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Exposure and Health Implications of Per- and Polyfluoroalkyl Substances (PFAS)

What are PFAS?

The compounds known as per- and polyfluoroalkyl substances (PFAS) comprise a large class of thousands of manmade chemicals used across wide swathes of daily life. The U.S. Environmental Protection Agency's (EPA's) CompTox Chemicals Dashboard, last updated in August of 2021, lists over 12,000 individual PFAS.[1] PFAS have been defined most recently by the Organization for Economic Development (OECD) as organic molecules having one fully fluorinated methyl $[CH_3]$ or methylene $[-CH_2-]$ carbon atom (without any H/Cl/Br/I atom attached to it).[2] The nomenclature has been disputed in academic and industrial settings and remains elusive and subject to the group using it. This necessitates something clear, descriptive, and specific, which was the goal of the OECD when naming this latest definition. What is more conclusive, however, is the basic chemistry behind PFAS and the reason for the chemicals' environmental persistence and accumulation. The carbon-fluorine bond, arguably the strongest chemical bond known,[3] which makes up the chemical structure of PFAS, allows PFAS to possess advantageous and distinctive characteristics that make their industrial and commercial applications attractive.

Figure 1: Sources of PFAS.

The initial invention, production, and use of PFAS as non-stick and protective coatings began in the 1940s and 1950s without recognizing some unintentional consequences. Some of the appealing properties of PFAS include their thermal stability, resistance to degradation, and surfactant ability, which simply means they lower the surface tension of water and allow greater spread and wetting application. This last property became useful in the application of PFAS within aqueous film-forming foams (AFFFs) for firefighting purposes.[4] The historical and present-day uses of PFAS are many and varied.[5-7] Semiconductor manufacturing, adhesives, textiles, cleaning products, personal care products, metal plating, packaging, and medical devices and implantable materials are just a few examples of goods and areas where PFAS are likely to be found.[5] A lot of these domains of use have included so-called "legacy" PFAS, which are primarily perfluorooctanoic sulfonate (PFOS) and perfluorooctanoic acid (PFOA), two eight-carbon chain PFAS that are well-known and characterized in the scientific literature. However, through regulatory action (see regulatory section below) and public awareness of the health concerns of these and other legacy PFAS, industry has transitioned to the use and application of smaller PFAS chemicals, which may also have environmental and health concerns.[8] Even though certain PFAS may potentially break down through various pathways, most often they transform into alternative PFAS that are still present in the environment and could lead to exposure and human health impacts.[9]

Exposure Sources and Pathways

According to the Centers for Disease Control and Prevention's (CDC's) National Health and Nutrition Examination Survey (NHANES), nearly all Americans have detectable levels of PFAS within their blood. This could be due to ingestion of PFAS contaminated water[10] or food.[11] However, other exposure pathways exist and contribute to adverse human health effects because of the numerous sources and forms of these pervasive chemicals. Historically, legacy PFAS were used in the automobile and manufacturing industries for several decades leading to contamination in various environmental matrices including soil,[12] water,[13,14] and air.[15] In 2012, the relevance of soil as a global reservoir of PFAS was first revealed as global soil loadings of PFOA (1,860 metric tons) and PFOS (>7,000 metric tons) were determined.[16] A separate study reported detectable levels of 32 PFAS in surface soil samples obtained from 62 locations across all continents.[17] Likewise, Brasseau and coworkers compiled data from 30,000 samples collected from 2,500 sites consisting of fire-training areas, manufacturing plants, and secondary-source sites (i.e., waste treatment plants) from around the world.[18] These findings as well as others indicate that PFAS soil levels are often orders-of-magnitude higher than average groundwater concentrations, which highlights soil as a significant reservoir for PFAS and potential source of exposure. While soil is a prominent source of PFAS, water has been the most studied environmental media to date. Currently, over 1,750 communities within the U.S. have PFAS contaminated water due to releases from industrial sites, wastewater treatment plants, and military fire training areas.[19,20]

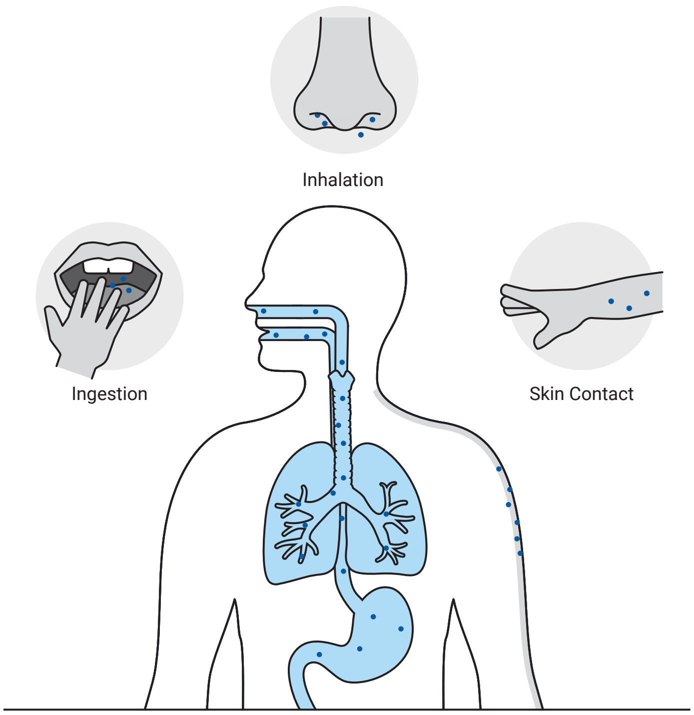

Figure 2: Exposure Pathways.

Air is another environmental matrix that poses a significant exposure risk to PFAS through inhalation. In particular, the impact of PFAS on indoor air quality has been an area of concern given that humans commonly spend 90% of their time indoors. Indoor exposure to specific PFAS such as fluorotelomer alcohols (FTOHs), perfluorooctane sulfonamides (FOSAs) and perfluorooctane sulfonamidoethanols (FOSEs) and other precursors such as perfluoroalkyl acids (PFAA) come primarily from consumer and construction products such as carpet and upholstered furniture typically found in most American homes.[21,22] Recent studies indicate indoor air causes the greatest exposure risk of FTOH and PFAA in young children.[23] Thus, these three environmental sources along with consumer products can lead to human exposure via either direct or indirect interaction through ingestion, dermal contact, or inhalation routes or pathways.

PFAS Use in Textiles

Performance textiles are those that provide additional functions such as repellency, resistance, or protection from a specific element. These functions include fabrics that resist wrinkles, soils, or odors, and protect from environmental conditions.[24] Furthermore, hydrophobic and oleophobic textile surfaces improve easy-care, durability, protection, self-cleaning, and comfort properties of performance textiles.[25] PFAS have been used for nearly 80 years in a variety of consumer products and are found in wearable textiles, upholstery fabrics, and firefighter turnout gear.[7]

Textiles found to have PFAS include consumer clothing items such as shorts and pants, leggings, yoga pants, children's clothing, raincoats, and upholstery textiles. PFAS can be released from these textiles through several mechanisms including chemical breakdown during laundering, evaporation of volatile PFAS as a residual from the fabric, and loss of particles and fiber fragments by abrasion.[7] Several different analytical methods were used in a study to quantify volatile and ionic PFAS from wearables and upholstery. The findings showed that during normal use, PFAS remained on the surface after extraction, indicating that PFAS are likely to continue to wash off gradually.[26] In the same study, PFAS in older textiles had a larger fraction of extractable PFAS, suggesting that older materials may be a greater potential source of exposure to PFAS than newer textiles.[26]

Firefighters may be occupationally exposed to PFAS through aqueous film-forming foam, the burning of household items, and from personal protective equipment (PPE).[27] Turnout gear is manufactured from textiles made, in part, from fluoropolymers and may be extensively treated with PFAS to provide durable water and oil resistance.[28] These materials containing PFAS are used as a moisture barrier in the inner layers of the turnout gear. Additionally, the outer shell of the assembly contains PFAS built into the fabric or treatments applied after the fabric is woven.[28] A study of used gear showed lower levels of PFAS in the materials as well as migration into untreated materials, indicating mobility of the chemicals. Exposure to PFAS may occur through degradation of the textiles with exposure routes including ingestion, inhalation, or through direct contact with the skin and dermal absorption.[29-31] The direct loss of PFAS from the fluoropolymers in the textiles from shedding represents a viable exposure source for firefighters and others in the near vicinity.[32] Features in performance textiles such as stain resistance and waterproofing are useful for consumers and firefighters, but the PFAS chemicals used to add functionality may pose human health and environmental risks.

Figure 3: Sources of PFAS in Textiles.

Health Effects of PFAS Exposure

The numerous PFAS exposure sources and pathways have unfortunately been linked to adverse health outcomes. Similar to other emerging chemicals, PFAS are capable of eliciting a wide range of adverse health effects depending on the exposure route, duration, and magnitude. Likewise, individual factors such as age, sex, ethnicity, health status and genetic predisposition also contribute to potential human health outcomes. Current epidemiological studies have found relationships between PFAS exposure and biomarkers of immunomodulation, inflammation, and disease. For example, when levels of PFOS were doubled in maternal serum, a 40% reduction in antibody concentrations was seen in children age 5 years old that persisted until age 13.[33,34] Likewise, prenatal exposure to PFOS and perfluorohexanesulfonic acid (PFHxS) have been linked to increased risk of airway and throat infections and diarrhea in children.[35,36] Studies evaluating the impact of PFAS on chronic autoimmune diseases in contaminated communities have shown an association between both prevalence and incidence of ulcerative colitis (UC) and PFOA exposure.[37] An occupational study revealed workers with increasing log PFOA serum concentrations had higher UC prevalence and incidence.[38] These studies and others indicate that immunotoxicity is an outcome that warrants further examination due to variances in immune response at different stages of life.

It is well known that the liver is a primary target organ for long-chain PFAS storage, which causes hepatic injury.[39] As evidenced by numerous in vitro and in vivo toxicological investigations, PFAS exposure causes hepatocyte dysfunction,[40] modification of liver enzymes,[41] cell death,[42] and liver cancer.[43] Human studies have also found modulation of liver enzymes including alanine aminotransferase in adults and adolescents exposed to long chain PFAS along with biomarkers of steatosis and non-alcoholic fatty liver disease.[44] Taken together, the aforementioned animal and human studies provide insight into the various modes of action PFAS exposure causes that can disrupt liver metabolism leading to disease or cancer.

Similar to the liver, the kidneys are also a major reservoir of PFAS due to the extended human half-lives of long-chain or legacy PFAS.[45] Specifically, legacy PFAS such as PFOA and PFOS are concentrated within the kidneys due to active renal tubular reabsorption. Histopathologic, cellular and epigenetic studies have revealed legacy PFAS are highly toxic to the kidneys.[45] Epidemiological evidence supports these findings as legacy PFAS exposure has been associated with reduced kidney function and chronic kidney disease in adults and children.[46,47]

Current Regulatory Status

The current regulatory landscape for PFAS when compared to their widespread presence is lacking and challenging not only because of the vast number of individual chemicals, but also the research needed to ascertain necessary guidelines. Only a few legacy PFAS—and no new compounds—have been investigated for potential regulatory action due to sparse health effects data. The first international body to introduce directives for PFAS was the European Union (EU). The Stockholm Convention, a group of representatives advising the EU's Persistent Organic Pollutants (POP) regulation, has addressed concern and put into place production and use restrictions for PFOS and PFOA and their salt and precursor forms, and most recently begun to evaluate PFHxS for restrictions.[48] Additionally, nine-carbon to fourteen-carbon perfluorinated carboxylic acids (PFCAs), which are notable transformation and breakdown products of other PFAS, will be restricted in the EU beginning in February 2023.[49]

From the United States perspective, the EPA issued advisories for PFOS and PFOA in drinking water in 2016.[50, 51] Legally, these advisories are not enforceable, but EPA is in the final stages of determining regulatory action[52] for the sum of PFOS and PFOA in drinking water under the Safe Water Drinking Act (SWDA), which involves the study of adverse health effects, likeliness of a chemical to be found in public water systems, and the opportunity for health risk reduction. Most recently at the federal level, EPA has updated the health advisories for PFOS and PFOA to be 0.02 parts per trillion (ppt) and 0.004 ppt, respectively, and given final health advisories for hexafluoropropylene oxide-dimer acid (HFPO-DA, commonly referred to as GenX) and perfluorobutane sulfonic acid (PFBS) of 10 ppt and 2,000 ppt, respectively.[53] In some cases, the health advisories are below current analytical detection capabilities so exposure may occur even if testing indicates non-detectable levels. The Centers for Disease Control's (CDC) Agency for Toxic Substances and Disease Registry (ATSDR) has only developed minimal risk levels for four specific PFAS—PFOA, PFOS, PFHxS, and perfluorononanoic acid (PFNA). When viewed from a state level, the guidelines and regulations for PFAS are variable,[54] but some do include enforceable standards for drinking water, groundwater, and/or surface water. For example, the state of Vermont regulates the sum (combination) of five PFAS (PFOA, PFOS, PFHxS, perfluoroheptanoic acid [PFHpA], and PFNA) as 20 ppt in drinking water.[55] A few states such as Maine and California have included the term "intentionally-added" PFAS to regulations banning the production and use of PFAS in consumer products[56-58] like food packaging, textiles, and cosmetics. California has even listed PFOA and PFOS as carcinogens under the Safe Drinking Water and Toxic Enforcement Act of 1986, commonly referred to as Proposition 65, that requires notification of PFAS content in goods by manufacturers.[59, 60] Since public awareness has grown in the past decade, the issue of PFAS exposure at the state and local level has just begun to be studied and addressed.

Current Air Exposure Research

Given the prominent health concerns and widespread contamination of PFAS, several research initiatives have been developed to address this global crisis. A major effort to understand PFAS air emissions and their contribution to adverse health effects has been on the forefront of these initiatives, as air is the least studied environmental matrix, but poses the greatest exposure risk. The Environmental Protection Agency recently awarded several research grants to develop PFAS air monitoring methods and technologies in indoor and outdoor environments. Several universities from across the nation were selected to address current knowledge gaps in characterizing PFAS air emissions including:

- Developing and validating novel passive sampling designs that can be used to measure a diverse suite of air toxics and contaminants of emerging concern at low detection limits (New York University)
- Designing and building a mobile platform to quantify and characterize emissions of sub- 10 nanometer particles (North Carolina State University)
- Developing and testing a moderate-cost, portable, small, low-power instrument for near real-time speciation and quantification of volatile organic compounds, including hazardous air pollutants (University of California - Davis)
- Combining online, high-resolution chemical ionization mass spectrometers with air- and particle-phase sampling techniques to increase understanding of fugitive emissions of PFAS from stationary point sources. (University of North Carolina - Chapel Hill)

Chemical Insights Research Institute (CIRI) of UL Research Institutes is also engaging in cutting-edge research to determine the health impacts of PFAS exposure from consumer products including performance, occupational, and upholstery textiles via various pathways. The overarching goals of this study are to develop methods for testing performance textiles for PFAS identification and quantification; acquire baseline data of PFAS levels in textiles from firefighter gear and uniforms, consumer wearables, and cover textiles for upholstered furniture; and determine potential routes for human exposure. More information on CIRI PFAS research may be found in "A Strategic Research Initiative on the Impact of Perfluoroalkyl and Polyfluoroalkyl Substances (PFAS) on Human Health." This work will address a major knowledge gap involving how textiles contribute to PFAS exposure in humans and potential health effects.

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