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Fact Cards of Major Groups of Per- and Polyfluoroalkyl Substances (PFASs)

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IOMC
INTER-ORGANIZATION PROGRAMME FOR THE SOUND MANAGEMENT OF CHEMICALS
A cooperative agreement among **FAO, ILO, UNDP, UNEP, UNIDO, UNITAR, WHO, World Bank and OECD**

Environment Directorate
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT
Paris 2022

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The OECD Per- and Polyfluoroalkyl Substances (PFAS) project has been produced with the financial assistance of the European Union. The views expressed herein can in no way be taken to reflect the official opinion of the European Union.

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Background, aims and scope

The OECD/UNEP Global PFC Group[1] was established to respond to the Resolution II/5 adopted at the second session of the UN International Conference on Chemicals Management (ICCM 2) in 2009, which calls upon intergovernmental organizations, governments and other stakeholders to "consider the development, facilitation and promotion in an open, transparent and inclusive manner of national and international stewardship programmes and regulatory approaches to reduce emissions and the content of relevant perfluorinated chemicals of concern in products and to work toward global elimination, where appropriate and technically feasible". Further work on this resolution was reaffirmed in Resolution III/3 adopted at ICCM 3 noting that a significant need remains for additional work to support implementation of Resolution II/5. This report is prepared within the framework of the Group. For more details on the Group and its work, see the OECD PFAS web portal (https://oe.cd/2M9).

This document contains a set of 15 fact cards[2] on major groups of per- and polyfluoroalkyl substances (PFASs), prepared by the OECD/UNEP Global PFC Group between June 2018 and June 2021. The fact cards aim to provide non-expert stakeholders a quick initial glance into these groups of PFASs with some basic information on: (1) chemical identities[3], synthesis and inherent properties such as bioaccumulation and transformation, (2) historical and ongoing industrial practices and commercial uses of some major commercial products, (3) regulatory status, (4) examples of reported occurrences in the environment and humans, and (5) major knowledge gaps in terms of previous sections. The fact cards also provide references where interested readers may find additional information; note that due to the fast-moving nature of the science and knowledge on PFASs, the listed references are by no means complete. For information and practical guidance on the use of terminology in regard to PFASs, readers are referred to the OECD PFAS Terminology report[4].

It should also be noted that health and environmental effects of PFASs are not included in the fact cards. For a number of well-studied legacy PFASs, most notably perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS), a wealth of knowledge on their related environmental and human health effects have been studied and synthesized, demonstrating that they may cause a wide range of adverse health effects. These studies have played a key role in the decision making of existing regulatory actions on them, including restrictions and setting up health guideline values. For many other PFASs, considerable efforts are being made to study their health and environmental effects; existing evidence shows that exposure to many novel and emerging PFASs may result in adverse

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[1] The term "PFC" in "OECD/UNEP Global PFC Group" refers to "per- and polyfluorinated chemicals", and not to perfluorocarbons. "Per- and polyfluorinated chemicals" or "PFCs" were widely used before the more precise term "per- and polyfluoroalkyl substances" was recommended by Buck et al. in 2011. As it is part of the official name of the Group, it remains unchanged here.

[2] Note that one fact card may contain more than one groups of PFASs that may share some similarities, e.g. in terms of structural traits, characteristics or uses; however, this arrangement does not imply any grouping strategies for PFASs.

[3] Note that the Markush structure representations and molecular formulas in each fact card represent only the linear isomer of the respective substances. In reality, for many PFASs, branched or cyclic isomers have also been generated, and may be identified in products or the environment.

[4] OECD (2021), Reconciling Terminology of the Universe of Per- and Polyfluoroalkyl Substances: Recommendations and Practical Guidance, OECD Series on Risk Management, No. 61, OECD Publishing, Paris, https://www.oecd.org/chemicalsafety/portal-perfluorinated-chemicals/terminology-per-and-polyfluoroalkyl-substances.pdf.

health and environmental effects of concern, including similar adverse effects as the PFASs that they replace (though possibly with different mechanisms of action). Interested readers are strongly recommended to consult the following sources, references therein, and other sources for information on the health and environmental effects of PFASs:

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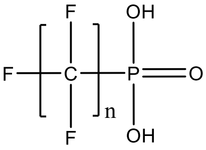
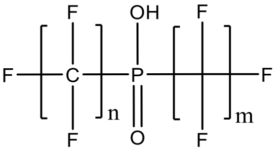
1. Perfluoroalkyl phosphonic (a) and phosphinic acids (b) (PFPAs & PFPIAs)

Key publication: Wang, Z., Cousins, I. T., Berger, U., Hungerbühler, K. & Scheringer, M. Comparative assessment of the environmental hazards of and exposure to perfluoroalkyl phosphonic and phosphinic acids (PFPAs and PFPIAs): Current knowledge, gaps, challenges and research needs. *Environ. Int.* 89–90, 235–247 (2016).

Chemical Information & Properties		
Identification and Terminology		
Name	Perfluoroalkyl phosphonic acids	Perfluoroalkyl phosphinic acids
Other Names	Phosphonic acid, perfluoro-alkyl derivatives[1]; perfluoroalkyl phosphonic acids [1]; mono-substituted perfluorinated phosphonic acids [2]	Phosphinic acid, bis(perfluoro-alkyl) derivatives [1]; bis(perfluoroalkyl) phosphinic acids [1]; di-substituted perfluorinated phosphonic acids [2]
Acronym	PFPAs	PFPIAs
Chemical Formula	$C_nF_{2n+1}P(=O)(OH)_2$ e.g. $4 \leq n \leq 12$	$C_nF_{2n+1}P(=O)(OH)(C_mF_{2m+1})$ e.g. $4 \leq n, m \leq 12$
General Structure (only linear isomers shown here)		
US EPA CompTox Markush ID	DTXSID801024679	DTXSID101024680
Common Terminology	e.g. perfluorooctyl phosphonic acid (C_8 PFPA)	e.g. bis(perfluorooctyl) phosphinic acid (C_8/C_8 PFPIA)
Degradability, Mobility, Bioconcentration		
Abiotic degradation	No degradation when exposed to heat, oxidants, and bases [3]	Hydrolyzes to yield PFPAs and $C_nF_{2n+1}H$ (a PFCA precursor) when exposed to heat or bases [3]
Biodegradation	No aerobic biodegradation in surface water [3]	Biotransforms to yield PFPAs in rainbow trout [3]
Adsorption on organic matter (log K_d, cm^3/g)	C_6 PFPA: −0.15 (soil) C_8 PFPA: 0.89 (soil), 1.07 (sludge) C_{10} PFPA: 1.1 (soil), 1.17–1.63 (sludge) [3]	C_6/C_6 PFPIA: 1.70 (soil) C_6/C_8 PFPIA: 2.09 (soil) C_8/C_8 PFPIA: 1.96 (soil) [3]
Sorption in soils	C_6 PFPA: 90% remaining in aqueous phase after 24 h; C_8 PFPA: 60% remaining in aqueous phase after 24 h; C_{10} PFPA: 15% remaining in aqueous phase after 24 h; [4]	C_6/C_6 PFPIA: 10% remaining in aqueous phase after 24 h; C_6/C_8 PFPIA, C_8/C_8-PFPIA: <LOD remaining in aqueous phase after 24 h; [4]

Bioaccumulation potential	Binds to proteins and blood cells [3] Elimination in rainbow trout [5]: $t_{1/2}$ (C_6 PFPA) = 0.13 d $t_{1/2}$ (C_8 PFPA) = 4.4 d $t_{1/2}$ (C_{10} PFPA) = 5.3 d Elimination in rats [2]: $t_{1/2}$ (C_6 PFPA) = ≤0.96 d (♂), ≤1.6 (♀) $t_{1/2}$ (C_8 PFPA) = ≤1.6 d (♂), ≤2.1 (♀) $t_{1/2}$ (C_{10} PFPA) = ≤2.5 d (♂), ≤2.8 (♀)	Binds to proteins [3] Elimination in rainbow trout [5]: $t_{1/2}$ (C_6/C_6 PFPIA) = 5.5 d $t_{1/2}$ (C_6/C_8 PFPIA) = 20.4 d $t_{1/2}$ (C_8/C_8 PFPIA) = 52.7 d Elimination in rats [2]: $t_{1/2}$ (C_6/C_6 PFPIA) = ≤1.8 d (♂), ≤2.3 (♀) $t_{1/2}$ (C_6/C_8 PFPIA) = ≤2.0 d (♂), ≤2.7 (♀) $t_{1/2}$ (C_8/C_8 PFPIA) = ≤2.7 d (♂), ≤4.0 (♀) $t_{1/2}$ (C_6/C_{10} PFPIA) = ≤2.0 d (♂), ≤3.0 (♀) $t_{1/2}$ (C_8/C_{10} PFPIA) = ≤5.1 d (♂), ≤9.3 (♀) $t_{1/2}$ (C_6/C_{12} PFPIA) = ≤5.4 d (♂), ≤8.4 (♀)
$BCF_{steady\ state}$ (zebrafish, whole body)	15.8–200 L/kg [6] *(for C_6, C_8, and C_{10} PFPAs; fish were exposed to mixture of PFAS at two different exposure levels)*	3.9×10^4–1.58×10^9 L/kg [6] *(for C_6/C_6, C_6/C_8, C_8/C_8, C_6/C_{10}, C_8/C_{10}, and C_6/C_{12} PFPIAs; fish were exposed to mixture of PFAS at two different exposure levels)*
Synthesis		
Main Synthesis Method [3]	Starting material: perfluoroalkyl iodides (PFAIs, often as a mixture of linear homologs) $6\ C_nF_{2n+1}I + P_4 \xrightarrow{heat} 2\ C_nF_{2n+1}PI_2 + 2\ (C_nF_{2n+1})_2PI$ Then, either $C_nF_{2n+1}PI_2\ or\ (C_nF_{2n+1})_2PI + H_2O \xrightarrow{oxidant} C_nF_{2n+1}PO(OH)_2\ or\ (C_nF_{2n+1})_2PO(OH)$ or $C_nF_{2n+1}PI_2\ or\ (C_nF_{2n+1})_2PI + AgCl \xrightarrow{oxidant} C_nF_{2n+1}PCl_2\ or\ (C_nF_{2n+1})_2PCl$ $C_nF_{2n+1}PCl_2\ or\ (C_nF_{2n+1})_2PCl + H_2O \xrightarrow{oxidant} C_nF_{2n+1}PO(OH)_2\ or\ (C_nF_{2n+1})_2PO(OH)$ Alternatively, tri(perfluoroalkyl)difluorophosphoranes can be used as a starting material. This route then yields PFPIAs with side chains of the same length, preferably n = 2 or n = 4. [7]	
Possible Impurities	PFCAs and/or other byproducts can be formed during PFAI manufacture. [3]	
Industrial Practices & Commercial Uses		
Major Commercial Products		
Name	Masurf-780 [2]	
Composition	80% aqueous solution of mixtures of PFPAs and PFPIAs. [3] Measured composition: 10% C_6 PFPA, 8% C_8 PFPA, 5% C_{10} PFPA 37% C_6/C_6 PFPIA, 33% C_6/C_8 PFPIA, 27% C_8/C_8 PFPIA *(amounting to 120%, likely due to empirical deviations)*	
Name	Tivida FL 2100 [3]	
CAS Number	52299-25-9	
Composition	C_4/C_4-PFPIA [3], [8]	

Production or import volumes	EU: 0–10 t/yr [3], [8]
Name	Phosphonic acid, perfluoro-$C_{6–12}$-alkyl derivatives (C_6–C_{12} PFPAs) [3]
CAS Number	68412-68-0
Production or import volumes	US: <1,000,000 lbs (500t) in 2015 [23] Denmark, Norway, Sweden: >4.33 t/yr in 1999–2011 (some amounts have been claimed as confidential business information) [3]
Name	Phosphinic acid, bis(perfluoro-$C_{6–12}$-alkyl) derivatives (C_6–C_{12} PFPIAs)
CAS Number	68412-69-1
Production or import volumes	US: <500t in 2015 [23] Denmark, Norway, Sweden: >3.33 t/yr in 1999–2011 (some amounts have been claimed as confidential business information) [3]
Uses	
Major applications	Surfactants, levelling and wetting agents in waxes and coatings, and defoaming agents in the textile industry, pharmaceutical industry, metal industry, and in pesticide formulations [2], [9]
Regulatory Status	
US	Some of these substances are regulated under 40 CFR §721.10536 Long-chain perfluoroalkyl carboxylate chemical substances [10]. A final rule to revoke the tolerance exemptions for mono- and bis-(1*H*,1*H*,2*H*,2*H*-perfluoroalkyl) phosphates (PAPs) where the alkyl group is even numbered and in the C_6-C_{12} range was published in August 2006 with an effective date 18 months after the publication of the final rule. They were used as surfactants (inert ingredients) in pesticide formulations in the past, but are no longer included in U.S. EPA's list of approved inert ingredients for pesticide products. [11], [12]
Canada	As CAS Numbers 68412-68-0 and 68412-69-1 are also precursors to long-chain (C_9–C_{20}) PFCAs, they were assessed together in 2012 and are managed pursuant to the *Prohibition of Certain Toxic Substances Regulations, 2012* [19], [20].
International efforts	
The proposal to list long-chain perfluorocarboxylic acids (PFCAs), their salts and related compounds in Annexes A, B and/or C to the Stockholm Convention on Persistent Organic Pollutants is under review by the Persistent Organic Pollutants Review Committee [22].	

Examples of reported occurrences

Type of locations/ samples	**(Environ-mental) media**	**Detected in one or multiple regions**	**Examples**		
			Location, year	**Levels [min.–max. (detection frequency)]**	**Ref.**
Note: Non-detects are reported as below the value of the limit of detection ("<LOD"). *ng = nanograms, NR = not reported, ww = wet weight*					
Close to fluorochemical manufacturing park	☐ air ☒ surface water ☐ soil ☐ sediment	☒ one ☐ multiple	China, 2012	C_6 PFPA: <0.04–30.2 ng/L (2/32)	[13]
Close to	☐ air	☒ one	North	C_6 PFPA: <0.025–1.2 ng/L (12/30)	[14]

agricultural inputs	☒ surface water ☐ soil ☐ sediment	☐ multiple	America, 2005 & 2007	C_8 PFPA: <0.025–3.4 ng/L (24/30) C_{10} PFPA: <0.025–0.87 ng/L (22/30)	
Not close to specific point sources	☐ air ☒ surface water ☐ soil ☐ sediment	☐ one ☒ multiple	Europe, 2009	C_8 PFPA: 1.0 ng/L (1/10)	[15]
			Asia, 2009	C_6 PFPA: <0.3–9.95 ng/L (14/76)	[16]
WWTP	☒ effluent ☐ sludge	☐ one ☒ multiple	North America, 2004 & 2007	C_6 PFPA: <0.083–6.5 ng/L (4/7) C_8 PFPA: <0.083–2.5 ng/L (6/7) C_{10} PFPA: <0.083–0.46 ng/L (3/7)	[14]
Indoor environment	Indoor dust	☒ one ☐ multiple	North America, 2007–2008	C_6 PFPA: <0.25–846 ng/g (57/102) C_8 PFPA: <0.38–290 ng/g (28/102) C_{10} PFPA: <2.1–152 ng/g (6/102) C_6/C_6 PFPIA: <0.088–525 ng/g (62/102) C_6/C_8 PFPIA: <0.086–944 ng/g (78/102) C_8/C_8 PFPIA: <0.17–525 ng/g (42/102)	[18]
Wildlife	Lake trout	☐ one ☒ multiple	North America, 2008–2010	C_6/C_6 PFPIA: <0.001–0.018 ng/g (NR) C_6/C_8 PFPIA: <0.002–0.032 ng/g (NR)	[9]
	Double-crested cormorants		North America, 2010–2012	C_6/C_6 PFPIA: 0.2–1.6 ng/g ww (grouped means, 66/66) C_6/C_8 PFPIA: 0.25–3.0 ng/g ww (grouped means, 66/66) C_8/C_8 PFPIA: <0.025–0.29 ng/g ww (grouped means, 55/66) C_6/C_{10} PFPIA: <LOD–0.15 ng/g ww (grouped means, 55/66) C_8/C_{10} PFPIA: <LOD ng/g ww (0/66) C_6/C_{12} PFPIA: <LOD ng/g ww (0/66)	[21]
Human	☒ general population ☐ occupational exposure	☐ one ☒ multiple	North America, 2009	C_6/C_6 PFPIA: <1–50.24 ng/g (17/70) C_6/C_8 PFPIA: <1–60.96 ng/g (28/40) C_8/C_8 PFPIA: <1–22.19 ng/g (1/40)	[17]

Knowledge gaps

- Information on commercial products, especially current production and use (including volumes).

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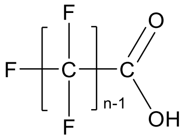
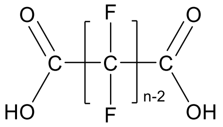
2. Perfluoroalkyl carboxylic (a) and dicarboxylic (b) acids

Key publication: Prevedouros, Konstantinos, Ian T. Cousins, Robert C. Buck, and Stephen H. Korzeniowski. 2006. “Sources, Fate and Transport of Perfluorocarboxylates.” *Environmental Science & Technology* 40 (1): 32–44. https://doi.org/10.1021/es0512475.

Chemical Information & Properties		
Identification and Terminology		
Name	Perfluoroalkyl carboxylic acids[5]	Perfluoroalkyl dicarboxylic acids
Other Names	Perfluorcarboxylic acids; perfluorinated carboxylic acids; perfluoroalkanoic acids [1]	Fluorinated dicarboxylic acids; perfluoroalkanedicarboxylic acids [2]
Acronym	PFCAs	PFdiCAs
Chemical Formula	$C_{(n-1)}F_{2n-1}COOH$	$C_{(n-2)}F_{2n-4}(COOH)_2$
General Structure (linear isomers)		
US EPA CompTox Markush ID	DTXSID00893893	DTXSID80893896
Individual acronyms and carbon chain length (as recommended by Buck et al. 2011)	*Short-chain PFCAs ($n \leq 7$)* TFA: n=2; PFPrA: n=3; PFBA: n=4; PFPeA: n=5; PFHxA: n=6; PFHpA: n=7; *Long-chain PFCAs ($n \geq 8$)* PFOA: n=8; PFNA: n=9; PFDA: n=10; PFUnDA: n=11: PFDoDA: n=12; PFTrDA: n=13; PFTeDA: n=14	
Degradability, Mobility, Bioconcentration Note: The following information refers only to PFCAs, due to a lack of information on PFdiCAs.		
Abiotic degradation	PFCAs generally do not undergo degradation in the environment [3].	
Atmospheric degradation	An estimated atmospheric lifetime regarding degradation (via reaction with OH radicals, forming COF_2) of PFCAs (n >1) is 130 days. Dry and wet deposition is more relevant, with time scales in the order of 10 days. [4]	
Biodegradation	No degradation of PFCAs under aerobic or anaerobic conditions over 15 weeks in closed bottle tests with municipal sewage sludge [5] [6]	
Bioaccumulation potential	Long-chain PFCAs (n ≥8) are known to be bioaccumulative [9], [10]. Due to their proteinophilic nature and slow elimination rates in air-breathing animals they are	

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[5] For more examples of compounds in the group of PFCAs and their associated information, one may search for “DTXSID40893892”, “DTXSID00893893”, “DTXSID60893894” at the U.S. EPA CompTox Chemicals Dashboard: https://comptox.epa.gov/dashboard.

[6] One study found PFOA was no longer detected after 26 d under anaerobic conditions in WWTP sludge [6]. However, since no increase in fluoride concentration was observed, it is doubtful that this result is due to anaerobic degradation, and more likely to be due to sorption phenomena [7]. In another study, PFOA was found to be partially degraded (removal of up to 60% over 100 day inoculations) by a specific bacterial strain (Acidimicrobium sp. Strain A6) under laboratory conditions where they were used as the sole source of carbon; the applicability of this method in the field environment is currently unclear. [8]

	especially bioaccumulative in higher trophic level wildlife and humans [11]. Some short-chain PFCAs (such as PFBA and PFHxA) are also biomagnifying with BMF values >1 [11].
TMF (trophic magnification factor)	*In the overall Arctic marine food web* [12]: PFHpA: 0.76; PFOA: 1.93; PFNA: 4.23; PFDA: 4.81; PFUnDA: 4.79; PFDoDA: 2.96; PFTeDA: 1.97 *In French riverine systems* [13]: PFOA: 0.39–0.58; PFNA: 0.61–9.9; PFDA: 2.6–10.9; PFUnDA: 2.4–4.2; PFDoDA: 1.4–2.7; PFTrDA: 0.9–14.9; PFTeDA: 0.7–2.8
BCF (carp, liver/blood, [L/kg])[7][14]	PFOA 134 / 611; PFNA: 150 / 4686; PFDA: 5957 / 34,896; PFUnDA: 1877 / 17,328; PFDoDA: 1945 / 11,988
Plant uptake	PFCAs have been found to accumulate in plants, with BCF values generally decreasing as chain lengths increase [61]–[64]. In various crops (lettuce, tomato, cabbage, zucchini), highest concentrations of long-chain PFCAs ($>C_{11}$) have been found in roots, while short-chain PFCAs have been found to accumulate in leaves. [61], [62] In trees (birch, spruce), the highest BCF values (chain-length-unspecified) have been found in foliage. [64]
Environmental transport	Main emissions sources of PFCAs lie in fluoropolymer manufacture and degradation of fluorotelomer compounds, among others [9]. Apart from manufacturing sites, relevant point sources also include airports, military bases, and other installations where AFFFs are or were used, as well as landfills. [15], [16] The majority of PFCAs in the environment are contained within the oceans, where sediment and the transport to deep oceans are sinks. Similarly, oceanic transport is believed to be most important transport pathway for PFCAs to the Arctic ocean. [3]
Adsorption on organic matter [8] *(log K_{oc}, [log L/kg])*	Log K_{oc} = 2.1 (for PFOA, average derived from multiple studies) [17]
Partition coefficients (K_d) between sediment and water	Increasing with chain length: 0.04 (PFOA)–0.72 (PFDoDA) [14] *(measured in Korea, n=17)*
Synthesis	
Main Synthesis Method	Mainly electrochemical fluorination of alkanoyl fluorides is employed to produce PFCAs (although in a mixture of linear and branched isomers): $C_nH_{2n+1}COF + (2n+1)HF \longrightarrow C_nF_{2n+1}COF + (2n+1)H_2$ Hydrolysis then yields the respective carboxylic acid. Yields decrease with increasing chain length, and when acid chlorides instead of acid fluorides are used. [1], [2], [18], [19] Alternatively, telomerization-based processes, followed by dehydroiodination and oxidation or direct carboxylation of the fluorotelomer iodide, to synthesize linear

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[7] Note that due to the acidic nature and the proteinophilic properties of PFCAs, BCFs are not necessarily accurate indicators of their overall biomagnification behavior in aquatic organisms. [11]

[8] It should be noted that "the behaviour of PFASs in the environment is more complex than can be explained by a single soil or sediment property and it is not appropriate to express the sorption behaviour of these chemicals normalized over the OC content of the sorbent (Koc). An assessment of the published data has shown that neither OC, pH nor clay content alone could explain the sorption behaviour of the PFASs." [18]

	PFCAs with one or two (respectively) more carbon atoms than the starting material (see also the fact cards #7 on n:2 fluorotelomers). [1], [2], [18], [56] $F(CF_2)_nI + CH_2CH_2 \longrightarrow F(CF_2)_nCH_2CH_2I \xrightarrow{-HI} F(CF_2)_nCHCH_2 \xrightarrow[\text{or } O_3]{+Cr_2O_7^{2-}} (CF_2)_nCOOH$ $F(CF_2)_nI + CO_2 + Zn\text{-}Cu \xrightarrow{(aq.)\ HCl} (CF_2)_nCOOH$ On a laboratory scale, there are several other synthesis methods available, see [19, p. 1488]. PFOA is synthesized by direct oxidation of the corresponding iodide ($C_8F_{17}I$) using SO_3 (or H_2SO_4)[9], yielding $C_7F_{15}CO_2X$ [20]. PFdiCAs are generally synthesized via the electrochemical fluorination method, followed by hydrolysis, acidification, and extraction (similarly to for PFCAs above) [2], or are obtained from diiodoperfluoroalkanes [67]
Possible Impurities	Electrochemical fluorination is not very selective and yields – besides the target compound – a number of linear, branched, or cyclic homologues. In the telomerization process, the purity of the product depends on the purity of the starting material.

Industrial Practices & Commercial Uses

Major Commercial Products

Name	Ammonium perfluorooctanoate (APFO)
Chemical Formula	$NH_4^+ \ C_7F_{15}COO^-$
CAS Number	3825-26-1
Use	As a processing aid in the dispersion process for production of fluoropolymers [1]; surfactant [1]
Production/Import volumes[10]	Global (1999): approx. 260 t/yr [3] US (2015): <500t in 2015 [21] Global (1951–2004): 3600–5700 t (estimated) [3]
Name	Ammonium perfluorononanoate (APFN)
Chemical Formula	$NH_4^+ \ C_8F_{17}COO^-$
CAS Number	4149-60-4
Use	Processing aid in polyvinylidene fluoride (PVDF) production. [3]
Production/Import volumes	Global (1951–2004): 800–2300 t (estimated) [3] Global (2004): 15–75 t/yr [3]
Name	Surflon® S-111 [1], [3]
Composition	74% APFN ($NH_4^+ \ C_8F_{17}COO^-$), 20% APFUnD ($NH_4^+ \ C_{10}F_{21}COO^-$), 5% APFTrD ($NH_4^+ \ C_{12}F_{25}COO^-$), 1% other linear PFCAs (with n=7,9,11) [1]
CAS Number	72968-38-8

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[9] According to information provided by representatives of the manufacturing industry.

[10] Long-chain PFCAs have largely been phased out and replaced in the past years; however, no information on more recent production volumes is available.

Use	Processing aid in polyvinylidene fluoride (PVDF) production. [3]
Uses	
Major applications	PFCAs have been used as polymerization aids in the production of fluoropolymers, as surfactants, in insecticide formulations, and in various consumer products. Historically, PFCAs were also ingredients of early generations of fire-fighting foams [9], [23], [24]. The use of silver salts of PFdiCAs in coordination polymers has been investigated [25], [26] and perfluoroadipic acid ($HOOC–C_4F_8–COOH$; CAS Number 336-08-3) is mentioned in a small number of patents (e.g. for thermoplastic elastomers or low-refractive-index layers in electrooptical devices) [27], [28]. PFdiCAs are also used to produce the corresponding alcohols via reduction [2]. Perfluorosuccinic acid (377-38-8), perfluoroglutaric acid (376-73-8), and perfluoroadipic acid (336-08-3) are listed as commercially *active* in the US TSCA Inventory, while their uses are unknown.
Regulatory Status	
General remarks	Most risk assessment activities focus mainly on PFOA, the most prominent PFCA [18]. Furthermore, regulations generally focus more on longer-chain PFCAs (n ≥8), and less on short-chain PFCAs, which are believed to be less bioaccumulative (although this belief is being challenged [10]) and are often used as replacement chemicals [10], [18], [29]. Many limit values for different environmental media have been set at regional, country and sub-country levels, and a comprehensive overview is available online by the US Interstate Technology Regulatory Council (ITRC) at https://pfas-1.itrcweb.org/fact-sheets/ (see “PFAS Water and Soil Values Table”). [30]
US	Under the 2010/2015 PFOA Stewardship Program by the U.S. EPA, eight major multi-national fluoropolymer and fluorotelomer manufacturers started to phase out long-chain PFCAs in 2006, which was achieved by 2015. [32] In July 2020, U.S. EPA issued a final rule requiring notice and U.S. EPA review before manufacturing/processing of certain long-chain PFAS that have been phased out in the United States could commence. [32] In March 2020, U.S. EPA made a preliminary determination to regulate PFOA in drinking water. U.S. EPA finalized regulatory determinations in February 2021. In addition, certain PFCAs are regulated at the state level in the United States. [33]
Europe	PFOA and its ammonium salt (APFO), as well as C_9–C_{14} PFCAs have been identified as substances of very high concern (SVHCs) under REACH in 2013 [34]. PFOA, APFO and related substances have been also added to the restricted substances list (REACH Annex XVII) in 2017. Restrictions of PFHxA, C_9–C_{14} PFCAs and related substances have also been proposed [35], [36]. In summer 2020, PFOA and related compounds moved to the EU POP regulation [37]. EFSA set a TWI (tolerable week intake) value for PFOA of 6 ng/kg bw (nanogram per kilogram bodyweight) in 2018 [18] and in 2020 set a TWI value for the sum of PFOA, PFNA, PFHxS and PFOS of 4.4 ng/kg bw [38].
Canada	PFOA, its salts and precursors as well as long-chain perfluorocarboxylic acids (LC-PFCAs), their salts and precursors were assessed in 2012. [39], [40] These substances are prohibited with a limited number of exemptions under the *Prohibition of Certain Toxic Substances Regulations, 2012* [41].
International Efforts	
PFOA, its salts, and PFOA-related compounds are listed as POPs (persistent organic pollutants) under the	

Annex A (Elimination) to the Stockholm Convention, with several specific exemptions [31]. See the listing for the definition of PFOA-related compounds covered.

In 2021, long-chain PFCAs (C_9–C_{21}), their salts and related compounds were proposed for listing under the Stockholm Convention (see UNEP/POPS/POPRC.17/7 at https://www.pops.int/poprc17).

Examples of reported occurrences

Type of locations/ samples	**(Environ-mental) media**	**Detected in one or multiple regions**	**Examples**		
			Location, year	**Levels [min. –max. (detection frequency)]**	**Ref.**
Note: Non-detects are reported as below the value of the limit of detection ("<LOD"). *ng = nanograms, dw= dry weight, ww = wet weight, ND = not detected, NR = not reported*					
Close to fluorochemical manufacturing park or other point sources	☐ air ☒ surface water ☐ soil ☐ sediment	☐ one ☒ multiple	Europe, 2016	PFBA: 4.6–12.0 ng/L (13/13) PFPeA: <4–8.2 ng/L (10/13) PFHxA: 4–6.4 ng/L (13/13) PFHpA: 1.5–2.2 ng/L (13/13) PFOA: 3.5–12 ng/L (13/13) PFNA: 0.49–1.0 ng/L (13/13) PFDA: 0.23–0.8 ng/L (13/13)	[42]
	☐ air ☐ surface water ☒ soil ☐ sediment	☐ one ☒ multiple	North America, 2009	PFHpA: 0.88–6.6 ng/g dw (19/19) PFOA: 47–470 ng/g dw (19/19) PFNA: 1.6–6.3 ng/g dw (19/19) PFDA: 2.1–5.3 ng/g dw (19/19) PFUnDA: 2.6–14 ng/g dw (19/19) PFDoDA: 2.2–11 ng/g dw (19/19)	[43]
	Earth worm	☒ one ☐ multiple	North America, 2009	PFHpA: ND–3.6 ng/g dw (14/19) PFOA: 51–860 ng/g dw (19/19) PFNA: 2.0–52 ng/g dw (19/19) PFDA: 5.9–74 ng/g dw (19/19) PFUnDA: 19–380 ng/g dw (19/19) PFDoDA: 22–660 ng/g dw (19/19)	[43]
	Surface water, groundwater, waste leachate	☒ one ☐ multiple	Sweden, 2017–2018	TFA: <34–14000 ng/L (21/34) PFPrA: <3.1–53000 ng/L (27/34)	[60]
Not close to specific point sources	☐ air ☒ surface water ☐ soil ☐ sediment	☐ one ☒ multiple	Asia, 2010 & 2012	PFHxA: ND–7.94 ng/L (15/19) PFHpA: ND–3.43 ng/L (16/19) PFOA: ND–8.34 ng/L (17/19) PFNA: ND–4.49 ng/L (16/19) PFDA: ND–4.80 ng/L (12/19) PFUnDA: ND–1.13 ng/L (15/19)	[14]

				PFDoDA: ND–0.33 ng/L (12/19)	
	Drinking water[11]	☐ one ☒ multiple	Europe, 2016	PFBA <2–13 ng/L (1/6) PFPeA: <4–5.7 ng/L (2/6) PFHxA: <0.1–5.3 ng/L (5/6) PFHpA: <0.05–2.4 ng/L (3/6) PFOA: <0.3–2.7 ng/L (4/6) PFNA: <0.03–0.28 ng/L (3/6) PFDA: <0.03–0.1 ng/L (2/6)	[42]
			Canada, 2012–2019	PFBA <1–10 ng/L (151/226) PFPeA: <1–15 ng/L (115/226) PFHxA: <1–13 ng/L (122/226) PFHpA: <1–3.6 ng/L (27/226) PFOA: <0.5–7.6 ng/L (165/226) PFNA: <0.5–1.2 ng/L (41/226) PFDA: <0.5–0.63 ng/L (5/226) PFUnDA: <1 ng/L (0/226) PFDoDA: <1 ng/L (0/226)	[55]
	DWTP influent		North America, 2013–2015	PFBA: <0.24–96.8 ng/L (23/25) PFPeA: <0.051–501 ng/L (23/25) PFHxA: <0.044–55.1 ng/L (24/25) PFHpA: <0.04–184 ng/L (24/25) PFOA: <0.56–112 ng/L (19/25) PFNA: <0.094–41.4 ng/L (24/25) PFDA: <0.084–31.1 ng/L (15/25) PFUnDA: <0.067–2.9 ng/L (8/25) PFDoDA: <0.062–0.28 ng/L (2/25) PFTrDA: <0.072 ng/L (0/25) PFTeDA: <0.13 ng/L (0/25) PFHxDA: <0.4 ng/L (0/25) PFOcDA: <0.29 ng/L (0/25)	[44]
	DWTP effluent			PFBA: <0.24–104 ng/L (22/25) PFPeA: <0.051–514 ng/L (24/25) PFHxA: NR–60.8 ng/L (25/25) PFHpA: <0.04–177 ng/L (23/25)	[44]

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[11] U.S. EPA has also collected nationwide drinking water data for certain PFAS, a summary of which can be found here: https://www.epa.gov/sites/production/files/2017-02/documents/ucmr3-data-summary-january-2017.pdf. Such data were further analyzed in, e.g., Guelfo, J.L. and D.T. Adamson. 2018. "Evaluation of a national data set for insights into sources, composition, and concentrations of per- and polyfluoroalkyl substances (PFASs) in U.S. drinking water." *Environmental Pollution* 236 (May): 505-513. Additionally, many U.S. states have also published data on the occurrence of PFAS in drinking water on their websites. Such data were recently analyzed in Andrews, D.Q. and Naidenko, O.V. 2020. Population-wide exposure to per- and polyfluoroalkyl substances from drinking water in the United States. *Enviornmental Science & Technology Letters* 7(12): 931–936.

				PFOA: <0.56–104 ng/L (19/25) PFNA: <0.094–38.6 ng/L (22/25) PFDA: <0.084–24.7 ng/L (13/25) PFUnDA: <0.067–1.85 ng/L (4/25) PFDoDA: <0.062–0.09 ng/L (1/25) PFTrDA: <0.072 ng/L (0/25) PFTeDA: <0.13 ng/L (0/25) PFHxDA: <0.4 ng/L (0/25) PFOcDA: <0.29 ng/L (0/25)	
	☐ air ☐ surface water ☐ soil ☒ sediment	☐ one ☒ multiple	Asia, 2010 & 2012	PFHxA: ND–0.05 ng/g dw (6/27) PFHpA: ND–0.06 ng/g dw (3/27) PFOA: ND–0.28 ng/g dw (24/27) PFNA: ND–0.15 ng/g dw (24/27) PFDA: ND–0.08 ng/g dw (24/27) PFDoDA: ND–0.09 ng/g dw (23/27) PFUnDA: 0.01–0.13 ng/g dw (27/27)	[14]
	Snow (ski area)		Northern Europe, 2010	PFHxA: <4.0–15.9 ng/L (7/8) PFHpA: <13.3 ng/L (0/8) PFOA: <7.8–55.5 ng/L (6/8) PFNA: <11.2–19.6 ng/L (1/8) PFDA: <4.15–17.2 ng/L (6/8) PFUnDA: <3.16–12.8 ng/L (5/8) PFDoDA: <0.168–21.8 ng/L (7/8) PFTrDA: <1.72–22.0 (6/8) PFTeDA: <0.377–57.9 (7/8) PFPeDA: <0.615–16.8 ng/L (5/8) PFHxDA: <1.36–108 ng/L (5/8) PFHpDA: <1.4–55.9 ng/L (4/8) PFOcDA: <5.59–786 ng/L (5/8) PFNDA: <4.03–60.6 ng/L (3/8) PFEiA: <3.29–113 ng/L (4/8)	[45]
Remote regions	Ice (41 cm depth)	☐ one ☒ multiple	Arctic, 2017	TFA: 137 ng/L (1/1) PFPrA: 6.3 ng/L (1/1) PFBA: 1.5 ng/L (1/1)	[46]
WWTP	☒ effluent ☐ sludge	☐ one ☒ multiple	Europe, 2007	PFPeA: 1.5–40.9 ng/L (9/9) PFHxA: 3.7–57.4 ng/L (9/9) PFHpA: 1.6–15.7 ng/L (9/9) PFOA: 12.3–77.6 ng/L (9/9) PFNA: 1.0–18.6 ng/L (9/9) PFDA: 0.9–34.5 ng/L (9/9)	[47]

				PFUnDA: <0.004–8.8 ng/L (7/9) PFDoDA: <0.01–0.5 ng/L (3/9)	
	☒ effluent ☐ sludge	☐ one ☒ multiple	United States, 2012 & 2013	PFHxA: 3.67–99.0 ng/L (28/28)	[57]
				PFHpA: ND–12.9 ng/L (27/28)	
				PFOA: 5.70–38.8 ng/L (28/28)	
				PFNA: 0.83–4.95 ng/L (28/28)	
				PFDA: 1.11–4.43 ng/L (28/28)	
				PFUnDA: ND–0.92 ng/L (16/28)	
				PFDoDA: ND–5.91 ng/L (9/28)	
Landfill leachate and impacted groundwater (historic = closed 25-90 years)		☐ one ☒ multiple	Canada, 2021	PFBA: NR–0.29 µg/L PFPeA: NR–0.21 µg/L PFHxA: NR–0.67 µg/L PFHpA: NR–0.27 µg/L PFOA: NR–0.85 µg/L PFNA: NR–1.0 µg/L PFDA: NR–0.006 µg/L PFUnA: NR–0.016 µg/L PFDoDA: NR–0.001 µg/L PFTriDA: NR–0.007 µg/L PFTeDA: NR–0.0002 µg/L	[58]
Indoor environment	Indoor air (hotel rooms)	☐ one ☒ multiple	Asia, 2015	C_4–C_7-PFCAs: 0.0444–0.541 ng/m^3 (13/13) > C_7-PFCAs: 0.0568–0.756 ng/m^3 (13/13)	[48]
	Indoor air (residential homes)			C_4–C_7-PFCAs: 0.351–1.970 ng/m^3 (19/19) > C_7-PFCAs: 0.091–0.686 ng/m^3 (19/19)	
	Indoor dust (hotel rooms)			C_4–C_7-PFCAs: ND–170 ng/g (7/13) > C_7-PFCAs 11.5–775 ng/g (13/13)	
	Indoor dust (residential homes)			C_4–C_7-PFCAs: 41.6–226 ng/g (19/19)	
				> C_7-PFCAs: 10.7–205 ng/g (19/19)	
Vegetation	Tree leaves	☐ one ☒ multiple	North America, 2009	PFHpA: 2.4–7.3 ng/g dw (19/19)	[43]
				PFOA: 200–700 ng/g dw (19/19) PFNA: 0.36–5.8 ng/g dw (19/19)	
				PFDA: 1.2–4.3 ng/g dw (19/19)	
				PFUnDA: 1.6–8.6 ng/g dw (19/19)	

				PFDoDA: <0.216–4.2 ng/g dw (15/19)	
Wildlife	Plankton	☐ one ☒ multiple	Asia, 2010 & 2012[12]	PFNA: ND–0.50 ng/g ww (10/12) PFDA: ND–0.39 ng/g ww (1/12) PFUnDA: ND–0.44 ng/g ww (6/12) PFDoDA: ND–1.08 ng/g ww (7/12)	[14]
	Crucian carp, blood		Asia, 2010 & 2012	PFHxA: ND–0.36 ng/ml (7/69) PFOA: ND–0.89 ng/ml (24/69) PFNA: ND–13.22 ng/ml (16/69) PFDA: 0.44–20.58 ng/ml (69/69) PFUnDA: 0.88–45.16 ng/ml (69/69) PFDoDA: 0.11–19.18 ng/ml (69/69)	[14]
	Crucian carp, liver		Asia, 2010 & 2012	PFOA: ND–0.33 ng/g ww (9/69) PFNA: ND–0.86 ng/g ww (30/69) PFDA: 0.06–3.48 ng/g ww (69/69) PFUnDA: 0.04–5.01 ng/g ww (69/69) PFDoDA: ND–2.08 ng/g ww (67/69)	[14]
	Peregrine falcons, plasma	☒ one ☐ multiple	Canada, 2016 & 2018	PFBA: ND–6.70 ng/g ww (5/57) PFPeA: ND–0.23 ng/g ww (3/57) PFHxA: ND–3.56 ng/g ww (41/57) PFHpA: ND–3.14 ng/g ww (28/57) PFOA: 0.17–2.38 ng/g ww (57/57) PFNA: 0.83–21.8 ng/g ww (57/57) PFDA: 0.45–9.65 ng/g ww (57/57) PFUnDA: 0.78–9.84 ng/g ww (57/57) PFDoDA: 0.24–3.62 ng/g ww (57/57) PFTrDA: 0.56–4.49 ng/g ww (57/57) PFTeDA: 0.22–2.81 ng/g ww (57/57)	[59]

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[12] PFHxA, PFHpA, and PFOA were not detected in any sample.

				PFHxDA: 0.09–3.00 ng/g ww (55/57) PFODA: 0.01–1.08 ng/g ww (18/57)	
	Peregrine falcons, egg	☒ one ☐ multiple	Canada, 2018	PFBA: ND ng/g ww (0/9) PFPeA: ND–0.64 ng/g ww (8/9) PFHxA: 0.06–0.09 ng/g ww (9/9) PFHpA: ND–0.06 ng/g ww (8/9) PFOA: 0.11–0.31 ng/g ww (9/9) PFNA: 0.46–4.05 ng/g ww (9/9) PFDA: 0.90–3.49 ng/g ww (9/9) PFUnDA: 1.12–7.22 ng/g ww (9/9) PFDoDA: 1.47–4.05 ng/g ww (9/9) PFTrDA: 1.93–8.18 ng/g ww (9/9) PFTeDA: 1.40–5.25 ng/g ww (9/9) PFHxDA: 0.19–0.46 ng/g ww (9/9) PFODA: ND–0.03 ng/g ww (7/9)	
Human serum	☒ general population ☐ occupational exposure	☐ one ☒ multiple	Asia, 2011	TFA: 5.36–12.55 ng/ml (244/252) PFPrA: 0.24–0.82 ng/ml (194/252) PFBA: 0.31–0.89 ng/ml (216/252) PFHxA: 0.41–0.76 ng/ml (251/251) PFHpA: ND–0.18 ng/ml (168/252) PFOA: 8.45–26.76 ng/ml (252/252) PFNA: 1.99–5.20 ng/ml (252/252) PFDA: 0.96–4.11 ng/ml (250/252) PFUnDA: 1.71–3.02 ng/ml (252/252) PFDoDA: 0.07–0.21 ng/ml (224/252)	[49]
	☒ general population ☐ occupational exposure		Canada, 2016-2017	PFOA: 1.3 ng/ml (mean; 2593/2593) PFNA: 0.51 ng/ml (mean; 2413/2442) PFDA: 0.18 ng/ml (mean; 2157/2360)	[65]
	☒ general population ☐ occupational exposure		North America, 2015–	PFNA: 0.577 ng/ml (mean; NR/1993) PFDA: 0.154 ng/ml (mean; NR/1993)	[66]

			2016	PFOA: 1.56 ng/ml (mean; NR/1993)	
	Children age 3-11		North America, 2013–2014	PFOA (linear): <0.07–8.22 ng/ml (638/639) PFOA (branched): <0.07–0.69 ng/ml (163/639) PFHpA: <0.07–0.97 ng/ml (124/639) PFNA: <0.07–52.92 ng/ml (638/639) PFDA: <0.07–2 ng/ml (300/639) PFUnDA: <0.07–2.83 ng/ml (208/639) PFDoDA: <0.07 ng/ml (0/639)	[50]

Other known occurrences and sources

Many other PFASs, such as fluorotelomer-based substances, can yield PFCAs upon degradation, including atmospheric oxidation of volatile precursors [9], [51], [52], [54]. For example, degradation (e.g. via OH-radicals) of fluoroalkylsilane substances can yield significant amounts of PFCAs [53].

Knowledge gaps

- Little is known about the uses, occurrence, and environmental fate of PFdiCAs.
- Current production volumes of PFCAs and PFdiCAs are unknown.

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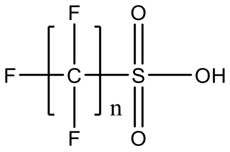
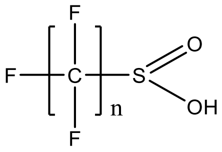
3. Perfluoroalkane sulfonic (a) and sulfinic (b) acids

Chemical Information & Properties		
Identification and Terminology[13]		
Name	Perfluoroalkane sulfonic acids	Perfluoroalkane sulfinic acids
Other Names	Perfluoroalkyl sulfonic acids; fluorinated alkanesulfonic acids	Perfluoroalkyl sulfinic acids; fluorinated alkanesulfinic acids
Acronym	PFSAs	PFSIAs
Chemical Formula	$C_nF_{2n+1}SO_2OH$	$C_nF_{2n+1}SOOH$
General Structure (linear isomers)		
US EPA CompTox Markush ID	DTXSID70892979	DTXSID801024681
Individual Acronyms (as used in this document)	*Short-chain PFSAs (n ≤5):* PFBS: n=4; PFPeS: n=5 *Long-chain PFSAs (n ≥6):* PFHxS: n=6; PFHpS: n=7; PFOS: n=8; PFNS: n=9; PFDS: n=10	PFOSI: n=8 (other PFSIAs exist, but no information on those was available)
Degradability, Mobility, Bioconcentration		
General remarks	PFOS and other long-chain PFSAs are known to be bioaccumulative and persistent in the environment [1], with PFHxS being the most bioaccumulative PFAS known [2]. Short-chain PFSAs (n ≤ 5) are less bioaccumulative, but are expected to be of similar persistence [1], [4].	PFSIAs are transformed to PFSAs in the environment. [3]
Photochemical degradation	PFOS photolyzes slowly under UV C light (100–280 nm), with complete degradation in 11 days [5].	
Hydrolysis	PFOS hydrolyzes at high temperatures (300 °C) [6].	
Biodegradation	No biodegradation of PFOS observed [7]. PFSAs are not effectively removed by conventional activated sludge processes in WWTP [8], [9].[14]	
Adsorption on organic matter (log K_d, cm^3/g)	Log K_{oc} = 2.68 (PFOS, in sediment) [10]	
Partition coefficients (K_d, sediment–water)	0.03 (PFHxS); 0.07 (PFOS) [11] *(measured in Korea, n=17)*	

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[13] For more examples of compounds in the group of PFSAs and their associated information, one may search for "DTXSID70892979" at the U.S. EPA CompTox Chemicals Dashboard: https://comptox.epa.gov/dashboard

[14] In one study, PFOS was found to partially degraded (removal of up to 60% over 100 day inoculations) by a specific bacterial strain (Acidimicrobium sp. Strain A6) under laboratory conditions where they were used as the sole source of carbon; the applicability of this method in the field environment is currently unclear. [56]

Bioaccumulation potential	PFOS: depuration half-life (rainbow trout) = 13d Blood elimination half-life (rat, male) = 8–30d [7] Short-chain PFSAs (PFBS) are accumulating in plants and trees [12-15]. In various crops (lettuce, tomato, cabbage, zucchini) PFBS and PFHxS accumulate rather in leaves, whereas PFOS accumulates rather in roots. In trees (birch, spruce), the highest BCF values have been found in foliage. [56]–[59]	
TMF in the overall Arctic marine food web [16]	PFOS: 17.4	
TMF in riverine systems [17]	PFHxS: 0.36–3.7 PFHpS: 0.65–8.3 PFOS (linear): 0.81–4.5 PFOS (branched): 1.4–8.3 PFDS: 0.73–3.0	
BAF (earthworm)	PFBS: 0.21–0.92 PFHxS: 0.51–4.69 [18]	
BMF (different species)	PFHxS: 6.9–22 [19]; 20 [20] PFOS: 30 [20] PFDS: 36 [20]	
BCF[15] (carp, liver/blood, [L/kg])	PFHxS: 8 / 342 PFOS: 4572 / 11,167 [11]	
Synthesis		
Main Synthesis Method	Mostly the Simons electrochemical fluorination process is used, where the hydrocarbon sulfonyl fluoride is electrolyzed in anhydrous hydrogen fluoride: $C_nH_{2n+1}SO_2F + (2n+1)HF \longrightarrow C_nF_{2n+1}SO_2F + (2n+1)H_2$ Alternatively, a nonelectrochemical route for the synthesis of trifluoromethanesulfonic acid derivatives is also possible: $F_3C-S-S-CF_3 \xrightarrow{Cl_2} 2\,F_3C-S-Cl \xrightarrow[H_2O]{Cl_2} 2\,F_3C-SO_2Cl$ Alkaline hydrolysis then gives the sulfonate salt, which can be acidified to yield the acid. [21] PFSIAs are similarly also synthesized via electrochemical fluorination [1].	
Possible Impurities	The electrochemical fluorination process is unselective and yields, besides the target compound, a mixture of linear, branched, and cyclic homologues, which can be found as impurities in the final product [1], [22]. Product yields decrease with increasing chain lengths [23].	

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[15] Note that due to the acidic nature and the proteinophilic properties of PFSAs, BCFs are not necessarily accurate indicators of their overall biomagnification behavior in aquatic organisms. [10]

Industrial Practices & Commercial Uses	
Major Commercial Products	
Name	Perfluorooctane sulfonic acid (PFOS)
CAS Number	1763-23-1
Production/Import volumes	PFOS production was phased out in the US (in 2002), but it is still being produced in China. The production volume of perfluorooctane sulfonyl fluoride (the parent compound of PFOS) in China in 2006 was more than 200 tonnes [1]. Global production between 2003 and 2008 reached 410 tonnes, mainly in China, followed by Japan and Germany [24]. Production volumes in 2015 were estimated at 170 tonnes per year in China [25].
Uses	Surfactant [1] (e.g. potassium salt of PFOS, CAS Number 2795-39-3, as a mist suppressant in electroplating) [24]
Name	Potassium perfluorobutanesulfonate (K-PFBS)
CAS Number	29420-49-3
Production/Import volumes	Registered under REACH with a production/import volume of 100–1000 tonnes/yr in Europe. [26]
Uses	Mainly used as flame retardant in polycarbonate, but also as intermediate in the synthesis of other chemicals. [27]
Uses	
Major applications	Short-chain PFSAs are used as esterification catalysts, as electrolytes in fuel cells and batteries (in the form of their lithium salts), as antistatic agents, and as flame retardants (K-PFBS is mainly used as flame retardant in polycarbonate) [27], [21]. Longer-chain PFSAs are used as surfactants and in fire extinguishing formulations [21]. PFSIAs themselves are not commercially used, but are known degradation products formed from perfluoroalkane sulfonamides. [1]
Regulatory Status	
General remarks	Current risk assessment and regulations mainly focus on PFHxS and PFOS, with short-chain PFSAs such as PFBS being used as replacements [4], [22]. Many limit values for different environmental media have been set at regional, country and sub-country levels, and a comprehensive overview is available online by the US Interstate Technology Regulatory Council (ITRC) at https://pfas-1.itrcweb.org/fact-sheets/ (see "PFAS Water and Soil Values Table"). [28]
US	Through its voluntary agreement with US EPA, 3M (the then largest manufacturer) phased out its global production of PFOS in 2002. [32] US EPA promulgated Significant New Use Rules (SNURs) in 2002 and 2007 under the Toxic Substances Control Act (TSCA) that require manufacturers (including importers) and processors to notify US EPA at least 90 days before starting or resuming manufacture, import, or processing for significant new uses of 271 PFSAs and related compounds, essentially encompassing all PFSAs and related compounds on the US market. Articles (except carpets) containing these substances may still be imported. [33] In March 2020, US EPA made a preliminary determination to regulate PFOS in drinking water. US EPA finalized regulatory determinations in February 2021. In addition, certain PFSAs have been regulated at the state level in the US. [34]
Canada	PFOS, its salts and precursors were assessed in 2006 and are prohibited with a limited number of exemptions under the *Prohibition of Certain Toxic Substances Regulations, 2012* [35], [36].

Europe	PFOS added to the restricted substances list (REACH Annex XVII) in 2017 [37]. In 2018, EFSA set the tolerable week intake (TWI) for PFOS to 13 ng/kg bw [38] and in 2020, EFSA set a TWI value for the sum of PFOA, PFNA, PFHxS and PFOS of 4.4 ng/kg bw [39]. The EU Water Framework Directive set an EQS (environmental quality standard) value for PFOS (and its derivatives) in surface waters of 0.65 ng/L [40]. PFBS and PFHxS (and their salts) are identified as SVHCs [41], [42].

International efforts

2002: OECD classified PFOS as a PBT chemical. [29]

2009: PFOS, its salts and perfluorooctane sulfonyl fluoride added to Annex B (Restriction) to the Stockholm Convention as persistent organic pollutants (POPs) [53], with specific exemptions and acceptable purposes amended in 2019 [54].

2013: Perfluorooctane sulfonic acid, perfluorooctane sulfonates, perfluorooctane sulfonamides and perfluorooctane sulfonyls added to Annex III to the Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade. [55]

PFHxS, its salts and related compounds are recommended by the Persistent Organic Pollutants Review Committee (POPRC) to the Stockholm Convention for listing under the Convention (to be determined by the Conference of the Parties (COP) in 2022). [30], [31]

Examples of reported occurrences

Type of locations/ samples	**(Environmental) media**	**Detected in one or multiple regions**	**Examples**		
			Location, year	**Levels [min. –max. (detection frequency)]**	**Ref.**
Note: Non-detects are reported as below the value of the limit of detection ("<LOD"). *pg = picograms, ng = nanograms, dw = dry weight, ww = wet weight, ND = not detected, NR = not reported*					
Close to fluorochemical manufacturing park	☐ air ☒ surface water ☐ soil ☐ sediment	☐ one ☒ multiple	Netherlands 2016	PFBS: 16–27 ng/L (13/13) PFHxS: 1.5–2.2 ng/L (13/13) PFHpS: 0.095–0.2 ng/L (13/13) PFOS: 2.7–6.5 ng/L (13/13)	[43]
Not close to specific point sources	☐ air ☒ surface water ☐ soil ☐ sediment	☐ one ☒ multiple	Korea 2010 & 2012	PFHxS: ND–3.97 ng/L (18/19) PFOS: 0.25–15.07 ng/L (19/19)	[11]
			Germany 2007	PFBS: 0.9–3.4 ng/L (15/15) PFHxS: 0.3–1.3 ng/L (15/15) PFOS: 0.5–2.9 ng/L (15/15) PFOSI: <0.01–0.1 ng/L (1/15)	[44]
		☐ one ☒ multiple	Brazil 2015	PFBS: 0.48–16 ng/L (19/21) PFOS: 4.6–44 ng/L (21/21)	[45]
			France 2015	PFBS: 2.0–15 ng/L (5/8) PFOS: 12–30 ng/L (3/8) PFDS: 5.9–12 ng/L (3/8)	[46]
				PFBS: 2.8–24 ng/L (9/29)	

	Drinking water[16]		Spain 2015	PFOS: 2.0–140 ng/L (11/29)	[45]
			Netherlands 2016	PFBS: 0.54–19.0 ng/L (6/6) PFHxS: 0.02–0.43 ng/L (6/6) PFHpS: <0.02–0.03 ng/L (3/6) PFOS: <0.03–0.41 ng/L (5/6)	[43]
			Canada 2012–2016	PFBS: <1–8.3 ng/L (14/226) PFHxS: <1–2.6 ng/L (43/226) PFOS: <0.5–5.9 ng/L (113/226) PFDS: <1 ng/L (0/226)	[61]
	Drinking water treatment plant (DWTP) influent		North America, 2013–2015	PFBS: <0.032–11.1 ng/L (24/25) PFHxS: <0.034–44.8 ng/L (23/25) PFOS: <0.13–48.3 ng/L (22/25) PFDS: <0.049 ng/L (0/25)	[46]
	DWTP effluent			PFBS: <0.032–11.9 ng/L (24/25) PFHxS: <0.034–21.1 ng/L (20/25) PFOS: <0.13–36.9 ng/L (20/25) PFDS: <0.049 ng/L (0/25)	[46]
	☐ air ☐ surface water ☐ soil ☒ sediment	☐ one ☒ multiple	Korea 2010 & 2012	PFHxS: ND–0.01 ng/g dw (9/27) PFOS: 0.01–0.048 ng/g dw (27/26)	[11]
	☐ air ☐ surface water ☒ soil ☐ sediment	☐ one ☒ multiple	North America 2016	∑PFSAs: 0.035–1.99 ng/g dw (33/33)	[47]
			Europe 2016	∑PFSAs: ND–3.27 ng/g dw (9/10)	
			Asia 2016	∑PFSAs: 0.079–0.421 ng/g dw (6/6)	
			Africa 2016	∑PFSAs: ND–0.144 ng/g dw (4/5)	
			Australia 2016	∑PFSAs: 0.044–0.297 ng/g dw (4/4)	
			South America 2016	∑PFSAs: 0.026–0.048 ng/g dw (3/3)	

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[16] U.S. EPA has also collected nationwide drinking water data for certain PFAS, a summary of which can be found here: https://www.epa.gov/sites/production/files/2017-02/documents/ucmr3-data-summary-january-2017.pdf. Such data were further analyzed in, e.g., Guelfo, J.L. and D.T. Adamson. 2018. Evaluation of a national data set for insights into sources, composition, and concentrations of per- and polyfluoroalkyl substances (PFASs) in U.S. drinking water. *Environmental Pollution* 236 (May): 505–513. Additionally, many U.S. states have also published data on the occurrence of PFAS in drinking water on their websites. Such data were recently analyzed in Andrews, D.Q. and Naidenko, O.V. 2020. Population-wide exposure to per- and polyfluoroalkyl substances from drinking water in the United States. *Environmental Science & Technology Letters* 7(12): 931–936.

Remote regions	☐ air ☐ surface water ☒ soil ☐ sediment	☐ one ☒ multiple	Antarctica 2016	∑PFSAs: 0.007 ng/g dw (1/1)	[47]
WWTP	☒ effluent ☐ sludge	☐ one ☒ multiple	Germany 2007	PFBS: 1.8–25.9 ng/L (9/9) PFHxS: 0.3–6.3 ng/L (9/9) PFHpS: <0.08–0.5 ng/L (3/9) PFOS: <0.06–82.2 ng/L (7/9) PFOSI: 0.1–1.2 ng/L (9/9)	[44]
	☒ effluent ☐ sludge	☐ one ☒ multiple	United States 2012 & 2013	PFBS: ND-14.0 ng/L (23/28) PFHxS: ND-2.48 ng/L (25/28) PFOS: 2.18-94.4 ng/L (28/28)	[62]
Landfill leachate and impacted groundwater (*historic, i.e. closed 25–90 years*)		☐ one ☒ multiple	Canada, 2018	PFBS: NR–710 ng/L (NR) PFHxS: NR–1300 ng/L (NR) PFOS: NR–2800 ng/L (NR) PFDS: NR–2 ng/L (NR) FOSA: NR–13 ng/L (NR) PFECHS: NR–9500 ng/L (NR)	[63]
Indoor environment	Indoor air (hotel rooms)	☒ one ☐ multiple	China 2015	∑PFSA: 0.0712–0.231 ng/m^3 (13/13)	[48]
	Indoor air (residential homes)			∑PFSA: 0.0868–0.567 pg/m^3 (19/19)	
	Indoor dust (hotel rooms)			∑PFSA: 2.44–99.1 ng/g (13/13)	
	Indoor dust (residential homes)			∑PFSA: 3.43–72.5 ng/g (19/19)	
Wildlife	Plankton	☐ one ☒ multiple	Korea 2010 & 2012	PFOS: ND–12.67 ng/g ww (6/12)	[11]
	Crucian carp, blood			PFHxS: ND–4.96 ng/ml (26/69) PFOS: 0.18–145.23 ng/ml (69/69) PFDS: ND–0.60 ng/ml (1/69)	[11]
	Crucian carp, liver			PFHxS: ND–0.30 ng/g ww (4/69) PFOS: ND–43.76 ng/g ww (58/69) PFDS: ND–0.58 ng/g ww (9/69)	[11]
	Harbor seals (*Phoca vitulina*, liver)		Germany 2007	PFBS: ND–0.78 ng/g ww (NR) PFPeS: 0.13–5.38 ng/g ww (NR) PFHxS: 1.11–10.4 ng/g ww (NR) PFHpS: ND–5.43 ng/g ww (NR)	[49]

				PFOS: 559–1665 ng/g ww (NR)	
				PFNS: 0.12–1.80 ng/g ww (NR) PFDS: 0.11–1.02 ng/g ww (NR) PFOSI: ND–0.16 ng/g ww (NR)	
	Eggs of Northern Fulmars and Thick-Billed Murres		North America, 2010-2011	PFBS: <0.1–0.57 ng/g ww (range of means, NR/60) PFHxS: <0.1–0.13 ng/g ww (range of means, NR/60) PFOS: <19.8–27.4 ng/g ww (range of means, NR/60) PFDS: <0.2 ng/g ww (NR/60)	[50]
	Ringed seals (*Pusa hispida*) plasma		Northern Europe, 2010	PFBS: <0.07 ng/g ww (mean, NR/11) PFHxS: 1.29 ng/g ww (mean, NR/11) PFOS: 48 ng/g ww (mean, NR/11) PFDS: <0.07 ng/g ww (mean, NR/11)	[51]
	Peregrine falcons, plasma		Canada, 2016 & 2018	PFEtCHxS: ND–3.96 ng/g ww (36/57) PFBS: ND–3.47 ng/g ww (27/57) PFHxS: ND–4.89 ng/g ww (56/57) PFOS: 4.97–124 ng/g ww (57/57) PFDS: ND–8.31 ng/g ww (53/57)	[64]
	Peregrine falcons, egg		Canada, 2018	PFEtCHxS: ND–0.26 ng/g ww (7/9) PFBS: ND–0.10 ng/g ww (3/9) PFHxS: 0.09–0.92 ng/g ww (9/9) PFOS: 11.8–53.2 ng/g ww (9/9) PFDS: 0.90–2.63 ng/g ww (9/9)	
Human serum	☒ general population ☐ occupational exposure		North America, 2015–2016	PFHxS: 1.18 ng/ml (mean; NR/1993) PFOS: 4.72 ng/ml (mean; NR/1993)	[65]
	Children age 3–11		North America, 2013–2014	PFBS: <0.07–0.17 ng/ml (27/639) PFHxS: <0.07–12.9 ng/ml (638/639) PFOS (linear): <0.07–26.54 ng/ml (639/639) PFOS (branched): <0.07–10.68 ng/ml (639/639)	[52]
	☒ general population		Canada, 2016-2017	PFHxS: 0.9 ng/ml (mean;	[66]

	☐ occupational exposure			2587/2595) PFOS: 3.0 ng/ml (mean; 2591/2594)	

Knowledge gaps

- Very little is known about the use, occurrence, and environmental fate of PFSIAs.

- Current production volumes are only available as estimates.

- More information on PFHxS and PFBS can be found in their EU REACH SVHC dossiers and in the PFHxS risk profile under the Stockholm Convention [13], [41], [42], [19].

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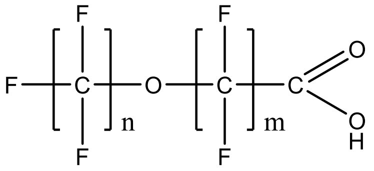
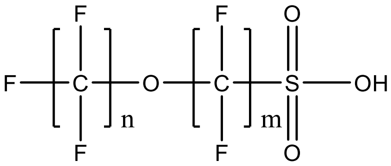
4. Per- and polyfluoroalkylether carboxylic (a) and sulfonic (b) acids

Key publication: Wang, Zhanyun, Ian T. Cousins, Martin Scheringer, and Konrad Hungerbuehler. 2015. "Hazard Assessment of Fluorinated Alternatives to Long-Chain Perfluoroalkyl Acids (PFAAs) and Their Precursors: Status Quo, Ongoing Challenges and Possible Solutions." *Environment International* 75: 172–79. https://doi.org/10.1016/j.envint.2014.11.013.

Chemical Information & Properties		
Identification and Terminology		
Name	Per- and polyfluoroether carboxylic acids	Per- and polyfluoroether sulfonic acids
Acronym	PFECAs	PFESAs
Exemplary Chemical Formula	$C_nF_{2n+1}OC_mF_{2m}COOH$	$C_nF_{2n+1}OC_mF_{2m}SO_3H$
Exemplary Structure (perfluorinated ones and linear isomers)		
US EPA CompTox Markush ID	DTXSID001024687	DTXSID301024686
Degradability, Mobility, Bioconcentration		
Abiotic degradation	Resistant to photolysis, hydrolysis, and OH radical-mediated reactions, under environmentally relevant conditions. [1]	Resistant to photolysis, hydrolysis, and OH radical-mediated reactions, under environmentally relevant conditions [1] F-53B shows only very low degradation in advanced oxidation processes [2]
Biodegradation	Resistant to biodegradation [1] Not being removed in conventional drinking water treatment plants [3]	Resistant to biodegradation [1] F-53B is not readily biodegradable in closed bottle tests [2]
Adsorption on PAC	PFECAs have a lower affinity for PAC than other PFASs of similar chain length. About 35% removal of HFPO-DA (CAS Number 62037-80-3) after 1h with 100 mg/L PAC. [3]	
Bioaccumulation potential	Likely low bioaccumulation potential, with BCF (fish) <10 [4]. Log $BAF_{\text{frogs, whole body}}$ (L/kg) = −0.12 (HFPO-TA) [5] $t_{1/2}$ (rats) = 44 h (ADONA)	log $BAF_{\text{frogs, whole body}}$ (L/kg) = ~3 (6:2 Cl-PFESA[17]) / ~4.2 (8:2 Cl-PFESA) *Black-spotted frogs sampled from several Chinese cities, which have large-scale fluorochemical industries* [5]

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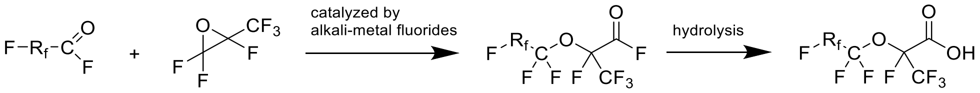
[17] Note on nomenclature: n:m here refers to the length of the carbon chain on each side of the ether bond. e.g. 6:2 means $C_6F_{13}OC_2F_4$–. Note that this commonly used nomenclature differs from the nomenclature of n:2 fluorotelomers.

	$t_{1/2}$ (humans) = 23 ± 11 d (ADONA) [1], [6]	
Environmental transport	expected to have similar transport properties as PFCAs [1]	
Synthesis		
Main synthesis method(s)	Some PFECAs are synthesized by an addition reaction of perfluoroalkyl fluorides with hexafluoropropylene oxide (HFPO), catalyzed by alkali-metal fluorides. Subsequent hydrolysis then yields the carboxylic acid. Other synthesis routes, including electrochemical or direct fluorination may exist as well. [7], [8]  R_f = perfluorinated chain	
Industrial Practices & Commercial Uses		
Major Commercial Products		
Trade name	GenX[18]	
Full name	Hexafluoropropylene oxide-dimer acid, ammonium salt	
Other names	PFPrOPrA, HFPO-DA (acid form) [9]	
Composition	$CF_3CF_2CF_2OCF(CF_3)COO^- NH_4^+$ [10]	
CAS Number	62037-80-3	
Production/Import volumes	Registered in 2011 under REACH with a production volume of 10–100 tonnes/yr in the EU. [10]	
Use	Used as a processing aid in fluoropolymer production, replacing APFO. [11]	
Trade name	ADONA	
Full name	3*H*-Perfluoro-3-[(3-methoxy-propoxy)propanoic acid], ammonium salt	
Composition	$CF_3OC_3F_6OCHFCF_2COO^- NH_4^+$ [6]	
CAS Number	958445-44-8	
Production/Import volumes	Registered under REACH with 1–10 tonnes/yr of production or import in the EU. [12]	
Use	As a processing aid, specifically as emulsifier, in fluoropolymer production. [6]	
Trade name	F-DIOX ammonium salt; cC6O4 ammonium salt	
Full name	Perfluoro{acetic acid, 2-[(5-methoxy-1,3-dioxolan-4-yl)oxy]}, ammonium salt	
Composition	$C_6F_9O_6^- NH_4^+$ [13]	
CAS Number	1190931-27-1	
Production/Import	Registered under REACH with 1–10 tonnes/yr of production or import in the EU. [14]	

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[18] Note that GenX has often been used interchangeably with hexafluoropropylene oxide dimer acid (HFPO-DA) and HFPO-DA ammonium salt.

volumes	
Use	As a processing aid in fluoropolymer production. [13]
Trade name	F-53B
Composition	$ClF_2C(CF_2)_5O(CF_2)_2SO_3^-$ K^+ [2]
CAS Number	73606-19-6
Use	A mist suppressant in chrome plating, used as a substitute to PFOS [2]
Uses	
Major applications	A number of PFECAs (usually in the form of their ammonium salts) are used as fluoropolymer processing aids, to replace APFO and APFN. [15] PFESAs like F-53B are used as PFOS substitutes, e.g. as mist suppressants in chrome plating [2].
Regulatory Status	
US	US EPA has released a draft reference dose of 80 ng/kg bw per day of HFPO-DA in 2018. [16]
Europe	HFPO-DA has been added to the list of Substances of Very High Concern (SVHC) due to its very high persistence, mobility, and potential harm to humans and the environment. [4]

Examples of reported occurrences

Type of locations/ samples	**(Environ-mental) media**	**Detected in one or multiple regions**	**Examples**		
			Location, year	**Levels [min.–max. (detection frequency)]**	**Ref.**
Note: Non-detects are reported as below the value of the limit of detection (“<LOD”). pg = picograms, ng = nanograms, ww = wet weight, ND = not detected, NR = not reported					
Close to fluorochemical manufacturing park	☐ air ☒ surface water ☐ soil ☐ sediment	☐ one ☒ multiple	Netherlands 2016	HFPO-DA: 1.7–433 ng/L (13/13)	[7]
			US 2013	HFPO-DA: 55–4560 ng/L (34/34)	[3]
Not close to specific point sources	☐ air ☒ surface water ☐ soil ☐ sediment	☐ one ☒ multiple	Germany & Netherlands 2013	HFPO-DA: <0.11–86.1 ng/L (4/23)	[17]
			China 2014	HFPO-DA: <0.25–3060 ng/L (22/29)	[17]
			China 2013	F-53B: 11.7–54.7 ng/L (7/7)	[2]
			China 2016	HFPO-DA: <0.05–1.54 ng/L (33/35)	[18]
				HFPO-TA: <0.1–1.29 ng/L (27/35)	
				4:2 Cl-PFESA: <0.01–0.04 ng/L (4/35)	

				6:2 Cl-PFESA: 0.12–12.94 ng/L (35/35)	
				8:2 Cl-PFESA: <0.01–0.29 ng/L (18/35)	
				6:2 H-PFESA: 0.02–4.07 ng/L (35/35)	
			UK 2016	HFPO-DA: 0.7–1.58 ng/L (6/6)	[18]
				HFPO-TA: <0.1–0.21 ng/L (4/6)	
				6:2 Cl-PFESA: 0.01–0.08 ng/L (6/6)	
			Germany 2016	HFPO-DA: 0.59–1.98 ng/L (20/20)	[18]
				HFPO-TA: <0.1–0.31 ng/L (14/20)	
				ADONA: <0.01–1.55 ng/L (15/20)	
				6:2 Cl-PFESA: 0.02–0.38 ng/L (20/20)	
			US 2016	HFPO-DA: 0.78–8.75 ng/L (12/12)	[18]
				HFPO-TA: <0.1–4.33 ng/L (9/12)	
				6:2 Cl-PFESA: <0.01–0.08 ng/L (8/12)	
	Drinking water	☐ one ☒ multiple	Netherlands 2016	HFPO-DA: <0.2–11 ng/L (3/6)	[7]
WWTP	☐ effluent ☒ influent ☐ sludge	☐ one ☒ multiple	China 2013	F-53B: 79.9–108.7 ng/L (5/5)	[2]
	☒ effluent ☐ influent ☐ sludge			F-53B: 45.7–74.8 ng/L (5/5)	
Wildlife	Black-spotted frogs (*P. nigromaculatus*, liver)	☐ one ☒ multiple	China	HFPO-TA: <0.05–27.3 ng/g ww (4/56)	[5]
				6:2 Cl-PFESA: 0.13–119.05 ng/g ww (56/56)	
				8:2 Cl-PFESA: 0.01–14.89 ng/g ww (56/56)	
	Polar bear (liver)		Greenland 2012–2013	F-53B: 0.27 ng/g (mean) (8/8)[19]	[19]

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[19] F-53B was also among a number of halogenated contaminants found in polar bears in Canada between 1984 and 2014 [20].

Knowledge gaps

- Main synthesis pathways for the commercial products of PFECAs and PFESAs.

- Global production volumes of commercial PFECAs and PFESAs.

- More information on the bioaccumulation potential needed.

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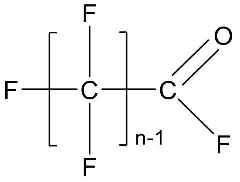
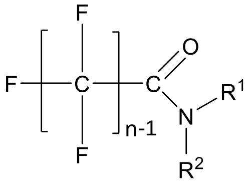
5. Perfluoroalkanoyl fluorides (a) and their derivatives (b)[20]

Chemical Information & Properties		
Identification and Terminology		
Name	Perfluoroalkanoyl fluorides	Perfluoroalkyl fluoride derivatives
Acronym	PACFs	PACF-based derivatives
Chemical Formula	$C_{n-1}F_{2n-1}COF$	$C_{n-1}F_{2n-1}CONR_2$ (e.g. perfluoroalkyl amides, PFAMs)[21]
General Structure (linear isomers)		
US EPA CompTox Markush ID	DTXSID10893647	
Examples of Individual Acronyms (as used in this document)		MeFOA: n = 8, $R^1 = CH_3$, $R^2 = H$ EtFOA: n = 8, $R^1 = CH_2CH_3$, $R^2 = H$ EtFBA: n = 4, $R^1 = CH_2CH_3$, $R^2 = H$
Degradability, Mobility, Bioconcentration		
Degradation	PACFs hydrolyze when released into the environment and form the corresponding perfluoroalkyl carboxylic acids (PFCAs), similarly to PASFs [1], [2]. These PFCAs then are persistent in the environment; for more information, see the fact card #2 on perfluoroalkyl carboxylic acids and perfluoroalkyl dicarboxylic acids.	MeFOA and EtFOA are expected to volatilize to the atmosphere and react with hydroxyl radicals, ultimately forming perfluorinated carboxylic acids (PFCAs) [2]. EtFBA is shown to degrade to PFBA, PFPrA, and TFA, among other products. [3]
Atmospheric lifetime		MeFOA: approx. 19 days (estimate) EtFOA: approx. 2.7 days (estimate) EtFBA: approx. 4.4 days (estimate) Perfluorobutyramide (the primary oxidation product of EtFBA): 7 times EtFBA [3]
Synthesis		
Main Synthesis Method	Electrochemical fluorination of an alkanoyl fluoride [1] $C_nH_{2n+1}COF + (2n+1)HF \longrightarrow C_nF_{2n+1}COF + (2n+1)H_2$	

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[20] For more examples of compounds in this group and their associated information, one may search for the following IDs at the U.S. EPA CompTox Chemicals Dashboard website: https://comptox.epa.gov/dashboard, namely DTXSID10893647, DTXSID70893648, DTXSID50893883, DTXSID10893884, DTXSID70893885, DTXSID30893886, DTXSID90893887, DTXSID10893889, DTXSID20893890, DTXSID80896827

[21] Note that PFCAs are also considered PACF-derivatives, but are discussed in their own fact card #2.

	Reaction of these PACFs or of perfluoroalkanoyl chlorides with amines yields PFAMs: [2] $C_nF_{2n+1}COF + NH_2R \longrightarrow C_nF_{2n+1}CONHR + HF$ PFAMs are also produced as by-products from POSF-based syntheses [2].
Possible Impurities	The electrochemical fluorination process is unselective and yields, besides the target compound, a mixture of linear, branched, and cyclic homologues, which can be found as impurities in the final product [1], [4].
Industrial Practices & Commercial Uses	
Major Commercial Products	
Full name	Perfluorobutanoyl fluoride (PBCF)
Composition	C_3F_7COF
CAS Number	335-42-2
Production/Import volumes	500 - <10,000t in the US in 2015 [11].
Use	Production of PFBA and potentially other, unknown uses [5].
Full name	Perfluorooctanoyl fluoride (POCF, sometimes also PFOF)
Composition	$C_7F_{15}COF$
CAS Number	335-66-0
Production/Import volumes	0 lbs in the US in 2015 [11].
Use	Used to produce PFOA [1], [6].
Full name	*N*-(3-Trimethoxysilylpropyl)perfluorohexanamide
Composition	$CF_3(CF_2)_4CONH(CH_2)_3Si(OCH_3)_3$
CAS Number	154380-34-4
Use	Surface treatment of glasses, natural stones, metals, wood, cellulose, cotton, leather, and ceramics [5].[22]
Uses	
Major applications	PACFs are raw materials or intermediates in the production of the respective carboxylic acids and derivatives thereof [5]. For example, POF is an intermediate in the production of PFOA [1], [6].
Regulatory Status	
General remarks	Since PACFs and their derivatives are precursors to PFCAs, most regulatory activities are directed towards PFCAs, but include PACFs explicitly or implicitly.
US	Under the 2010/2015 PFOA Stewardship Program by the US EPA, eight major multinational fluoropolymer and fluorotelomer PFCA manufacturers started to phase out long-chain PFCAs in 2006, which was achieved by 2015. [4] In July 2020, the US EPA issued a final rule requiring notice and US EPA review before manufacturing/processing

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[22] Note that these might be historical uses, as the manufacturer, Miteni, has declared bankruptcy since 2018 [10].

	of certain long-chain PFASs that have been phased out in the United States could commence. [7]
Europe	PFOA and its ammonium salt (APFO), as well as some related substances, including POF, have been classified as substances of very high concern (SVHCs) under REACH in 2013. In 2017, these substances were also added to the restricted substances list. [4]

International efforts

PFOA, its salts and PFOA-related compounds are listed as POPs (persistent organic pollutants) under Annex A (Elimination) to the Stockholm Convention with several specific exemptions (see listing for the chemical definition of PFOA-related compounds covered) [8].

PFOA, its salts and PFOA-related compounds are recommended by the Chemical Review Committee (CRC) of the Rotterdam Convention for listing under the Convention (to be determined by the Conference of the Parties (COP) in 2022). [9]

Examples of reported occurrences

Note: As noted above**,** PACFs and their derivatives form the corresponding carboxylic acids when released to the environment, similarly to PASFs. For examples of reported occurrences of the carboxylic acids in the environment, see the fact card #2 on PFCAs and PFdiCAs. No direct measurements of PACFs or their derivatives (other than PFCAs) in the environment have been found.

Knowledge gaps

- Information on recent uses and production volumes of PACFs is very limited.

- Information on PACF-based derivatives (such as PFAMs) is very limited and no environmental monitoring studies of these compounds could be found.

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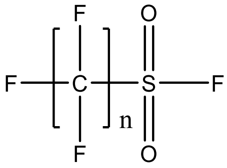
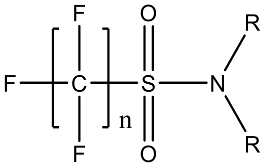
6. Perfluoroalkanesulfonyl fluorides (a) and their derivatives (b) [23]

Chemical Information & Properties		
Identification and Terminology		
Name	Perfluoroalkanesulfonyl fluorides	Perfluoroalkanesulfonyl fluoride derivatives
Acronym	PASFs	PASF-based derivatives
Chemical Formula	$C_nF_{2n+1}SO_2F$	$C_nF_{2n+1}SO_2NR_2$ (example of a sulfonamide)
General Structure (linear isomers)		 (example of a sulfonamide)
US EPA CompTox Markush ID	DTXSID601024685	DTXSID501024694
Examples of Individual Acronyms (as used in this document)	POSF: n = 8	FOSA: n = 8, R = H MeFOSA: n = 8, $R^1 = CH_3$, $R^2 = H$ MeFOSE: n = 8, $R^1 = CH_3$, $R^2 = CH_2CH_2OH$ EtFOSA: n = 8, $R^1 = CH_2CH_3$, $R^2 = H$ EtFOSE: n = 8, $R^1 = CH_2CH_3$, $R^2 = CH_2CH_2OH$ MeFBSA: n = 4, $R^1 = CH_3$, $R^2 = H$ MeFBSE: n = 4, $R^1 = CH_3$, $R^2 = CH_2CH_2OH$ SAmPAP diester: *N*-ethyl perfluorooctane sulfonamido ethanol-based phosphate diester
Degradability, Mobility, Bioconcentration		
Degradation	PASFs rapidly hydrolyze to form the corresponding sulfonic acids [1]. These sulfonic acids then are persistent in the environment, for more information see the fact card #3 on perfluoroalkane sulfonic and sulfinic acids.	Biotic degradation of perfluorosulfonamides mostly yields the corresponding sulfonic acids[24], while abiotic degradation yields sulfonic acids, carboxylic acids, and other degradation products [2] [3]. For example, EtFOSE is transformed in marine sediments to *N*-ethyl perfluorooctane sulfonamidoacetate, perfluorooctane

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[23] For more examples of compounds in this group and their associated information, one may search for the following IDs at the U.S. EPA CompTox Chemicals Dashboard website: https://comptox.epa.gov/dashboard, namely DTXSID50892977, DTXSID10892978, DTXSID80893634, DTXSID40893635, DTXSID70896775, DTXSID30896832, DTXSID101010201, DTXSID801010202, DTXSID701010209, DTXSID701010211, DTXSID101010213, DTXSID001010234, DTXSID701010235, DTXSID401010236, DTXSID101010237, DTXSID801010238, DTXSID501010239, DTXSID801010240, DTXSID501010241, DTXSID201010242, DTXSID901010243, DTXSID601010244, DTXSID201010254, DTXSID901010255, DTXSID601010256, DTXSID301010257, DTXSID001010258, DTXSID701010259, DTXSID001010260, DTXSID701010261, DTXSID401010262, DTXSID101010263

[24] For more information on those compounds, see the fact card #3 on perfluoroalkane sulfonic and sulfinic acids.

		sulfonamidoacetate, *N*-ethyl perfluorooctane sulfonamide, perfluorooctane sulfonamide, and perfluorooctane sulfonate, with $t_{1/2}$=44 d (25°C) and 160 d (4°C). SAmPAP diester showed little to no biotransformation over 120 d. [4]
Adsorption on soil & sediment		FOSA adsorbs strongly to organic matter, making soils an important environmental sink [5].
Bioaccumulation potential		FOSA can be accumulated by various plants [5].

Synthesis	
Main Synthesis Method	Mostly the Simons electrochemical fluorination process is used, where the hydrocarbon sulfonyl fluoride is electrolyzed in anhydrous hydrogen fluoride [6]: $C_nH_{2n+1}SO_2F + (2n+1)HF \longrightarrow C_nF_{2n+1}SO_2F + (2n+1)H_2$ Reaction with an amine then yields sulfonamides: $C_nF_{2n+1}SO_2F + RNH_2 \longrightarrow C_nF_{2n+1}SO_2NHR + HF$ These can be further reacted with, for example, ethylene carbonate, to give perfluoroalkane sulfonamido ethanols. Possible subsequent reaction steps can yield *N*-alkyl perfluoroalkane sulfonamidoethyl acrylates and *N*-alkyl perfluoroalkane sulfonamidoethyl methacrylates. [1]
Possible Impurities	The electrochemical fluorination process is unselective and yields, besides the target compound, a mixture of linear, branched, and cyclic homologues, which can be found as impurities in the final products [1], [7].

Industrial Practices & Commercial Uses	
Major Commercial Products	
Full name	Perfluorooctane sulfonyl fluoride (POSF)
Composition	$C_8F_{17}SO_2F$
CAS Number	307-35-7
Production/Import volumes	Globally: 96 000 tonnes (estimated) between 1970 and 2002; 410 tonnes between 2003 and 2008 [8] China: 250 tonnes (estimated) between 2003 and 2008 [8] Japan: 100 tonnes between 2003 and 2008 [8] Germany: 25 tonnes between 2003 and 2008 [8]
Full name	Perfluorobutane sulfonyl fluoride (PBSF)
Composition	$C_4F_9SO_2F$
CAS Number	375-72-4
Production/Import volumes	Global production: in total, 317 tonnes in 2015 (299 tonnes in China). [9]
Full name	Sulfluramid / *N*-ethyl perfluorooctane sulfonamide
Composition	$C_8F_{17}SO_2NH(C_2H_5)$

CAS Number	4151-50-2
Production/Import volumes	Production phased out in the US. [1], [10] Production in Brazil in 2013 was estimated to be about 60 tonnes. [10]
Uses	Pesticide, especially used against leaf-cutter ants [1] [10]
Full name	Sodium 2-(*N*-ethylperfluorooctane-1-sulfonamido)ethyl phosphate / perfluorooctane sulfonamido ethanol-based phosphate diester / SAmPAP
Composition	$F_3C(F_2C)_7SO_2N(C_2H_5)CH_2CH_2OPO(ONa)_2$
Production/Import volumes	A high production volume chemical until 2002, then phased out in North America. [4]
Uses	Used in food contact paper and packaging until it was phased out in North America 2002 [4]
Other PASF derivatives	PBSF-derivatives are used as surfactants (e.g. in coatings), as intermediates in the manufacture of other chemicals, or as plastic additives. [9] Other PASF derivatives, such as *N*-MeFOSEA and *N*-EtFOSE, have been produced by 3M (which were phased out in 2002) and others [1]. They were used in surface treatment products, as paper protectors, and as performance chemicals (e.g. fire extinguishing foams and surfactants) [11].
Uses	
Major applications	PASFs are used as starting material in the synthesis of sulfonamides and other derivatives including side-chain fluorinated polymers, which have been and are used as plant growth regulators, herbicides, in paper-protecting applications, and as surfactants and surface protection products in other applications [1], [2], [6]. PASFs are precursors to PFSAs with the same chain length [8].
Regulatory Status	
US	In 2002, 3M - the then largest manufacturer of POSF phased out the production of POSF-based products, in agreement with the US EPA [7]. Certain PASFs are subject to a TSCA significant new use rule [12]. US EPA cancelled the last remaining manufacturing-use product registration for Sulfluramid in May 2008 and all remaining pesticide end-use product registrations by 2013. [13]
Canada	Some of these substances are precursors to PFOS, and they were assessed and managed along with PFOS, its salts and precursors in 2006. They are prohibited with a limited number of exemptions under the Prohibition of Certain Toxic Substances Regulations, 2012 [14], [15]
Europe	PFOS and its derivatives (including POSF and FOSA) are regulated as persistent organic pollutants (POPs) and their production, sale, and use in the EU is prohibited, with certain exemptions [8]. PFBS, PFHxS and their salts are listed as SVHC under REACH [16].
International efforts	
POSF[25] was added to Annex B to the Stockholm Convention as POP in 2009, together with PFOS and its salts. [19] The acceptable pursposes and specific exemptions were amended in 2019. [20] POSF was added to Annex III to the Rotterdam Convention in 2013, together with PFOS, perfluorooctane sulfonates, perfluorooctane sulfonamides. [21]	

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[25] In the Stockholm Convention and the Rotterdam Convention the acronym PFOSF is used.

Examples of reported occurrences

Type of locations/ samples	**(Environmental) media**	**Detected in one or multiple regions**	**Examples**		
			Location, year	**Levels [min. –max. (detection frequency; substance)]**	**Ref.**
Note: As noted above, PASFs and their derivatives transform in the environment, forming PFSAs and PFCAs (not in the case of PASFs). For examples of reported occurrences of those, see the fact cards #2 on perfluoroalkyl carboxylic and dicarboxylic acids and #3 on perfluoroalkane sulfonic and sulfinic acids.					
Non-detects are reported as below the value of the limit of detection (“<LOD”). *pg = picograms, ng = nanograms, ND = not detected, NR = not reported*					
Close to WWTP and landfills	☒ air ☐ surface water ☐ soil ☐ sediment	☒ one ☐ multiple	Canada 2009	MeFOSA: 6.11–48.2 pg/m^3 (16/16)	[17]
				EtFOSA: 6.07–30 pg/m^3 (16/16)	
				MeFOSE: 1.06–41.5 pg/m^3 (16/16)	
				EtFOSE: <4.8–29.2 pg/m^3 (16/16)	
Not close to specific point sources	☐ air ☒ surface water ☐ soil ☐ sediment	☐ one ☒ multiple	Germany 2007	FOSA: 0.1–1.0 ng/L (15/15)	[18]
WWTP and on-site septic systems	☒ effluent ☐ influent ☐ sludge	☐ one ☒ multiple	Germany 2007	FOSA: 0.3–1.1 ng/L (9/9)	[18]
				MeFBSA: <0.17–14 ng/L (3/9)	
				MeFBSE: <0.07–0.5 ng/L (3/9)	
	☒ effluent ☐ sludge	☐ one ☒ multiple	United States 2012 & 2013	PFOSA: ND-6.56 ng/L (12/28)	[22]
Wildlife	Peregrine falcons, serum	☒ one ☐ multiple	Canada, 2018	FOSA: ND–0.12 ng/g ww (5/29) MeFOSA: ND–0.05 ng/g ww (3/29) EtFOSA: ND–0.02 ng/g ww (1/29)	[23]
	Peregrine falcons, egg	☒ one ☐ multiple	Canada, 2018	FOSA: ND (0/9) MeFOSA: ND (0/9) EtFOSA: ND–0.01 ng/g ww (1/9)	

Knowledge gaps

- Current commercial products of PASF-derivatives, especially their production and uses (including volumes), are largely unknown.

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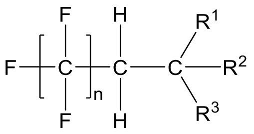
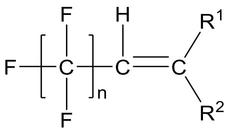
7. n:2 Fluorotelomer-based compounds

Key publications: J. W. Washington, T. M. Jenkins, K. Rankin, and J. E. Naile. 2015. Decades-Scale Degradation of Commercial, Side-Chain, Fluorotelomer-Based Polymers in Soils and Water. Environ. Sci. Technol., 49(2): 915–923.

Buck, Robert C, James Franklin, Urs Berger, Jason M Conder, Ian T Cousins, Pim de Voogt, Allan Astrup Jensen, Kurunthachalam Kannan, Scott A Mabury, and Stefan PJ van Leeuwen. 2011. “Perfluoroalkyl and Polyfluoroalkyl Substances in the Environment: Terminology, Classification, and Origins.” *Integrated Environmental Assessment and Management* 7 (4): 513–41.

Chemical Information & Properties		
Identification and Terminology		
Name	n:2 Fluorotelomers	n:2 Fluorotelomer olefins
Acronym	n:2 FT[R], e.g. FTOH	n:2 FTO
Chemical Formula	$C_nF_{2n+1}C_2H_4R$	$C_nF_{2n+1}C_2HR^1R^2$
General Structure (linear isomers)	 R^1 and R^2 = H, unless for carboxylic acids	
US EPA CompTox Markush ID	DTXSID401024691	DTXSID601024928
Terminology	n:m FT[R], where n = number of perfluorinated carbons and m = number of non-fluorinated carbons.	
Overview of n:2 Fluorotelomer derivatives [1][26]		

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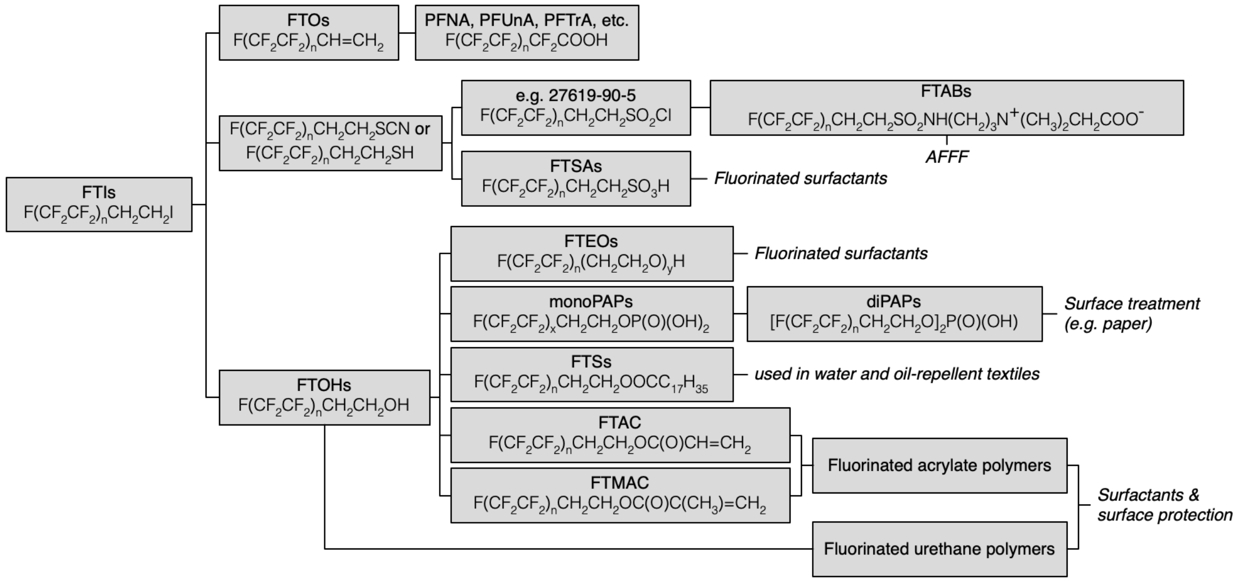
[26] For more examples of compounds in this group and their associated information, one may search for the following IDs at the US EPA CompTox Chemicals Dashboard website: https://comptox.epa.gov/dashboard, namely DTXSID50892558 (FTSAs), DTXSID90893802 (FTOHs), DTXSID50892972, DTXSID70892974, DTXSID30892975, DTXSID90892976, DTXSID40893817, DTXSID70893820, DTXSID80893876, DTXSID60893879, DTXSID301010245, DTXSID801010264, DTXSID501010265. In addition, fluorinated acrylate and urethane polymers belong to so-called “side-chain fluorinated polymers” (polymers with nonfluorinated polymer backbones and fluorinated side chains).



Acronyms: FTI = fluorotelomer iodide; FTO = fluorotelomer olefin; FTSA = fluorotelomer sulfonic acid; FTOH = fluorotelomer alcohol; sFTOH = fluorotelomer secondary alcohol; FTAB = fluorotelomer sulfonamide alkylbetaine; FTEO = fluorotelomer ethoxylate; monoPAP = fluorotelomer monophosphate; diPAP = fluorotelomer diphosphate; FTS = fluorotelomer alkyl stearate; FT(M)AC = fluorotelomer (meth)acrylate; FTUCA = unsaturated fluorotelomer carboxylic acid[27]

Degradability, Mobility, Bioconcentration	
General remarks and degradation products	Degradation pathways of n:2 fluorotelomer-based chemicals depend on the environmental matrices and can be very complex [2], [3]. Generally, though, the alcohols are transformed to aldehydes, which are further oxidized to form the corresponding carboxylic acids. These can then be further transformed to a range of saturated and unsaturated compounds, including PFCAs [3]. For more detailed information on the degradation of fluorotelomer-based compounds, see Buck et al. 2011 and Frömel & Knepper 2010.
Atmospheric degradation	Reaction of n:2 FTOHs with OH radicals in the atmosphere (or surface waters) yields PFCAs [4].
(Bio)degradation in soil and sediment	8:2 FTOH degraded rapidly (<7 d) in aerobic soil and yielded (on average) 25% PFOA, and 11% 7:3 FTCA, both of which did not degrade further [5]. 6:2 FTOH degraded rapidly ($t_{1/2}$ <2 d) in aerobic soil and formed 30% PFPeA, 15% 5:3 FTCA, and 8% PFHxA after 180 days. [6] 6:2 FTSA was rapidly ($t_{1/2}$ <5 d) transformed in aerobic river sediment to form PFPeA (21%$_{mol}$), PFHxA (20%$_{mol}$), and 5:3 FTCA (16%$_{mol}$) after 90 days. No degradation at all was observed in anaerobic sediment after 100 days. [7] Fluorotelomer-based side-chain fluorinated polymers degrade in saturated soil and water to form FTOHs and PFCAs, among other PFAS species. Hydrolysis occurs slowly under neutral conditions ($t_{1/2}$ = 55–89 yrs), but much faster at higher pH values ($t_{1/2}$ at pH 10 = 4.9 yrs, $t_{1/2}$ at pH 12 = 0.7 yrs). [8], [9]
Biodegradation in bacterial culture	6:2 FTOH degraded rapidly ($t_{1/2}$ <2 days) in mixed bacterial culture to form 23% FTUA, 16% 5:2 sFTOH (secondary alcohol, $[F(CF_2)_5CH(OH)CH_3]$), 6% 5:3 FTCA, and 5% PFHxA after 90 days. [6] In activated sludge from WWTPs, 6:2 FTOH was found to be transformed mainly to 5:2

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[27] Note that often a different nomenclature is used for FTUCAs in literature. According to this nomenclature, **6**:2 FTUCA is referred to as F**H**UEA, **8**:2 FTUCA as F**O**UEA, and so forth. This fact card will keep the general n:2 fluorotelomer nomenclature though.

	sFTOH (40%$_{\text{mol}}$) after 2 months [10].
Metabolism in mammals	FTOHs are mostly rapidly eliminated in urine as conjugates, although PFCAs have also been detected as transformation products [3]. In rats, 8:2 FTOH has been found to be excreted mainly via feces, with metabolites including 7:2 sFTOH, 7:2 Ketone, and PFOA, among others [11]. 6:2 FTOH is reported to be rapidly metabolized and eliminated in humans, although its main metabolites PFHxA, PFHpA, PFBA, and 5:3 Acid can exhibit elimination half-lives of 1–2 months after a period of high exposure [12].
Mobility	FTOHs generally exhibit high volatilities and poor water solubilities, resulting in high water-air partition coefficients and high tendency for sorption onto particles when dissolved in water. [2]
Synthesis	
Main Synthesis Method	Telomerization: A perfluoroalkyl iodide (usually perfluoroethyl iodide) is reacted with tetrafluoroethylene to increase the perfluorinated chain length. Subsequently, ethylene is inserted (using catalysts or increased temperature and pressure) to form perfluoroalkyl ethyl iodides [3] $F(CF_2)_nI + CH_2 = CH_2 \longrightarrow F(CF_2)_nCH_2CH_2I$
Possible Impurities	The telomerization process yields only homologues. Whether they are linear (common) or branched (uncommon) isomers, depends on the starting perfluoroalkyl iodide [3].
Industrial Practices & Commercial Uses	
Major Commercial Products[28]	
Full name	6:2 Fluorotelomer sulfonamide betaine
Composition	$F(CF_2)_6(CH_2)_2SO_2NH(CH_2)_3NH_2^+CH_2COOH$
CAS Number	34455-29-3
Production/Import volumes	Registered in the EU under REACH with a production/import volume of 100–1000 t/yr. [13]
Use	Used in fire-fighting foams, professional cleaning products, and inks and films. [13]
Full name	Triethoxy(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl)silane
Composition	$F(CF_2)_6(CH_2)_2Si(OCH_2CH_3)_3$
CAS Number	51851-37-7
Production/Import volumes	Registered in the EU under REACH with a production/import volume of 10–100 t/yr. [14]
Use	Used as oil/water repellence for carpets, fabric/upholstery, apparel, leather and glass. [14]
Full name	3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctanesulfonic acid
Other names	6:2 Fluorotelomer sulfonic acid
Composition	$F(CF_2)_6(CH_2)_2SO_3H$
CAS Number	27619-97-2
Production/Import volumes	Registered in the EU under REACH with a production/import volume of 10–100 t/yr. [15]

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[28] Note that these are just some examples of fluorotelomer-based products, not including polymers. For a more comprehensive overview see the overview figure above.

Use	Used as a mist suppressant in metal plating [15]
Uses	
Major applications	Raw material intermediates such as n:2 FTOHs are used to produce surfactants and surface protectors, including side-chain fluorinated polymers. n:2 FTSAs are also directly used as surfactants. diPAPs have also been used as grease-proofing agents for food-contact paper, as defoaming adjuvants in pesticide formulations and as surfactants in industrial cleaning products [3]. For more details on the applications of side-chain fluorinated polymers, see Buck et al. (2011).
Regulatory Status	
US	Some of these substances are regulated under 40 CFR §721.10536, the long-chain perfluoroalkyl carboxylate chemical substances significant new use rule. [16] A final rule to revoke tolerance exemptions for mono- and bis-(1*H*,1*H*,2*H*,2*H*-perfluoroalkyl) phosphates where the alkyl group is even numbered and in the C_6-C_{12} range was published in August 2006 with an effective date 18 months after the publication of the final rule. [17] Under the 2010/2015 PFOA Stewardship Program by the US EPA, eight major multi-national fluoropolymer and fluorotelomer PFCA manufacturers started to phase out long-chain PFCAs and related chemicals in 2006, which was achieved by 2015. [26]
Canada	Certain fluorotelomers (including diPAPs) are precursors to PFOA and long-chain (C_9–C_{20}) PFCAs. Non-exhaustive lists of precursors to PFOA and long-chain (C_9–C_{20}) PFCAs can be found in the ecological screening assessments for PFOA and long-chain (C_9–C_{20}) PFCAs [18], [19]. These substances are prohibited with a limited number of exemptions under the *Prohibition of Certain Toxic Substances Regulations, 2012* [20].
Europe	(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl) silanetriol and any of its mono-, di- or tri-O-(alkyl) derivatives (TDFAs) have been added to the restricted substances list (REACH Annex XVII) in 2021. [27]
International efforts	
Some long-chain fluorotelomers (n≥8 and n≤16) are considered PFOA-related compounds under the Stockholm Convention on Persistent Organic Pollutants. [28]	

Examples of reported occurrences

Type of locations/ samples	**(Environmental) media**	**Detected in one or multiple regions**	**Examples**		
			Location, year	**Levels [min.–max. (detection frequency)]**	**Ref.**
Non-detects are reported as below the value of the limit of detection (“<LOD”). *pg = picograms, ng = nanograms, ND = not detected, NR = not reported*					
Close to WWTP and landfills	☒ air ☐ surface water ☐ soil ☐ sediment	☐ one ☒ multiple	Canada 2009	6:2 FTOH: 0.09–12.3 ng/m^3 (16/16)	[10]
				8:2 FTOH: 0.14–17.4 ng/m^3 (16/16)	
				10:2 FTOH: 0.07–2.15 ng/m^3 (16/16)	
	Landfill leachate		US	4:2 FTUCA: ND–6.3 ng/L (1/87)	[23]

			2013–2014	6:2 FTUCA: <2.0–52.0 ng/L (45/87)	
				8:2 FTUCA: <2.0–161 ng/L (24/87)	
				10:2 FTUCA: ND–49.3 ng/L (9/87)	
				4:2 FTSA: <5.0–22.7 ng/L (22/87)	
				6:2 FTSA: <2–2247.8 ng/L (84/87)	
				8:2 FTSA: <2–667.0 ng/L (64/87)	
				6:2 diPAP: <1.9–26.4 ng/L (14/87)	
				8:2 diPAP: <2.0–208.8 ng/L (12/87)	
				10:2 diPAP: ND–47.7 ng/L (6/87)	
Not close to specific point sources	☐ air ☒ surface water ☐ soil ☐ sediment	☐ one ☒ multiple	Germany 2007	6:2 FTSA: <0.2–1.1 ng/L (8/15)	[21]
				8:2 FTUCA: <0.01–0.1 ng/L (1/15)	
				10:2 FTUCA: <0.03–0.3 ng/L (3/15)	
			Japan 2007–2008	8:2 FTOH: <0.2–3.38 ng/L (19/33)	[22]
				10:2 FTOH: <0.2–4.06 ng/L (4/33)	
				8:2 FTAc: <0.05–0.16 ng/L (6/33)	
WWTP	☒ effluent ☐ influent ☐ sludge	☐ one ☒ multiple	Germany 2007	6:2 FTOH: <0.2–37.9 ng/L (5/9)	[21]
				6:2 FTUCA: <0.07–0.9 ng/L (1/9)	
Indoor environment	Indoor air, hotels	☐ one ☒ multiple	China 2015	6:2 FTOH: <0.026–1.9 ng/m^3 (16/19)	[24]
				8:2 FTOH: 0.253–48.0 ng/m^3 (19/19)	
				10:2 FTOH: 0.054–13.6 ng/m^3 (19/19)	
				6:2 diPAP: <0.001–0.0067 ng/m^3 (10/19)	
				8:2 diPAP: <0.002–0.0177 ng/m^3 (6/19)	
				6:2 FTUCA: <0.002–0.0084 ng/m^3	

				(13/19)	
				8:2 FTUCA: <0.001–0.005 ng/m^3 (13/19)	
	Indoor dust, hotels		China 2015	6:2 FTOH: 4.71–372 ng/g (11/11)	[24]
				8:2 FTOH: 15.6–438 ng/g (11/11)	
				10:2 FTOH: 3.96–123 ng/g (11/11)	
				6:2 diPAP: 1.08–67.4 ng/g (11/11)	
				8:2 diPAP: <0.06–115 ng/g (10/11)	
				6:2 FTUCA: <0.06–0.75 ng/g (6/11)	
				8:2 FTUCA: 0.11–8.29 ng/g (11/11)	
	Indoor dust, residential		Germany 2008–2009	6:2 FTOH: <1.6–246 ng/g (24/31)	[25]
				8:2 FTOH: 2.4–256 ng/g (31/31)	
				10:2 FTOH: 1.0–232 ng/g (31/31)	

Knowledge gaps

- Current global production and use volumes are unknown.

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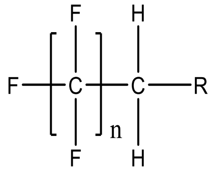
8. n:1 Fluorotelomer-based compounds

Chemical Information & Properties	
Identification and Terminology	
Name	n:1 Fluorotelomers[29]
Acronym	n:1 FT[R], e.g., n:1 FTOH[30]
Chemical Formula	$C_nF_{2n+1}CH_2OH$
General Structure (linear isomers)	 R = e.g. OH, NH_2, I
US EPA CompTox Markush ID	DTXSID901024684
Terminology	n:m FT[R], where n = number of perfluorinated carbons and m = number of non-fluorinated carbons
Degradability, Mobility, Bioconcentration	
Degradation	n:1 FTOHs can react with OH radicals in the environment to form corresponding aldehydes and subsequently carboxylic acids [1].
Reaction with OH radicals	3:1 FTOH: 1.0–1.1 × 10^{-13} $k_{(OH+R)}$/cm^3 $molecule^{-1}$ s^{-1} Note: The reaction rate constant is likely largely independent of the chain length, and therefore, valid also for other n:1 FTOHs [1].
Synthesis	
Main Synthesis Method	n:1 Fluorotelomer compounds are NOT produced via the telomerization process. Instead, they are synthesized through catalytic reduction (hydrogenation) of the corresponding perfluoroalkyl carboxylic acids [1], [2]. For example, $LiAlH_4$ can be used to produce n:1 FTOHs [3]: $$F(CF_2)_nCOOH \xrightarrow{LiAlH_4} F(CF_2)_nCH_2OH$$
Possible Impurities	Unreacted PFCAs may remain as impurities in n:1 fluorotelomer derivative products. Additionally, the PFCAs themselves, which are used as starting material, are likely to contain both branched and linear isomers, due to them being produced via the ECF process. [1]
Industrial Practices & Commercial Uses	
Major Commercial Products	

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[29] As known commercial *n*:1 fluorotelomer-based compounds are not derived from the telomerization process, but rather from the reduction of perfluoroalkyl carboxylic acids, they are not, strictly speaking, fluorotelomers. Despite this, they are termed "*n*:1 FT-based compounds" here for readability, since the pattern of the perfluorocarbon:hydrocarbon chain is the same (*i.e.*, *n*:1 *vs.* *n*:2). Future work may consider to identify more proper terminology for this group of PFASs.

[30] While other n:1 fluorotelomers (such as n:1 fluorotelomer amins or iodides) exist [4], no information on them could be found.

Trade Name	RM 610
Full Name	(Perfluoropropyl)methanol (3:1 FTOH)
Composition	$C_3F_7CH_2OH$
CAS Number	375-01-9
Use	Used as monomers to produce side-chain fluorinated polymers. [1]
Uses	
Major applications	Acrylates or methacrylates of n:1 FTOHs are monomers used to produce side-chain fluorinated polymers, which can be used as levelling agents, dispersants, and oil and water repellents, especially for textiles and electronics [1], [5].
Regulatory Status	
US	Together with the phase-out of other long-chain PFAS and in agreement with the EPA, 3M ceased its production of 7:1 FTOH (used to produce acrylate and methacrylate monomer for side-chain fluorinated polymethacrylate-acrylate copolymers – e.g., CAS Number 53515-73-4) in 2002. [1]
Knowledge gaps	
- Recent production and use volumes of n:1 FTOHs and their derivatives are unknown. - Knowledge about the environmental fate of n:1 FTOHs is very limited, especially regarding their side-chain fluorinated acrylate and methacrylate polymers. - Knowledge about other n:1 fluorotelomers is very sparse.	
References	
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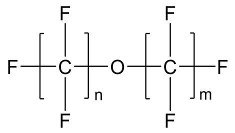
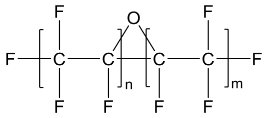
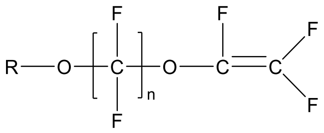
9. Perfluoroalkylethers (a), epoxides (b), and vinyl ethers (c) (non-polymers)

Chemical Information & Properties			
Identification and Terminology			
Name	Perfluoroalkylethers[31] Trade names: Fluorinert liquids; galden fluorinated fluids [1]	Perfluoroalkyl epoxides	Perfluorovinyl ethers
Acronym	PFEs	PFEp	PFVEs
Chemical Formula (linear isomers)	e.g. $C_nF_{2n+1}OC_mF_{2m+1}$	$C_nF_{2n}OC_mF_{2m}$	$RO(C_3F_6O)CF=CF_2$
General Structure			
US EPA CompTox Markush ID	DTXSID90893882	DTXSID501024682	DTXSID301024929
Synthesis			
Main Synthesis Method	Electrochemical fluorination of aliphatic ethers, alcohols, or carboxylic acids, or fluorination of ethers with cobalt fluoride or elemental fluorine under controlled conditions [1]		HFPO (hexafluoropropylene oxide) is reacted with a fluorinated alkoxide or other nucleophiles. This yields acid fluorides, which are then converted to acid salts that are subsequently heated in an aprotic environment to lose carbon dioxide and metal fluoride and yield PFVEs [1]

Major Commercial Products	
Name	FC-75
CAS Number	335-36-4
Composition	Mostly perfluorobutyltetrahydrofurans [1]
Use	Solvent [1]
Name	Hexafluoropropylene oxide (HFPO)
CAS Number	428-59-1
Composition	C_3F_6O
Production/Import volumes	Registered in Europe under REACH with a production/import volume of 100–1000 tonnes per year. [2] 500 - <10,000t in the US in 2015 [4]

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[31] For more examples of compounds in this group and their associated information, one may search for the following IDs at the US EPA CompTox Chemicals Dashboard website: https://comptox.epa.gov/dashboard, namely DTXSID90893882.

Use	Starting material for the synthesis of hexafluoroacetone, perfluoropolyethers, and fluorinated vinyl ethers. [1]
Uses	
Major applications	Perfluoroalkylether chemicals mentioned here and mixtures thereof (perfluorinated fluids) are used in the electronics industry, as immersion coolants for supercomputers and testing applications. [3]
Knowledge gaps	
- Little information is available on perfluoroalkylethers that do not feature acids groups or are considered polymers. - There is limited to no information on their degradation or reported occurrences in the environment.	

References

[1] G. Siegemund *et al.*, "Fluorine Compounds, Organic," *Ullmann's Encycl. Ind. Chem.*, pp. 1–56, 2016.

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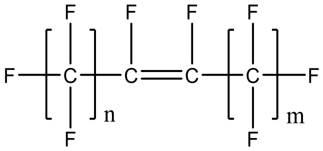
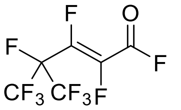
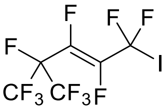
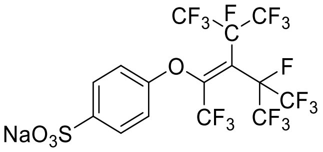
10. Perfluoroalkenes (a) and derivatives (b)

Chemical Information & Properties		
Identification and Terminology		
Name	Perfluoroalkenes	Perfluoroalkene derivatives[32]
Other Names	Fluorinated Olefins; fluoroolefins	
Chemical Formula	C_nF_{2n} (n>2)[33]	
General Structure (linear isomers) *(Examples of derivatives shown on the right taken from [1])*		CAS 88022-48-4 CAS 120695-78-5 CAS 70829-87-7 (OBS, also see below under Major Commercial Products)
US EPA CompTox Markush & Substance IDs	DTXSID201024683	DTXSID40897491, DTXSID20694127, DTXSID601020833
Degradability, Mobility, Bioconcentration		
Degradation in the atmosphere	Atmospheric lifetimes: 6 d for C_3F_6 [1] Reaction rate constants with OH-radicals: 2.6 (C_3F_6) × 10^{-12} cm^3 $molecules^{-1}$ s^{-1}, yielding CF_3CFO and CF_2O, then enter the aqueous phase in 5–10 days, where they are eventually degraded to HF and TFA, and HF and CO_2, respectively. [2]	
Ozonolysis	Reaction with ozone under atmospheric conditions is slow [1], but perfluoroalkenes can be broken down via reductive ozonolysis [3].	
Biodegradation	OBS is non-readily biodegradable [4]	
Other degradation methods	OBS can be decomposed by photolysis combined with hydrogen peroxide [4]	
Synthesis		
Main Synthesis Method	Dehalogenation of halofluoroalkanes with zinc and an alcohol or dehydrohalogenation of haloalkanes with alcoholic alkali or by heating. Alternatively, addition of hydrogen halides to alkynes, decarboxylation of fluorocarboxylic acid salts, or pyrolysis of	

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[32] For more examples of compounds in this group and their associated information, one may search for the following IDs at the US EPA CompTox Chemicals Dashboard website: https://comptox.epa.gov/dashboard, namely DTXSID101010249, DTXSID401010250.

[33] According to the revised PFAS definition in the latest OECD PFAS Terminology report (https://www.oecd.org/chemicalsafety/portal-perfluorinated-chemicals/), tetrafluoroethylene (TFE; CF_2=CF_2) and hexafluorobutadiene (F_2C–CF=CF–CF_2) are not PFASs due to a lack of saturated fluorinated atoms.

	fluorohydrocarbons are also common synthesis methods. [5]
Other sources	Perfluoroalkenes (such as C_3F_6 or C_4F_8) can also be released when fluoropolymers are incinerated and the polymers are degraded to release the monomers. [6]

Industrial Practices & Commercial Uses

Major Commercial Products

Name	Hexafluoropropene (HFP)
CAS Number	116-15-4
Use	Most importantly in the production of copolymers, e.g. with TFE or VDF, also to produce the epoxide hexafluoropropylene oxide. [5]
Production/Import volumes	Registered in Europe under REACH with a production/import volume of 1000–10 000 tonnes per year. [7] 5000 – <25,000t in the US in 2015 [8]

Name	Sodium ρ-perfluorous nonenoxybenzene sulfonate (OBS)
Composition	$C_9F_{17}OC_6H_4SO_3Na$
CAS Number	70829-87-7
Use	Additive for fire-fighting foams; surfactant for oil production, mainly used in China [9], [4]
Production/Import volumes	3500 tonnes/yr in China (reported in 2017) [9], [4]
Degradation	Can be decomposed by UV/H_2O_2 or UV, while in aqueous solution [4]

Examples of reported occurrences

Type of locations/ samples	**(Environ-mental) media**	**Detected in one or multiple regions**	**Examples**		
			Location, year	**Levels [min.–max. (detection frequency)]**	**Ref.**
Non-detects are reported as below the value of the limit of detection (“<LOD”). *pg = picograms, ng = nanograms, ww = wet weight, ND = not detected, NR = not reported*					
Close to point sources	☐ air ☒ surface water ☐ soil ☐ sediment	☐ one ☒ multiple	China 2015 (close to new oilfield)	OBS: 9.9–110 ng/L (9/9)	[10]
			China 2015 (close to old oilfield)	OBS: 10–3200 ng/L (26/26)	
Not close to specific point sources	☐ air ☒ surface water ☐ soil ☐ sediment	☒ one ☐ multiple	China 2015	OBS: <0.96–19 ng/L (NR/8)	

Knowledge gaps

- Little information is available on long-chain perfluoroalkenes and derivatives.
- Environmental monitoring data are missing.

References

[1] OECD, "New Comprehensive Global Database of PFASs," [Online]. Available: https://www.oecd.org/chemicalsafety/portal-perfluorinated-chemicals/ [Accessed: 24-Jul-2020]

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11. Specific hydrofluoro-carbons (a), -ethers (b), and -olefins (c) [34]

Chemical Information & Inherent Properties			
Identification and Terminology[35]			
Name	Hydrofluorocarbons	Hydrofluoroethers	Hydrofluoroolefins
Other Names			Fluorinated olefins [1]
Acronym	HFCs	HFEs	HFOs
Chemical Formula (those with at least one saturated fully fluorinated carbon atom)	$C_nH_xF_y$ with $x + y = 2n + 2$	$C_nH_xF_yOC_mH_pF_q$ with $x + y = 2n + 1$; $p + q = 2m + 1$; $x + y + p + q = 2(n + m + 1)$	$C_nH_xF_y$ with $x + y = 2n$
Degradability, Mobility, Bioconcentration			
Atmospheric lifetime	13.4 years (HFC-134a; CH_2FCF_3) [2]	Between 0.8 (HFE-7200; $C_4F_9OCH_3$) and 165 (HFE-125; CHF_2OCF_3) years [3]	ca.10 d (HFO-1234yf; $CF_3CF{=}CH_2$) [4,5]
	Atmospheric reactions with OH radicals can yield PFCAs. [1], [6] For HFCs and HFOs used as refrigerants and foam blowing agents, some yield TFA (trifluoroacetic acid) and not longer-chain PFCAs. [7] [8] [9]		
Ozone Depletion Potential (ODP)	Between 10^{-5} and 10^{-3} (varying between studies) [10]. Atmospheric changes in temperature and circulation arising from HFC emissions lead to a weak, indirect depletion of stratospheric ozone [11].	Negligible [12]	Negligible [9]
100 Year Global Warming Potential (GWP)	Between 1300 (HFC-134a) and 8060 (HFC-236fa; $CF_3CH_2CF_3$) [2]	Between 60 (HFE-7200) and 14 000 (HFE-125) [3]	<1 (HFO-1234yf) [2] 2 (HFO-1336mzz; $CF_3CH{=}CHCF_3$) [2]
Biodegradation	(The commercially relevant) HFCs, HFEs, and HFOs are gases with low water solubility. They almost entirely partition into the atmosphere, with atmospheric degradation as a major degradation process. For this reason and others, there are limited data on biodegradation or bioconcentration.		
Bioconcentration			
Synthesis			
Main Synthesis	Addition of hydrogen	Synthesized from alkoxides	Dehalogenation of

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[34] Note that not all HFCs, HFEs and HFOs are included here, but only those that contain at least one perfluorinated methyl (–CF_3) or methylene (–CF_2–) group. Many HFCs and HFOs used as refrigerants and foam blowing agents do not fall under PFAS according to the revised PFAS definition in the latest OECD PFAS Terminology report (https://oe.cd/2M9), e.g. those having CF_2XY (where X and Y ≠ F) structures.

[35] Common naming conventions have been established for HFCs, HFEs, HFOs and many other fluorinated gases; for more details, see for example https://www.fluorocarbons.org/wp-content/uploads/2020/06/EFCC-NamingNumbering_A4_V01-23062020.pdf; https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014R0517&from=EN.

Method	fluoride to olefins or alkynes; exchange of chlorine for fluorine, via hydrogen fluoride or metal fluorides; addition of hydrogen to perfluoroalkenes; decarboxylation of perfluorocarboxylates; electrochemical fluorination. [1]	or phenoxides and fluoroolefins. [1]	haloalkanes; dehydrohalogenation of hydrogen-containing haloalkanes; addition of hydrogen halides to alkynes; decarboxylation of fluorocarboxylic acids; pyrolysis of fluorohydrocarbons. [1]
Possible Impurities			$CHCl_2F$ and hexafluoropropene in the production of tetrafluoroethylene. [1]
Industrial Practices & Commercial Uses			
Major Commercial Products			
Name(s)	1,1,1,2-Tetrafluoroethane		
Trade Name(s)	HFC-134a / R-134a / Freon 134a / Forane 134a / Genetron 134a / Florasol 134a / Suva 134a / Norflurane		
Chemical Formula	CH_2FCF_3		
CAS Number	811-97-2		
Use	See *Major applications* below.		
Production/Import volumes	Between 1990 and 1995, 159 500 t have been produced [1]. HFC-134a is registered in the EU under REACH with a production/import volume of 10 000 – 100 000 tonnes per year [13]. 50,000 - <125.000t in the US in 2015 [14]		
Name(s)	2,3,3,3-Tetrafluoropropene		
Trade Name(s)	HFO-1234yf / R-1234yf / Opteon YF / Solstice YF / HFC-1234yf		
Chemical Formula	$CH_2{=}CFCF_3$		
CAS Number	754-12-1		
Use	See *Major applications* below.		
Production/Import volumes	Registered in the EU under REACH with a production/import volume of 1000 – 10 000 tonnes per year. [15] 500 - <10,000t in the US in 2015 [14]		
Uses			
Major applications	HFCs are mostly used as substitutes for CFCs and HCFCs: in refrigeration and air-conditioning, as propellants in aerosols, and as foaming agents in closed cell foams (e.g. for building insulation), as	HFEs replace HFCs in some of the applications mentioned, due to their lower global warming potential [6]. Some HFEs are also used as inhalation anesthetics. [1]	Replacements for HFCs and HFEs [17]. Production of fluorinated polymers and inert fluids [1].

	well as in fire extinguishing systems, and other applications [1], [16], [7]. HFC-134a and HFC-227ea (CF_3CFHCF_3) have been used as propellants for metered dose inhalers. [7]		

Regulatory Status	
US	Under the SNAP (Significant New Alternatives Policy) Program the US EPA identifies and approves climate-friendly alternatives for ozone-depleting substances. Federal Agencies have to report their greenhouse gas emissions, including HFC emissions, and have to procure alternatives to HFCs with high global warming potentials, if possible. [16]. Several US states have implemented stricter regulations to reduce HFC emissions. [18]. In December 2020, the US passed the American Innovation and Manufacturing Act, mandating an 85 % phasedown of HFCs by 2036, consistent with the Kigali Amendment and other emission-reducing measures. [19]
European Union	The F-gas Regulation 517/2014 limits the total amount of fluorinated greenhouse gases (including HFCs, perfluorocarbons, Sulphur hexafluoride and other greenhouse gases that contain fluorine, listed in Annex I; note that HFEs and HFOs are not addressed by this regulation) that can be sold in the EU, with the goal to cut emissions by two-thirds by 2030 compared to 2014. Use of these gases is banned where less harmful alternatives are available, and emissions are to be prevented by proper servicing of equipment and recovery of the gases at the end of the product life cycle. The regulation also sets requirements of reporting on production, import, export, feedstock use and destruction of the substances listed in Annexes I or II (including HFO, HFEs and other perfluorinated compounds). [20] The use of refrigerants in new cars (in heating, ventilation and air conditioning), which have global warming potentials higher than 150 (which includes HFC-134a) is prohibited by the MAC Directive [17], [20].
Canada	HFCs are regulated pursuant to the Ozone-depleting Substances and Halocarbon Alternatives Regulations. The purpose of these Regulations is to implement Canada’s obligations under the Montreal Protocol, including the Kigali amendment, by setting out rules concerning HFCs and certain products containing or designed to contain HFCs [21].

International efforts

The Kigali Amendment to the Montreal Protocol specifically addresses HFCs (not HFEs and HFOs), with the goal to reduce HFC production and consumption by 85 % by 2036 for developed countries, by 80 % by 2045 for most developing countries and by 85 % by 2047 for a small group of developing countries (reduction based on baseline levels). [22] The Amendment came into effect in 2019, with some countries that are parties to the Protocol yet to ratify the amendment. [18]

The Scientific Assessment Panel and the Environmental Effects Assessment Panel to the Montreal Protocol provide regular updates on emissions and environmental fate of HFCs [23, 24].

Examples of reported occurrences

Type of locations/ samples	**(Environmental) media**	**Detected in one or multiple regions**	**Examples**		
			Location, year	**Levels [min. –max. (detection frequency)]**	**Ref.**
Non-detects are reported as below the value of the limit of detection (“<LOD”).					

ppt = parts per trillion, ppt_v = parts per trillion (volume fraction), ND = not detected, NR = not reported					
Not close to specific point sources	☒ air ☐ surface water ☐ soil ☐ sediment	☐ one ☒ multiple	China 2010	HFC-134a: 87 ppt_v *(mean)* (NR/92)	[25]
			US 2010	HFC-134a: 65.4 ppt_v *(mean)* (NR)	
			Global surface mean 2016	HFC-125: 20.1–20.8 ppt (*means derived by different methods)* HFC-134a: 89.3–92.1 ppt (*means derived by different methods)* HFC-143a (CH_3CF_3): 19.0–19.3 ppt (*means derived by different methods)* HFC-245fa ($CHF_2CH_2CF_3$): 2.43 ppt (*mean)* HFC-365mfc ($CF_3CH_2CF_2CH_3$): 0.87–1.0 ppt (*means derived by different methods)* HFC-227ea: 1.17–1.24 ppt (*means derived by different methods)* HFC-43-10mee ($CF_3CHFCHFCF_2CF_3$): 0.27 ppt (*mean)* HFC-236fa: 0.15 ppt (*mean)*	[23]
Urban area	☒ air ☐ surface water ☐ soil ☐ sediment	☒ one ☐ multiple	Switzerland 2016	HFO-1234yf: <0.003–approx. 9.2 ppt (NR) HFO-1234ze (*trans*-CHF=$CHCF_3$): <0.003–approx. 25 ppt (NR)	[23]
Remote regions	☒ air ☐ surface water ☐ soil ☐ sediment	☐ one ☒ multiple	Swiss alps 2004	HFC-134a: approx. 30–approx. 130 ppt (NR)	[26]
			Italian alps 2004	HFC-134a: approx. 30–approx. 140 ppt (NR)	
			Swiss alps 2016	HFO-1234yf: <0.003–approx. 8.2 ppt (NR) HFO-1234ze: <0.003–approx. 10 ppt (NR)	[23]

Knowledge gaps

- Environmental concentrations of less commonly known HFEs and some of the newer HFOs.

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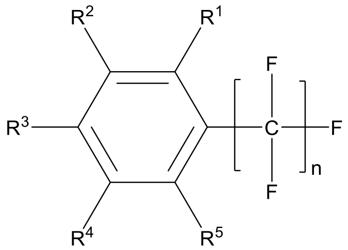
12. Side-chain fluorinated aromatics

Chemical Information & Inherent Properties	
Identification and Terminology	
Name	Side-chain fluorinated aromatics
Other Names	Aromatic compounds with perfluorocarbon moieties on the side chain(s)
Chemical Formula	e.g. $C_6R_5C_nF_{2n+1}$
Exemplary Structure (linear isomers)	 Note that fluorinated side chains may also be attached via other types of bonds, e.g. via an ester bond.
General remarks	Benzotrifluorides (e.g. $C_6R_5CF_3$, n=1) are a group of commercially relevant side-chain fluorinated aromatics [1]. As there is little information on other side-chain fluorinated aromatics, this fact card focuses on benzotrifluorides and their derivatives.
Degradability, Mobility, Bioconcentration	
Biodegradation	No biodegradation of benzotrifluoride (BTF) in activated sludge after 28 days [2]; Complete mineralization of fluorinated drugs is rare. Fluoxetine (see in section on commercial products below) is not eliminated by conventional wastewater treatment, but is removed via ozone or active carbon [3]–[5]. Fluometuron (see in section on commercial products below) is not readily biodegradable [6].
Bioaccumulation	BCF (aquatic species) of BTF = 58 [2] BCF (fish) of fluoxetine = 8.8–260 (estimated) [7] BCF (fish) of norfluoxetine = 80–650 (estimated) [7] BCF (mussels) of fluoxetine = 125–1347 [8]
Synthesis	
Main Synthesis Method	Halogen exchange using hydrogen fluoride [1]: $C_6H_5CCl_3 + 3\,HF \longrightarrow C_6H_5CF_3 + 3\,HCl$
Possible Impurities	Typically, a yield between 70–90% is obtained, depending on the specific process conditions. It remains unclear what side products and possible impurities are generated. [1]
Industrial Practices & Commercial Uses	
Major Commercial Products	
Name	Benzotrifluoride / α,α,α-trifluorotoluene / trifluoromethylbenzene
Acronym	BTF

Chemical Formula	$C_6H_5CF_3$
CAS Number	98-08-8
Use	Intermediate in the synthesis of dyes, pesticides, and pharmaceuticals.
Production/Import volumes	Registered in the EU under REACH with a production/import volume of 0–10 tonnes per year. [2]
Name	4-chlorobenzotrifluoride / Parachlorobenzotrifluoride
Acronym	4CBTF / PCBTF
Trade Name(s)	Oxsol 100 [9]
Chemical Formula	$C_6H_4ClCF_3$
CAS Number	98-56-6
Use	Solvent, especially for paint and ink formulations; cosmetic stain remover; aerosol rust inhibitor [9]
Production/Import volumes	Registered in the EU under REACH with a production/import volume of 100–1000 tonnes per year. [10] 5,000 - <25,000t in the US in 2015 [16]
Name	Fluoxetine
Trade Name(s)	(active ingredient in) Prozac [8]
Chemical Formula	$C_{17}H_{18}F_3NO$
CAS Number	54910-89-3
Use	Antidepressant, specifically selective serotonin reuptake inhibitor (SSRI) [8]
Production/Import volumes	Volumes sold in 2003 and 2004: 3.7 t/yr (France), 4.8 t/yr (UK), 4.2 t/yr (Spain) [4]
Name	*N,N*-dimethyl-*N′*-[3-(trifluoromethyl)-phenyl]-urea
Trade Name(s)	Fluometuron
Chemical Formula	$C_{10}H_{11}F_3N_2O$
CAS Number	2164-17-2
Use	Herbicide, especially used in cotton production [1], [11]
Production/Import volumes	Registered in the EU under REACH with a production/import volume of 10–100 tonnes per year. [6]
Uses	
Major applications	Benzotrifluorides derivatives are used as dyes, where the trifluoromethyl group improves color clarity, as well as pharmaceuticals [12] and pesticides, since the trifluoromethyl group accelerates absorption [1]. BTF and PCBTF are also used as organic solvents [13].

Examples of reported occurrences

Type of locations/ samples	**(Environmental) media**	**Detected in one or multiple regions**	**Examples**		
			Location, year	**Levels [min. –max. (detection frequency)]**	**Ref.**

Non-detects are reported as below the value of the limit of detection ("<LOD"). *ng = nanograms, ww = wet weight, ND = not detected, NR = not reported*					
Close to point sources	☐ air ☐ surface water ☐ soil ☒ sediment	☐ one ☒ multiple	US *(close to WWTP effluent)* 2010 *(year of publication)*	Fluoxetine: 17.4 ng/g ww *(mean)* (NR/12)	[8]
	Groundwater		Italy 2008 *(Valleagno area, site of chemical spill in 1977)*	BTF: 98 ng/L *(mean)* (3/3)	[15]
				4-Chloro-BTF: 11900 ng/L *(mean)* (3/3)	
				3,4-dicholoro-BTF: 6400 ng/L *(mean)* (3/3)	
				2,4-dicholoro-BTF: 220 ng/L *(mean)* (3/3)	
				3-nitro-BTF: 430 ng/L *(mean)* (3/3)	
				3-amino-BTF: 580 ng/L *(mean)* (3/3)	
				3-amino-4-chloro-BTF: 2600 ng/L *(mean)* (3/3)	
				3-nitro-4-chloro-BTF: 5900 ng/L *(mean)* (3/3)	
Not close to specific point sources	☐ air ☒ surface water ☐ soil ☐ sediment	☐ one ☒ multiple	Portugal 2013–2014	Fluoxetine: 2.01–19.5 ng/L (55/55)	[14]
WWTP	☐ effluent ☒ influent ☐ sludge	☐ one ☒ multiple	Portugal 2013–2014	Fluoxetine: 5.21–17.8 ng/L (55/55)	[14]
	☒ effluent ☐ influent ☐ sludge		Portugal 2013–2014	Fluoxetine: 10.5–34.0 ng/L (55/55)	[14]
			US 2010 *(year of publication)*	Fluoxetine: 118.8 ng/L *(mean)* (NR/6)	[8]
Wildlife	Freshwater mussels *(Elliptio complanata)* at WWTP effluent	☐ one ☒ multiple	US 2010 *(year of publication)*	Fluoxetine: 79.1 ng/g ww *(mean)* (NR)	[8]

Knowledge gaps

- Biodegradation properties of many side-chain fluorinated aromatics are still not thoroughly investigated. [3]

- Current production volumes are unknown, especially outside the EU.

- Environmental monitoring data are sparse.

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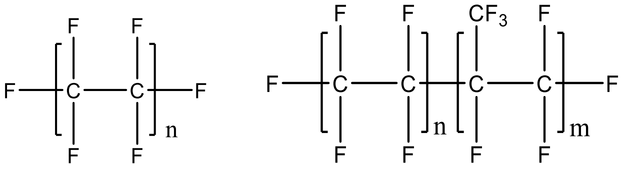
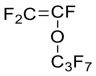
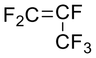
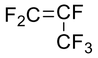
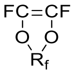
13. Fluoropolymers

Key publications: Dams, Rudy, and Klaus Hintzer. 2017. “Chapter 1. Industrial Aspects of Fluorinated Oligomers and Polymers.” In *Fluorinated Polymers: Volume 2: Applications*, edited by Bruno Ameduri and Hideo Sawada, 1–31. Royal Society of Chemistry. https://doi.org/10.1039/9781782629368-00001.

Ebnesajjad, S., Introduction to Fluoropolymers – Materials, Technology and Applications. Plastics Design Library (PDL) Handbook Series. Elsevier. 2011

<table>
<tr><th colspan="9">Chemical Information & Inherent Properties</th></tr>
<tr><td colspan="9">Identification and Terminology</td></tr>
<tr><td colspan="2"><i>Name</i></td><td colspan="7">Fluoropolymers</td></tr>
<tr><td colspan="2"><i>Other Names</i></td><td colspan="7">Fluoroplastics</td></tr>
<tr><td colspan="2"><i>Chemical Formula (Examples)</i></td><td colspan="7">$(C_2F_2)_n$ (PTFE) / $(C_2H_2F_2)_n$ (PVDF, ETFE)</td></tr>
<tr><td colspan="2"><i>General Structure (Examples, left: PTFE, right: FEP)</i></td><td colspan="7">
Note: End-groups of these polymers can differ. Beside non-functionalized ones (as shown above), functional end-groups (e.g. carboxyl end-groups) are also possible.</td></tr>
<tr><td colspan="9"><i>Examples of major fluoropolymers (adapted from [1])</i></td></tr>
<tr><td colspan="6">TFE Co-polymers
$F_2C=CF_2$</td><td colspan="3">Homopolymers</td></tr>
<tr>
<td>+
PPVE

$F_2C=CF-O-C_3F_7$
↓
PFA</td>
<td>+
HFP

$F_2C=CF-CF_3$
↓
FEP</td>
<td>+
Ethene
$H_2C=CH_2$
↓
ETFE</td>
<td>+
HFP

$F_2C=CF-CF_3$
+
VDF
$F_2C=CH_2$
↓
THVs</td>
<td>+
CTFE
$F_2C=CFCl$
+
Ethene
$H_2C=CH_2$
↓
ECTFE</td>
<td>+

↓
Teflon AF</td>
<td>TFE
$F_2C=CF_2$
↓
PTFE</td>
<td>CTFE
$F_2C=CFCl$
↓
PCTFE</td>
<td>VDF
$F_2C=CH_2$
↓
PVDF</td>
</tr>
<tr><td colspan="9">Acronyms: TFE = tetrafluoroethylene; PPVE = perfluoropropylvinylether; HFP = xexafluoropropylene; VDF = vinylidene fluoride; CTFE = chlorotrifluoroethyle; VF = vinyl fluoride</td></tr>
<tr><td colspan="9">Degradability, Mobility, Bioconcentration</td></tr>
<tr><td colspan="2"><i>Abiotic degradation</i></td><td colspan="7">Fluoropolymers exhibit high chemical resistance and weather resistance. [2]</td></tr>
<tr><td colspan="2"><i>Thermal degradation</i></td><td colspan="7">Fluoropolymers are stable up to high temperatures, e.g., PTFE is stable up to 250 °C. Thermal degradation begins slowly at higher temperatures and results mainly in monomer formation (e.g. tetrafluoroethylene), although the formation of hydrogen fluoride is also possible at higher temperatures [2]–[4]. Also, the formation of C_2–C_{14} per- and polyfluoroalkyl carboxylic acids have been reported. [5], [6]</td></tr>
<tr><td colspan="9">Synthesis</td></tr>
</table>

Main Synthesis Method	Free-radical polymerization, either in aqueous suspension or aqueous emulsion. The latter often requires fluorinated emulsifiers (fluorosurfactants) as polymerization aids. Water soluble peroxides or trialylboron catalysts are used to initiate the polymerization process. [7], [8] In some cases, free-radical solvent polymerization can also be utilized.[36]
Possible Impurities	Residues of fluorosurfactants, used as processing aids in the emulsion polymerization process, can potentially remain in the final products and can be released during later life-cycle stages [8]. Low molecular weight oligomers are also produced and can be released to the environment [9].
Industrial Practices & Commercial Uses	
Major Commercial Products	
Name(s)	Polytetrafluoroethylene (PTFE)
Trade Name(s)	Teflon
Chemical Formula	$–[CF_2–CF_2]_n–$
CAS Number	9002-84-0
Use	Chemical processing, resistant components & coatings, pipes, fittings, linings, tapes, seals, filters, wire & cable insulation, laminates, waterproof & stain repellent clothing, architectural coatings, printing, cookware, fabrics, biomedical devices [8]
Production/Import volumes	Global production in 2013: 200 000 tonnes; 15 000 tonnes produced in Europe [10] Global demand in 2016: 160 000 tonnes [3]
Name(s)	Polyvinylidene fluoride (PVDF)
Chemical Formula	$–[CH_2–CF_2]_n–$
CAS Number	24937-79-9
Use	Fluid handling systems, valves, pumps, water piping, resistant paints, architectural coatings, wire & cable insulation, electronic components, solar panels, printing [7]
Production/Import volumes	Global consumption in 2012: 35 500 tonnes [11] Global demand in 2016: 33 000 tonnes [3]
Name(s)	Fluorinated ethylene propylene (FEP)
Chemical Formula	$–[CF_2–CF_2]_n–[CF_2–CF(CF_3)]_m–$
CAS Number	25067-11-2
Use	Chemically resistant components & coatings, plenum cable insulation [7]
Production/Import volumes	Global demand in 2016: 40 000 tonnes [3]
Name(s)	Perfluoroalkoxy alkane (PFA) / Perfluoroalkoxy polymer
Chemical Formula	$–[CF_2–CF_2]_n–[CF_2–CF(OR_F)]_m–$ (R_F = fluorinated group)
CAS Number	26655-00-5 / 31784-04-0
Use	Chemical processing, resistant components and fittings, electrical insulation, industrial & architectural coatings, semiconductor manufacturing [4], [7]

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[36] According to information provided by representatives of the manufacturing industry.

Uses	
Major applications	Chemically resistant coatings and linings in chemical processing (e.g. pipe linings, tanks, reaction vessels, valves, membranes), electrical insulation, nonstick coatings (e.g. for cookware), high-performance textiles, medical devices (such as catheters, heart patches, sutures, and others) [3]

Regulatory Status	
General remarks	In the US, fluoropolymers and their safety are reviewed in the context of specific applications (e.g. as food contact materials or for use in a medical context) by the US EPA, the US FDA, and the US Consumer Product Safety Commission, and similarly in the EU [2], [3].

Examples of reported occurrences					
Type of locations/ samples	**(Environmental) media**	**Detected in one or multiple regions**	**Examples**		
			Location, year	**Levels [min. –max. (detection frequency)]**	**Ref.**
Non-detects are reported as below the value of the limit of detection (“<LOD”). *pg = picograms, ng = nanograms, ww = wet weight, ND = not detected, NR = not reported*					
Remote regions	☐ air ☐ surface water ☐ soil ☒ sediment	☒ one ☐ multiple	Arctic ocean 2015	0.89–9.43 particles/kg sediment (9/9; PTFE)	[12]

Knowledge gaps

- Quantified environmental occurrences of fluoropolymers, especially others than PTFE, are largely unknown.

- Production volumes are not publicly available.

- Limited information is available regarding chemical identities of commercial PFPE products (including molecular weight range, molar ratio and composition of monomer units, impurity content, functional groups).

- More information is needed on how much PFCAs and other organofluorine compounds are currently emitted from fluoropolymers throughout their life cycle, although fluoropolymer manufacturing was shown to be a major historical source of PFOA in the environment.

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fluoropolymers," *The Analyst*, vol. 128, no. 6, pp. 756-764, 2003.

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Gangal, S. V.; Brothers, P. D., Perfluorinated Polymers, Perfluorinated Ethylene–Propylene Copolymers. In Encyclopedia of Polymer Science and Technology, John Wiley & Sons, Inc.: 2002; http://doi.org/10.1002/0471440264.pst417.pub2

Gangal, S. V.; Brothers, P. D., Perfluorinated Polymers, Tetrafluoroethylene–Ethylene Copolymers. In Encyclopedia of Polymer Science and Technology, John Wiley & Sons, Inc.: 2002; http://doi.org/10.1002/0471440264.pst419.pub2

Gangal, S. V.; Brothers, P. D., Perfluorinated Polymers, Tetrafluoroethylene–Perfluorovinyl Ether Copolymers. In Encyclopedia of Polymer Science and Technology, John Wiley & Sons, Inc.: 2002; http://doi.org/10.1002/0471440264.pst418.pub2

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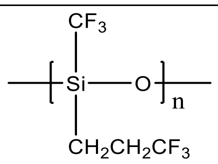
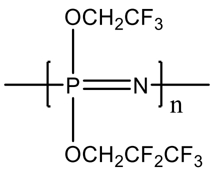
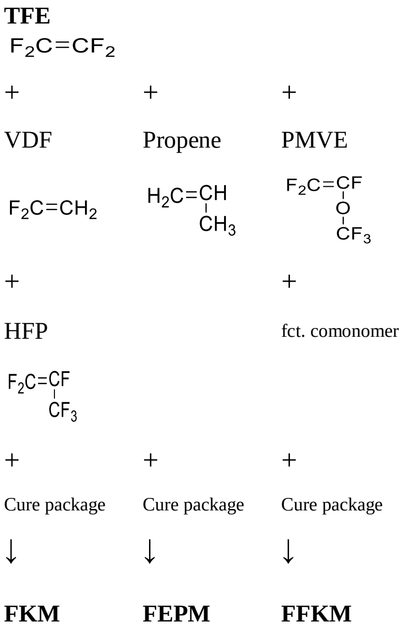
Scheirs, J. e., Modern Fluoropolymers - High Performance Polymers for Diverse Applications. Wiley. ISBN 0-471-97055-7: 1997.

Ameduri and Sawada, 2017. Fluorinated Polymers. Volume 2: Applications. Royal Society of Chemistry.

14. Fluoroelastomers[37]

Key publications: Worm, A. T.; Gorrtaert, W., Fluorocarbon Elastomers. *Encyclopedia of Polymer Science & Engineering* 2015. https://doi.org/10.1002/0471440264.pst137

Améduri, B.; Boutevin, B.; Kostov, G., Fluoroelastomers: Synthesis, properties and applications. Progress in Polymer Science (Oxford) 2001, 26, (1), 105-187. https://www.sciencedirect.com/science/article/pii/S0079670000000447?via%3Dihub.

Chemical Information & Inherent Properties			
Identification and Terminology			
Name	Fluorocarbon elastomers	Fluorosilicones	Fluorinated polyphosphazenes
Other Names		Fluorocarbon-modified silicones	
Acronym	FKM	FLS	PNF elastomers
General structures (exemplary)	Copolymers of VDF ($C_2H_2F_2$) & HFP (C_3F_6) Terpolymers of VDF, HFP & TFE (C_2F_4) Terpolymers of VDF, TFE & PMVE (C3F6O) [19]		
Schematic overview (adapted from [2])			
Acronyms: TFE = Tetrafluoroethylene; VDF = Vinylidene fluoride; HFP = Hexafluoropropylene; FKM = fluorocarbon elastomers; FEPM = Tetrafluoroethylene propylene; PMVE = Perfluoromethylvinylether; FFKM = perfluoro-elastomers			

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[37] Fluoroelastomers are also fluoropolymers, but have rather different physical and chemical properties from those presented in the previous fact card on fluoropolymers. Therefore, they are made into a separate fact card here.

Degradability, Mobility, Bioconcentration			
Stability	Mostly resistant towards light, ozone, heat, solvents, aggressive chemicals, and combinations thereof. Heat resistant until 250 °C. In general, stability increases with fluorine content. [3] FKM is more susceptible to alkaline degradation, e.g. FKM was found to degrade slowly (>12 weeks) in a warm alkaline environment (10% NaOH, 80 °C). [4], [5] Some "base-resistant" FKMs and FEPM resist degradation in high pH environments.[38]	Inert under normal conditions, but decompose at extreme pH-values or at high temperatures, in which case toxic fluorinated compounds such as 3,3,3-trifluoropropion-aldehyde are produced. [6]	Depolymerization occurs at temperatures above 300 °C. Fluorinated polyphosphazenes are very resistant to combustion. [7]
Synthesis			
Main Synthesis Method	High-pressure, free-radical aqueous emulsion polymerization, with organic or inorganic peroxy-compounds as initiators. Fluorosurfactants (or non-fluorinated surfactants) can be added as emulsifiers, and ethyl acetate, methanol, acetone, or others can be used as chain-transfer agents. For curing, bisphenol cross-linking agents are added as well as a cure accelerator, such as triphenylbenzylphosphonium chloride. [1], [8]	Base-catalyzed ring-opening polymerization of cyclic trimers, obtained through hydrolysis of the corresponding dichlorosilane. [1]	First, ring-opening polymerization of the cyclic trimer $(NPCl_2)_3$ or living cationic condensation polymerization of a phosphoranimine yields poly(dichloro-phosphazene). In a second step, chlorine is replaced with fluoro-organic side groups. [7]
Possible Impurities	Residues of processing aids can potentially remain in the final product.		
Industrial Practices & Commercial Uses			
Major Commercial Products			
Production/Import volumes	Total fluoroelastomers consumption globally: approximately 10 000 t/yr as of 2001, 40% of which in the US, 30% in Europe, 20% in Japan, and 10% in Asia-Pacific (excl. Japan). [8]		
Name(s)	1,1-difluoroethylen-hexafluoropropene polymer / polyvinylidenefluoride/hexafluoropropene [9], [10] Vinylidene fluoride-hexafluoropropylene copolymer [16]		
CAS Number	9011-17-0		
Trade Name(s)	DAI-EL; Dyneon; Tecnoflon, Viton		
Use	O-ring and oil seal applications in high-heat environments [17]		

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[38] According to information provided by representatives of the manufacturing industry.

<table>
<tr><td><i>Name(s)</i></td><td colspan="3">Vinylidene fluoride-hexafluoropropylene-tetrafluoroethylene terpolymer
Poly(TFE-ter-VDF-ter-PMVE)</td></tr>
<tr><td><i>CAS Number</i></td><td colspan="3">25190-89-0</td></tr>
<tr><td><i>Trade Name(s)</i></td><td colspan="3">Viton GLT [12] DAI-EL; Dyneon; Tecnoflon; Viton</td></tr>
<tr><td><i>Use</i></td><td colspan="3">Transfer or compression molded automotive fuel, chemical, and petroleum industry seals [13]. Extruding fuel tubing and hose [20].</td></tr>
<tr><td><i>Name(s)</i></td><td colspan="3">Vinylidene fluoride-tetrafluoroethylene-perfluorovinyl methyl ether terpolymer
Poly(TFE-ter-PMVE-ter-VDF)</td></tr>
<tr><td><i>CAS Number</i></td><td colspan="3">56357-87-0</td></tr>
<tr><td><i>Trade Name(s)</i></td><td colspan="3">DAI-EL LT [17], Tecnoflon-PL [12]; Viton GLT [12]</td></tr>
<tr><td><i>Use</i></td><td colspan="3">O-rings, seals, gaskets used in the automotive, aerospace, and energy industries. [14]</td></tr>
<tr><td><i>Name(s)</i></td><td colspan="3">Fully fluorinated copolymers of tetrafluoroethylene and a perfluoroalkyl vinyl ether
Poly(TFE-ter-PMVE-ter-8CNVE)</td></tr>
<tr><td><i>Trade Name(s)</i></td><td colspan="3">DAI-EL Perfluor [17]; Kalrez [12]; Tecnoflon PFR, PFR-HT, PFR-LT</td></tr>
<tr><td><i>Composition</i></td><td colspan="3">Perfluorinated rubbers of polymethylene type having all fluoro, perfluoroalkyl or perfluoroalkoxy substituent groups on the polymer chain (e.g. TFE and PMVE).</td></tr>
<tr><td><i>Use</i></td><td colspan="3">O-rings, seals, gaskets used in the automotive, aerospace, and energy industries. [14]
O-rings, seals, gaskets and tubing used in the semiconductor processing industry [17]</td></tr>
<tr><td><i>Names(s)</i></td><td colspan="3">Copolymers of tetrafluroethylene and propylene [18]</td></tr>
<tr><td><i>Trade names(s)</i></td><td colspan="3">Aflas</td></tr>
<tr><td><i>Use</i></td><td colspan="3">O-rings, seals, gaskets and wire covering for the oil and gas, chemical process, industrial equipment, food handling, pharmaceutical, heavy duty diesel and automotive industries. [18]</td></tr>
<tr><td><i>Name(s)</i></td><td colspan="3">1-Propene, 1,1,2,3,3,3-hexafluoro-, polymer with 1,1,1,2,2,3,3-heptafluoro-3-((1,2,2-trifluoroethenyl)oxy)propane and 1,1,2,2-tetrafluoroethene</td></tr>
<tr><td><i>CAS Number</i></td><td colspan="3">63654-41-1</td></tr>
<tr><td><i>Use</i></td><td colspan="3">Wire coating and small diameter transparent tubing. [12]</td></tr>
<tr><td colspan="4">Uses</td></tr>
<tr><td><i>Major applications</i></td><td>Mainly in ground transportation, i.e. engine oil seals, fuel system components, and drive-train seals. Also in the aerospace industry, in industrial hydraulic and pneumatic applications as well as the chemical processing industry and semiconductor manufacturing. [8], [15]</td><td>Fuel-resistant elastomers, anti-graffiti and antifouling coatings, silicone pressure-sensitive adhesive release liners. [6]</td><td>Fibers and nanofibers, impact-absorbing elastomers, surface coatings (e.g. ice-phobic coatings on helicopter rotor blades, coatings for biomedical devices), as radiation resistant polymers. [7]</td></tr>
<tr><td colspan="4">Knowledge gaps</td></tr>
<tr><td colspan="4">- Specific production volumes are not publicly available.</td></tr>
</table>

- Environmental monitoring data are not available for these compounds.

- Limited information is available regarding chemical identities of commercial products (including molecular weight range, molar ratio and composition of monomer units, impurity content, functional groups) and their life cycle, including possible releases of low molecular weight compounds.

References

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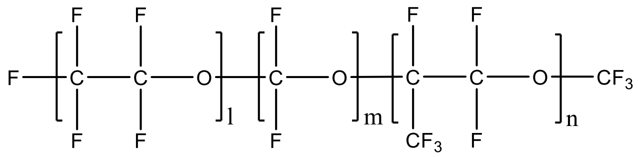
Améduri, B.; Boutevin, B.; Kostov, G., Fluoroelastomers: Synthesis, properties and applications. Progress in Polymer Science (Oxford) 2001, 26, (1), 105-187. Fluoroelastomers: synthesis, properties and applications - ScienceDirect.

15. Perfluoropolyethers

Key publications: Moffett, et al., Perfluoroalkylpolyethers. In *Synthetics, Mineral Oils, and Bio-Based Lubricants. Chemistry and Technology*, Rudnick, L. R., Ed. Taylor & Francis, 2020. https://doi.org/10.1201/9781315158150.

Chemical Information & Inherent Properties	
Identification and Terminology	
Name	Perfluoropolyethers
Acronym	PFPEs
An example of general structure (linear isomer examples) [1]	 *Note: monomer units distributed randomly along the polymer backbone. In different PFPEs, different monomer units may present.*
Degradability, Mobility, Bioconcentration	
Stability	Thermally stable, non-flammable, chemically resistant, resistant to ionizing radiation, non-volatile (up to 350 °C) [2]
Synthesis	
Main Synthesis Method	Anionic ring opening polymerization or UV-catalysed radical oxopolymerization (e.g. copolymerization of tetrafluoroethylene with O_2) [1], [2]
Industrial Practices & Commercial Uses	
Major Commercial Products	
Name(s)	Poly[oxy[trifluoro(trifluoromethyl)-1,2-ethanediyl]], α-(1,1,2,2,2-pentafluoroethyl)-ω-[tetrafluoro(trifluoromethyl)ethoxy]-
Trade Name(s)	Krytox PFPE High Performance Lubricant (60–100% of total product), Krytox Sodium Nitrite Inhibited PFPE/PTFE Greases (71–80% of total product) [3]
Chemical Formula	$-[OCF(CF_3)CF_2OCF(CF_3)CF_2OCF(CF_3)CF_2]-$
CAS Number	60164-51-4
Use	Nonflammable, stable and inert lubricant for applications in the aerospace and nuclear industries. [4]
Name(s)	Diphosphoric acid, polymers with ethoxylated reduced methyl esters of reduced polymerized oxidized tetrafluoroethylene
Trade Name(s)	Possibly Fomblin HC/P2-1000 [3]
CAS Number	200013-65-6
Use	Lubricant, and water and oil repellent in paper products and food packaging. [3]
Production/Import volumes	Produced or imported in volumes of over 11 340 kg in the US. Estimated value of dutiable imports to the US by 2017: 13 000 000 $ [3]

Name(s)	1-Propene, 1,1,2,3,3,3-hexafluoro-, oxidized, polymd.
Trade Name(s)	Fomblin Y (also in Fomblin HC, Fomblin Y LVAC, Galden HT-90 Assay, Solkatherm SES 36) [3]
Chemical Formula	$–[CF(CF_3)CF_2OCF_2CF(CF_3)CF_2OCF_2CF(CF_3)CF_2OCF_2]–$
CAS Number	69991-67-9
Use	As a lubricant, welding and soldering agent, and in personal care products (cosmetics) [3]
Production/Import volumes	0.5 tonnes used in Sweden in 2017 0.3 tonnes used in Denmark in 2016 [3]
Name(s)	Ethene, 1,1,2,2-tetrafluoro-, oxidized, polymd.
Trade Name(s)	Fomblin Z60, Fomblin Z-15, FOMBLINCR 862 (50 - 55% of total product) [3]
CAS Number	69991-61-3
Name(s)	Tetrafluoroethylene, oxidized, oligomers, reduced, methyl esters, reduced, reaction products with ethylene oxide
Trade Name(s)	Fluorolink E10-H
CAS Number	162492-15-1
Use	Non-stick coating [3]
Name(s)	Hexafluoropropene, oxidized, oligomers, reduced and hydrolyzed
Trade Name(s)	Carbaflo XTR S5 F80 (1–2,4% of total weight) [3]
CAS Number	161075-14-5
Use	Lubricant used in automotive industry, also corrosion inhibitor and used in surface treatment applications effective in sub-zero temperatures. [3]
Production/Import volumes	Estimated value of dutiable imports to the US by 2017: 2 000 000 $ [3]
Trade Name(s)	Fluorolink AD1700
Chemical Formula	$XCF_2O\text{-}(CF_2CF_2O)_m(CF_2O)_n\text{-}CF_2X$ where $X = CH_2OCOCH{=}CH_2$
Use	Used as additive for coatings, in battery systems and smart devices [3]
Trade Name(s)	Optool DSX
Chemical Formula	$CF_3CF_2CF_2O\text{-}(CF_2CF_2CF_2O)_n\text{-}CF_2CF_2X$ where $X = CH_2CH_2Si(OR)_3$
Use	Used in anti-smudge coatings [3]
Uses	
Major applications	Mainly high performance lubricants for engines and machinery [2], but also as surface treatments for natural stone, metal, glass, plastic, textiles, leather, and paper, as well as paperboard treatment for food-contact applications [1].
Knowledge gaps	
- Production and use volumes are not publicly available. - Environmental fate and monitoring data are not available for these compounds.	

- Limited information is available regarding chemical identities of commercial PFPE products (including molecular weight range, molar ratio and composition of monomer units, impurity content, functional groups) and their life cycle (including releases and degradation).

References

[1] R. C. Buck *et al.*, “Perfluoroalkyl and polyfluoroalkyl substances in the environment: Terminology, classification, and origins,” *Integr. Environ. Assess. Manag.*, vol. 7, no. 4, pp. 513–541, Oct. 2011.

[2] J. Gardiner, “Fluoropolymers: Origin, Production, and Industrial and Commercial Applications,” *Aust. J. Chem.*, vol. 68, no. 1, p. 13, 2015.

[3] Z. Wang, G. Goldenman, T. Tugran, A. McNeil, and M. Jones, “Per- and polyfluoroalkylether substances: identity, production and use,” 2019.

[4] “Krytox Lubricants | High Performance Greases & Oils | PFPE,” *Miller-Stephenson*. [Online]. Available: https://miller-stephenson.com/krytox/. [Accessed: 31-Jan-2020].

Annex A. List of PFASs Included in the Fact Cards, Their Acronyms, CAS Registry Numbers (CASRNs), DTXSIDs and Fact Card Location

Full name	**Acronym/ Trade name**	**CASRN**	**DTXSIDs[39]**	**Fact card**
Phosphinic acid, *P*,*P*-bis(1,1,2,2,3,3,4,4,4-nonafluorobutyl)-; Bis(nonafluorobutyl)phosphinic acid	C_4/C_4-PFPIA / Tivida FL 2100	52299-25-9	DTXSID60556851	#1
A mixture of perfluoroalkyl phosphonic and phosphinic acids	Masurf-780		DTXSID801027192	#1
Phosphonic acid, perfluoro-$C_{6–12}$-alkyl derivs.		68412-68-0	DTXSID80882003	#1
Phosphinic acid, bis(perfluoro- $C_{6–12}$-alkyl) derivs.; Phosphinic acid, bis(perfluoro- $C_{6–12}$-alkyl) derivatives ($C_{6–12}$ PFPIAs)	(C_6–C_{12} PFPIAs)	68412-69-1		#1
Phosphonic acid, *P*-(1,1,2,2,3,3,4,4,5,5,6,6,6-tridecafluorohexyl)-; Perfluorohexyl phosphonic acid	C_6-PFPA	40143-76-8	DTXSID90880439	#1
Phosphonic acid, *P*-(1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,8-heptadecafluorooctyl)-; Perfluorooctyl phosphonic acid	C_8-PFPA	40143-78-0	DTXSID80879832	#1
Phosphonic acid, *P*-(1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-heneicosafluorodecyl)-; Perfluorodecyl phosphonic acid	C_{10}-PFPA	52299-26-0		#1
Phosphinic acid, *P*-(1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,8-heptadecafluorooctyl)-*P*-(1,1,2,2,3,3,4,4,5,5,6,6,6-tridecafluorohexyl)-; (Perfluorohexyl) (perfluorooctyl) phosphinic acid	C_6/C_8-PFPIA	610800-34-5		#1
Phosphinic acid, *P*,*P*-bis(1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,8-heptadecafluorooctyl)-; Bis(perfluorooctyl) phosphinic acid	C_8/C_8-PFPIA	40143-79-1		#1
Phosphinic acid, *P*,*P*-bis(1,1,2,2,3,3,4,4,5,5,6,6,6-tridecafluorohexyl)-; Bis(perfluorohexyl) phosphinic acid	C_6/C_6-PFPIA	40143-77-9		#1

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[39] DTXSID = Distributed Structure-Searchable Toxicity Database (DSSTox) substance ID

Phosphinic acid, *P*-(1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-heneicosafluorodecyl)-*P*-(1,1,2,2,3,3,4,4,5,5,6,6,6-tridecafluorohexyl)-; (Perfluorohexyl) (perfluorodecyl) phosphinic acid	C_6/C_{10}-PFPIA	1240600-40-1		#1
Phosphinic acid, *P*-(1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-heneicosafluorodecyl)-*P*-(1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,8-heptadecafluorooctyl)- ; (Perfluorooctyl) (perfluorodecyl) phosphinic acid	C_8/C_{10}-PFPIA	500776-81-8		#1
(Perfluorohexyl) (perfluorododecyl) phosphinic acid	C_6/C_{12}-PFPIA			#1
Octanoic acid, 2,2,3,3,4,4,5,5,6,6,7,7,8,8,8-pentadecafluoro-, ammonium salt (1:1); Ammonium perfluorooctanoate	APFO	3825-26-1	DTXSID8037708	#2
Nonanoic acid, 2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,9-heptadecafluoro-, ammonium salt (1:1); Ammonium perfluorononanoate	APFN	4149-60-4	DTXSID20880205	#2
Ammonium henicosafluoroundecanoate; Ammonium perfluoroundecanoate	APFUnD	4234-23-5	DTXSID20897176	#2
Ammonium pentacosafluorotridecanoate; Ammonium perfluorotridecanoate	APFTrD			#2
Fatty acids, $C_{7–13}$, perfluoro, ammonium salts	Surflon® S-111	72968-38-8	DTXSID80104590	#2
Acetic acid, 2,2,2-trifluoro-; Trifluoro acetic acid	TFA	76-05-1	DTXSID9041578	#2
Propanoic acid, 2,2,3,3,3-pentafluoro-; Perfluoropropionic acid	PFPrA	422-64-0	DTXSID8059970	#2
Butanoic acid, 2,2,3,3,4,4,4-heptafluoro-; Perfluorobutanoic acid; Heptafluorobutyric acid	PFBA	375-22-4	DTXSID4059916	#2
Pentanoic acid, 2,2,3,3,4,4,5,5,5-nonafluoro-; Perfluoropentanoic acid; Perfluorovaleric acid	PFPeA	2706-90-3	DTXSID6062599	#2
Hexanoic acid, 2,2,3,3,4,4,5,5,6,6,6-undecafluoro-; Perfluorohexanoic acid	PFHxA	307-24-4	DTXSID3031862	#2
Heptanoic acid, 2,2,3,3,4,4,5,5,6,6,7,7,7-tridecafluoro-; Perfluoroheptanoic acid	PFHpA	375-85-9	DTXSID1037303	#2
Octanoic acid, 2,2,3,3,4,4,5,5,6,6,7,7,8,8,8-pentadecafluoro-; Perfluorooctanoic acid	PFOA	335-67-1	DTXSID8031865	#2

Nonanoic acid, 2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,9-heptadecafluoro-; Perfluorononanoic acid	PFNA	375-95-1	DTXSID8031863	#2
Decanoic acid, 2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-nonadecafluoro-; Perfluorodecanoic acid	PFDA	335-76-2	DTXSID3031860	#2
Undecanoic acid, 2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,11-heneicosafluoro-; Perfluoroundecanoic acid	PFUnDA	2058-94-8	DTXSID8047553	#2
Dodecanoic acid, 2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,12,12,12-tricosafluoro-; Perfluorododecanoic acid	PFDoDA	307-55-1	DTXSID8031861	#2
Tridecanoic acid, 2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,12,12,13,13,13-pentacosafluoro-; Perfluorotridecanoic acid	PFTrDA	72629-94-8	DTXSID90868151	#2
Tetradecanoic acid, 2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,12,12,13,13,14,14,14-heptacosafluoro-; Perfluorotetradecanoic acid	PFTeDA	376-06-7	DTXSID3059921	#2
Pentadecanoic acid, 2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,12,12,13,13,14,14,15,15,15-nonacosafluoro-; Perfluoropentadecanoic acid	PFPeDA	141074-63-7	DTXSID30893341	#2
Hexadecanoic acid, 2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,12,12,13,13,14,14,15,15,16,16,16-hentriacontafluoro-; Perfluorohexadecanoic acid	PFHxDA	67905-19-5	DTXSID1070800	#2
Heptadecanoic acid, 2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,12,12,13,13,14,14,15,15,16,16,17,17,17-tritriacontafluoro-; Perfluoroheptadecanoic acid	PFHpDA	57475-95-3	DTXSID60896623	#2
Octadecanoic acid, 2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,12,12,13,13,14,14,15,15,16,16,17,17,18,18,18-pentatriacontafluoro-; Perfluorooctadecanoic acid	PFOcDA	16517-11-6	DTXSID1066071	#2
Eicosanoic acid, 2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,12,12,13,13,14,14,15,15,16,16,17,17,18,18,19,19,20,20,20-nonatriacontafluoro-; Perfluoroeicosanoic acid	PFEiDA	68310-12-3	DTXSID90887327	#2

1-Butanesulfonic acid, 1,1,2,2,3,3,4,4,4-nonafluoro-, potassium salt (1:1); Potassium perfluorobutanesulfonate	K-PFBS	29420-49-3	DTXSID3037707	#3
1-Butanesulfonic acid, 1,1,2,2,3,3,4,4,4-nonafluoro-; Perfluorobutanesulfonic acid	PFBS	375-73-5	DTXSID5030030	#3
1-Pentanesulfonic acid, 1,1,2,2,3,3,4,4,5,5,5-undecafluoro-; Perfluoropentanesulfonic acid	PFPeS	2706-91-4	DTXSID8062600	#3
1-Hexanesulfonic acid, 1,1,2,2,3,3,4,4,5,5,6,6,6-tridecafluoro-; Perfluorohexanesulfonic acid	PFHxS	355-46-4	DTXSID7040150	#3
1-Heptanesulfonic acid, 1,1,2,2,3,3,4,4,5,5,6,6,7,7,7-pentadecafluoro-; Perfluoroheptanesulfonic acid	PFHpS	375-92-8	DTXSID8059920	#3
1-Octanesulfonic acid, 1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,8-heptadecafluoro-; Perfluorooctanesulfonic acid	PFOS	1763-23-1	DTXSID3031864	#3
1-Nonanesulfonic acid, 1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,9-nonadecafluoro-; Perfluorononanesulfonic acid	PFNS	68259-12-1	DTXSID8071356	#3
1-Decanesulfonic acid, 1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-heneicosafluoro-; Perfluorodecanesulfonic acid	PFDS	335-77-3	DTXSID3040148	#3
1-Octanesulfinic acid, 1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,8-heptadecafluoro-; Perfluorooctane sulfinic acid	PFOSI	647-29-0	DTXSID10904262	#3
Ethanesulfonic acid, 2-[(6-chloro-1,1,2,2,3,3,4,4,5,5,6,6-dodecafluorohexyl)oxy]-1,1,2,2-tetrafluoro-, potassium salt (1:1); Potassium 9-chlorohexadecafluoro-3-oxanonane-1-sulfonate	F-53B / 6:2 Cl-PFESA	73606-19-6	DTXSID60881236	#4
Propanoic acid, 2,3,3,3-tetrafluoro-2-(1,1,2,2,3,3,3-heptafluoropropoxy)-, ammonium salt (1:1); Hexafluoropropylene oxide-dimer acid, ammonium salt	GenX / PFPrOPrA, HFPO-DA (acid form)	62037-80-3	DTXSID40108559	#4
Propanoic acid, 2,2,3-trifluoro-3-[1,1,2,2,3,3-hexafluoro-3-(trifluoromethoxy)propoxy]-, ammonium salt (1:1); 3H-Perfluoro-3-[(3-methoxy-propoxy)propanoic acid], ammonium salt	ADONA	958445-44-8	DTXSID00874026	#4

Acetic acid, 2,2-difluoro-2-[[2,2,4,5-tetrafluoro-5-(trifluoromethoxy)-1,3-dioxolan-4-yl]oxy]-, ammonium salt (1:1); Perfluoro{acetic acid, 2-[(5-methoxy-1,3-dioxolan-4-yl)oxy]}, ammonium salt	F-DIOX ammonium salt; cC6O4 ammonium salt	1190931-27-1	DTXSID00882626	#4
Propanoyl fluoride, 2,3,3,3-tetrafluoro-2-[1,1,2,3,3,3-hexafluoro-2-(1,1,2,2,3,3,3-heptafluoropropoxy)propoxy]-; Hexafluoropropene oxide trimer	HFPO-TA	2641-34-1	DTXSID2044630	#4
2-(4-chloro-1,1,2,2,3,3,4,4-octafluorobutoxy)-1,1,2,2-tetrafluoroethane-1-sulfonic acid	4:2 Cl-PFESA	737728-96-0		#4
2-[(8-Chloro-1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8-hexadecafluorooctyl)oxy]-1,1,2,2-tetrafluoroethanesulfonic acid	8:2 Cl-PFESA	763051-92-9	DTXSID40892507	#4
2-((1,1,2,2,3,3,4,4,5,5,6,6-dodecafluorohexyl)oxy)-1,1,2,2-tetrafluoroethane-1-sulfonic acid	6:2 H-PFESA	874280-03-2		#4
Butanoyl fluoride, 2,2,3,3,4,4,4-heptafluoro-; Perfluorobutanoyl fluoride	PBCF	335-42-2	DTXSID0041696	#5
Octanoyl fluoride, 2,2,3,3,4,4,5,5,6,6,7,7,8,8,8-pentadecafluoro-; Perfluorooctanoyl fluoride	POCF	335-66-0	DTXSID0059829	#5
Hexanamide, 2,2,3,3,4,4,5,5,6,6,6-undecafluoro-*N*-[3-(trimethoxysilyl)propyl]-; *N*-[3-(trimethoxysilyl)propyl]-perfluorohexanamide		154380-34-4	DTXSID80893356	#5
Octanamide, 2,2,3,3,4,4,5,5,6,6,7,7,8,8,8-pentadecafluoro-*N*-methyl-; *N*-methylperfluorooctanamide	MeFOA	89685-56-3	DTXSID50478336	#5
N-ethylperfluorooctanamide	EtFOA			#5
N-ethylperfluorobutanamide	EtFBA			#5
1-Octanesulfonyl fluoride, 1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,8-heptadecafluoro-; Perfluorooctanesulfonyl fluoride	POSF	307-35-7	DTXSID5027140	#6
1-Butanesulfonyl fluoride, 1,1,2,2,3,3,4,4,4-nonafluoro-; Perfluorobutanesulfonyl fluoride	PBSF	375-72-4	DTXSID20861913	#6
1-Octanesulfonamide, *N*-ethyl-1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,8-heptadecafluoro-; *N*-Ethylperfluorooctanesulfonamide	Sulfluramid EtFOSA	4151-50-2	DTXSID1032646	#6
Sodium 2-(*N*-ethylperfluorooctane-1-sulfonamido)ethyl phosphate; perfluorooctane sulfonamido ethanol-based phosphate diester	SAmPAP			#6
1-Octanesulfonamide, 1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,8-heptadecafluoro-; Perfluorooctanesulfonamide	FOSA	754-91-6	DTXSID3038939	#6

1-Octanesulfonamide, 1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,8-heptadecafluoro-*N*-methyl-; *N*-methyl perfluorooctane sulfonamide	MeFOSA	31506-32-8	DTXSID1067629	#6
1-Octanesulfonamide, 1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,8-heptadecafluoro-*N*-(2-hydroxyethyl)-N-methyl-; *N*-methyl perfluorooctane sulfonamidoethanol	MeFOSE	24448-09-7	DTXSID7027831	#6
1-Octanesulfonamide, N-ethyl-1,1,2,2,3,3,4,4,5,5,6,6,7,7,8,8,8-heptadecafluoro-*N*-(2-hydroxyethyl)-; *N*-ethyl perfluorooctane sulfonamidoethanol	EtFOSE	1691-99-2	DTXSID6027426	#6
1-Butanesulfonamide, 1,1,2,2,3,3,4,4,4-nonafluoro-*N*-methyl-; *N*-methyl perfluorobutane sulfonamide	MeFBSA	68298-12-4	DTXSID1071373	#6
1-Butanesulfonamide, 1,1,2,2,3,3,4,4,4-nonafluoro-*N*-(2-hydroxyethyl)-*N*-methyl-; *N*-methyl perfluorobutane sulfonamidoethanol	MeFBSE	34454-97-2	DTXSID0067848	#6
1-Octanesulfonic acid, 3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluoro-; 6:2 Fluorotelomer sulfonic acid		27619-97-2	DTXSID6067331	#7
1-Propanaminium, *N*-(carboxymethyl)-*N*,*N*-dimethyl-3-[[(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl)sulfonyl]amino]-, inner salt; 6:2 Fluorotelomer sulfonamide betaine		34455-29-3	DTXSID4041284	#7
Silane, triethoxy(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl)-; Triethoxy(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl)silane		51851-37-7		#7
1-Octanol, 3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluoro-; 6:2 Fluorotelomer alcohol; 2-(perfluorohexyl)ethanol; 1*H*,1*H*,2*H*,2*H*-perfluorooctan-1-ol	6:2 FTOH	647-42-7	DTXSID5044572	#7
1-Decanol, 3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-heptadecafluoro-; 8:2 Fluorotelomer alcohol; 2-(perfluorooctyl)ethanol; 1*H*,1*H*,2*H*,2*H*-Perfluorodecan-1-ol	8:2 FTOH	678-39-7	DTXSID7029904	#7
1-Dodecanol, 3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,12,12,12-heneicosafluoro-; 10:2 Fluorotelomer alcohol; 2-(perfluorodecyl)ethanol; 1*H*,1*H*,2*H*,2*H*-perfluorododecan-1-ol	10:2 FTOH	865-86-1	DTXSID2029905	#7

1-Hexanesulfonic acid, 3,3,4,4,5,5,6,6,6-nonafluoro-; 4:2 Fluorotelomer sulfonic acid; 1*H*,1*H*,2*H*,2*H*-perfluorohexanesulphonic acid	4:2 FTSA	757124-72-4	DTXSID30891564	#7
1-Octanesulfonic acid, 3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluoro-; 6:2 Fluorotelomer sulfonic acid; 1-Octanesulfonic acid, 3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluoro-	6:2 FTSA	27619-97-2	DTXSID6067331	#7
1-Decanesulfonic acid, 3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-heptadecafluoro-; 8:2 Fluorotelomer sulfonic acid; 3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-heptadecafluorodecanesulphonic acid	8:2 FTSA	39108-34-4	DTXSID00192353	#7
1-Octanol, 3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluoro-, 1,1'-(hydrogen phosphate); 6:2 Fluorotelomer phosphate diester; Bis[2-(perfluorohexyl)ethyl]phosphate	6:2 diPAP	57677-95-9	DTXSID50561590	#7
1-Decanol, 3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-heptadecafluoro-, 1,1'-(hydrogen phosphate); 8:2 Fluorotelomer phosphate diester; Bis[2-(perfluorooctyl)ethyl]phosphate	8:2 diPAP	678-41-1	DTXSID90218051	#7
1-Dodecanol, 3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,12,12,12-heneicosafluoro-, 1,1'-(hydrogen phosphate); 10:2 Fluorotelomer phosphate diester; Bis[2-(perfluorodecyl)ethyl]phosphate	10:2 diPAP	1895-26-7	DTXSID30172360	#7
3,3,4,4,5,5,6,6,7,7,7-Undecafluoro-2-heptanol; 5:2 fluorotelomer secondary alcohol	5:2 sFTOH (secondary alcohol, $[F(CF_2)_5CH(OH)CH_3]$),	914637-05-1	DTXSID80597206	#7
4:2 Fluorotelomer unsaturated carboxylic acid	4:2 FTUCA	70887-90-0		#7
2-Octenoic acid, 3,4,4,5,5,6,6,7,7,8,8,8-dodecafluoro-; 6:2 Fluorotelomer unsaturated carboxylic acid; 2*H*-perfluoro-2-octenoic acid	6:2 FTUCA	70887-88-6		#7
8:2 Fluorotelomer unsaturated carboxylic acid; 2-Decenoic acid, 3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-hexadecafluoro-	8:2 FTUCA	70887-84-2	DTXSID60825615	#7
2-Dodecenoic acid, 3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,12,12,12-eicosafluoro-; 10:2 Fluorotelomer unsaturated carboxylic acid; 2*H*-perfluoro-2-dodecenoic acid	10:2 FTUCA	70887-94-4	DTXSID70895723	#7

2-Propenoic acid, 3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-heptadecafluorodecyl ester; 1*H*,1*H*,2*H*,2*H*-perfluorodecyl acrylate	8:2 FTAc	27905-45-9	DTXSID5067348	#7
1-Butanol, 2,2,3,3,4,4,4-heptafluoro-; (Perfluoropropyl)methanol	3:1 FTOH / RM 610	375-01-9	DTXSID4059914	#8
2-Propenoic acid, 2-methyl-, 2,2,3,3,4,4,5,5,6,6,7,7,8,8,8-pentadecafluorooctyl ester, polymer with 2-propenoic acid		53515-73-4	DTXSID30880458	#8
Oxirane, 2,2,3-trifluoro-3-(trifluoromethyl)-; Hexafluoropropylene oxide / Trifluoro(trifluoromethyl)oxirane	HFPO	428-59-1	DTXSID6029177	#9
Furan, 2,2,3,3,4,4,5-heptafluorotetrahydro-5-(1,1,2,2,3,3,4,4,4-nonafluorobutyl)-; Perfluoro-2-butyltetrahydrofuran	FC-75	335-36-4	DTXSID60871632	#9
Ethene, tetrafluoro-; Tetrafluoroethylene	TFE	116-14-3	DTXSID6021325	#10
Benzenesulfonic acid, 4-[[3,4,4,4-tetrafluoro-2-[1,2,2,2-tetrafluoro-1-(trifluoromethyl)ethyl]-1,3-bis(trifluoromethyl)-1-buten-1-yl]oxy]-, sodium salt (1:1); Sodium ρ-perfluorous nonenoxybenzene sulfonate	OBS	70829-87-7	DTXSID601020833	#10
2-Pentenoyl fluoride, 2,3,4,5,5,5-hexafluoro-4-(trifluoromethyl)-; Perfluoro-4-methylpent-2-enoyl fluoride		88022-48-4	DTXSID40897491	#10
2-Pentene, 1,1,2,3,4,5,5,5-octafluoro-1-iodo-4-(trifluoromethyl)-, (E)-; (2E)-1,1,2,3,4,5,5,5-Octafluoro-1-iodo-4-(trifluoromethyl)-2-pentene		120695-78-5	DTXSID20694127	#10
1-Propene, 1,1,2,3,3,3-hexafluoro-; Hexafluoropropene	HFP	116-15-4	DTXSID2026949	#10
Ethane, 1,1,1,2-tetrafluoro-; 1,1,1,2-Tetrafluoroethane	HFC-134a / R-134a / Freon 134a / Forane 134a / Genetron 134a / Florasol 134a / Suva 134a / Norflurane	811-97-2	DTXSID1021324	#11
Ethene, 1,1-difluoro-; 1,1-Difluoroethylene; vinylidene fluoride	VDF	75-38-7	DTXSID3021439	#11
1-Propene, 2,3,3,3-tetrafluoro-; 2,3,3,3-Tetrafluoropropene	HFO-1234yf	754-12-1	DTXSID4074728	#11
Butane, 1-ethoxy-1,1,2,2,3,3,4,4,4-nonafluoro-; Ethylnonafluorobutylether	HFE-7200	163702-05-4	DTXSID0073118	#11

Methane, (difluoromethoxy)trifluoro-; Pentafluorodimethylether	HFE-125	3822-68-2	DTXSID4073968	#11
Propane, 1,1,1,2,3,3,3-heptafluoro-; 1,1,1,2,3,3,3-heptafluoropropane	HFC-227ea	431-89-0		#11
Propane, 1,1,1,3,3,3-hexafluoro-; 1,1,1,3,3,3-hexafluoropropane	HFC-236fa	690-39-1	DTXSID8052435	#11
2-Butene, 1,1,1,4,4,4-hexafluoro-, (2Z)-; (Z)-1,1,1,4,4,4-hexafluorobut-2-ene	HFO-1336mzz	692-49-9	DTXSID00883476	#11
Ethane, 1,1,1,2,2-pentafluoro-; 1,1,1,2,2-pentafluoroethane	HFC-125	354-33-6	DTXSID1024251	#11
Propane, 1,1,1,3,3-pentafluoro-; 1,1,1,3,3-pentafluoropropane	HFC-245fa	460-73-1	DTXSID6052110	#11
Butane, 1,1,1,3,3-pentafluoro-; 1,1,1,3,3-pentafluorobutane	HFC-365mfc	406-58-6	DTXSID5073901	#11
Pentane, 1,1,1,2,2,3,4,5,5,5-decafluoro-; 1,1,1,2,2,3,4,5,5,5-decafluoropentane	HFC-43-10mee	138495-42-8	DTXSID30869884	#11
1-Propene, 1,3,3,3-tetrafluoro-, (1E)-; 1,3,3,3-tetrafluoroprop-1-ene	HFC-1234ze	29118-24-9	DTXSID60936952	#11
Benzene, (trifluoromethyl)-; Benzotrifluoride		98-08-8	DTXSID2024589	#12
Benzene, 1-chloro-4-(trifluoromethyl)-; 1-Chloro-4-(trifluoromethyl)benzene		98-56-6	DTXSID7024821	#12
Benzenepropanamine, *N*-methyl-γ-[4-(trifluoromethyl)phenoxy]-	Fluoxetine	54910-89-3	DTXSID7023067	#12
Urea, *N*,*N*-dimethyl-*N*′-[3-(trifluoromethyl)phenyl]-	Fluometuron	2164-17-2	DTXSID8020628	#12
Ethene, 1,1,2,2-tetrafluoro-, homopolymer; Polytetrafluoroethylene	PTFE	9002-84-0	DTXSID7047724	#13
Ethene, 1,1-difluoro-, homopolymer; Polyvinylidene fluoride	PVDF	24937-79-9	DTXSID80895097	#13
1-Propene, 1,1,2,3,3,3-hexafluoro-, polymer with 1,1,2,2-tetrafluoroethene; Fluorinated ethylene propylene	FEP	25067-11-2	DTXSID70880371	#13
Propane, 1,1,1,2,2,3,3-heptafluoro-3-[(1,2,2-trifluoroethenyl)oxy]-, polymer with 1,1,2,2-tetrafluoroethene; Perfluoro-3-[(trifluoroethenyl)oxy]propane, polymer with tetrafluoroethene		26655-00-5	DTXSID40880383	#13
Ethene, 1,1,2,2-tetrafluoro-, polymer with 1,1,2-trifluoro-2-(1,1,2,2,2-pentafluoroethoxy)ethane; Tetrafluoroethene polymer with trifluoro(pentaflurorethoxy)ethene		31784-04-0	DTXSID10881948	#13

1-Propene, 1,1,2,3,3,3-hexafluoro-, polymer with 1,1-difluoroethene; 1,1-Difluorethylene-hexafluorpropene polymer		9011-17-0	DTXSID30880211	#14
1-Propene, 1,1,2,3,3,3-hexafluoro-, polymer with 1,1,1,2,2,3,3-heptafluoro-3-[(1,2,2-trifluoroethenyl)oxy]propane and 1,1,2,2-tetrafluoroethene; Hexafluoropropene, 1-((trifluoroethenyl)oxy)hepta-fluoropropane, tetrafluoroethene polymer		63654-41-1	DTXSID10880532	#14