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Abstract

Per and polyfluoroalkyl substances (PFAS) are a large (over 14,000) and varied classification of organic substances. They are very persistent and do not degrade in the environment. Fluoropolymers are *polymeric* PFAS that have distinctly different chemical, physical and biological properties from *all* other PFAS. The weight of evidence has confirmed the lack of toxicity of fluoropolymers in mammals (and other biota). Over sixty years of safe clinical history of use in implantable medical devices also confirms their lack of toxicity. Their insolubility and lack of volatility prevent their environmental mobility dissolved in water or in the atmosphere as gas or vapor. They are not toxic, bioaccumulative or mobile organic substances. Fluoropolymers are unique PFAS.

Authorities from five countries in Europe seeking to prevent the buildup of persistent, toxic and bioaccumulative PFAS known as per and polyfluoroalkyl acids, PFAAs, (like perfluorooctanoic acid, PFOA, perfluorooctane sulfonic acid, PFOS) and the PFAS that degrade into PFAAs (known as PFAA precursors), initiated an EU Annex XV REACH restriction on the premise that all PFAS are persistent in the environment, and that their persistence (alone, not in combination with toxicity and/or bioaccumulation) will lead to their increasing environmental concentrations until toxicity thresholds (not proven to exist) will be exceeded causing adverse health and environmental effects. The restriction argues that *any emission* of *any PFAS* is a risk and that the *risk can only be managed through a REACH restriction*; no other regulatory mechanism would be sufficient.

Fluoropolymers share only one feature with other PFAS: ≥ 1 fully fluorinated carbon. Despite that one structural similarity, fluoropolymers have significantly different chemical, physical and biological properties from *all other PFAS.* By excluding fluoropolymers *from the PFAS groups associated with toxicity, bioaccumulation and global contamination* (PFAAs, per and polyfluoroalkyl substances; PFAA precursors), OECD recognized fluoropolymers as distinctly different "other PFAS". Being labeled a PFAS does not denote hazard or risk as the OECD clearly stated in their 2021 PFAS terminology paper. "The term 'PFAS' is a broad, general, non-specific term, which does not inform whether a compound is harmful or not, but only communicates that the compounds under this term share the same trait for having a fully fluorinated methyl or methylene carbon moiety."

The EU proposed PFAS restriction and the regulatory actions on PFAS elsewhere in the world have introduced uncertainty into the fluoropolymer global supply chain, negatively impacting multiple industry sectors and a plethora of product lines reliant upon the unique constellation of properties that fluoropolymers alone can provide. If a given market is uncertain, investors question financial commitments to the upstream supply chain to enable continued production of the polymers. Instability in the supply of fluoropolymers is then felt by downstream users (who incorporate fluoropolymers and fluoropolymer components into their products) and on through the supply chain ultimately having significant socioeconomic impact. The ECHA proposed PFAS restriction does not, however require demonstration of equivalent performance of fluoropolymer alternatives or that the hazard assessment of alternatives consider the entire life cycle which would put the comparisons to fluoropolymers on equal ground. Therefore, as the restrictions continue to rollout globally without the benefit of knowing the health and environmental consequences across the alternative life cycle or their efficacy, it is challenging

to ensure continued compliance with performance specifications or the ability of alternatives to “drop into“ existing manufacturing supply chains without enormous capital expense and further market disruption.

ECHA has targeted emissions of fluoropolymers and non-polymeric PFAS during their manufacture, processing and disposal. This report examines the state-of-the-science on emissions anywhere in the fluoropolymer life cycle, specifically focusing on end-of-life. The state of the science supports that fluoropolymers can be safely and sustainably managed without sacrificing human or environmental health.

In the “beginning of the life” stage, very significant progress has been and continues to be made in minimizing emissions of non-polymeric PFAS (monomers, ultra short-, short- and long chain PFAS, polymerization aids) during the manufacture and processing of fluoropolymers. A reduction in emissions from fluoropolymer manufacturing and processing facilities *has been documented* in peer-reviewed journals and by regulatory authorities. Science has made these advances with the transparent commitments of fluoropolymer manufacturers and collaboration with analytical scientists, regulators, and the public. The Fluoropolymer Products Group of Plastics Europe publicly committed to aggressively manage emissions from fluoropolymer manufacturing. Member companies met their end of 2024 commitment to reduce average emission factors for non-polymeric PFAS residues to 0.009% (to air; 99.991% efficient removal) and 0.001% (to water, 99.999% efficient removal). Through commitments to continuous improvement, they are on track to meet their end of 2030 targets of 0.003% (to air) and 0.0006% (to water). That is 99.997% and 99.9994% emission free manufacturing to air and water, respectively. Through active engagement with stakeholders, their commitment to *continuous improvement to further manage the lifecycle of fluoropolymers* is documented, measurable and continues to evolve. Improvements to PFAS abatement technologies continue to progress, as do improvements to PFAS analytical methods to monitor non-polymeric PFAS emissions.

The “in life” use of fluoropolymers in existing and new products has been assisted by public reports and statements from key US authorities, such as the Food and Drug Administration stating they have no reason to intervene and prevent the use of fluoropolymers in life saving/improving medical devices received by millions of patients (worldwide).The US Departments of Defense and Energy have also publicly supported the ongoing use of fluoropolymers in applications related to the military and energy supply within the US. More US states (New Mexico, Illinois, California, Rhode Island and Maine are handling fluoropolymers differently than other PFAS in their PFAS legislation, acknowledging they *structurally* meet the PFAS definition but *present significantly reduced risk* due to the differences in their chemical, physical and biological properties compared to other PFAS. Canada has also acted to remove fluoropolymers from their PFAS legislation. Data on the biocompatibility and lack of toxicity of fluoropolymers in medical devices (and low migration/leaching potential of food contact polymers into foodstuffs) continues to be submitted to regulatory authorities worldwide in support of new products and revisions to existing ones. The weight of evidence of the low chemical, physical and biological risk of the “in life” phase of the fluoropolymer life cycle continues to grow.

Though a small amount of fluoropolymer waste at the "end of life" goes to landfill (~13% in Europe) and recycling (~3% in Europe), *the majority of fluoropolymer waste in Europe (84%) is subject to incineration*. In recent years, tremendous knowledge has been gained in the conditions under which destruction and mineralization of PFAS occur. We have learned that incinerator configuration, temperature of primary and secondary combustion chambers, residence time at temperature, turbulence of the waste in the chambers, oxygen concentration, a hydrogen source and the use of catalysts all can *steer the result of PFAS incineration towards complete destruction*, mitigating products of incomplete combustion and mineralizing the PFAS. These conditions are reflected in the EU Industrial Emissions Directive (IED) requirements for hazardous and non-hazardous waste incinerators. Published, peer-reviewed studies in *real-world incineration facilities,* operating with control over the key factors in compliance with the IED, have proven the 99.7 to >99.9999% destruction and removal efficiency *has been achieved*. Near complete (100%) mineralization with negligible emission of non-polymeric PFAS (in flue gas without transfer to fly ash, bottom ash or flue gas scrubber condensate) has been demonstrated.

End of life emissions have *met regulatory established environmental permits* (under the EU IED) *and national limits*.

A recent editorial in Nature Water noted that thermal decomposition, particularly *incineration, is currently the only commercially available full-scale method for destructive PFAS treatment*. Achievement of a 99.7 to 99.9999% destruction and removal efficiency of PFAS is a tremendous technological achievement, but some will say *it is still not 100%.* The ECHA proposed PFAS (UPFAS) restriction does not treat fluoropolymers differently from other substances. PFAS, including fluoropolymers, are not degraded in the environment; they are persistent. But any emission of other persistent organic substances that are not toxic or bioaccumulative (or mobile) are not *considered as being the equivalent of an unacceptable human and environmental health risk, as is the UPFAS restriction does.*

The United Nations Environment Programme (UNEP) has published global consensus documents, such as the Stockholm, Basel and Rotterdam Conventions, to control persistent organic pollutants, POPs. Some PFAS are specifically called out in the Stockholm Convention (PFOA, PFOS, perfluorohexane sulfonate, PFHxS, long chain perfluoroalkyl carboxylic acids, PFCAs). These conventions with signatory countries around the world established *acceptable limits* for the presence of these substances. The Stockholm Convention allows 25 ppb PFOA, PFOS and PFHxS: *not zero*.

The Basel Convention allows a "low POP content" concentration above which the substance has to be destroyed or irreversibly transformed, but below which, those obligations do not apply. For polychlorinated biphenyls (PCBs), that low POP content concentration is *50 mg/kg*, which is the same for pesticides aldrin, chlordane, DDT, dieldrin, endrin, heptachlor, HCB, mirex and toxaphene. The low POP content concentration for dioxins and furans (PCDDs and PCDFs) is *15 toxic equivalency per kg* (15 TEQ/kg). But the greenhouse gases CF_4 and C_2F_6, and various volatile fluorinated organic compounds (products of incomplete combustion or destruction, PIC or PID) that are PFAS, *do not* have similar low POP content concentrations. Note that CF_4 and C_2F_6, are currently regulated as greenhouse gases under the Kyoto Protocol United Nations Framework Convention on Climate Change (UNFCCC) and are not classified by the EU Classification, Labelling and Packaging directive as toxic, mobile or bioaccumulative.

With respect to the European Chemical Agency's (ECHA) Background Document (BD), the Risk Assessment Committee (RAC) determined that the emission factor for non-hazardous waste incinerators should be 0.02 (assuming 98% destruction and removal efficiency), and 0.01 for hazardous waste incinerators (assuming 99% destruction and removal efficiency). Multiple studies between 2023 and 2026 show even greater destruction efficiencies in practice (99.7 - 99.9999%) which would significantly drop the ECHA emission factors (0.0001% which is the equivalent of 1 second in 11.5 days) from 0.01 or 0.02 to 0.003 to 0.000001. This would drop the calculated quantity of non-polymeric PFAS emitted to air annually by a factor of 3.3 to 10,000 without a specific PFAS restriction.

The RAC also assumed that fluoropolymer landfill waste would have 33.6 ppm leachable non-polymeric PFAS migrating out of the fluoropolymer into the landfill waste or leachate to water (based on the background document release factor of 0.0336 applied only to the non-polymeric fraction of 0.1% set by RAC). Henry et al., 2018 and Korzeniowski et al., 2023 showed leachables in 96% of commercially available fluoropolymers to be < 1 ppm in 2023. Regulatory submissions demonstrate low levels of leachables also as fluoropolymers with food contact applications met "migration limits" and medical device under the EU Medical Device Regulation must establish low levels of "extractables and leachables". These data support the conclusion that the RAC assumption for leachable concentration of 33.6 ppm is too high for 96% of the commercially available fluoropolymers.

Therefore, the ECHA BD *overestimates PFAS emissions to <u>air</u> by up to 10,000x*, *emissions to <u>water</u> and to landfill leachate by 33.6x.*

The ECHA BD noted uncertainty over the toxicity of fluoropolymer microplastics. Fluoropolymers in the market sectors covered in this report are *not manufactured* to be primary microparticles, as has been the case for some applications (such as microparticle additions to cosmetics to improve the flow of the product on the skin). According to the US EPA, the existing mechanisms for the generation of *secondary (environmentally created) fluoropolymer microparticles* are unlikely to occur with fluoropolymers due to resistance to weathering, the absence of microbial weakening increasing fluoropolymer susceptibility to fragmentation, and the low probability of microparticle generation as a result of mechanical forces in landfills. However, end uses involving high degrees or sustained periods of friction *are* likely to generate fluoropolymer particulate which could be < 5 mm (microparticle) size and therefore should be limited and responsibly managed. The ECHA Risk Assessment Committee stated in their March 2, 2026 report that fluoropolymer particles were generally less bioavailable and had lower toxicity than PFAAs and their precursors and that fluoropolymer particle concern mostly relates to the general plastic pollution (rather than to something specific to fluoropolymers), which is consistent with the state of the science.

Though fluoropolymer microplastics have been reported in scientific publications to have been found in several human tissues and organs, as have other microplastics, serious methodological and analytical issues have been raised with these studies in the peer reviewed literature and media. More research is needed to determine the source of the microparticle and their route of entry into the body (administration), distribution within the body, metabolism and excretion (ADME). More information is needed as to whether their physical size alone is responsible for movement to organs and tissues or if

chemical and physical properties such as particle electrical charge or surface reactivity influences distribution, retention, toxicity and elimination.

Existing microplastic data predominantly includes laboratory studies in animals and in cell culture with fluoropolymers milled or cryoground to achieve microparticle size for dosing. Human data is lacking. Are those lab-generated particles mimicking environmentally generated secondary fluoropolymer microparticles? The impact of the differences in the characteristics of the lab-generated versus environmentally generated fluoropolymer microparticles needs to be researched. The impacts may extend to the extrapolation of toxicity results in lab tests to real world scenarios. Since there are no standard methods for the generation of secondary microplastics or testing for them, no standard analytical methods and no reference standards for these studies, *more work is needed* with respect to the microparticulate question.

Existing peer-reviewed literature supports the lack of active or passive transport of fluoropolymers into cells as well as the lack of cell surface receptor binding of fluoropolymers to trigger events within the cell. That data supports the lack of bioavailability of fluoropolymers. Will the research on fluoropolymers as microparticles alter that finding? Technically, small particles can be transported into cells by other mechanisms such as endocytosis or pinocytosis. But the chemical and physical properties of fluoropolymer (especially their hydrophobicity and low adsorptive properties) decrease the probability of these mechanisms for entry into the cell. Research is currently underway to investigate whether or not those are the means by which the fluoropolymer microplastics moved from the respiratory or digestive systems into distant organs and tissues. Is the reason that so few studies reported fluoropolymer microparticles in humans due to the relatively low volume (0.1%) of fluoropolymers commercialized versus all other plastics, or, are there biological, chemical or physical properties that explain more?

Laboratory animal studies exist in the peer reviewed literature in which non-fluoropolymer (such as polystyrene) microparticles have been administered to animals in one group and fluoropolymer (usually PTFE) microparticles administered to another group. While existing data has focused on *one plastic type* (polystyrene) primarily, head-to-head comparison of effects in these studies demonstrate that the fluoropolymer has lower toxicity (if any) compared to the non-fluoropolymer.

Therefore, while there are areas of research needed in microplastics, the weight of the evidence across the fluoropolymer life cycle strongly supports they can continue to be safely used and that responsible control of emissions at all life cycle stages is possible. The state of the science supports the uniqueness of fluoropolymers and their exclusion from the ECHA proposed PFAS restriction.

Table of Contents

Abstract **2**
Glossary **10**
List of Tables **16**
List of Figures **16**
Introduction **17**
Figure 1 OECD 2021 Structural Grouping of PFAS (modified from OECD Reconciling Terminology of the Universe of Per- and Polyfluoroalkyl 17
Substances: Recommendations and Practical Guidance, 2021) 17
Table 1 PFAS used in the polymerization of fluoropolymers 19
Background – the European Universal PFAS Restriction Proposal **19**
History 19
Purpose of Report **20**
UPFAS Restriction Current Status 20
Beginning of Life 21
Figure 2 History of Polymer Hazard Assessment 21
Plastics Europe Fluoropolymer Products Group Responsible Manufacturing Program 23
In Life: 23
End of Life 23
Methods **24**
Results **24**
Incineration of Fluoropolymers - Background 25
Figure 3 Grate incinerator in the EU 25
Figure 4 Rotary kiln incinerator 26
Figure 5 Fluidised bed incinerator 26
Incineration of Fluoropolymers – Key Literature 26
Figure 6 Advanced thermal reactor system (Yamada et al., 2005) 27
Figure 7 Pilot scale thermal reactor (Taylor et al., 2014) 27
Table 2 PFAS Incineration Highlights 2005 to 2026 28
Figure 8a Steps 1 and 2 of Fluoropolymer Material (FPM) Incineration and Destruction (Modified from Stephen R. Jackson, NEWMOA PFAS Analytical Developments Webinar, September 25, 2024) 31
Figure 8b Steps 3 and 4 of Fluoropolymer Material (FPM) Incineration and Destruction (Modified from Stephen R. Jackson, NEWMOA PFAS Analytical Developments Webinar, September 25, 2024) 32
Table 2 PFAS Incineration Highlights 2005 to 2026 - continued 33
Table 2 PFAS Incineration Highlights 2005 to 2026 - continued 36
Incineration key points: 36

Landfill of Fluoropolymers **36**
Figure 9 Diagram of a municipal solid waste landfill (properly closed) 37
Figure 10 Diagram of a hazardous waste landfill (Adapted from publicly available educational materials; no original source identifiable. Conceptual elements based on U.S. EPA landfill design guidance (EPA, 2026). 38
Landfill leachate 39
Landfill key points 39
Recycling of Fluoropolymers **40**
Mechanical recycling 40
Macromolecular recycling (solvent-based recovery) 41
Monomer recycling (thermal depolymerization) 41
Feedstock recycling (breaking down into chemical precursors) 41
Upcycling of Fluoropolymers 42
Figure 11 Closing the life cycle loop on perfluorinated polymers (PFPs) 42
Recycling key points 43
Microplastics **43**
Microplastics – definition and mechanisms of generation 43
Table 3. Comparison of micro- and nanoparticles (modified from Kadak-Czapska et al., 2025) 44
Microplastics – analytical approaches 45
Table 4. Overview of challenges and limitations associated with the analysis of micro- and nanoparticles in human matrices (from Kadak-Czapska et al.,2025.) 46
Microplastics – routes of entry into the human body 47
Figure 12 – Endocytosis (from Endocytosis: Definition, Types, & Examples with Diagram) 48
Microplastics – evidence in human tissues and criticisms 49
Table 5. Summary of research finding in micro- and nanoparticles detected in human samples 50
Table 5. Summary of research finding in micro- and nanoparticles detected in human samples - continued 51
Microplastics – toxicity certainty and uncertainty 52
Microplastics – what is needed for human health risk assessment 52
Microplastics – routes of entry into the body and translocation 53
Microplastics – research needs, gaps and criticisms 53
Study needs 53
More than 1 polymer type 53
Lab v reality 53
Status on all MNPs 53
Microplastics key points 54
Discussion **54**

Spectaris Market Sectors and End of Life 54
Table 6 Spectaris Products, Market Sectors and End of Life Options 56
Conclusions 57
References 61

Glossary

Terms used	Definition
2,3,7,8-TCDD	2,3,7,8-tetrachlorodibenzo-*p*-dioxin
Adsorption	is a heterogeneous reaction in which gas molecules are retained on a solid or liquid surface that prefers specific compounds to others .
Aerobic	means requiring oxygen.
Anaerobic	means not requiring oxygen.
ASTM D4895	American Society of Testing and Materials D4895 is a standard specification for powder resins of polytetrafluoroethylene produced from dispersion.
BD	European Chemical Agency's (ECHA) restriction proposal in a report called the Background Document, which forms the basis for the opinions of the ECHA's Risk and Socioeconomic Assessment committees
Bioaccumulative	According to REACH (2023), a substance shall be considered to fulfil the bioaccumulation criterion (B) where the bioconcentration factor in aquatic species is higher than 2 000.
Bottom ash	is the coarse, incombustible residue that collects at the base of a furnace or incinerator after waste is burned.
C_2F_6	Hexafluoroethane
Caveolae	protein coating flask-shaped pits in the cell membrane to bind particles and create caveolin protein-coated vesicles
Cell surface receptor binding	process by which a substance in the fluid outside the cell wall attaches to a receptor in the cell membrane, leading to events within the cell
CF_4	carbon tetrafluoride
Clathrin	protein coating vesicles in the cell membrane
CO	carbon monoxide
CO_2	carbon dioxide
Emission factor	a characteristic value that relates to the quantity of a pollutant released into the atmosphere with an activity associated with the release of that pollutant. These factors are usually calculated by dividing the weight of a pollutant by a unit weight, volume, distance or interval of the activity emitting the pollutant.
Endocytosis	is the process by which cells actively transport substances into the cell by engulfing them with their plasma membrane.
Environmental weathering	is the process by which substrates are acted upon by sunlight, air, water, microbes whereby the substrate is degraded
Flue gas	gas stream exiting from a chimney or flue from an incinerator or furnace

Flue gas condensate	In air pollution abatement, the gas scrubber technique is used to eliminate solvent vapors from a waste gas stream, reducing its temperature below its dew point. When the vapor pressure falls below the partial pressure of the pollutant, the substance will condense into a mist or droplets, which are collected and appropriately treated as flue gas condensate.
Fluoropolymer	is a type of polymeric PFAS with a carbon-only backbone and fluorines directly attached. Fluoropolymers are a distinct class of per- and polyfluoroalkyl substances (PFAS), high molecular weight polymers with fluorine attached to their carbon-only backbone.
Fly ash	is the finely divided residue that results from combustion in a furnace or incinerator which is transported from the combustion chamber by exhaust gases.
Fragmentation	mechanism of secondary microparticle generation by which larger substrates are mechanically broken down
FTOHs	fluorotelomer alcohols
Greenhouse gases	also known an ozone depleting substances, such as hexafluoroethane or carbon tetrafluoride or carbon dioxide
Half-life	the time it takes for one half the amount of a substance to break down in the environment, known as half-life or $T_{1/2}$.
Hazardous waste incinerator	is an incinerator used to dispose of/destroy waste; in the EU these operate at > 1100 °C
HCl	hydrochloric acid
HF	hydrofluoric acid
Hydrophobicity	is a water-repelling property of unmodified fluoropolymer surfaces that reduces the adherence of non-specific proteins and limits receptor binding.
In vitro	means in cell culture as opposed to in live animals or in silico by computer.
In vivo	means in live animals.
Landfill leachate	is the decomposition products that depart the landfill as a liquid leachate.
LC-MS/MS	or liquid chromatography – mass spectrometry/mass spectrometry, is a powerful analytical technique allowing for the effective separation and dentification of complex liquid mixtures.
Leachate	in the case of a landfill, refers to water that has percolated through a landfill and pulled out some constituents.
Limit of detection	or LOD, is the smallest measure and concentration which can be detected, but not quantified, in the experimental conditions described by the method. Concentrations that are too low to be analytically detected are considered to be < LOD.

Limit Of Quantitation	or LOQ, is the lowest concentration of a target analyte that can be reliably measured with a given method with acceptable precision and accuracy, typically defined as the concentration at which the signal-to-noise (S/N) ratio is at least 10:1 or the relative standard deviation (RSD) is $\leq$ 20%. Ideally an analytical report should inform the reader as to whether the result was detectible ($\geq$ the LOD) and whether or not it was quantifiable ($\geq$ LOQ).
Long Chain PFAS	or long chain perfluoroalkyl substances, are perfluoroalkyl acids with 8-21 carbons; carboxylic or sulfonic acids.
Lysozyme	is an enzyme enclosed in vesicles in the cell that is engaged to dissolve foreign bodies, viruses, etc. in vesicles.
Mass balance	is a principle in which the total mass of pollutant entering the abatement system equals the total mass leaving the system.
Media (or matrix)	refers to environmental media such as air, water, soil, sediment, waste streams.
Microparticle	is a particle less the 5 mm (5,000 µm) in diameter (per EC 2023).
Micropinocytosis	is a form of endocytosis in which cells internalize small amounts of extracellular fluid and solutes through tiny vesicles.
Mineralization	refers to the complete chemical breakdown of per- and polyfluoroalkyl substances (PFAS) into their simplest inorganic components — primarily fluoride ions (F^-) and carbon dioxide (CO_2)
Mobile	or M, is defined in EU REACH as a substance with a log Koc less than 3 or very mobile (vM) when the log Koc is less than 2.
Monomers	are building block chemicals used to make (fluoro)polymers.
MSWI	means municipal solid waste incinerator (non-hazardous waste incinerator).
NH_3	means ammonia.
NO	means nitrogen oxide.
Non-targeted analysis	uses 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.).
NO_x	means oxides of nitrogen.
O_2	means oxygen.
OECD	stands for the Organisation for Economic Co-operation and Development.
Particle	is a very small piece of matter.

PBT	According to REACH (2023), a substance is considered to be persistent, bioaccumulative and toxic (PBT) if it fulfills the criteria for each individual hazard classification. See definitions of persistent, bioaccumulative and toxic for specific details.
PCBs	are polychlorinated biphenyls.
PCDDs	are polychlorinated dibenzo-*p*-dioxins.
PCDFs	are polychlorinated dibenzofurans .
Persistent	According to REACH (2023), a substance shall be considered to fulfil the persistence criterion (P) where any of the following conditions is met: (a) the degradation half-life in marine water is higher than 60 days; (b) the degradation half-life in fresh or estuarine water is higher than 40 days; (c) the degradation half-life in marine sediment is higher than 180 days; (d) the degradation half-life in fresh or estuarine water sediment is higher than 120 days; (e) the degradation half-life in soil is higher than 120 days.
PFAA	or perfluoroalkyl acid, which can be either carboxylic (also known as PFCAs) or sulfonic acids (also known as PFSAs), such as PFOA, PFOS, respectively.
PFAA precursor	is a precursor to a perfluoroalkyl acid. These are PFAS that degrade to perfluorocarboxylic or sulfonic acids.
PFAS	means per and polyfluoroalkyl substances, which are defined per OECD 2021 as fluorinated organic substances that contain at least one fully fluorinated methyl or methylene carbon atom (without any H/Cl/Br/I atom attached to it).
PFBA	means perfluorobutanoic acid; 4-carbon perfluorocarboxylic acid.
PFBS	means perfluorobutane sulfonic acid; 4-carbon perfluorosulfonic acid.
PFCAs	means perfluoroalkyl carboxylic acids; the perfluoroalkyl acids that are carboxylic acids .
PFDA	means perfluorodecanoic acid; 10-carbon perfluorocarboxylic acid.
PFHpA	means perfluoroheptanoic acid; 7-carbon perfluorocarboxylic acid.
PFHxA	means perfluorohexanoic acid; 6-carbon perfluorocarboxylic acid.
PFHxS	means perfluorohexane sulfonic acid; 6-carbon perfluorosulfonic acid.
PFOA	means perfluorooctanoic acid; 8-carbon perfluorocarboxylic acid.
PFOS	means perfluorooctane sulfonic acid; 8-carbon perfluorosulfonic acid.
PFPeA	means perfluoropentanoic acid; 5-carbon perfluorocarboxylic acid.
Phagocytosis	is the process by which a cell engulfs and usually destroys solid particles such as bacteria, dead cells, debris, or other foreign matter; a specialized form of endocytosis in which the cell membrane extends around the target particle, enclosing it within an internal vesicle called a phagosome.

PIC	stands for product of incomplete combustion.
PID	stands for product of incomplete destruction.
Pinocytosis	is the process in which a small pocket of extracellular fluid and particles forms a vesicle.
PM	means particulate matter, solid or liquid droplets, usually followed by a mean particle diameter in micrometers, such as PM 2.5.
PMT	According to REACH (2023), a substance is considered to fulfill the criteria to be considered persistent, mobile, and toxic if it fulfills the criteria for each category. See persistent, mobile, toxic definitions for specifics.
Polymerization aids	are substances used to reduce surface tension to enable aqueous polymerization (fluorinated examples include Adona®, GenX®, etc.; replacements for PFOA and PFOS).
RAC	is the European Chemical Agency's Risk Assessment Committee.
Receptor-mediated endocytosis	is the process in which a receptor lined protein-coated pit in the cell membrane binds substances, such as particles.
SEAC	stands for the European Chemical Agency's Socioeconomic assessment committee.
Short Chain PFAS	are perfluoroalkyl substances which are perfluoroalkyl acids with 4-7 carbons; can be carboxylic or sulfonic acids.
SO_x	means oxides of sulfur.
Targeted analysis	is an analytical approach by which the analyst is looking only for specific chemicals. The mass spectra 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.
Total Delta Destruction Rate	or TD2R, is the fluorine-related degradation rate calculated as the difference between the PFAS-dosed trial and the reference state.
Toxic	According to REACH (2023), a substance shall be considered to fulfil the toxicity criterion (T) in any of the following situations: (a) the long-term no-observed effect concentration (NOEC) or ECx (e.g. EC10) for marine or freshwater organisms is less than 0,01 mg/l; (b) the substance meets the criteria for classification as carcinogenic (category 1A or 1B), germ cell mutagenic (category 1A or 1B), or toxic for reproduction (category 1A, 1B, or 2) according to Sections 3.5, 3.6 or 3.7; (c) there is other evidence of chronic toxicity, as identified by the substance meeting the criteria for classification: specific target organ toxicity after repeated exposure (STOT RE category 1 or 2) according to Section 3.9; (d) the substance meets the criteria for classification as endocrine disruptor (category 1) for humans or the environment according to Sections 3.11 or 4.2.

Toxicity Equivalence Factor	or TEF, is an estimate of the potency, relative to 2,3,7,8 TCDD, of an individual polychlorinated dibenzo-*p*-dioxin, dibenzofuran, or biphenyl congener, determined using careful scientific judgment after considering all available relative potency data. EPA presently applies this term only to TEFs derived through an international scientific consensus-building process supported by the World Health Organization. The use of the toxicity equivalence methodology for human health risk assessment and risk management purposes has since been formally adopted by a number of other countries (e.g., Canada, Germany, Italy, the Netherlands, Sweden, and the United Kingdom) (US EPA, EPA/100/R-08/004 June 2008).
Ultra-short chain PFAS	are perfluoroalkyl substances which are perfluoroalkyl acids with 2-3 carbons; can be carboxylic or sulfonic acids.
Vapor	is a substance in a gaseous phase.
Very Bioaccumulative	According to REACH (2023), a substance shall be considered to fulfil the "very bioaccumulative" criterion (vB) where the bioconcentration factor in aquatic species is higher than 5 000.
Very Mobile	According to REACH (2023), a substance shall be considered to fulfil the "very mobile" criterion (vM) when the log Koc is less than 2. For an ionisable substance, the mobility criterion shall be considered fulfilled when the lowest log Koc pH between 4 and 9 is less than 2.
Very Persistent	According to REACH (2023), a substance shall be considered to fulfil the "very persistent" criterion (vP) where any of the following conditions is met: (a) the degradation half-life in marine, fresh or estuarine water is higher than 60 days; (b) the degradation half-life in marine, fresh or estuarine water sediment is higher than 180 days; (c) the degradation half-life in soil is higher than 180 days.
Vesicle	is a small fluid filled sac.

List of Tables

Table 1: PFAS used in the polymerization of fluoropolymers

Table 2: PFAS incineration highlights 2005 to 2026

Table 3: Comparison of micro- and nanoparticles

Table 4: Overview of the challenges and limitations associated with analysis of micro- and nanoparticles in human matrices

Table 5: Summary of research finding in micro- and nanoparticles detected in human samples

Table 6: Spectaris products, market sectors and end of life options

List of Figures

Figure 1: OECD 2021 Structural grouping of PFAS

Figure 2: History of Polymer Hazard Assessment

Figure 3: Grate Incinerator in the EU (Neuwahl et al., 2019)

Figure 4: Rotary Kiln Incinerator (Neuwahl et al., 2019)

Figure 5: Fluidised Bed Incinerator (Neuwahl et al., 2019)

Figure 6: Advanced Thermal Reactor System (Yamada et al., 2005)

Figure 7: Pilot Thermal Reactor (Taylor et al., 2014)

Figure 8a: Steps 1 and 2 of Fluoropolymer Material Incineration and Destruction (modified from Stephen R. Jackson, 2024)

Figure 8b: Steps 3 and 4 of Fluoropolymer Material Incineration and Destruction (modified from Stephen R. Jackson, 2024)

Figure 9: Diagram of a municipal solid waste landfill (properly closed) (US EPA)

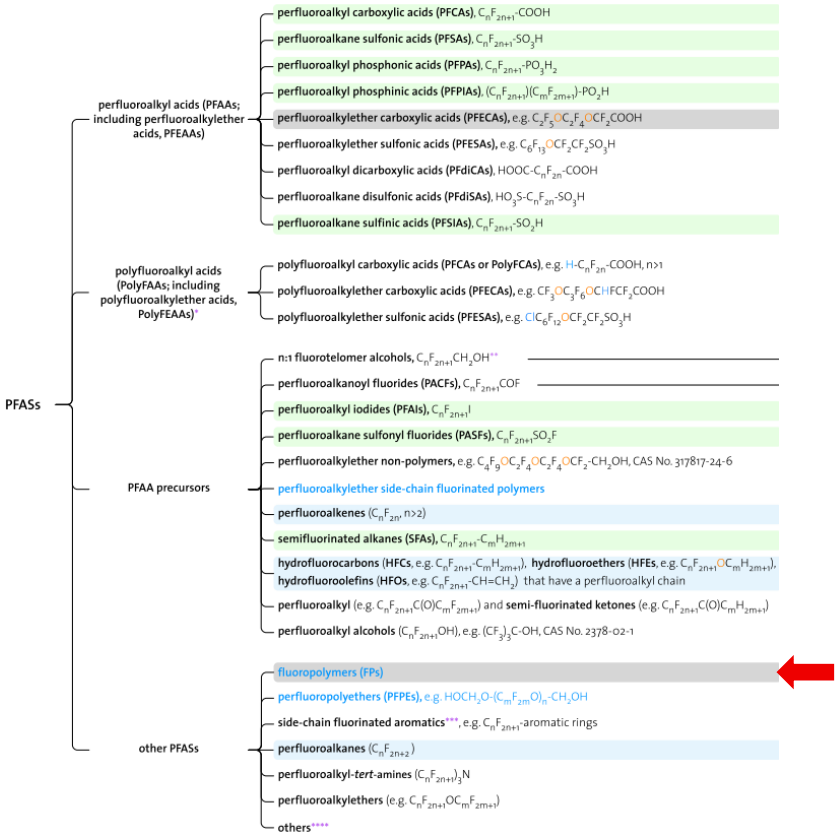
Figure 10: Diagram of a hazardous waste landfill (US EPA)

Figure 11: Closing the life cycle loop on perfluorinated polymers (PFP) (Schlipf and Swalm, 2014)

Figure 12: Endocytosis (from Endocytosis: Definition, Types and Examples with Diagram, ScienceFacts.net)

Introduction

Per- and polyfluoroalkyl substances, PFAS, are a large and varied group of organic compounds containing at least one fully fluorinated methyl or methylene carbon, according to the OECD (2021). The OECD (2021) divided PFAS up into Perfluoroalkyl acids (PFAAs) (in which the carbon atoms are fully fluorinated), Polyfluoroalkyl acids (PolyFAAs) (in which at least one hydrogen atom remains), PFAA precursors (Substances that degrade to PFAAs), and other PFAS. See figure 1.



Fluoropolymers, the topic of this report, are polymeric PFAS with a carbon only backbone with fluorine atoms directly attached. That envelope of fluorine atoms protects the fluoropolymer background from biotic and abiotic degradation. They are not PFAA precursors.

Figure 1 OECD 2021 Structural Grouping of PFAS

(modified from OECD Reconciling Terminology of the Universe of Per- and Polyfluoroalkyl Substances: Recommendations and Practical Guidance, 2021)

Despite sharing that one structural feature of a fully fluorinated carbon, there are significant differences in chemical, physical, and biological properties among the 14,000 PFAS. Fluoropolymers have *very high* molecular weight, are *not* soluble, *not* volatile, *not* mobile or bioaccumulative, and have *low* toxicity and bioavailability. Non polymeric perfluoroalkyl substances, PFAAs such as perfluorooctanoic acid (PFOA), are *small*, *water soluble (mobile)*, *volatile*, *toxic*, *bioavailable*, and *bioaccumulative*. The PFAS which are mobile in the environment, toxic, and bioaccumulative, and those PFAS that transform into PFAAs in the environment ("PFAA precursors"), are therefore the most relevant from a human and environmental health perspective. It is these non-polymeric PFAS that are of concern in emissions due to their toxicity, bioavailability, bioaccumulation and ability to move from one environmental medium (air, water, soil, sediment) to another as well as their uptake by plants to enter the food chain for livestock and humans.

This document will discuss these non-polymeric PFAS (see Table 1), including:

- *Monomers* (used to make fluoropolymers)
- *Ultra-short* chain PFAS (PFAAs with 2-3 carbons; can be carboxylic or sulfonic acids)
- *Short* Chain PFAS (PFAAs with 4-7 carbons; can be carboxylic or sulfonic acids)
- *Longer* Chain PFAS (PFAAs with 8-21 carbons; can be carboxylic or sulfonic acids)
- *Polymerization aids* (such as Adona®, GenX®, etc.; replacements for PFOA and PFOS)
- *Substances with global warming potential* (such as carbon tetrafluoride,CF_4, hexafluoroethane, C_2F_6, etc., also known as greenhouse gases)

PFAAs can be either carboxylic acids (PFCAs) or sulfonic acids (PFSAs). The most widely known and extensively studied PFAAs are perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS) which are ubiquitous in the environment and often found in human blood. Table 1 provides an overview of substances used in fluoropolymer manufacture and processing that may end up as non-polymeric PFAS emissions to air, water or soil. This report will address fluoropolymer end of life and technologies for minimizing PFAS emissions to the environment.

The incredible strength of the carbon-fluorine bond imparts great stability to PFAS (aka persistence). While this extreme durability of fluoropolymers enables many highly technical products, this persistence means they do not degrade in the environment leading, to significant attention recently, especially in Europe.

Fluoropolymers are used widely today particularly in highly technical products of considerable societal value such as medical devices, communications, aerospace and defense, automotive and semiconductor applications. SPECTARIS is a Berlin-based industry association representing the following industries using fluoropolymer materials in their products: consumer optics, photonics, medical technology, analytical, biological and laboratory technology, including research and development. Fluoropolymers are essential for SPECTARIS high-tech industries and are difficult or impossible to substitute. This report commissioned by SPECTARIS, summarizes the current state of the science of fluoropolymers and their uses by these industries to demonstrate the weight of evidence in support of their continued safe contribution to modern society, and, to address residual uncertainties for regulators and the public, particularly concerning fluoropolymers end-of-life.

Table 1 PFAS used in the polymerization of fluoropolymers (Note that not all are used in every fluoropolymer.)

FUNCTION	CHEMICAL NAME
MONOMER	(**TFE**) tetrafluoroethylene, (**VDF**) vinylidene fluoride, (**HFPO**) hexafluoropropylene oxide, (**TrFE**) trifluoroethylene, (**PFBA**) perfluorobutanoic acid
MODIFYING MONOMER	(**PMVE**) perfluoromethyl vinyl ether, (**PEVE**) perfluoroethyl vinyl ether, (**PPVE**)perfluoropropyl vinyl ether, (**PFBE**) perfluorobutyl ethylene, (**CNVE**) perfluoro[3-(1-methyl=2= vinyloxy-ethoxy) propionitrile
POLYMERIZATION AID*	(**HFPO-DA**) hexafluoropropylene oxide dimer acid; (**ADONA**) perfluoro-4,8-dioxa-3H-nonanoic acid, ammonium salt; (**EEA**) perfluoro(2-ethoxy-2-fluoroethoxy)-acetic acid, (**Surflon S-111**) perfluorononanoic acid; (**PMPA**) perfluoro-2-methoxypropanoic acid; (**PFOA**) perfluorooctanoic acid
CHAIN TRANSFER AGENT	(**DIOFE**) 1,1,2,2-tetrafluoro-1,2-diiodoethane; (**DIOFB**) 1,4,-diiodoperfluorobutane; (**DIOFH**) 1,6-diiodoperfluorohexane; difluoroethane
BYPROUCTS, DECOMPOSITION PRODUCTS (OVER HEATING)	(**HF**) hydrogen fluoride, (**COF_2**) carbonyl fluoride, (**CO**) carbon monoxide, (**PFIB**) perfluoroisobutylene, (**NOx**) oxides of nitrogen, (**SOx**) oxides of sulfur, (**CO_2**) carbon dioxide, (**HFP**) hexafluoropropylene, (**HFPO**) hexafluoropropylene oxide, (**HFPO-DA**) hexafluoropropylene -dimer acid, (**VOCs**) volatile organic carbons, (**EEA-NH4**) perfluoro(2-ethoxy-2-fluoroethoxy)-acetic acid, (**PFNA**) perfluorononanoic acid, (**PFHpA**) perfluoroheptanoic acid, (**PFDA**) perfluorodecanoic acid, (**PFUnDA**) perfluoroundecanoic acid, (**PFDoDA**) perfluorododecanoic acid
NON-POLYMERIC PFAS	(**PFHxA**) perfluorohexanoic acid, (**E1**) heptafluoropropyl 1,2,2,2-tetrafluoroethyl ether, (**Ether A**) 2-[difluoro(methoxy)methyl]-1,1,1,3,3,3-hexafluoropropane, (**Ether B**) 1-methoxy(perfluoro-2-methyl-1-propene), (**6:2 FTS**) 6:2 fluorotelomer sulfonate, (**PFHxS**) perfluorohexane sulfonate, (**1H-PFHx**) 1H-perfluorohexane, (**PFAC**) perfluoroallyl chloride
PFCs	(**PFC-116**) hexafluoroethane, (**PFC-218**) octafluoropropane, (**PFC-318**) perfluorocylobutane
CFCs	(**CFC-12**) difluorodichloromethane, (**CFC-13**) chlorotrifluoromethane
HCFCs	(**HCFC-124**) tetrafluorochloroethane, (**HCFC-142b**) 1,-chloro-1,1-difluoroethane, (**HCFC-21**) dichlorofluoromethane, (**HCFC-22**) chlorodifluoromethane
HFCs	(**HFC-125**) pentafluoroethane, (**HFC-134a**) 1,1,2,2-tetrafluoroethane, (**HFC-141b**) 1,1-dichloro-1-fluoroethane, (**HFC-143a**) 1,1,1-trifluoroethane, (**HFC-152a**) 1,1-difluoroethane, (**HFC-23**) trifluoromethane, (**HFC-32**) difluoromethane, (**HFC-365mfc**) 1,1,1,3,3-pentafluorobutane, (**HFC-4310mee**) 1,1,1,2,3,4,4,5,5,5-decafluoropentane
*Fluorinated or non-fluorinated polymerization aid or none at all may be used, depending on the fluoropolymer manufactured.	

Background – the European Universal PFAS Restriction Proposal

History

The culmination of European interest in PFAS persistence occurred in 2023 when the national authorities of five EU member countries (Germany, the Netherlands, Denmark, Sweden and Norway) submitted an

Annex XV report to the European Chemicals Agency (ECHA) proposing a restriction on PFAS under EU REACH Regulation. The country dossier submitters presented evidence on hazards, risks, uses, and socio-economic impacts. In 2025 (August 20), the five authorities completed their evaluation of public comments (>5600) and updated their initial restriction proposal in a report called the Background Document (BD), which forms the basis for the opinions of the ECHA's Risk and Socioeconomic Assessment committees (RAC and SEAC, respectively). The report is currently based on 23 sectors or groups of economic activities and/or industrial areas in which PFAS are used. It describes the environmental and human health risks associated with the use of PFAS and assesses the appropriateness (proportionality) of different restriction options to manage them.

Simply put, the BD says that the lack of degradation (or persistence) of all PFAS (including fluoropolymers) leads to increased environmental concentrations of PFAS leading to increased (bioavailable) exposure until (as of yet undefined) toxicity thresholds are exceeded resulting in adverse effects. Therefore, the BD reasons that *exposure* to PFAS leads to *risk*, and therefore, *any* level of PFAS (including fluoropolymer) *emission increases (bioavailable) exposure and presents a risk*. The BD argues that PFAS *persistence is a hazard and a risk* that can only be managed through an EU REACH restriction. It is worth noting that the EU REACH, the EU Classification, Labelling and Packaging Directive, the US EPA Toxic Substances Control Act, the UN Environment Program's Globally Harmonized System of Classification and Labelling of Chemicals, and Stockholm Convention do <u>not</u> consider persistence alone as a hazard. Persistence is an *inherent characteristic* of a substance defined under EU REACH by the time it takes for one half the amount of a substance to break down in the environment, known as half-life or $T_{1/2}$. Under REACH, the substance is considered *very persistent* if the half-life is >60 days in marine, fresh or estuarine water or >180 days in marine, fresh or estuarine sediment or soil. The half-life of a substance is, therefore, a *physical* property independent of toxicity, bioavailability, bioaccumulation or mobility.

Purpose of Report

UPFAS Restriction Current Status

In the comitology phase of the PFAS restriction process, the ECHA Socio-Economic Analysis Committee agreed upon their draft opinion (on March 10, 2026), followed by a public consultation (from March 26 to May 25, 2026) to collect evidence-based comments to help inform SEAC's final opinion. During that 60-day comment period, input was accepted only in a structured survey format, where ECHA invited participants to respond to questions on the potential impacts of restricting the use of PFAS across various sectors and to provide specific information about the availability and feasibility of alternatives to these widely used chemicals. Information on the hazards and risks to human health and the environment associated with PFAS was not considered, as these were covered by the opinion of the Committee for Risk Assessment (RAC). At the end of the consultation period (May 25, 2026) the SEAC assesses relevant information submitted and confirms or modifies their conclusions. Procedurally, the Committee then adopts its final opinion (expected by the end of 2026) concluding ECHA Committee's scientific evaluation of the proposed restriction. In this process, ECHA then formally submits the proposed restriction to the European Commission, who proposes a restriction for discussion and vote in the REACH Committee, composed of EU Member States.

The BD takes a lifecycle approach to PFAS emissions such that <u>*any*</u> *emission* during beginning of life (manufacture, processing), in life (use) or end of life (disposal, incineration, landfill, recycling, upcycling)

is considered to *present a risk only* mitigated by management under REACH. Other mitigation options such as stricter emission standards within existing regulation were not considered.

Beginning of Life: Historically, fluoropolymer manufacturing did result in emissions of PFAS into the environment, notably legacy non polymeric PFAS, such as the perfluoroalkyl acid PFOA. The focus of research and regulatory attention was on the fluorosurfactant (PFOA, PFOS) emissions which ultimately resulted in detection of these legacy substances throughout the world and in animals, plants and humans. To put the interest in the emissions of substances related to fluoropolymer manufacture and processing in context, it is necessary to understand the history of the hazard assessment of polymers and the evolution of PFAS analytical methods.

As was discussed in detail in Henry et al. (2018), prior to the mid-20th century, regulation of new chemical substances, mixtures, and polymers in general was very limited. National chemical inventories were being created around the world with notification requirements for new chemical substances, mixtures, and polymers. In the United States, new chemicals submitted to the US Environmental Protection Agency (USEPA) under the Toxic Substances Control Act (TSCA) (US Congress 1976) for addition to the US chemical inventory were reviewed for potential physical, chemical, and biological effects (human and non-human), as well as their exposure potentials and use. Over time, the USEPA regulatory scientists reviewed thousands of polymer data packages. They noted differences between polymers and non-polymers. They developed tools to assist in the identification of physical–chemical properties, potential hazard, and potential exposure to assist in and expedite their chemical review and assessment process (Auer et al. 1990; Wagner et al. 1995; USEPA 2012; USEPA 2017). The predictive power and reliability of these approaches were tested and refined (Wagner et al. 1995). Certain characteristics or properties of polymers were demonstrated to be predictive of health and environmental hazard, which required a different approach to hazard assessment for polymers than non-polymers.

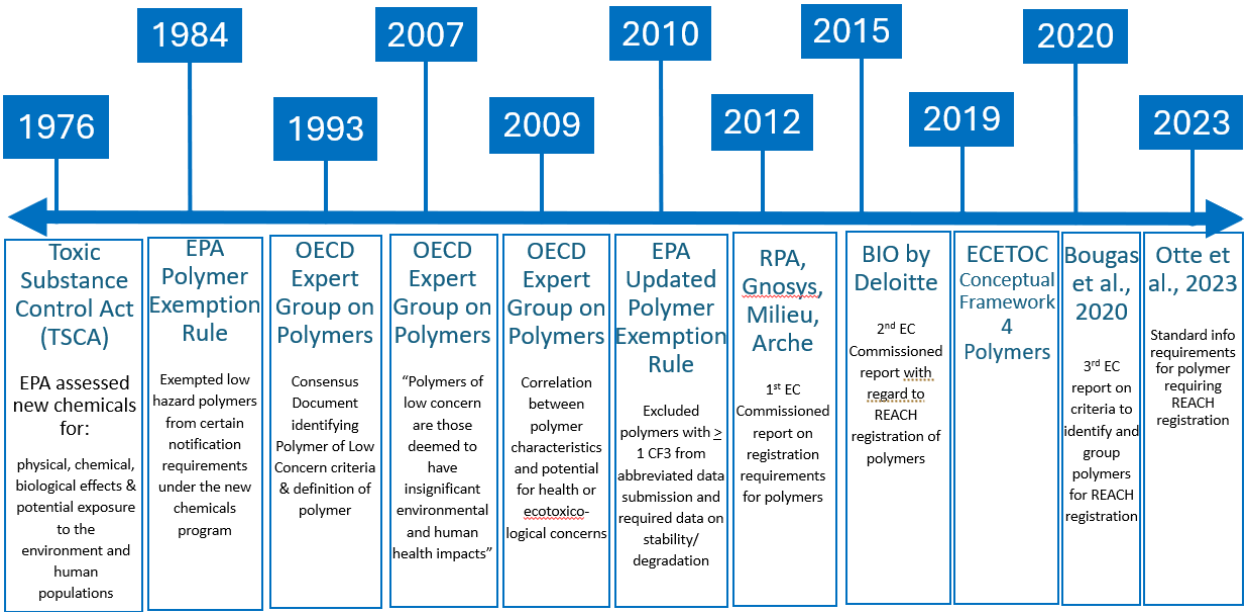


Figure 2 History of Polymer Hazard Assessment

Further examination of general physical–chemical properties and their relationship to hazard potential led to the development of general principles or criteria for the identification of chemicals, including

polymers with low hazard potential. Starting in the early 1990s the OECD Expert Group on Polymers started to examine physical, chemical and biological properties of polymers and try to correlate those to health and environmental hazards. A number of countries (such as Australia, Canada, Japan, Korea, New Zealand, the United States, etc.) started to base the regulatory requirements for polymers around these criteria initially developed by the USEPA. In general, their hazard assessment decision-making focused on about 13 properties, such as molecular weight, solubility, the presence of reactive functional groups, etc. (Henry et al., 2018). So, polymers and non-polymers were hazard assessed differently.

It is important to note that the state of the science of polymer hazard assessment at that time *did not* formally entail a life cycle approach. Polymer hazard assessment was primarily chemical, physical and biological property-focused. By 1984, the USEPA had sufficient polymer experience to establish the Polymer Exemption under the Toxic Substances Control Act which permitted polymer commercialization with an abbreviated data submission focused on the properties predictive of polymer hazard, instead of the full data package submission required for non-polymers seeking approval to commercialize, use or import into the US.

How does all of this relate to fluoropolymers? Polytetrafluoroethylene (PTFE) was discovered in 1938 and fluoropolymer technology flourished due to their uniquely useful properties and the high-tech products they enabled. Fluoropolymers were introduced to commerce *before* national chemical inventories and notification regulations for polymers and non-polymers were established. So, it should not be surprising that analytical chemistry methods and standards related to PFAS and fluoropolymer manufacture, processing and emissions were lagging behind.

Initially chemical analyses were primarily focused on emissions of the fluorosurfactants (PFOA or PFOS), not on byproducts of manufacturing or products of incomplete combustion (PICs) or greenhouse gases. Adverse effects of the legacy fluorosurfactants were becoming more widely known and were garnering significant attention. Publications like those from Yamada and Taylor, 2005 and Taylor et al., 2014 focused on the fluorosurfactant PFOA, which by this time was the subject of the phase out, by eight major leading companies in the PFAS industry, under the US EPA Voluntary PFOA Stewardship Program. Significant investments were made in PFAA research from industry, universities and non-governmental organizations. Interest in emissions of the non-polymeric polymerization aid PFOA and PFOS was high. The polymers themselves received less attention, especially in the EU, where polymers were not (and still are not) subject to chemical notification. Therefore, less attention was paid to the substances that went into the polymerization pot and their emissions from polymerization and processing. Hazard assessment in the EU focused on monomers, not polymers, although recently, the EU has been pursuing the REACH registration of polymers, with the EC commissioning three studies to investigate polymer REACH registration (RPA/Gnosys/Milieu/Arche, 2012; BIO by Deloitte, 2015; Bougas et al., 2020).

Pollution abatement technology and its implementation in the fluoropolymer industry have evolved significantly in recent years (as has the analytical technology and methods to detect, identify and quantify PFAS in environmental and biological media). Initially focused on fluorinated surfactants enabling polymerization of fluoropolymers (e.g., PFOA), as knowledge was gained about potential emissions of other fluorinated substances and greenhouse gases (with global warming potential), technologies were developed to control their emissions. Since the phase out of PFOA, by eight major leading companies in the PFAS industry under the US EPA Voluntary PFOA Stewardship Program, a 95 percent reduction in both manufacturing facility emissions of PFOA, precursor chemicals that can break down to PFOA, and related chemicals was achieved by 2010, as well as elimination of PFOA from emissions and products by 2015.

A tremendous explosion of PFAS information has occurred over the last several decades. A Dimensions search on "PFAS" resulted in 523,997 publications, 410,803 patents, 2,725 grants, and 8,634 policy documents! PFAS detection limits are, in some environmental media, now down to parts per trillion or less. Analytical methods have been established and validated in multiple environmental and biological media. More and more peer-reviewed research publications on environmental fate and transport, toxicology and ecotoxicology are published daily, and the management of emissions has significantly increased as well. Evidence that effective fluoropolymer manufacturing controls work to decrease bioavailable exposure to PFAS includes the decreasing non polymeric PFAS blood levels as reported by the US NHANES (2003-2004 to 2017-2018) and the Australian Human Biomonitoring Program (2002–2003 to 2020–2021) (Taucare et al., 2024). In addition, the ECHA UPFAS BD reflects the Plastics Europe Fluoropolymer Products Group voluntary manufacturing program to reduce emissions to air and water for non-polymeric PFAS residues from polymerization aid technology (see below). Control of fluoropolymer emissions during manufacturing has made significant progress in PFAS emissions abatement, though subject to ongoing continuous improvement (Dalmijn et al., 2024).

Plastics Europe Fluoropolymer Products Group Responsible Manufacturing Program

Emission Reduction Targets

Members are committed to achieving specific average emission factors for non-polymeric PFAS residues from polymerisation aid technology. The targets are:

- By end 2024: 0.009% to air and 0.001% to water.
- By end 2030: 0.003% to air and 0.0006% to water.

In Life: The published, peer-reviewed literature demonstrate that fluoropolymers have properties predictive of low health and environmental hazards (also known as „polymer of low concern" criteria) (Henry et al. 2018; Korzeniowski et al., 2022; Ameduri, 2023; Dourson, Lasee and Onyema, 2024; Henry and Timmer, 2025) as does the sixty years of safe clinical use of fluoropolymers in millions of medical devices implanted in patients worldwide. Recently (August 2025) the US Food and Drug Administration, responsible for monitoring the safety of fluoropolymers in medical devices, found no reason to intervene in the use of fluoropolymers citing no conclusive evidence of patient health issues associated with PTFE. This was based on the available scientific evidence and an independent safety review by ECRI (formerly the Emergency Care Research Institute) of over 1,750 published and peer reviewed scientific articles, plus the real-world surveillance network of clinics and health providers (PFAS in Medical Devices | FDA). Despite the history of safe clinical use and data submitted to regulatory authorities on fluoropolymers, the ECHA BD noted uncertainty about the toxicity of fluoropolymer microparticles, based on limited available data. Microparticle research is another rapidly emerging area which is discussed extensively later in this report. (See Microplastics.)

End of Life: The BD, and the recent OECD synthesis paper on fluoropolymers (2025), reflect particular uncertainty regarding the quantities of PFAS emissions during the end-of-life phase of the fluoropolymer life cycle. The end-of-life emissions quantites presented in the BD were largely responsible for the risk management options recommended in the restriction proposal. Emissions quantities are discussed later in this report.

Given the uncertainty about the degree risk fluoropolymers present, expressed by the dossier submitters in the BD, SPECTARIS commissioned this report to summarize the current state of the science on fluoropolymers and their uses by these industries to demonstrate the weight of evidence in support of

their continued safe contribution to modern society and to address residual uncertainties for regulators and the public, particularly concerning fluoropolymer end-of-life and fluoropolymer microparticles.

This report involved review, evaluation, and preparation of the existing, publicly available scientific knowledge considering all waste streams (i.e., incineration, landfilling, recycling/ upcycling, and environmental residues in the form of fluoropolymer microplastics) to be used in political and specialist media discussions. When possible, findings were restricted to those of relevance to the optics, photonics, analytical and medical technology sectors (hereinafter referred to as "high-tech applications") and medical technology separate from pharmaceuticals. This report summarizes the current weight of evidence and notes areas of uncertainty, contradictions or deviations between BD and the recognized state of science. Challenges for further scientific debate are also identified.

Methods

Literature searches were performed in Dimensions (with over 140 million publications, conference proceedings, patents, etc.) for the following search terms: fluoropolymer, fluoropolymers, disposal, end of life, incinerate, incineration, mineralize, municipal solid waste (MSW), landfill, landfilling, recycle, recycling, upcycle, upcycling, consumer optics, photonics, medical technology, analytical technology, biological technology, laboratory technology, research and development, microplastic, microplastics, microparticle, microparticles.

Peer-reviewed publications, industry studies (e.g. those by Conversio, KIT, GKS Schweinfurt), the UPFAS Background Document, and other relevant publicly available reports, policy papers, and trade association documents were also searched. Where sufficient data on a European level was not available, international data was utilized.

"Hits" from these searches were screened to restrict to documents in English, and to those published between 2000 and 2026, with a few exceptions. (Given the advances in analytical instrumentation, methods and regulations, literature prior to 2000 was referenced only as needed.) They were sorted into the topics of this report: incineration, landfill, recycle, upcycle and microplastics. Whenever possible, within those topics, the hits were then sorted into the product categories of interest to Spectaris: consumer optics, photonics, medical technology, analytical technology, biological technology, laboratory technology, research. Articles in each of these topics and categories as well as the non-industry sector specific articles are summarized here. Pertinent publications were screened and synthesized according to the report's purpose. Key data were systematically extracted and integrated to provide a robust foundation for this thematic analysis.

Results

In this section, the key articles for each end-of-life option are summarized: incineration, landfilling, recycling, upcycling. A section reviewing current literature on microplastics and fluoropolymer microparticles follows. The studies demonstrate the evolution of knowledge on fluoropolymer end of life options, analytical methods evolution, progress in pollution control and the degree of certainty that fluoropolymers can be manufactured and processed safely enabling high-tech products with significant contributions to modern life.

Incineration of Fluoropolymers - Background

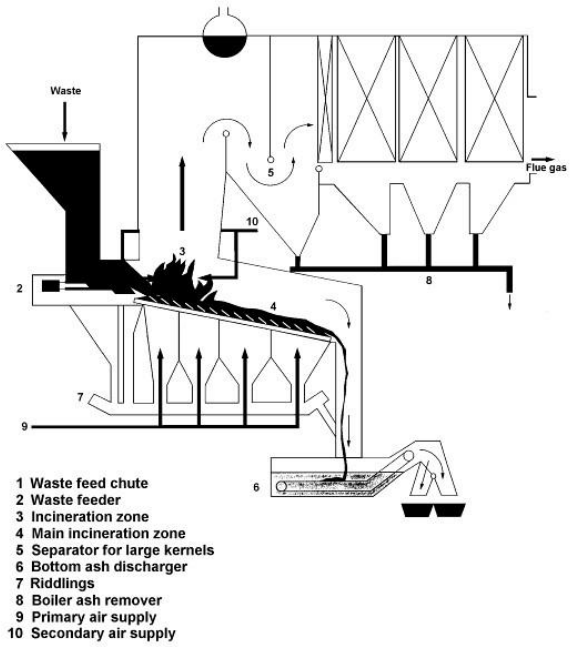


Figure 3 Grate incinerator in the EU (Neuwahl et al., 2019)

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

- travelling grate (≥ 850 - 1100 °C, ≥ 2 sec, ≥ 6% oxygen)
- rotary kiln (500 – 1450 °C, usually > 850 °C) and
- fluidised bed incinerators (760 - 871 °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. The secondary combustion chamber is required by law in the US, Australia, Cananda and the EU.

Pyrolysis and gasification systems are also thermal treatments but are not combustion processes.

Most fluoropolymer waste in Europe (84%) is incinerated (Conversio, 2022). Incineration addresses some problems of solid waste management and pollution through a reduction in the volume and mass of wastes, detoxification, destruction of organic components of biodegradable waste that may generate landfill gas, and waste heat recovery potential (Oumarou, Abubakar and Abubakar, 2018).

Directive 2000/76/EC 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 1 100 °C for at least two seconds."

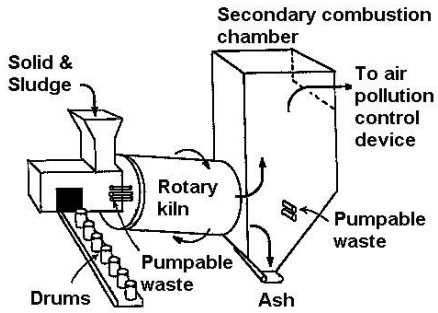


Figure 4 Rotary kiln incinerator
(Neuwahl et al., 2019)

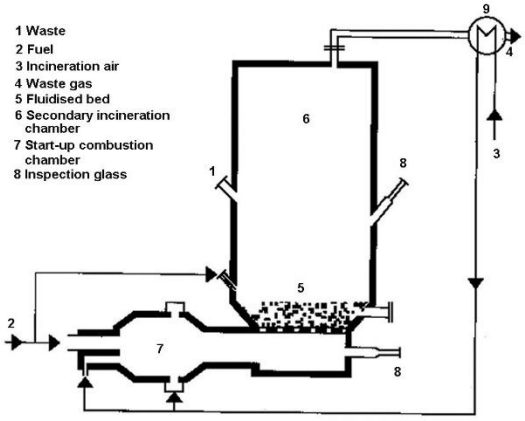


Figure 5 Fluidised bed incinerator
(Neuwahl, et al., 2019)

There are three main stages of the incineration process according to the European Union's Best Available Techniques (BAT) Reference Document for Waste Incineration (Neuwahl et al., 2019):

1) drying and degassing (in which volatiles have evolved at temperatures between 100 and 300 °C),

2) pyrolysis and gasification (in which organic substances are further decomposed at between 250 and 700 °C and residues are reacted with water vapor and CO_2 at temperatures typically between 500 and 1000 °C), and

3) oxidation (in which the combustible gases from the previous stage are oxidized at flue gas temperatures generally between 850 and 1450 °C). These stages somewhat overlap, occur in parallel and influence each other.

The key messages for this section are that municipal solid waste incinerators and hazardous waste incinerators operate differently, and, that it is possible to influence polluting emissions by controlling key elements like furnace design, air distribution and control engineering (Neuwahl et al., 2019).

TTTO is the acronym to remember: (residence) time, temperature, turbulence (for effective mixing) and oxygen concentration (Reinhart, Bolyard and Chen, 2023).

Incineration of Fluoropolymers – Key Literature

Table 2 summarizes the key articles regarding fluoropolymer incineration and the important information learned about conditions leading to destruction of PFAS with the lowest probability of PFAS emissions. They are presented in chronological order with key points in italics presented to highlight the progression of PFAS emissions knowledge.

Yamada et al., 2005 used an advanced thermal reactor system (ATRS) shown below to *determine if perfluorooctanoic acid* (PFOA), a „legacy" fluorosurfactant in fluorinated polymer production, *was formed when a fluorotelomer-based acrylic product (FTAB) was incinerated*. The ATRS, a pilot scale incinerator is shown below.

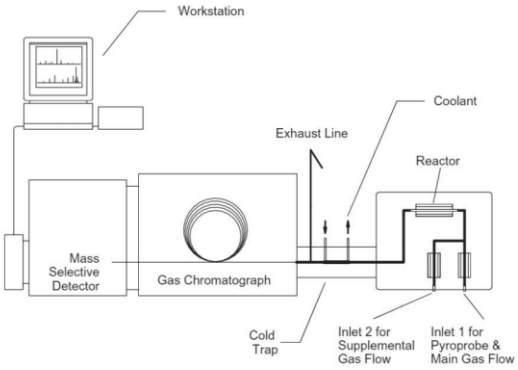


Figure 6 Advanced thermal reactor system (Yamada et al., 2005)

Thermal degradation was performed at 1000 °C for 2 seconds residence time and 85% excess air to *simulate US municipal solid waste incinerator conditions* (Yamada et al., 2005). They analyzed the reactor effluent for perfluorooctanoic acid (PFOA) by gas chromatography mass spectroscopy (GC-MS) and high power liquid chromatography with tandem mass spectroscopy (HPLC-MS-MS), and, fluoride and chloride ions by ion chromatography. *The temperature to achieve 99.9% destruction of the FTAB was 1000 °C.*

Huber et al., 2009 is notable for their *interest in the emission of greenhouse gases during incineration of fluoropolymers*. Surveying existing literature, especially that by Garcia et al., 2007, they found *CF_4, C_2F_6, CHF_3, C_3F_6 and C_4F_8 were produced at incinerator temperatures from 750 – 1050 °C. Other operating conditions were not known.*

Taylor et al., 2014 used a pilot/lab scale thermal reactor. They concluded that operating an *incinerator at 1000 °C over a 2 second residence time with oxygen levels averaging 13% did not result in detectable emissions of PFOA under conditions representative of US municipal waste incinerators*.

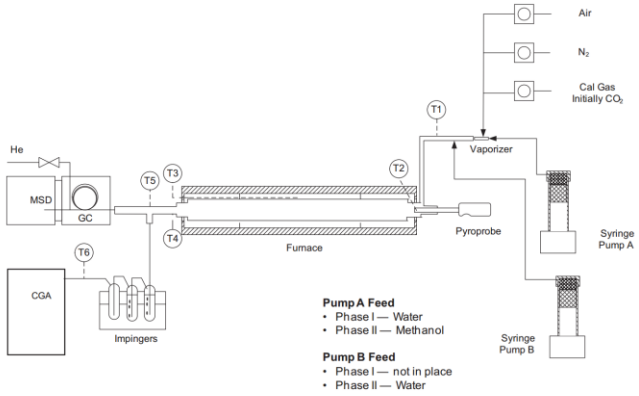


Figure 7 Pilot scale thermal reactor (Taylor et al., 2014)

They fluorotelomer-based polymers and fluoropolymers were incinerated in a non-flame, batch charged, continuous flow reactor system configured *to represent gas-phase behavior in a full-scale US waste incinerator* prior to air pollution controls. The two fluorotelomer based polymers (FTBP) composites they tested were representative of all FTBP in commerce.

Analysis was by LC-MS/MS with a limit of detection of 5 ng/L. Phase I of the study demonstrated that *if PFOA were present in the exhaust gases, it would be captured by the impingers*. However, *no detectable PFOA was produced from this combustion*. *Hydrogen fluoride* (HF), a highly corrosive acid gas, was *formed during combustion suggested mineralization of the starting polymers*, per the authors.

Table 2 PFAS Incineration Highlights 2005 to 2026

Temperature °C	Residence Time seconds	% Oxygen	Year Published	Reference	Incinerator Type	Results
≥1000	2	85% excess air	2005	Yamada et al.	lab/pilot Advanced Thermal Reactor System	>99.9% PFAS destruction
750 - 1050	not provided	not provided	2009	Huber et al.	various	found CF_4, C_2F_6, CHF_3, C_3F_6, C_4F_8
1000	2	13	2014	Taylor et al.	lab/pilot Advanced Thermal Reactor System	waste incineration of FTBP does not result in formation of detectable levels of PFOA
870	4	11	2019	Aleksandrov et al.	rotary kiln with heat recovery boiler and flue gas cleaning system	Results (for 31 PFAS) were not significantly different in ether run from baseline/control levels
1020	2.7	11				
1400	1	not provided	2021	Bakker, Bokkers and Broekman	various	for CF_4; consider temperatures on grates not combustion chamber
961	1	not provided				for C_2F_6; decomposes at ~950 °C which is close to typical combusion temperatures
850	2	≥6				for non hazardous waste incinerators
1100	2	≥6				for hazardous waste incinerators
>850	not provided	not provided	2021	Liu, et al.	moving grate	short chain PFAS found in bottom ash, fly ash, plant leachate
1000	2	not provided	2023	Reinhart et al.	moving grate with gas afterburner	low temperature regions within the incinerator may result in incomplete composition (PICs) which can be found in fly ash and bottom ash
>970	~2-4*	9.2	2023	Shields et al.	pilot scale	destruction efficiency (DE) >99.9999% for 5 PFSAs
870	~4*	11.8				DE >99.9% for PFCAs, DE 99.999% for PFSAs
810	~5*	12				DE >94% for 4 PFCAs, DE 99.9% for PFSAs
1090	~3*	9				DE >99.99 for 5 PFSAs
1180	~3*	7.2				at >1000 °C, non targeted analysis do not result in PFAS mass significantly above blanks
850	2	not provided	2023	Bjorklund, Weideman and Jansson	full scale waste-to-energy plant	short chain PFAS and PFOA found in bottom ash, fly ash and flue gas condensate; DE 99.9-99.93%
860	2	not provided	2024	Gehrmann, Wohter, Aleksandrov, et al. (slide presentation on GKS Schweinfurt study)	rotary kiln with heat recovery boiler and flue gas cleaning system	included PICs, >99.99% F-based destruction efficiency
1095	2	not provided				included PICs, >99.99% F-based destruction efficiency
860	2	~7-11%	2024	Gehrmann, et al.	rotary kiln	included PICs, C1-C3, CF_4, C_2F_6 and >99.99% R2PIC
1095	2	~7-11%				
>1000		not provided	2024	Johansson et al.	moving grate	PFAS found in fly ash, bottom ash and flue gas condensate

Aleksandrov et al., 2019 incinerated PTFE and wood pellets in the pilot plant "BRENDA" at Karlsruhe Institute of Technology. It had a rotary kiln facility equipped with a boiler for heat recovery and a flue gas cleaning system compliant which was with German emissions regulations (17 BImSchV, 2003). *The incinerator conditions were selected to match those in the EU: 870 °C with 4 sec residence time and 1020 °C with 2.7 seconds residence time an ~11% oxygen.* A partial load was run at 870 °C and a full load at 1020 °C. Thirty-one (31) specific PFAS were selected as analytes due to their occurrence in the environment, literature citations and availability of validated methods from commercial labs. These include *13 potential combustion products*. Liquid chromatography - mass spectrometry-mass spectrometry, LC-MS/MS, was used for the analyses. *Results were not significantly different in ether run from baseline/control levels*, according to paired t-tests. There was *no significant evidence that PFAS studied were created during the incineration* of PTFE, therefore, they concluded that *municipal incineration using best available techniques is not a significant source of the studied PFAS or combustion products and should be considered an acceptable form of waste treatment*.

Bakker, Bokkers and Broekman, 2021 (RIVM) studied per and polyfluorinated substances in waste incineration flue gases, particularly PFAS and greenhouse gases. They concluded that for PTFE complete thermal decomposition is achieved at a temperature above 800 °C. They assumed, therefore, that other *fluorine-containing products are thermally decomposition capable at a temperature of 800 °C.* From the literature they studied they said that *the minimum combustion temperature of 850 °C as required by Directive 210/75/EU for municipal waste incinerators, to thermally degrade PFAS*. They noted that *most of the PFAS will largely degrade during the incineration process and then be removed when the flue gases*

are cleaned. They noted that *if CF4 was present it would take 1440 °C for 1 second to degrade. For C2F6, they concluded it would take about 961 °C for 1 second*. Even with these results they stated that "despite efficient thermal degradation in the combustion chamber, the presence of PFAS in the flue gas of waste incinerators cannot be ruled out." They concluded that *combustion temperatures of at least 850 °C for at least 2 seconds in the presence of at least 6% oxygen were the minimum requirements for non-hazardous waste incinerators to destroy PFAS*, *while hazardous waste incinerators must have a minimum temperature of 1100 °C (per the EU Directive 2000/76/EC)*. *Short chain PFAS, C1 and C2 are likely to be formed as PICs if these minimum conditions of PFAS incineration are not met*. They argue that the *higher the combustion temperature, the fewer byproducts are formed*, the smaller the absolute quantitation and the smaller their molecular masses. It is worth noting that they judged the formation of fluorine containing dioxins and furans (major concerns for waste incineration) and perfluoro acetic acid were unlikely to be formed.

Bakker, Bokkers and Brockman (2021) noted that *PFAS that are in liquid or solid form a typical processing temperature were expected to be the most strongly adhered to fly ash particles. Some PFAS that are liquid at processing temperatures may pass to the next flue gas cleaning stage*. PFCs are more likely to remain in the gas phase and pass through the different flue gas scrubbing stages. Generally, they concluded that *PFAS with 6 or fewer carbons, are likely to be in the flue gas*.

According to **Liu et al., 2021**, Municipal Solid Waste Incinerators (MSWI) in S. China, predominantly moving grate or circulating fluidized bed types, typically run at >850 °C. They *examined PFAS in leachate, fly ash and bottom ash from waste incinerators*. Using Thermal Gravimetric Analysis-DTA method *they detected high PFAS concentrations* (225 ng/ml mean concentration) *in leachate*, mostly short chain PFAS (PFBA and PFBS). Circulating fluidized bed incinerators have high fly ash production, per Han et al, 2025. PFOS was the predominant PFAS in fly ash. It is important to note unlike S. China, rotary kilns are the predominant hazardous waste incinerator configurations according to the European Union for Responsible Incineration and Treatment of Special Waste (Eurits), a nonprofit organization representing 22 members operating 40 EU incinerators treating 3 metric tonnes of hazardous waste annually, not moving grate or fluidised beds. The Liu et al data informs that if conditions and configurations of incineration are not optimized, matrices other than flue gas may contain PFAS.

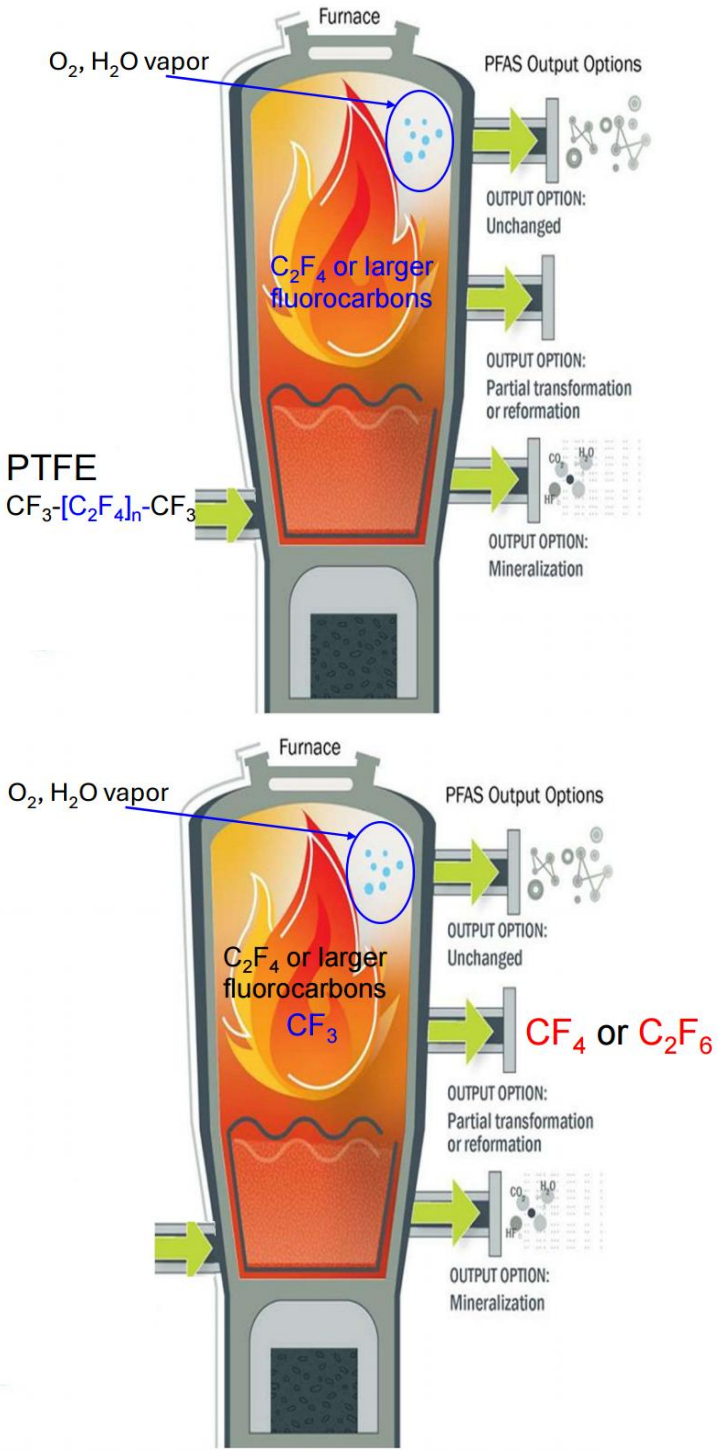
Bjorkland, Weideman and Jansson (2023) examined emission of *per and polyfluoroalkyl substances from a waste to energy plant occurrence in ashes, treated process water and flue gas*. Two different waste mixes were incinerated in a *full-scale waste to energy plant* in northern Sweden: normal MSWI and incineration of a waste mix *with 5-8% sewage sludge added to MSWI*. The conditions were 850 °C with 2 seconds residence time, but the grate temperature was 1100 °C. C4-C7 PFCAs were found in all residues though *levels were higher with the addition of the sewage sludge*. PFHxA and PFOA were found in one sample of bottom ash each. The most abundant PFAS in flue gas was PFBA, PFHxA PFOA, PFHpA and PFOS, PFDA and PFBS. The runs containing *sewage sludge had twice the concentration than runs without sewage sludge*, which is reasonable considering that wastewater treatment successfully concentrates PFAS from larger water volumes to smaller volumes of sludge. Per kg incinerated waste, 99.9 – 99.93% of the PFAS was destroyed.

According to **Reinhart, Bolyard and Chen (2023**) *temperature, residence time (time of reaction), oxygen concentration, the configuration of the incinerator and the addition of calcium hydroxide to stimulate decomposition influence the destruction of PFAS*. They worked with moving grate incinerator with a gas afterburner. Reinhart et al., 2023 noted that most thermal treatment of municipal solid waste is accomplished using incinerators with waste to energy recovery during which *temperatures typically exceed 1000 °C in both the grate system and the gas afterburner region with gas residence times of > 2 seconds. They concluded that those conditions were optimal for PFAS destruction*. However, they added

that there may be *low temperature regions within the MSW incinerator furnace resulting in PICs and that they could be found in both the fly ash and the bottom ash*. *Turbulence within the combustion chamber increases mixing and potentially ensures all waste sees high temperatures for complete destruction.*

Shields et al. (2023) ran at pilot-scale thermal destruction of per and polyfluoroalkyl substances in a legacy aqueous film forming foam. In a small, pilot scale research combustor, they used LC-MS/MS using USEPA Method 533 for PFAS and Fourier Transform Infrared spectrometry, FTIR, for continuous emissions monitoring for O_2, CO, CO_2 levels as well as HF, SO_2 and NO. UISEPA OTM-45 was employed for semi volatile and non-volatile polar PFAS. *A non-targeted analysis was also performed* with OTM-45 and LC-MS. Run temperatures spanned the hazardous waste incinerator *temperatures from 810 – 1180 °C*. They calculated *destruction efficiencies for PFSAs of >99.9999% at 970 °C, 99.999% at 870 °C and 99.9% at 810 °C*. *For PFCAs they had destruction efficiencies of >99.99% for >1090 °C and >99.9% at 870 °C.* Though these destruction efficiencies were high, Sheilds et al. noted that *high destruction efficiencies do not necessarily mean the absence of fluoroorganic PICs*. At 810 °C, they found mg/m3 emissions of C1-C8 perfluoroalkanes, while *at >1090 °C the PIC data showed very little volatile PFAS demonstrating the importance of optimal conditions on PIC formation*. At <1000 °C the non-targeted analysis showed an increase in PFAS emissions. They concluded that *high destruction efficiency and the absence of PICS was needed to show high destruction of PFAS.*

PICs were addressed in the **Gehrmann et al., 2024** work which *studied the mineralization of fluoropolymers from combustion in a pilot plant with representative European municipal and hazardous waste combustion conditions* in a rotary kiln facility equipped with a boiler for heat recovery and a flue gas cleaning system compliant with German emissions regulations (17 BImSchV, 2003). This was the same BRENDA reactor at KIT as was used by Aleksandrov et al. (2019). They incinerated commercial fluoropolymers, and fully fluorinated, partially fluorinated, non-melt processible, melt processible, plastic and rubber types of fluoropolymers including homopolymers, copolymers and terpolymers. Ultra-high pressure liquid chromatography (UPLC) with LC-MS and Gas Chromatography – mass spectrometry, G-MS were used for the analysis. In order to *mimic waste to energy EU incineration plants, setting 1 was 860 °C for 2 seconds with ~7-11% oxygen*. *Setting 2 to mimic EU hazardous waste incinerators was run at 1095 °C for 2 seconds residence time and the same oxygen levels*. Samples were taken at the exit of the primary combustion chamber, downstream of the boiler and in the stack. Adsorbable organic fluorine using combustion ion chromatography (CIC), was performed, along with measurements for inorganic fluorine. *Long chain, short chain, ultra short chain PFAS and greenhouse gases (CF_4 and C_2F_6) were measured*. In addition, *liquid and solid samples were analyzed* for long chain PFAS. *Gas scrubber water* (from the scrubbers 1 and 2, and neutral water) and *water from the wet deslagger* were also sampled, as were *solid residues from the filter and the boiler*. USEPA's OTM-45 method was employed in analyses. *The reduction rate for products of incomplete combustion (R2PIC) was calculated and found to be >99.99% demonstrating mineralization*. Slightly above (0.20 ng/m3) the limit of quantitation (0.9 ng/m3) levels of PFOA were detected in stack gas in one run only and were reasoned to be likely from external contamination. PFBS and PFOA were detected in solid residue and PFOS in wastewater but was likely coming from the wood chips containing trace level of sulfur. *By using the R2PIC*, (1- the sum of PFAS in outflow divided by the sum of PFAS in the inflow), Gehrmann et al. *circumvented the complication of needing a 100% fluorine mass balance, which is challenging given that fluorine reacts readily with silica and alumina in the reactor surfaces*. Even so fluorine recovery in the 860 °C run was ~80% and about ~70% for the 1095 °C run. They stated that the R2PIC characterizes the effectiveness of the combustion as a function of operational conditions such as temperature and residence times. The overall conclusion from the study was that *there were no discernible effects of temperature on the mineralization of fluoropolymers tested at 860 °C versus 1095 °C. Both conditions resulted in no evidence of an increased emission of PFAS including PICs*.



Example of Fluoropolymer (PTFE) Incineration – Step 1

(Filatov et al., 2011; Henry et al., 2018)

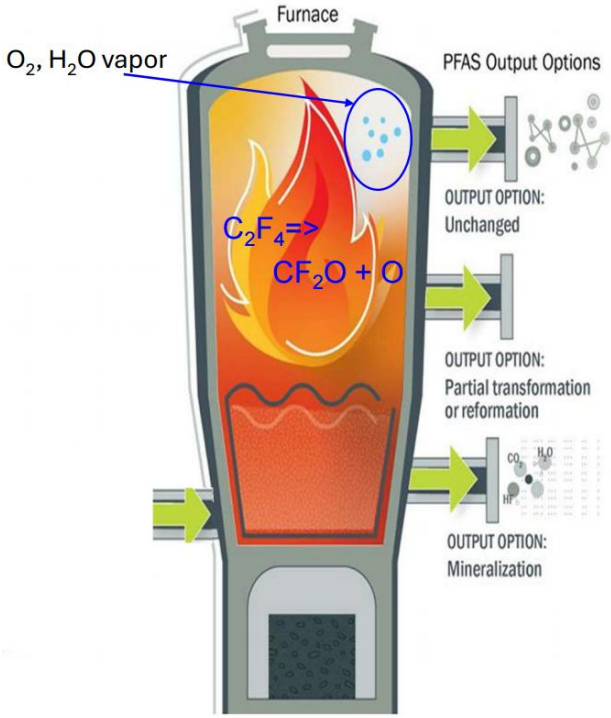
Step 1 of Figure 8a shows the first step in the incineration of a fluoropolymer, such as polytetrafluoroethylene (a chain of tetrafluoroethylene, C_2F_4) starting with the removal of the end groups (usually -CF_3) from the polymer chain. If the incineration was halted at this stage, the result would be C_2F_4 or larger fluorocarbons.

Example of Fluoropolymer (PTFE) Incineration – Step 2

(Burgess et al., 1996)

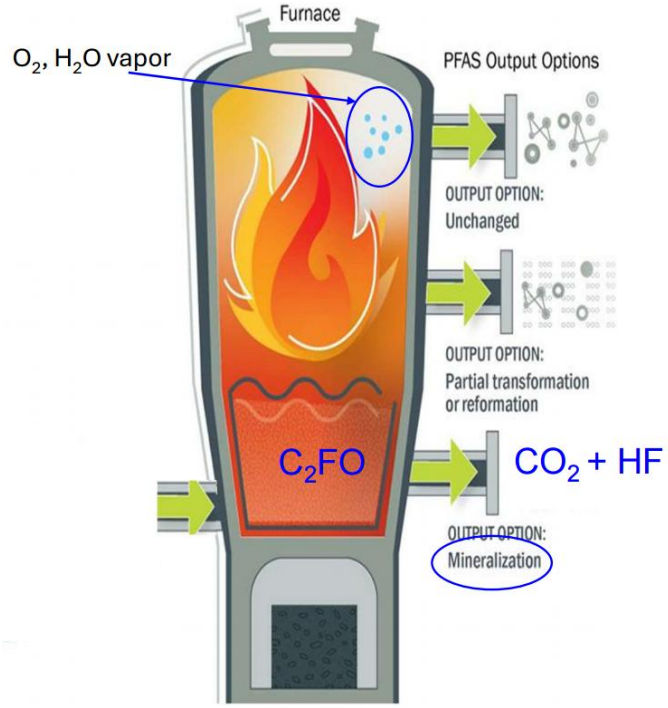
Step 2 of Figure 8a shows that if conditions are not optimal or incineration allowed to continue long enough and the process stopped here, the results would be greenhouse gases such as CF_4 or C_2F_6 which are currently restricted under the Montreal Protocol.

Figure 8a Steps 1 and 2 of Fluoropolymer Material (FPM) Incineration and Destruction (Modified from Stephen R. Jackson, NEWMOA PFAS Analytical Developments Webinar, September 25, 2024)



Example of Fluoropolymer (PTFE) Incineration – Step 3 (Burgess et al., 1996)

Step 3 of Figure 8b shows the breakdown of C_2F_4 to CF_2O and oxygen.



Example of Fluoropolymer (PTFE) Incineration – Step 4 (Francisco, 1993)

Step 4 of Figure 8b shows the breakdown of CF_2O to carbon dioxide, CO_2, and hydrogen fluoride, HF (or CO_2 and CaF if a calcium source is present).

Incineration of a fluoropolymer in compliance with the EU Industrial Emissions Directive starts with the fluoropolymer chain losing end groups and being broken to shorter and shorter pieces until it ends with mineralization to carbon dioxide and hydrogen fluoride or CaF, if calcium is present.

Figure 8b Steps 3 and 4 of Fluoropolymer Material (FPM) Incineration and Destruction (Modified from Stephen R. Jackson, NEWMOA PFAS Analytical Developments Webinar, September 25, 2024)

Johansson et al., 2024 studied *emissions of PFAAs and unidentified organofluorine* from Swedish municipal waste incinerator plants. The furnaces operated between 850 and 1125 °C. Samples of *fly ash, bottom ash and flue gas condensate* from 27 of the 38 Swedish MWI *were analyzed for the presence or 133 PFAAs* by LC-MS/MS. Total fluorine was analyzed by combustion ion chromatography, while inorganic fluorine was measured by ion chromatography. They demonstrated PFAS found in solid residues (fly ash, bottom ash), as well as condensate from the flue gas scrubber. *PFCAs were found in the fly ash* (PFPeA and PFHxA), *bottom ash* (PFHxA, PFBA, PFOS and PFBS) *and condensate* (PFBA, PFPeA and PFHxA). Low levels of PFOS were also detected.

Note that the Johansson et al., 2024 and Liu et al., 2021 work were done in moving grate or fluidised bed incinerators, which are not the predominant hazardous waste incinerator configuration in the EU. In both instances, the incinerator configuration and conditions were not optimized to achieve the highest PFAS destruction efficiencies. Therefore, the residual PFAS partitioned to solid residue (fly ash and bottom ash) and/or liquid residue (condensate from flue gas scrubbers). These studies show the evolution of knowledge of the impact of incinerator configuration and conditions on the degree of destruction efficiency and the matrices into which residual PFAS may partition.

Table 2 PFAS Incineration Highlights 2005 to 2026 - continued

Temperature °C	Residence Time seconds	% Oxygen	Year Published	Reference	Incinerator Type	Results
>1100	>2	"Precisely regulate oxygen concentration to steer reaction pathways away from the formation of short-chain PFASs and stable perfluoroalkanes".	2024	Weitz et al.	7 lab scale and 18 commercial combustion-based systems	~99.99% destruction efficiency with PICs; notes that air pollution controls are primarily for acid gas and particulate abatement not ultra shorts, short chain, long chain PFAS
≥850	2	not provided	2025	Murakami et al.	lab scale	99.999% destruction efficiency for PFOA, PFOcDA
>950	30 minutes to 1 hour	not provided	2025	Hofman et al.	rotary kiln with rotating drum (real world, full scale)	Quantified PFAS emissions, when detected, were significantly lower than emission limit value of the Dutch government (1 mg/Nm^3 PFOS); most chimney emissions did not exceed the chronic exposure threshold of 0.3 ng/m^3 EFSA4;sum of all 45 quantified PFAS <0.0104 ng/m^3
900-1090	2	not provided	2025	Warnecke et al.	commercial grate furnace and wet flue gas cleaning system	Scenario I (municipal solid waste, reference), Scenario II (municipal solid waste coincinerated with PFAS-contaminated oil with compost and swage sludge); Scenario II ("overdoing of PFAS" into municipal solid waste) - for all three, no significant increase in PFAS at the stack relative to reference scenario (I) <2 ng/m3 STP. Scenario III CF_4 detected above LOQ (0.7 mg/m3 STP). ≥850C for 2 s, Total Delta Destruction Rate >99.9999% (excluding CF_4); Including CF_4, 99.7%. 0.000108 wt.% F in residues, except bottom ash
1,097 - 1,223	primary chamber non combustible solids ~60 (minutes)	9-11	2025	Troxler et al.	commercial rotary kiln	DREs as high as 99.9999% for a variety of PFAS. DRE values from 99.99 to 99.9999% for C2F6. Low to non-detectable concentration of VFCs, below 1.00 ppb (PIDs).
1120-1147	afterburner gases ≥2					Modified Method 0010 to detect semi volatile VFCs in emissions is still under development.

Though conducted in the United States, **Weitz et al., 2024** reviewed per and polyfluoroalkyl treatment in combustion based thermal waste systems including seven lab scale and eighteen commercial or pilot scale facilities. They concluded that *PFAS can be destroyed at about 99.99% in thermal treatment systems*

operating at >850 °C, though they may emit fluorinated PICs. **The authors believed that *destruction efficiency depends on the feedstock fed to the incinerator, the design of the combustor and the operating temperatures*.** Weitz et al. (2024) *blame the previous lack of available methods to characterize PFAS destruction and PIC concentrations in facility air emission for the data gaps*. **They concluded that *an efficient secondary combustion chamber maintained above 1100 °C was needed to ensure complete combustion*.**

In **2025, Murakami et al.** examined the destruction of PFOA and perfluoroctadecanoic acid (PFOcDA) by incineration. *Temperature, residence time, turbulence, waste, fuel, oxygen and gas phase components influenced the combustion process* (Murakami et al., 2025). They used a laboratory scale furnace and conducted tests at temperatures from 450 to 1000 °C for PFOA and 450 to 850 °C for PFOcDA with a residence time or 2 seconds in a pure air atmosphere. Residue and flue gas samples were collected and analyzed by LC-HRMS for thirteen PFCAs, five PFSA, four PFECAs. They concluded that *incineration above 850 °C achieved a 99.999% destruction efficiency* for PFOA and PFOcDA.

Full-scale, real -world incineration studies examining the impacts of process parameters (temperature, residence time, turbulence, mixing ratio, oxygen level, waste stream, etc.) on the destruction efficiency and formation of PICs was lacking (**Hofman et al., 2025**). Repeated emission monitoring campaigns were conducted at the Indaver site in Antwerp, Belgium, where hazardous and industrial wastes are processed by three high temperature *rotary kilns operating at > 950 °C with residence times of 30 min to 1 hour, and rotating drum for turbulence*. While quantified PFAS emission concentrations were detected, they were at *emission levels significantly lower than the risk-based emission limit* values set by the Dutch government (0.01-0.05 ng/Nm3 for PFOA and 0.01 to 0.1 ng/Nm3 for PFOS) indicating the emission presented an acceptable risk (Hofman et al., 2025). The quantified chimney emissions were modelled for total stack contributions to ambient air. *This work in real world incinerators demonstrated that the right equipment operated at the right temperature, residence time and turbulence resulted in PFAS destruction meeting regulatory requirements for individua PFAS*.

Warnecke et al., 2025, performed investigations at the TWT (Thermal Waste Treatment) plant in Schweinfurt (Germany), which is equipped with a grate furnace and wet flue gas cleaning system, the PFAS concentration in the waste was gradually increased using the following scenarios:

I. Combustion of municipal solid waste (*household waste and household-type commercial waste*) as the reference Scenario I.
II. *Co-incineration of PFAS-contaminated soil with compost and sewage sludge*, added to the waste steam of Scenario I.
III. *Substantial over-dosing of PFAS*, introduced into the waste from Scenario I.

In addition to the internal process streams – such as scrubber process water and boiler ash – *all outgoing material streams were sampled and analyzed for PFA*S. This included bottom ash, all residues from flue gas cleaning (FGC), and the stack flue gas. All subsequent results refer, by way of example, to 22 polar and semi-volatile PFAS compounds and partly further PFAS up to 45 PFAS-species. Furthermore, *combustion air from the waste bunker, ambient air, FGC process water, and all other operating resources (e.g. activated carbon, limestone) were examined for PFAS and included in the mass balance.*

The combustion conditions in the furnace ranged from approximately 900 °C and 1090 °C for all scenarios, *meeting the regulatory requirements for thermal waste treatment, including a minimum temperature of 850 °C for 2 seconds in the first pass*.

Across all scenarios, *no significant increase in PFAS concentrations was observed at the stack relative to the reference Scenario I*. *The sum of PFAS remained below 2 ng/m^3 STP (median) for all scenarios*. *Only in Scenario III, the drastically "overdosed" PFAS scenario was tetrafluoromethane (CF_4) was detected above*

the limit of quantification[1] at 0.7 mg/m^3 STP in addition to the 22 PFAS compounds, *representing a "product of incomplete combustion* (PIC). Background trifluoroacetic acid (TFA) in the incoming process water from the TFA-contaminated River Main resulted in its capture in filter ash.

The fluorine-related degradation rate was calculated as the difference between the PFAS-dosed trial and the reference state, expressed as the Total Delta Destruction Rate (TD2R). *At ≥ 850 °C for 2 seconds, this results in a TD²R > 99.9999 wt.% for the 22 PFAS - excluding CF_4. When CF_4 concentrations from the PFAS overdosing in Scenario III are included in the calculation, the TD²R decreases to 99.7%.* CF_4 is considered to be inert and non-toxic. CF_4 is not classified under EU Classification, Labelling and Packaging Directive as toxic, mobile or bioaccumulative, and is already regulated as a greenhouse gas under the Kyoto Protocol.

When the overdosing PFAS Scenario 3 was compared to the reference Scenario 1, it was determined that *of the 100% fluorine from the PFAS added to the municipal household waste* was considered, *only 0.000108 wt.-% of that fluorine was not destroyed and remained in the residues (bottom ash).* The bottom ash is disposed of in deep underground repositories and is not dispersed in the environment.

Another key learning from the Warnecke et al. 2025 work is the necessity to correctly consider "field blank measures". Although all tests strive to minimize measurement errors, recognition is needed that systematic measuring errors happen and are reflected in the outcomes.

Troxler et al., 2025 reported on a commercially operated hazardous waste incinerator in Utah (USA) operating a rotary kiln. Non-combustible solid residence time in the first combustion chamber was about 60 minutes. The O_2 concentration was 9-11% with exit gas from the rotary kiln of 1,097 to 1,223 °C with afterburner exit gas temps of 1,120 to 1,147 C. *This demonstrated >99.9999% destruction and removal efficiency (DRE) for PFAS* in aqueous film-forming foam. *They achieved < 1 ppb by volume of volatile fluorinated compounds, VFCs in exhaust emissions*. Modified US EPA Method 00100 for detection of non-polar semi volatile PFAS is still under development, however. *DREs from 99.99 to 99.9999 percent were demonstrated for C_2F_6, supporting its potential use as an indicator for PFAS destruction*. Still, since there are no standard methods for detection of polar volatile VFCs, such as TFA, *more development is needed.*

Chen et al., 2026 found that *furnace type and operating parameters governed the degradation efficiency and ultimate fate of PFAS during incineration*. Oxygen concentration dictates the reaction pathways and product distributions in combustion systems; *improving oxygen availability significantly reduces the yield of perfluoroalkylene species*. *The presence of an efficient secondary combustion chamber at ≥ 1100 °C was critical to reducing fluorinated emissions*. Though a 99% removal rate of PFAS indicates destruction, it doesn't confirm the absence of hazardous byproducts or complete mineralization. *Precise control of the combustion atmosphere is an effective strategy to suppress formation of harmful byproducts*.

Silsby et al., 2026 noted that "…*accounting for the fate of every fluorine atom to achieve a complete fluorine balance is difficult at all scales and improbable at large scales" because fluorine reacts with reactor surfaces and matrix constituents and the quantitative analytical methods for many PIDs are still in development*. Because some PIDs may be high risk even at low concentrations comprehensive PID characterization is important. The authors *suggest adding hydrogen sources* like water or natural gas or calcium hydroxide in order to generate volatile hydrofluoralkances that subsequently can be defluorinated to simpler organic fluorine compounds that are more easky to completely mineralize. *Hazardous waste incinerators, like rotary kilns with primary and secondary combustion chambers* with sufficient residence time and operating temperatures (10-90 minutes at $\geq$ 650 °C and 2–4 s at ≥950 °C) *are the most effective* at mineralizing organic contaminants achieving high DREs (>99.9999%) and emissions

[1] The limit of quantification, or LOQ, is useful to know if the analyte detected can accurately and precisely be quantified and that it is unlikely to reflect a variation in measurement or background.

with low to non-detectable levels of PIDs. *Silsby et al. (2026) suggest that a high DRE for C_2F_6 can serve as a potential indicator for effective PFAS destruction*.

Table 2 PFAS Incineration Highlights 2005 to 2026 - continued

Temperature °C	Residence Time seconds	% Oxygen	Year Published	Reference	Incinerator Type	Results
≥1100	≥2	regulate O2 to steer reaction pathways away from formation of short chain PFAS and stable perfluoroalkanes	2026	Chen et al.	rotary kiln	Promote the use of advanced furnaces (e.g., rotary kilns and multiple hearth furnaces) integrated with secondary combustion chambers to insure intense turbulent mixing and uniform temperatures, eliminating localized cold spots where PFASs can escape destruction.
≥ 650	10-90 min primary chamber	not provided	2026	Silsby et al.	rotary kiln	PIDs indicate operational conditions and kinetic bottlenecks preventing complete PFAS mineralization.
						Add H sources (e,g,H_2O or Ca(OH)2) to transform recalcitrant species to hydrofluoroalkanes and simpler organic fluorine species to facilitate complete mineralization to inorganic fluorine species.
≥ 950	2-4 secondary combustion chamber					A high DRE for C_2F_6 can serve as a potential indicator for effective PFAS destruction
						Complete fluorine mass balance is difficult at all scales/improbable at large scales because F reacts with reactor surfaces & matrix constituents; quantitative analytical methods for many PIDs are still in development.
Note the US CFR Part 63.1203 says 99.99% destruction of most chemicals achieved at 810-1180°C, but is not specifically for PFAS						
Note also that Directive 2010/75/EU calls for MSWI to operate at 850°C						
*extrapolated from Figure S1.						

Incineration key points:

- Significant progress in PFAS incineration technologies and PFAS analytical chemistry has been achieved over the past twenty (20) years.
- 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.
- DREs ≥ 99.9999% are possible in real-world/commercial incinerators using optimal incinerator conditions, exceeding the ECHA RAC's recommendation of a minimum destruction and removal efficiency of 98% / non-hazardous waste respectively 99% / hazardous waste.
- Even though analytical methods for all products of incomplete combustion (PICs)/products of incomplete destruction (PIDs) are ongoing, a low concentration of C_2F_6 is a reasonable indicator of complete PFAS mineralization.

Landfill of Fluoropolymers

The Landfill Directive of 2018 (Directive 1999/31/EC on the landfill of waste) notes that *landfill sites* are divided into 3 categories: *hazardous waste*, *non-hazardous waste* (e.g. municipal waste), and *inert waste* (that will not decompose or burn, such as gravel, sand, stone).

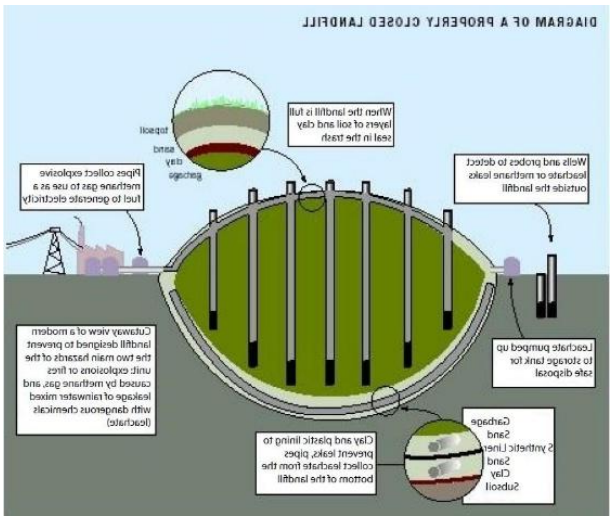


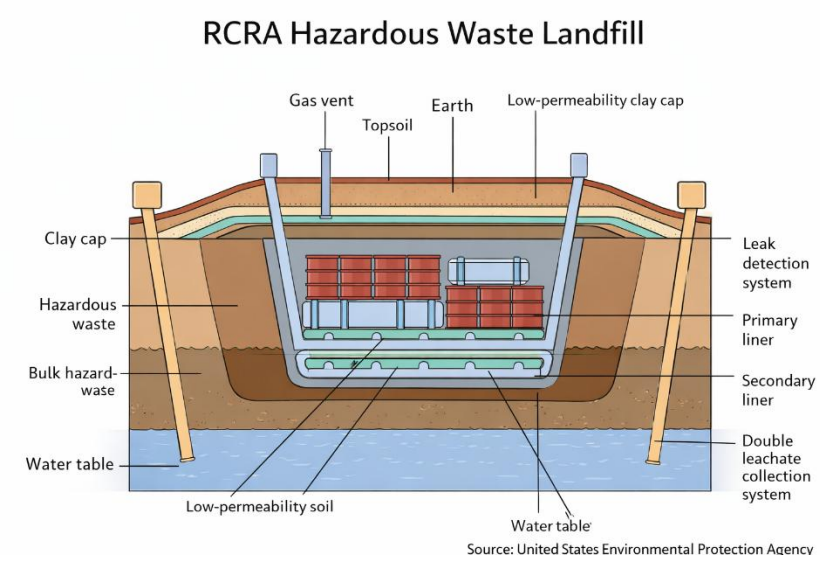
Figure 9 Diagram of a municipal solid waste landfill (properly closed). (See Municipal Solid Waste Landfills | US EPA)

Non-hazardous waste landfills consist of:

- a *liner* (typically a flexible membrane covering two feet of compacted clay soil lining the landfill bottom and sides) that functions to protect the groundwater and underlying soil from any leachate released;
- a *leachate collection and drainage/removal system* that sits on top of the liner and removes leachate from the landfill for treatment and disposal;
- a *gas collection system* (for methane gas from organic matter decomposition, and other gases released);
- the *trash* itself.

There are standard operating practices for non-hazardous waste landfills including compacting and covering waste frequently with several inches of soil to help reduce odor, control litter, insects, and rodents, and protect public health.

Municipal waste landfills also have procedures to test the groundwater to determine if the waste materials escaped from the landfill. Groundwater is tested to determine whether the waste materials have escaped from the landfill. Procedures also exist on closure and post-closure care requirements including covering landfills and providing long-term care for them. In addition, corrective action provisions exist for the control and cleanup of any landfill releases in order to protect groundwater.



Hazardous waste landfills are excavated or engineered sites with double liners, double leachate collection and removal systems. Leak detection systems, run on, runoff and wind dispersal controls, and construction quality assurance programs (Hazardous Waste Management Facilities and Units | US EPA).

Figure 10 Diagram of a hazardous waste landfill (Adapted from publicly available educational materials; no original source identifiable. Conceptual elements based on U.S. EPA landfill design guidance (EPA, 2026).

Operators must also comply with inspection, monitoring, and release response requirements. Since landfills are permanent disposal sites and are closed with waste in place, they are subject to closure and post-closure care requirements including: installing and maintaining a final cover; continuing operation of the leachate collection and removal system until leachate is no longer detected; maintaining and monitoring the leak detection system; maintaining ground water monitoring; preventing storm water run on and runoff; installing and protecting surveyed benchmarks (Hazardous Waste Management Facilities and Units | US EPA).

In 2018 in Europe, DG Environment noted that 24% of all municipal waste was landfilled (Landfill waste - Environment - European Commission). About 13% of the fluoropolymer waste in the EU is disposed of in landfills (Conversio Market & Strategy GmbH, 2022). Landfilling is the least preferable end of life option per the EU Waste Hierarchy.

Fluoropolymer material-containing products that have not contacted hazardous chemicals or been used in medical procedures involving contact with bodily fluids or infectious materials would be considered non-hazardous waste. According to the World Health Organization (2024) about 85% of the waste generated by health care activities is non-hazardous. That health care waste would include items from hospitals, health facilities, laboratories, research facilities, mortuary and autopsy centers, animal research and testing laboratories, blood banks and collection serves and nursing homes and would consist of items that did not contact bodily fluids, infectious materials, radioactive materials or hazardous chemicals (WHO, 2024).

Within the non-hazardous waste landfill, the active breakdown phase is when the physical, chemical and microbiological systems work on the non-hazardous waste. Microbes within the landfill begin to work on the trash to break down the waste.

Landfill leachate

Decomposition products depart the landfill as a liquid known as leachate specifically due to contact with water or a gas. PFAAs and their precursor were found in landfill leachate (ex. PFOA, PFBS, PFHxS, PFOS, etc.) (Solo-Gabriele et al., 2020; Chen et al., 2023; Tolaymat et al., 2023). The amount of PFAS concentration in the leachate increases with the age of the landfill and the volume of leachate increases with increased precipitation (Tolaymat et al., 2023).

Given that municipal solid waste in non-hazardous landfills is heavily composed of food packaging materials, biosolids from waste water treatment plants, carpets, textiles, and non-stick cookware it is not surprising that PFAS have been detected in landfill leachate as they degrade (Tolaymat et al., 2023). Given those products are heavily represented in municipal solid (non-hazardous) waste, the composition of landfill gas is also predictable, namely fluorotelomer alcohols (FTOHs), acrylates (FTAC), olefin (FT olefins) and PFAAs. Goukeh et al., 2025 noted that landfill leachate contains PFAAs, FTCAs, diPAPs and FTSs. Weinberg et al., 2011 noted that the average fluorotelomer alcohol concentrations at two German landfill sites (0.086 and 0.271 ng/m3) represented 80 and 92% of the total gas phase PFAS. Flaring and combustion are common landfill gas management techniques. In addition, the potential presence of municipal solid waste incinerator ash from suboptimal incineration may also add to the PFAS in landfill leachate concentration.

However, fluoropolymer products (and products containing fluoropolymer materials) in hazardous or non-hazardous landfills are not the source of PFAS in landfill leachate or gas. OECD 100 and 300 series environmental fate and behaviour tests confirmed the lack of biotic, abiotic, and (simulated) sewage treatment degradation of PTFE meeting the ASTM D4895 standard (Henry and Timmer, 2025). Since fluoropolymers do not degrade (to PFAAs or FTOHs or any other PFAS) they could not be the source or the FTOH in the landfill gas phase. Fluoropolymers have a long history of durability and resistance to weathering making them the materials of choice for products with exposure to environmental elements. Therefore, fluoropolymers from various products in landfills are not degrading and subsequently contributing PFAS, volatile fluorinated compounds, greenhouse gases or other substances of concern to landfill leachate or landfill gas. Tolaymat et al., 2023 stated that the fate of solid waste-derived PFAS with landfills is dominated by transformation and partitioning, neither of which are seen with fluoropolymers. Finally, the US EPA (2024) noted that fluoropolymers in landfills were stable and would be expected to be retained (as such) for a prolonged time.

Therefore, based on the literature demonstrating the stability and durability of fluoropolymers in a wide range of conditions (temperature, chemical environments, environmental conditions) the resistance of fluoropolymers to degradation is well established.

Landfill key points

- Only about 13% of fluoropolymer waste in the EU ends up in a landfill
- Depending on whether or not the fluoropolymer material-containing products have contacted hazardous chemicals, bodily fluids or infectious materials, they could be disposed of in municipal solid waste landfills (non-hazardous) or hazardous landfills.
- According to scientific studies, based on the types of PFAS detected in landfill leachate (predominantly PFAAs and their precursors), and the lack of abiotic or biotic degradation of fluoropolymers, fluoropolymers are unlikely to be the source of PFAS in leachate or gas.

Recycling of Fluoropolymers

According to a report by Conversio Market & Strategy GmbH (2020) only about 3.4% of fluoropolymer waste in the EU is recycled. This very small quantity makes establishing dedicated fluoropolymer collection streams difficult. The cost of collecting, sorting, cleaning, and reprocessing often exceeds the cost of virgin fluoropolymer production limiting economic viability. Markets for recycled fluoropolymers may also present difficulties as high performance, highly technical applications often have regulatory or customer performance standards that may restrict the use of recycled content or make meeting specifications and regulatory requirements challenging. Therefore, at the present time, recycling is not a primary end of life option for fluoropolymers as it faces significant technical and economic barriers.

Fluoropolymers cannot be recycled together with other bulk polymers due to their chemical composition and low market volume (Schmidt-Rodenkirchen et al., 2023). But, the indispensable utility of fluoropolymers and their energy intensive production and high cost make them it worthwhile to try avenues for recycling. At the end of their useful life, recycling of fluoropolymer products should be done in a way that closes material loops as far downstream in the value chain as possible. Schmidt-Rodenkirchen et al., 2023 see the following as the preferred order or fluoropolymer recycling, when quality requirements allow:

1. Mechanical recycling (size reduction, milling, reprocessing without breaking chemical bonds),
2. Macromolecular recycling (solvent-based recovery),
3. Monomer recycling (thermal depolymerization),
4. Feedstock recycling (breaking down into chemical precursors).

Recycling of fluoropolymer products could begin with efficient take-back networks and appropriate logistics, whenever possible, followed by collection, sorting, and refinement for reuse of the fluoropolymer as either raw materials or an energy source (Ameduri, 2023). Finished articles containing fluoropolymer material components require deconstruction to find the fluoropolymer component in the product, separate it for recycling, which may make recover time- and resource-consuming.

Mechanical recycling:

For cleaner, post-industrial PTFE scrap there are some methods for recycling that are reasonably straightforward. For sintered, unfilled PTFE resin, start with thorough cleaning. Contaminants must be cleaned off as even small amounts of impurities in the PTFE can drastically alter performance. After cleaning, the scrap can be milled into certain particle size classes which can then be reused as “repro-PTFE” in, for example, ram extrusion (Dams and Hintzer, 2016) or compression molding applications. The original processing of the PTFE involved heat and combined with regrinding, this can degrade the polymer limiting its usefulness in highly technical applications after recycling.

Repro-PFE can also be mixed with virginal PTFE and used in less demanding end use applications (Dams and Hintzer, 2016). Note that the ASTM D4895 standard for PTFE fine powder – an internationally recognized source of standards for various substances, tests and methods - does not permit the use of reground or reprocessed resin.

On a commercial scale, clean, unfilled PTFE can be thermally degraded in ovens, kneaders or preferably extruders at temperatures of about 500 °C (Dams and Hintzer, 2016). The lower molecular weight PTFE materials are further milled into much smaller particles often called PTFE micropowders (Dams and Hintzer, 2016).

Another commercially widespread recycling technique for PTFE is high energy (X-ray, gamma-ray or electron beam) radiation used with clean, unfilled PTFE, followed by milling to the desired particle size (Dams and Hintzer, 2016). The use of such PTFE is usually as additives in plastics, inks, oils, lubricants and coatings (Dams and Hintzer, 2016).

Filled PTFE grades are much harder to recycle mechanically as separating the filler from the polymer is difficult, if not impossible.

Macromolecular recycling (solvent-based recovery)

Due to the very limited solubility of fluorinated materials (fluoropolymers, fluorinated thermoplastics, etc.), solution-based recycling routes are generally not technically feasible except for some perfluorinated ionomers with sulfonic acid side groups (Schmidt-Rodenkirchen et al., 2023).

Monomer recycling (thermal depolymerization)

Fully fluorinated polymers of clean, single-grade production scrap can be mechanically recycled, in addition to being chemically recycled with excellent yields (up to 90% relative to CF_2 content). (Schmidt-Rodenkirchen et al. 2023). The perfluorinated ionomers with sulfonic acid side groups can also be partially cleaved into TFE/HFP by pyrolysis, but with lower yields that those of fully fluorinated polymers (Schmidt-Rodenkirchen et al. 2023). Partially fluorinated polymers, composite materials, and most partially fluorinated by-products from polymer production are not yet chemically recyclable on an industrial scale, however (Schmidt-Rodenkirchen et al., 2023).

Feedstock recycling (breaking down into chemical precursors)

Chemical recycling by pyrolysis, or upcycling, involves heating the fluoropolymer waste in controlled conditions to break it down to constituent monomers or other valuable fluorochemicals which are then recovered or potentially used to synthesize new virgin fluoropolymers. However, these processes require sophisticated technology and are very expensive. Managing the byproducts of pyrolysis is also necessary. As a result, this recycling option is very limited globally.

According to Dams and Hintzer (2016), at least 10-30% of PTFE compound waste tends to be recycled into TFE and HFP monomers due to a lack of large-scale recycling technologies for PTFE compounds because of the presence of a large variety of fillers and pigments.

Clean, unpigmented, and uncured waste from the manufacturing and processing of perfluorinated/ partially fluorinated thermoplastics or elastomers, generated in the low percentage range, are recycled back into the corresponding processes with little effect on end-use properties (Dams and Hintzer, 2016).

Partially fluorinated polymers, like tetrafluoroethylene-hexafluoropropylene-vinylidene fluoride (THV), ethylene tetrafluoroethylene (ETFE) and polyvinylidene fluoride (PVDF) and perfluorinated polymers in combination with larger amounts of hydrocarbon-containing polymers can also be recycled by the High Temperature Conversion (HTC) process into monomers, but only in low to moderate yields (Dams and Hintzer, 2016). The HTC of fluorinated polymers into monomers is not avilable on a large scale at present. Dams and Hintzer (2016) report that this process is particularly well suited to convert filled PTFE compounds (filled with carbon, graphite, glass fiber and metal compounds) and unfilled materials (from manufacturing, processing and end-of-life materials) into monomers. The continuation or expansion of

this „upcycling“ of fluorinated polymers to monomers (previously available at the 3M/Dyneon facility in Burgkirchen, Germany, implemented in 2015) has an uncertain future after the 3M announcement to exit the fluoropolymer business. (See Schlipf M and T Schwalm, 2014.)

Another approach to fluoropolymer recycling is to use the polymer, as is, as a processing and recycling aid for plastics that are not fluoropolymers. Ameduri (2023) reports that PVDF and vinylidene fluoride (VDF) copolymers are reported to be used by Arkema as a processing and recycling aid (PPRA) for polyethylene and polypropylene films, pipes, cables, and injection molded parts.

Upcycling of Fluoropolymers

The literature supports that the technology exists, on a small scale to return fluoropolymers to their fluorinated monomers suitable for new fluoropolymer manufacturing through thermal treatments. See Feedstock recycling above.

Within the framework of a federally supported project, the University of Bayreuth has developed a depolymerization process in cooperation with InVerTec and the 3M Dyneon company. Fluoropolymers can be converted into their monomers with 90% efficiency. (See InVerTec: PTFE recycling) However, at the present there are no commercially available upcycling facilities, which explains the low use of this disposal option.

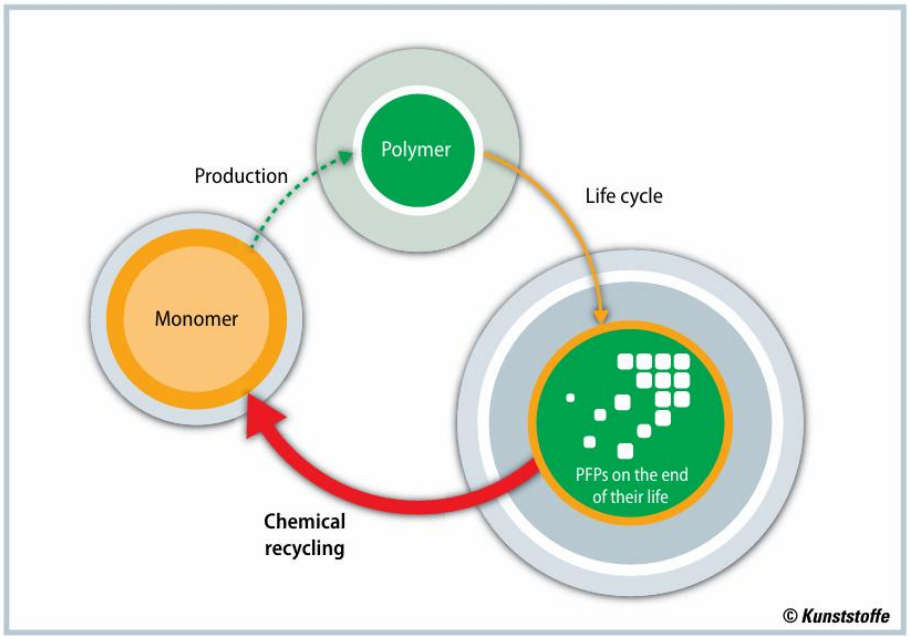


Figure 11 Closing the life cycle loop on perfluorinated polymers (PFPs)

(Schlipf and Swalm, 2014, *Kunststoffe international* 6: 59.)

Additional upcycling approach has been being developed through a reductive mechanochemical process mediated by potassium metal (Hattori et al., 2025). This process efficiently degrades PTFE within an hour at an ambient temperature to potassium fluoride and carbon black referred to as “KFPTFE-Carbon” (Hattori et al., 2025). The authors suggest that this can be directly used in fluorination reactions, yielding fluorochemicals in moderate to excellent results (Hattori et al., 2025). Since the process involves only PTFE and potassium-based reagents, there were no fluorinated or environmentally harmful byproducts generated, and no extreme temperatures, solvents, gaseous emissions, secondary waste generation or

excesses of energy consumed (Hattori et al., 2025). Hattori et al found this approach to be compatible with polychlorotrifluoroethylene (PCTFE), ethylene tetrafluoroethylene (ETFE), perfluoroalkoxy alkane (PFA), fluorinated ethylene propylene (FEP) as well as PTFE and PVDF with decomposition rates and successful recovery of fluorine content as KF up to 99% (Hattori et al., 2025). Lowe et al (2025) used sodium metal (rather than potassium) to reductively defluorinated PTFE at up to ≥99.9% conversion. The authors suggest that the operational simplicity combined with the ability to produce noncomplex fluoride-carbon mixtures holds substantial potential for other fluoride upcycling processes (Lowe et al., 2025). As this reductive mechanochemical approach is very new, widescale adoption of this upcycling approach has not yet been achieved, though adoption of it will be worthwhile to watch prospectively as it offers an alternative approach which appears to be an environmentally, chemically and fiscally robust approach to fluoropolymer solid waste management.

Other upcycling approaches include subcritical water or molten sodium or magnesium complex.

Recycling key points

- Only about 3.4% of fluoropolymer waste in the EU is recycled.
- Establishing dedicated fluoropolymer collection streams for such a small amount of materials is difficult.
- Collecting, sorting, cleaning, and reprocessing fluoropolymers is cost prohibitive.
- The high-tech applications and their regulatory specifications and standards present challenges for use of recycled fluoropolymers.
- Upcycling or fluoropolymers to monomers is promising but is not widely available for commercial quantities at this time.
- At the present time, recycling is not a primary end of life option for fluoropolymers as it faces significant technical and economic barriers.

Microplastics

As was briefly discussed previously in this report, the UPFAS Background Document expresses uncertainty regarding fluoropolymer microparticles and their toxicity. This portion of the report will provide a summary of the state of knowledge of fluoropolymer microparticles and microplastics in general.

Microplastics – definition and mechanisms of generation

Microplastics are plastic *particles less than 5 mm in size* (Akdogan and Guven, 2019; EC, 2023) and fiber-like particles below 15 mm in length (EC, 2023). There are two types of microparticles: *primary* and *secondary.* Primary microparticles are *manufactured to be less than 5 mm* in size while secondary microplastics are the result of *environmental weathering* and mechanical breakdown (*fragmentation*) of larger substrate pieces (GESAMP, 2015). See Table 3. Primary microplastics account for about 75% of microplastic emissions, according to current knowledge (Janzik et al., 2025).

Table 3. Comparison of micro- and nanoparticles (modified from Kadak-Czapska et al., 2025)

Properties	Microparticles (MPs)	Nanoparticles (NPs)	References
Size	0.1 to 5,000 µm	0.001 to 0.1 µm	EFSA , 2016
Main sources	Intentionally manufactured, fragmentation/ degradation of larger pieces of plastics	Fragmentation of MPs	Ziani et al., 2023; Yee et al,, 2021
Environmental behavior and transport	Tend to settle, float or be trapped in sediments; mobility depends on shape and size	Tend to create colloidal solution; high mobility through porous media and biological barriers	Strojny et al., 2025; Wang et al., 2024
Detection and analytical method	µ-FTIR, µ-Raman, LDIR, PLM, Py-GC/MS, SEM-EDX	AFM, fluorescence microscopy, LIBD, NTA, Py-GC/MS, SERS, TEM	Strojny et al., 2025; Pandey et al., 2023; O'sko et al., 2025
Abbreviations: **µ-FTIR** - micro Fourier transform infrared spectroscopy; **µ-Raman** - micro-Raman spectroscopy; **AFM** - atomic force microscopy; **LDIR** - laser direct infrared imaging; **LIBD** - laser induced breakdown spectroscopy; **MPs** -microplastics; **NPs** - nanoplastics; **NTA** - nanoparticle tracking analysis; PLM - polarized light microscopy; **Py-GC/MS** - pyrolysis gas chromatography/mass spectrometry; **SEM-EDX** - scanning electron microscopy-energy dispersive X-ray spectroscopy; **SERS** - surfaced enhanced Raman spectroscopy; **TEM** - transmission electron microscopy.			

Weathering may be a mechanism for generation of microparticles for some polymers, though it is unlikely to be one for generation of secondary *fluoropolymer* microparticles. Based on Henry and Timmer, 2025, and published data submitted to ECHA in public comments to the UPFAS restriction, fluoropolymers are resistant to weathering. Acknowledging that weathering in the environment is an integrative process involving sunlight, oxidative degradation, hydrolysis, etc., the lack of PFAS analytes, even at ng/L levels in the PTFE exposed to artificial sunlight continuously or 16 days (Henry and Timmer, 2025) suggests that weathering is unlikely. Henry and Timmer (2025) produced data from biotic and abiotic degradation studies (OECD 300 series) under aerobic and anaerobic conditions also demonstrating a *lack of weathering*. Data submitted to ECHA (July 10, 2023; comment number 6167; reference number 50d3d582-d7e1-4877-bbf4-2101a2a07b1c) show that larger pieces or PTFE are *not subject to weathering*, supporting that the low potential of PTFE to form microplastics via weathering.

Polyvinylidene fluoride (PVDF), another fluoropolymer, has an established record of environmental durability and *resistance to weathering* having been successfully used in: exterior cladding of commercial buildings (with up to 15% reduction in repainting over 20 years); in bridges and infrastructure (with fewer repairs and lower lifecycle costs); in stadiums and sports arenas, iconic landmarks (like the Sydney Opera House) and cultural sites; and residential high rise buildings (with up to 30% reduction in repainting cycles) (Global PVDF Architectural Coating Market Size, Growth Analysis & Global Forecast 2026-2034). It therefore seems unlikely that weathering would be a mechanism for generation of secondary PVDF microparticles.

Though Fleming (1998) showed that *microbial action* may weaken other plastics thereby increasing their *susceptibility to fragmentation* and microparticulation, published data of explanted PTFE hernia patches examined by scanning electron microscopy attenuated total reflectance Fourier transform infrared spectroscopy (ATR-FTIR), modulated differential scanning calorimetry (DSC) and optical microscope showed no PTFE degradation (King et al., 2013; Henry et al., 2018). Henry and Timmer, 2025 demonstrated that *aerobic and anaerobic microbes do not degrade/weaken fluoropolymers*, thereby *not* increasing their susceptibility to microparticulation. (See also submission of July 12, 2022 to the firefighting foam

proposed restriction: comment number 3582; reference number 3403a4cd-28bb-4397-b8ab-e013cb97f0fa). Expanded PTFE (that met the same specifications as the test material in Henry and Timmer, 2025) was subjected to real-world environmental ageing in Phoenix, AZ for 1,556 days at temperatures of 7.2 - 40.6 °C and 16 – 45 % relative humidity. Mechanical strength tests (tensile break strength and elongation %) showed *no effect of weathering*. (See public comment to ECHA on the UPFAS restriction number 6167; reference number 50d3d582-d7e1-4877-bbf4-2101a2a07b1c.)

GESAMP (2015) and Zhang et al. (2021) note another mechanism of secondary microplastic generation: *mechanical forces* such as wind, waves, abrasion, compaction, etc. Larger pieces of plastic may be fragmented by these mechanical forces. For some plastics, microbial action may weaken them thereby increasing their susceptibility to fragmentation. But as demonstrated in King et al, 2013 and Henry and Timmer, 2025, the fluoropolymer PTFE is *not* subject to aerobic or anaerobic degradation and therefore, *would not have increased susceptibility to fragmentation*.

With respect to whether or not the *mechanical forces within a landfill* (e.g., compaction/ abrasion/shear) are sufficient to cause secondary fluoropolymer microparticle generation, the USEPA recently noted "…the physical processes that lead to the development of microplastics are *expected to be relatively low in landfills*, the bulk of stable fluoropolymers would be expected to be retained for a long duration" (USEPA, 2024). Fluoropolymers are resistant to weathering, not subject to microbial degradation/weakening and increased susceptibility to fragmentation and are not expected to microparticulate in landfills due to mechanical forces.

End uses of fluoropolymers involving high or prolonged periods of friction may, however, generate particulate based on unintended consequences of historical end use applications for which fluoropolymers were not an optimal material choice. One such example is the lining of acetabular cups in artificial hip implants with fluoropolymers. The repetitive friction from the head of the femur on the fluoropolymer lining leads to sufficient particulation to overwhelm natural clearance mechanisms, resulting in loosening of the hip implant, culminating in failure and the need for replacement of the artificial hip. High friction end uses of fluoropolymers should be limited and responsibly managed to mitigate dispersion of microparticles. Research is recommended to establish harmonized methods to test polymers for potential environmental generation of secondary microplastics.

Microplastics – analytical approaches

Standardized protocols for analyzing nanoparticles and microparticles in human organs and tissues are lacking. Current analytical approaches for microplastics in biological tissue samples *often use only a single detection method, potentially missing valuable information*. Zhang et al., 2025 compared Raman microscopy and pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS) as parallel techniques for identifying microplastics in forty-eight (48) paired endometrial and uterine samples from patients. While *Raman microscopy excels at particle identification and size analysis*, *Py-GC/MS can reveal detailed chemical compositions* and modifications (Zhang et al., 2025). Raman microscopy identified six polymer types with PTFE and polystyrene as the main microplastic components across both sample types. However*, Py-GC/MS revealed that samples initially classified as single-polymer PTFE* or polystyrene *were, in fact, co-occurrences of other polymers*, supporting the use of complementary analytical methods in these investigations (Zhang et al., 2025).

In practice, various techniques are used by researchers to detect MPs and NPs in human samples, but *each comes with significant limitations*. See Table 4.

Table 4. Overview of challenges and limitations associated with the analysis of micro- and nanoparticles in human matrices (from Kadak-Czapska et al.,2025.)

Analytical Methods	Advantages	Limitations	References
LDIR	Characterization of MPs by size, shape, and polymer type	Not suitable for determining NPs	Wang et al., 2024
μ-Raman	Identification and quantification of MPs	Not suitable for determining NPs	Jahedi et al., 2025
SED-EDX	Observation of surface morphology and elemental composition of MPs and NPs		Baeza-Martinez et al., 2022
μ-FTIR	Identification and quantification of MPs	Not suitable for determining NPs	Rotchell, et al., 2024
FTIR with attenuated total reflectance	Assessment of the functional chemistry and polymer type of MPs	Limited to particles with a size of >1-20 μm	Garcia et al, 2024
Py-GC/MS	Speciation and quantification of MPs and NPs in native human tissues	Lipids in the human matrix may interfere with analysis. Oxidative degradation during pyrolysis may underestimate MPs/NPs.	Garcia et al., 2024; Nihart et al., 2025
TEM	Observation of shapes and sizes of NPs and MPs in different tissue types	Polymer composition of MPs/NPs cannot be confirmed.	Nihart et al., 2025
General limitations and challenges with MPs and NPs analysis in human matrices		Lack of standardization of methodological protocols. Lack of consistent concentration units within the matrix. Method validation rarely performed. Limited number of studies on human matrices.	

Standardized protocols for detecting plastic particles in human organs or tissues remain lacking. See Table 4. Note the variety of analytical methods used and the inconsistent units for quantity/concentration of microparticles, making comparisons challenging.

A key way of measuring the mass of MNPs in a sample is, perhaps counterintuitively, vaporizing it, then capturing the fumes. But this method, dubbed Py-GC-MS, has come under particular criticism. Rauert et al., 2025 concluded that it is not currently a suitable technique for identifying polyethylene or PVC due to persistent interferences.

Monikh et al., 2025 further criticized the use of only py-GC/MS for polymer identification noting that many biological lipids, especially long-chain atty acids, produce pyrolysis products that minim polyethylene mass fragments. In the absence of adequate analytical expertise, procedural precision and robust QA/QC protocols, this resemblance may lead to misclassification. Monikh and coauthors (2025) questioned whether the observed polyethylene (only) signals may have come from residual fatty acids rather than synthetic polyethylene since ~60% or brain tissue is lipid (by dry weight). They questioned the reported increase in MNP concentrations over time as not being reflective of true bioaccumulation but instead the result of variability from the lipid content or sample handling.

Dr. Rauert et al., 2025 noted that researchers use these techniques because “we have not got anything better available to us”. But a lot of studies that we’ve seen coming out use the technique without fully understanding the data that it’s giving you (Rauert et al., 2025). She also stressed the critical need to employ normal quality control checks (Rauert et al., 2025).

Py-GC-MS begins by pyrolyzing the sample – heating it until it vaporizes. The fumes are then passed through the tubes of a gas chromatograph, which separates smaller molecules from large ones. Last, a mass spectrometer uses the weights of different molecules to identify them.

Dr. Rauert et al.(2025) noted that the problem with Py-GC/MS is that some small molecules in the fumes derived from polyethylene and PVC can also be produced from fats in human tissue. Human samples are “digested” with chemicals to remove tissue before analysis, but if some remains the result can be false positives for MNPs.

Microplastics – routes of entry into the human body

The three primary routes of exposure for microplastics and nanoparticles (MNPs) are ingestion, inhalation and potentially skin contact. Plastic particles in the millimeter and micrometer range are unlikely to be taken up through the intact skin barrier (Facciola et al., 2021). Microplastic-containing dust may be inhaled, or contaminated food may be ingested. In all cases, uptake depends primarily on particle size (Borgatta and Breider, 2024; EFSA 2016). Most inhaled microparticles settle in the naso pharyngeal region or the bronchioles and may be coughed up via the mucociliary escalator or swallowed. Wardani et al., 2024 noted that the vast majority of particles pass through the intestinal passage and are excreted without being absorbed. Based on in-vitro studies with human tissue, it is assumed that approximately 0.3% of all particles measuring between 1 and 10 µm are absorbed in the intestine (Wardani et al., 2024). Janzik et al, 2025 reported that the current state of knowledge suggests that the risk to consumers from microplastics is relatively low, given that *the majority of particles do not become bioavailable*, and the overall quantities taken up are likely insufficient to trigger health effects.” (Janzik et al., 2025)

Although ingestion is the primary route or entry into the body for micro- and nanoparticles (MNPs), currently no studies directly link food packaging contact directly to the release of MNPs (Kadac-Czapska et al., 2025).

In vitro cellular experiments suggest that MNPs can enter cells via *endocytosis* or direct penetration through the cell membrane (Liu et al., 2025). (See Figure 12.) Most of these studies were exclusive studies with only polystyrene (PS) (Liu et al., 2025). The toxicity or particles depends on *size* (<15 µm are more toxic), *shape* (fibrous and irregular fragments are more cytotoxic), *type, surface charge*, and *environmental weathering* (Kadac-Czapska et al., 2025). Weathering alters the surface chemistry of the particles and may increase the formation of *protein corona* that can influence toxicity or the MNPs (Kadac-Czapska et el., 2025). Environmental weathering was previously discussed. Fluoropolymers are not subject to environmental weathering, reducing the likelihood of protein corona formation to increase the chance of microparticle endocytotic uptake.

Although the mechanism(s) by which microparticles gain entry into cells from the digestive, respiratory and integumentary (skin) systems are not definitively established, *endocytosis* is one possible option. In Figure 12 the *four types of endocytosis* are illustrated: *phagocytosis* (in which the cell membrane engulfs the particle into a vesicle which later fuses with enzyme containing intracellular lysozymes to be digested), *pinocytosis* (in which a small pocket of extracellular fluid and particles forms a vesicle), *receptor-mediated endocytosis* (in which a receptor lined protein-coated pit in the cell membrane bind

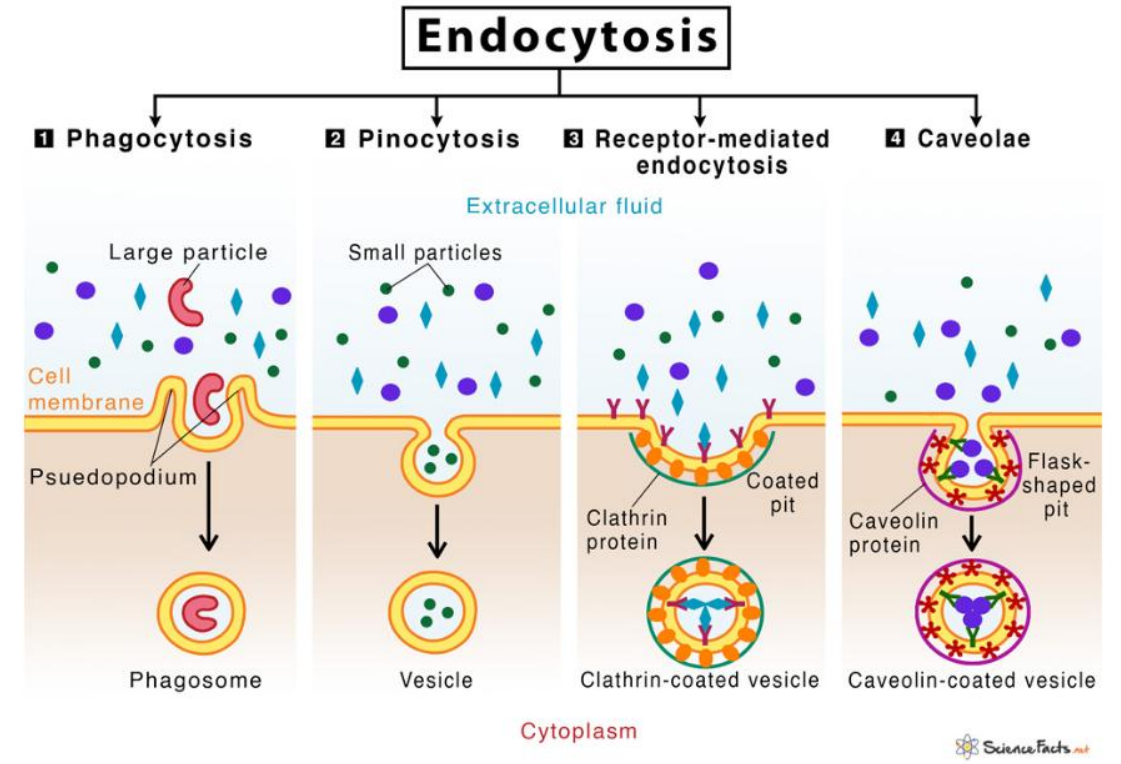


Figure 12 – Endocytosis (from Endocytosis: Definition, Types, & Examples with Diagram)

particles and forms clathrin protein-coated vesicles), and *caveolae* (in which flask-shaped, caveolin protein coated pits in the cell membrane bind particles and create caveolin protein-coated vesicles). It is unlikely that unmodified fluoropolymers would be bound to either clathrin or caveolin receptors for entry into the cells based on their hydrophobicity and inert nature. Therefore, clathrin- and caveolin-coated vesicles of fluoropolymer microplastics are unlikely.

Due to the inherent hydrophobicity of fluoropolymers and their lack of most surface functional groups, theoretically, it would be challenging for proteins and/or cells to adhere and for the endocytosis process to efficiently occur. Consider the challenge of endothelialization of fluoropolymer-based vascular grafts. These vascular grafts are well known for their absence of an endothelial layer and are prone to thrombosis (clotting) and internal hyperplasia (Mi et al., 2018*). Surface modifications, coatings (such as heparin), and treatments (such as oxygen plasma)* are used to reduce platelet adherence to fluoropolymer vascular grafts to reduce clotting and retain graft patency and to promote an endothelial cell layer on the grafts. Therefore, clathrin- and caveolin-coated vesicles of fluoroparticles are unlikely.

This same hydrophobicity of unmodified fluoropolymer surfaces reduces the adherence of non-specific proteins and *limits ligand-receptor interactions*. Without integrin-binding motifs for adhesion endocytotic uptake of fluoropolymer particles may be minimized (Mi et al., 2018). Modified fluoropolymer surfaces may improve endothelialization/cell adhesion, alter surface chemistry and may improve the odds of endocytotic uptake.

Fluoropolymer particles may be identified as foreign bodies and engulfed via *phagocytosis* or *maropinocytosis* depending on particle size, shape and surface modifications as shown in Figure 12, the phagocytized particles in vesicles would then be combined with enzyme-containing lysosomes to digest the foreign particle. Based on the current knowledge, phagocytosis and pinocytosis are the more likely

mechanism for endocytotic uptake of fluoropolymer microparticles. *Research into endocytosis of PTFE microparticles is ongoing* through subchronic oral toxicity studies in laboratory animals to determine if the microparticles can be absorbed by the intestinal tract. The distribution, metabolism and elimination of these particles will also be examined (Anderson, personal communication, March 2026).

Microplastics – evidence in human tissues and criticisms

Table 5 shows the variety of human organ systems and tissues in which microparticles have been reported. There is, however, a great deal of controversy in the scientific literature surrounding these microplastics in human tissues articles.

The Nihart et al., 2025 study was the subject of much criticism in a piece in The Guardian January 13, 2025. Monikh et al., 2025 specifically addressed issues with the Nihart study noting that the absence of reported QA/QC procedures makes it difficult to evaluate the extent to which contamination from reagents, labware or airborne particulates may have influenced the findings, all of which are well-documented sources of false positives in MNP analysis. They noted the tissues samples in the study were collected across different years and locations, raising uncertainty about whether harmonized, contamination-minimizing protocols were consistently applied. The need to standardize sample preparation was also questioned by Monikh et al., 2025 who noted that the manner in which the brain tissue is digested to isolate the MNPs was criticized as being known as suboptimal for lipid-rich tissues such as the brain. Incomplete tissue removal often resulting in residual particulates that can be misidentified as synthetic polymers (Monikh et al., 2025). The authors further stated that the study does not report polymer-spiking experiments to validate recovery efficiency, limits of detection and quantification, or identification accuracy, nor does it describe the approach used to assess the possible impact of the extraction method on particle integrity (Monikh et al., 2025). The need for use of certified reference materials that reflect relevant particle size, type and morphology and allow recovery measurements to validated enrichment stage with high efficiency and minimal artifacts."

Table 5. Summary of research finding in micro- and nanoparticles detected in human samples (from Kadak-Czapska et al., 2025)

Human Body System	Type of sample	Determination Method	Polymer Composition	Shape	Size	Quantity/ Concentration	Region	References
Digestive	Feces	μ-Raman	PP,HDPE, PS, PET	Unspecified	Unspecified	10.19 μm/g	Indonesia	Wibowo, et al., 2021
		μ-FTIR	PP, PET, PS, PE, PVC, PC, PA, PU	Unspecified	20-800 μm	1-36 particles/g	China	Zhang et al., 2021
		μ-Raman	PS, PP, PE, PET PVC	Unspecified	300-1800 μm	20.4 - 138.9 particles/g wet weight	China	Ho et al., 2022
		μ-FTIR	PA, PE, PET, PMMA, PCM, PP, PS, PU, PVC	Fragments, fibers	5-5,000 μm	3.5 particles/g feces	Australia	Hartmann, et al., 2024
		μ-Raman	PET, PA, PP, PE, PC, PVC, POM, PTFE, EVA, PS, PMMA, PBT, AS PES, TPU	Sheets, fibers, fragments, pellets	50 - 300 μm	41.8 items/g (IBD patients) 28.0 items/g (healthy)	China	Yan, et al., 2022
		LDIR	PET, PA , PE, PP, PC, PS, PVC, POM, PFE, EVA, PMMA, PES, TPU, PBT, PBAT, PU, AS	Unspecified	5-500 μm	62 items/g (CRC patients) 43 items/g (healthy)	Iran	Xu et al., 2025
Respiratory	Bronchoalveolar fluid	μ-Raman	PE, PS, PP, PET	Fibers, fragments	20-500 μm	4.1 particles/sample	Iran	Jahedi et al., 2025
		μ-FTIR, SEM-EDX	PET, semi-synthetic polymers	Fibers	2.34 μm (median length)	9.18+/-2.45 particles/100 mL	Spain	Baeza-Martinez, et al., 2022
Circulatory	Serum	Py-GC/MS	PE, PVC, PS,PET, N66, PP	Unspecified	Unspecified	20.81 μg/g (median)	China	Song et al., 2024
	Thrombi	Py-GC/MS, LDIR, SEM	PE, N66, PVC	Irregular fragments	20-100 μm	61.75-141.8 μg/g (median)	China	Wang et al., 2024
	Blood	Py-GC/MS	PE, PS, PP, PET, PMMA	Unspecified	0.7 - 500 μm	3.53 μg/mL (average)	Netherlands	Leslie et al., 2022
	Plaques	Py-GC/MS	PE/ PVC	Irregular fragments	<1 μm	PE 21.7 +/- 24.5 μg/mg of plaque (mean) PVC 5.2 +/- 2.4 ug/mg of plaque (mean)	Italy	Marfella et al., 2024

Janzik et al., 2025 criticized a study with MNPs detected in carotid artery plaques for not testing blank samples taken in the operating room to measure background contamination and another study on MNPs in human testes was criticized for using an analytical approach that was not robust enough to support the authors' claims.

Standardized protocols for detection of plastic particles in human organs and tissues remain lacking. Researchers detect MNPs in human samples using various techniques, each of which has significant limitations (Table 5). Other key challenges include developing methods to isolate plastic particles from human tissues without loss or contamination and the scarcity of studies applying consistent protocols across the same sample type (Kadac-Czapska et al., 2025). The units used to report MNPs concentrations vary across studies complicating comparisons. The wide variety of analytical techniques applied to various matrices, often without thorough validation further complicates reliable comparisons. The lack of standardized methods for detecting MNPs in human tissues is a serious challenge. Rigorous Quality Assurance/Quality Control, QA/QC protocols are needed, including clear false-positive identification strategies, consistent use or sampling and processing blanks, contamination-controlled procedures and validated digestion and recovery methods using well-characterized reference materials. Multiple analytical approaches should be used to ensure specificity, alongside characterization of MPs size and shape. All of these criticisms underscore the uncertainty on the existing data on microplastics in human tissues.

Table 5. Summary of research finding in micro- and nanoparticles detected in human samples - continued (from Kadak-Czapska et al., 2025).

Urinary/Excretory	Urine	µ-Raman	PE, PP, PVA, PVC	Irregular fragments, spheres	4-15 µm	0-3 particles/sample	Italy	Pironti et al., 2023
		µ-Raman	PE, PS, PP	Fibers	20-100 µm	0-2 particles/sample	Iran	Jahedi et al., 2025
		µ-Raman	PE, PS, Styrene-Isoprene	Fiber, fragments	3-13 µm	2.3 particles/sample	Italy	Exacoustos et al., 2023
		µ-Raman	PE, PS, Styrene-Isoprene	Fragments	>0.2 µm	1.28 +/- 0.49/sample (mean)	Italy	Exacoustos et al., 2023
		µ-FTIR, SEM-EDX	PE, PS, PP, PTFE, resins	Fragments, films, fibers	19-400 µm (length) 10-128 µm (width) 15->300 µm (length) - >300 µm (width)	0-9,600 particles/L (healthy) 0-36,000 particles/L (endometriosis patients)	Great Britain	Rotchell et al., 2024
		Py-GC/MS, LDIR	PE, PVC, N66, PMMA, PU, PP, PET	Diversity of shape	<50 µm	1.50 mg/kg 15.17 particles/kg	China	Song et al., 2024
	Kidney	µ-Raman	PE, PS	Fragments	1-29 µm	4.3 particles/sample	Italy	Massardo et al., 2024
		µ-Raman	PE, PS, Styrene-Isoprene	Fragments	>0.2 µm	1.7 +/- 2.11/ µm sample (mean)	Italy	Exacoustos et al., 2023
Reproductive	Sperm	µ-Raman	PS,PP, PVC, PTFE, PET, PE, ABS, PC	Unspecified	1.2-20 µm	Unspecified	China	Zhang et al., 2024
	Placenta	Py-GC/MS	PR, PVC, N66, SBR, ABS, PET, N6, PMMA, PU, PC, PP, PS	Unspecified	1-20 µm	6.5-685 µg/g	US	Garcia et al, 2024
	Amniotic fluid	Raman, Py-GC/MS	PTFE, PS, ABS, PE, PC, PVC	Unspecified	3.05+/- 1.05 µm	Unspecified	China	Tian, et al., 2025
Nervous	Brain	Py-GC/S, TEM, SEM-EDS	PE, PP, PVC, styrene-butadiene rubber	Unspecified	1-5 µm (brain tissues) <1 µm (brain parenchyma) 100-200 nm (brain pellets)	median =1254 µg/g (East Coast samples) median 26,076 µg/g (dementia samples)	US	Nihart et al., 2025
	Olfactory bulb	µ-FTIR	PP, PA, NYL, N6, PVA, PE, wool-PP	83.4% of fragments 16.6% of spheres 25% of fibers	5.5-26.4 µm (length) 3.0-25.4 µm (width)	1-4 particles/olfactory bulb	Brazil	Amato-Lourenco et al., 2024
	Cerebrospinal fluid	LDIR, Py-GC/MS	PP, PE, PS, PVC	Unspecified	<100 µm	0-3 µg of polymer/g of cerebrospinal fluid	China	Xie et al., 2024

Abbreviations: **ABS -** acrylonitrile butadiene styrene; **ASA -** acrylonitrile styrene acrylate; **EVA -** ethylene vinyl acetate; **HDPE -** high density polyethylene; **N6 -**nylon 6; **N66 -** nylon 66; **NYL -**nylon; **PA -**polyamide; **PBAT -** poly(butadiene adipate terephthalate); **PBT -**poly(butadiene terephthalate); **PC -**polycarbonate; **PCM-** phase change materials; **PE -**polyethylene; **PET -**poly(ethylene terephthalate); **PES -**poly(ethylene succinate); **PMMA -**poly(methyl methacrylate); **POM -**Polyoxymethylene; **PP -** polypropylene; **PS -**polystyrene; **PTFE -** polytetrafluoroethylene; **PU -**polyurethane; **PVA -**poly(ethylene vinyl acetate); **PVC -**poly(vinyl chloride); **SBR -**styrene butadiene rubber; **TPE -**thermoplastic polyurethane; **US -**Unted States

Rotchell et al., 2023 analyzed samples of (human) saphenous veins (being taken for bypass surgical grafts) for the presence of microplastics. Five tissue samples were digested and analyzed by µFTIR. *The microparticle levels within the tissue samples were not significantly different than the procedural blanks. No fluoropolymer was identified in any tissue sample*, though it was present in 3 of 5 procedural blanks, potentially indicating its presence in operating theater air. Five polymer types were identified in the tissue samples alkyd resin, poly(vinyl propionate / acetate), polyvinyl acetate: ethylene, tie layer consisting of nylon-EVA or ethylene vinyl alcohol, and polyurethane. Zhang et al., 2025 also analyzed urine samples for

microplastics and found 60.6% of the thirty-three samples had polystyrene and 24.2% had PTFE microparticles.

Dzierżyński et al., 2025 analyzed samples of human brain, liver, thyroid, kidney, heart, skeletal muscle, and lung tissue collected post-mortem for the presence and composition of micro- and nanoplastics. Tissue samples were digested. Retained residues and filtrates were characterized using optical microscopy, scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM–EDS), dynamic light scattering (DLS), matrix-assisted laser desorption/ionization time-of-flight mass spectrometry (MALDI-TOF MS), and optical photothermal infrared (O-PTIR) microscopy. Results showed the thyroid, kidney and brain and the highest levels of microplastic accumulation which suggests translocation and retention of microplastics within the body. Even though all solutions used in this study were filtered through PTFE filters, no PTFE or other fluoropolymer microparticles were identified. Nylon blend, polyacrylic resin/polyacrylonitrile, polycarbonate, polyethylene terephthalate, polylactic acid, polyimide polyvinyl chloride, polystyrene, resin alkyd/epoxy /hydrocarbon, cellulose fibers and viscose type fibers were identified. The authors state that „[t]he heterogeneity in particle type, size, and abundance among organs indicates that MNP translocation and retention are tissue-specific processes.“ (Dzierżyński et al. 2025).

Microplastics – toxicity certainty and uncertainty

Janzik et al., 2025 stated that “The current state of knowledge suggests that the risk to consumers from microplastics is relatively low, given that the majority of particles do not become bioavailable, and the overall quantities taken up are likely insufficient to trigger health effects.”

There is a need to reduce uncertainty regarding the likelihood of (eco)toxicological effects of fluoropolymer microparticles. Existing data from Lee et al. (2022), Feng et al. (2022), Sfriso et al. (2020), Dewan et al. (1995) and Geiser at al. (2003) *demonstrated low (eco)toxicity of PTFE microparticles*.

Microplastics – what is needed for human health risk assessment

Further studies are needed to clarify the relationship between human exposure to micro and nanoparticles, their presence in the body and resulting health effects. Estimating human health risks from MPs and NPs remains challenging due to the limited data on their occurrence, exposure pathways, and biodistribution. Determining human exposure to MPs and NPs remains scientifically challenging, primarily due to the limited data available for such assessments. MPs and NPs encompass a broad spectrum of chemical compounds complicating the assessment for potential toxicity. Further research is needed to determine exposure thresholds for MPs in human biological matrices (blood, urine, placenta, amniotic fluid, cerebrospinal fluid, semen, bile, feces, etc.)

Establishing a causal link between MPs and human disease requires well-structured prospective and case controlled epidemiological studies across varied populations to measure association through ingestion inhalation and skin contact and health outcomes while accounting for confounding variables. Risk assessments should therefore prioritize environmentally relevant doses, chronic exposure data and individual susceptibility. Currently no studies exist in the human biokinetics of MNPs (Ali et al., 2025).

Current literature does neither conclusively highlight the detrimental effects of plastic on human health, nor does it confirm its safety (Winiarska et al., 2024). Research investigating the chronic effects of microplastics exposure, studying effects at very low concentrations, developing in vivo testing methods and establishing direct links between microplastic exposure and human health effects is needed Winiarska et al., 2024). Perhaps the World Health Organizations work on micro- and nanoplastics will help.

Microplastics – routes of entry into the body and translocation

The three primary routes of exposure for entry of microplastics (and nanoplastics) into the human body are ingestion of food and/or water, inhalation, and potentially skin contact. How microparticles move to tissues and organs distant from their site of entry is not yet known. Existing data focuses primarily on determining potential toxic effects in plants, mussels, mice and rats. Significant gaps exist regarding the effects and behaviors of identified polymer types and shapes. The mechanisms by which plastic particles affect human cells, and consequently organs, are also of significant concern. Direct evidence linking MNP exposure to human diseases remains scarce (Ali et al., 2025).

Microplastics – research needs, gaps and criticisms

Study needs

Standardized methods for the *detection of MPs and NPs* are needed. Dzierżyński et al. 2025 highlighted the need for the development of standardized protocols for tissue digestion and particle digestion as well as research into the long-term human health effects of chronic exposure to microparticles. Standardized protocols for detecting plastic particles in human organs and tissues remain lacking. Isolating plastic particles from the human tissues without loss or contamination is challenging and the scarcity of studies applying consistent validated analytical methods, standard sampling methods, testing more than one polymer type, standardization of units, etc. are needed now. Ali et al., 2025 noted: the absence or universal reference materials limits method validation and consistency across studies. They noted that inconsistencies in sample collection, storage and processing introduce further uncertainty in measurement reliability (Ali et al., 2025).

More than 1 polymer type

Over interpreting findings that assess MPs toxicity based on a single polymer type are not recommended. Polystyrene particles have been the subject of most recent experimental studies making extrapolation complicated. This approach of studying one polymer type does not provide a comprehensive view of the risks posed by these particles. Larger studies encompassing diverse types and particle shapes are needed for a comprehensive risk assessment. As polystyrene is one of the most studies plastics, future research should expand to include other commonly detected polymers such as polyethylene (PE), polyvinyl chloride (PVC), polyethylene terephthalate (PET), and polypropylene (PP).

Lab v reality

There is insufficient knowledge of the similarities and differences between lab-generated microplastics and environmentally-generated microplastics. The toxicity of particles depends on size (with the smaller being more toxic), shape (with fibrous and irregularly shaped more cytotoxic), polymer type, surface charge, and environmental weathering (which may alter surface chemistry and may increase the formation of protein corona that can influence toxicity)(Liu et al., 2025). Although existing data is limited, the toxicity of “true to life MPs” is believed to significantly differ from that of synthetic PS microbeads and lab-generated microparticles.

Status on all MNPs

Distinguishing the effects of MPs from those of the contaminants that adhere to their surfaces is challenging (Ali et al., 2025). Also distinguishing the effects of plastics additives leachables from the effects of the MNPs is essential.

Are fluoropolymer microparticles treated differently by ECHA than other microplastics? How does the microplastics directive address fluoropolymers?

Does the existing data support different restriction/regulation of fluoropolymer microplastics than all other microplastics?

Bottom line: There are data/knowledge gaps in micro- and nanoparticles, but they do not preferentially support treating fluoropolymers differently than all other plastics, especially since fluoropolymers are not toxic, bioaccumulative or mobile and do not contain leachables/additives like other plastics types. The data does not support restriction of fluoropolymers more severely than all other plastic micro-nanoparticles.

Microplastics key points

- Microplastics are plastic *particles less than 5 mm in size* and fiber-like particles below 15 mm in length, that can either be manufactured to be that size (primary microparticles) or can be generated environmentally (secondary microplastics) through weathering and fragmentation.
- Fluoropolymers are resistant to weathering, microbial degradation, fragmentation and are not expected to microparticulate in landfills due to mechanical forces (per the US EPA).
- Fluoropolymer end uses involving high degrees or durations of friction should be limited and responsibly managed to mitigate dispersion of microparticles.
- To combat the controversy and high degree of uncertainty regarding existing microplastics data and to facilitate its utility in human health risk assessment, standardization and validation is needed in every area of microparticle testing from reference standards, analytical methods, contamination control, protocols, units for reporting results, etc.
- Current literature does neither conclusively highlight the detrimental effects of plastic on human health, nor does it confirm its safety (Winiarska et al., 2024). Direct evidence linking micro and nanoparticle exposure to human diseases remains scarce (Ali et al., 2025).
- Existing data does not support preferentially treating fluoropolymers differently than all other plastics. The data does not support restriction of fluoropolymers more severely than all other plastic microparticles.

Discussion

In this section, the article summaries from the Results section are synthesized here into overall findings from the peer-reviewed scientific literature regarding weight of evidence, challenges and limitations and areas for further study. Those overall findings from the weight of evidence are presented to compare to the ECHA BD.

Spectaris Market Sectors and End of Life

The Berlin-based industry association Spectaris represents these industries using fluoropolymer materials in their products: consumer optics, photonics, medical technology, analytical, biological and laboratory

technology, including research and development. Fluoropolymers are essential for SPECTARIS high-tech industries and are difficult or impossible to substitute.

Table 6 shows the high-tech market sectors represented within Spectaris and the products within those sectors. The end-of-life options used for products within those market sectors are also shown. These high-tech products are likely to be incinerated as hazardous or non-hazardous waste depending upon their use and contact with bodily fluids, hazardous chemicals, etc. Products that are electronic or electrical in nature would likely be regulated under the Waste Electrical and Electronic Equipment (WEEE) Directive 2012/19/EU, which requires collection, recycling and recovery rather than landfilling. Though some products within the consumer optics sector are likely to be recycled, note that this refers more to the collection, donation and redistribution of the products to other users, rather than the deconstruction of products, separation of materials and recycling as described in the previous section. The least likely end-of-life option for the products in these market sectors is landfilling and recycling as described above.

Also shown in Table 6 are the types of fluoropolymer materials used in/on those products within the various market sectors. The properties of the fluoropolymer materials making them so valuable to the products within the various sectors are also explained.

Ideally, based on the number of each product within a market sector annually and the mass of fluoropolymer material within those products, the mass of fluoropolymer materials used within each sector and all sectors could be estimated. That cumulative market sector mass then would be useful in contrasting with the ECHA UPFAS Restriction Proposal's Background Document. However, that level of granularity was not publicly available. If one considers the market sectors within the BD and the fraction of each represented by the products shown in Table 6, one can readily appreciate that the bulk of fluoropolymer material used annually within the EU is not used in consumer optics, photonics, analytical laboratory, research and medical technology sectors.

Table 6 Spectaris Products, Market Sectors and End of Life Options

ECHA UPFAS Restriction Sector (April 2026)	High Tech Market Sector	Products	End of Life Option Used	Number of Products Sold Annually	Fluoropolymer Materials in Market Sector Products	Range of Mass of Fluoropolymer Material/ Product	Range of Fluoropolymer Materials Used/Year in Market Sector
Consumer	Consumer Optics	optical lenses	Most eyeglasses are donated or recycled. Many European opticians (e.g., Fielmann, Specsavers, local optometrists) run donation programs for used glasses. Nonprofits across the EU collect glasses for redistribution in low-income regions.	~120,000,000 Europeans require glasses or progressive lenses	fluoropolymers are used in specialized lens coating (e.g., CYTOP) for optical transparency		
		spectacle frames			specialized, high performance optical coatings represent a small fraction of EU fluoropolymer consumption		
		sunglasses			AGC CYTOP exhibits high optical transparency, good solubility in some fluorinated solvents, and offers transparency level equivalent to a quartz at higher workability, enabling thin film coatings that generate anti-reflective properties over eyeglasses, photo masks and optical fiber.		
		sports glasses			Fluoropolymer materials are used for their durability, water- and oil-repelling properties which improve performance and extend product life.		
		contact lenses	landfill with household trash		Scratch resistant coatings, easy-to-clean coatings, anti-reflective coatings		
		contact lens care accessories			Contain "extremely small quantities of PFAS"		
		visual enhancement aids	may qualify as e-waste or take backs by manufacturers or recycled	No data found	Most premium lenses have these high performance coatings.	No data found	
		eyesight testing devices					
		telescopes					
		telescopic sights					
		spective scopes					
		opticians' supplies					
Electronics	Photonics	laser	may qualify as e-waste or take backs by manufacturers or recycled	No data found	~8% of total EU fluoropolymer volume goes to high-tech applications. Photonics does not represent the majority of consumption. The electrical and electronics sector (including photonics) accounted for ~10% of EU fluoropolymer market by revenue in 2022.	No data found	5,487 - 18,989 tonnes/ year per Table B.9.12 of Annex B of ECHA UPFAS RD
		optical components			Fluorinated polymers are valued in photonics due to their properties of low refractive indices, low propagation optical losses at communication wavelength of 1550 nm.		
		imaging & photo technology					
		geodesy					
		microscopy					
		measurement instrumentation					
		sensor technology					
Other Medical Applications or Medical Devices	Medical Technology	industrial goods and appliances	Medical Technology that contains electronics falls under the Waste Electrical and Electronic Equipment (WEEE) Directive 2012/19/EU, which requires collection, recycling and recovery, not landfilling.	No data found	Fluoropolymers facilitate surgical procedures helping to shorten their duration and the patient's risk. (PLEUR)	No data found	
Laboratory Equipment and filtration	Analytical, Bio and Laboratory Technology	devices, equipment, consumables and accessory for laboratories in the food and quality control sector	electronics containing products fall under WEEE, which requires collection, recycling and recovery, not landfilling . Products that have contacted bodily fluids are disposed of as hazardous waste and incinerated, otherwise incinerated as non-hazardous waste.	No data found		No data found	
		environmental technology and materials testing in pharmaceutical laboratories		No data found		No data found	
		environmental technology and materials testing in chemical laboratories		No data found		No data found	
		environmental technology and materials testing in medical laboratories		No data found		No data found	
		research and development		No data found		No data found	

Conclusions

The previous sections have shown that fluoropolymer emissions can be controlled throughout the life cycle. Significant progress in beginning of life emissions during manufacturing has been achieved and factors steering the incineration towards complete destruction without PFAS emissions have been documented in peer-reviewed scientific publications in real-world incinerators. Landfill and recycling options for fluoropolymer end of life have also been discussed, though they remain limited in volume of fluoropolymer waste managed (13 and 3%, respectively).

Microplastics is an area of rapidly evolving research with no data to indicate that fluoropolymers are preferentially more of concern than any other plastic in use today.

But fluoropolymers are different than other PFAS and other plastics. Fluoropolymers inherently have a constellation of characteristics that make them unique amongst plastics, such that they do not need traditional plastics additives, thousands of which are in use in other plastics today. Therefore, the potential for the "Trojan horse effect" of the plastics bringing with them a plethora of plastics additives as potential leachables is not applicable to fluoropolymers. Polyvinyl chloride may have phthalates. Polycarbonates may have bisphenol A. Polystyrene contains styrene. Polyethylene terephthalate may have antimony-based fire retardants, etc. Some specifications for types of fluoropolymers do not permit additives, such as fluoropolymer fine powders meeting the ASTM D4895 standard, which may not contain additives like plasticizers, flame retardants, UV absorbers, colorants, etc. And due to the inherent properties of fluoropolymers, they are already flexible, flame retardant and resistant to sunlight, water, chemicals, and microbial degradation without additives.

From a volume of plastics, perspective, the volume of fluoropolymers compared to all plastics is remarkably small. Fluoropolymers constitute only about 0.1% of the total plastics processing demand in the EU, according to the Conversio report of 2022. This informs the relative contribution and potential risk impacts of fluoropolymers and any microplastics fluoropolymer particles

Restricting fluoropolymers because of persistence alone is not supported by the UNEP, EU REACH, EU CLP or the US TSCA or the scientific literature demonstrating the absence of mobility. The ECHA BD relies on Crookes and Fisk (2018) to support the "Persistence-Alone" (P-alone) position on which the restriction is founded. Crookes and Fisk found that the persistent AND mobile substances had the potential for long range transport and could reach levels in the environment that would have effects on ecosystems and human health. However, fluoropolymers are *not* mobile, making the Crookes and Fisk reasoning irrelevant. The scientific weight of evidence proves that persistent-alone substances (not mobile, M, nor bioaccumulative , B, nor toxic, T) are different from PM (persistent and mobile) or PMT (persistent, mobile and toxic) or PBT (persistent, bioaccumulative and toxic) or vPvB (very persistent and very bioaccumulative), etc. substances. Therefore, the scientific evidence supports the exclusion of fluoropolymers from the ECHA PFAS restriction.Although some uncertainty remains regarding the potential risk of secondary fluoropolymer microparticles, considering that fluoropolymers are such a tiny percentage (0.1%) of the total plastics processing demand in the EU, removing fluoropolymers from commerce would have a negligible impact on the volume of microplastics in the environment even if they were environmentally generated. And the data supports that fluoropolymers do not degrade in sunlight, water, or microbial action and are resistant to weathering, fragmentation and mechanical degradation in landfills. Eliminating fluoropolymers would not significantly impact global microplastics regardless of the outcome of future toxicity studies.

The state of the science supports that fluoropolymers can be safely and sustainably managed without sacrificing human or environmental health or the high-tech products so critical to modern society.

Very significant progress has been and continues to be made in minimizing emissions of non-polymeric PFAS (monomers, ultra short, short and long chain PFAS, and polymerization aids) during manufacture and processing of fluoropolymers ("beginning of life"). The Fluoropolymer Products Group of Plastics Europe has committed to aggressively manage emissions to water and air from the manufacture of fluoropolymers, has met their current commitments and is actively engaging with stakeholders to continuously improve abatement technologies to further reduce and prospectively control non-polymeric PFAS emissions.

The US FDA, Departments of Defense and Energy have supported the ongoing use of fluoropolymers in critical (in life) applications, such as medical devices, technical fabrics used by the military, and critical applications in the energy sector. More US States (Illinois, California, Rhode Island, Maine) are carving out fluoropolymers from their PFAS legislation acknowledging and acting upon the differences between the chemical, physical and biological properties of fluoropolymers and other PFAS. Though there is still work ongoing regarding the degree of exemption fluoropolymers will ultimately receive in each US state, the trend is clearly that fluoropolymers are recognized from a regulatory perspective as different from other PFAS and that at least some uses should be permitted to continue.

For most fluoropolymer waste (84%) in the EU, the "end of life" option is incineration. Conditions of incineration in real-world, commercial facilities necessary for mineralization of PFAS without products of incomplete combustion/destruction have been established resulting in >99.9999% destruction and removal efficiency of non-polymeric PFAS. Very significant progress has been made in the past twenty years in PFAS analytical method development, incinerator configuration and design, optimizing operating conditions, achieving near complete PFAS destruction with demonstration of lower levels of emissions to air, water, and solid residues (fly ash and bottom ash).

<u>But, will anything less than 100% fluorine mass balance ever be acceptable?</u> The persistence of per- and polyfluoroalkyl substances is at the heart of the proposed universal PFAS restriction in the EU. Any emission of these forever chemicals is interpreted to be a risk to human health and the environment singling out these persistent but not bioaccumulative or toxic fluoropolymers who are caught in the PFAS net by virtue of the presence of at least one fully fluorinated carbon.

<u>Are fluoropolymers regulated/restricted differently than other persistent organic pollutants (POPs)?</u> Yes. The UN Environment Programme and all their global signatories to the Stockholm and Basel Conventions acknowledge the dangers of persistent organic pollutants like PFOA, PFOS, PFHxS, long chain PFCAs, dioxins, furans, and pesticides, etc. Yet UNEP's Stockholm Convention *does not consider persistence alone*, in the absence of toxicity or bioaccumulation, to be a hazard. The Stockholm Convention has defined non-zero concentrations of these PFAS that may be present in products (≤ 25 ppb): PFOA, PFOS, PFHxS and soon for long chain PFCAs, but *not* for any fluoropolymer. Why? The weight of evidence clearly proves that fluoropolymers do not have the hazard profiles of PFOA, PFOS, PFHxS or even long chain PFCAs. OECD acknowledged that fluoropolymers did not belong in the same class as per- or polyfluoroalkyl acids or their precursors (on the basis of structure).

The UNEP's Basel Convention has set "low POP content" concentrations above which the product must be "destroyed or irreversibly transformed". But if the POP content is below that concentration, then the obligations to destroy or transform do not apply. There is no "low POP content" for any fluoropolymer or any PFAS, but there is for the most potent toxins known to man: polychlorinated dibenzo-p- dioxins (PCBs) (50 mg/kg), polychlorinated dibenzofurans (PCDFs) and polychlorinated dibenzo-p-dioxins PCDFs (15 µg TEQ/kg), and the pesticides aldrin, chlordane, DDT, dieldrin, endrin, heptachlor, HCB, mirex and toxaphene (50 mg/kg). These substances are arguably the most potent man-made toxins on the planet and yet they have UNEP "low POP content" concentrations.

Some may say that the substances compared using the toxicity equivalence factor (TEF) act through a mechanism that is not relevant for PFAS (the aryl hydrocarbon receptor, AHR), making this an unfair comparison. But consider aldrin, chlordane, DDT and the other initial substances in the Stockholm Convention which do not act through the AHR either. Maybe not as toxic as TCDD still these pesticides were identified as needing to be eliminated or severely restricted in production and use because they were halogenated organics with high stability and lipophilicity, long environmental half-lives, demonstrated bioaccumulation in wildlife and humans, the ability to biomagnify in species as one goes up the food chain, and toxic to humans and other biota. If "low POP content" limits can be internationally agreed upon for these worst-case organic substances, why does ECHA believe that emissions of any fluoropolymers with no potential toxicity, bioaccumulation, or mobility present an unacceptable risk to human health and the environment? Clearly this logic is inconsistent with the data and international treatment of other POPs.

The UNEP and their many global signatories have determined acceptable, above zero limits for the presence of these many persistent AND toxic AND bioaccumulative organic substances but none for any persistence-alone fluoropolymers with >99.9999% destruction and removal efficiency. The two greenhouse gases of interest as PICs of fluoropolymer incineration are CF_4 (tetrafluoromethane) and C_2F_6 (hexafluoroethane), which are perfluorocarbon (PFC) gases, which are not directly listed in the original Montreal Protocol as ozone-depleting substances. They are, however, regulated as greenhouse gases (GHG) under the Kyoto Protocol United Nations Framework Convention on Climate Change (UNFCCC), which requires that they be included in national GHG emissions inventories working towards a phase out date of 2036. No acceptable emissions limits, however, were set for CF_4 or C_2F_6 by the UNEP. These two perfluorocarbons do not have near the hazard profiles of the PCBs, PCDDs, PCDFs, pesticides, etc. They are not mobile, toxic or bioaccumulative.

Are other persistence-alone organic substances regulated such that any emissions constitute an unacceptable risk? This question is hard to answer since the EU REACH-registered substances must be individually searched to find their persistence classification. There is no ECHA list of persistence-alone substances to search. But it is more likely than not that fluoropolymers are one of, if not the only, type of persistent-but-not-toxic-not-bioaccumulative-or-mobile substances to be restricted in this way.

With respect to the ECHA Background Document, the RAC determined that the *emission factor for non-hazardous waste incinerators should be 0.02* (98% destruction and removal efficiency), *and 0.01 for hazardous waste incinerators* (99% destruction and removal efficiency). Multiple studies between 2023 and 2026 show greater destruction efficiencies (99.7 - 99.9999%) which would drop the emission factor from 1-2% to 0.3% - 0.0001%. Emissions would drop by a factor of 3.3 to 10,000.

Table 2 Incineration Highlights see Shields et al., 2023, **>99.9999% at >970 °C** and a non-targeted analysis that did not show anything different than the blanks, meaning **no PICs or PIDs or GHGs at >1000 °C**; Troxler et al., 2025 achieved **99.9999% at >1000 °C**; Gehrman et al., 2024, achieved **>99.99% at 860 °C and 1095 °C**; Warnecke et al., 2025, **99.9999% ≥ 850 °C**, (99.7% including CF_4).

The RAC also assumed that the fluoropolymer waste in the landfill would have *33.6 ppm leachable*, non-polymeric PFAS. Henry et al., 2018 and Korzeniowski et al., 2023 show leachables <1 ppm on the finished, commercial fluoropolymers.

Regarding potential leachable migration from plastics into landfills, it is important to note that since fluoropolymers do not need traditional plastics additives, such as plasticizers or flame retardants so they would not be the source of such leachables within the landfill or landfill leachate. Maddela et al., 2023, reported that ~70% of the 10,000 additives in plastics are plasticizers (such as phthalates), and ~25% are flame retardants (such as brominated or organophosphate flame retardants). Many fluoropolymers have received UL 94 V-0 ratings, indicating an inherently high level of flame resistance (meaning they extinguish

within 10 seconds after being ignited and do not produce flaming drips). Therefore, fluoropolymers have been shown to have low levels of leachables (<1 ppm) and are not a source of traditional plastics additives (plasticizer, flame retardants, UV absorbers, stabilizers, etc.) in landfills or landfill leachate.

Therefore, while there are areas of research needed in microplastics, the weight of the evidence across the fluoropolymer life cycle strongly supports fluoropolymers can continue to be safely used and that responsible control of emissions at all life cycle stages is possible now. The ECHA background document overestimated emissions to both air and water.

The RAC emissions estimates for fluoropolymers in their March 2, 2026, ECHA Risk Assessment Committee (RAC) report differs significantly from the ECHA BD. The RAC applied the BD's release factor only to non-polymeric PFAS fraction emissions from fluoropolymers, rather than to the whole fluoropolymer volume as was done in the BD. The emission of non-polymeric PFAS from fluoropolymer in use ("service life") and from landfilling was deemed by the RAC to be negligible or generally very low. Even with these improvements made by RAC, they are still not using the most recent destruction and removal efficiency values from the most recent literature (see Table 2) which incorporate the learnings of the past 20 years. These most recent studies adjusted temperatures, residence times, oxygen concentrations, turbulence, real-world incinerators, the most recent analytical methods and looked for PFAS and volatile fluorinated compounds and products of incomplete combustion, achieving 99.7 to 99.9999% destruction efficiency. The RAC uses a 2% or 1% release factor for emissions from fluoropolymer incineration. This report demonstrates that the release factor(RF) for FP incineration is more like 0.0001% to 0.3%. These most recent studies are those that should be utilized by the RAC.

The RAC estimates 10,000 t/y are emitted to the environment from PFAS other than fluorinated gases. RAC's calculations are not transparent such that it is not possible to determine the emission of non-polymeric PFAS from fluoropolymer applications (alone), but it would be a fraction of that 10,000 t/y. If the contribution to emissions from TULAC (6,526 t/y) are removed (since that includes PFAA precursors, side chain fluorinated polymers), that reduces the total non-polymeric PFAS emissions from polymeric PFAS to 3,474 t/y, or about 5% of the total PFAS emissions per year. Note that polymeric PFAS is the combination of fluoropolymers and perfluoropolyethers. Although not provided by the RAC, the emissions of fluoropolymers can be calculated by subtracting 928 t/y, the total of perfluoropolyether emissions using the individual sector assessments in the background document, from the polymeric PFAS emission total of 3,474 t/y. The total emissions of fluoropolymers would, therefore, be 2,815 t/y, or about 4% of the total PFAS emissions per year. This is in contrast to the background document's 21.8%.

As noted previously, the ECHA background document expressed uncertainty regarding the toxicity of fluoropolymer microparticles. The RAC report of March 2026 considers fluoropolymer particles to be generally less bioavailable and less toxic than PFAAs and their precursors and therefore distinguishes between emissions of non-polymeric PFAS and particles from fluoropolymers. They state that fluoropolymer particle concern mostly relates to the general plastic pollution rather than to something specific to fluoropolymers, which is consistent with the state of the science.

Therefore, the state of the science supports the uniqueness of fluoropolymers and their exclusion from the ECHA proposed PFAS restriction.

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