percent of the participants. This suggests that people have been exposed to these chemicals by consuming PFAS-contaminated water or food (NIEH, 2019). Their recent studies showed a reduction in the PFAS (PFOA and PFOS) levels in people's blood and urine; however, the concern remains as the PFAS chemicals appear to be growing in numbers and exposure to PFAS compound is difficult to manage accurately (NIEH, 2019).

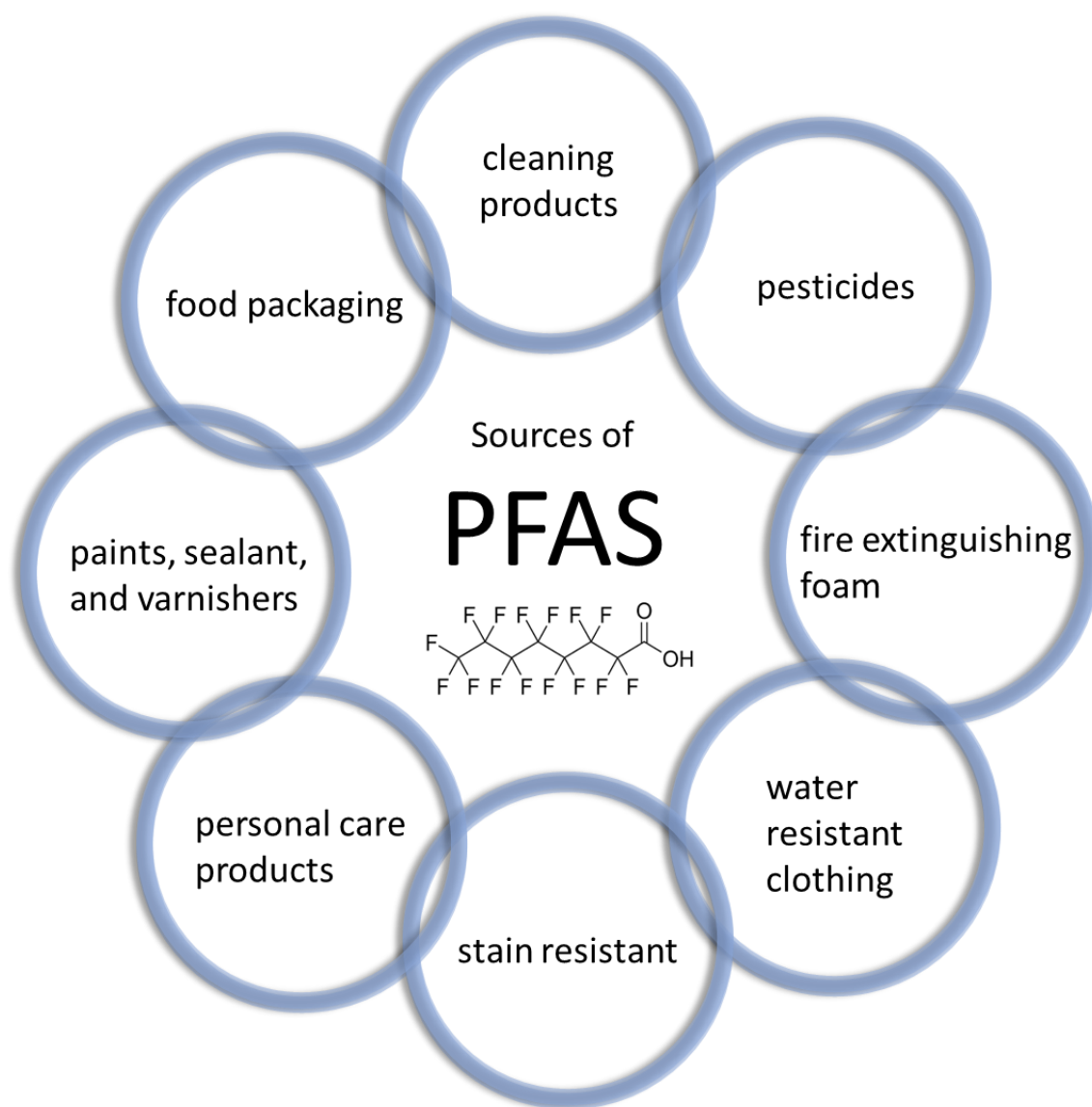


Figure 1 sources of PFAS

To date, more than 9,000 PFAS chemicals are manufactured and the numbers are growing (NIEH, 2019). Two well-known types of PFAS are Perfluorooctane Sulfonate (PFOS) and Perfluorooctanoic Acid (PFOA) Figure 2. Due to highly recalcitrant characteristics of these compounds, non-treated PFAS have been detected in various water and waste streams.

CHEMICAL CHARACTERISTIC OF PFAS

PFAS are comprised of fluorinated carbon chains attached to functional groups (such as carboxylic acids, sulfonic acids, alcohols, etc.). PFAS are categorized into two groups namely, long-chain and short-chain compounds. Long-chain PFAS have usually more than six carbon in the carbon chain. Long-chain and short-chain PFAS are man-made chemical compounds, however, there are known PFAS compounds that form from the degradation of more complex PFAS.

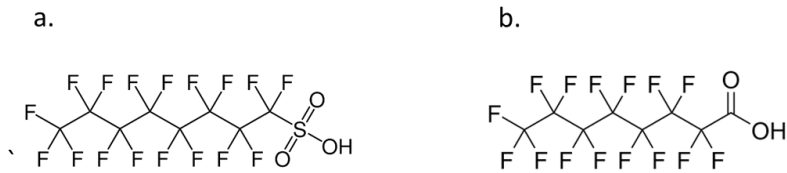


Figure 2 long-chain PFAS a. PFOS b. PFOA

Made by saturating double-bonded carbon chains (alkenes) with fluorine, the carbon-fluorine (C-F) bond is one of the strongest in organic chemistry, meaning many PFAS compounds are very difficult to break down. Some of the most common, such as PFOS and PFOA, are environmentally persistent. They are referred to as 'the forever chemical'. They dissolve in water, including in droplets such as rain and aerosols.

The C-F covalent bond is so strong that it takes about 485 kJ/mol energy to break only one C-F bond. The strong bond between carbon and fluorine atom means that PFAS can travel thousands of kilometres through the air, soil and water environments without degrading.

In the US, NZ and a few other countries, PFOS and PFOA manufacturing is banned, however, there are traces of these chemicals found in the environment. Chemical manufacturers are reverting to the manufacture of short-chain PFAS, such as GenX, however their impact on human health is still being studied.

PFAS TRAITS IN THE ENVIRONMENT

More common traits of PFAS includes:

- Water-soluble therefore can travel significant distances and generally low volatility
- Exceptional stability retards degradation
- Affinity for media interfaces (particularly air-water)
- Persistence and potential toxicity at low concentrations
- Bio-accumulative and prevalent in the environment, detected in plants, animals and humans.

EFFECTS OF PFAS ON HUMAN'S HEALTH

The persistent nature of PFAS results in the accumulation of these materials in the environment, animals and humans. Due to recalcitrant characteristic of PFAS, scientists are unable to estimate the environmental half-life of PFAS. PFAS bio-accumulate up the food chain which means that they keep building up in the bodies of living organisms and move up the food chain and, in some cases, do not leave the body of living organisms. PFAS have been associated with many diseases and health problems such as weakened childhood immunity, thyroid diseases, cancer, and more health risk can be as follows (The Department of Health and Aged Care, 2022):

- Disrupted foetal and child development
- Decrease in fertility and interference with the body's natural hormones
- Increased cholesterol
- Immune system disorders

- Increased risk of some cancers

WHERE HAVE SCIENTISTS FOUND PFAS TO DATE?

The solubility of many PFAS compounds makes them very mobile and they can travel hundreds to thousands of kilometres in the environment. They have been found in various waterbodies and the environment. Table 1 shows locations that PFAS has been identified in the environment. PFAS has also been found in the flesh of living organisms and people's blood and urine.

Table 1 where have we found PFAS?

PFAS found in	How is it found?
Soil	PFAS can be found in soil which can leach into surface water, stormwater and groundwater sources and can be taken up by plants used for food production.
Water	PFAS is soluble in water and this allows it to spread widely in surface water, marine and groundwater systems.
Concrete and other infrastructure	Concrete has been found to absorb significant levels of PFAS if exposed to PFAS contamination
Sludge	Found in the solids streams of municipal and industrial wastewater treatment plants.
Air emissions (near manufacturing and incinerator facilities)	Found in air and aerosols and on soil and in water adjacent to industries that once manufactured PFAS or that incinerate municipal or industrial wastes.
Firefighting training grounds and accidents (AFFF storage, handling and use)	Sites where AFFF has been used can exhibit significant residual PFAS contamination.

PFAS IN NEW ZEALAND:

In late 2017, PFOS and PFOA were found at two of New Zealand's airbases. Thereafter, investigations by New Zealand's Environmental Protection Authority (EPA) were undertaken into the broader presence of PFAS in New Zealand's environment.

Concurrently, New Zealand Defence Force (NZDF) conducted an investigation for potential contamination of the environment around the Ohakea base in the Manawatu-Wanganui region of New Zealand. High concentrations of PFOS + PFHxS on the base covering a plume of 1,100 ha to 1,600 ha were detected (New Zealand Defence Force & PDP, 2019). This can pose a risk to the surface waterbodies and wells in the surrounding area. The key receptors of PFAS are

reported to be the wells and water bodies and they are located within 2 – 3 km of the base (New Zealand Defence Force & PDP 2019).

A similar study was carried out in late 2017 and early 2018 on the surrounding environment of Woodbourne base in the Marlborough region including groundwater, surface water, soil, sediment pore water, trade waste and terrestrial and aquatic animal tissue. The results showed detectable concentrations of PFOS and PFHxS in all the sampled media (New Zealand Defence Force & PDP, 2019).

In a recent study (Lenka et al., 2022) in New Zealand, PFAS contamination in urban water and wastewater was investigated. The study zone included samples from three sources including: 1. Influent and effluent of two wastewater treatment plants in Auckland, 2. Surface water receiving the effluent of the two wastewater treatment plants, 3. Water treatment plant whose water was supplied from a surface water downstream of the wastewater treatment plants. Total PFAS at concentrations 0.1-13 ng/L were detected in all wastewater samples. Ultrashort-chain PFPrA was detected in drinking water but not in the source water, and the authors were unable to identify the source of PFPrA. Hence, the authors suggest further and broader studies on exploring PFAS contamination in NZ's water systems and incorporation of PFAS removal technologies for drinking water treatment plants.

The Stockholm Convention - an international agreement - has given PFAS the name 'persistent organic pollutants (PoPs)' as these compounds do not readily break down via biological or chemical reactions. In New Zealand, regulations have been implemented to limit the production and use of such chemicals. This update has been reflected in New Zealand's Hazardous Substances and New Organisms Act (1996), and in a new decision on the Fire Fighting Chemicals Group Standard (Group Standard, 2021).

The decision by the Fire Fighting Chemicals Group means that uncontained use of firefighting foams containing PFOA-related compounds, for example at the scene of a plane or truck crash, must be phased out by the end of 2022. Contained use, for example at an enclosed fuel tank fire where the substance can be restricted from contaminating the environment, must be phased out by 3 December 2025.

Aqueous Film Forming Foam (AFFF) containing PFOS and PFOA was used on all the RNZAF bases for firefighting, fire prevention and firefighting training since the 1980s until about 2002. However, in 2006, importing and manufacturing of firefighting foams containing PFOS or PFOA was banned. And since 2011, the use of firefighting foams that contain PFOS has been prohibited and the use of PFOA has been restricted.

PFAS TREATMENT TECHNOLOGIES

Many techniques have been trialled for PFAS removal from the contaminated medium, including incineration. Incineration has been used as a waste management means for PFAS destruction to break the C-F bond with high temperature requiring a great deal of energy. However, this solution has faced many hurdles as it is not only energy-intensive, but it also releases toxic material into the environment and requires disposal of the hazardous waste post-incineration.

There are also other types of PFAS removal and destruction technologies that have been tested such as electro-oxidation (EC), sonochemical oxidation, thermolysis, plasma oxidation, hydrated electron reduction, and photochemical oxidation (Meegoda et al., 2020). Still more technologies include filtration (e.g. nanofiltration (NF) and reverse osmosis (RO)), and adsorption processes (e.g., granular activated carbon (GAC) and ion exchange resins (IXR)) are being studied and used.

NF and RO have shown effective PFAS removal whereas other filtration processes such as microfiltration and ultra-filtration were ineffective in PFAS removal. NF and RO have shown successful PFAS removal with all carbon numbers and chain length.

Granular activated carbon (GAC) is an adsorption method that comprises of physical mass transfer of PFAS onto the surface of the adsorbents. GAC has been prevalently used for PFAS removal (Meegonda et al. 2020). It has shown moderate to high removal rates with longer chain carbon compounds, however GAC loses its effectiveness when the PFAS compound in the contaminated media is short-chain.

Ion exchange resin (IXR), as the name suggests, comprises ion exchange and adsorption of PFAS contaminants onto the surface of a synthetic polymer media. The resins hold positively charged exchange areas which react with the carboxyl or sulfonic head of PFAS to create a bond for PFAS to be separated from the media. The carbon-chain tail will then bind onto the hydrophobic backbone of the resin surface. IXR is one of the most effective methods of PFAS separation to date (Meegonda et al., 2020).

Electrocoagulation is an alternative to conventional chemical coagulation. Electrocoagulation is commercially available, and many studies have been conducted on its performance and energy use optimization. Several studies have been focusing on automation and use of less corrosive material to reduce labours and construction costs. In this process, a sacrificial electrode such as aluminium, iron, zinc or magnesium is used to deposit charged cations followed by generation of hydroxyl complex species. The hydrophobic tail of PFAS will then be sorbed onto the hydroxyl complex (e.g. zinc hydroxide flocs) (Chiang et al., 2021).

All the above technologies have been tested for treating groundwater with more common methods such as granular activated carbon and ion exchange, however, the problem with these technologies is that they usually leave behind the spent carbon and also ion exchange media which requires downstream treatment. Although these technologies can be effective in treating water with PFAS contaminants, the long-term and substantial costs of these treatment systems inhibit prevalent use of them. In addition, because PFAS are not destroyed and only removed from the water sources, the PFAS remains in the environment and further processes such as landfilling, or incineration have been found to have cycled the removed PFAS back into the environment. In addition, these technologies are not economic when it comes to treatment of wastewater where PFAS concentration is low, and the volume of the PFAS-impacted media is large. Alternatively, if the concentrated PFAS waste remains on -site and accumulates over time, this can lead to the site's closure or may lead to the property being flagged as a hazardous or contaminated site.

Electrochemical oxidation (EO) is a technology that oxidizes organic pollutants in water by applying a current through a conductive solution between anodes and cathodes. PFAS destruction can be achieved by EO via direct electron transfer on “non-active” anodes under room temperature and atmospheric pressure at fast rates. electrochemical oxidation of PFAS occurs starting by a single electron transfer from PFAS to the anode followed by generating PFAS radicals. Then the PFAS radicals will go through decarboxylation or defluorination and as a result fluoride, sulphate or carbon dioxide will be released.

Our PFAS project team has conducted multiple PFAS removal research studies as well as case studies over the past couple of decades to find the most efficient way of removing PFAS from aquatic streams. A few studies are as follows:

1. Coupling ion-exchange resin with electrochemical oxidation

PFAS decomposition was studied in a concentrated IXR waste by EO. The regeneration of IXR results in a liquid waste that contains high concentration of PFAS, salt, and other residual organic compounds. This high-concentration waste is called ‘still bottom’. Figure 3 shows the processes used in this study. The study was carried out by our PFAS team in conjunction with University of Georgia (Liang et al, 2022). The reactor was powered by an AMETEK XG 20-75 DC power supply, which provided a constant current of 10 A and a voltage of 30 V during a normal operation. Approximately 19 L of still bottom sample was treated in the EO reactor for approximately 80 h of cumulative treatment time.

PFAS samples were collected from treatment solutions in the EO reactor at time 0 (T0), 8 h, 40 h, and 80 h during each batch of EO treatment to understand PFAS degradation kinetics. Fluoride is an important indicator of PFAS destruction and was monitored during treatment.

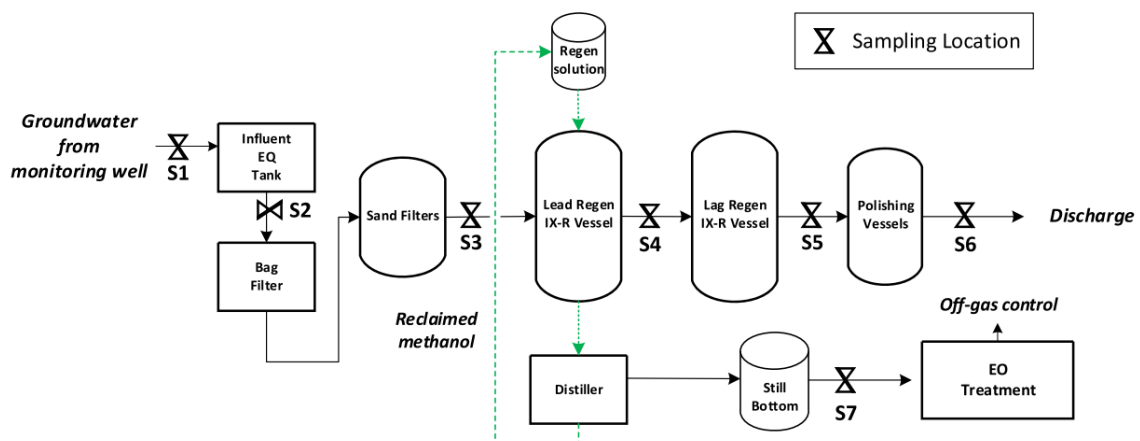


Figure 3 PFAS removal process (IXR coupled with EO)

The results showed that treatment of a concentrated stream of contaminated water via IXR coupled with EO can be more energy-efficient than a stand-alone EO that treats the diluted groundwater which requires a great deal of energy.

This train of technology concentrates the PFAS first and then feeds it to a deconstruction unit. It is more desirable as it ensures compliance of the treated effluent to levels below EPA levels which is 70 ng/L (Australian Government, Department of Health, 2022) (for combined concentration of PFOA and PFOS).

2. Electrochemical oxidation of PFOA and PFOS in concentrated waste streams

In another study (Liang. et al, 2018) a stand-alone EO was used to destruct PFOA and PFOS. The results showed that, in a solution of 10 mg/L of PFOA and PFOS, the electrochemical oxidation of this recalcitrant material led to 96 percent and 98.9 percent removal, respectively. This was validated by the observed increase in the fluoride concentration from 0.84 mg/L to 836 mg/L.

3. An Electrocoagulation and Electrooxidation Treatment Train

In another study (Liang et al, 2021) electrocoagulation along with electrochemical oxidation were used in a train of treatment steps to destruct PFAS from groundwater-sourced drinking water. In this research, the electrocoagulation method was implemented to force the PFAS to flocculate, and then the PFAS flocs were destroyed effectively with the electrooxidation (EO) process. Liang et al. (2021) reported that EC treatment can achieve more than 90% removal of Long-chain PFAS removal under optimised conditions tested in their experiments.

Our PFAS team has been focusing on investigating and managing of PFAS for at least two decades. In parallel, we have developed and trialed a world-first PFAS destruction method. The results of the research studies and collaboration of various teams inside the firm and our partners culminated in an innovative technology. Our effective and efficient PFAS destruction technology trademarked as DE-FLUORO™.

DESCRIPTION OF THE TREATMENT TRAIN USED IN THIS SYSTEM

A proprietary electrode was implemented to mineralize PFAS (C₄ – C₈) with evidence of complete defluorination and desulfurization. PFAS are destroyed via direct electron transfer and free radical reactions under room temperature and atmospheric pressure with relatively low energy consumption. Our project team has successfully used this proprietary electrode to treat PFAS in ion-exchange regenerant waste, soil washing wastewater and other PFAS-impacted natural waters and wastewaters containing Aqueous Film Forming Foam (AFFF) concentrate.

DE-FLUORO™ is the world's first technology that destroys PFAS economically and environmentally from contaminated liquid streams. It can be coupled with other available technologies that are used for water treatment such as separation solutions. It can also be used as a stand-alone treatment system that can reach complete PFAS destruction solution.

In this technology a train of processes such as filtration, heat exchange and also electrochemical oxidation will occur. The main reactor tank uses electrochemical oxidation. Figure 4 and Figure 5.



Figure 4 DE-FLUOROTM case study

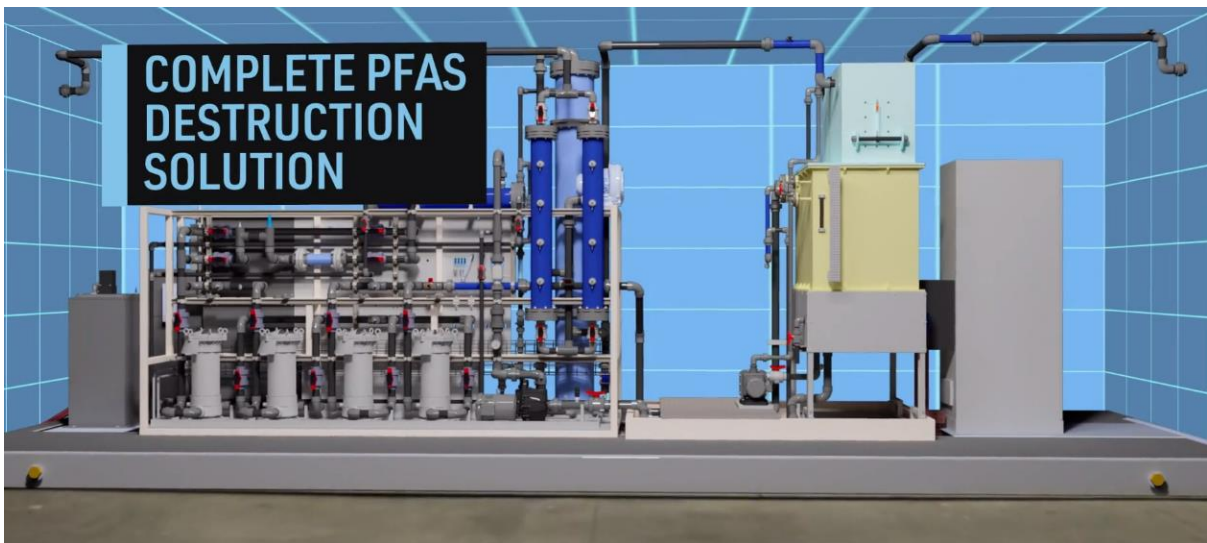


Figure 5 inside the PFAS treatment train

DEMONSTRATED RESULTS

DE-FLUORO™ has been tested using various waste streams with various PFAS-contaminant concentrations. The results showed that under different conditions (high or low strength PFAS-impacted water) more than 90 percent removal was obtained. A summary of results is presented in Table 2.

Table 2 demonstrated results in PFAS removal

Sample Description	Initial PFAS Concentration (ppb)	Reduction (%) post-treatment		
		PFOA	PFOS	Total PFAS*
Untreated Wastewater	400	100 %	100 %	100 %
Source zone groundwater	500	100 %	99.9 %	98.6 %
Fractionation wastewater	1,800	99.7 %	99.6 %	99.4 %
Soil washing wastewater	14,000	100 %	99.9 %	99.2 %
Ion exchange resin regenerant	400,000	98.5 %	98.5 %	92.9 %

* 31 components

The rate of PFAS removal over time using this train of treatment process was also recorded, and the results showed that total PFAS removal can be achieved in under 16 hours of treatment. The results showed great success with regulated PFAS compounds (PFOA, PFOS and PFHxS) generally being destroyed in under eight hours, followed by the non-regulated PFAS compounds. Figure 6 below shows the PFAS reduction using this train of treatment processes.

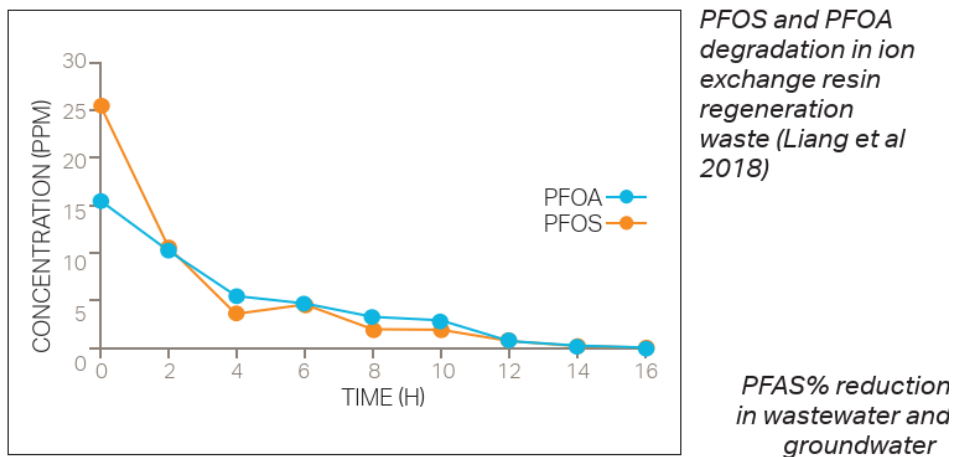


Figure 6 PFAS removal rate in wastewater and groundwater

ADVANTAGES OF USING DE-FLUORO™

Table 3 presents the advantages of implementing this technology for efficient and effective PFAS destruction.

Table 3 DE-FLUORO™ potentials

Permanent solution	Unlike other separation techniques this technology is a permanent solution that offers complete destruction.
Permanent or temporary installation	It can be used and installed permanently where there is an ongoing PFAS problem on-site, it can also be used as a mobile solution to be installed temporarily until the PFAS contamination removal is complete and then removed from the site for use on another site.
Flexible with the initial concentration of PFAS	It is very flexible in terms of the strength of the waste, which means that it has the capability of removing PFAS from concentrated waste streams as well as low-strength wastes such as drinking water.
Can be retrofitted	It is flexible in that it can be used on site where there are other separation technologies, where it can be installed downstream of the processes to successfully destroy the compounds to a safe level before discharge to the environment.
Safety of use	It is fully automated and equipped with alarm systems to ensure safe performance of the treatment system.
Air emission control	Treated water and air emissions are monitored continuously to ensure safe discharge of any off-gas and the effluent
Energy efficient	It can be powered by renewable energy sources such as solar systems to minimize energy needs for operation of the system

Potential applications of this technology include:

- groundwater
- industrial wastewater
- drinking water
- liquid waste
- surface water
- soil wash

There are a number of case studies using this technology for PFAS destruction. One example, is at Wright-Patterson Air Force Base (Ohio, USA), where the water goes through a separation process and after resin regeneration a small volume of PFAS-concentrated liquid is left. The resultant still bottom then goes through DE-FLUORO™ for PFAS destruction. This technology has treated approximately 2,000 kL of PFAS-impacted groundwater.

Since 2001, AECOM has helped clients to understand and remediate PFAS contamination and the firm has worked on over 300 PFAS projects. Figure 7 shows

the location of the PFAS treatment projects our project team has conducted globally.

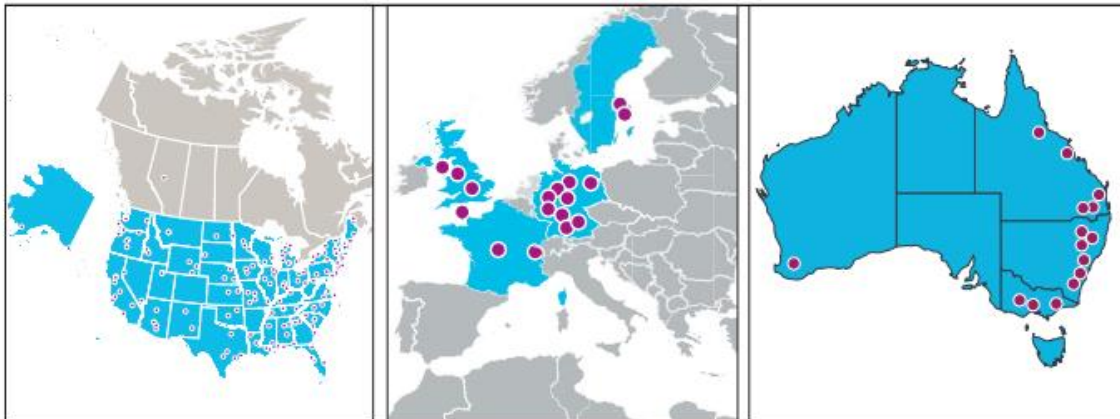


Figure 7 location of AECOM's PFAS projects globally

CONCLUSIONS

PFAS has been widely used in manufacturing due to its unique chemical and physical properties such as high resistance under harsh thermal and chemical changes. To date, more than 9,000 compounds have been manufactured and used in various industries. However, its persistence has caused significant issues for the environment and human health. Many technologies have been used and tested to remove PFAS, however, many of these solutions are designed to separate PFAS from an existing medium and concentrate it in another form that will require further treatment. PFAS concentrate is traditionally removed from site for destruction at thermal treatment facilities, which is expensive and requires a lot of energy. Alternatively, if not taken offsite for destruction, this PFAS concentrate continues to accumulate onsite until a cost-effective destruction solution is identified, increasing liability and management requirements as well as contamination risks.

DE-FLUORO™ as the world-first economically and environmentally sustainable treatment technology developed that destroys PFAS in contaminated liquids without generating hazardous waste. Unlike existing treatment technologies, it offers a complete PFAS destruction solution through electrochemical oxidation. It can be coupled with non-destructive pre-treatment technologies to deliver a 'whole of life cycle' solution, or as a stand-alone onsite destruction technology. It is seen as the last step in closing the loop on PFAS impacted water and concentrate remediation.

ACKNOWLEDGEMENTS

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NOMENCLATURE

PFAS	Per- and poly-fluoroalkyl substances
EC	Electrocoagulation
EO	Electrochemical oxidation or electrooxidation
IXR	Ion exchange resin
AGC	Activated granular carbon
DE-FLUORO™	AECOM's PFAS removal technology
PFOS	Perfluorooctane Sulfonate
PFOA	Perfluorooctanoic Acid
GenX	hexafluoropropylene oxide to form the fluoride
AFFF	Aqueous Film Forming Foams
PFHxS	Perfluorohexanesulphonic acid
NZDF	New Zealand Defense Force
EPA	Environmental Protection Authority
MfE	Ministry for the Environment
HFPO	Hexafluoropropylene oxide
HFPO-DA	Hexafluoropropylene oxide-dimer acid

REFERENCES

- Australian Government, Department of Health, *Health Based Guidance Values for PFAS* [Online]. Available: [https://www1.health.gov.au/internet/main/publishing.nsf/Content/2200FE086D480353CA2580C900817CDC/\\$File/HBGV-Factsheet-20190911.pdf](https://www1.health.gov.au/internet/main/publishing.nsf/Content/2200FE086D480353CA2580C900817CDC/$File/HBGV-Factsheet-20190911.pdf), accessed 17 August, 2022.
- Chiang, D., Huang, Q., Liang, S. and Zhou, J., 2021. 'An Electrocoagulation and Electrooxidation Treatment Train to Degrade Perfluoroalkyl Substances and Other Persistent Organic Contaminants in Groundwater', Wood PLC.

- Group Standard, 2021. *Fire Fighting Chemicals Group Standard 2021, HSR002573 Hazardous Substances and New Organisms Act 1996* [online]. Available: <https://www.legislation.govt.nz/act/public/1996/0030/latest/DLM381222.html>, accessed 15 August, 2022.
- Lenka, S.P., Kah, M. and Padhye, L.P., 2022. Occurrence and fate of poly-and perfluoroalkyl substances (PFAS) in urban waters of New Zealand. *Journal of Hazardous Materials*, 428, p.128257.
- Liang, S., Mora, R., Huang, Q., Casson, R., Wang, Y., Woodard, S. and Anderson, H., 2022. 'Field demonstration of coupling ion-exchange resin with electrochemical oxidation for enhanced treatment of per- and polyfluoroalkyl substances (PFAS) in groundwater', *Chemical Engineering Journal Advances*, 9, p.100216.
- Liang, S., Pierce Jr, R.D., Lin, H., Chiang, S.Y. and Huang, Q.J., 2018. 'Electrochemical oxidation of PFOA and PFOS in concentrated waste streams', *Remediation Journal*, 28(2), pp.127-134.
- Meegoda, J.N., Kewalramani, J.A., Li, B. and Marsh, R.W., 2020. 'A review of the applications, environmental release, and remediation technologies of per- and polyfluoroalkyl substances', *International journal of environmental research and public health*, 17(21), p.8117.
- The National Institute for Occupational Safety and Health (NIOSH). *Per- and polyfluoroalkyl substances (PFAS)* [online]. Available: <https://www.cdc.gov/niosh/topics/pfas/default.html>, accessed 15 August, 2022.
- National Institute of Environmental Health Sciences (NIEH). *Perfluoroalkyl and Polyfluoroalkyl Substances (PFAS)* [online]. Available: https://www.niehs.nih.gov/health/materials/perfluoroalkyl_and_polyfluoroalkyl_substances_508.pdf, accessed 15 August, 2022.
- Interstate Technology and Regulatory Council (ITRC). *PFAS Technical and Regulatory Guidance Document* [online]. Available: <https://pfas-1.itrcweb.org/>, accessed 15 August, 2022.
- The Department of Health and Aged Care. *Per- and poly-fluoroalkyl substances (PFAS)* [online]. Available: [Department of Health and Aged Care | Per- and poly-fluoroalkyl substances \(PFAS\)](#), accessed 15 August, 2022.
- RNZAF Base Woodbourne PFAS Investigation: *Comprehensive Site Investigation Report* [online]. Available: <https://environment.govt.nz/assets/what-government-is-doing/Land/woodbourne-csir-2019-part-1.pdf>, accessed 15 August, 2022.
- Summary of RNZAF Base Ohakea PFAS Investigation: Comprehensive Site Investigation Report* [online]. Available: [Summary-of-RNZAF-Base-Ohakea-PFAS-Investigation-September-2019.pdf \(environment.govt.nz\)](#), accessed 15 August, 2022.