Polyfluorinated Compounds: Past, Present, and Future

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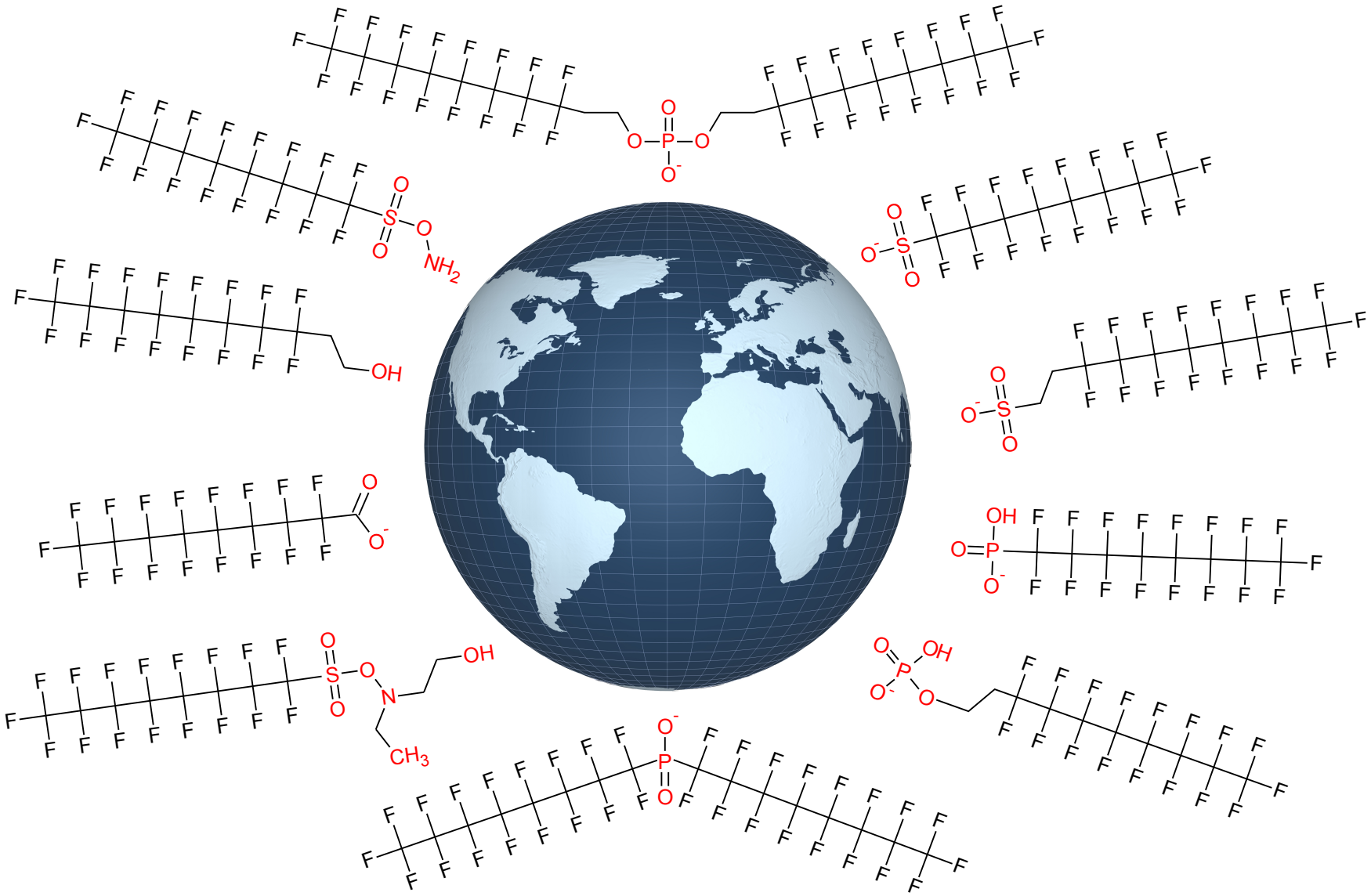
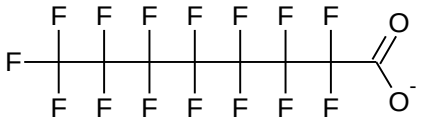
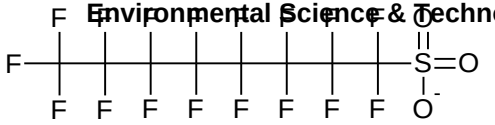
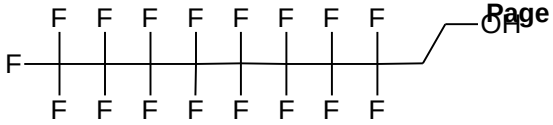




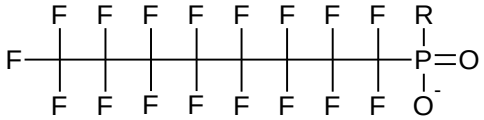
Perfluorocarboxylic acids
(e.g., PFOA)



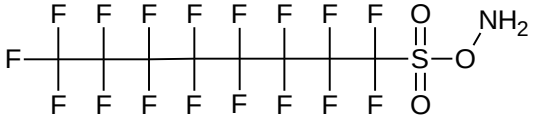
Perfluorosulfonic acids
(e.g., PFOS)



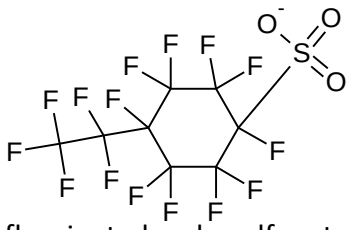
Fluorotelomer alcohol
(e.g., 8:2 FTOH)



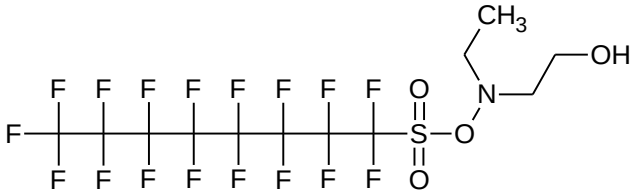
Perfluorophosphonic/phosphinic acids
(e.g., If R=OH then PFOPA
If R=C8 perfluoroalkane then 8:8 PFPi)



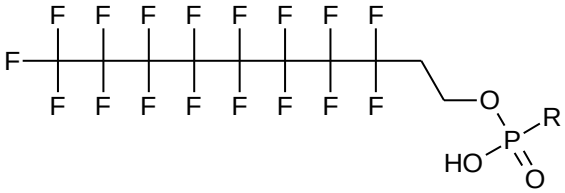
Perfluorosulfonamide
(e.g., FOSA)



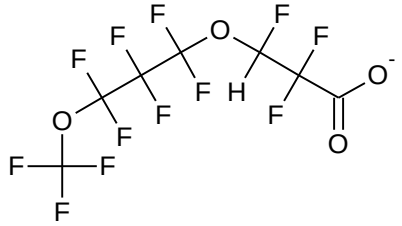
Perfluorinated cyclo sulfonates
(e.g., PFECHS)



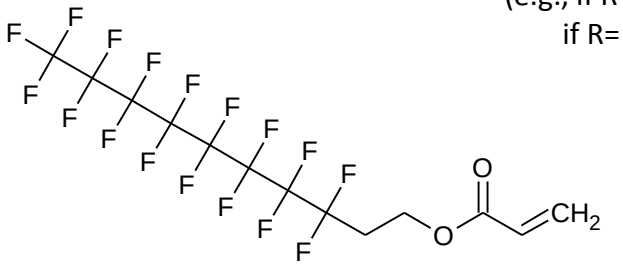
Perfluorosulfonamidoethanol
(e.g., N-EtFOSE)



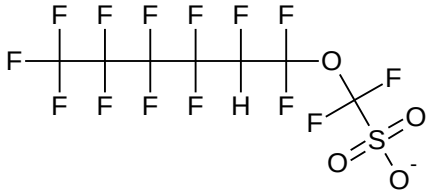
Fluorotelomer phosphate esters
(e.g., if R= OH then 8:2 monoPAP
if R= 8:2 FTO ester then 8:2 diPAP)



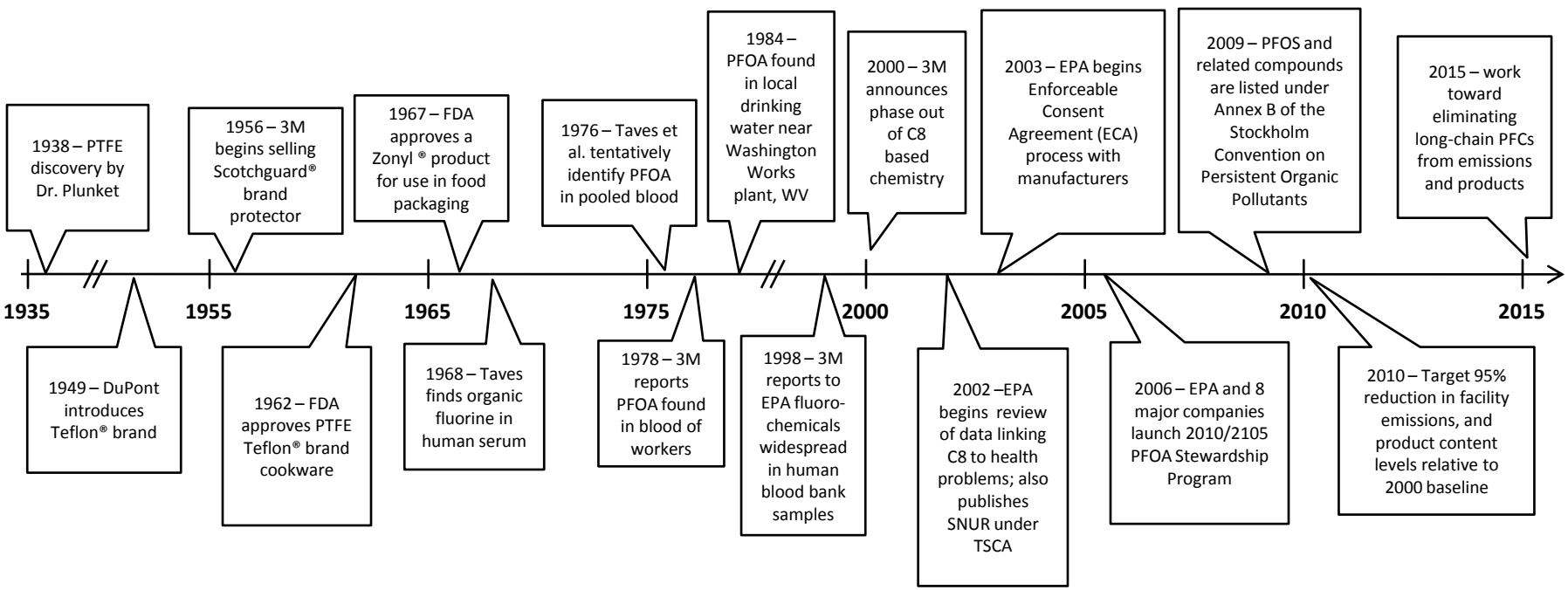
Polyfluorinated ether carboxylates
(e.g., 4,8-dioxa-3H-perfluorononanoate)



Polyfluorinated polymeric unit
(e.g., 1H,1H,2H,2H-perfluorodecyl acrylate)



Polyfluorinated ether sulfonates
(e.g., Perfluoro [hexyl ethyl ether sulfonate])


1938 – PTFE discovery by Dr. Plunket
1949 – DuPont introduces Teflon® brand
1956 – 3M begins selling Scotchguard® brand protector
1962 – FDA approves PTFE Teflon® brand cookware
1967 – FDA approves a Zonyl ® product for use in food packaging
1968 – Taves finds organic fluorine in human serum
1976 – Taves et al. tentatively identify PFOA in pooled blood
1978 – 3M reports PFOA found in blood of workers
1984 – PFOA found in local drinking water near Washington Works plant, WV
1998 – 3M reports to EPA fluoro-chemicals widespread in human blood bank samples
2000 – 3M announces phase out of C8 based chemistry
2002 –EPA begins review of data linking C8 to health problems; also publishes SNUR under TSCA
2003 – EPA begins Enforceable Consent Agreement (ECA) process with manufacturers
2006 – EPA and 8 major companies launch 2010/2105 PFOA Stewardship Program
2009 – PFOS and related compounds are listed under Annex B of the Stockholm Convention on Persistent Organic Pollutants
2010 – Target 95% reduction in facility emissions, and product content levels relative to 2000 baseline
2015 – work toward eliminating long-chain PFCs from emissions and products
1935
1955
1965
1975
2000
2005
2010
2015

Polyfluorinated Compounds: Past, Present, and Future

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Abstract

Interest and concern about polyfluorinated compounds (PFCs), such as perfluorooctane sulfonate (PFOS), perfluorooctanoic acid (PFOA), and an increasing number of other related compounds is growing as more is learned about these ubiquitous anthropogenic substances. Many of these compounds can be toxic, and they are regularly found in the blood of animals and humans worldwide. A great deal of research has been conducted in this area, but a surprising amount remains unknown about their distribution in the environment and how people ultimately become exposed. The utility of these compounds seems to ensure their continued use in one form or another for the foreseeable future, presenting a long term challenge to scientists, industry leaders, and public health officials worldwide.

Introduction

Polyfluorinated compounds (PFCs) are useful anthropogenic chemicals that have been incorporated into a wide range of products for the past six decades. This class of compounds includes thousands of chemicals but is best known for the perfluorosulfonates (PFSAs) such as perfluorooctane sulfonate (PFOS), and the perfluorocarboxylic acids (PFCAs) which include perfluorooctanoic acid (PFOA). Their numerous uses and unique physical and chemical characteristics have made it difficult to develop an understanding of how they are distributed in the environment and how people become exposed. Concerns about these compounds have developed as many satisfy the defining characteristics of persistent organic pollutants (POPs): they are toxic, extremely resistant to degradation, bioaccumulate in food chains, and can have long half-lives in humans. After research efforts documented their presence in the environment and wildlife worldwide, and further studies verified that they are very common in human blood serum, efforts

were undertaken in the U.S. and elsewhere to limit the production and emission of some of the most widely used PFCs. Recent studies have indicated that these efforts may be responsible for a reduction of some PFCs in the blood of humans and animals in some locations, but other PFCs have remained stable or have even increased. The diversity of the PFCs and their high production volume has made it difficult to gauge global trends. An additional complication is that some developing regions have taken up the production of materials that have been restricted in other parts of the world, making it difficult to determine if progress is being made with regard to reducing global PFC emissions. Moreover, the utility of polyfluorinated chemistry makes it highly likely that commercial industries will continue to develop and use these materials for the foreseeable future. This feature article will explore some of the important history in this area, summarize much of our current understanding, and briefly consider what might be expected in the near future. Because this is intended to be a general overview, we will highlight what has motivated recent interest and what still needs to be determined.

Figure 1 summarizes the basic structures of some different types of PFCs, organized by the functional group (e.g., carboxylate, sulfonate, alcohol) at one end of the molecule. *Poly*fluorinated hydrocarbons have multiple sites where hydrogen has been substituted with fluorine (e.g., telomer alcohols), and *per*fluorinated species have had all of the hydrogens substituted with fluorine (e.g., PFOS and PFOA). These compounds have a number of unique physical and chemical characteristics imparted by the fluorinated region of the molecule, including water and oil repellency, thermal stability, and surfactant properties that make them very useful for a wide range of industrial and consumer-use applications [1]. For example, coating an exterior surface of a textile or paper product leaves the perfluorinated tail of the molecule projecting away from the

surface. Because this part of the molecule repels both water and oil, this treatment is ideal for paper packaging, textiles, and other surfaces one wants to keep clean and dry. This chemistry is also useful for surfactants and dispersants, leading to their widespread use as leveling agents for paints, lubricants, mist suppression, and fire fighting foams. A major use of PFCAs is as an emulsifier in the production of fluoropolymers [1, 2].

Toxicity

Compounds in this class were first produced in the 1940s and 1950s, well before it became common for governmental agencies in the industrialized world to require significant testing of new materials being brought to market. As companies producing these materials continued production and diversification of their product lines, more in-depth evaluations of potential health effects were conducted. The results of many of these investigations were in the form of internal reports that were not published in the peer reviewed literature. By the early 2000s, when it became apparent that PFCs were broadly distributed in the environment [3] and almost all human blood samples collected worldwide were found to contain measureable quantities of many PFCs at the ng/mL level [4], regulatory agencies began calling for a full review of all previous research and a more thorough evaluation of toxicity began. Studies involving chronic exposure of rats and monkeys to PFOS showed decreased body weight, increased liver weight, and a steep dose-response curve for mortality [5-7]. An increase in hepatocellular adenomas and thyroid follicular cell adenomas was observed in rats exposed to high levels of PFOS in their food [8] . In rodents, PFOA has been associated with increased incidence of liver, pancreas, and testicular tumors as well as weight loss, liver enlargement, and changes in lipid metabolism [9-11]. When either PFOS or PFOA is administered to pregnant mice, there is neonatal mortality and reduced

growth for the surviving pups [12]. The carcinogenicity associated with PFOA in rodents has been found to be mediated by the peroxisome proliferator-activated receptor-alpha (PPAR- α) pathway [13], but the relevance of this mechanism in humans is a matter of scientific debate.

Using these laboratory animal studies to try to estimate potential human health effects is always difficult, but in this case it is made more difficult by the fact that the toxicokinetics of different PFCs differ considerably between animal species and even between different genders within a given species [12]. For example, the half-life of PFOA in female rats is approximately four hours, while in male rats from the same strain it is closer to six days [14]. In mice, the half-life was found to be considerably longer (17-19 days), but the effect of gender was much less pronounced [15]. In humans, data suggest that the half-lives are much longer, with PFOS and PFOA approximately 5.4 and 3.8 years (arithmetic means), respectively [16], with no difference noted between genders. While half-life has generally been observed to increase in proportion to compound chain length, this is not always true, as perfluorohexane sulfonate (PFHxS, 6 carbons) has a half-life of 8.5 years in humans [16]. This relatively long half-life in humans heightens concerns about potential health effects.

While the toxicity of PFOS and PFOA has been documented in animal studies, investigations of potential health effects in workers occupationally exposed to these compounds have generally shown inconsistent results [17]. These workers may have circulating blood levels of PFCs that are hundreds of times those of non-occupationally exposed individuals [18], but it is difficult to determine conclusive results in these studies (either positive or negative) because sample populations are small, historical exposure levels are uncertain, individuals often have had

simultaneous exposures to other compounds, and they may have preexisting conditions that complicate evaluations. In one study of PFOS exposed workers, bladder cancer mortality was elevated among individuals with at least one year of exposure, but this finding was based on an incidence of only three cases [19]. In a subsequent reevaluation of this cohort, bladder cancer incidence was found to be similar to that of the general U.S. population, but a 1.5 – 2.0-fold risk for the most highly exposed workers could not be ruled out [20]. Compared to PFOS, more studies of PFOA exposed workers have been conducted. Several studies have shown a positive association between PFOA exposure and cholesterol, which could have implications for the development of cardiovascular disease [18, 21-23]. PFOA has also been associated with elevated uric acid, which may in turn impact hypertension and cerebrovascular disease [21, 23]. Some studies have found an association between PFOA exposure and prostate cancer [24, 25], but data are sparse and do not allow conclusive determinations [26]. An excellent review of this evolving area of research can be found in Steenland et al. [17].

Studies involving more typical background exposures in the general population are also inconsistent but suggest a number of important potential health effects. Among these are studies showing an association between PFOS and PFOA and decreased sperm count [27], a negative association between PFOS and PFOA with birth weight and size [28, 29], higher blood levels of PFOS and PFOA being related to current thyroid disease [30], and an association between PFOA and elevated cholesterol [31]. Overall these data are inconclusive and the associations do not necessarily indicate causality. Steenland et al. also cover this literature in their recent review [17].

Considering the widespread environmental occurrence and the potential health effects, the U.S.

Environmental Protection Agency (EPA) has issued provisional short-term health advisories for PFOS (200 ng/L) and PFOA (400 ng/L) in drinking water, estimating that short term consumption below these levels will safeguard public health [32]. Chronic exposure guidelines are being developed by the EPA and have been published by various entities for water and food, but little has been done thus far for compounds other than PFOS and PFOA. A review of current global guidelines and regulations can be found in Zushi et al. [33].

History of Production

Among the many ways used to produce PFCs, two major synthetic routes should be discussed. In the electrochemical fluorination (ECF) process, a straight chain hydrocarbon is reacted with HF and electricity to substitute all of the hydrogen atoms with fluorine [1]. Perfluorooctane sulfonyl fluoride (POSF) has been the major target compound produced in this manner, but ECF is a relatively crude process, leading to approximately 70% straight chain POSF with the balance being a variety of branched and cyclic isomers primarily from 4 – 9 carbons in total length. POSF can then be used in a series of reactions to produce *N*-methyl and *N*-ethyl perfluorooctane sulfonamidoethanol (N-MeFOSE and N-EtFOSE, Figure 1), which historically were used to produce surface coatings for textiles and paper products [34, 35]. All compounds produced from POSF have been thought of as "PFOS equivalents" as these materials have the potential to ultimately degrade or transform to PFOS. In contrast, PFOS itself is extraordinarily stable in the environment, with no known natural mechanism of degradation. The other main process for the production of PFCs is called telomerization [1]. This involves the reaction of perfluorethylene (a taxogen, $CF_2=CF_2$) and perfluoroethyl iodide (a telogen CF_3-CF_2I) to produce straight chain prefluoroinated iodides with chain lengths that are generally divisible by 2. These perfluoroinated

iodides are then used as a feedstock to make perfluorinated carboxylic acids, fluorotelomer alcohols, and fluorotelomer olefins that are almost exclusively straight chain without the branched or cyclic materials that are characteristic of ECF synthesis. The fluorotelomer-based materials are used to produce polymers, textile treatments, surfactants, and food contact packaging [36]. PFOA, the eight carbon carboxylate, has been widely used as an emulsion polymerization aid in the production of polytetrafluoroethylene, an inert polymer used in a wide variety of applications, including nonstick coatings in kitchenware, nonreactive containers for corrosive materials, insulators, lubricants, and many other uses [2].

It is also important to note that thousands of different polyflourinated compounds have been synthesized and used by industry. The polyfluoroalkyl phosphate esters (PAPs) and perfluorinated phosphonic acids (PFPAs) surfactants are two other groups that have recently been gaining attention [37, 38]. Both classes of compounds have multiple congeners which have been identified in environmental matrices at concentrations that are similar to PFOS, PFOA, and related materials. Moreover, the PAPs have been recently quantified in human blood serum samples, confirming exposures through some unknown pathway(s) [39].

The history of PFC production is difficult to accurately portray due to the proprietary nature of this information, industry responses to various forms of regulation, and changing product lines. The 3M Company was the major producer of POSF, starting production in 1949, with the total cumulative production estimated to be approximately 96,000 t in the peak years between 1970 and 2002 [34]. After 3M discontinued production in 2002, other companies began production to meet existing market demands, with an estimated 1,000 t per year being produced since 2002 [34]. The

fluorotelomer alcohols have been widely used in the production of polymers and surface coatings with an estimated annual production in 2004 of 11,000 – 13,000 t/yr [36].

As research has demonstrated that many of the long-chain PFCs are toxic, persistent, and bioaccumulative, government and regulatory bodies in some parts of the world have been working toward agreements and regulations that limit the production of some of the PFCs [33]. The EPA worked with 3M to bring about the voluntary discontinuation of PFOS and related compounds between 2000 – 2002. Starting at the same time, a series of Significant New Use Rules (SNUR) were also put in place (2000, 2002, and 2007) in the U.S. to restrict the production and use of materials that contained PFOS or its various precursors. The EPA then worked with 8 leading chemical companies in the 2010/15 PFOA Stewardship Program to reduce emissions and residual content of PFOA and long-chain PFCs by 95% by 2010, with the long term goal to work toward elimination of long-chain PFCs by 2015 [40]. In 2009, PFOS and related compounds were listed under Annex B of the Stockholm Convention on Persistent Organic Pollutants, which restricts manufacturing and use to a few specific applications [41]. Figure 2 is a summary of some of the key events in PFC history.

Refining Analytical Approaches

In many ways research in this area has been dependent on improvements in analytical instrumentation, the synthesis and availability of analytical standards, and a gradually increasing sophistication in analytical approaches that have evolved over the past five decades. In 1968 D.R. Taves presented evidence of two forms of fluorine in human blood, one of which was the inorganic fluorine ion, and another which was closely associated with serum albumin having the

characteristics of a "large stable molecule…consistent with the presence of a fluorocarbon molecule" [42]. By 1976 Taves et al. had used NMR to tentatively identify PFOA or a related compound in concentrates from human blood serum, the source of which they speculated to be common household consumer products known to contain PFCs [43]. Early analytical methods for the measurement of organic fluorine in the blood of occupationally exposed workers started in the 1970s with a laborious and nonspecific ashing technique similar to that used by Taves et al., but soon progressed to less labor intensive (but still nonspecific) methods involving electron capture detection or microwave plasma detection [44]. These techniques had relatively high levels of detection (in the µg/mL or ppm range) and only gave tentative identification of the target analytes, but were nonetheless adequate for the evaluation of highly exposed workers. It was only after liquid chromatography/mass spectrometry (LC/MS) instrumentation became commonly available in the mid- to late 1990's that it became possible to measure PFCs in the low ng/mL (ppb) range, allowing for the first time the accurate evaluation of background levels of PFCs in biological and environmental matrices [45]. Early work in this area was difficult due to the relatively low concentrations found in most matrices, a lack of pure authentic standards and appropriate internal standards, a lack of standardized extraction and preparation techniques, and relatively poor quality assurance procedures [46]. A series of interlaboratory comparison studies in the early 2000s indicated relatively poor comparability between labs for complex and variable matrices like water and fish, with somewhat better performance for serum samples [47, 48]. Refinement of instrumentation and methods continued, with LC triple quadrupole mass spectrometer (LC/MS/MS) quickly becoming the standard approach used by most laboratories. As research and regulatory interest in these chemicals have increased, commercial laboratories have found a market for high purity standards and mass labeled internal standards, making it possible for more

analytical laboratories to take up this research. Better quality assurance procedures, such as the routine use of daughter ion ratios to help distinguish PFCs (such as PFOS), from commonly occurring matrix contaminants, has helped refine compound identification and accuracy considerably [49]. Another important recent development is the increasing use of standard reference materials (SRM) to develop consensus values for different compounds in differing matrices, thereby providing a way to demonstrate analytical performance in each analytical batch [50]. At present, instrumentation continues to improve, with lower cost time of flight mass spectrometers now becoming available, giving many labs the ability to conduct analyses using high resolution mass accuracy and greatly improved specificity [51].

Occurrence in the Environment

Early studies which documented the presence of PFOS and other PFCs in the blood of many species of wildlife collected from wide ranging locations around the world sparked initial interest and concern [3]. Of particular interest was the fact that PFCs were both ubiquitous in humans [4] and measureable in the blood of arctic mammals, ocean going birds, and other species only found in remote locations far from human settlement [52, 53]. It was apparent that PFCs, like other POPs, undergo a "global distillation" wherein persistent materials emitted in the temperate regions are transported to polar regions where they can accumulate in the environment far from any known sources. Polar bears, seals, and whales are well known to accumulate POPs like PCBs , PBDEs, and persistent pesticides, and these species were also found to take up PFOS and some of the long-chain PFCAs [54-56]. At the same time, other studies began documenting the occurrence of PFCs in rivers, lakes, and oceans the worldwide. The highest concentrations of PFCs have typically been documented in areas with direct industrial emissions that have impacted fresh water

rivers and lakes with concentrations typically ranging 1 – 1000s of ng/L [57-59]. Oceanic levels are typically 3 orders of magnitude lower, with levels of PFOS and PFOA typically being in the range of 10 - 100 pg/L [60].

An important environmental concern is that the long-chain PFCs can bioaccumulate as they move though food webs. Compounds with a perfluoroalkyl chain length (number of carbons with fluorine bonds) ≥ 8 are generally more bioaccumulative than those with ≤ 7 [61, 62]. Note that while PFOA has 8 total carbons, only 7 are perfluoroalkyl carbons with one additional carboxylate carbon, giving it a tendency to be less well retained in many biological matrices. Humans seem to be an important exception to this observation as PFOA appears to readily accumulate in human serum [63]. The functional group also has an effect on bioaccumulation, with a sulfonate being more likely to be retained than a carboxylate of the same size [61, 64]. These general observations form the basis for the call to restrict or eliminate the use of long-chain PFCs (i.e. those $\geq$ C8) [40].

Human Exposure

The fact that virtually all people living in the industrialized world have many PFCs in their blood serum in the ng/mL range [4] indicates widespread exposure, but developing an understanding how people become exposed is complicated by a number of factors. One of the first important considerations is the long half-life of some PFCs in humans. This slow elimination time makes it difficult to determine how changes in lifestyle, diet, or other exposure-related factors influence blood levels. Studies have also indicated that while age apparently has little influence on circulating PFC levels, gender and ethnicity do seem to influence the accumulation of some compounds [65]. This indicates that lifestyle and possibly genetic factors play a role in uptake and

retention of the PFCs. There are also clear geographical differences that have been observed, indicating that proximity to major sources or degree of urbanization also play an important role [57, 63]. But one of the biggest factors influencing human exposure is likely to be changes in industrial production, which have largely come about in response to regulatory pressures to decrease production and emission of compounds considered to be potentially hazardous. Since 3M terminated production of POSF in 2002, PFOS in North American blood samples has decreased at a rate that is consistent with its half-life in humans, suggesting that the factors responsible for exposure were greatly reduced or eliminated at that time [66]. It is interesting to note that blood levels of PFOA also began a sharp decline in 2002, but the rate of decrease has been slower than the estimated half-life. This suggests that POSF production may have been related to PFOA exposure in some way, but other sources remain.

The U.S. Center for Disease Control and Prevention (CDC) conducts the National Health and Nutrition Examination Survey (NHANES) on a regular basis to monitor pollutant trends in the U.S. population. In a study summarizing recent NHANES data, geometric mean PFOS and PFOA levels declined by 32% and 25%, respectively from 1999/2000 until 2003/2004 [67]. The most recent NHANES results (2007/2008) indicate that while PFOS concentrations continue to decline, other PFCs have essentially remained flat (PFOA) or have increased (PFHxS, PFNA) [65]. These results suggest that deliberate efforts to reduce the production of PFOS have led to reductions in human exposure (in the U.S.) but the routes of exposure and control mechanisms for other PFCs remain obscure.

Data from other countries indicate a more complex global situation with regard to human blood

levels. In a study involving pooled serum samples from Norwegian men aged 40 - 50 collected from 1977 until 2006, PFOS, PFOA, and perfluoroheptanoic acid (PFHpA) increased by a factor of 9 between 1977 and the mid 1990s [68]. Between 2000 and 2006 PFOS and PFOA then decreased by a factor of 2. PFHxS, perfluorononanoic acid (PFNA), perfluorodecanoic acid (PFDA), and perfluoroundecanoic acid (PFUnA) also increased between 1977 and the mid 1990s, but their concentrations either leveled off or continued to increase until 2006 [68]. A study in Germany found relatively stable PFOS and PFOA concentrations in adult males between 1977 and 2004 [69], while data from China have indicated dramatically increasing level of PFOS in some parts of this country, while PFOA has remained relatively low [70].

At present, a number of modeling studies have estimated that low level PFC contamination of food is likely to be responsible for most nonoccupational exposures in industrialized nations. In a recent review, Fromme et al. evaluated potential PFC exposures from indoor and outdoor air, house dust, drinking water, and food [71]. They concluded median uptake of PFOS and PFOA was on the order of 2 - 3 ng/kg/day, respectively, with food being responsible for greater than 90% of this exposure. However, with the wide variety of foods consumed and the difficulty in establishing sensitive analytical methods that accurately measure contaminants, there is still a great deal of uncertainty about the role of food as an exposure route [72]. Fish are the most thoroughly examined food item, and an increasing number of studies have begun to suggest that fish from contaminated water bodies may dominate exposures to PFOS and possibly other long-chain PFCAs [73, 74]. For example, in a recent study of fish taken from a contaminated section of the Mississippi River, bluegill fillets were found to have median PFOS concentrations of between 50 and 100 ng/g of fillet [75]. Consumption of a meal sized portion (195 g) of this fish

leads to exposures in the range of 150 – 330 ng/kg /day, which is approximately 100 times higher than the daily intake predicted in the study by Fromme et al [71]. This underscores the facts that fish can be a major source of intake for some people and there is still a great deal to be learned about PFC contamination of food. Studies have also indicated that crops grown on contaminated soils can accumulate PFCs, suggesting that this may also be a source of human exposure [76]. This may be a particular concern in agricultural areas that receive amendments of biosolids from wastewater treatment plants, as these effluents contain PFC precursors and terminal degradants [77, 78]. It is also clear that consumption of contaminated drinking water can be an important route of human exposure for people living in certain areas that are impacted by industrial emissions. Situations where locally contaminated drinking water resources have been linked with increased blood levels have been documented in Germany [69], Japan [57], Ohio and West Virginia [63], and Minnesota [79].

Other potential routes of human exposure include air, house dust, and direct contact with PFC containing consumer use items. Many of the labile precursor materials like telomer and FOSE alcohols are volatile, and studies show that they can occur in the indoor environment at pg/m^3 – ng/m^3 levels [80]. Once inhaled, these materials may be metabolized by normal enzymatic processes, likely leading to accumulation of the end terminal degradants *in vivo*. Studies of house dust indicate that contamination in 10- 100 ng/g range is quite common [81, 82], suggesting inhalation of airborne material or the hand to mouth contact (particularly for children) could contribute to human exposure. Direct contact with consumer use items that have been treated with PFCs or which contain residuals from a manufacturing process is another potential source of human exposure [83].

The Future of PFCs

While most of the research and regulatory effort thus far has focused on PFOS and PFOA, it is important to realize that hundreds to thousands of different polyflourinated compounds are currently in use. Moreover, new formulations are being brought to market continuously and little if anything is known about the environmental disposition and toxicity of these compounds [84-86]. While there has been some success with voluntary controls for some PFCs [40], there is limited incentive for companies to join in these voluntary agreements. In fact, considering that the C8-based chemistries often have the most desirable performance characteristics, it is attractive for companies that are not party to the 2010/15 PFOA Stewardship Program to increase their production of long-chain materials to meet continuing international market demands. Some members of the international community believe that regulations to limit PFC production are unnecessary because there is little evidence of human health effects or environmental damage thus far. Without strong coordinated regulatory efforts, economic factors may simply shift the production of these materials to locations that place greater value on economic development than long term environmental concerns.

In conclusion, it is evident that scientific and regulatory communities are only starting to understand and effectively manage polyfluorinated compounds. Environmental distributions, routes of human and environmental exposure, and long term ecological and human health consequences are still poorly described. Limited regulatory controls have been established in some nations, but their long term effectiveness on a global scale remains to be determined. The extreme stability of the terminal breakdown products and the increasing trend toward an integrated

world economy makes a strong case for global research and regulation, especially as new alternatives are being introduced to the market. Environmental professionals of all types face an enormous challenge in trying to meet these pressing research needs. We are at the very beginning of a new age of environmental chemistry.

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Figure 1. Generic structures for polyfluorinated compounds*

* The n = 8 linear carbon structures are shown for many of these examples, but n = 4-14 linear and/or branched carbon units are generally possible.

Figure 2. Timeline of important events in the history of polyfluorinated compounds