

Summary of the State of the Art Technologies in Emission Control and Monitoring for the Manufacture of Fluoropolymers Utilised by the Members of the Manufacturing Programme

WATER EMISSIONS

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Glossary

Terms used

Definition

Adsorption	the process by which molecules from a gas or liquid phase accumulate on the surface of a solid or liquid adsorbent, thereby removing them from effluent streams.
AOX	adsorbable organically bound halogens
Baseline efficiency	refers to the efficiency of an abatement technology at the beginning of its implementation, which can be compared to a time point in the future as a way of measuring change in technique efficiency.
BAT	refers to EU best available technique, in this report it refers to PFAS abatement techniques
BOD	biochemical oxygen demand
Breakthrough	is the point at which the adsorbent is no longer able to adsorb new molecules. The PFAS removal efficiency is reduced and targeted substances may “breakthrough” the adsorbent. It is at this point that the targeted substance concentration in the treated water reaches an unacceptable level and must be replaced by fresh adsorbent or be reactivated to remove the targeted substances and restore removal efficiency of the treatment bed.
BREF	EU Best Available Techniques reference document per EC Industrial Emissions Directive
CMR	carcinogen, mutagen or reproductive toxin, per Global Harmonized Classification System (GHS) or the Classification Labelling and Packaging Directive (CLP) in the EU.
COD	chemical oxygen demand
Coagulation	is a chemical process in water treatment in which coagulants (like metallic salts) are added to neutralize the negative charge of suspended particles allowing them to clump together to be removed from the water.
Condensation	is a technique used to remove solvent vapors from a waste gas stream by reducing its temperature below its dew point. When the vapor pressure of a substance falls below its partial pressure in the gas stream, the substance condenses into a mist or droplets, which are collected and appropriately treated.
Cross media effects	are unintentional impacts to one form of environmental media due to application of abatement technology to another environmental media. For example, minimizing emissions to air but shifting the impact from air to waste streams dealing with used filters.

CWW	Common Waste Water and Waste Gas Treatment/Management Systems in the Chemical Sector
Defluorination	is the process of removing fluorine atoms from a molecule or compound
Electrostatic interaction	traps electrically charged particles on oppositely charged filter fibers
EU DWD	European Drinking Water Directive recently recast which sets parameters for “PFAS Total” and “Sum of PFAS” in drinking water and requires monitoring, compliance, remediation, and derogations under applicable national implementation rules.
Flocculation	is the process by which smaller aggregates of particles/substances are encouraged to form larger clumps, called flocs, through the addition of flocculants (like polymers) to enhance removal efficiency.
Flue gas	is the mixture of gases exiting an incinerator via a pipe or flue.
Fluoropolymers	are a distinct class of per- and polyfluoroalkyl substances (PFAS), high molecular weight polymers with fluorine attached to their carbon-only backbone.
Foamate	refers to the foam containing PFAS adsorbed at the air liquid interface during foam fractionation. The foamate is the waste formed during this process.
Fly ash	is one of the two main solid waste products (fly ash and slag) generated during incineration
GAC	granular activated carbon
HF	hydrofluoric acid
IED	EU Industrial Emissions Directive
IER	ion exchange resin
LC-MS/MS	or liquid chromatography – mass spectrometry/mass spectrometry is a powerful analytical technique allowing for the effective separation and identification of complex liquid mixtures.
Limit of detection (LOD)	is the smallest measure and concentration which can be detected, but not quantified, in the experimental conditions described by the method.
Limit of quantification (LOQ)	is the smallest measured concentration which can be quantified, in the experiment conditions described for the method.
Long chain PFAS	PFAS perfluoroalkane carboxylic acids/carboxylates with 8 or more total carbon atoms, and perfluoroalkane sulfonic acids/sulfonates with 6 or more carbon atoms
Mass balance	is a principle in which the total mass of substance entering the abatement system equals the total mass leaving the system.

Media	refers to environmental media such as air, water, soil, sediment, waste streams
Membrane fouling	refers to the clogging of membranes by organic materials in the water treatment process, reducing the removal efficiency of the membrane or filter.
Mineralization	is the conversion of organic compounds into inorganic substances, primarily carbon dioxide and water. For PFAS, complete mineralization would imply breakdown of the carbon–fluorine structure into inorganic carbon species, such as CO ₂ , and inorganic fluorine species, such as fluoride or HF.
MSWI	is the abbreviation for municipal solid waste incinerator (non-hazardous waste incinerator).
Non-targeted analyses	utilise analytical techniques that explore unknown compounds using mass spectrometry by identifying a peak in a chromatogram. Typically, a nontargeted method allows for detection of known and unknown chemicals. However, not all chromatographic peaks will be identified. Techniques can be specific to the matrix (air, water, soil, sediment, etc.) and type of PFAS of interest (non-polymeric or polymeric, polyfluoroalkyl versus perfluoroalkyl, etc.).
OPEX	operating expenses
Particle	a very small piece of matter
Per- and polyfluoroalkyl substance	abbreviated, PFAS, is a fluorinated organic substance that contains at least one fully fluorinated methyl or methylene carbon atom (without any H/Cl/Br/I atom attached to it), per OECD 2021.
Periodic measurement	is a measurement at specified time intervals using manual or automated methods.
Regenerate	is the restoration of an adsorbent like granular activated carbon after it has reached its breakthrough capacity. PFAS compounds are extracted from the adsorbent for example through solvent, chemical, thermal or other processes that remove or destroy adsorbed substances thereby restoring the adsorptive capacity of the adsorbent.
Residence time	refers to the time materials spend within the incineration chamber during the combustion process. The duration of time is a critical factor in achieving complete mineralization of PFAS, along with temperature and oxygen content.
Short chain PFAS	PFAS carboxylates with fewer than 8 carbons and sulfonates with fewer than 6 carbons are referred to as short chain PFAS.
Size exclusion	is the physical process by which molecules in target substance containing water are separated based on their size as they pass through a porous medium or membrane.
Slag	is one of the two main solid waste products (fly ash and slag) generated during incineration. In municipal solid waste incinerators, slag is dark, porous and semi-flowing solid

	consisting of non-flammable substances, water insoluble silicates, aluminum and iron oxides.
Spent	when an adsorbent, such as granular activated carbon, is no longer able to adsorb new molecules, the adsorbent is referred to as "spent" and its PFAS removal efficiency is reduced allowing targeted substances to “breakthrough” into the treated water. The adsorbent must either be replaced by fresh adsorbent or be reactivated (by removing the targeted substances) in order to restore removal efficiency.
Targeted analysis	is an analytical approach by which the analyst is looking only for specific chemicals. The mass spectrum and retention times for each compound are known and all targeted chemicals above the noise level will be detected by this approach. The determination is typically optimized for sensitivity and selectivity and subsequently reduced by limiting the number of analytes.
TOC	total organic carbon
TSS	total suspended solids
Ultra-short chain PFAS	are PFAS with two or three carbon atoms

1. Introduction

This report outlines state-of-the-art technologies used by members of the Manufacturing Programme to prevent and reduce PFAS emissions to water from fluoropolymer manufacturing. It draws on publicly available information and current technical insights, and forms part of a series of technical documents covering abatement technologies for air and water, as well as PFAS waste management in fluoropolymer manufacturing.

There is currently no existing EU Best Available Techniques reference document (BREF) or best available technology (BAT) conclusions for the fluoropolymer manufacturing industry. The existing 2007 polymer BREF does not specifically address fluoropolymers. Significant evolution in emissions control technology and fluoropolymer manufacture has been achieved since 2007. According to chemical/molecular structure, fluoropolymers are defined (OECD 2021) as a type of polymeric per- and polyfluoroalkyl substance (PFAS).

Though removal efficiencies vary between specific water abatement technologies based on water solubility and functional groups (e.g., carboxylic, sulfonic, phosphoric acid, hydroxyl groups, etc.), the technologies employed by Manufacturing Programme Members can remove or manage PFAS monomers, long chain, short chain and ultra short chain PFAS and polymerization aids.

This report does not address industries producing finished articles containing fluoropolymers or using fluoropolymers in operations.

1.1 Scope – Water emissions

Emissions to water from the manufacture and processing of fluoropolymers generally may be in the form of solid particles and liquids. In the 2016 BAT for Common Waste Water and Waste Gas, almost every compound present or arising during polymerization may end up in water if not managed appropriately. Therefore, this report addresses the state-of-the-art technologies collected by the Manufacturing Programme member companies and used to prevent and limit PFAS emissions to water from fluoropolymer manufacturing (See sections 2-7).

These technologies are classified as: removal (or separation), destruction, and stabilization (or sequestration).

Removal technologies include:

- adsorption
- membrane technology
- filtration
- evaporation

Destruction technologies include:

- incineration with flue gas scrubbing,

Stabilization (or sequestration) technologies include:

- buffer storage (and landfill).

Buffer storage is addressed in this document whereas landfill will be addressed in the summary of the State of the Art Technologies Waste document.

According to the Innovative and Collaborative Initiatives for the Transition to Elimination (INCITE) categorization used by the European Chemicals Agency (ECHA) and the EU's

Committee for Socio-Economic Analysis (SEAC) reference documents, their relevance for each water emissions technology is structured as follows.

1. basic information about technology,
2. information on the current use of that section's technology in PFAS abatement systems,
3. the environmental performance of technology,
4. cross media effects / environmental co-benefits,
5. economics.

This water emissions report also contains a glossary of terms used herein and an overview of analytical techniques used with these technologies.

Generally, there are some water parameters that should be monitored regardless of the emissions being abated, since these may impact the efficacy and efficiency of these water emission technologies: mass flow of water, temperature and pH of water, critical (single) substances from simple plant/units, data on targeted substance concentration and loads, conductivity, BOD, TOC, COD, AOX and rainfall amounts.

1.2 General BAT Reference Documents

The Industrial Emissions Directive (EU) 2024/1785 amending Directive 2010/75/EU establishes the following key requirements for installations:

1. Prevent and control emissions through BATs
2. Take measures to ensure energy efficiency
3. Waste prevention and management
4. Resource conservation
5. Accident prevention and limiting their consequences
6. Compliance with integrated permits.

This report aims to address these key elements related to emissions to water.

Other BAT conclusions and reference documents which could be relevant for the activities covered by these BAT conclusions in this document are the following:

- Common Waste Water and Waste Gas /Treatment/Management Systems in the Chemical Sector (CWW)
- Waste Treatment (WT)
- Production of Polymers (POL)
- Monitoring of Emissions to Air and Water from IED Installations (ROM)
- Economics and Cross Media Effects (ECM)
- Energy Efficiency (ENE).

These BAT conclusions apply without prejudice to other relevant legislation, e.g. on the registration, evaluation, authorization and restriction of chemicals (REACH), on classification, labelling and packaging of substances and mixtures (CLP).

In addition, companies producing fluoropolymers can become certified to the most widely recognized and adopted environmental management (EMS) framework, ISO 14001:2026. The standard provides a framework for organizations to design and implement an EMS and continually improve their environmental performance. By adhering to this standard, organizations can ensure they are taking proactive measures to minimize their environmental footprint, comply with relevant legal requirements, and achieve their environmental objectives. By adopting this standard, a commitment is made not only to regulatory compliance but also to continuous environmental improvement.

According to ISO 14001:2026: “The purpose of this International Standard is to provide organizations with a framework to protect the environment and respond to changing environmental conditions in balance with socio-economic needs. It specifies requirements that enable an organization to achieve the intended outcomes it sets for its environmental management system.

A systematic approach to environmental management can provide top management with information to build success over the long term and create options for contributing to sustainable development by:

- protecting the environment by preventing or mitigating adverse environmental impacts;
- mitigating the potential adverse effect of environmental conditions on the organization;
- assisting the organization in the fulfilment of compliance obligations;
- enhancing environmental performance;
- controlling or influencing the way the organization's products and services are designed, manufactured, distributed, consumed and disposed of by using a life cycle perspective that can prevent environmental impacts from being unintentionally shifted elsewhere within the life cycle;
- achieving financial and operational benefits that can result from implementing environmentally sound alternatives that strengthen the organization's market position;
- communicating environmental information to relevant interested parties.”

The ISO 14001 requires the establishment of an environmental policy, identification of environmental aspects and impacts, setting environmental objectives and targets, implementing operational controls to minimize environmental impact, establishment of procedures to monitor environmental performance, and the review and updating of the environmental plan. Monitoring and measurement of environmental performance are requirements of the standard, as is training employees to the EMS and compliance with applicable environmental laws and regulations.

The principles and practices are also embodied in the general BATs in the Appendix.

1.3 Overview of Potential Water Emissions Relevant for Fluoropolymer Manufacturing

In 2021, the OECD defined per- and polyfluoroalkyl substances (PFAS) as fluorinated substances that contain at least one fully fluorinated methyl or methylene carbon atom (without any H/Cl/Br/I atom attached to it) (OECD, 2021).

Fluoropolymers are a polymeric PFAS with a carbon-only polymer backbone and fluorine atoms directly attached. The OECD wrote a report outlining fluoropolymer production, use, degradation and environmental emissions from a life cycle perspective (OECD, 2025).

All fluoropolymers begin with similar types of substances (e.g., monomers, initiators, chain transfer agents, reaction medium, inert gas stabilizer, pH adjuster, etc.). Some fluoropolymers require the use of polymerization aids in their manufacture. The starting substances in fluoropolymers were assigned hazard, use, exposure controls and physical chemical properties when they were EU REACH-registered. This information is available for use by authorities setting permits for water emissions from fluoropolymer manufacturing.

The types of potential PFAS water emissions from fluoropolymer manufacture discussed in this document are shown here.

- Monomers
- Ultra-short chain PFAS (with 2-3 carbons)
- Short Chain PFAS (with 4-7 carbons)
- Longer Chain PFAS (with 8-21 carbons)

Not all of these substances are relevant for all fluoropolymer manufacturing facilities, therefore potential water emission composition will vary. Note also that detection of substances in water and reporting of emissions per government permits does not equate to noncompliance.

2. Adsorption on activated carbon and ion exchange resin technology

2.1 Basic information about the technology

Adsorption is a treatment process where molecules or ions are removed from water by binding to the surface of the solid adsorbent. Hydrophobic or electrostatic interactions, ligand exchange and hydrogen bonding are the mechanisms by which substances of interest in water are removed by adsorption (O'Connor et al., 2022; Collivignarelli et al., 2023; Tshangana et al., 2025; Asharuddin et al., 2026). Activated carbon and ion exchange resin media are commonly used to remove PFAS from wastewater streams from manufacturing of fluoropolymers.

Adsorption is based on the transfer of soluble substances from the water phase to the surface of the adsorbent, which consists of solid, highly porous particles.

Adsorption processes are divided into (Brinkmann et al., 2016):

- Mixing, which is usually used for batch-wise treatment.
- Percolation, which is used for continuous treatment. This is normally done with a fixed bed adsorber packed in two columns that are alternately on duty and undergoing backwashing.
- Pulse-bed or moving-bed process, which is applied in continuous treatment systems where wastewater percolates through the column while the adsorbent is conveyed counter-currently.

2.1.1 Granular Activated Carbon (GAC)

Activated carbon in powder, granular or impregnated form is a commonly used adsorption material. This technology is frequently used on a large scale to remove PFAS from industrial wastewater and drainage water, but any type of aqueous stream such as surface water, leachate water, process water in physicochemical soil remediation can be treated as well (Brinkmann et al., 2016; Goelen et al., 2023).

Granular activated carbon beds can be used on their own or with other technologies. They are usually used in series with one bed serving as the main bed which removes the bulk of foreign substances and the other one as either a polishing step or for safety in case of breakthrough.

Since the adsorbent-active surface is often liable to clogging and blockage, the wastewater needs to be as free of solid content as possible to protect carbon beds. This can be resolved by installing upstream filtration, e.g. sand filtration. Exchange sites on the activated carbon sometimes get clogged with debris (PFAS, non-PFAS compounds, solids and microbial growth)

requiring a wash step to maintain the bed capacity to adsorb PFAS (US EPA, 2024). The backwash liquid is subsequently treated.

The adsorbent has to be replaced with fresh material when its capacity is exhausted. This is due to the finite capacity of adsorbent for each compound to be removed. Spent adsorbent is either regenerated or incinerated. According to Sanzana et al., 2025, most GAC is not regenerated.

2.1.2 Ion exchange resin (IER) technology

Ion exchange technology is based on the removal of unwanted or targeted ions from the water/solution. Captured ions are temporarily retained and afterwards released into a regeneration or backwashing liquid (Brinkmann et al., 2016).

Ion exchange resins are usually macroporous granules with cationic or anionic functional groups. These include (Brinkmann et al., 2016):

- strong acid cation exchangers that can neutralize strong bases. They convert neutral salts into their corresponding acids
- weak acid cation exchangers that can neutralize strong bases. They are used for dealkalisation
- strong base anion exchangers that can neutralize strong acids. They convert neutral salts into their corresponding bases
- weak base anion exchangers that can neutralize strong acids. They are used for partial demineralization

Ion exchange resins for removal of PFAS can include single-use and regenerable resins. Single-use anion exchange resins are used until breakthrough occurs, which occurs when the ion exchange resin is no longer able to bind new molecules and targeted substances may breakthrough the IER. At that point, when the substance concentration in the treated water reaches a pre-established threshold, known as the breakthrough concentration, the resin is then removed and disposed of by incineration or landfilling. Regenerable resins are used until breakthrough but are then regenerated on site using a regenerant solution capable of returning a reduced capacity to the resin (ITRC, 2023).

Ion exchange resins are used to exchange ions with PFAS removing them from water. The efficiency of the ion exchange is dependent on the functional groups of the PFAS molecule which binds with resin. This technology can be used to capture and remove a broad range of PFAS such as long-chain, short-chain and ultra-short PFAS, as well as fluorinated polymerization aids, efficiency depending on resin design and operating conditions. According to the ITRC and other sources, IER have a higher capacity for removing shorter chain PFAS than GAC (ITRC, 2023; Yadav et al., 2022; O'Connor et al., 2022). Manufacturing programme members dispose of ion exchange resin waste containing fluorinated polymerization aid, and potentially other captured PFAS, by incineration by third party.

2.2 Information on the current use of the technology

Adsorption using granular activated carbon and ion exchange media has been proven effective at full scales (ITRC, 2023) and both of those technologies are used for a treatment of PFAS. Adsorption is widely recognized as a practical and effective treatment method due to its technological advancement and ease of implementation (Zeeshan et al., 2025).

2.3 Environmental performance of the technology (key data)

2.3.1 Adsorption on carbon bed

The efficiency of adsorption processes varies with wastewater composition as well as concentration of the feed. Treatment needs to take into account the concentration of influent and the desired final concentration, PFAS type and the matrix. The input and output of the adsorber have to be monitored for compounds in question (Brinkmann et al., 2016).

Adsorption is influenced by surface area of the adsorbent, particle size, pore size distribution, pH, co-existing ions, and coexisting organic matter (Sanzana et al., 2025; O'Connor et al., 2022; Gal et al., 2025; Zeeshan et al., 2025).

Activated carbon can achieve a removal efficiency of 90 to >99% for PFAS but this is highly dependent on the type of PFAS, the type of activated carbon used, the presence of other components in the influent, the service life of the carbon beds and the number of carbon beds in series that are used. Removal of PFAS by activated carbon is generally more efficient for long chain rather than short chain PFAS, as the latter will break through first. Therefore, an efficiency of PFAS removal decreases with decreasing chain length of PFAS (Goelen et al., 2023; ITRC, 2023). However short chain PFAS can be removed with an efficiency of up to 99% under optimised operating conditions if water treatment is controlled by the type of PFAS and more frequent bed changes (Goelen et al., 2023). It is possible to enhance short chain adsorption by GAC by incorporating modified carbon-based adsorbents that better target short chain PFAS capture (Chen et al., 2025). In addition, the ITRC (2023) noted that Shorter-chain PFAS can be effectively removed by GAC adsorption if the changeout frequency is determined based on the breakthrough of these short-chain PFAS.

Since most of PFAS monomers have limited (or no) water solubility, adsorption has limited efficiency in their removal.

2.3.2 Ion exchange resin technology

As reported by Goelen et al. (2023) ion exchange resins can remove 90 to >99% of PFAS mixture composed of short and long chains. This technology has a higher PFAS removal capacity, shorter contact times and lower material consumption possible compared to granular activated carbon.

PFAS removal efficiency by ion exchange is dependent on the type of PFAS, resin material, the nature of matrix, number of filters in the series used and their service life. A selective removal of PFAS can be achieved by choosing the most suitable resin or by taking into account resin properties such as matrix, functional groups and pore sizes. The input and output of the ion exchange column have to be monitored for compounds in question and the moment of breakthrough. Pressure drops, pH, effluent concentration of the ions and electrical conductivity must be controlled (Brinkmann et al., 2016).

Hydrophobic or electrostatic interactions, ligand exchange and hydrogen bonding are the mechanisms by which water contaminants are removed by adsorption (O'Connor et al., 2022; Collivignarelli et al., 2023; Tshangana et al., 2025; Asharuddin et al., 2026). The PFAS removal efficiencies of adsorption technologies are related to the way the PFAS is bound to the adsorbent and to the size of the PFAS. It is thought that hydrophobicity of the resin influences efficiency of removal of PFAS. The mechanism of PFAS removal from water is dependent on the length of the PFAS chain. Longer chain PFAS can be removed by direct adsorption on the resin and binding of functional groups in PFAS molecule with functional groups of the resin. Electrostatic interaction (Zeidabadi, Esfahani and Mohseni, 2023) and ion exchange govern the removal of short chain PFAS. The capacity of removal of shorter chain PFAS is therefore lower

than longer chain PFAS although ion exchange is more efficient in removal of short chain PFAS comparing to granular activated carbon (Goelen et al., 2023).

Efficiency is also dependent on the nature of functional groups. Sulphonamide groups will be removed with higher efficiency than sulphonic acid groups. Sulfonic acid groups are reported to be separated with a higher efficiency than carboxyl groups (Goelen et al., 2023).

Not specific to PFAS, generally, ion exchange can achieve effluent ion concentrations in the range of 0.1–10 mg/l for influent concentrations at 10–1 000 mg/l (Brinkmann et al., 2016). Furthermore, high volume reduction of waste stream is possible in the range of 300,000:1 to 1,000,000:1. According to Manufacturing Programme members operational experience, ion exchange resin technology can achieve efficiency in the range of 80 to 99% and in principle, a significant reduction of emissions of fluorinated polymerization aid, and potentially other captured PFAS, can be achieved.

2.4 Cross media effects / environmental co-benefits

2.4.1 Adsorption on carbon bed

Activated carbon technology is characterized by low energy demand, simplicity and reliability. Clogging can be easily managed by installation of filters (Goelen et al., 2023). This technology is considered to be non-selective, so other components in the waste stream could adsorb on the activated carbon.

When the adsorptive capacity of the adsorbent has been exhausted, it must be replaced and either subsequently regenerated or if not possible, incinerated. Regeneration and incineration require large amounts of energy. A destruction efficiency of 99.95 to 99.9999% (Troxler et al., 2025) can be obtained by incineration of PFAS adsorbed to granular activated carbon at high temperature. Factors impacting the degrees of PFAS removal and destruction have been documented, including temperature, turbulence, (residence) time, oxygen concentration, incinerator configuration, source of hydrogen, etc. (Reinhart, Bolyard and Chen, 2023; Murakami et al., 2025; Hofman et al., 2025). Hazardous waste incinerators, like rotary kilns with primary and secondary combustion chambers (2-4 sec at $\geq 950^{\circ}\text{C}$) are the most effective with PFAS destruction and removal efficiencies of $\geq 99.9999\%$ (Silsby, et al., 2026). While some incinerators operate at a minimum of 850°C , temperatures within the incinerators are closer to 1000°C . Mixture regeneration and disposal of activated carbon by incineration are recommended.

2.4.2 Ion exchange resin technology

Ion exchange resin technology is simple to use and low energy intensive. Clogging can be easily managed with pretreatment however ion exchange resins are more susceptible to clogging than granular activated carbon technology due to the presence of suspended solids and some solutes in the matrix therefore more intensive pretreatment is necessary (Goelen et al., 2023). Competing ions in the wastewater being treated may cause interference (Brinkmann et al., 2016).

Ion exchange results in the consumption of resins, regeneration liquids, consumption of water for backwashing and rinsing, and energy required to operate the pumps. Incineration may be a preferable disposal route for the ion exchange resins and incinerating resins containing fluorinated polymerisation aid.

The regeneration of ion exchange resins results in a small volume of concentrated acid or salt solution, which contains the removed ions originating from the resin. This enriched liquid has to be treated separately to remove these ions. This is not an energy intensive process. The rinsing

water from regeneration contains the same ions as the brine, but in relatively low concentrations. Whether this part can be discharged directly or has to undergo treatment depends on the actual concentration. Ion exchange implies the consumption of ion exchange resins, regeneration liquids, water for backwashing and rinsing, and energy for the pumps. This technique is simple to use and clogging is easily manageable.

2.5 Economics

2.5.1 Adsorption on carbon bed

Adsorption on granular activated carbon requires initial investment in equipment and installation. Operating costs are fairly low although the costs of ongoing exchanges of carbon beds and filters and the cost of disposal of spent carbon must be considered. There are additional costs for the necessary monitoring for the control of water treatment, such as the moment of PFAS breakthrough.

According to Brinkmann et al. (2016) the investment required in the activated carbon bed equipment in general, and not specifically for PFAS, is in the range of €50,000 to 1,000,000. Regeneration or destruction is more expensive than the treatment itself.

Rental of mobile carbon bed unit is also an option at EUR 600-1,500 per month with additional cost of pumps and pipes to be considered on top. The numbers reported by Goelen et al. (2023) show that the average cost of activated carbon material is €1.5-6.0 per kg. Replacing 8.5 tons of granular activated carbon containing PFAS can cost €52,000 per filling. A processing, transport and cleaning cost of mobile unit can cost over €3,000 depending on the presence of PFAS and other components.

2.5.2 Ion exchange resin technology

Ion exchange technology requires initial investment in equipment and installation. Operating costs involve ongoing exchanges of ion exchange resins and the cost of disposal of spent resin. There are additional costs for the necessary monitoring for the control of water treatment, such as the moment of PFAS breakthrough.

According to Goelen et al. (2023), resins cost between €12 and 15 per kg. The price for a fixed ion exchange resin column with capacity of 4.5 m³ and a maximum flow rate of 65-90 m³/hr requires investment of €2,000,000 and the annual operating costs of, when single use resin is used, €100,000 per year. Rental of mobile unit, transport, cleaning and waste disposal costs are comparable to that of granular activated carbon unit with additional cost of pumps and pipes to be considered on top.

3. Membrane technology: nanofiltration and reverse osmosis

3.1 Basic information about the technology

Membrane separation technology is a widely used method for separating substances from liquid mixtures by employing semi-permeable membranes. Membrane separation works by adsorption, size exclusion, electrostatic interactions and charge neutralization mechanisms (Asharuddin et al., 2026). This membrane acts as a selective barrier, allowing certain species (molecules, ions, particles) to pass through while retaining others, resulting in a clean permeate and a concentrate stream. The driving force for separation can be pressure, concentration,

electrical potential, or temperature gradient, depending on the process. Membranes are classified by the size of their pores and their intended function, ranging from microfiltration and ultrafiltration to nanofiltration and reverse osmosis.

Microfiltration (100-10,000 nm) is typically used for removing large particles, like suspended solids and bacteria, while *ultrafiltration* (10-100 nm) can retain smaller entities such as proteins and colloids. *Nanofiltration* (1-10 nm) targets even smaller organic molecules and divalent ions, and reverse osmosis (0.1-1 nm) is employed to remove dissolved salts and solids from water, enabling effective purification and desalination.

As nanofiltration (NF) and reverse osmosis (RO) membranes can hold back all particles down to the size of organic molecules and even ions, these technologies can be used in the removal of PFAS components from wastewater. Based on the pore size of these technologies NF is mainly efficient in the removal of long chain PFAS while RO is capable of PFAS removal up to the ultra-short chain compounds.

Nanofiltration utilizes membranes with pore sizes in the 1–10 nm range. These membranes are selectively permeable, meaning they allow water and some small molecules to pass while blocking larger dissolved molecules and multivalent ions such as calcium, magnesium and sulfate. The separation mechanism in nanofiltration combines both size exclusion (the physical blocking of particles larger than the membrane's pores) and charge effects (the membrane surface often carries a charge that repels similarly charged ions). NF does not effectively remove all salts or monovalent ions, so it is not suitable when very high purity is needed. Reported PFAS removal efficiencies for NF are in the range of 90-99% (Tshangana et al., 2025). Membrane fouling (blockage or degradation due to accumulation of contaminants) can reduce efficiency and require periodic cleaning or pretreatment steps.

Reverse osmosis is the most selective membrane process with a molecular-size separation ~0.1–1 nm, capable of removing nearly all dissolved solids, inorganic ions, organics, and even bacteria and viruses. RO membranes are extremely dense (typically non-porous), so separation is achieved primarily by a solution-diffusion mechanism: water molecules dissolve into the membrane material and diffuse across in response to applied pressure, leaving solutes behind. RO has a >99% PFAS removal efficiency (Tshangana et al., 2025) and is effective for removing short and long chain PFAS. Manufacturing Programme members report RO removal of monomers and ultra short chain PFAS under appropriate operating conditions. Despite its remarkable effectiveness, reverse osmosis does present certain operational challenges. The high pressures required lead to greater energy consumption, and the dense nature of the membranes means they are prone to fouling and scaling, particularly if the feed contains particulates or organic matter. Therefore, rigorous pretreatment is essential—this may involve sedimentation, filtration, or the use of chemical antiscalants and biocides. Additionally, RO membranes are sensitive to chlorine and other oxidants, which can degrade the membrane material and compromise performance.

3.2 Information on the current use of the technology

Membrane based separation technology is a proven technology that is widely used in industry for various applications and has also been applied to PFAS removal from (waste) water.

Nanofiltration is widely used for water softening, where hardness ions are removed while retaining most of the salts, and in the treatment of industrial wastewater to eliminate color, organic compounds, and heavy metals. Food and beverage industries employ nanofiltration for processes such as sugar concentration and decolorization, while chemical manufacturers utilize it for the recovery of valuable chemicals from process streams and the recycling of water.

Similarly, the applications of reverse osmosis are extensive. It is a cornerstone technology for desalination, converting seawater or brackish water into potable water. In the chemical and electronics industries, RO is used to produce ultrapure water and recover valuable chemicals from waste or process streams. Its ability to remove dissolved salts, heavy metals, and organic substances makes it indispensable for compliance with stringent environmental discharge regulations and for producing high-quality process water.

3.3 Environmental performance of the technology (key data)

Membrane separation technologies (NF and RO) can achieve high PFAS removal efficiencies when properly designed and operated with the required pre-treatment to prevent extensive membrane fouling. This technology is not specific for any one type of PFAS. Factors affecting removal efficiencies for monomers include their concentration, water solubility, hydrophobicity and functionality.

NF is mainly effective for long chain PFAS, removal efficiency of >95% can be achieved. For RO membranes >99% removal can be achieved for long, short and ultrashort PFAS compounds.

Both membrane separation techniques create a clean permeate stream, a smaller highly concentrated waste stream, and spent membranes which need further treatment by other technologies.

3.4 Cross media effects / environmental co-benefits

The most direct effect of NF and RO processes is in addition to the efficient removal of PFAS components, other substances could be removed from water streams enabling safer drinking water, reliable water reuse, and compliance with environmental regulations for industrial effluents. However, the treatment process produces a concentrated waste stream, often referred to as brine or concentrate, which contains high levels of the targeted substances removed from the feed water. In wastewater abatement, the membrane separation technology should not be seen as a final step, but as a concentration step that could improve the efficiency of upstream PFAS removal technologies, like adsorption or (thermal) destruction. Coupling membrane separation with adsorption could reduce the PFAS load entering the membrane unit, while the membrane step concentrates remaining PFAS into a smaller stream requiring further treatment or disposal (Tshangana et al., 2025).

3.5 Economics

The economics of nanofiltration and reverse osmosis are shaped by initial investment costs, depending on the volumetric flow, the complexity of the wastewater, the permeate requirements and operating expenses. Reverse osmosis systems typically require a higher capital investment, since the process relies on tighter membranes and robust components capable of withstanding high operating pressures. These systems also need sophisticated pre-treatment solutions to minimize scaling and fouling, which adds to the overall complexity and cost. In contrast, nanofiltration operates at lower pressures, usually between 5 and 20 bar, allowing for smaller and less expensive pumps and pressure vessels. Pre-treatment is still necessary but generally less demanding, resulting in lower capital costs for NF installations.

When it comes to operating costs, energy consumption is a major factor. RO demands more energy due to its higher pressure requirements, which could account for up to half of the total operating expenses. Nanofiltration is more energy-efficient, with energy costs typically 30 to 60 percent lower than those of RO, thanks to its greater permeability and moderate pressure needs. Both technologies require regular maintenance and membrane replacement, but RO membranes are subject to more frequent cleaning and replacement because of the harsher conditions involved. The use of chemicals is also higher in RO systems, which often need

antiscalants and pH adjustment to protect the membranes, while NF systems generally have milder chemical requirements. Labor costs for both technologies are relatively moderate, since both are largely automated, though RO plants may require more technical expertise due to their complexity.

Inherent to membrane technology is the generation of a highly concentrated PFAS effluent stream (~10% of feed) that needs to be dealt with. Additional costs will be associated for downstream abatement technologies, like adsorption or thermal destruction. A benefit from this could be the higher efficiency of the downstream abatement systems due to the highly concentrated waste stream provided by the RO system. NF may also have a higher water recovery than RO.

4. Filtration technology

4.1 Basic information about the technology

Filtration describes the separation of suspended solids from wastewater effluents passing through a porous medium yielding a clarified liquid as a filtrate. The solid particles remain on the filter medium forming a filter cake. The structure and permeability of this cake evolve over time, influencing both the rate and efficiency of filtration. A filter aid can be added to improve permeability and create a more favorable cake structure. Periodic removal of the solids or replacement of the filter medium is required to maintain required filtration capacity and efficiency. In PFAS abatement filtration is mainly used as a pre-treatment step to protect downstream equipment from fouling or abrasion.

Filtration is driven by various forces, depending on the process requirements. Gravity filtration relies simply on gravity and tends to be relatively slow. Applying a pressure difference, either vacuum or positive pressure accelerates the liquid flow. For rapid separation, especially when fine particles are involved, centrifugal filtration is utilized.

Commonly used types of filter systems include:

- Filter presses: These batch-operated systems use plates and frames or recessed plates to trap solids between filter cloths. After filtration, the press is opened to remove the cake, which is often quite dry, making this technology ideal for capturing high-value or hazardous solids.
- Rotary drum vacuum filters: Widely used for continuous processes, these feature a rotating drum partially submerged in the slurry. A vacuum draws liquid through the drum's surface, and the resulting cake is removed by a scraper or blow-off.
- Nutsche filters: Enclosed vessels allowing filtration under pressure or vacuum. They are widely used for hazardous or sensitive materials and facilitate washing and drying of the filter cake within the same unit.
- Centrifuges (e.g., peeler, decanter, basket types): These use high rotational speeds to generate centrifugal forces, rapidly separating solids from liquids and achieving low moisture in the cake.

4.2 Information on current use of the technology

Filtration is a widely used process in industrial environments for removing suspended solids from liquids. This technique is rarely used as a stand-alone treatment and is frequently used as a pre-treatment step for other downstream PFAS abatement technologies. Filters typically

require a cleaning operation, i.e. backwashing, with the reverse flow of fresh water and the accumulated material returned to the sedimentation tank.

4.3 Environmental performance of the technology (key data)

The environmental performance of filtration is dependent on the characteristics of the wastewater and the filtration technology employed. The CWW BREF reports Total Suspended Solids abatement efficiencies ranging from 50% to 99.99% for filtration systems such as sand filters (Page 191, Brinkmann et al 2016).

4.4 Cross media effects / environmental co-benefits

When a granular filter, e.g. a sand filter, is used, the backwashed material is normally recirculated to the process from where it originated, e.g. to the sedimentation tank. The residue from other kinds of filters (drum filter, belt filter, etc.) can either be recycled or needs to be discharged as waste or to undergo further treatment.

Sand filtration, as an example of deep-bed filtration, entails less frequent backwashing than cake filtration (e.g. belt or drum filtration) and thus a lower requirement for backwash water. In oily water removal, the backwash water is typically 4-7% of the forward processed flow volume. Cake filtration is applied only in exceptional cases in wastewater treatment.

The operating equipment can be a significant noise source, which can be controlled by enclosing the main sources.

If odorous substances are released, closed devices might be necessary. Pressure filters and filter presses are placed in closed vessels and the exhaust air passes through a duct to a gas abatement system. To ensure reliable operation, the turbidity of the filtered effluent has to be monitored to recognise disturbances, or a breakthrough in semi-continuous sand filter. The pressure drop has to be registered to indicate clogging and blocking.

4.5 Economics

Filtration is a relatively inexpensive simple treatment option usually used to complement other more complex processes. The investment costs are related to the volume of water to be treated. Investment and operating costs for a simple filtration system are EUR < 0.1 per m³ and EUR 0.01 per m³, respectively (Brinkmann et al 2016, page 193).

5. Evaporation technology

5.1 Basic information about the technology

Evaporation is a concentration technology used to separate water from PFAS-containing wastewater. During the process, water is removed as a vapour phase while dissolved and suspended constituents, including PFAS, remain in a concentrated residual stream. Because PFAS and their associated salts are significantly less volatile than water, evaporation can effectively reduce wastewater volumes and increase targeted substance concentrations in the residual liquid. The resulting concentrate may subsequently require treatment by another technology, such as thermal destruction, to achieve final removal of PFAS.

The technology is commonly applied where wastewater volume reduction, resource recovery, or preparation of waste streams for downstream treatment is required. Water vapour generated

during evaporation is condensed and may be recycled, reused, or subjected to additional treatment depending on site-specific requirements and water quality objectives.

Evaporation systems may operate under atmospheric pressure or under vacuum conditions. Vacuum operation reduces the boiling temperature of the liquid, which can improve energy efficiency and minimise thermal stress on temperature-sensitive substances. The selection of evaporator design depends on the characteristics of the wastewater, operational requirements and recovery objectives.

A range of evaporator technologies is available for industrial applications. Common designs include natural circulation evaporators for relatively stable process streams, short-tube vertical and basket evaporators for non-corrosive liquids, falling-film evaporators for efficient concentration of aqueous solutions, and agitated thin-film evaporators for more demanding applications involving viscous materials or products requiring enhanced heat transfer. These technologies are used across a variety of industrial sectors, including chemical manufacturing, polymer production, pharmaceuticals and fertiliser production.

5.2 Information on current use of the technology

Evaporation systems used for industrial wastewater treatment are frequently configured in multiple stages to improve energy efficiency. In these systems, thermal energy recovered during the condensation step may be reused elsewhere within the process, reducing overall energy demand. Where appropriate, evaporation can also be operated under vacuum conditions, allowing water to evaporate at lower temperatures and thereby reducing thermal stress on the process stream. Typical operating conditions depend on system design, wastewater composition, and recovery objectives. Typical operating conditions reported in the CWW BREF (Brinkmann et al, 2016) are pressures of 12–20 kPa and temperatures of 50–60 °C.

The concentrated residual stream generated during evaporation requires appropriate management. Depending on its composition, the concentrate may be temporarily stored before further treatment, recycling, recovery, or disposal. Storage capacity and handling arrangements should therefore form an integral part of the overall evaporation system design.

5.3 Environmental performance of the technology (key data)

Evaporation is a technique used to concentrate PFAS, enabling the implementation of zero liquid discharge systems and allowing for water recovery within the process. The resulting waste, which contains the concentrated PFAS, must then undergo thermal destruction to achieve complete mineralization.

5.4 Cross media effects / environmental co-benefits

Evaporation can contribute significantly to wastewater volume reduction by separating water from dissolved and suspended substances, thereby generating a concentrated residual stream that can be managed more effectively by downstream treatment technologies. In many applications, the condensed water may be reused within the process or subjected to further treatment prior to discharge, supporting water conservation objectives. Where this approach is implemented as part of an integrated treatment strategy, evaporation can contribute to a reduction in liquid waste requiring final treatment or disposal.

The environmental performance of evaporation is influenced by energy consumption, operational conditions, and the characteristics of the wastewater being treated. According to the CWW BREF, vacuum evaporation typically requires 0.25–0.45 kWh/L of energy, while water consumption may range from 5 to 16 kg of water per kilogram of steam generated. Where

feasible, the use of waste heat recovery, multi-stage evaporation systems, or other energy efficiency measures can reduce operational impacts.

Effective operation requires ongoing maintenance and process control. Heat transfer surfaces may be affected by fouling, scaling, or corrosion, which can reduce efficiency and increase maintenance requirements. In addition, wastewater streams containing suspended solids, colloidal material, or substances prone to foaming may require pretreatment to ensure reliable operation. Monitoring of condensate quality, including parameters such as pH, conductivity and total organic carbon (TOC), can help verify process performance and identify any transfer of volatile contaminants into the recovered water stream.

Evaporation is commonly applied where recovery of valuable materials, concentration of wastewater streams, or preparation of residuals for further treatment is required. The concentrated residue generated by the process may subsequently require recycling, recovery, thermal treatment or disposal, depending on its composition and the site's waste management strategy. In the case of PFAS-containing streams, evaporation is generally considered a concentration step rather than a final treatment technology, as the concentrated PFAS-containing residue typically requires further management, such as thermal destruction.

Advantages of evaporation include wastewater volume reduction, potential recovery of materials and water, and improved efficiency of downstream treatment technologies through concentration of contaminants. Limitations include energy demand, management of concentrated residual streams, sensitivity to fouling and corrosion, and the potential transfer of volatile substances into the condensate if appropriate controls are not maintained.

5.5 Economics

Table 3.96 page 265 from the CWW BREF (Brinkmann et al., 2016) indicates that vacuum evaporation is associated primarily with significant capital (investment) costs. The investment costs depend strongly on plant capacity. For example, a system handling a flow of 70 l/h is estimated at around EUR 50,000, while a larger system of 300 l/h may cost about EUR 155,000. These costs can increase further, up to approximately EUR 245,000, when more corrosion-resistant materials such as high-grade stainless steel (e.g. AISI 316) are required.

6. Destruction Technology – Incineration with flue gas scrubbing

6.1 Basic information about the technology

6.1.1 Incineration

In Europe, municipal solid waste (MSW) is incinerated in:

- travelling grate ($\geq 850 - 1100\text{ }^{\circ}\text{C}$, $\geq 2\text{ sec}$, $\geq 6\%$ oxygen)
- rotary kiln ($500 - 1450\text{ }^{\circ}\text{C}$, usually $> 850\text{ }^{\circ}\text{C}$) and
- fluidised bed incinerators ($760 - 871\text{ }^{\circ}\text{C}$) (Neuwahl, et al., 2019).

Sewage sludge (from waste treatment plants) is incinerated in rotary kiln, multiple hearth or fluidised bed incinerators (Neuwahl, et al., 2019).

Hazardous and clinical waste is usually incinerated in rotary kilns (Neuwahl, et al., 2019) at 600 - 850 °C in the primary combustion chamber and at 1100 °C ≥ 2 sec in the secondary combustion chamber or afterburner.

Incineration is one of the disposal techniques for selected wastewater derived streams. In addition to municipal solid waste, secondary wastes generated in other abatement technologies (e.g., spent adsorbent, flue gas condensate, water from scrubbers, etc.) are incinerated. Most fluoropolymer waste in Europe is incinerated. Hazardous waste incineration is the dominant end-of-life route (~50%), achieving destruction efficiencies exceeding 99.9999% under regulated conditions. Municipal waste-to-energy (~22%) achieves comparable performance under routine operating conditions. (Ramboll Deutschland GmbH, 2026, Conversio, 2022).

Directive 2010/75/EU requires all plants to “keep the incineration or co-incineration gases at a temperature of at least 850 °C for at least two seconds. If hazardous waste with a content of more than 1 % of halogenated organic substances, expressed as chlorine, is incinerated, the temperature has to be raised to 1100 °C for at least two seconds.”

6.1.2 Flue gas scrubbing

For highly contaminated or complex wastewater streams, thermal destruction through incineration, followed by scrubbing, is an effective and commercially applied method. Usually, prior to incineration, waste in water is concentrated by e.g. reverse osmosis, nanofiltration, foam fractionation, or (vacuum-) evaporation or coagulation/flocculation.

6.2 Information on current use of the technology

Incineration is the predominant end of life option for ~72% of the fluoropolymer applications (Ramboll Deutschland GmbH, 2026). Waste-to-energy recovery (860 °C, 2 sec) or waste incinerators (1095 °C, 2 sec) are the PFAS destruction technologies used in the EU. The degree of mineralization can be assessed by destruction or reduction rate for products of incomplete combustion (R2PIC) or less effectively by a fluorine mass balance, which is challenged by high PFAS background levels and fluorine reactivity with refractory materials in incinerator construction (Yamada et al., 2005). R2PIC was >99.99% for incinerators operating at > 860 °C for 2 sec residence time (Gehrmann et al., 2024). The second study expands and validates these findings in a full-scale thermal waste treatment (TWT) plant in Schweinfurt in 2025 with a throughput of 190,000 t per year, achieving destruction efficiencies exceeding 99.9999% under regulated conditions. Water-soluble PFAS emissions remain below 1 gram per tonne of fluoropolymer treated. Municipal waste-to-energy achieves comparable performance under routine operating conditions. (Warnecke et al 2026).

For complex wastewater streams or those with high concentrations of targeted substances, thermal destruction through incineration, followed by scrubbing, is an effective and commercially applied PFAS abatement method. Wet scrubbers are used to neutralize and capture hydrogen fluoride (HF) neutralized with alkaline solutions (e.g. lime or caustic soda) and other acid gases and particulates.

Activated carbon filters may be used as a polishing step to capture residual organics and micropollutants.

6.3 Environmental performance of the technology (key data)

Incineration at temperatures and residence times > 1000 °C and 2 sec are extremely effective (>99.9%) at reducing emission of products of incomplete combustion and PFAS destruction. Waste incineration at lower temperatures and different residence times may result in release of products of incomplete combustion and fly ash or slag containing residual PFAS. A joint study

verified by the US EPA and the US Department of Defense found PFAS at hazardous waste incinerator destruction and removal efficiencies from 99.95 to 99.9999% (Troxler et al., 2025). No products of incomplete destruction were observed.

6.4 Cross media effects / environmental co-benefits

At inappropriate temperatures and residence times (<860 °C, < 2 sec), products of incomplete combustion may be formed and released from the incinerator. However, appropriate incinerator design, temperature, residence time, turbulence, oxygen concentration, etc. can steer the results of incineration towards substantially complete destruction (Reinhart, Bolyard and Chen, 2023; Murakami et al., 2025; Hofman et al., 2025).

The GKS waste-to-energy plant in Schweinfurt, Germany completed studies on measurement and analysis methods for PFAS in flue gas and residues of municipal solid waste incinerators (Warnecke, et al., 2026). Three different operating conditions were studied: 1) household waste and household-type commercial waste, 2) scenario 1 waste plus co-incineration of PFAS-contaminated soil with compost and sewage sludge, 3) worst-case scenario, a blend of PTFE, PFA, PVDF, FKM, PFPE-based lubricants, polymer-based coating suspensions with side-chain fluorinated polymers, as well as fluorinated firefighting foams. Volatile and non-volatile PFAS and products of incomplete combustion were analysed in addition to HF and inorganic F. At temperature ≥ 850 °C for 2 seconds, the total delta destruction ratio was > 99.9999 wt.% (excluding CF₄) or 99.7% with CF₄ included. Silsby et al., 2026 found that high destruction ratios (>99.9999%) could be achieved with 2–4 seconds at temperature ≥ 950 °C, and, that concentration of C₂F₆ could serve as a potential indicator for effective PFAS destruction. Warnecke et al. 2026 found no C₂F₆ above the LOD indicating substantially complete destruction.

Wet scrubbers are used to neutralize and capture hydrogen fluoride (HF) from the incinerator flue gas stream, which is then neutralized with alkaline solutions (e.g. lime or caustic soda). These wet scrubbers are also used to remove other acid gases and particulates from the gas stream.

The resulting scrubber water (effluent) may contain fluoride ions and trace PFAS degradation products. This effluent must be treated or disposed of appropriately (e.g. further treatment, evaporation, or incineration).

6.5 Economics

For most destructive technologies a larger space is required. These technologies are extremely expensive and energy intensive. The design of the reactors is complicated. Energy costs are high and capital expenses are higher than separation technologies. However, destructive technologies destroy PFAS, whereas separation technologies do not. Incineration is energy intensive. Capital and operating expenses are high.

7. Stabilization (or sequestration) technology: buffer storage

7.1 Basic information about the technology

Under both routine and non-routine operating conditions, events such as equipment malfunctions, leaks, unintended contamination of cooling water, or disruptions to production and

storage activities can lead to increased substance discharges, including PFAS, to receiving waters via the wastewater treatment plant (WWTP) or adversely affect treatment performance. To manage these risks, facilities may implement centralized or decentralized collection and buffer systems to temporarily retain impacted wastewater streams. The effectiveness of these systems depends on the timely identification of abnormal operating conditions through a combination of monitoring, operational controls and organisational procedures. When integrated into a site's overall wastewater management strategy, buffer systems can help minimise the risk of uncontrolled releases and reduce pollutant emissions to receiving waters.

7.2 Information on current use of the technology

A range of buffer storage approaches may be used to temporarily contain wastewater during abnormal operating conditions or system upsets. Buffer capacity is typically determined through a site-specific assessment that considers wastewater volumes, characteristics of targeted substances, treatment system capacity, and potential environmental impacts.

Facilities may operate dedicated storage tanks that allow wastewater potentially containing targeted substances to be isolated, sampled and evaluated before being discharged for treatment, recycling or disposal. In some cases, wastewater is diverted automatically to buffer storage following the detection of an operational disturbance, equipment malfunction or other abnormal event. The design and capacity of these systems depend on the nature of the wastewater streams being managed and the anticipated duration of the event.

Buffer systems can be applied to individual process units, selected wastewater streams or site-wide wastewater management systems. The choice of configuration is influenced by factors such as operational complexity, available space, wastewater volumes and the level of environmental protection required.

In addition to dedicated buffer tanks, facilities may implement separate drainage and collection systems to capture water potentially containing targeted substances arising from production areas, storage facilities or accidental releases. These systems help prevent unintended discharges and allow collected wastewater to be managed appropriately before treatment or disposal.

7.3 Environmental performance of the technology (key data)

Successful sequestration of water containing targeted substances prevents discharge to the environment. In conjunction with timely leak detection and monitoring of normal operations capable of detecting failure events, this technology is effective at preventing emissions to the environment.

The main driver for implementing this technique is the need to comply with regulatory requirements aimed at protecting receiving waters from pollution.

7.4 Cross media effects / environmental co-benefits

The use of storage buffer tanks prevents increased discharge of targeted substances such as PFAS into the environment resulting from other than normal operating conditions (e.g., operational failures, equipment leakage, unintentional contamination of cooling water, or other disturbances in production or storage units). Centralized or decentralized receiving (or buffer) facilities sequester water containing targeted substances from entering the environment. In conjunction with timely detection of the failure event, which can be ensured by both analytical and organizational means, buffer storage allows for lower emissions to the receiving water.

7.5 Economics

According to the CWW BREF (Brinkmann et al., 2016), the costs associated with buffer storage are influenced by factors such as storage capacity, site conditions, installation requirements and construction materials. As an indicative example, a concrete storage tank may cost approximately EUR 100 per cubic meter, excluding installation and ancillary equipment. Alternative materials may result in higher costs; for example, a covered polyester tank with a capacity of 100 m³ and a mixer has been reported to cost approximately EUR 50,000.

8. Monitoring and Analysis

8.1 Information on the current use of the technology

The Manufacturing Programme members use a variety of technologies to monitor non-polymeric PFAS emissions to water. Monitoring programmes agreed upon with national authorities are routinely performed.

Periodic monitoring of abatement technology performance (e.g. GAC, ion exchange, reverse osmosis) is done by LC-MS/MS in the internal laboratory or by an external company.

Ultraviolet Visible (UV-VIS) Spectroscopy based monitoring is performed for fluorinated polymerisation aids. PFCAs and PFSA's (C4-C14, C16, C18) are analysed by LC-MS/MS according to ISO 21675 (internally validated procedure). Ultrashort-chain PFAS may be analysed by LC-MS/MS using an internally validated method.

Mass balances for some non-polymeric PFAS are performed periodically.

8.1.1 LC-MS/MS

LC-MS/MS by direct injection or Solid Phase Extraction (SPE) is the analytical technique in the EU Drinking Water Directive (DWD) for total PFAS and PFAS sum. LC-MS/MS methods include U.S. EPA 533, 537.1, 1633, and EU DWD methodology; online monitoring by LC/MS/MS can be performed at certain locations.

Automated sampling based on effluent flow rates can be used to generate average daily samples. Analyses of automated monthly composite samples of onsite effluent treatment plant discharge can be done by LC-MS using internal and external laboratories. Monthly monitoring can be performed at emission points on samples captured using 24-hour automated sampling.

The Manufacturing Programme members perform manual periodic sampling based on the water emissions where the frequency is dependent on the selected abatement technology. For example, periodic monitoring of GAC abatement technology is done by LC-MS/MS in the internal laboratory or by an external company. Activated carbon beds and ion exchange resins are sampled with a frequency that will indicate the moment of breakthrough.

8.1.2 Mass balances

Periodic mass balances are currently performed for a small number of non-polymeric PFAS. Annual mass balances are performed for additional non-polymeric PFAS used in the fluoropolymer manufacturing process and other non-polymeric PFAS expected to be generated or released.

8.2 Environmental performance of the technology (key data)

8.2.1 LC-MS/MS

The LC-MS/MS technique may allow for the information to be obtained on the presence and emissions of specific non-polymeric PFAS as well as information on the efficiency of emission reduction technologies.

The analytical detection limit could be limiting in verifying efficiency of abatement technology. The EU DWD calls for the monitoring of the following 20 PFAS for the *sum of PFAS*: substances which contain a perfluoroalkyl moiety with 3 or more carbons (i. e. $-\text{C}_n\text{F}_{2n}-$, $n \geq 3$) or a perfluoroalkyl ether moiety with 2 or more carbons (i. e. $-\text{C}_n\text{F}_{2n}\text{OC}_m\text{F}_{2m}-$, n and $m \geq 1$). The overall chain length comprises 4 to 13 carbon atoms with 10 perfluoroalkyl carboxylic acids (PFCAs) and 10 perfluoroalkyl sulfonic acids (PFSAAs).

8.2.2 Mass balances

Mass balances are useful estimates of overall emissions to all compartments.

8.3 Cross media effects / environmental co-benefits

8.3.1 LC-MS/MS

Although monitoring has no direct environmental benefit, it provides the information necessary to identify and implement improvement measures. The foundation for continuous improvement is verification of the baseline efficiency of existing abatement technologies and the commitment to open and transparent research into new technologies to further reduce emissions. This water emissions document and the Manufacturing Programme members' commitment to reduce emissions is evidence of action to improve emissions control.

8.3.2 Mass balances

According to the European BREF (Brinkmann et al, 2016), mass balances support a better understanding of process operations and emissions, thereby facilitating the identification of process improvements, and optimization of emission abatement measures. While monitoring does not directly reduce emissions, it can provide an indirect environmental benefit by informing corrective actions and improvement strategies. The value of these benefits is dependent on the reliability of the mass balance, with increasing uncertainty limiting its effectiveness.

8.4 Economics

All monitoring techniques require initial investment in equipment, ongoing maintenance and operating costs. External analytical costs also need to be considered.

8.4.1 LC-MS/MS

The Manufacturing Programme members report that implementation of LC-MS/MS may require high investment cost but running costs are low in comparison. Per sample, PFAS water analysis using EPA Method 537.1 costs approximately 338-507€, per Waters Corporation website. If high resolution mass spectrometry techniques are used, the cost per sample will increase.

8.4.2 Mass balances

Mass balances require additional costs due to measurements and staff time.

9. Appendices

The following BAT provisions are reproduced from the BAT Conclusions for Common Waste Water and Waste Gas Treatment/Management Systems in the Chemical Sector (Brinkmann et al, 2016).

9.1 General BAT 1

In order to improve overall environmental performance, best available techniques to elaborate and implement an environmental management system (EMS) incorporate all of the following features:

1. Commitment, leadership, and accountability of the management, including senior management, for the implementation of an effective EMS;
2. An analysis that includes the determination of the organization's context, the identification of the needs and expectation of interested parties, the identification of characteristics of the installation that are associated with possible risks for the environment as well as of the applicable legal requirements relating to the environment and human health;
3. Development of an environmental policy that includes the continuous improvement of the environmental performance of the installation;
4. Establishing objectives and performance indicators in relation to significant environmental aspects, including safeguarding compliance with applicable legal requirements;
5. Planning and implementing the necessary procedures and actions (including corrective and preventative actions where needed, to achieve the environmental objectives and avoid environmental risks;
6. Determination of structures, roles and responsibilities in relation to environmental aspects and objectives and provision of the financial and human resources needed;
7. Ensuring the necessary competence and awareness of staff whose work may affect the environmental performance of the installation (e.g., by providing information and training);
8. Internal and external communication;
9. Fostering employee involvement in good environmental management practices;
10. Establishing and maintaining a management manual and written procedures to control activities with significant environmental impact as well as relevant records;
11. Effective operational planning and process control;
12. Implementation of appropriate maintenance programmes;
13. Emergency preparedness and response protocols, including the prevention and/or mitigation of the adverse (environmental) impacts of emergency situations;
14. When (re)designing a (new) installation or a part thereof, consideration of its environmental impacts throughout its life, which includes construction, maintenance, operation and decommissioning;
15. Implementation of a monitoring and measurement programme; if necessary, information can be found in the Reference Report on Monitoring of Emissions to Air and Water from IED Installations;
16. Application of sectoral benchmarking on a regular basis;
17. Periodic independent (as far as practicable) internal auditing and periodic independent external auditing in order to assess the environmental performance and to determine

- whether or not the EMS conforms to planned arrangements and has been properly implemented and maintained;
18. Evaluation of causes of nonconformities, implementation of corrective actions in response to nonconformities, review of the effectiveness of corrective actions, and determination of whether similar nonconformities exist or could potentially occur;
 19. Periodic review, by senior management, of the EMS and its continuing suitability, adequacy and effectiveness;
 20. Following and taking into account the development of cleaner techniques.

9.2 General BAT 2

In order to improve the overall environmental performance, BAT is to establish, maintain and regularly review (including when a significant change occurs) an inventory of inputs and outputs, as part of the EMS (see BAT 1), that incorporates all of the following features:

1. Information about the production processes, including:
 - i. Simplified process flow sheets that show the origin of the emissions to air, water and soil;
 - ii. Descriptions of process-integrated techniques and wastewater/waste gas treatment techniques to prevent or reduce emissions, including their performance (e.g., abatement efficiency);
 - iii. Information about the quantity and characteristics of raw materials and fuels used;
 - iv. Information about water consumption and usage (e.g., flow diagrams and water mass balances);
 - v. Information about energy consumption and usage;
 - vi. Information about the characteristics of the wastewater streams, such as:
 1. Average values and variability of flow, pH, temperature and conductivity;
 2. Average concentration and mass flow values of relevant substances/parameters (e.g., total suspended solids, TOC or COD, metals, etc.) and their variability;
 - vii. Information about the quantity and characteristics of the process chemicals used:
 1. The identity and the characteristics of process chemicals, including properties with adverse effects on the environment and/or human health;
 2. The quantities of process chemicals used and the location of their use;
 - viii. Information about the characteristics of the waste gas streams, such as:
 1. Average values and variability of flow and temperature;
 2. Average concentration and mass flow values of relevant substances (e.g., dust, NO_x, SO_x, CO, etc.) and their variability;
 3. Presence of other substances that may affect the waste gas treatment system (e.g., oxygen, nitrogen, water vapour) or installation safety;
 4. Presence of substances classified as CMR 1A, CMR 1B or CMR 2; the presence of such substances may for example be assessed according to the criteria of Regulation (EC) No. 1272/2008 on classification, labelling, and packaging, (CLP);
 - ix. Information about the quantity and characteristics of residue generated.

Applicability

The level of detail and the degree of formalization of the inventory will generally be related to the nature, scale and complexity of the plant and the range of environmental impacts it may have.

9.3 General BAT 3

In order to improve overall environmental performance, BAT is to elaborate and implement a chemicals management system (CMS), as part of the EMS, that incorporates all of the following features:

1. A policy to reduce the consumption of and risks associated with process chemicals, including a procurement policy to select less harmful process chemicals and their suppliers with the aim of minimising the use of and risks associated with hazardous substances and substances of very high concern as well as to avoid the procurement of an excess amount of process chemicals. The selection is based on:
 - a. the comparative analysis of their hazard classification and potential to be released into the environment in order to reduce emissions to the environment.
 - b. the pathways of the process chemical through the plant, potential release and level of exposure
 - c. the potential for recovery and reuse;
 - d. the regular analysis of the potential for substitution with the aim to identify potentially new available and safer alternatives that meet performance standards and socioeconomic feasibility;
 - e. the anticipatory monitoring of regulatory changes related to hazardous substances and substances of very high concern and the safeguarding of compliance with applicable legal requirements.

Applicability

The level of detail and the degree of formalization of the inventory will generally be related to the nature, scale and complexity of the plant and the range of environmental impacts it may have.

9.4 General BAT 9

In order to prevent uncontrolled emissions to water, BAT is to provide an appropriate buffer storage capacity for wastewater incurred during other than normal operating conditions based on a risk assessment (taking into account e.g. the nature of the pollutant, the effects on further treatment, and the receiving environment), and to take appropriate further measures (e.g. control, treat, reuse).

9.5 General BAT 12

In order to reduce emissions to water, BAT is to use an appropriate combination of final wastewater treatment techniques.

Description

Final treatment is carried out as part of an integrated management and treatment strategy (see BAT 10).

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Contact:

Caroline Andersson, Director Fluoropolymers Product Group: caroline.andersson@plasticseurope.org
Tel: +32 2 7923 53, Mobile: +32 477 639165

About Fluoropolymers Product Group (FPG):

The FPG is part of Plastics Europe, the industry association representing European polymer producers. It operates in accordance with the Plastics Europe governance rules, including Competition Compliance Rules. Plastics Europe covers the EU, plus UK, Norway, Turkey and Switzerland.

About Fluoropolymers:

Fluoropolymers are advanced materials that provide unmatched durability, chemical and thermal resistance, and stability in extreme environments. Their unique set of properties makes them essential in many industries, from healthcare and renewable energy to transportation, aerospace and semiconductors