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The Cookware Sustainability Alliance is pleased to submit comments under HJM3 with the strong recommendation that the Fluoropolymer Exemption at Section 3 of the Per- and Poly-Fluoroalkyl Substances Protection Act (House Bill 212) be continued. We also are submitting four independent refereed science journal articles demonstrating the fundamental safety of fluoropolymers, such as PTFE.



September 14, 2026

Submitted electronically to the New Mexico Environment Department

Attn: House Joint Memorial 3 — Public Comment (<https://nmed.commentinput.com>)

Re: Public Comment of the Cookware Sustainability Alliance (CSA) on House Joint Memorial 3 Report. Recommendation that the Fluoropolymer Exemption at Section 3 of the Per- and Poly-Fluoroalkyl Substances Protection Act (House Bill 212) be Continued

Dear Secretary Kenney and Members of the Environment Department:

The Cookware Sustainability Alliance (CSA) submits this comment to inform the report the New Mexico Environment Department (NMED or the Department) has been requested to prepare under House Joint Memorial 3 ("HJM 3"); in particular the Department's recommendation to the Legislature on whether the exemption for fluoropolymers should be continued, modified or removed. We believe strongly that it should be continued.

The CSA is an organization dedicated to providing facts and science-based information about the safety of cookware products for consumers and policymakers to make informed decisions.

The purposes of the Per- and Poly-Fluoroalkyl Substances Protection Act are legitimate. New Mexico faces real and increasing costs from PFAS contamination of drinking water supplies, wastewater systems, septic systems, and solid waste infrastructure. The CSA is not asking the Department to weaken the Act. We urge the NMED and Legislature to preserve a scientific distinction that the Legislature itself drew with the support of the Department, on a record that has become substantially stronger since that decision was made.

HJM 3 records that the exemptions were adopted "based on limited scientific literature regarding chemical degradation, environmental mobility and persistence, potential human exposure pathways and possible health impacts," and finds that additional study is needed to understand more fully the toxicological profiles, exposure risks and public health implications of fluoropolymers. We take that finding seriously and treat it as an invitation to supply what the Legislature said was missing from the debate. However, to be clear, this information was part of the legislative debate, and the science is clear and undisputed. Section IV addresses each of those four subjects in turn.

I. Interest of the commenter

We are a diverse group of businesses and responsible manufacturers of food preparation products. Our products are sold throughout New Mexico through national and regional retailers, as well as online.

Our interest is direct. Fluoropolymer coatings — PTFE, PFA, and FEP — are used on food-contact cooking surfaces in our cookware and on food-contact surfaces in small electric appliances, and fluoroelastomers (FKM) are used in internal sealing components that can be wetted from liquids. Whether the Section 3 exemption is continued determines whether these safe, durable and affordable products remain available to New Mexico households.

II. Summary

We urge the Department to follow the facts, recognize the science, and accordingly we recommend that the fluoropolymer exemption be continued. In summary:

1. **Removal would not deliver a demonstrated benefit to New Mexico.** The contamination pathways HJM 3 identifies — drinking water, wastewater, septic systems — require an environmentally - mobile, water-soluble substance, which solid fluoropolymers are not. Fluoropolymers cannot dissolve in water, a fact recognized for decades. Section III.
2. **The literature the Legislature called limited is not limited, it is expansive and covers over 60 years of study and consistent findings.** Section IV.
3. **Removal would forfeit affirmative health benefits.** The cooking surface sets the dose of added fat; in appliances, fluoropolymers prevent metal-ion migration into beverages and seal failure in pressurized systems. Section V.
4. **No reasonably available alternative exists.** The leading substitute is documented to be less durable, is significantly more expensive, has been less studied, and is carry its own emerging regulatory concerns. Section VI.
5. **Removal would worsen environmental outcomes.** Life-cycle evidence indicates the alternative to nonstick cookware generates approximately seven times more end-of-life waste, and increases the use of oils, which are not healthy and which are the source of the majority of fires in homes. Section VII.
6. **Removal would fall hardest on lower-income New Mexico households.** Section VIII.
7. **New Mexico's approach is being validated, including by governments that designed Europe's most aggressive PFAS restriction.** Section X.

III. The threshold question: what would removal accomplish?

If the exemption were removed and fluoropolymer cookware and appliances were prohibited in New Mexico, what measurable environmental or public health benefit would the State obtain?

HJM 3 identifies the harms the Act addresses with precision: contamination of public drinking water supplies, public wastewater systems, private drinking water supplies, private septic systems, and municipal solid waste management and disposal infrastructure. Each is a pathway that requires a substance capable of moving — dissolving, leaching, migrating, or being carried in water.

A solid fluoropolymer coating bonded to a pan in a New Mexico kitchen or a landfill does not enter those pathways. It is water-insoluble and non-mobile. It does not wash into wastewater. It does not leach into groundwater from a septic field. The peer-reviewed record on this is set out in Section IV.

The releases that generate harmful, water soluble PFAS contamination occur at facilities that manufacture, use or process fluorochemicals. A retail prohibition would remove products from New Mexico shelves without eliminating any release into New Mexico air, water, or soil. That leaves end-of-life as the only plausible pathway, and Section VII addresses it directly — with the finding that removal would increase, not decrease, the volume of cookware entering New Mexico’s waste stream.

The question we request the Department to test

Not “are fluoropolymers PFAS?” — the statute already answers that, and the Legislature drew its line with that answer in view. The operative question for the report is whether removing the exemption would measurably reduce the contamination and the costs HJM 3 identifies. The evidence shows it would not, and that removal of the exemption would impose substantial offsetting harms.

IV. Responding to the four subjects identified in HJM 3

HJM 3 names four areas in which the Legislature considered the literature limited: Chemical degradation, environmental mobility and persistence, human exposure pathways, and health impacts are addressed in turn.

A. Chemical degradation

The concern is whether a fluoropolymer breaks down into smaller, mobile PFAS compounds of the kind that drive contamination.

The OECD’s Synthesis Report on Understanding Fluoropolymers and Their Life Cycle treats fluoropolymers as a distinct category rather than as interchangeable with other PFAS. A September 2025 environmental-fate study reaffirms that stability.

The practical point is that the property most often cited as alarming — that these materials do not break down — is, for an already-inert solid, precisely the property that prevents formation of the mobile compounds of concern.

In a recently released study, Jappen, Michell, *et al* studied the effective mineralization of polytetrafluoroethylene (PTFE) during thermal treatment under municipal solid waste incinerator (MSWI) conditions and to evaluate the potential formation of per- and polyfluoroalkyl substances (PFAS) and select other products of incomplete destruction (PIDs). A commercial grade PTFE sample was first subjected to elemental analyses and then incinerated in a bench-scale combustion system designed to represent conditions typical of MSWIs in the United States and European Union. Calculated destruction efficiency across the experiments averaged 99.99962 % for PTFE. These findings indicate that PTFE undergoes effective mineralization under typical incineration conditions, and that MSWI is a means of responsible end-of-life management for the fluoropolymer. (The study is being submitted as an accompaniment to this letter.)

B. Environmental mobility and persistence

Fluoropolymers are persistent.

The question is whether persistence alone is the harm the Act was written to prevent. HJM 3's own findings indicate it is not: the Legislature identified adverse health implications, bioaccumulation in people and wildlife, and high persistence — in combination. And the costs it identified arise from pathways that require movement.

Fluoropolymers are materials that are negligibly water-soluble, non-mobile, non-bioavailable, and non-bioaccumulative. A persistent solid that does not dissolve, does not migrate, and cannot be taken up by an organism does not travel the pathways the Act was designed to close.

The physical distinctions that separate these materials from the compounds that generated the concern are important to understand. Fluoropolymers are extremely long molecules built from repeating units — orders of magnitude larger than compounds such as PFOA and PFOS. On physicochemical properties, fluoropolymers are better understood as a separate class than as a subset behaving like the rest. Their size and stability leave them insoluble in water, which is precisely why they present very low or no risk of environmental contamination and why they are not bioaccumulative. Fluoropolymers cannot penetrate a human cell.

The relevant difference between fluoropolymers and compounds such as PFOA is not the degree of fluorination — both are highly fluorinated — but molecular size and physical form. PFOA is a small molecule that dissolves and travels, and PFOA has oxygen and a hydroxyl atom at the acidic end of the molecule, allowing it to interact with water. On the other hand, a fluoropolymer molecule is a solid too large to dissolve in water, migrate, or be absorbed by the human body. The two substances share a definitional label but behave nothing alike.

Persistence is a hazard unless it's paired with toxicity, mobility or bioavailability. When all three of those additional attributes are absent, persistence describes a durable material rather than a contaminant — and durability, as Section VII shows, is environmentally advantageous in this product category.

Korzeniowski, Buck, *et al* found in their June 2022 study that fluoropolymers are insoluble (e.g., water, octanol) solids too large to migrate into the cell membrane making them nonbioavailable, and therefore, of low concern from a human and environmental health standpoint. Further, the study results demonstrate that fluoropolymers are a distinct and different group of PFAS and should not be grouped with other PFAS for hazard assessment or regulatory purposes. (The study is being submitted as an accompaniment to this letter.)

Henry, Carlin, *et al* found in their study that with a molecular weight well over 100 000 Da, fluoropolymers cannot cross a cell membrane. Fluoropolymers are not bioavailable or bioaccumulative, as evidenced by toxicology studies on polytetrafluoroethylene (PTFE): acute and sub-chronic systemic toxicity, irritation, sensitization, local toxicity on implantation, cytotoxicity, in vitro and in vivo genotoxicity, hemolysis, complement activation, and thrombogenicity. Clinical studies of patients receiving permanently implanted PTFE cardiovascular medical devices demonstrate no chronic toxicity or carcinogenicity and no reproductive, developmental, or endocrine toxicity. (The study is being submitted as an accompaniment to this letter.)

C. Potential human exposure pathways

For cookware and food-contact appliance surfaces, the pathway of concern is migration into food.

Direct testing addresses the most common consumer concern. A laboratory study published October 1, 2025 by dTest, a Czech consumer organization, found that even intentionally damaged non-stick pans did not release measurable PFAS. That finding was produced by an independent consumer-testing body, not by industry, and it speaks directly to the scratched-pan scenario that drives most public anxiety about this product category.

This is consistent with long-standing U.S. regulatory treatment. Fluoropolymer coatings have been authorized for food contact under 21 C.F.R. § 177.1550 since the early 1960s, under a U.S. Food & Drug Administration regulation that requires the coated article to meet defined extraction limits when tested with aqueous, alcoholic, and fatty food simulants at reflux temperature.

US-FDA's current public materials on PFAS acknowledge that only very small amounts may enter food through processing and cookware — a non-quantified statement consistent with the testing record noted above.

We would draw the Department's particular attention to what US-FDA did in January 2025, under the Biden Administration, because it is an example of a regulator applying to PFAS food-contact uses precisely the distinction the New Mexico Legislature drew.

On January 3, 2025, US-FDA issued a notice in the Federal Register determining that 35 food contact notifications related to PFAS were no longer effective, effective January 6, 2025. Those notifications had authorized grease-proofing coatings applied to paper and paperboard food packaging. US-FDA has stated that this action, combined with its earlier work on long-chain PFAS, removes all PFAS grease-proofers with known safety concerns from the market, and that completing that phase-out eliminates the primary source of exposure to PFAS from authorized food contact uses.

Two features of that action bear on the Department's inquiry. First, US-FDA reviewed PFAS in food-contact applications comprehensively and removed an entire category of authorized uses. Second, having done so, it left the authorization for perfluorocarbon resins at 21 C.F.R. § 177.1550 — the authorization under which fluoropolymer cookware coatings are used — in place.

This was not inattention. It was an agency with full jurisdiction over food-contact materials, conducting an active PFAS review, deciding which authorized uses to withdraw and which to retain — and characterizing the uses it withdrew as the primary exposure source. We would note as well that this determination was made under the prior Administration, which was pursuing PFAS regulation vigorously across multiple agencies. It was not the product of a deregulatory posture.

The federal regulator with the deepest evidentiary base on food-contact PFAS has therefore drawn the same line the New Mexico Legislature drew; that is, not all PFAS in food contact present the same risk, and fluoropolymer cookware coatings fall on the retained side of that line.

In Europe, the German Federal Institute for Risk Assessment (BfR) concluded in February 2025 that no adverse health effects are expected from PTFE non-stick surfaces, and that inert particles, if ingested, pass through the body unchanged.

D. Possible health impacts

What we would ask the Department to weigh here is convergence. Independent bodies, applying different methods in different jurisdictions, all reached the same conclusions—that PTFE is safe: the European Food Safety Authority (EFSA), the International Agency for Research on Cancer (IARC), Health Canada, the Interstate Technology and Regulatory Council, and the American Cancer Society.

PFOA and PFOS have already been phased out of commerce in the U.S. Those are the compounds behind the health findings most often cited in support of broad restriction. Fluoropolymers are a different material with different properties, and sharing a definitional label with PFOA and PFOS is not a reason to treat them the same way.

Lee, Kang, *et al* found that tested PTFE for toxicity using two sizes of polytetrafluoroethylene (PTFE) microplastics, approximately 5 µm and 10–50 µm, which were manufactured and used for single and four-week repeated toxicity and pharmacokinetic studies. Toxicological effects were comprehensively evaluated with clinical signs, body weight, food and water consumption, necropsy findings, and histopathological and clinical-pathological examinations. Blood collected at 15, 30 60, and 120 min after a single administration of microplastics were analyzed by Raman spectroscopy. In the toxicity evaluation of single and four-week repeated oral administration of PTFE microplastics, no toxic changes were observed. (The study is being submitted as an accompaniment to this letter.)

We also offer a body of evidence from the medical-device field, and we state its scope precisely. PTFE has been used to coat pacemakers planted into human bodies since the early 1960s. PTFE continues to coat stents, catheters, vascular grafts, and sutures.

In evaluating fluoropolymers as used in implantable and interventional medical devices, the US-FDA has stated that fluoropolymers are typically comprised of molecules too large to cross cell membranes and are therefore very unlikely to cause toxicity to patients. US-FDA partnered with ECRI on an independent review drawing on more than 1,750 published, peer-reviewed articles and real-world surveillance across more than 1,800 health care providers; that review found no conclusive evidence of patient health issues associated with PTFE as a material.

That work was conducted in the medical-device context, and we do not present it as a cookware finding. We offer it because it evaluates the same polymer under conditions of sustained internal contact considerably more demanding than food preparation, by an independent reviewer applying a large evidence base. The Department should view this this for what it is — which, in our submission, is substantial evidence after decades of use by the highly cautious medical profession.

And to be clear, the temperature of cookware during normal use does not distinguish its safety from that of PTFE's use in medical devices. A pan would have to be heated to about 800°F for approximately 2 hours in order for measurable degradation to occur. Your home would be filled with smoke long before then and any food in the pan would be incinerated. A study by Alaboodi, et al. (2024) demonstrated that for the pans measured, PTFE exposure to temperatures of 842 °F/ 450 °C for 2 hours caused the pans to lose only 0.05-0.1g of material.

On the Legislature's premise

HJM 3 asked whether the literature remains limited. The answer is no; the body of science is vast and the direction of the evidence has been consistent, not mixed. We cite independent, refereed, science journal articles; not industry funded or commissioned studies. We would welcome the Department testing that proposition against the sources listed in the Appendix, which we are happy to provide, as well as the studies we are submitting to accompany this letter.

V. Removal would forfeit affirmative health benefits

The Department's report is asked to assess the public health risks of the exemptions. The public health consequences of removing them should be likewise considered, because in this product category those consequences are real and measurable.

A. Cookware: the cooking surface sets the dose of added fat

Non-stick cookware uniquely enables low- and no-fat home cooking. This is not a marketing claim; it is measurable at the pan. Consumer testing found that releasing a fried egg required no added oil in a fluoropolymer-coated pan, versus approximately one teaspoon for ceramic, one and a half teaspoons for stainless steel, and two tablespoons for cast iron.

The public health significance follows from how households actually cook:

- Most Americans who cook at home cite health as their primary motivation (63 percent), and home cooking is associated with better dietary outcomes (Wolfson et al., 2015).
- Roughly 60 percent of recipes call for added fat, with butter — a saturated fat — the second-most-used at 32 percent.
- Approximately 70 percent of households use non-stick cookware, valuing it for easy release (37 percent) and easy cleanup (31 percent).
- If non-stick were unavailable, 75 percent of consumers report they would compensate by seasoning pans or using more oil — directly undercutting the health rationale.

Repeatedly heated cooking oils also release aldehydes and acrolein, which are associated with adverse health effects. A measure that predictably increases the volume of oil used and reheated in New Mexico kitchens carries a health cost that should appear in the Department's analysis. Cooking fats are themselves a recognized burden on municipal wastewater systems, where fats, oils and grease contribute to line blockages and complicate treatment — a cost borne by the same public infrastructure HJM 3 identifies among the Act's concerns.

Heart disease is the leading cause of death in New Mexico, accounting for close to one in five deaths and averaging roughly 3,406 deaths annually over the past decade, according to the New Mexico Department of Health. A measure that predictably increases cooking fat use and shifts consumption toward processed and restaurant food carries a cardiovascular cost that belongs in the Department's analysis.

B. Small kitchen appliances: three functions with no equivalent substitute

The exemption's effect on small electric appliances deserves separate treatment, because the functions are different and the alternatives are weaker.

Hot-liquid and beverage conveyance

In coffee and espresso appliances, fluoropolymer linings ensure chemical inertness under sustained, controlled heat and pressure, preventing corrosion and the migration of metal ions into the beverage stream. Removing them would introduce a direct and inadequately studied food-safety risk into a product category used daily by probably most of New Mexico's 800,000 households.

Internal sealing and mechanical components

Fluoroelastomer seals that can be wetted by beverages maintain the barrier between the food-contact zone and the mechanical interior of motor-driven and pressurized appliances, under chemical exposure, controlled heat, and abrasion. Seal failure in a high-temperature, high-pressure system is a safety matter and a contamination pathway. Seals are also used for room temperature or cooled beverages for durability and cleanability. Seal durability also determines how often a consumer must replace the entire appliance — a point that bears on the waste analysis in Section VII.

Food-contact cooking surfaces in appliances

Waffle plates, sandwich grills, woks, and similar geometries depend on non-stick release for their core function, and are physically incompatible with bare-metal substitution. Removal of the coating without substitution does not degrade the appliance; it eliminates the function that defines it.

New Mexico's exemption ensures that these products remain available to New Mexico households. Maine has taken the opposite course: having declined to grant a currently unavoidable use determination for fluoropolymer components in small kitchen appliances, the state has intentionally brought coffee machines into the scope of its cookware restriction. Maine is the only jurisdiction in the United States, Canada or Europe to have reached that result. It is a concrete illustration of what removing an exemption means in practice — not a narrowing of a product category, but the disappearance of a functioning household appliance as popular as coffee machines from the market. And all the while, PTFE is proven to be perfectly safe. We ask the Department to preserve New Mexico's approach.

A distinction the Department should preserve is internal components

In many of these applications — internal seals, valves, and internal liquid pathways — the fluoropolymer is an engineering element within the sealed body of the appliance. It is not a surface the consumer handles, and in most cases not one that the consumer will ever see.

The Department has already recognized this distinction. The current regulation permits a label waiver where a product appears on the exemption list and there is no direct consumer contact with the substance. That provision reflects a considered judgment that excluding fluoropolymers for practical reasons will not impact human health or the environment.

That recognition, however, is conditioned on exemption-list status. If fluoropolymers were removed from the list, the waiver would become unavailable to these products as a matter of eligibility, regardless of whether consumer contact occurs. A sealed internal component that the consumer never

touches would be treated identically to a food-contact surface — not because the exposure facts had changed, but because the mechanism that recognized them had been withdrawn.

We ask the Department to weigh that consequence explicitly. Delisting would have two distinct effects: the phaseout, and the loss of a waiver provision the Department itself designed to calibrate obligations to actual exposure. The second is easily overlooked, and it would apply to a substantial share of fluoropolymer use in small appliances — internal seals, valves, and liquid pathways within sealed bodies, which perform safety and containment functions without ever contacting the user.

VI. No reasonably available alternative exists

A. Documented performance gap

Ceramic coatings are not intrinsically non-stick. They are often cited, however, as the best alternative to PTFE-coated nonstick pots and pans. Their release performance depends on modifiers that degrade with heat and washing (Rossi et al., 2022). The measured consequences:

- In the 2012 National Advertising Division proceeding *DuPont v. GreenPan Thermolon*, the ceramic surface failed a standardized egg-release test at its 10th cycle (2.45 of 5), while the fluoropolymer surface averaged 4.7 after 10 cycles and did not fail until its 67th (4.08 of 5).
- An April 2025 study found that after 90 cooking cycles the lowest-performing ceramic surface required nearly nine times more force to release food than a fluoropolymer-coated pan, and that fluoropolymer coating offered the best protection against impact wear.
- Consumer research confirms ceramic cookware wears out and is replaced sooner (Palermo, 2020).
- Independently, the New York Times' Wirecutter has advised readers against relying on ceramic non-stick pans, concluding that fluoropolymer coatings retain non-stick performance substantially longer.

B. Bare metals, alternative polymers, and elastomers

Cast iron, stainless steel, and raw aluminum lack intrinsic non-stick performance; even with added oil, release is inferior. For hot-liquid pathways and sealing applications, unlined metal, silicone, thermoplastics, and common elastomers including NBR and EPDM each fail on at least one of the required axes — chemical inertness, thermal stability, or durability — and none carries equivalent food-contact authorization that nonstick cookware has obtained from the US-FDA.

C. Cost — and the Act's own reasonable-availability criterion

The regulatory definition of "reasonably available" includes comparable costs, and changes to the manufacturing process. On the market data, no alternative to fluoropolymer-coated cookware meets that standard.

Beginning with initial purchase price, before any adjustments, independent market data (Circana NPD, L52W, May 2026) shows fluoropolymer-coated cookware averaging \$36.63, versus \$51.30 for ceramic, \$43.44 for uncoated cookware, and \$62.69 for other specialty products. Fluoropolymer-coated cookware is the least expensive option in the category on the day of purchase — including against bare metal. That comparison requires no methodology at all.

The gap widens when service life is accounted for, which is the measure that matters to many households focused on affordability today. The durability differential is taken from the 2012 National Advertising Division proceeding *DuPont v. GreenPan Thermolon*, in which the ceramic surface failed a standardized egg-release test at its 10th cycle while the fluoropolymer surface did not fail until its 67th — a ratio of approximately seven to one, which we apply as the replacement-frequency assumption.

Cast iron and stainless steel likewise cost more on average, and cast iron carries practical accessibility burdens — weight, storage, and lifting — that matter disproportionately for older consumers.

In New Mexico, fluoropolymer-coated cookware averages \$41.34 and ceramic averages \$53.41. Applying the same replacement-frequency assumption, a New Mexico household choosing ceramic cookware would face roughly \$374 in cookware cost over the same period in which it would spend just \$41 on fluoropolymer-coated cookware.

The distributional consequence follows. Purchaser data (Stackline Shopper, L52W) show 51.3 percent of fluoropolymer-coated cookware buyers earning under \$75,000. Ceramic purchasers skew higher income, with 53.9 percent earning above \$75,000. Removing the fluoropolymer option would not remove a cost from New Mexico households. It would transfer one, and it would fall most heavily on those least able to absorb it.

D. The alternative – Ceramic - is less studied — and carries its own emerging regulatory risk

Ceramic coatings have not been studied for the same duration or with equivalent rigor as fluoropolymers, which as we've submitted, have been US-FDA-authorized for food contact since the early 1960s, and are among the most examined materials in the entire food-contact space.

Further, the process depends on siloxane precursors — the precursors to the silicone oils in ceramic coatings — which are themselves attracting increasing regulatory scrutiny, and curing generates volatile organic compound emissions that fluoropolymer coating does not.

Substituting a less-studied material, with an active and unresolved regulatory profile, for a well-characterized and extensively reviewed one is not a precautionary outcome. At minimum, we submit that the Department should expect the same standard of scrutiny for the proposed alternative as has been applied to the incumbent before recommending a substitution. We all want to avoid regrettable substitutions, lessons we learned when BPA was replaced by BPS and BPF, and incandescent light bulbs were replaced by CFL bulbs—only to learn later that the replacement was as bad, if not worse, and the original product being phased out.

E. Manufacturing and supply-chain consequences

Ceramic coating on cookware cannot be roller-applied; because cured ceramic cannot be re-formed, it requires spray application. Converting coating lines would raise production costs by an estimated 10 to 15 percent in capital expenditure, downtime, and requalification. Because spray-configured infrastructure is concentrated in Asia, a forced transition would advantage offshore production — particularly in China — and erode U.S. and allied manufacturing capacity, without a demonstrated health or environmental benefit.

VII. Removal would worsen environmental and safety outcomes

This section bears most directly on the Department's own mission, and we would encourage close examination of it.

A full product life-cycle assessment of the two coating technologies (Maabi cookware LCA) finds that ceramic's overall health and environmental footprint is materially higher than fluoropolymer's. Two findings drive the result:

- **Cooking fats dominate the life-cycle impact.** Fats and oils account for roughly 40 percent of a coated pan's total life-cycle impact — the single largest contributor — and ceramic requires added oil far more often than fluoropolymer coating (on the order of 100 percent of cooking occasions versus 71 percent).
- **Shorter service life compounds everything.** Ceramic must be replaced roughly seven times more often over the same period of use, multiplying upstream manufacturing and raw-material burden, and generating on the order of seven times more end-of-life waste going into municipal and rural landfills.
- **Cooking causes most house fires in the U.S.** Every year in the United States, cooking oil ignites roughly 170,000 home fires, kills 135 people, and causes nearly half a billion dollars in property damage. In addition, when heated past its smoke point — which most home cooks exceed routinely, without noticing — oils release fine particulate matter, aldehydes, and acrolein into unventilated kitchen air. When poured down the drain, oil congeals into the blockages that drive untreated sewage into streets and waterways.

HJM 3 identifies municipal solid waste management and disposal infrastructure as one of the cost burdens the Act was intended to address. On the life-cycle evidence, removing the fluoropolymer exemption would increase the volume of cookware entering New Mexico's waste stream by a substantial multiple. That is the opposite of the outcome the Legislature sought when passing the PFAS Protection Act. We recognize that end-of-life for nonstick cookware is a legitimate area of concern.

VIII. Equity and access for New Mexico households

HJM 3 asks the Department to assess economic risk. The distributional dimension is, in our submission, the most important part of that assessment.

As we've already highlighted, market data show fluoropolymer-coated cookware buyers skewing toward lower-income households — 51.3 percent earning under \$75,000, compared with 46 percent for ceramic. Ceramic buyers skew higher income. Removing the affordable option therefore shifts cost onto precisely the households least able to absorb it, and toward products that cost more and last less.

These figures land on a population less able to absorb added cost than most. According to the American Community Survey, the median household income in New Mexico is \$67,816, approximately 80 percent of the national median household income of \$81,604. The share of New Mexicans living below the poverty line is 16.4 percent, roughly 34 percent higher than the national poverty rate of 12.2 percent. Analysis of Census county-level income data indicates that in 32 of New Mexico's 33 counties, median household income falls below the U.S. average.

Geography compounds this. New Mexico's population density is approximately 17 people per square mile, against a national average of roughly 94. For households distant from full-line retailers, the practical range of cookware available locally is narrower than a statewide market analysis would suggest, and the cost of traveling to obtain an alternative is a real component of the price. Where the affordable option is removed from the shelf, the substitute is not simply more expensive — for some households it is materially harder to obtain at all.

The combination is what concerns us. Fluoropolymer-coated cookware is the least expensive option in the category at initial purchase, and its purchasers skew lower-income. New Mexico households have roughly four-fifths of the national median income to work with, face poverty at nearly one and a half times the national rate, and the Western region of the U.S. has the highest cookware prices in the country. A measure that removes the accessible—but perfectly safe—option from this market does not distribute its costs evenly. It concentrates them.

We note that the Legislature required labeling in both English and Spanish, including for exempt products — a recognition that New Mexico's consumer protections must reach households in practice and not only in form. We would ask that the same practical consideration extend to affordability and access.

IX. What removal would communicate to New Mexico households

The Department's consumer materials advise New Mexicans that PFAS can enter the body and remain there for decades, that these substances may take up to a thousand years to break down in nature, and that the class is associated with cancer, liver disease, kidney damage, impaired immunity, and reproductive problems. For the mobile, bioavailable compounds that drove the Act, such as PFOA, PFOS and Gen-X, those communications are appropriate and well founded.

They attributes do not describe fluoropolymers, however. The evidence set out in Section IV indicates these materials are not absorbed into human bodies or water, do not bioaccumulate, are non-toxic, and do not meaningfully migrate into food. If the exemption were removed, however, that is nonetheless the message New Mexico households would receive about the cookware in their kitchens, which is not grounded in evidence.

A regulatory determination carries a communicative effect as well as a legal one. We would ask the Department to consider whether conveying that misleading specific set of associations — cancer, liver disease, reproductive harm — in relation to a material the evidence indicates does not enter the body and is perfectly safe, serves the public understanding the PFAS Protection Act was meant to advance.

X. Responses to the principal arguments for removal

We anticipate the Department will receive comment urging removal. We address the likely arguments directly, and we would welcome the chance to respond to any others the Department finds persuasive.

Argument for removal	Response
“Fluoropolymers are PFAS by definition, so they should be regulated as PFAS.”	The definitional point is accepted — we have never argued otherwise. But the Legislature drew the line at fluoropolymers knowing that, and drew it by molecular architecture rather than by product category. The US-FDA drew the same distinction in January 2025, withdrawing 35 PFAS food-contact authorizations for paper grease-proofers while retaining the authorization covering fluoropolymer cookware coatings. The question for the report is not classification but consequence: whether removal would reduce the contamination and costs HJM 3 identifies. It will not. Sections III and VII address that.
“Fluoropolymer manufacture emits PFAS of concern.”	This concern was legitimate; however, it is about upstream chemistry, not the finished consumer good. The PTFE used by the cookware industry represents less than 1% of global PTFE produced each year. The “PFAS of concern” raised here is primarily PFOA, which was completely phased out of manufacturing throughout the U.S. in 2013. In other words, a retail prohibition in New Mexico reaches no manufacturing process anywhere and leaves 99% of the market untouched.
“Disposal and incineration release PFAS.”	A legitimate concern, and the one we take seriously. Removal is worse, not better: the life-cycle evidence indicates the alternative generates on the order of seven times more end-of-life waste over the same period of use. We propose addressing disposal directly through collection and recycling. See Sections VII and XIII.
“The precautionary principle favors removal.”	Applied evenly, it does not. The proposed substitute is less studied, less durable, and depends on precursors under active regulatory scrutiny, with VOC emissions the incumbent does not generate. The Fiscal Impact Report to HB 212 acknowledged there is no current consensus on a safe level of PFAS; where uncertainty is general, precaution supports differentiation rather than uniform prohibition, and it also supports retaining the extensively characterized material until the alternative has been examined to a comparable standard, to avoid regrettable substitutions.
“Other states restrict this category.”	The trend runs the other way. Illinois removed cookware and directed a fluoropolymer risk assessment; Vermont delayed its cookware provision after reviewing the science; California’s SB 682 cookware phase-out was vetoed over affordability and access. See Section XI.
“Safer alternatives exist.”	“Alternative” and “safer” are distinct findings. Section VI sets out the documented performance, cost, and study-depth gaps. We would ask that any alternatives finding rest on evidence specific to the alternative, not on the absence of evidence about it.

XI. The broader regulatory record supports continuation

Since New Mexico acted, other jurisdictions have moved in the same direction of keeping either cookware, or fluoropolymers, or both, out of PFAS product bans. Illinois removed cookware from its

restriction and directed a fluoropolymer risk assessment. Vermont delayed its cookware provision after reviewing the fluoropolymer science. California's SB 682 cookware phase-out was vetoed over affordability and access concerns.

Developments in Europe are even more striking. In mid-2026, four European governments — Germany, Belgium, Slovakia, and the Czech Republic — filed comments in the European Chemicals Agency's socio-economic assessment consultation on the proposed universal PFAS restriction, opposing a universal ban as an approach. Germany, which was among the original architects of that restriction, cautioned that a universal restriction risks disproportionate burdens and enforcement gaps, particularly for downstream users and specialized applications.

When governments that helped design the world's most ambitious PFAS restriction revisit their treatment of fluoropolymers specifically, that is material the Department's report should reflect.

New Mexico was the first state to enact a fluoropolymer exemption, and you did so with near-unanimous support in both chambers and support of environmental groups. That is worth recording. The provision was not an oversight; it was a considered judgment, adopted by wide bipartisan margins, that a class of thousands of chemicals should not be regulated as though every member behaved identically. Developments around the world since then suggest New Mexico was early rather than wrong.

XII. Requested recommendation

The Cookware Sustainability Alliance respectfully requests that the Department's report to the Governor and Legislature **recommend that the fluoropolymer exemption at Section 3 of the Act be continued.**

We would welcome the opportunity to meet with Department staff, to answer questions, and to provide any of the underlying studies referenced here. We would particularly welcome hearing what evidence the Department considers still missing. If there are gaps we can help fill, we would prefer to fill them than to have the report rest on an incomplete record.

Thank you for your consideration and for the opportunity to participate.

Respectfully submitted,

(submitted electronically)

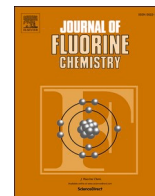
Steve Burns, President, Cookware Sustainability Alliance

Appendix: Sources referenced

Offered for the Department's convenience. Full copies available on request.

Category	Source
Classification	OECD, Synthesis Report on Understanding Fluoropolymers and Their Life Cycle
Hazard assessment	Peer-reviewed critical review applying polymer-of-low-concern criteria, Integrated Environmental Assessment and Management, Vol. 19, No. 2, 326–354
Environmental fate	Environmental-fate study, September 2025
Migration testing	dTest (Czech Republic), laboratory testing of damaged non-stick cookware, October 1, 2025
Health assessment	German Federal Institute for Risk Assessment (BfR), February 2025
Health assessment	EFSA; IARC; Health Canada; Interstate Technology and Regulatory Council; American Cancer Society
Federal framing	U.S. EPA, Our Current Understanding of the Human Health and Environmental Risks of PFAS
New Mexico legislative record	Fiscal Impact Report accompanying House Bill 212 (2025)
Medical-device context	FDA / ECRI independent review (2021; further FDA statement August 2025) — medical-device scope
U.S. food-contact authorization	21 C.F.R. § 177.1550, Perfluorocarbon resins
FDA PFAS food-contact action	FDA notice, Federal Register, January 3, 2025 — determination that 35 PFAS-related food contact notifications (paper/paperboard grease-proofers) are no longer effective, effective January 6, 2025; FDA, Authorized Uses of PFAS in Food Contact Applications
Durability and performance	Rossi et al. (2022); NAD, DuPont v. GreenPan Thermolon (2012); peeling-force study (April 2025); Palermo (2020)
Independent consumer testing	The New York Times / Wirecutter, non-stick cookware evaluations
Home cooking and diet	Wolfson et al. (2015); consumer research on cooking motivation, recipe fat use, and substitution behavior
Life-cycle assessment	Maobi cookware life-cycle assessment
Market and pricing data	Circana NPD, L52W, May 2026

Category	Source
European regulatory	ECHA socio-economic assessment consultation comments — Germany, Belgium, Slovakia, Czech Republic, mid-2026
Multistate record	Illinois cookware removal and risk assessment directive; Vermont cookware delay; California SB 682 veto



Mineralization of PTFE under conditions representative of municipal solid waste to energy incineration facilities

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ABSTRACT

The objective of this study was to assess the effective mineralization of polytetrafluoroethylene (PTFE) during thermal treatment under municipal solid waste incinerator (MSWI) conditions and to evaluate the potential formation of per- and polyfluoroalkyl substances (PFAS) and select other products of incomplete destruction (PIDs). Analyses were performed on aqueous phase impinger samples (long chain PFAS under a modified EPA Method 537, and short chain C1-C3), as well as gas phase byproducts under OTM-50. A commercial grade PTFE sample was first subjected to elemental analyses and then incinerated in a bench-scale combustion system designed to represent conditions typical of MSWIs in the United States and European Union. Experimental system setpoints were chosen by computational fluid dynamic modeling and compared with an empirically measured temperature profile, to achieve a bulk material temperature as high as 1150 °C and remain in the reactor for approximately 2 s. These parameters were informed by a comprehensive literature review of MSWI operating conditions.

The experiment was run in triplicate and all instances demonstrated that all target analytes as non-detectable, or below the respective method reporting limit. In-line FTIR monitoring of hydrogen fluoride (HF) concentration achieved between 95.6 % and 97.4 % fluorine recovery, compared to between 79.0 % and 80.4 % fluorine recovery via aqueous fluoride-ion based calculations. Calculated destruction efficiency across the experiments averaged 99.99962 % for PTFE. These findings indicate that PTFE undergoes effective mineralization under typical incineration conditions, and that MSWI is a means of responsible end-of-life management for the fluoropolymer.

1. Introduction

Polytetrafluoroethylene (PTFE) is a widely used fluoropolymer within the broader class of per- and polyfluoroalkyl substances (PFAS). PTFE is further distinct from many others in the fluoropolymer family in that it consists of a fully fluorinated carbon backbone; a structural feature that imparts exceptional chemical stability and inertness distinguishing it from other polymers [1]. PTFE is one of the most widely used fluoropolymers in global commerce [2] due to its performance and unique combination of properties making it indispensable across critical industries. Further, PTFE is classified as a polymer of low concern due to its high molecular weight, chemical inertness, and negligible solubility, which together limit bioavailability and reactivity. Additionally, absence of reactive functional groups and low residual monomer content

further reduce potential toxicological and environmental risks under typical conditions of use [2].

PTFE is the dominant fluoropolymer in commercial use, accounting for an estimated ~45 % of global fluoropolymer consumption by volume, with reported shares ranging from ~35 % to >60 % depending on market segmentation and methodology [3]. Consequently, PTFE can be expected to represent a substantial fraction of fluoropolymer waste streams, particularly in industrial and high-volume applications, although the precise proportion will depend on differences in product lifetimes, recycling practices, and sector-specific usage patterns.

Numerous assessments have demonstrated that PTFE remains chemically inert during its service life and does not undergo environmentally relevant transformation into smaller fluorinated species [4]. PTFE's exceptional resistance to degradation derives from the strength

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and shielding of its carbon-fluorine framework. The C-F bond dissociation energy in fluorocarbons is on the order of $\sim 480\text{--}540\text{ kJ mol}^{-1}$, among the strongest single bonds in organic chemistry, while the fully fluorinated backbone effectively protects the C—C bonds ($\sim 350\text{--}370\text{ kJ mol}^{-1}$) from chemical attack. Thus, thermal destruction of PTFE requires substantial energy input to fully mineralize rendering it among the most chemically inert fluoropolymers to destroy.

As PTFE-containing products reach their end-of-life, thermal treatment via municipal solid waste-to-energy incineration represents a common disposal pathway in many regions [5]. Although incineration is broadly recognized as an effective method for destroying organic materials, the fate of fluorine-containing polymers during thermal treatment has been the subject of ongoing scrutiny. Questions persist regarding whether PTFE undergoes complete mineralization to inorganic end products or whether partial breakdown could lead to the formation of volatile or semi-volatile fluorinated organic species [6,7]. While some recent studies have evaluated the fate of composite fluoropolymers, or other individual fluoropolymers [8], a gap existed for PTFE as a standalone test subject with a robust set of PFAS analytes suspected to be products of incomplete destruction (PIDs), and exacting QA/QC checks before this study.

Given PTFE's prevalence in commercial and industrial applications and the inherent strength of its structure, it is especially important to study its thermal decomposition under realistic waste management conditions. Lab scale investigation designed to replicate municipal solid waste incineration conditions were conducted to evaluate and characterize the mineralization efficacy of PTFE. This study was conducted to support regulatory decision-making by demonstrating that the incineration of PTFE under standard conditions does not produce PFAS above respective method limits of quantification and is a means of end of life destruction consistent with protection goals. A review of existing literature and peer reviewed studies informed the selection of test conditions characteristic of normal municipal solid waste (MSW) waste-to-energy (WTE) incineration plant operating conditions. A summary of these conditions based on key publications [9,10] are noted below and the supplemental information contains a list of relevant literature reviewed during the study's initial planning phase. It is important to note that full-scale systems are dynamic and measured temperature and residence time may vary from discrete points or sections.

- Reactor Temperature: $850\text{--}1150\text{ }^{\circ}\text{C}$.
- Oxygen in Exhaust: $6\text{--}13\%$ (dry basis).
- Gas Residence Time: 2 s.
- Moisture: $>10\%$.

A review of PFAS treatment in combustion-based thermal waste systems by Weitz et al. [11] highlights significant uncertainty in both the extent of PFAS mineralization and the formation and emission of fluorinated PIDs. Recent thermolysis studies of PTFE and PTFE-containing mixtures [5,12,13] lack comprehensive analysis of volatile fluorinated compounds (VFCs) and ultra-short-chain PFAS (C1–C3), key PIDs. Although two of these studies quantified trifluoroacetic acid (TFA), only one included limited analysis for five VFCs via Tedlar® bag grab sampling.

The release of EPA Other Test Method 50 (OTM-50) in 2024 enables standardized measurement of VFCs allowing more complete identification of PIDs. Application of OTM-50 in a recent bench-scale polychlorotrifluoroethylene (PCTFE) incineration study [8] identified trifluoromethane (CHF_3) and chlorotrifluoromethane (CClF_3) as PIDs at the lower temperature setting. Analysis for 42 additional PFAS (including five ultra-short chain PFAS) in impinger water showed substantial TFA formation and trace perfluoropropionic acid (PFPrA) at this same setting, with no $\geq\text{C4}$ PFAS detected despite near-complete fluorine recovery ($97\text{--}101\%$). FTIR sampling further indicated the formation of carbonyl fluoride (COF_2). Similar VFC PIDs have been detected in recent incineration studies of other PFAS containing materials including

carbon tetrafluoride (CF_4), hexafluoroethane (C_2F_6), tetrafluoroethene (C_2F_4), and COF_2 [11,14]. The results of these recent studies underscore the importance of including analysis for VFCs and ultra-short chain PFAS (C1–C3) in thermal treatment evaluation studies.

OTM-50 was used to assess PFAS PIDs in exhaust from PTFE incineration in a bench-scale system simulating U.S. and EU MSWI conditions. Beyond the 30 OTM-50 target analytes, non-targeted analysis of canister samples was performed to potentially identify additional VFCs. Impinger water was analyzed for five ultra-short-chain PFAS (C1–C3) and $36\geq\text{C4}$ PFAS, as well as fluoride ions to support fluorine mass balance. Exhaust gases were also analyzed by FTIR as an independent method to quantify HF and screen for PIDs.

The goal of this study is to contribute to the collective understanding of the fate of PTFE under operating conditions representative of real-world MSWI.

2. Materials and methods

2.1. University of Dayton research institute facility

The bench-scale reactor dimensions were $50\text{ mm} \times 45\text{ mm}$ (outer diameter $\times$ inner diameter) with a total length of 137 cm, composed of fused silica quartz. The setup contained three heating element zones with lengths of 6 inches, 18 inches, and 6 inches, respectively through the length of the reactor totaling 30 inches for an effective length of approximately 27 inches. Heating elements external to the reactor were set to and controlled via feedback loop at $1176\text{ }^{\circ}\text{C}$, $1140\text{ }^{\circ}\text{C}$, and $1165\text{ }^{\circ}\text{C}$ for Zones 1, 2 and 3, respectively. The reactor, front- and back- end flange assembly, including the feed sample thermocouple (TC), the outlet gas temperature monitoring TC, and the stainless-steel manifold used to split the gas flow, were replaced after each run with new components for each experimental set to avoid any carryover from the previous experiments. The stainless-steel manifold and the flange at the reactor exit were silico-coated to minimize surface reactions. The reactor exit temperature was continuously monitored to ensure it remained above the transfer line temperature to the FTIR ($\geq 191\text{ }^{\circ}\text{C}$).

2.2. Characterization of PTFE

A commercial grade sample of PTFE beads was acquired to be used in all test sequences. To validate the identity of the fluoropolymer, elemental analysis was carried out by Toray Research Center in Japan. The analytical method verifies the material identity by confirming the stoichiometry of carbon and fluorine. The analytical laboratory thermally decomposed the polymer in a combustion tube with an inlet temperature of $1000\text{ }^{\circ}\text{C}$ and outlet of $1100\text{ }^{\circ}\text{C}$. The system operated with a flow rate of 200 mL/min of Ar and O_2 . The decomposition breaks the sample down to measurable fragments of its constituent elements. The decomposition products were then absorbed into a 20 mL solution of 0.009% H_2O_2 , and examined using ion chromatography (AQF-2100H by Nittoseiko Analytech Co., Ltd). An internal standard of Br $8\text{ }\mu\text{g/mL}$ was employed, along with a mobile phase of $2.7\text{ mmol/L Na}_2\text{CO}_3/0.3\text{ mmol/L NaHCO}_3$ for a flowrate of 1.5 mL/min . Injection volume was $20\text{ }\mu\text{L}$ and ions were detected via a conductivity detector.

Considering the PTFE monomer as C_2F_4 (i.e., $\text{CF}_2\text{--CF}_2$) and taking the molecular weight of fluorine as 18.998 g/mol , and carbon as 12.011 g/mol , calculated mass percentage of F in a pure, or nearly pure, PTFE

Table 1
Elemental Analysis of PTFE Sample.

	Result (Mass % F)
n1	76.52
n2	76.42
Average	76.47

sample to be 75.981 %. The PTFE sample composition used for these experiments is detailed in Table 1 below.

2.3. Experimental design and bench-scale set-up

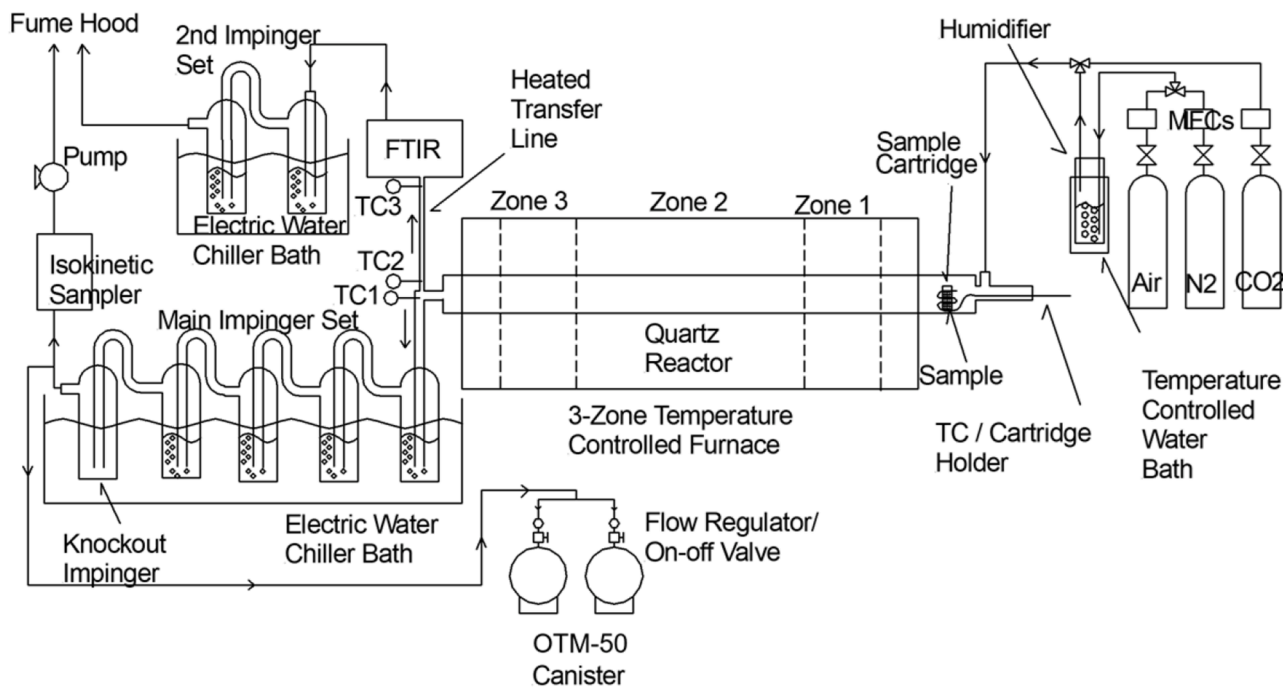
Experiments were conducted decomposing PTFE using a system setup designed by University of Dayton Research Institute (UDRI), as illustrated in Fig. 1A and 1B. The same system was developed and employed in a recent bench-scale incineration study of polychlorotrifluoroethylene (PCTFE) [8]. Carrier gases, including zero-grade air (21 vol.% O₂, 79 vol.% N₂), ultra-high-purity (UHP) nitrogen (N₂), and UHP carbon dioxide (CO₂), were supplied by Airgas. Gas flow rates were controlled using mass flow controllers (MFCs; Alicat MC series) set at 3.278 L/min for air, 2.546 L/min for N₂, and 0.343 L/min for CO₂, resulting in a gas composition representative of typical MSWI off-gas conditions (approximately 10 vol.% O₂ and 5 vol.% CO₂). The air/N₂ gas mixture was passed through a temperature-controlled humidifier to achieve a moisture content of 10–11 vol.%, which was monitored using FTIR spectroscopy (MKS MultiGas 2030). The total gas flow rate, including moisture, was 6.852 L/min.

A fused silica quartz tube reactor (50 mm OD × 45 mm ID, 137 cm length) was used for the experiments. The reactor was connected to the gas transfer line via flanges and housed within a three-zone

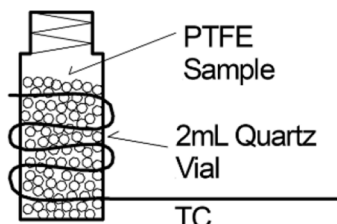
temperature-controlled furnace (Thermcraft, SST-3.00–0–30–3C-D2155-BE). The effective heated length, defined as the region maintaining temperatures within $\pm 5\%$ of the target temperature, was 27 in. Temperature was measured using a K-type thermocouple (KMQXL-125U-48, OMEGA) connected to a temperature reader (HH501DK, OMEGA) under flowing conditions of air, N₂, CO₂, and H₂O at the flow rates described above. The resulting temperature profile is provided in the Supplemental Information (Figure S19), and all experiments were conducted under these conditions. Based on the specified total gas flow rate and effective heated length, the gas residence time within the reactor was 2 s.

PTFE samples, consisting of beads with diameters of ≤ 1 mm provided by AGC (Japan), were placed in a 2 mL quartz vial (Cuvet Co.). The vial was held with a TC (OMEGA KMQXL-062 G), which also served to monitor the gasification temperature which can be taken as approximately 400 °C, corresponding with a distance of 0 in Figure S19 in the Supplemental Information. Approximately 1 g of PTFE was loaded into the vial for each experiment, with approximately 32 % of the sample mass gasified per test. The position of the vial within the reactor was minorly adjusted at its position before Zone 1 to achieve a stable gasification rate. Steady gasification was confirmed by monitoring the HF concentration in the effluent gas using FTIR spectroscopy.

The off-gas stream was split into two branches: one directed to the



(A)



(B)

Fig. 1. (A) Schematics of the Bench-Scale PTFE Incineration System and (B) Sample Cartridge Holder with TC.

main impinger sampling train and the other to the FTIR and secondary impinger sampling train. An isokinetic sampler (Apex, XC-5000) was used to draw gas through the main impinger train at an approximate flow rate of 5.3 L/min, including moisture. The main impinger train consisted of five 500 mL impingers (Apex), with the first four each containing 250 mL of analytically PFAS-free water (below laboratory reporting limits for target analytes as verified through analysis with each run) supplied by SGS (British Columbia, Canada), followed by an empty knockout impinger.

The remaining off-gas, at an approximate flow rate of 1.6 L/min, was directed to the FTIR for continuous monitoring of off-gas components, including HF, carbonyl fluoride (COF₂), H₂O, and CO₂, before passing through a secondary impinger train consisting of two 500 mL impingers (Apex), each containing 250 mL of analytically PFAS-free water. Additional details regarding the FTIR analysis is provided in the Supplemental Information, including a complete list of compounds monitored by FTIR (Table S3).

Approximately 2.2 m³ of gas was sampled through the main impinger train for PFAS and fluoride ion analyses, while approximately 0.66 m³ was sampled through the secondary impinger train for fluoride ion analysis. The heated transfer line and FTIR gas cell were maintained at 191 °C to minimize condensation and maximize off-gas transfer efficiency. Temperatures at critical locations, designated TC1–TC3 (the split line to the main impinger train, and the front and rear ends of the heated transfer line, respectively), were monitored and recorded every 30 min to ensure they remained above 190 °C. Table 2 summarizes the experimental conditions.

2.4. Experimental system cleaning process

The system cleaning procedure employed in this study has been described in detail elsewhere [8] and is only briefly summarized here. The impinger sampling trains, flanges, TC, sample vial, and associated connecting components were replaced with clean components for each test. The impinger sampling trains were initially washed with laboratory detergent (Liquinox, Millipore-Sigma), followed by sequential solvent rinsing with acetone, methylene chloride, and methanol. They were then baked at 450 °C under a nitrogen (N₂) atmosphere (PYRO—CLEAN TRACE, Barnstead Thermolyne), followed by a final rinse with 5 wt.% ammonium hydroxide and air-dried under ambient conditions.

The reactor was cleaned using the same detergent and solvent

washing procedure, followed by a 5 wt.% ammonium hydroxide rinse and air drying under ambient conditions, but were not subjected to the baking step. In addition, UDRI requested the analytical laboratory, Eurofins Environment Testing, to replace all tubing used for sample transfer within the analytical instrumentation, as well as all containers used for solid-phase extraction (SPE), in addition to implementing their standard cross-contamination prevention protocols.

2.5. Computational fluid dynamic modeling

Computational fluid dynamic (CFD) modeling was conducted to characterize the conditions throughout the length and cross-section of the gas during its residence in the reactor. Model development and results are included in the Supplemental Information.

The streamline analysis of the model was developed for a clamshell furnace with setpoint temperatures of 1176 °C, 1140 °C, and 1165 °C for Zones 1, 2 and 3, respectively, heated from outside of the reactor shell. Fig. 2 shows the volume where the gas was at these conditions and flowing axially in the positive direction for the vertical and horizontal planes; white space areas indicate temperatures below 982 °C or negative direction flow. All gas passed through the reactor at a median residence time of 2.1 s (1.96 s on average). Greater than 50 % of the gas reached above 982 °C, up to 1150 °C near the quartz tube walls, for at least 1.8 s. Modeling confirms the experimental design and operating conditions sufficiently represent those identified during the literature review.

2.6. Temperature profile empirical characterization

Prior to PTFE experiments, the furnace and reactor system were initiated at temperature and gas flow target conditions which would be used in the experiments, (1176 °C, 1140 °C, and 1165 °C for Zones 1, 2 and 3, respectively) and those gas flows outlined in Table 2. The gas flow rates were controlled using calibrated and certified digital mass flow controllers, and the temperatures were measured using a certified and calibrated thermocouple and thermocouple reader. No PTFE was gasified during the empirical temperature profile characterization. Once steady state was achieved, the thermal profile along the reactor length was determined by incrementally positioning a TC along the centerline of the reactor in one-inch intervals. At each location, the TC was allowed to equilibrate to the local temperature before recording the measurement. All temperature readings were collected at the approximate center of the reactor's cross-section. The resulting thermal profile is available in the Supplemental Information, Figure S1.

The experimentally generated thermal profile shows a relatively stable centerline temperature of approximately 1150 °C along the reactor length at steady-state, consistent with the modeled temperature distribution shown in Fig. 2. The CFD model analysis can improve our understanding of temperature distribution and residence time within the reactor systems of MSWI, compared with single-point experimental measurements. Unlike discrete thermocouple readings, which capture localized conditions and may not fully reflect spatial gradients under laminar flow conditions, CFD simulations resolve the coupled effects of fluid flow, heat transfer, and reactor geometry to generate continuous, spatially resolved profiles and velocity-weighted averages. This allows for the identification of temperature heterogeneity, flow recirculation, and residence time distributions that are inherently inaccessible through point measurements alone. Still, EU Industrial Emissions Directive (IED) compliant MSWI temperatures result in successful (>99.99 %) destruction efficiency, pockets of lower temperatures may exist within the chamber making sufficient turbulence within the combustion chamber necessary to ensure sustained temperatures adequate for PFAS destruction. The CFD model offers improvements in MSWI operator monitoring of temperature within the reactor. Further, single-point thermocouple measurements at the bench-scale may overestimate the temperature experienced by reactor contents due to spatial temperature

Table 2
Summary of the Experimental Conditions.

Parameters	
Reactor Length (cm)	127
Reactor OD (mm)	50
Reactor ID (mm)	45
Effective length (cm)	68.58
Zone 1 Temperature Setting (°C)	1176
Zone 2 Temperature Setting (°C)	1140
Zone 3 Temperature Setting (°C)	1165
Average Centerline Temperature within Effective Length (°C)	1151
Velocity-Weighted (Modeled) Average Temperature (°C)	982
Gas Residence Time (s)	2
Air Flow Rate (L/min.)	3.278
N ₂ Flow Rate (L/min.)	2.546
CO ₂ Flow Rate (L/min.)	0.343
Total Flow Rate (L/min.) (Dry-gas basis)	6.167
Moisture (%)	10
Total Flow Rate (L/min.) (Wet basis)	6.852
Expected O ₂ Conc. (%)	10
Expected CO ₂ Conc. (%)	5
Incineration Time (hour)	7
Steam cleaning Time (hour)	1 or until HF concentration reached below 1 ppm
Sample Gasified (g)	Approximately 0.32

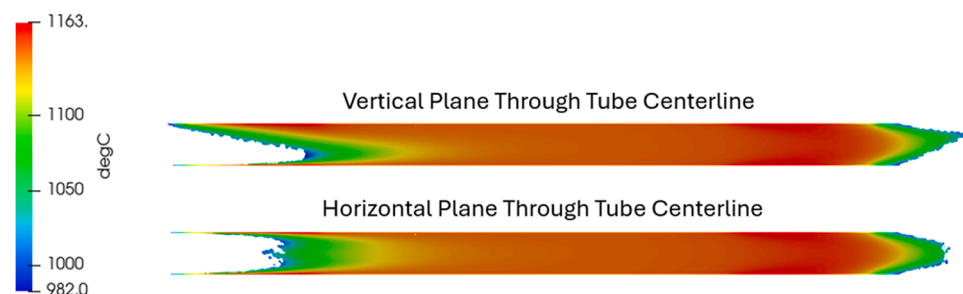


Fig. 2. Gas achieving $T > 982\text{ }^{\circ}\text{C}$ and axial velocity $> 0\text{ m/s}$ for vertical and horizontal planes.

gradients within the reactor and radiative heat experienced by unshielded probes. As a result, the CFD-derived profile offers a comprehensive and mechanistically meaningful depiction of reactor behavior under the system operating conditions, improving interpretation of experimental data and enabling more accurate assessment of system performance.

The empirical temperature profile provides additional evidence of temperature for bench-scale PTFE destruction approximating MSWI conditions. CFD modeling and empirical characterization of the temperature profile confirmed the experimental design and operating conditions sufficiently achieved those identified during the literature review in MSWI.

2.7. Experimental procedure, test sequence, sample collection, and analysis

Incineration tests were conducted in triplicate to demonstrate experimental repeatability. For each incineration test, blank runs using the identical experimental procedure but without PTFE sample introduction were performed both before and after the incineration test. Accordingly, each test sequence consisted of the following three experiments:

1. Blank Run before Incineration Test: To check for any background PFAS contamination in the experimental system.
2. Incineration Test: To examine if PTFE generates PFAS through the incineration process.
3. Blank Run after Incineration Test: To check for any carryover of PFAS, HF, and COF_2 from the incineration test.

Note: The temperature is based on the CFD and empirical characterization of the temperature profile in Table 2 throughout the experiments. The temperature was maintained automatically at the set points at the zone heating elements, external to the reactor tube.

From each experiment, including a blank run before and after the experiment, four sample types were extracted.

1. Analytically PFAS-free water: The original water used for the test was analyzed for PFAS to check for contamination in the water or the analytical laboratory.
2. Impinger Blank: Collected after the impingers were filled with analytically PFAS-free water, connected in series, and then disassembled. Impinger rinsate was also added to the collection container. Analyzed for PFAS to verify the impingers' cleanliness.
3. Main Impinger: Effluent gases passed through at approximately 5.3 L/min, analyzed for PFAS and fluoride ions. Indicates system contamination (blank run before the incineration test), PFAS generation (incineration test), and residual PFAS (blank run after the incineration test).
4. 2nd Impinger: Remaining gases passed through at approximately 1.6 L/min, first through FTIR, then the impinger. Analyzed for fluoride

ions to determine overall mass balance (incineration test) and cleanliness (blank runs).

During aqueous sample collection from the impinger trains, the U-shaped connecting tubes between impingers were also rinsed, and the rinsates were combined with the corresponding sample collection containers to ensure complete recovery.

Aqueous PFAS and fluoride ions were analyzed by Eurofins Environment Testing (Knoxville, Tennessee) using modified EPA Method 537 and EPA Method 9056, respectively. Gas samples collected in OTM-50 canisters were analyzed by Eurofins Environment Testing Air Toxics (Folsom, California) for non-condensable and water-insoluble fluorocarbons using the EPA OTM-50. Aqueous PFAS with carbon chain lengths of C1-C3 were analyzed separately by SGS-AXYS (British Columbia, Canada). PFAS target analyte lists are provided at the end of the manuscript.

2.8. Quality assurance and quality control (QA/QC)

To ensure that observed PFAS emissions could be attributed exclusively to PTFE incineration, rigorous measures were implemented to minimize background contamination and prevent false-positive detection. A comprehensive quality assurance and quality control (QA/QC) protocol was established prior to experimental testing.

Before each incineration experiment, a system blank run, conducted in the absence of any sample, was performed to verify that no detectable PFAS were present above the RL within the experimental apparatus. This evaluation encompassed all relevant components, including the sample introduction system, reactor, transfer lines, and impinger-based sampling train. Incineration experiments were initiated only after confirming the absence of PFAS in the system background.

To further mitigate potential contamination, all major system components, including the reactor, associated flanges, and the manifold connecting the reactor to both the impinger sampling train and the heated FTIR transfer line, were replaced with new parts prior to each experimental run. All components were subjected to thorough cleaning procedures, consisting of washing with laboratory-grade detergent followed by solvent rinsing.

In addition, the source water used in the impinger sampling train and the corresponding sampling blanks (i.e. pre-use rinsates collected from the sampling train) were analyzed for PFAS to confirm the absence of background contamination. These measures also enabled identification and traceability of any potential contamination sources, should they arise. A detailed description of the QA/QC procedures is provided in the Supplemental Information from a previous study [8].

2.9. Analytical methods

Effluent gas composition was continuously monitored via FTIR, including moisture, CO_2 , and HF to ensure a stable sample feed rate. The FTIR also qualitatively monitored SiF_4 as an indicator of fluorine reaction with the reactor walls. Sampling commenced when the PTFE sample

was introduced into the furnace's hot zone, where the fluoropolymer underwent decomposition and gasification. The effluent gas composition was monitored in real time using FTIR to maintain near-steady-state system conditions. The full suite of compounds monitored by FTIR is detailed in Table 3. Additional information regarding the FTIR analysis is provided in the Supplemental Information.

Each experimental run consisted of the following analyses:

1. The analytically PFAS-free water used in the impingers was analyzed for PFAS compounds with carbon numbers of 4 or greater (PFAS $\geq$ C4) using EPA Method 537 (modified), which targets analysis of 36 unique PFAS; a full analyte list is available in the Supplemental Information. This step verifies that the original water is free from PFAS contamination and monitors potential PFAS cross-contamination from the analytical laboratory.
2. The impinger blank involved placing analytically PFAS-free water in the first four impingers of the main impinger set and collecting the sample. This blank was analyzed for PFAS $\geq$ C4 using EPA Method 537 (modified) to verify the cleanliness of the impinger sampling train and is comparable to the Sampling Train Proof Blank described in Method OTM-45.
3. The main impinger sample was collected during both the before blank runs and the incineration test to capture off-gases. It was analyzed for C1-C3 PFAS (summary of method, analyte list, and reporting limits provided in Supplemental Information), PFAS $\geq$ C4 and fluoride ions (F⁻) by EPA Method 9056.
4. The second impinger sample captures off-gases from the FTIR system and was analyzed in comparison with fluoride ion data from both the main and second impinger sets, to characterize the F mass balance across the experimental system.
5. OTM-50 canisters were analyzed for 30 target volatile fluorinated compounds using the OTM-50 method. The OTM-50 canisters were also analyzed by TO-15 to evaluate non-target compounds that may be present.

3. Results

3.1. F ion based mass balance

Table 4 summarizes the F recovery based on fluoride ion analysis. The fourth row presents the total mass of fluorine introduced, calculated from the mass of PTFE gasified and the corresponding F/PTFE mass ratio. The second row from the bottom shows the total mass of fluorine recovered, determined from the fluoride ion concentration and volume of the impinger aqueous samples.

As illustrated in Fig. 1A, the effluent gas stream was split into two pathways: one directed to the main impinger and the other routed through the FTIR system followed by a secondary impinger. With this configuration, the entire exhaust gas stream passed through either the main or secondary impinger.

The final row reports the fluorine recovery as a percentage. The average fluorine recovery across the three experiments was 78.7 %, which is lower than that observed in a prior UDRI study [8], where near-complete (~100 %) fluorine recovery was achieved. Potential

Table 3
FTIR Analytes.

Gas-phase Compounds		Gas-phase Compounds	
1	Hexafluoroethane (C ₂ F ₆)	9	Difluoromethane (CF ₂ H ₂)
2	Octafluoropropane (C ₃ F ₈)	10	Ethane (C ₂ H ₆)
3	Decafluorobutane (C ₄ F ₁₀)	11	Ethylene (C ₂ H ₄)
4	Dodecafluoropentane (C ₅ F ₁₂)	12	Water (H ₂ O)
5	Tetrafluoromethane (CF ₄)	13	Hydrogen fluoride (HF)
6	Carbon monoxide (CO)	14	Silicone tetrafluoride (SiF ₄)
7	Carbon dioxide (CO ₂)	15	Trifluoromethane (CF ₃ H)
8	Carbonyl fluoride (COF ₂)		

Table 4

F Recovery Based on Impinger Aqueous Sample.

Experimental Run #	1	2	3
Gasified PTFE mass (g)	0.3234	0.3216	0.3191
Elemental analysis based F/PTFE Mass Ratio	0.7647	0.7647	0.7647
F mass introduced (g)	0.2473	0.2459	0.2440
F ion conc. in the main impinger (mg/L)	95.9	93.2	95.9
Main impinger aqueous sample volume (L)	1.67533	1.67155	1.68337
F ion conc. in the 2nd impinger (mg/L)	43.3	40.7	43.6
2nd impinger aqueous sample volume (L)	0.79869	0.80151	0.79759
F mass recovered	0.1952	0.1884	0.1962
F recovery (%)	79.0	76.6	80.4

explanations for the difference in fluorine recovery are covered in the discussion.

Table 5 summarizes the F recovery based on hydrogen fluoride (HF) measurements obtained by FTIR. The FTIR system recorded HF concentrations (ppm) at 0.491 min intervals, with a total gas flow rate of 6.852 standard liters per minute (L/min).

The incremental volume of HF corresponding to each FTIR measurement was calculated as:

$$(\text{HF concentration by ppm}) \times 10^{-6} \times 6.852 \text{ L/min.} \times 0.491 \text{ min.}$$

These values were integrated over the entire measurement period, from the start of FTIR monitoring through the completion of steam cleaning, to obtain the total volume of HF generated.

The total moles of HF were then calculated using the ideal gas law at T = 293.15 K. The total mass of fluorine recovered was determined by converting HF moles to fluorine mass using the atomic mass of fluorine (18.998 g/mol).

The average fluorine recovery based on FTIR HF measurements was 96.3 %, which is significantly higher than the recovery obtained from fluoride ion analysis.

3.2. PFAS generation

Aqueous impinger results measured for modified EPA Method 537, short-chain PFAS (C1-C3), and OTM-50 are reported summarized in Tables 6–8, respectively. Eurofins Environment Testing performed the modified EPA Method 537 and OTM-50 analysis and reported results to the method detection limit (MDL). SGS-Axys performed the short-chain PFAS (C1-C3) analysis using ultra-high performance liquid chromatography/mass spectrometry using the isotope dilution/extracted internal standard method and reported results to the (QLs, treated as the laboratory reporting limit, RL). PFAS ($\geq$ C4) were not detected above the laboratory QLs of approximately 2–3 ng/L by modified EPA Method 537. Analytes detected above the MDL but below the QL in the Main Impinger samples for blank and incineration test runs are summarized in Table 6. Short-chain PFAS (C1-C3) were not detected above the laboratory reporting limits in the before blank and incineration test runs, confirming the absence of measurable background contamination (Table 7). Volatile fluorinated compounds were not detected above the laboratory QLs by OTM-50. Analytes detected above the MDL but below the QL in the gas samples for the incineration test runs are summarized in Table 8. OTM-50 canisters were not analyzed from the blank runs to determine whether the trace-levels observed in the incineration test runs may be related to system contamination. It is especially likely that the detections for chlorodifluoromethane originate from background contamination as

Table 5

F Recovery Based on FTIR HF Concentration.

Experimental Run #	1	2	3
F mass introduced (g)	0.2473	0.2459	0.2440
(from Table 4, row 3)			
F mass recovered	0.2373	0.2350	0.2375
F recovery (%)	96.0	95.6	97.4

Table 6PFAS Analysis ($\geq C4$) in Units of ng/L.

Run #	Description	PFNA	PFOA	PFHpA	PFPeA
1	Blank Before	<MDL (0.215)	0.395	<MDL (0.266)	<MDL (0.266)
1	Incineration Test	<MDL (0.210)	0.729	<MDL (0.260)	<MDL (0.260)
1	Blank After	0.216	<MDL (0.380)	<MDL (0.260)	<MDL (0.260)
2	Blank Before	<MDL (0.210)	0.675	MDL (0.260)	<MDL (0.260)
2	Incineration Test	<MDL (0.217)	<MDL (0.393)	MDL (0.269)	<MDL (0.269)
2	Blank After	<MDL (0.210)	0.381	MDL (0.260)	<MDL (0.260)
3	Blank Before	0.230	0.493	MDL (0.260)	0.472
3	Incineration Test	<MDL (0.210)	<MDL (0.380)	1.58	<MDL (0.260)
3	Blank After	<MDL (0.210)	<MDL (0.380)	MDL (0.260)	<MDL (0.260)

Table 7

PFAS Analysis (C1-C3) RESULTS in Units of ng/L.

Run #	Description	TFA	PFPrA	PFMeS	PFEtS	PFPrS
1	Blank Before	<RL (97.7)	<RL (19.4)	<RL (9.72)	<RL (4.86)	<RL (4.86)
1	Incineration Test	<RL (101)	<RL (20.0)	<RL (10.0)	<RL (5.00)	<RL (5.00)
2	Blank Before	<RL (98.8)	<RL (19.7)	<RL (9.83)	<RL (4.92)	<RL (4.92)
2	Incineration Test	<RL (98.5)	<RL (19.6)	<RL (9.80)	<RL (4.90)	<RL (4.90)
3	Blank Before	<RL (98.5)	<RL (19.6)	<RL (9.80)	<RL (4.90)	<RL (4.90)
3	Incineration Test	<RL (99.7)	<RL (19.8)	<RL (9.92)	<RL (4.96)	<RL (4.96)

PTFE does not contain chlorine, and there was no other source of chlorine in the system. Observed QC deviations in the PFAS data are discussed in the Supplemental Information and were minor, well characterized, and did not introduce meaningful uncertainty into the interpretation of the experimental results. Collectively, the trace-level detections appeared to be random and did not demonstrate systematic trends indicative of PFAS formation under the evaluated incineration conditions. Additional volatile fluorinated compounds were not detected in the non-targeted analysis performed on the OTM-50 canister samples from the incineration test runs. Analyte lists and detection and reporting limits for the incineration test runs are provided at the end of the manuscript. A full set of analytical results are provided in the Supplemental Information.

4. Discussion

4.1. PFAS destruction efficiency

The PFAS destruction efficiency (DE) calculations were conducted using the following equation:

$$PFAS\ DE\ (\%) = \left(1 - \frac{\Sigma PFAS_{out}}{\Sigma PFAS_{in}}\right) \times 100$$

The $\Sigma PFAS_{in}$ was a value determined from the measured amount of PTFE gasified over the duration of the experiment (Table 4, row 2). The fundamental assumption in the PFAS DE calculation was that all PTFE could theoretically form PFAS during the combustion process. The PFAS DE calculations were normalized to the F content of input PTFE (Table 4, Row 3) and output PFAS measurements.

The $\Sigma PFAS_{out}$ was determined from the analytical results obtained from the impinger and OTM-50 canister sampling for each run. This included LC-MS-MS analysis of the main impinger set for both short-chain (C1 – C3) and long-chain PFAS ($\geq C4$) and analysis of the OTM-50 canister for volatile fluorinated compounds (VFCs). The majority of PFAS and VFCs were not detected. In Table 9, non-detect results were treated as zero. Since the second set of impingers were not analyzed for PFAS, a correction factor was applied to the F content of PFAS from the main impinger set based on the ratio of the total gas flow to the main impinger gas flow.

The details of these calculations are given in the Supplemental Information, Table S19. PFAS DE was approximately 99.99962 %. The average mass of PFAS potentially generated across the three runs was 0.919 μg . The average PFAS emission concentration based on the total gas volume was 0.319 $\mu\text{g}/\text{m}^3$.

The absence of PFAS and gaseous fluorinated PIDs detectable above the respective method reporting limits combined with an FTIR-based fluorine recovery above 95 % suggests complete mineralization of PTFE under the setpoints of this study. The experimental conditions used in this study are consistent with MSWI operating conditions reported in a cross-section of studies detailed in the literature review described in the Supplemental Information. PTFE's fully fluorinated backbone, consisting only of C-F and C—C bonds, and expected degradation pathway at the identified temperature, confirm the polymer chain degrades and rapidly oxidizes. The lack of detectable short-chain (C1-C3) PFAS, as well as volatile fluorinated hydrocarbons (including non-target analysis), supports the conclusion that intermediate organic fluorine species, if formed, are transient and further oxidized before discharge from the system under typical MSWI operation conditions. This study's results can strengthen confidence that PTFE incineration under typical MSWI conditions does not yield environmentally persistent fluorinated byproducts at quantifiable levels. These findings are particularly relevant in the context of regulatory and product lifecycle discussions, where concern often centers on the potential generation of PFAS byproducts during thermal treatment. The present results provide experimental evidence that, at least under lab-scale conditions designed to mimic MSWI conditions, PTFE does not appear to be a significant source of PFAS emissions.

As with all lab-scale studies, caution can be warranted when

Table 9

PFAS DESTRUCTION EFFICIENCY AND EMISSION CONCENTRATION (NDs = 0).

Experimental Run #	$\Sigma PFAS_{in}$ (μg)	$\Sigma PFAS_{out}$ (μg)	DE (%)	$\mu\text{g}/\text{m}^3$
1	247,300	0.281	99.99989	0.0966
2	245,900	0	100.0000	0.000
3	244,000	2.48	99.99899	0.861
Average	245,700	0.919	99.99962	0.319

Table 8Volatile Fluorinated Compounds Detected at $>MDL$ in units of ppb v/v (ND $\leq$ MDL).

Experimental Run #	Description	Sample	Chlorodifluoromethane	Difluoromethane	Carbon Tetrafluoride
1	Incineration Test	OTM-50 Canister	0.0688	<MDL (0.0601)	<MDL (0.240)
2	Incineration Test	OTM-50 Canister	<MDL (0.0601)	<MDL (0.0601)	<MDL (0.240)
3	Incineration Test	OTM-50 Canister	0.0618	0.105	0.224

extrapolating results to full-scale incineration systems. Factors such as residence time, turbulence, waste heterogeneity, and make-up air configuration can influence reaction pathways and emissions profiles. That notwithstanding, this study's use of representative temperatures and residence time, under controlled gas compositions enhances the relevance of these findings to real-world systems. From an analytical perspective, non-detect results support effective mineralization within the sensitivity of current analytical techniques. Continued advances in non-targeted and ultra-trace methods may further contribute to further understanding fluorine fate during PTFE decomposition.

4.2. Fluorine balance approach comparison

Experimental procedures and recorded data were carefully reviewed to elucidate the discrepancy in F recovery between aqueous fluoride ion analysis and FTIR-based HF measurements.

Fluoride ion quality control and raw data were reviewed and did not reveal any evidence of analytical bias that would explain the low recovery. Concentrations measured in the impinger samples from the incineration test runs were substantially above QIs and within the calibrated range of the instrument. Calibration verification documented that the instrument was performing as required (within 90–110 % of true values), and sample spikes did not reveal evidence of matrix interference (F ion recoveries of 101–102 % were observed on matrix spikes on the main impinger samples from the first two incineration tests). The spectra from the FTIR analysis were examined and did not reveal evidence of an interference that would have elevated the results, as further documented in the Supplemental Information.

Prior to each experiment, a helium (He) leak check was conducted by introducing He throughout the experimental system (Fig. 1A). The reactor effluent was split into two streams: one directed to the main impinger, and the other routed through the FTIR system followed by a secondary impinger sampling train. This configuration resulted in slight system pressurization via the impinger trains. Experiments were conducted only after confirming the absence of detectable leaks.

Each experimental run utilized new reactor components, transfer line manifolds, and impingers. While any potential leakage location and magnitude would therefore be random, the observed fluorine recovery remained relatively consistent across the three experiments. Based on this consistency, system leakage is unlikely to be the primary cause of the lower recovery observed in the aqueous fluoride ion measurements. Following experimental runs, the FTIR was examined and tested for leaks within the equipment and confirmed to demonstrate no measurable loss.

In addition, every effort to minimize HF interaction with system surfaces and reduce potential losses under the circumstances was made including maintaining the HF gas concentration at approximately the 100 ppm level, using Silco-coated (Restek) treatment on all metal surfaces, and heating the transfer line and FTIR cell to 191 °C.

Another possible explanation is the loss of HF through volatilization from the impinger sampling solutions (i.e., breakthrough). Both the main and secondary impinger trains were maintained in electrically cooled baths set to 1 °C. Impinger outlet temperatures were monitored and are summarized in Table 10, with average values of 19.5 °C and 22.1 °C for the main and secondary impinger sets, respectively. The partial pressure of HF depends on both temperature and concentration; for example, the reported vapor pressure of a 2 wt. % HF aqueous solution at 25 °C is 0.048 mmHg [15], which is negligible compared to atmospheric pressure (760 mmHg). Therefore, it is unlikely that HF losses due

to volatilization account for the discrepancy. However, when the F recovery was calculated for each impinger set individually (Table 11), much lower recovery was observed in the 2nd impinger set (~61 %) than in the first impinger set (~84 %). The low recovery in the 2nd impinger set (61 %) is especially notable given that it is placed after the FTIR where F recovery measurements were much higher (~96 %). This pattern in recoveries was observed consistently across the three test runs. Breakthrough would not be expected to be equal for both sets of impingers given the differences in gas flows (Table 11) and configurations (4 water impingers with a knockout impinger for the main impinger set and 2 water impingers for the 2nd impinger set). In addition, breakthrough may be repeatable when test conditions remain the same Table 12, 13, 14.

Low F recovery in the impingers was not observed in a prior UDRI study [8] with very similar test conditions. While many of the test conditions were similar, the lengths of the overall test runs were different. A 5.5-hour run time with a ~0.5 hour steam cleaning was used in a prior UDRI study with the same experimental system while a 7-hour run time with an ~1 hour steam cleaning was used in this study. While other minor differences exist, a longer run time could be a plausible factor that could increase the opportunity for breakthrough.

At present, there is no definitive explanation for why the fluorine recovery based on fluoride ion analysis is approximately 18 % lower than that derived from FTIR HF measurements. Additional experimental runs would be necessary to determine if breakthrough could occur under the study conditions where the last impinger of each set could be analyzed separate from the other impingers to ensure low F concentrations (no more than 10 % of the total F) was observed in the last impinger. A basic solution could be used in the 2nd impinger set as noted in other methodology (EPA Method 26 or State of California Air Resources Board Method 421) in order to facilitate capture of HF (this solution could not be used in the main impingers due to the PFAS analysis to be performed).

4.3. Regulatory relevance

The results of this study are directly relevant to ongoing and prospective regulatory evaluations by the U.S. Environmental Protection Agency (EPA) and the European Chemicals Agency (ECHA), assessing the lifecycle impacts of PFAS and PFAS-related materials, including fluoropolymers such as PTFE. Regulatory initiatives in these jurisdictions emphasize potential emissions from waste management practices, including thermal treatment. By demonstrating that PTFE incineration under conditions representative of permitted MSWIs does not generate quantifiable PFAS of regulatory concern, this study provides empirical evidence that can inform agency determinations regarding the necessity and proportionality of additional controls, monitoring requirements, or restrictions specific to PTFE-containing waste.

Additionally, for EPA and ECHA, the findings contribute to scientific differentiation between PTFE and other PFAS substances or precursors that may degrade to regulated analytes during thermal processing. Both agencies are advancing risk-based and grouping-based regulatory approaches that must balance precaution with material-specific behavior. The confirmation that PTFE undergoes effective thermal destruction without measurable PFAS byproduct formation under standard MSWI operating conditions supports the position that PTFE should not be treated as an incineration-related PFAS emission source under compliant combustion scenarios. This evidence may reduce uncertainty in regulatory impact assessments, technical guidance documents such as EPA's annually updated Interim PFAS Destruction and Disposal Guidance, and best available techniques (BAT) discussions related to waste incineration of fluoropolymers within existing regulatory frameworks. Collaboration between regulatory authorities, industry, and waste facility operators can support further advancement of our collective understanding of these processes and interplay with human health and the environment.

Table 10
Averaged impinger exit temperature.

Experimental Run #	1	2	3	Average
Main Impinger	19.1	19.2	20.1	19.5
2nd Impinger	22.2	22.1	22.0	22.1

Table 11

F Recovery For Main and 2nd Impinger Sets.

Analysis Fraction	Gas Flow		F Mass Fraction Calculation			Ion Chromatography Measurements						FTIR
	Main ¹	2nd ²	Total	Main	2nd	Total	Main	2nd	Total	Main	2nd	Total
Test #	(L/Min)	(L/Min)	F from PTFE (g)	F Load (g)	F Load (g)	F Ion (g)	F Mass Balance (%)	F Ion (g)	F Mass Balance (%)	F Ion (g)	F Mass Balance (%)	F Mass Balance (%)
1	5.276	1.577	0.2473	0.1904	0.05690	0.195	79.0	0.161	84.4	0.0346	60.8	96.0
2	5.243	1.609	0.2459	0.1882	0.05774	0.188	76.6	0.156	82.8	0.0326	56.5	95.6
3	5.358	1.494	0.2440	0.1908	0.05322	0.196	80.4	0.161	84.6	0.0348	65.3	97.4
Average							78.7		83.9		60.9	96.3

1 - Apex Pump Rate (SLM) (Treated as dry gas flow then adjusted for moisture content).

2 - Difference between total gas flow of 6.852 L/min and the main impinger gas flow.

Table 12PFAS Analysis ($\geq$ C4) mdlS AND rls.

	CAS	Analyte	Acronym	MDL (ng/m ³)		RL (ng/m ³)	
				Min	Max	Min	Max
1	375-22-4	Perfluorobutanoic acid	PFBA	0.82	0.87	1.5	1.6
2	2706-90-3	Perfluoropentanoic acid	PFPeA	0.19	0.20	1.5	1.6
3	307-24-4	Perfluorohexanoic acid	PFHxA	0.57	0.60	1.5	1.6
4	375-85-9	Perfluoroheptanoic acid	PFHpA	0.19	0.20	1.5	1.6
5	335-67-1	Perfluorooctanoic acid	PFOA	0.28	0.30	1.5	1.6
6	375-95-1	Perfluorononanoic acid	PFNA	0.16	0.16	1.5	1.6
7	335-76-2	Perfluorodecanoic acid	PFDA	0.19	0.20	1.5	1.6
8	2058-94-8	Perfluoroundecanoic acid	PFUnA	0.22	0.24	1.5	1.6
9	307-55-1	Perfluorododecanoic acid	PFDoA	0.16	0.16	1.5	1.6
10	72,629-94-8	Perfluorotridecanoic acid	PFTriA	0.24	0.25	1.5	1.6
11	376-06-7	Perfluorotetradecanoic acid	PFTeA	0.34	0.35	1.5	1.6
12	67,905-19-5	Perfluorohexadecanoic acid	PFHxDA	0.43	0.45	1.5	1.6
13	16,517-11-6	Perfluorooctadecanoic acid	PFODA	0.38	0.40	1.5	1.6
14	375-73-5	Perfluorobutanesulfonic acid	PFBS	0.13	0.14	1.5	1.6
15	2706-91-4	Perfluoropentanesulfonic acid	PFPeS	0.18	0.19	1.5	1.6
16	355-46-4	Perfluorohexanesulfonic acid	PFHxS	0.17	0.18	1.5	1.6
17	375-92-8	Perfluoroheptanesulfonic acid	PFHpS	0.34	0.36	1.5	1.6
18	1763-23-1	Perfluorooctanesulfonic acid	PFOS	0.19	0.20	1.5	1.6
19	68,259-12-1	Perfluorononanesulfonic acid	PFNS	0.11	0.12	1.5	1.6
20	335-77-3	Perfluorodecanesulfonic acid	PFDS	0.25	0.26	1.5	1.6
21	79,780-39-5	Perfluorododecanesulfonic acid	PFDoS	0.24	0.25	1.5	1.6
22	754-91-6	Perfluorooctanesulfonamide	FOSA	0.17	0.18	1.5	1.6
23	4151-50-2	N-ethylperfluoro-1-octanesulfonamide	NEtPFOSA	0.40	0.42	1.5	1.6
24	31,506-32-8	N-methylperfluoro-1-octanesulfonamide	NMeFOSA	0.25	0.27	1.5	1.6
25	2355-31-9	N-methylperfluorooctanesulfonamidoacetic acid	NMeFOSAA	0.31	0.32	1.5	1.6
26	2991-50-6	N-ethylperfluorooctanesulfonamidoacetic acid	NEtFOSAA	0.22	0.24	1.5	1.6
27	24,448-09-7	2-(N-methylperfluoro-1-octanesulfonamido) ethanol	NMeFOSE	0.31	0.32	1.5	1.6
28	1691-99-2	2-(N-ethylperfluoro-1-octanesulfonamido) ethanol	NEtFOSE	0.22	0.23	1.5	1.6
29	757,124-72-4	4:2 fluorotelomer sulfonate	4:2FTS	0.17	0.18	1.5	1.6
30	27,619-97-2	6:2 fluorotelomer sulfonate	6:2FTS	1.7	1.8	2.2	2.4
31	39,108-34-4	8:2 fluorotelomer sulfonate	8:2FTS	0.39	0.41	1.5	1.6
32	120,226-60-0	10:2 fluorotelomer sulfonate	10:2FTS	0.32	0.34	1.5	1.6
33	919,005-14-4	Dodecafluoro-3H-4,8-dioxananoic acid	DONA	0.42	0.44	1.5	1.6
34	13,252-13-6	Hexafluoropropylene oxide-dimer acid	HFPO-DA	1.6	1.7	2.2	2.4
35	756,426-58-1	9-Chlorohexadecafluoro-3-oxanonane-1-sulfonic acid	9Cl-PF3ONS	0.19	0.20	1.5	1.6
36	763,051-92-9	11-Chloroeicosafluoro-3-oxaundecane-1-sulfonic acid	11Cl-PF3OUDS	0.21	0.22	1.5	1.6

Table 13

PFAS Analysis (C1-C3) rls.

	CAS	Analyte	Acronym	RL (ng/m ³)	
				Min	Max
1	1493-13-6	Trifluoromethanesulfonic acid (Triflic acid)	PFMeS	7.42	7.47
2	354-88-1	Pentafluoroethanesulfonic acid	PFETs	3.71	3.74
3	423-41-6	Heptafluoropropanesulfonic acid	PFPrS	3.71	3.74
4	76-05-1	Perfluoroethanoic acid (Trifluoroacetic acid, TFA)	PFETa	74.6	75.5
5	422-64-0	Pentafluoropropionic acid (Perfluoropropanoic acid)	PFPrA	14.8	14.9

5. Conclusion

Laboratory scale incineration of PTFE was conducted in triplicate under conditions representative of MSWI in the United States and European Union to identify the potential for generation of PFAS byproducts of PTFE. Under such conditions, approximately 2 s residence time with temperatures up to 1150 °C, all PFAS analytes for PTFE decomposition yielded non-detect (ND) or below reporting limit (RL) for aqueous samples under modified EPA Method 537 as well as C1-C3 PFAS analysis, as well as gas samples measured under OTM-50. Fluorine mass balance calculations across experimental runs varied based on characterization approach. In-line FTIR monitoring of HF concentration achieved between 95.6 % and 97.4 % recovery, by fluoride-ion based calculations yielded between 79.0 % and 80.4 % fluorine recovery. These measurements represent an advancement over prior PTFE

Table 14
Volatile Fluorinated Compounds MDLs and rls.

	CAS	Analyte	MDL (ng/m ³)		RL (ng/m ³)	
			Min	Max	Min	Max
1	2252-84-8	1H-Heptafluoropropane	381	418	7650	8340
2	375-17-7	1H-Nonafluorobutane	493	541	9900	10,800
3	375-83-7	1H-Perfluoroheptane	829	910	16,600	18,200
4	355-37-3	1H-Perfluorohexane	2870	3140	14,400	15,700
5	335-65-9	1H-Perfluorooctane	941	1030	18,900	20,600
6	375-61-1	1H-Perfluoropentane	2420	2650	12,100	13,300
7	3330-14-1	2H-Perfluoro-5-methyl-3,6-dioxanone	1919	1110	20,300	22,200
8	75-45-6	Chlorodifluoromethane (HCFC-22)	194	213	3890	4240
9	75-72-9	Chlorotrifluoromethane (CFC-13)	234	257	4700	5130
10	355-25-9	Decafluorobutane	533	585	10,700	11,700
11	75-10-5	Difluoromethane	117	128	2340	2550
12	678-26-2	Dodecafluoropentane	646	708	13,000	14,100
13	811-97-2	1,1,1,2-Tetrafluoroethane	229	251	4590	5010
14	593-53-3	Fluoromethane (HFC-41)	305	334	1530	1670
15	3330-15-2	Heptafluoropropyl 1,2,2,2-tetrafluoroethyl ether	2420	2650	12,100	13,300
16	335-57-9	Hexadecafluoroheptane	3480	3810	17,500	19,000
17	76-16-4	Hexafluoroethane (FC-116)	309	339	6210	6770
18	116-15-4	Hexafluoropropene	336	369	6750	7360
19	307-34-6	Octadecafluorooctane	982	1080	19,700	21,500
20	115-25-3	Octafluorocyclobutane	448	492	9000	9820
21	559-40-0	Octafluorocyclopentene	475	521	9540	10,400
22	116-14-3	Tetrafluoroethene	224	246	4500	4910
23	354-33-6	1,1,1,2,2-Pentafluoroethane (HFC-125)	269	295	5400	5890
24	355-42-0	Tetradecafluorohexane	3030	3320	15,200	16,600
25	420-46-2	1,1,1-Trifluoroethane (HCFC-143a)	753	825	3780	4120
26	75-46-7	Trifluoromethane (HFC-23)	942	1030	3150	3440
27	75-69-4	Trichlorofluoromethane (CFC-11)	308	338	6180	6740
28	76-19-7	Octafluoropropane	421	462	8460	9230
29	428-59-1	Hexafluoropropylene oxide (HFPO)	22,300	24,400	74,700	81,500
30	75-73-0	Carbon Tetrafluoride	788	864	3960	4320

incineration [13] work which reported fluorine recovery via FTIR between 56 % and 78 % and assessment of 31 PFAS analytes compared with 71 PFAS in this study, including ultra-short chain PFAS (C1-C3) and VFCs. We acknowledge that there are potential losses of fluorine in this study and should be further addressed in future studies.

In a prior study conducted at UDRI [8], a significant amount of TFA and small amount of PFPrA were observed in a lower temperature run where full mineralization of the fluoropolymer was not observed. The gas phase samples in this prior study also showed that small amounts of trifluoromethane and chlorotrifluoromethane were detected above the OTM-50 RLs. Neither TFA nor PFPrA, and PFMeS, PFETs, and PFPrS, were detected in any of the incineration test runs and the OTM-50 analytes were not detected above the RLs in this bench-scale study. The lack of detectable short-chain (C1-C3) PFAS, as well as volatile fluorinated hydrocarbons (including non-target analysis), supports the conclusion that intermediate organic fluorine species, if formed, are transient and further oxidized before discharge from the system under typical MSWI operation conditions. This bench-scale test procedure could be utilized for other fluoropolymers to conduct further studies to simulate incineration at different operating conditions for MSWIs. The calculated destruction efficiency across the experiments averaged 99.99962 % for PTFE. These results can indicate that incineration of products containing PTFE in MSWIs can be carried out without generation of quantifiable PFAS byproducts.

CCRediT authorship contribution statement

Owen Jappen: Writing – review & editing, Writing – original draft, Visualization, Project administration, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Meg Michell:** Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis, Data curation, Conceptualization. **Takahiro Yamada:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Moshan Kahandawala:** Supervision, Project

administration.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Takahiro Yamada reports financial support was provided by American Chemistry Council Chemical Products and Technology Division. Moshan Kahandawala reports financial support was provided by American Chemistry Council Chemical Products and Technology Division. Meg Michell reports financial support was provided by American Chemistry Council Chemical Products and Technology Division. We are aware of no "other activities" which may present conflict relating to this submission. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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Data availability

Data will be made available on request.

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Critical Review

A critical review of the application of polymer of low concern regulatory criteria to fluoropolymers II: Fluoroplastics and fluoroelastomers

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Abstract

Fluoropolymers are a distinct class of per- and polyfluoroalkyl substances (PFAS), high molecular weight (MW) polymers with fluorine attached to their carbon-only backbone. Fluoropolymers possess a unique combination of properties and unmatched functional performance critical to the products and manufacturing processes they enable and are irreplaceable in many uses. Fluoropolymers have documented safety profiles; are thermally, biologically, and chemically stable, negligibly soluble in water, nonmobile, nonbioavailable, nonbioaccumulative, and nontoxic. Although fluoropolymers fit the PFAS structural definition, they have very different physical, chemical, environmental, and toxicological properties when compared with other PFAS. This study describes the composition, uses, performance properties, and functionalities of 14 fluoropolymers, including fluoroplastics and fluoroelastomers, and presents data to demonstrate that they satisfy the widely accepted polymer hazard assessment criteria to be considered polymers of low concern (PLC). The PLC criteria include physicochemical properties, such as molecular weight, which determine bioavailability and warn of potential hazard. Fluoropolymers are insoluble (e.g., water, octanol) solids too large to migrate into the cell membrane making them nonbioavailable, and therefore, of low concern from a human and environmental health standpoint. Further, the study results demonstrate that fluoropolymers are a distinct and different group of PFAS and should not be grouped with other PFAS for hazard assessment or regulatory purposes. When combined with an earlier publication by Henry et al., this study demonstrates that commercial fluoropolymers are available from the seven participating companies that meet the criteria to be considered PLC, which represent approximately 96% of the global commercial fluoropolymer market. *Integr Environ Assess Manag* 2023;19:326–354. © 2022 The Authors. *Integrated Environmental Assessment and Management* published by Wiley Periodicals LLC on behalf of Society of Environmental Toxicology & Chemistry (SETAC).

KEYWORDS: Applications, Fluoropolymers, Low concern, PFAS, Property Combinations

This article contains online-only Supporting Information.

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INTRODUCTION

“Fluoropolymers are high MW polymers with fluorine atoms directly attached to their carbon-only backbone” (Ebnesajjad, 2017). The carbon–fluorine (C–F) bond is the strongest bond between carbon and another atom and imparts unique, outstanding, and beneficial properties and extraordinary functional performance to fluoropolymers (Ameduri, 2020; Ameduri & Sawada, 2017a, 2017b; Banks et al., 1994; Fluoropolymer Products Group of Plastics Europe [FPG], 2021a; Scheirs, 2007). These properties

include chemical, biological, and thermal stability, heat and chemical resistance, unique dielectric properties, and durability. Additional fluoropolymer properties include fire resistance, weather resistance, nonwetting, and nonstick. Fluoropolymers are regarded as irreplaceable in many applications because their unique combination of specific properties, which are critical to ensure optimal performance in many applications, cannot be achieved or guaranteed by alternative materials (FPG, 2021a, 2017; Henry et al., 2018; Performance Fluoropolymer Partnership of the American Chemistry Council [PFP], 2020).

Per- and polyfluoroalkyl substances (PFAS), a universe of substances with widely diverse properties that have been used in industrial and consumer applications since the 1950s, include fluoropolymers as a distinct class (Buck et al., 2011; Henry et al., 2018). A single, globally harmonized definition for PFAS has not yet been agreed upon. PFAS have been defined differently based on their structure and atomic composition (Buck et al., 2021; Wallington et al., 2021). For example, the USEPA's working PFAS structure definition is "a structure that contains the unit $R-CF_2-CF(R')(R'')$, where R, R', and R'' do not equal "H" and the carbon-carbon bond is saturated (note: branching, heteroatoms, and cyclic structures are included)" (USEPA, 2021a). The European Chemicals Agency (ECHA) employed a much broader PFAS structural definition (ECHA, 2020). A recent Organisation for Economic Cooperation and Development (OECD) report, which defined PFAS as fluorinated substances that contain in their structure at least one fully fluorinated methyl or methylene carbon atom (without any H/Cl/Br/I atom attached to it), that is, with a few noted exceptions, any chemical with at least a perfluorinated methyl group ($-CF_3$) or a perfluorinated methylene group ($-CF_2-$; OECD, 2021). This report acknowledges that the term "PFAS" is broad, general, and nonspecific, which does not inform whether a compound presents risk or not, but only communicates that the compounds under this term share the same structural trait of having a fully fluorinated methyl or methylene carbon moiety. Further, the report highlights that, among the substances defined as PFAS, there are distinct substances with very different properties: polymers and nonpolymers; solids, liquids and gases; persistent and nonpersistent substances; highly reactive and inert substances; mobile and insoluble (immobile) substances; and (eco) toxic and nontoxic chemicals. In addition, the report recognizes that PFAS have diverse molecular structures (e.g., neutral, anionic, cationic, or zwitterionic; with or without aromatic rings; nonpolymers or polymers; low or high molecular weight (MW), and thus diverse physical, chemical, and biological properties (e.g., involatile or volatile; water soluble or water insoluble; reactive vs. inert; bioaccumulative or nonbioaccumulative) and as such highly recommends that such diversity be properly recognized and communicated in a clear, specific, and descriptive manner when communicating about PFAS.

There is considerable media and public confusion and misunderstanding regarding PFAS, as the many different chemicals and groups are often not clearly differentiated under the broad term PFAS. Per- and polyfluoroalkyl substances, a large, diverse group of substances with vastly different properties, is too broad to allow effective, science-based assessment and regulation of chemical compounds as an entire group. This point has been raised in recent publications that suggest approaches to effectively group PFAS for regulatory assessment (American Chamber of Commerce in Europe [Amcham], 2020a; Buck et al., 2021; Bundesverband der Deutschen Industrie e.V. [BDI], 2021; Fiedler et al., 2020; Miller et al., 2020; Orgalim, 2021; Royal Society of Chemistry [RSC], 2021; Sha et al., 2019; Wallington et al., 2021). A clear understanding of the origin of PFAS found in the environment, the PFAS that are commercially relevant (Buck et al., 2021), and assessment of their properties are needed to be able to determine which classes of PFAS require management action. PFAS must be assessed based on their chemical, physical, thermal, and biological property differences and uses (Amcham, 2020a; BDI, 2021; Buck et al., 2021; RSC, 2021; Wallington et al., 2021). As regulatory frameworks, such as the EU REACH regulation, continue to evolve, more work is needed to distinguish clearly among PFAS based on their properties to assure that regulations are appropriate in scope, proportionate, and are science-based.

Per- and polyfluoroalkyl substances are divided into two primary categories: nonpolymers and polymers (Buck et al., 2011). Polymeric PFAS, generally known as "fluorinated polymers," include fluoropolymers (discussed here), perfluoropolyethers (PFPE), and side-chain fluorinated polymers (SCFP; Buck et al., 2011; Henry et al., 2018 and Supporting Information: Figure 6.1). This article deals strictly with fluoropolymers. Neither PFPE nor SCFP are discussed here.

The nonpolymer category includes perfluoroalkyl substances and polyfluoroalkyl substances. Certain nonpolymer PFAS substances, for example, short- and long-chain per- and polyfluoroalkyl carboxylic acids and sulfonic acids, received regulatory scrutiny recently due to their toxicity, as well as their persistence, potential to bioaccumulate, and/or mobility in the environment. Regulatory processes have been launched worldwide to address these concerns related to specific nonpolymer PFAS. These targeted regulatory measures have evolved increasingly into restrictions on the entire family of PFAS. For example, five Member States of the European Economic Area have initiated a procedure to prepare a joint restriction proposal under the EU REACH Regulation to limit the risks to human health and the environment from the manufacture and use of all substances in the PFAS family based on structure alone (ECHA, 2020). Although fluoropolymers fit the PFAS structural definition, they have vastly different physicochemical, environmental, and toxicological properties than other PFAS in addition to substantial societal benefits and importance (Fluoropolymer Products Group of Plastics Europe [FPG], 2017, 2021a). For

these reasons, fluoropolymers should be considered separately and not aggregated with all other PFAS for regulatory action. Concurrently, the USEPA prepared a PFAS Strategic Roadmap laying out how it plans to evaluate and potentially regulate PFAS (USEPA, 2021a). Recognizing that there are many PFAS very diverse in their physical form, chemical structure and composition, functional characteristics, and toxicity profiles, USEPA “is conducting new research to better understand the similar and different characteristics of specific PFAS and whether and how to address groups and categories of PFAS.”

Fluoropolymers have documented safety profiles, are thermally, biologically, and chemically stable, negligibly soluble in water, nonmobile, nonbioavailable, non-bioaccumulative, and nontoxic (Henry et al., 2018). Some fluoropolymers have been demonstrated to meet the “polymers of low concern” (PLC) criteria, and as such do not present notable concern for human health or the environment (Henry et al., 2018). PLC criteria were developed over time within regulatory frameworks around the world as an outcome of chemical hazard assessment processes, which identified physical–chemical properties of polymers that determine polymer bioavailability and thereby report a polymer's potential hazard. For example, many of the physicochemical properties, such as MW, limit the ability of a polymer to cross the cell membrane and therefore limit its bioavailability (Kostal, 2016; Lipinski et al., 2001; USEPA, 2012). The USEPA built on this knowledge to adopt a polymer exemption rule to exempt low-hazard polymers from certain regulatory notification requirements under the Toxic Substances Control Act's (TSCA) new chemicals program (United States Federal Register [USFR], 1984). An OECD expert group on polymers reached consensus on these criteria and their respective metrics, documenting the data required for a polymer to qualify as a PLC to human health and the environment (OECD, 1993). Subsequently, an additional OECD work group concurred that PLC have “insignificant environmental health and human health impacts” (OECD, 2009). In addition, the European Commission commissioned a report (BIO by Deloitte, 2015) wherein several member countries agreed on the polymer properties predictive of adverse human health and environmental hazard. The report outlined eligibility criteria for a polymer to be considered a PLC. In 2019, the industry-led European Centre for Ecotoxicology and Toxicology of Chemicals (ECETOC) developed a “Conceptual Framework for Polymer Risk Assessment” (“CF4Polymers”; ECETOC, 2019). CF4Polymers provides guiding elements to be considered in assessing potential ecological and human health hazards and risks posed by polymer substances. CF4Polymers also considers specific life-cycle stages of polymer products and their associated routes of exposure. The authors of the CF4Polymers framework support the PLC approach as a means to accomplish polymer risk assessments. They specifically support the findings of Henry et al. (2018) and state that they are “...unaware of scientific evidence to justify generally assigning fluoropolymers the same level of

regulatory concern as other PFAS” (ECETOC, 2019). In 2020, the European Commission contracted a study to propose criteria for the identification of polymers requiring registration (PRR) under REACH (Wood, 2020a). The Wood report states that the authors consider that fluoropolymers meet the criteria to be considered PLC, “following the recommendations of Henry et al.” Considerable debate and comment on proposals have been put forward as the process and discussion advances (American Chamber of Commerce in Europe [Amcham], 2020b; FPG, 2021a; Hafer, 2021).

Four major fluoropolymers have previously been demonstrated to meet the criteria as PLC (Henry et al., 2018). This 2018 study raised interest in gathering similar data for additional commercial fluoropolymer products, both in scope and polymer type. In this study, seven global fluoropolymer manufacturers from the USA, Europe, and Asia collaborated to gather and present data for 14 additional fluoropolymers. In addition to information describing chemical composition, uses, performance properties, and functionalities of the 14 fluoropolymers, author company data for each of the PLC criteria are presented and discussed. The results demonstrate that each of the 14 commercially manufactured fluoropolymers in this study satisfy the widely accepted assessment criteria to be considered PLC and merit such designation. The study results add further evidence to demonstrate that fluoropolymers are demonstrably different and should not be grouped with other PFAS for hazard assessment or regulatory purposes.

USES, PERFORMANCE PROPERTIES, AND FUNCTIONALITY OF FLUOROPLASTICS AND FLUOROELASTOMERS IN THIS STUDY

The fluoropolymers described and evaluated in this study are high-performance materials used in commercial and industrial applications. Described herein are the industries and sectors (Table 1) and the performance properties and functionalities (Table 2) of the study fluoropolymers. The unparalleled combination of properties makes fluoropolymers critical materials for a broad range of applications and industrial sectors including automotive, aerospace, energy production and storage, and electronics (Table 1). Fluoropolymers are an important driver of the European Green Deal (FPG, 2021a) and UN Sustainability Development Goals (United Nations [UN], 2021), supporting smart mobility, clean energy, and sustainable industry. They are used in various components of renewable energy installations, such as hydrogen and photovoltaic panels and facilitate advanced energy storage and conversion technologies such as lithium-ion batteries (FPG, 2021a). Fluoropolymers are (i) durable, stable, and mechanically strong in harsh conditions; (ii) chemically inert, meeting the requirements for low levels of contaminants and particulates in manufacturing environments that are critical to the food and beverage, pharmaceutical, medical, and semiconductor industries; and (iii) biocompatible, nonwetting, nonstick, and highly resistant to

TABLE 1 Fluoropolymer end uses and industries

Industries End uses	Transportation		Health care		Chemical		Consumer		Telecommunications		Infra-structure	Renewable energy				
	Automotive	Aerospace	Pharma- ceuticals	Medical devices	Oil and gas industry (CPI)	Chemical process industry (CPI)	Production of goods	Protection and packaging	Filtration	Electronics and semicon- ductors	Internet and wireless communica- tions	Textiles Technical textiles	Construc- tion and archi- tecture	Energy production	Hydrogen production	Energy storage
Fluoroplastics																
PVDF homopolymer	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
PVDF copolymer	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
ECTFE copolymer	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
ECTFE terpolymer			•		•	•										
PCTFE		•	•							•						
FEVE	•	•								•			•			
EFEP	•			•		•				•						
CPT	•									•						
THV	•	•	•	•		•	•	•	•	•			•	•		•
Fluoroelastomers																
FEPM	•	•	•	•	•	•	•			•			•	•		
FKM	•	•	•	•	•	•	•	•		•		•	•	•	•	•
FFKM		•	•	•	•	•	•			•						
Specialty																
Amorphous		•	•	•		•				•	•				•	•
Ionomer	•			•		•	•		•	•				•	•	•

Note: See also Chapter 5 in the Supporting Information.
 Abbreviations: CPT, chlorotrifluoroethylene-tetrafluoroethylene; ECTFE, ethylene-chlorotrifluoroethylene; EFEP, ethylene-tetrafluoroethylene-hexafluoropropylene; FEPM, trifluoroethylene-propylene copolymer; FEVE, fluoroethylene-vinyl ether; FKM, HFP-VF2 polymer and HFP-VF2 TFE polymers; FFKM, TFE-PMVE perfluoroelastomer; PCTFE, polychlorotrifluoroethylene; PVDF, polyvinylidene fluoride; THV, TFE-HFP-VF2.

TABLE 2 Fluoropolymer properties and functionality

See Supporting Information: Chapter 2 for property descriptions	Durable				Inert—Stable				
	Mechanical strength	Wear resistance	Flexibility	Low coefficient of friction	Resistance to chemicals	Weatherability	Cryogenic properties (lower than −50 °C)	High operating temperature range	High limiting oxygen index
Fluoroplastics									
PVDF Homopolymer	•	•		•	•	•		•	•
PVDF Copolymer	•	•		•	•	•		•	•
ECTFE Copolymer	•	•		•	•	•	•	•	•
ECTFE Terpolymer		•		•	•	•		•	•
PCTFE	•	•		•	•	•	•	•	•
FEVE	•	•	•	•	•	•		•	•
EFEP	•	•		•	•	•	•	•	•
CPT				•	•	•	•	•	•
THV			•		•	•		•	•
Fluoroelastomers									
FEP	•	•	•		•	•		•	•
FKM	•	•	•		•	•		•	•
FFKM	•	•	•		•			•	•
Specialty									
Amorphous			•	•	•			•	•
Ionomer			•		•				•
Functional									
See Supporting Information: Chapter 2 for property descriptions	Electrical insulator—high data transmission rate	Ionic conductivity	Piezo-electrical properties	Barrier properties	Nonstick properties	Ultra high purity grades for clean applications	Optical clarity	Low refractive index—used for optical effects	Polymer processing additive (PPA) ^a
Fluoroplastics									
PVDF Homopolymer			•	•		•		•	•
PVDF Copolymer			•	•				•	•

(Continued)

(Continued)

TABLE 2 (Continued)

See Supporting Information: Chapter 2 for property descriptions	Functional								Polymer processing additive (PPA) ^a
	Electrical insulator—high data transmission rate	Ionic conductivity	Piezo-electrical properties	Barrier properties	Nonstick properties	Ultra high purity grades for clean applications	Optical clarity	Low refractive index—used for optical effects	
ECTFE Copolymer	•			•					
ECTFE Terpolymer				•					
PCTFE				•	•	•	•	•	
FEVE				•			•		
EFEP				•	•		•	•	•
CPT				•	•	•	•	•	
THV				•			•	•	•
Fluoroelastomers									
FEPM	•			•					
FKM				•	•				•
FFKM	•			•		•			
Specialty									
Amorphous	•	•		•	•	•	•	•	
Ionomer	•	•		•			•		

Note: See Chapter 5 in the Supporting Information.

Abbreviations: CPT, chlorotrifluoroethylene-tetrafluoroethylene; ECTFE, ethylene-chlorotrifluoroethylene; EFEP, ethylene-tetrafluoroethylene-hexafluoropropylene; FEPM, trifluoroethylene-propylene copolymer; FEVE, fluoroethylene-vinyl ether; FKM, HFP-VF2 polymer and HFP-VF2-TE polymers; FFKM, TFE-PMVE perfluoroelastomer; PCTFE, polychlorotrifluoroethylene; PVDF, polyvinylidene fluoride; THV, TFE-HFP-VF2. ^aPolymer Processing Additives (PPA); also known as Polymer Processing Aid, Extrusion Process Aids or Polymer Processing and Recycling Aids.

temperature, fire, and weather (Table 2). Fluoropolymers are the preferred choice of material because of their unique combination of properties that are not achievable from other materials or via other functions. As a result, fluoropolymers have become a critical mainstay for our society providing vital, reliable functionality to a broad range of industrial and consumer products.

Three fluoropolymer types are included in this study: fluoroplastics, fluoroelastomers, and specialty fluoroplastics. Here, we describe briefly each included in this study. Additional details about each polymer are provided in the Supporting Information: Chapter 5.

Fluoroplastics

The fluoroplastics included in this study are: polyvinylidene fluoride (PVDF) homopolymer, PVDF copolymer, ethylene-chlorotrifluoroethylene (ECTFE) copolymer, ECTFE terpolymer, polychlorotrifluoroethylene (PCTFE), fluoroethylene-vinyl ether (FEVE), ethylene-tetrafluoroethylene-hexafluoropropylene (EFEP) terpolymer, chlorotrifluoroethylene-tetrafluoroethylene (CPT) terpolymer, and tetrafluoroethylene, hexafluoropropylene, vinylidene fluoride (TFE-HFP-VF2 [THV]) terpolymer as well as the specialty fluoroplastics, amorphous fluoropolymers, and fluorinated ionomers. Typical monomers used in the manufacture of fluoroplastics include tetrafluoroethylene (TFE), hexafluoropropylene (HFP), vinylidene fluoride (VDF or VF2), chlorotrifluoroethylene (CTFE), vinyl fluoride (VF), trifluoroethylene (TrFE), and perfluoroalkyl vinyl ethers (PAVEs), which include trifluoromethyl trifluorovinyl ether (PMVE), pentafluoroethyl trifluorovinyl ether (PEVE), and heptafluoropropyl trifluorovinyl ether (PPVE). In some copolymers, monomers that do not contain fluorine attached to the olefinic carbons may be used. These include ethylene, propylene, perfluoroalkyl-substituted ethylenes, and others (Ebnesajjad, 2000, 2003; Grot, 2011).

Fluoroelastomers

The fluoroelastomers included in this study are: trifluoroethylene-propylene copolymer (FEP), HFP-VF2 polymer and HFP-VF2-TFE polymers (FKM), and TFE-PMVE perfluoroelastomer (FFKM). Typical monomers used in the manufacture of fluoroelastomers include VDF, HFP, TFE, CTFE, PAVEs, as well as propylene, 1-hydropentafluoropropene (HPFP), and 2,3,3,3-tetrafluoropropene (HFO-1234yf; FPG, 2021a). Although fluoroelastomers are based on many of the monomers that are also used for the synthesis of fluoroplastics, they are different because of the specific composition, flexibility with subambient glass transition temperatures, as well as their elastomeric properties, resulting from the cross-linking process. Cross-linking, known as curing or vulcanizing, is a hardening process to form chemical bonds between polymer chains that gives polymers their elasticity (Améduri et al., 2001; Drobny, 2016).

PVDF homo- and copolymers

Polyvinylidene fluoride fluoropolymers are specified by end users across the world for their outstanding combination of properties. Because they have high temperature resistance, low permeability, and high mechanical strength, and provide chemical resistance to a wide range of aggressive chemicals, PVDF fluoropolymers are used as a contact surface for the production, storage, and transfer of corrosive fluids (chemically resistant to halogens and acids) in the chemical processing industry, oil and gas transportation, and cables industry (Arkema, 2021a; Gujarat Fluorochemicals Limited, 2018, 2022; Solvay, 2021a). The outstanding resistance to sunlight/UV exposure make PVDF suitable for architectural coatings. The outdoor aging and weathering properties of PVDF resin led to its use in long-lasting paints for coating metal sheet for the past 50 years. PVDF resins can also be used to protect thermoplastics through coextrusion or film lamination techniques to obtain antigraffiti surfaces with exceptional weathering properties. PVDF fluoropolymers also exhibit radiation resistance, desirable burn characteristics, flame, and smoke properties, easy processing on industry-standard equipment, and easy postprocessing steps, such as welding and fabrication. PVDF is used as a binder in lithium-ion batteries as well as PVDF film for solar power panels because of its high thermal and electrochemical stability, its stability under harsh environmental conditions, and its strong adhesion properties are critical to achieving environmental goals.

ECTFE (co- and terpolymers)

Ethylene chlorotrifluoroethylene (ECTFE) is a semicrystalline and melt-processable fluoropolymer obtained by the copolymerization of the two monomers, ethylene and chlorotrifluoroethylene, with an essentially 1:1 alternating structure (Ebnesajjad, 2017). Due to its chemical structure, ECTFE offers a unique combination of properties including chemical resistance, high thermal rating, and very good mechanical properties (Solvay, 2021b). ECTFE terpolymer with added hexafluoroisobutylene monomer displays enhanced stress-cracking performances resulting from chain-structure modifications of the polymer. ECTFE is used widely in anticorrosion applications such as coatings or in self-supporting construction (pipes) and architectural films (Solvay, 2021c). One of the principal advantages of ECTFE fluoropolymer is the ease with which it can be processed. It is a true thermoplastic that can be handled by conventional techniques of extrusion as well as by blow, compression, injection, rotational, and transfer molding. Powder coating methods are also applicable. ECTFE embodies an exemplary trade-off among general properties, offering high chemical and mechanical resistance combined with easy processing of the resin.

PCTFE

Polychlorotrifluoroethylene is a homopolymer of chlorotrifluoroethylene. PCTFE is melt processable and can be

extruded or molded (Satokawa, 1990). PCTFE has outstanding mechanical properties, especially hardness, and chemical resistance compared with PTFE and PFA, although it is slightly inferior to PFA and FEP in heat resistance and chemical resistance (Daikin, 2021a; Satokawa, 1990). PCTFE has been applied widely in the semiconductor industries and aerospace industries (Curbell, 2021; Daikin, 2021a). In addition to distinguished thermal and chemical stability, it has very low moisture absorption and permeation; therefore, PCTFE is used in pharmaceutical packaging (Honeywell, 2021).

FEVE

Fluoroethylene-vinyl ether fluoropolymer resins are manufactured by copolymerization of fluoroethylene monomer and a vinyl ether monomer and consist of alternating fluoroethylene and alkyl vinyl ether segments (AGC Chemicals Company, 2021a; Parker & Blankenship, 2015). They were developed in 1982 as the first solvent-soluble fluoropolymers in the world (Darden & Parker, 2021; Kojima & Yamabe, 1984; Munekata, 1988; Yamabe et al., 1984). The alternating fluorinated segments provide outstanding UV stability, weather resistance, and chemical resistance, while the vinyl ether segments provide solvent compatibility and cross-linking sites (Parker & Blankenship, 2015; Scheirs, 2007). FEVE resins are used to make ultra-weatherable coatings for architectural, aerospace, automotive, bridge, and industrial maintenance markets (Hoshino & Morizawa, 2017).

EFEP

Ethylene-tetrafluoroethylene-hexafluoropropylene is a terpolymer of ethylene, tetrafluoroethylene, and hexafluoropropylene. It was designed to have many of the properties of ETFE. It has a lower processing temperature, which allows it to be coextruded with conventional thermoplastic polymers such as polyamide, ethylene vinyl alcohol (EVOH), and modified polyethylene. EFEP can be extruded, injection molded, and blow molded, and it is used in many applications such as those identified in Supporting Information: Chapter 4.7 (Daikin, 2011a). EFEP is a melt-processable resin with good processability because of its low melting point. It also has excellent mechanical properties, provides chemical resistance, low permeability, exceptional weatherability, and good heat resistance. Other prominent features include inherent flame retardancy as well as good optical properties given that EFEP is highly transparent and has both a low dielectric constant and loss tangent.

CPT

Chlorotrifluoroethylene-tetrafluoroethylene is a terpolymer of chlorotrifluoroethylene, tetrafluoroethylene, and perfluoroalkyl-vinyl-ether. It is a melt-processable polymer and resin, which is readily processed because of its lower melting point. It can be melt-molded as a thermoplastic resin by extrusion, injection, and compression molding. CPT

is a modified perfluoroalkoxy fluoropolymer (PFA), which utilizes chlorotrifluoroethylene to provide low permeability to PFA, and it has many outstanding properties as a hybrid polymer of PFA and PCTFE as shown below. It has demonstrated permeation resistance to organic solvent, chemicals, water vapor, and gasoline (Daikin, 2011b). CPT offers superior permeation resistance against gasoline and flexible fuel and can be part of construction meeting the LEV III requirements (US environmental protection regulations in this automotive application). CPT also has notable barrier properties against many kinds of organic solvents and strong acids, especially HF, HCl, and HNO₃. This is very useful for semiconductor applications (Daikin, 2021b). In addition to the features noted above, CPT also provides heat resistance, excellent weatherability, flame retardancy, and good optical properties owing to its high transparency.

THV

THV fluoropolymers are a group of fluorinated thermoplastic polymers composed mainly of tetrafluoroethylene (TFE), hexafluoropropylene (HFP), and vinylidene fluoride (VDF; Dominghaus, 1998; Hintzer & Schwertfeger, 2014; Hull et al., 1997). The melting point of the different grades ranges from approximately 100 °C to nearly 250 °C. THV fluoropolymers are easy to process due to their broad processing windows. Different THV grades exhibit high flexibility, high transparency, bondability to fluorinated and nonfluorinated materials, and very good permeation resistance against fuels and other chemicals. The polymers are used as a barrier layer in fuel hoses, for transparent films and tubing, as matrix materials in composites, and the bonding layer in multilayer construction (Dams & Hintzer, 2017; Hull et al., 1997). The high transparency of the special film makes it an ideal adhesive film for laminated glass and the optimal protective film for surfaces. THV grades compete against other fluorothermoplastic materials for applications that require transparency and low refractive index as well as with fuel barrier materials. Commercial nonfluorinated materials cannot be used as substitutes for THV because of the unique combination of properties. Polymethylmethacrylate (PMMA) is used in conjunction with THV to provide differences in refractive index to create the total reflection needed for polymer optical fibers (Park et al., 2008). Transparent polymers, such as PMMA or polycarbonate, do not have the same chemical resistance or UV resistance to compete directly with THV.

FEPM

Trifluoroethylene-propylene copolymer elastomers, ASTM D1418, are high MW fluoropolymers with alternating tetrafluoroethylene and propylene segments (Kojima et al., 1977). They are also known as TFE-P copolymers. Various articles can be produced by means of compression molding, extrusion, injection molding, and calendaring. FEPM elastomers are compounded and cured (cross-linked) to deliver unique and valuable properties by providing exceptional heat resistance with a continuous service temperature higher than

200 °C, outstanding chemical resistance with little or no deterioration even in contact with strong acids, bases, and oxidants at high temperatures, steam resistance, and high electrical resistivity on the order of 10^{15} – 10^{16} Ω /cm (bulk resistivity). Formulated FEPM components are now used worldwide in many critical industrial applications where they must function safely in harsh environments, thereby extending the life of critical components and reducing downtime and costly repairs. FEPM elastomers are used in a range of applications including thermal power plants, oil and gas industry, ocean development, chemical and nuclear plants, automotive, aerospace, heavy-duty diesel, electronics, machinery, renewable energy, food processing, and medical. Their noted heat and chemical resistance make them especially valuable in oil and gas extraction (downhole) applications, where reliability is essential to cost effective and environmentally responsible production (Hull, 1983). FEPM elastomers are also used in high-performance wire and cable applications as insulating materials with the highest heat resistance, for example, lightweight, high-voltage automotive cables and motor cables for Japanese high-speed bullet trains (AGC Chemicals Company, 2021b).

Fluoroelastomers (FKM)

FKM are a family of fluoroelastomer materials defined by ASTM international standard D1418 (ASTM, 2021). FKM fluoroelastomers contain vinylidene fluoride (VDF) as a monomer combined with a variety of other fluoromonomers to create a palette of polymers with properties tailored for specific uses (Dams & Hintzer, 2017; Drobny, 2016; Van Cleeff, 1997; Worm & Grootaert, 2001). Cross-linked FKM fluoroelastomers are amorphous polymers designed for demanding service applications in hostile environments characterized by broad operating temperature ranges in contact with industrial chemicals, oils, or fuels (Worm & Grootaert, 2001). FKM fluoroelastomers are used mainly in fabricated parts (e.g., o-rings, gaskets, seals) to provide barriers against a wide range of fluids under severe service conditions (Drobny, 2016). Their design allows stable extrusion and molding processes and fitting in a wide range of processing constraints, reducing the risk of failure and increasing productivity. FKM fluoroelastomers provide high temperature and aggressive fluids resistance and retention of properties over a wide and demanding range of operating use conditions (high and low temperatures) for sealing and fluid transport applications, offering far superior performance than hydrocarbon elastomers. Applications include aerospace, automotive, oil and gas, chemical processing, electrical, office equipment, food, pharmaceuticals, and consumer wearables. Additionally, uncured FKM fluoroelastomers are used as a polymer processing additive (PPA) or polymer extrusion aids in small amounts (50–2000 ppm) dispersed in polyolefins such as high-density polyethylene (HDPE) and linear low-density polyethylene (LLDPE), significantly improving their film extrusion characteristics, reducing melt fracture and die build-up, as well as increasing productivity, minimizing energy and

water footprint, and enabling the extrusion of thin films (Lavallée, 2020; Shell, 2020).

FFKM

Perfluoroelastomers, designated by ASTM D1418 as FFKM, are a fully fluorinated class of elastomers that are typically made up of tetrafluoroethylene (TFE), a perfluoro (alkyl vinyl ether; PAVE), and a cure site monomer(s) (Ohkura & Morizawa, 2017). FFKM elastomers offer superior chemical and temperature resistance, excellent resistance to gas and liquid permeation, and resistance to weather and ozone with operating temperatures ranging from -40 °C to 325 °C (Drobny, 2016; Greene-Tweed, 2021a, 2021b). These polymers can also be compounded to meet the special requirements of upstream, midstream, and downstream oil and gas exploration due to their superior properties (Barnwell, 2021; Daemar, 2021). Because of these properties, FFKM elastomers are used in a wide variety of applications such as critical sealing solutions for the aerospace, pharmaceutical, medical, chemical processing, semiconductor, and oilfield industries (Atkinson, 2018; Marshall, 2017).

Amorphous fluoropolymers

Amorphous fluoropolymers are copolymers of TFE and specialty monomers that yield linear, high molar mass non-crystalline polymers (AGC Chemicals Company, 2021c; Gangal & Brothers, 2010; Hintzer et al., 2013; Korinek, 1994; Resnick & Buck, 1997, 1999). Amorphous fluoropolymers have the outstanding chemical and thermal stability and surface properties of semicrystalline perfluoropolymers as well as the unique properties associated with amorphous materials such as optical clarity and high gas permeability. The optical properties are outstanding, with more than 90% transmission, and thereby low dissipation, over a wide range of wavelengths (e.g., 200–2000 nm). TFE/PDD (2,2-bis(trifluoromethyl)-4,5-difluoro-1,3-dioxole) copolymers have the lowest refractive index known for a solid organic polymer (Groh & Zimmermann, 1991). This unique combination of properties makes amorphous fluoropolymers unmatched for uses in degassing, fiber optics, photolithography, antireflective coatings, passivation and protective coatings for medical, military, and aerospace devices, as well as electronic applications (Gangal & Brothers, 2010; Hintzer et al., 2013).

Fluorinated ionomers

Fluorinated ionomers are copolymers of TFE and a perfluorovinylether monomer containing an ionic group, typically a sulfonic acid or carboxylic acid (Grot, 2011, 2013). Fluorinated ionomers can be extruded or cast into film and converted into ion exchange materials (IXMs). IXMs come in a variety of useful forms offering a broad range of solutions for different applications (AGC Chemicals Company, 2021d; Asahi-Kasei, 2021; Chemours, 2021a). These forms include ion exchange membranes (IEMs), dispersions, and resins. IEMs must possess the required ion transport properties for the electrochemical cell in which they reside to perform well

and work effectively. Some of these properties include high ionic conductivity, chemical resistance, high operating temperature range, low permeability, and balanced durability and performance (Chemours, 2021b).

Ion exchange membranes (IEMs) stand to play a noteworthy role in today's modern world (Chemours, 2021b) and as such, are utilized in a wide range of applications and end-use industries including electrochemical processing, energy production, and hydrogen production. IEMs revolutionized the chlor-alkali industry (Grot, 2013), the manufacture of primarily caustic soda and chlorine, by eliminating the use of hazardous materials such as mercury and asbestos (Asahi-Kasei, 2021) and, in doing so, reducing energy consumption. Water electrolysis, the process of converting water into hydrogen and oxygen, relies on IEM technology. Although this process requires electricity, renewable energy sources such as solar or wind power can be utilized, allowing the potential for hydrogen to be a “clean” energy source (Science Center, 2021). Hydrogen fuel cells, some of which use a type of IEM known as a proton exchange membrane, can then convert hydrogen to electricity, a crucial technology to reach the stated target of the EU New Green Deal (EC, 2021).

STUDY METHODOLOGY AND DATA

Seven global fluoropolymer manufacturers (AGC Chemicals Americas, Arkema, The Chemours Company, Daikin Industries, Gujarat Fluorochemicals Limited, Solvay Specialty Polymers, and 3M Company) participated in this study and contributed data, writing, critique, and analysis. The companies noted above are members of the US-based Performance Fluoropolymer Partnership (PFP) and/or EU-based Fluoropolymer Product Group (FPG).

This study provides data on 14 fluoropolymers, building on a prior study (Henry et al., 2018). The study was characterized within two global industry groups. Participants put forward candidate fluoropolymers of notable commercial importance for the study and provided company and published data that address the PLC criteria. Thirteen PLC criteria that relate to the polymer structure and properties, including three to physicochemical properties and five to

stability, set forth in BIO by Deloitte (2015) and presented in prior work on four fluoropolymers (Henry et al., 2018), are addressed in this study (Figure 1). These criteria are briefly described in Table 3 with further description provided in Supporting Information: Chapter 3 and in the prior work (Henry et al., 2018). Participants provided company and published data and a description of methods and/or public references to demonstrate the origin of the data provided. These methods and references are provided in detail in Supporting Information: Chapter 4. The PLC criteria data were compiled and are presented in Tables 4 and 5.

The data assessment was done in two ways: Companies could self-assess the PLC data if they had the technical resources to do so or they could submit their PLC data to a third-party contractor for an independent technical review. The third-party consultant hired by PFP was GSI Environmental Inc. The objective was to be able to publish the references and methods behind the PLC data provided for each fluoropolymer in the study. In cases where the data and/or methods contained confidential business information, the third-party consultant independently evaluated the information supplied before it was shared in a blinded, aggregate form with the participating project companies. In several cases—FKM, PVDF, and ionomers—several companies submitted data for the same fluoropolymer. The data were combined and are presented in Tables 4 and 5. There is no intentional company attribution for the data presented.

The following describes further how the study data were generated and compiled.

- A third-party consulting company (GSI) was engaged to comment independently on data, methods, and references initially supplied by study participants for their respective fluoropolymers. Several study participants used this third-party consultant.
- Following the initial third-party assessment and assembly of the master data Tables 4 and 5 as well as the FKM data in Supporting Information: Table 4.11, a series of subsequent assessments were conducted (within PFP)

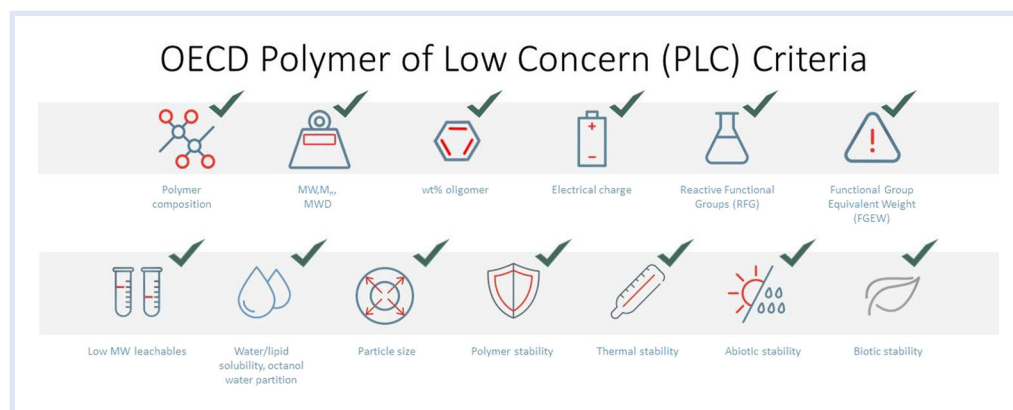


FIGURE 1 OECD polymer of low concern (PLC) criteria add (C) 2021 W.L.Gore & Associates

TABLE 3 Polymer of low concern (PLC) criteria descriptions

(See Supporting Information: Chapter 3 for additional details) Criterion	Description
Polymer composition	The polymer composition criterion requires structure and elemental composition of the polymer be described and identified (e.g., by Chemical Abstracts Service [CAS] number).
Molecular weight, number average molecular weight, MW distribution, and % oligomer <1000 Da	The number average molecular weight (Mn) and oligomer content are the most commonly used criteria for PLC assessment. The EU assessment report (BIO by Deloitte, 2015) states that the “most potential health concern polymers have a number average molecular weight, Mn, <1000 Da and oligomer content >1%.” The higher the oligomeric content, the more likely a polymer is to be a health or ecotoxicological (OECD, 2009, p. 9). Molecular weight (MW) is an important predictor of biological effect because large molecules (>1000–10 000 Da) are too large to penetrate cell membranes (Supporting Information: in Beyer, 1993, p. 14). Because large molecular weight polymers cannot enter the cell, they cannot react with “target organs,” such as the reproductive system, and are not bioavailable. “Therefore, as the Mn of a polymer increases, a reduced incidence of potential health concern effects might be expected” (OECD, 2009, p. 20). An additional PLC consideration is the weight percentage of oligomers that are <1000 Da. Oligomers may be composed of, for example, dimers, trimers, and tetramers, meaning they have 2- monomer, 3- monomer, and 4-monomer units, respectively. The EU report (BIO by Deloitte, 2015) concluded that most potential health concern polymers have Mn of <1000 Da and oligomer content of >1%: “...the distribution of potential health concern polymers exhibited an increased incidence of higher oligomer content that began at 5% for <1000 Da and 2% for <500 Da oligomeric content” (OECD, 2009, p. 24). Molecular weight distribution (MWD), also known as “polydispersity index,” measures the heterogeneity of size of polymer molecules in a polymer. The MWD is an important parameter for predicting potential biological effects of polymers because, although Mn may be a large value, low MW oligomers <1000 Da may be present, which could penetrate the cell.
Ionic character	Electrical charge or ionic character can be anionic, cationic, amphoteric, or nonionic. Specifically, cationic polymers have been associated with aquatic toxicity (Auer et al., 1990; USEPA, 1997a).
Reactive functional groups and RFG ratio to MW	A “reactive functional group” (RFG) is defined as an atom or associated group of atoms in a chemical substance that is intended or can be reasonably expected to undergo facile chemical reaction (USFR, 2012). Some highly reactive functional groups (or a high ratio of RFGs per mole) have been associated with adverse human health and ecotoxicology (e.g., acrylates, methacrylates, isocyanates, anhydrides, aziridines; USEPA, 2010). The functional group equivalent weight (FGEW) is used to determine if the RFGs in a polymer are substantially diluted by polymeric material to allow the polymer to be a PLC (USEPA, 1997). The FGEW of a polymer is defined as the ratio of the Mn to the number of functional groups in the polymer. The FGEW is used as an indication of the degree of reactivity of the polymer; the lower the FGEW, the more reactive the polymer and the greater the potential for health and environmental impact (OECD, 2009, p. 10).
Low MW leachables	Low MW leachables are chemical molecules, either inorganic or organic, that migrate (i.e., leach) out of the polymer. These could be residual monomers or oligomers resulting from incomplete polymerization processes, surface residues, or other chemicals used in the manufacturing processes (e.g., initiators, catalysts, chain transfer agents, surfactants). Low MW leachables are critically important to the potential for a polymer to affect health and the environment, given that they may be able to migrate out of the polymer and cross cell membranes to potentially react with biomolecules. A report to the EU (BIO by Deloitte, 2015) concluded that “Polymers with <1% MW < 1000 Da and low water extractability are not able to cause systemic effects which are toxicologically or ecotoxicologically relevant.” Monomers, by nature, are reactive. Unreacted monomers left in a polymer may migrate out of the polymer to react with biomolecules to cause potential adverse effects. Regulatory authorities (BIO by Deloitte, 2015) and the OECD Expert Group on Polymers (OECD, 2009) agree that the residual monomer content of a polymer is critical to determining if it qualifies as a PLC.

(Continued)

TABLE 3 (Continued)

(See Supporting Information: Chapter 3 for additional details) Criterion	Description
Particle size	Particle size is also a PLC criterion. Particles that are small enough to reach the deep lung upon inhalation are often associated with adverse health effects. Therefore, to qualify as a PLC, median mass aerodynamic diameter (MMAD) of the polymer particle size should be >5 µm.
Structural and elemental composition	In the US, Chemical Categories of Concern are the result of the review of new chemicals by the USEPA under the TSCA (see https://www.epa.gov/reviewing-new-chemicals-under-toxic-substances-control-act-tsca/chemical-categories-used-review-new). The categories describe the molecular structure, boundary conditions such as MW, equivalent weight, the log of the octanol–water partition coefficient, log <i>P</i> , or water solubility, and standard hazard (mammalian and ecological) and (environmental) fate tests to address concerns.
Elemental composition	The elemental composition is a factor in the assessment of the eligibility of polymers for reduced notification requirements. The exclusion of polymers under this step is not a conclusion of hazard but a determination that the elemental composition does not fall within the parameters of the polymer set under which this rule was formulated, and consequently, these polymers would have to follow the standard notification and review process. These elemental requirements differ across jurisdictions as covered in the report to the EU on global regulatory approaches to polymer assessment (BIO by Deloitte, 2015). For example, in the EU under REACH it is proposed that polymers composed from among these elements, covalently bound to C, have reduced hazard: H, N, O, Si, S, F, Cl, Br, or I (BIO by Deloitte, 2015). In contrast, the USEPA Polymer Exemption Rule states that a polymer is eligible for reduced agency review when it has at least two of the following elements: C, H, O, N, S, or Si (USFR, 1995).
Water and lipid solubility and the octanol–water partition coefficient	Water solubility is the extent to which a compound will dissolve in water. According to the OECD (2009) meeting of the Expert Group on Polymers, polymers with “negligible” water solubility, or those described as “hydrophobic” have been represented with a water solubility of 0.000001 mg/L (1×10^{-6} mg/L; assigned arbitrarily; OECD, 2009). That is equivalent to 1 ppt, a very conservative definition.
	Polymers with water solubility <10 mg/L showed generally low health concerns.
	The octanol–water partition coefficient (K_{ow}) is another criterion to assess chemicals and their environmental and health impact. The K_{ow} is a physical–chemical property at equilibrium to represent the lipophilic or hydrophilic nature of a chemical, the distribution of a compound in octanol, representing the lipophilic nature, to its solubility in water, representing the aqueous nature. The higher the K_{ow} , the more lipophilic the compound. Typically, a K_{ow} >5000 or a log K_{ow} >5 means high lipophilicity and, thus, a high potential to bioaccumulate or bioconcentrate. According to the Stockholm Convention, a bioconcentration factor of >5000 and a log K_{ow} >5 is used as a criterion for bioaccumulation.
Stability	Stability is resistance to physical, chemical, or biological transformation. Loss of stability in the polymer breaks it down into smaller pieces, producing low MW species. As was previously described in the Polymer of Low Concern section under the molecular weight, number average molecular weight, MW distribution, and % oligomer <1000 Da heading, molecules with Mn <1000 Da are capable of crossing cell membranes, making unstable polymers potentially hazardous to health and the environment.
Abiotic stability	Polymers are stable; monomers are not. Abiotic degradation may involve sunlight, water, or oxygen. Photochemical transformation is a reaction involving the radiation energy of sunlight (ultraviolet radiation) that may break a bond in a molecule to change it to another chemical entity. Hydrolytic degradation of polymers is another potential way to break the polymer bonds, creating smaller oligomers that may be bioavailable. Chemical oxidation is a reaction involving the loss of electrons from one atom to another.
Biotic stability: aerobic, anaerobic, and in vivo	Biotic stability is assessed by whether the polymer is degraded by microorganisms under oxygenated (aerobic) or anoxic (anaerobic) conditions; in vitro and in vivo stability studies demonstrate this. In vivo biodegradation involves the breaking of the polymer bonds by the action of bacteria, enzymes, and oxidants within the organism.
Thermal stability	Thermal stability of a polymer can be assessed when used as intended under normal, foreseeable use conditions or in extreme temperatures during disposal, such as by incineration. Thermal stability testing may involve Thermogravimetric Analysis (TGA), which determines mass loss over time and temperature of a test substance.

TABLE 4 Fluoroplastics and PLC criteria

Supporting Information Data: Chapter	Fluoroplastics				
	4.1 PVDF	4.2 PVDF-HFP copolymer	4.3 ECTFE	4.4 ECTFE	4.5 PCTFE
	Polyvinylidene fluoride	Vinylidene fluoride, hexafluoropropene copolymer	Ethylene, chlorotrifluoroethylene copolymer	Ethylene, chlorotrifluoroethylene, hexafluoroisobutylene terpolymer	Polychlorotrifluoroethylene
PLC assessment criterion ^a	CAS 24937-79-9	CAS 9011-17-0	CAS 25101-45-5	CAS 54302-04-04	CAS 9002-83-9
Structure	$-(CF_2-CH_2)_n-$	$-(CF_2-CH_2)_n-[CF(CF_3)-CF_2]_m-$	$-(CF_2-CFCl-CH_2-CH_2)_n-$	$-(C_4H_2F_6)_n-(C_2H_4)_m-(C_2ClF_3)_l-$	$-(CF_2-CFCl)_n-$
Polymer composition (must have C, H, Si, S, F, Cl, Br, or I covalently bound to carbon)	Yes	Yes	Yes	Yes	Yes
Molecular weight (Mn) ^b (Mn > 1000 Da and oligomer content <1%)	70 000–300 000	80 000–300 000	Mn >50 000	Mn >50 000	70 000–400 000 average based on grade type
Molecular weight distribution Mw ^c ÷ number average Mn	2–3	2–3	1.1	1.7	3
Wt% oligomer (<5% for <1000 Da oligomers, <2% for <500 Da oligomers)	Negligible	Negligible	Negligible	Negligible	Negligible
Ionic character	Neutral	Neutral	Neutral	Neutral	Neutral
Reactive functional groups (RFGs) ^d and functional group equivalent weight (FGEW)	None and N/A	None and N/A	None and N/A	None and N/A	None and N/A
Low molecular weight leachables	No active leachables by USP class VI (121 °C)	No active leachables by USP class VI (121 °C)	No active leachables by USP class VI (121 °C)	No active leachables by USP class VI (121 °C)	Negligible
Residual monomers	<50 ppb	<50 ppb	<50 ppb	<50 ppb	<0.1 wt%
Ratio of residual monomers to molecular weight (typical value)	$\sim 10^{-12}$ – $\sim 10^{-13}$	$\sim 10^{-12}$ – $\sim 10^{-14}$	$\sim 10^{-13}$	$\sim 10^{-13}$	<10 ⁻⁵
Structural similarities to RFG of concern	None	None	None	None	None
Reference standard	ASTM D3222-18a	ASTM D5575-18	ASTM D3275-81	ASTM D3275-81	

(Continued)

TABLE 4 (Continued)

Fluoroplastics		4.1	4.2	4.3	4.4	4.5
Supporting Information Data: Chapter	PVDF	PVDF-HFP copolymer	ECTFE	ECTFE	PCTFE	
Physical-chemical properties						
Water solubility and octanol/water partition coefficient, K_{ow}	Insoluble/practically insoluble and N/A	Insoluble/practically insoluble and N/A	Insoluble/practically insoluble and N/A	Insoluble/practically insoluble and N/A	Insoluble/practically insoluble and N/A	
Particle size (median mass aerodynamic diameter, MMAD, should be >5 μ m)	Powders: 5–300 μ m pellets: 2–4 mm	Powders: 5–300 μ m pellets: 2–4 mm	D50%: 50–70 μ m (typical)	D50%: 50–70 μ m (typical)	Pellet: 2–4 μ m, flake: 0.54 mm powder: 5–300 micron	
Stability						
Hydrolysis, light (hv), Oxidation, biodegradation (aerobic and anaerobic)	Stable	Stable	Stable	Stable	Stable	
Thermal stability at normal foreseeable use maximum continuous temp. (°C)	150 °C	150 °C	150 °C	150 °C	120 °C	
Meets ^a PLC criteria (Yes or No)	Yes	Yes	Yes	Yes	Yes	
Fluorinated polymerization aid (PA) used? (Yes or No)	No	No	No	No	No	
Recommended processing/application (use) temperature (T°C)	Processing: 200 °C–250 °C Use max temp: 150 °C	Processing: 180 °C–250 °C Use max temp: 100 °C–140 °C depending on HFP content	Processing: 250 °C–280 °C Use max. Temp: 150 °C	Processing: 250 °C–280 °C Use max. Temp: 150 °C	Molding: 230 °C–330 °C Use Max same as above at 120 °C	
Fluoroplastics						
Supporting Information Data: Chapter	4.6 FEVE	4.7 EFEP	4.8 CPT	4.9 THV		
Fluoroethylene-vinyl ether copolymer	Fluoroethylene-vinyl ether copolymer	1-Propene, 1,1,2,3,3,3-hexafluoro-, polymer with ethylene and 1,1,2,2-tetrafluoroethylene	1,1,1,2,2,3,3-Heptafluoro-3-[(trifluoroethenyl)oxy]propane polymer with chlorotrifluoroethylene and tetrafluoroethylene	1-Propene, 1,1,2,3,3,3-hexafluoro-polymer with 1,1-difluoroethylene and tetrafluoroethylene		
PLC assessment criterion ^a	cbi	35560-16-8	116018-07-6	25190-89-0		(Continued)

TABLE 4 (Continued)

Supporting Information Data:		Fluoroplastics				
Chapter	4.6 FEVE	4.7 EFEP	4.8 CPT	4.9 THV		
Structure	cbi	$-(CH_2-CH_2)_n-(CF_2-CH_2)_m-(CF_2-CF(CF_3))_l-$	$-(CF_2-CH_2)_n-(CFCl-CF_2)_m-(CF_2-CF(CF_3))_l-$	$-(CF_2CH_2)_x-(CF_2-CF-CF_3)_y-(CF_2-CF_2)_z$		
Polymer composition (must have C, H, Si, S, F, Cl, Br, or I covalently bound to carbon)	Yes	Yes	Yes	Yes		
Molecular weight (Mn) ^b (Mn > 1000 Da and oligomer content < 1%)	7000–46 000	130 000	200 000–300 000	131 000		
Molecular weight distribution Mw ^c ÷ number average Mn	2.0–4.0	4	2–5	1.8		
Wt% oligomer (< 5% for < 1000 Da oligomers, < 2% for < 500 Da oligomers)	Mn < 1000 range of < 3.5% and Mn < 500 is < 0.7%	Negligible; < 0.1 wt% oligomer content	Negligible; < 0.1 wt% oligomer content	wt.% < 1000: None		
Ionic character	Neutral	Neutral	Neutral	Neutral		
Reactive functional groups (RFGs) ^d and functional group equivalent weight (FGEW)	None and N/A	None and N/A	None and N/A	None and N/A		
Low molecular weight leachables	Negligible; cross-linked as final product	Negligible	Negligible	No active leachables by USP class VI (121 °C)		
Residual monomers	0.12%–1.43% non-fluorinated	Negligible	Negligible	None detected		
Ratio of residual monomers to molecular weight (typical value)	10^{-7} – 10^{-8}	< 10^{-5}	< 10^{-5}	$\sim 10^{-13}$		
Structural similarities to RFG of concern	None	None	None	None		
Reference standard		ASTM D7472	ASTM D7471			

(Continued)

TABLE 4 (Continued)

Supporting Information Data: Chapter	Fluoroplastics			4.7 EFEP	4.8 CPT	4.9 THV
	4.6 FEVE					
Physical-chemical properties						
Water solubility and octanol/ water partition coefficient, K_{ow}	Insoluble/practically insoluble and N/A	Insoluble/practically insoluble and N/A	Insoluble/practically insoluble and N/A	Insoluble/practically insoluble and N/A	Insoluble/practically insoluble and N/A	Insoluble/practically insoluble and N/A
Particle size (median mass aerodynamic diameter, MMAD, should be >5 μm)	Solution or flake 150 nm for emulsion	2–4 mm (pellets)	2–4 mm (pellets)	2–4 mm (pellets)		Pellets ~400–750 μm
Stability						
Hydrolysis, light (hv), oxidation, biodegradation (aerobic and anaerobic)	Stable	Stable	Stable	Stable	Stable	Stable
Thermal stability at normal foreseeable use maximum continuous temp. ($^{\circ}\text{C}$)	220 $^{\circ}\text{C}$	130 $^{\circ}\text{C}$; low melting point 160 $^{\circ}\text{C}$ –190 $^{\circ}\text{C}$ and high decomposition temperature of 357 $^{\circ}\text{C}$ –380 $^{\circ}\text{C}$	200 $^{\circ}\text{C}$; low melting point 239 $^{\circ}\text{C}$ –251 $^{\circ}\text{C}$ and high decomposition temperature of >400 $^{\circ}\text{C}$	Continuous use is expected ~room T. (<100 $^{\circ}\text{C}$ as host resin melts at 120 $^{\circ}\text{C}$); No expected degradation; fluoropolymer degrades >350 $^{\circ}\text{C}$ by TGA		
Meets ^a PLC criteria (Yes or No)	Yes	Yes	Yes	Yes	Yes	Yes
Fluorinated polymerization aid (PA) used? (Yes or No)	No	No	No	No	No	Yes and No
Recommended processing/ application (use) temperature ($^{\circ}\text{C}$)	180 $^{\circ}\text{C}$ –200 $^{\circ}\text{C}$	Molding temperature: 200 $^{\circ}\text{C}$ –280 $^{\circ}\text{C}$; Use max as noted above	Molding temperature: 310 $^{\circ}\text{C}$ –330 $^{\circ}\text{C}$; Use max as noted above	Melt processing: <350 $^{\circ}\text{C}$ Application: <100 $^{\circ}\text{C}$ (in LLDPE)		

Abbreviations: ECTFE, ethylene-chlorotrifluoroethylene; HFP, hexafluoropropylene; PCTFE, polychlorotrifluoroethylene; PLC, polymer of low concern; PVDF, polyvinylidene fluoride.

^aSee OECD (2009) and BIO by Deloitte (2015) for details on characteristics of a “Polymer of Low Concern” and Supporting Information: Chapter 3.

^bMolecular Weight is number average molecular weight which is defined as the total weight of the polymer divided by the total number of molecules. It is the mole fraction of molecules in a polymer sample.

^cMolecular weight is weight average molecular weight which is determined by summing the weights of all the chains and then dividing by the total number of chains. It is the weight fraction of molecules in a polymer sample.

^dFor definition of reactive functional group, lists of low-, moderate-, and high-concern functional groups and FGEW limits, see USEPA polymer exemption guidance manual, BIO by Deloitte (2015, pp. 191–192), and USEPA (2010). See Supporting Information.

TABLE 5 Fluoroelastomers and specialty fluoroplastics—PLC criteria

Supporting Information Data: Chapter	Specialty fluoroplastics		Fluoroelastomers		
	4.13 Amorphous	4.14 Ionomer	4.10 FEPM	4.11 FKM	4.12 FFKM
	Perfluoro(alkenyl vinyl) ether polymer	Sodium or potassium salts of perfluorosulfonic acid/TFE copolymer or perfluorocarboxylic acid/TFE copolymer	Tetrafluoroethylene-propylene copolymer	1-Propene, 1,1,2,3,3,3-hexafluoro-polymer with 1,1-difluoroethylene copolymer and terpolymers	Tetrafluoroethylene-trifluoromethyl trifluorovinyl ether copolymer
PLC assessment criterion ^a	37626-13-4	9002-84-0, 1314-23-4, 409-21-2, 111173-25-2	27029-05-6	9011-17-0, 26425-79-6, 25190-89-0	26425-79-6
Structure	See Supporting Information	See Supporting Information	See Supporting Information	Supporting Information	-(CF ₂ CF ₂) _x -[CF ₂ -CF(OCF ₃)] _y -(Cure Site Monomer) _z
Polymer composition (must have C, H, Si, S, F, Cl, Br, or I covalently bound to carbon)	Yes	Yes	Yes	Yes	Yes
Molecular weight ^b (M _n > 1000 Da and oligomer content <1%)	150 000–300 000	>100 000	Various grades vary between 146 000–275 000	30 000–340 000	10 000–1 000 000
Molecular weight distribution Mw ^c ÷ number average M _n	1.4–2.5	1.0–2.4	Various grades give various ratios from 1.4 to 3.3	1.2–2.4	1.2–3.5
Wt% oligomer (Figure MWD) (<5% for <1000 Da oligomers, <2% for <500 Da oligomers)	Negligible	Negligible	<0.01%	Negligible to <1%	Negligible
Ionic character	Neutral	Neutral	Neutral	Neutral	Neutral
Reactive functional groups (RFGs) ^d	None and N/A	None and N/A	None and N/A	None and N/A	None and N/A
Functional group equivalent weight (FGEW; typical value)	>10 ⁵	>10 ⁵	>10 ⁵	>10 ⁴ –10 ⁵	>10 ⁴

(Continued)

TABLE 5 (Continued)

Supporting Information Data: Chapter	Specialty fluoroplastics		Fluoroelastomers		
	4.13 Amorphous	4.14 Ionomer	4.10 FEPM	4.11 FKM	4.12 FFKM
Low molecular weight leachables	<1 ppm	<1 ppm	No active leachables	<0.4 ppm to <1 ppm	No active leachables
Residual monomers	<1 ppm	<1 ppm	No residual monomers Only cross-linking agent at <1 ppm	<50 ppt to <5 ppm	<50 ppb
Ratio of residual monomers to molecular weight (typical value)	>10 ⁻⁵	>10 ⁻⁵	10 ⁻¹¹ –10 ⁻¹²	>10 ⁻¹⁰ –10 ⁻¹³	0.25 ppt as Mn = 10 ⁵ (for representative FKM)
Structural similarities to RFG of concern	None	None	None	None	None
Reference standard	ASTM D 1418				
Physical–chemical properties					
Water solubility and octanol/water partition coefficient, K _{ow}	Insoluble/practically insoluble and N/A	Insoluble/practically insoluble and N/A	Insoluble/practically insoluble and N/A	Insoluble/practically insoluble and N/A	Insoluble/practically insoluble and N/A
Particle size (median mass aerodynamic diameter, aerodynamic diameter, MMAD, should be >5µm)	Solution, sheet or pellets	(1) Aqueous dispersion casting (as a film) followed by annealing or (2) Melt extrusion as a membrane (reinforced)	Sheet or crumb	Sheet or block; powders 300–350 µm stability increased/enhanced when cross-linked	Sheet or block; or “crumb”
Stability					
Hydrolysis, light (hν), oxidation, biodegradation (aerobic and anaerobic)	Stable	Stable	Stable	Stable	Stable

(Continued)

(Continued)

TABLE 5 (Continued)

Supporting Information Data: Chapter	Specialty fluoroplastics		Fluoroelastomers		
	4.13 Amorphous	4.14 Ionomer	4.10 FEPM	4.11 FKM	4.12 FFKM
Thermal stability at normal foreseeable use maximum continuous Temp (°C)	>250 °C	Sulfonic acid polymer: maximum operating temperature of 175 °C under anhydrous conditions, 220 °C –240 °C in aqueous systems carboxylic acid polymer: use below 120 °C	200 °C	180 °C	200 °C–300 °C
Meets ^a PLC criteria (Yes or No)	Yes	Yes	Yes	Yes	Yes
Fluorinated polymerization aid (PA) used? (Yes or No)	Yes and No	Yes and No	No	Yes and No	Yes and No
Recommended processing/ application (use) temperature (T °C)	<280 °C	Sulfonic acid polymer: maximum operating temperature of 175 °C under anhydrous conditions, 220 °C–240 °C in aqueous systems carboxylic acid polymer: use below 120 °C	–60 °C–204 °C (AFLAS Technical Document)	Melt processing: <300 °C 160 °C–320 °C (cross- linking temperature)	160 °C–320 °C (cross-linking temperature)

Abbreviations: FEPM, trifluoroethylene-propylene copolymer; FKM, HFP-VF2 polymer and HFP-VF2-TFE polymers; FFKM, TFE-PMVE perfluoroelastomer; PLC, polymer of low concern.

^aSee OECD (2009) and BIO by Deloitte (2015) for details on characteristics of a “Polymer of Low Concern.”

^bMolecular weight is number average molecular weight.

^cMolecular weight is weight average molecular weight.

^dFor definition of reactive functional group, lists of low-, moderate-, and high-concern functional groups and FGEW limits, see USEPA polymer exemption guidance manual, BIO by Deloitte (2015, pp. 191–192), and USEPA (2010). See Supporting Information.

until all data cells in the tables cited above were backed up with a narrative, a testing method, and/or references where publicly available.

- Where several companies have provided data on the same fluoropolymers, the table data presented provide a multicompany compilation and assessment along with appropriate methods and references.
- Individual companies supplying data are identified as authors, but there is no direct attribution regarding which company supplied which data for this study.

PLC ASSESSMENT RESULTS

This study was conducted on commercial fluoropolymer products using the PLC criteria to characterize their potential hazard. Figure 1 illustrates the PLC criteria used (BIO by Deloitte, 2015; Henry et al., 2018). The pictured criteria encompass structure, physicochemical property, and stability criteria evaluated in the study. Data informing structure criteria, MW, Mn, and MW distribution (MWD), physicochemical property criteria, water and lipid solubility and K_{ow} , and stability criteria are presented in Tables 4 and 5. The study also gathered structural data on (a) residual monomers, (b) ratio of residual monomers to MW, (c) structural similarities to reactive functional groups (RFGs) of concern, and (d) thermal stability at normal foreseeable maximum continuous use temperatures. Brief descriptions of PLC criteria are provided in Table 3 with additional details, including references for each criterion in Supporting Information: Chapter 3. An additional data point gathered was whether the fluoropolymer(s) presented utilized a fluorinated polymerization aid (PA) during manufacture. The study results are presented in Tables 4 and 5 and summarized below.

Polymer composition: Each of the fluoroplastics, specialty fluoroplastics, and fluoroelastomers assessed in this study met the criterion of polymer composition whereby either fluorine (F) and/or chlorine (Cl) must be covalently bound to the carbon-only polymer backbone.

MW and MWD: All fluoroplastics, specialty fluoroplastics, and fluoroelastomers in the study met the criteria for MW ($M_n > 1000$ Da) and MWD (1–3). The data demonstrate the fluoroplastics, specialty fluoroplastics, and fluoroelastomers in the study are high-MW solid polymers with fairly narrow MWD and negligible to low wt% oligomer content. The MW for fluoroplastics in Table 4 and specialty fluoroplastics in Table 5 ranged from 50 000 to 300 000, and the MWD ranged from approximately 1.4 to 3. We note that FEVE was measured in its uncured state and that, upon curing, its MW increased significantly. The MW and MWD were determined in a variety of ways depending on the fluoropolymer and its solubility (or insolubility) in various solvents. The MW and MWD data for fluoroelastomers and specialty fluoroplastics in the study are presented in Table 5. The MW and MWD varied because of the various grades of fluoroelastomers ranging from 100 000 to 250 000 with some less than (down to 10 000) and greater than (up to 500 000). MWD was on

the order of 1.4 to 3.5. Fluoroelastomer MW is lower for uncured fluoroelastomer versus cured fluoroelastomer. Cured fluoroelastomer is the form used in many formed-use applications (e.g., gaskets and o-rings). The methods and references for MW and MWD data are presented in the Supporting Information: Chapter 4 with the specific chapter noted in Tables 4 and 5. Methods included size exclusion chromatography (SEC), gel permeation chromatography (GPC) along with osmotic pressure, and parallel plate rheometry methods.

Weight % oligomer: The criteria for wt% oligomer are less than 5% oligomer content for M_n less than 1000 Da, and less than 2% oligomer content for M_n less than 500 Da (BIO by Deloitte, 2015; Henry et al., 2018; see also the Supporting Information). All fluoroplastics, specialty fluoroplastics, and fluoroelastomers in the study met the wt% oligomer criteria. Many polymers in the study were reported as “negligible” for oligomers based on analyses conducted. Polymers in the study not cited as negligible have reported numerical data presented in Tables 4 and 5. In addition to SEC and GPC, analytical methods employed included a weight loss upon heating method and the FDA 21 CFR 177.1380 method. The methods and references for wt% oligomer are presented in the Supporting Information: Chapter 4 with the specific chapter noted in Tables 4 and 5.

Ionic character: The fluoroplastics, specialty fluoroplastics, and fluoroelastomers in the study are neutral polymers, either containing no ionic groups or may contain anionic at the terminus of their high MW polymer chains as noted in the prior study of fluoropolymers (Henry et al., 2018). Notably different are fluorinated ionomers, which have neutralized (salts) sulfonic acid or carboxylic acid groups pendant to the polymer backbone and as such are neutral and not ionically charged in their polymeric solid form and are low in toxicity and not dermally irritating on skin contact (USEPA, 1997). None of the evaluated polymers in the study have cationic nature. The methods and references for ionic character are presented in the Supporting Information: Chapter 4 with the specific subchapter noted in Tables 4 and 5.

RFG, functional group equivalent weight (FGEW) and structural similarities to RFG of concern: All fluoroplastics, specialty fluoroplastics, and fluoroelastomers in the study met the RFG and FGEW criteria. The polymers in this study do not contain the reactive functional groups set forth in the PLC criteria (e.g., acrylates, alkoxysilanes, amines, aziridines, carbodiimides, and so forth; see Supporting Information: Chapter 3). Given that the polymers in this study have no RFGs, the FGEW values in Tables 4 and 5 are very large numbers (such as $>10^4$ – 10^5) or the value given is not applicable due to the lack of RFGs altogether. Even the polymers with some functional groups present (e.g., fluorinated ionomers) are not reactive. For example, the FEVE polymerization process leads by design to a polymer with neutral and/or anionic end groups. FEVE resins do contain a small amount of hydroxyl and carboxyl functional groups. These functional groups are classified as low concern RFG

by the USEPA (1997) and OECD (2009). There are no RFG structural similarities across the polymers in this study.

Low MW leachables (MW < 1000 Da): All fluoroplastics, specialty fluoroplastics, and fluoroelastomers in the study met the low MW leachable PLC criteria, which has been widely discussed (see Supporting Information: Chapter 3 for references). Many of the study polymers report no active leachables, whereas the rest cite values less than 1 ppm (Tables 4 and 5). For FEVE, it is reported that some non-fluorinated polymer PA may well remain in the uncured polymer resin. The methods and references for low MW leachables are presented in the Supporting Information: Chapter 4 with the specific chapter noted in Tables 4 and 5. The data presented in Tables 4 and 5 were determined for each of the respective polymers in this study using techniques such as SEC and GPC as the predominant analytical methods along with the use of USP Class VI testing. Additional methods included 21 CFR 177.2600 (USCFR, 2022) and the USEPA's toxicity characteristic leaching procedure (TCLP; SW-846 Test Method 1311; USEPA, 1992).

Residual monomers and ratio of residual monomers to typical MW: PLC criteria of equal interest to the low MW leachables are the residual monomers and the ratio of residual monomers to typical MW (see Supporting Information: Chapter 3 for references). All fluoroplastics, specialty fluoroplastics, and fluoroelastomers in the study met the residual monomers and ratio of residual monomers to typical MW PLC criteria. The study data presented in Tables 4 and 5 show the polymers in this study have residual monomers ranging from less than 50 ppb for several fluoropolymers and up to less than 0.1% for PCTFE based on the methods utilized. Fluoroelastomers in this study have residual monomers ranging from less than 50 ppb up to less than 5 ppm. Residual monomers were determined in several ways including dynamic and static headspace gas chromatography/mass spectrometry (GC/MS) at 150 °C. The monomers used in most cases have very low boiling points and are thus readily volatilized (and captured or destroyed) during polymer manufacture processing and drying steps. The methods and references for residual monomer determination are presented in the Supporting Information: Chapter 4 with the specific chapter noted in Tables 4 and 5. Given the very low residual monomer levels reported, the ratio of residual monomers to polymer MW range from 10^{-11} to 10^{-13} for the study polymers.

Water solubility and octanol/water partition coefficient (K_{ow}): The fluoroplastics, specialty fluoroplastics, and fluoroelastomers in this study are solids that are hydro- and oleophobic, practically insoluble in both water and n-octanol. Therefore, a K_{ow} cannot be computed and is not applicable to these substances. It is worth noting that the practical lack of solubility in water (<10 mg/L) and n-octanol indicate the inability for the study fluoropolymers to actively or passively cross cell membranes. This does mean there is no indication that these polymers can bioaccumulate or bioconcentrate in biota (Henry et al., 2018 and this study). The methods and references for solubility are presented in the

Supporting Information: Chapter 4 with the specific chapter noted in Tables 4 and 5.

Particle size: To meet the PLC assessment criteria for particle size, a powder must be 5 μ m or greater in size (median mass aerodynamic diameter [MMAD]). All fluoroplastics, specialty fluoroplastics, and fluoroelastomers in the study met the particle size PLC criterion. As shown in Tables 4 and 5, the fluoroelastomers in this study are provided in sheets, blocks, pellets, or "crumb," and the fluoroplastics and specialty fluoropolymers in this study are provided in the form of powders, pellets, sheets, flake, or in dispersions. References and additional information regarding the form of the study polymers is provided in the Supporting Information: Chapter 4.

Stability: All fluoroplastics, specialty fluoroplastics, and fluoroelastomers in the study met the PLC criteria for hydrolysis, light stability, oxidative stability, and aerobic and anaerobic biodegradability (e.g., breakdown into species with Mn <1000 Da). Public literature has abundant thermal, chemical, and biological stability data for the polymers in this study as stability is a hallmark property for these polymers (Ebnesajjad, 2017). For biodegradation, the assessments were largely made based on property data of the study polymers demonstrating they are insoluble and stable in environmental media and thus are not expected to be bioavailable and therefore not biodegrade.

Additionally, published literature reports (Drobny, 2016; Ebnesajjad, 2017; Grot, 2013; Henry et al., 2018; Polymer Industry Association [PIA], 2019) that the study polymers are stable at foreseeable maximum continuous use temperatures presented in Tables 4 and 5. All polymers, including fluoropolymers can degrade when misused or when heated above their recommended use temperatures (Fluoropolymer Products Group of Plastics Europe [FPG], 2012; PIA, 2019). Of course, users are expected to follow guidance for use provided by manufacturers. Hence, the recommended temperatures for reasonably foreseeable use for the study substances are presented in Tables 4 and 5. References and additional information regarding the stability of the study polymers is provided in the Supporting Information: Chapter 4.

Fluorinated PA: If a fluorinated PA was used in the manufacture of the polymer, it was reported for each fluoropolymer in this study. Nine of the 14 fluoropolymers in the study were reported not to have used a fluorinated PA in their manufacture. It is industry practice to use fluorinated PAs when it is necessary to obtain specific end-use property or performance requirements generally related to very high-polymer MWs (see also Supporting Information: Chapter 7). For five study polymers, THV, FKM, FFKM, fluorinated ionomers, and amorphous fluoropolymers, a response of "Yes and No" was provided indicating that for some polymer grades a fluorinated PA is used, but not for others. See Supporting Information: Chapter 4 for additional information.

Results summary: This study examined three fluoroelastomers, nine fluoroplastics, and two specialty fluoroplastics:

ionomers and amorphous. Data for each were gathered from the author companies and assessed by the PLC criteria applicable to the polymer itself “in use” (BIO by Deloitte, 2015; Henry et al., 2018; OECD, 2009). All fluoroplastics, specialty fluoroplastics, and fluoroelastomers in the study met the PLC criteria based on the data presented in Tables 4 and 5 with additional details provided describing methods and references in the Supporting Information: Chapter 4.

Including the four fluoroplastics in the prior study (Henry et al., 2018), data for 18 fluoropolymers have been provided for PLC assessment. These polymers have a wide range of compositions and structures and represent most of the global commercial fluoropolymer market (see additional text in the Discussion). These 18 fluoropolymers represent the major fluoropolymers manufactured and are used worldwide in innumerable critical end-use products and applications. Tables 1 and 2 highlight examples of the end-use markets as well as critical functionality and benefits these polymers provide.

Each of the assessed polymers in this study are insoluble in both water and *n*-octanol, and thus K_{ow} is not applicable. This lack of solubility in water and octanol confirms that fluoropolymers are not mobile in the environment and are not bioaccumulative and not able to bioconcentrate. The stability studies reported here on each of the study fluoropolymers reveal their stability in terms of light, hydrolysis, heat, oxidation, and biodegradation. When coupled with the lack of solubility, these fluoropolymers are most often characterized as relatively inert materials in the environment. Like any other chemical material or product, it is important to follow the fluoropolymer manufacturer's recommended use and temperature conditions. Tables 4 and 5 describe these recommendations for each fluoropolymer. As reported, the physical forms of the fluoropolymers are largely pellets, blocks, crumb, sheets, some powders (all with MMAD >5 μ m). The solid fluoropolymers are not nanoparticles, and concerns related to nanoparticles do not apply during normal product use. Due to the properties described above for the assessed fluoropolymers—large molecules with no water solubility—the fluoropolymers are biologically inert without the practical ability to cross cell membranes.

During the evaluation of the study fluoropolymers, there was a conscious focus on several core PLC parameters: MW, low MW leachables, % oligomers, and residual monomers, which are direct outcomes related to fluoropolymer manufacturing. In addition to what is reported here in Tables 4 and 5 for the fluoropolymers themselves, industry efforts to manage emissions during manufacturing are discussed below.

DISCUSSION

Fluoropolymers have substantial, unique societal value: Fluoropolymers possess a remarkable combination of properties and functional characteristics, as shown in Tables 1 and 2, that make them valued materials of choice in a broad range of industries and applications critical to life

and a sustainable environment in the 21st century. Their unparalleled combination of properties and performance characteristics deliver functionality to a wide variety of products and systems critical to achieving important societal goals (Amcham, 2020c; FPG, 2021a; Wood, 2020b). They are strategically important to innovation in vital sectors of the global economy requiring high-speed, high-volume data transmission, miniaturization, or operations in extreme temperatures. Moreover, they are crucial to achieving important societal goals such as decarbonization, renewable energies, and/or competitiveness in the digital transition (FPG, 2021a). Fluoropolymers are indispensable for critical applications in the chemical, electronic, semiconductor, healthcare, and transport sectors and the deployment of 5G networks (FPG, 2021a). For many critical applications, fluoropolymers are the material of choice because alternatives are unable to provide the full complement of performance and functionality required. As such, there are currently no viable commercial alternatives to fluoropolymers in virtually every critical application in which they are used (FPG, 2021a, 2017; PFP, 2020).

Commercial fluoropolymers in this study meet the PLC criteria: Widely used by regulators, PLC criteria have been established around the world and documented by OECD expert groups as an appropriate hazard assessment methodology for polymers in-use and can effectively identify low risk fluoropolymers to help prioritize regulatory action (BIO by Deloitte, 2015; OECD, 1993, 2009). Here, we present PLC data, for hazard assessment, that define a group of fluoropolymers' “in-use” properties. PLC is not a comprehensive life-cycle assessment tool. Full life-cycle assessments consider all phases of product “life” including creation (manufacturing) and end-of-life (disposal). Information on manufacture and end-of-life is provided later in this study. Recently, polymers have been under increased regulatory scrutiny. In 2019, the industry-led European Centre for Ecotoxicology and Toxicology of Chemicals (ECETOC) developed a Conceptual Framework for Polymer Risk Assessment (“CF4Polymers”; ECETOC, 2019). CF4Polymers provides guiding elements to be considered in assessing potential ecological and human health hazards and risks posed by polymer substances. CF4Polymers also considers specific life-cycle stages of polymer products and their associated routes of exposure. The authors of the CF4Polymers framework support the PLC approach as a means to accomplish polymer risk assessment. They specifically support the findings of Henry et al. (2018) and state that they are “unaware of scientific evidence to justify generally assigning fluoropolymers the same level of regulatory concern as other PFAS” (ECETOC, 2019). In 2020, the European Commission contracted a study to propose criteria to identify PRR under REACH (Wood, 2020a). The report states that the authors consider fluoropolymers meeting the criteria to be considered PLC, “following the recommendations of Henry et al. (2018).”

The properties and characteristics of fluoropolymers are anchored in the strength of the carbon–fluorine bond, which

render them highly stable (thermally, chemically, and biologically), inert, and durable—long lasting in use—under exacting and high-performance conditions. Physical, chemical, thermal, and biological stability are important criteria for a polymer to be considered a PLC. The data presented in Tables 4 and 5 demonstrate that commercial fluoropolymers from the author companies meet the criteria to be considered PLC. The PLC criteria for physicochemical properties reflect the state of the polymers in this study, solids, as well as their inertness and stability. None of the fluoropolymers assessed in this study were soluble in water or octanol. They are biologically inert, insoluble in water and octanol, and not expected to move in or between environmental media. Fluoropolymers are also twice as dense as water. These properties and water insolubility mean fluoropolymers are not mobile in the environment and therefore would not be expected to be found in sources of drinking water. Fluoropolymers are neither bioavailable nor bioaccumulative. These solid polymers cannot be absorbed through a cell membrane via passive or active transport and do not bind or interact with the cell surface (see also Supporting Information: Chapter 8). In addition, whereas aquatic and mammalian toxicology studies of fluoropolymers may be desirable for some, they are technically difficult for insoluble, solid, high-MW polymers. The OECD test guidelines reiterate this in many cases. This is confirmed for example in REACH Annex VII guidance, which repeatedly states toxicity is unlikely to occur “if a substance is highly insoluble in water or the substance is unlikely to cross biological membranes” (see Supporting Information: Chapter 9).

Finally, structure criteria including MW, MWD, residual monomer(s), oligomers, and other synthesis by-products, as represented by low MW extractables and leachables have been determined for the fluoropolymers presented and meet values established for the PLC criteria and regulated uses (e.g., USP). The concentrations in the fluoropolymer that have been evaluated are extremely low, reflective of effective manufacturing processes that minimize these compounds complemented by capture and/or destruction systems for such materials. For additional information, see the section below discussing responsible manufacturing. This study and prior work (Henry et al., 2018) provide a guide for other global fluoropolymer manufacturers to gather and present data on additional commercial fluoropolymers to determine if they too meet the PLC criteria.

Fluoropolymer stability, aka persistence, is not an intrinsic hazard: Fluoropolymers are stable, inert, solid materials. Fluoropolymers resist degradation by acids, bases, oxidants, reductants, photolytic processes, microbes, and metabolic processes; for this reason, they are thermally, chemically, and biologically highly inert. Fluoropolymer stability was presented in the introduction and is further considered in the Supporting Information: Chapters 4 and 5. Fluoropolymers are not expected to degrade under environmental conditions or normal use and processing conditions (Wood, 2020a). They are stable and remarkably durable and are

therefore persistent. However, persistence alone does not imply that there is a present or future risk to human health or the environment (Rüdel et al., 2020). Persistence itself is not an intrinsic hazard, as it does not in itself imply or inform the potential for an adverse effect (aka toxicity). There is no language in REACH supporting the notion that persistence alone justifies risk-management measures. REACH has regulated persistence in combination with other properties that do inform potential hazards. In fact, REACH combines persistence with bioaccumulation and toxicity (or “very persistent” with “very bioaccumulative/very mobile” vPvB/vPvM) to justify designation as a substance of very high concern (SVHC) and consideration of potential risk-management measures for uses associated with unacceptable risk. Therefore, persistence on its own does not justify the need for specific risk-management measures. Fluoropolymers themselves are persistent, but they are not bioaccumulative, not mobile, and not toxic and therefore not SVHCs from a regulatory perspective (Ruwona and Henry, 2021).

PFAS grouping and segmentation—Scope of regulatory measures: The OECD definition of PFAS is based only on chemical structure (OECD, 2021). It describes a universe of fluorinated organic substances with vastly different physical, chemical, and biological properties, including polymers and nonpolymers; solids, liquids, and gases; highly reactive and inert substances; soluble and insoluble substances; and volatile and involatile substances and is too broad to allow effective, science-based assessment and regulation of chemical compounds as an entire group (Amcham 2020a; BDI, 2021; Buck et al., 2021; Orgalim, 2021; Wallington et al., 2021). A 2021 OECD report states: “it is highly recommended that such diversity be properly recognized and communicated in a clear, specific and descriptive manner” and “the term ‘PFASs’ does not inform whether a compound is harmful or not, but only communicates that the compounds under this term share the same trait for having a fully fluorinated methyl or methylene aliphatic carbon moiety” (OECD, 2021).

In this context, the available property data (Tables 4 and 5) reveal that fluoropolymers have distinctly different properties from nonpolymeric PFAS and from SCFPs that have a polymeric backbone that does not contain C–F bonds directly attached to it. The perfluoroalkyl moiety in SCFPs is found in a side-chain connected via a functional group to the polymer backbone and “can potentially lead to the formation of non-polymer PFAS as a result of degradation” (Fluoropolymer Products Group of Plastics Europe [FPG], 2021b; Wood, 2020a; see Supporting Information: Chapter 6). Segmentation that clearly differentiates the broad PFAS family according to their properties, rather than using a structure-based classification alone (OECD, 2021), is needed for a scientifically sound, risk-based regulatory approach. Regulating all PFAS as one homogenous group (ECHA, 2020) absent consideration of their properties, particularly when the properties are so demonstrably different, neglects basic scientific consideration of these properties, which are the foundation of substance differentiation. The USEPA does not consider all PFAS to have

similar risk profiles and therefore they are following a categorical grouping approach based on information about similarities in structure, physicochemical properties, and existing test data on the toxicity of PFAS (USEPA, 2021b). Therefore, segmentation based on properties should be conducted before performing any grouping-based risk assessment, placing stable, nonhazardous fluoropolymers that meet the criteria to be considered PLC in a separate category (see also Supporting Information: Chapter 6).

Fluoropolymer market perspective: The commercial fluoropolymer global market sales have been reported to be approximately 230 000 MT (Dams & Hintzer, 2017). Given the expected fluoropolymer market growth, ranging from approximately 4%–5% to 7%–8% (Allied Market Research [AMR], 2022; Future Market Insights [FMI], 2022; FPG, 2021a; Globe Newswire, 2021), a pro forma market table was created for 2021 using a 5% growth rate. Adding ionomers as well as updated amorphous market information (company data) to the above, the total commercial fluoropolymer market sales is estimated to be approximately 330 000 MT in 2021 (see Supporting Information: Chapter 10). Four fluoropolymers: PTFE, FEP, PFA, and ETFE, were the focus of the first fluoropolymer PLC paper (Henry et al., 2018) and account for approximately 64% of fluoropolymers sold globally in 2021 (pro forma basis). The sales volume of these four fluoropolymers is represented by the first four bars in Figure 10.1 in Supporting Information: Chapter 10. This study discusses 14 fluoropolymers representing an additional 32% (pro forma basis) of the global fluoropolymer market. Therefore, this study, in combination with Henry et al. (2018), presents PLC data from the cited manufacturers of commercial fluoropolymers representing approximately 96% of the global commercial fluoropolymer market that meet the criteria to be considered PLC. The projected 2021 sales volume of the major types of commercial fluoropolymers covered in this study (PVDF, FKM, FEP, amorphous, ionomers, THV, ECTFE, PCTFE, and FFKM, EFEP, CTP, and FEVE) are also represented in Figure 10.1 in Supporting Information: Chapter 10. As noted, estimated market volumes were provided for the sum of FEP, CPT, EFEP, and FEVE as well as a small “others” category. The fluoropolymer polyvinyl fluoride (PVF) was not covered by these two papers but is also shown in Figure 10.1 in Supporting Information: Chapter 10. Other fluorinated polymers, perfluoropolyethers, and SCFPs are not addressed in this study (see Supporting Information: Chapter 6).

FLUOROPOLYMER LIFE-CYCLE CONSIDERATIONS

This study focuses on the properties of the 14 selected commercial fluoropolymers themselves in-use providing data that demonstrate they meet the criteria to be considered PLC. Additionally, the life-cycle stages of fluoropolymer creation (manufacturing) and disposal at the end of industrial or consumer use (end-of-life) are important to consider. The primary focus in these life-cycle stages is generally nonpolymer PFAS from the manufacturing process or fluoropolymer

degradation in end-of-life disposal (ECHA, 2020; FPG, 2021a; Guelfo et al., 2021; Lohmann et al., 2020).

The long-established life-cycle assessment approach to environmental protection and risk management first considers the extent of emissions, their toxicity, and their exposure potential (Guinee et al., 2011). When emissions are sufficiently large in scope, toxicity, and exposure potential, emission-management methods are then considered, including process input changes and emission controls to reduce or eliminate the risk of the emissions. Fluoropolymer manufacturing and disposal life-cycle stages were discussed in the paper that first presented fluoropolymer PLC data (Henry et al., 2018). Here we provide an update and current perspective.

Responsible manufacturing: As corroborated by the data presented here and in prior work (Henry et al., 2018), a large volume percentage and number of commercial fluoropolymers are manufactured that meet the criteria to be considered PLC. Emissions from fluoropolymer manufacture are a key product life-cycle focus. The main focus during the manufacturing phase is not directly related to fluoropolymers but from emissions. Emissions of concern may include nonpolymer PFAS such as fluorinated PAs, unreacted monomers, oligomers, or other unintended by-products formed during manufacturing. It is important to note that, although some high-MW fluoropolymers require use of a fluorinated PA in manufacturing (see also Supporting Information: Chapter 10), it has been reported that at least 50% of commercial fluoropolymers are made without one (Pro-K Fluoropolymer Group, 2021).

Recently, a group of fluoropolymer member companies of FPG voluntarily committed to responsible manufacturing principles through the commissioning of a Regulatory Management Option Analysis, developed by independent consulting firm Chemservices (FPG, 2021a). Member companies of this group are working on individual projects and joint projects at the trade association level with third-party experts. Specifically, companies have committed to continuously improving and/or developing the best available techniques in the manufacturing process, managing environmental emissions, developing R&D programs for the advancement of technologies allowing for the replacement of nonpolymer PFAS PAs and/or working with downstream users to increase the recyclability and reuse of its products in line with the objectives of circular economy (FPG, 2021a). Implementation of this voluntary industry initiative to address concerns relating to fluoropolymers will strengthen already ongoing efforts performed by the fluoropolymer industry promoting responsible manufacturing practices. In addition, member companies are committed to working with EU authorities to establish and implement technical actions to guarantee adequate control of the risks derived from the manufacture and use of fluoropolymers to mitigate such risks wherever possible. This will be done following transparency principles and agreements to monitor progress. For example, important emission reduction has been demonstrated by major fluoropolymer manufacturers including fluorinated PA recovery for reuse, 99% removal of fluorinated PA in wastewater treatment, and

99.99% capture and destruction efficiency of gaseous emissions routed to a thermal oxidizer (Chemours, 2021c), as well as 99–99.9 plant emission reductions (Daikin, 2021c, 2022). Four other companies have reported replacement of fluorinated PAs with nonfluorinated PAs (Arkema, 2008, 2021b; Chemours, 2022; Gujarat Fluorochemicals Limited, 2022; Solvay, 2022). These are substantial efforts toward mitigating emissions associated with fluoropolymer manufacturing being worked on by fluoropolymer manufacturers. This study and the prior study (Henry et al., 2018) provide a guide for other global fluoropolymer manufacturers to gather and present data on their commercial fluoropolymers in-use demonstrating that they meet the PLC criteria.

End-of-use: At the end of industrial or consumer use, fluoropolymers may be disposed via the following routes: landfill, incineration (e.g., waste-to-energy [WTE] facilities), or reuse/recycling. There is considerable data demonstrating that fluoropolymers such as PTFE do not degrade in the environment or release substances of toxicological or environmental concern (FPG, 2021a; Hintzer & Schwertfeger, 2014). FPG member companies are working with the industry and end users on this subject and are engaged in a research project aimed at identifying conditions required for proper disposal (incineration) of fluoropolymers (FPG, 2021a).

Fluoropolymers are chemically, thermally, and biologically stable (Henry et al., 2018; this study) and therefore are not expected to transform to dispersive nonpolymeric PFAS when disposed of in a landfill. A recent study presented results from OECD guideline biodegradation studies demonstrating that PTFE is stable and does not degrade under environmentally relevant conditions (Ruwna and Henry, 2021). Further, fluoropolymers that meet the criteria to be considered PLC, such as those in this study and prior work (Henry et al., 2018), have negligible leachables, unreacted monomers, and oligomers most likely destroyed in fluoropolymer use processing and would therefore not be expected to significantly contribute to landfill leachate (Ruwna and Henry, 2021).

Available data reveal that fluoropolymers are mineralized (i.e., all C–F bonds broken, hydrofluoric acid generated, and scrubbed to calcium fluoride) under commercial WTE incineration operating conditions (Aleksandrov et al., 2019; Bakker et al., 2021; DEC, 2021; Giraud et al., 2021a, 2021b). In recent pilot scale studies representative of full-scale WTE facilities, the most common form of end-of-life destruction conducted on PTFE found that combustion converted the fluorine into controllable hydrogen fluoride gas and that, of the 31 PFAS studied, no fluorine-containing products of incomplete combustion were produced above background levels (Aleksandrov et al., 2019). Further, a recent study investigating the presence of PFAS in waste incinerator flue gas stated: “based on a literature review, RIVM expects that most of the PFASs will largely degrade during the incineration process and then be removed when the flue gases are cleaned. The remaining PFASs are expected to be removed during the recovery of the carbon dioxide” (Bakker et al., 2021). The RIVM report affirmed that PTFE is the most stable fluorine-containing polymer. For PTFE, the RIVM report

concluded that complete thermal decomposition is achieved at a temperature of approximately 800 °C. It was therefore assumed that other fluorine-containing polymers also thermally decompose completely at a temperature of 800 °C. Temperatures at the pyrolysis front and the combustion front in the waste-burning bed range from 900 °C to 1100 °C (As-thana et al., 2006; Ménard et al., 2006), which is well above 800 °C, the temperature at which the complete thermal decomposition of PTFE is achieved (Bakker et al., 2021). Studies for additional fluoropolymers and those with additional pilot and/or full-scale fluoropolymer studies would contribute to this body of data and further affirm their results. The PFP and FPG currently have joint projects working on these potential contributions.

Recycling of fluoropolymer products and articles containing fluoropolymers is difficult because separation of the fluoropolymer from the end products is not always possible (FPG, 2021a; Hintzer & Schwertfeger, 2014; Pro-K Fluoropolymer Group, 2018). This is because fluoropolymers are used predominantly in small components of larger finished articles involving a wide variety of materials. There are several options to recycle fluoropolymer products. In primary recycling, solid fluoropolymer waste is ground and later fed back into the manufacturing cycle of some fluoropolymer products. Recycled fluoropolymers may be used in high-end applications when correctly collected, cleaned, and reprocessed. In secondary recycling, solid fluoropolymer waste is ground, followed by degradation to approximately 1% of the original degree of polymerization by using electron beams, gamma rays, or thermomechanical degradation. The recovered material can be used in the manufacturing of new fluoropolymer products. Lastly, in tertiary recycling or upcycling, solid fluoropolymer is ground, then decomposed into the starting monomers at temperatures higher than 600 °C (pyrolysis) to obtain the same chemical components from which the fluoropolymer was manufactured; monomers, such as tetrafluoroethylene, are purified by distillation, and can then be reused to manufacture new fluoropolymer (3M, 2021; Schlipf & Schwalm, 2014). For the primary and secondary schemes, recycling treatments can be undertaken by the manufacturers of fluoropolymers themselves (onsite), or at a larger scale, mainly by specialist recycling companies. The upcycling needs to be colocated to a fluoropolymer manufacturing plant that can use tetrafluoroethylene.

Primary and secondary recycling is limited because of the presence of fillers, colorants, and other materials in the composition of their final articles. Further, recycling might not work for all end-of-life components, as they are used predominantly in small components of larger finished articles involving a wide variety of materials. Therefore, collecting and dismantling for recycling might not be feasible for all products (FPG, 2021a; Hintzer & Schwertfeger, 2014; Pro-K Fluoropolymer Group, 2018). However, it should be noted that upcycling treatment is applicable to some articles containing fluoropolymers, such as pipe liners in chemical plants, as well as other plant components such as pumps, tank liners, seals, hoses, compensators, and many other fluoropolymer

components and systems. These are the products for which the high quantities of fluoropolymers are used offering significant recycling potential.

SUMMARY

This study has described the composition, uses, performance properties, and functionalities of 14 commercially available fluoropolymers, including fluoroplastics and fluoroelastomers. Fluoropolymers are the preferred material of choice because of their unique combination of properties, which are not achievable from other materials or via other functions. As a result, fluoropolymers have become a critical mainstay for society and are useful to modern living, as they provide vital, reliable functionality to a broad range of industrial and consumer products. Further, the study has presented data demonstrating the subject fluoropolymers satisfy the widely accepted polymer hazard assessment criteria to be considered PLC. The data presented demonstrate the fluoropolymers in the study are thermally, biologically, and chemically stable, negligibly soluble in water, nonmobile, nonbioavailable, nonbioaccumulative, and nontoxic, and contain low levels of impurities. These results further demonstrate that the fluoropolymer class should be considered distinctly different and should not be grouped with other PFAS for hazard assessment or regulatory purposes. When combined with earlier work (Henry et al., 2018), the study demonstrates that commercial fluoropolymers are available that meet the criteria to be considered PLC, which represent approximately 96% of the global fluoropolymer market. Lastly, emissions from fluoropolymer manufacture and disposal at end-of-use are a product life-cycle focus. Emissions may include nonpolymer PFAS such as fluorinated PAs, unreacted monomers, oligomers, or other unintended by-products formed during manufacturing. Fluoropolymer manufacturers recently committed voluntarily to responsible manufacturing principles by continuously improving and/or developing the best available techniques in the manufacturing process, managing environmental emissions, developing R&D programs for the advancement of technologies allowing for the replacement of fluorinated PAs, and/or increasing recyclability and reusing fluoropolymers in line with the objectives of circular economy.

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CONFLICT OF INTEREST

The authors are employed by companies that commercially manufacture fluoropolymers. SHK is an independent fluorotechnology consultant working on behalf of AGC Chemicals Americas Inc. and principal of BeachEdge Consulting LLC.

DATA AVAILABILITY STATEMENT

Data gathered for this paper is presented in the paper itself and the Supporting Information: Data file provided. Additional data are available upon request from the corresponding author Stephen Korzeniowski (shkorzo@gmail.com).

SUPPORTING INFORMATION

The Supplement contains a glossary of terms as well as additional information on the study of fluoropolymers properties and functionalities, polymer of low concern (PLC) background and criteria, references and methods for the PLC data for the study of fluoropolymers, benefits, features and alternatives assessment for the study of fluoropolymers, the differences between fluoropolymers and side-chain fluorinated polymers, fluoropolymer bioavailability and toxicity studies, fluoropolymer global market information, fluoropolymer socioeconomic analyses and risk-management options analysis (RMOA).

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Article

In Vivo Toxicity and Pharmacokinetics of Polytetrafluoroethylene Microplastics in ICR Mice

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Abstract: The increased use of plastics has led to severe environmental pollution, particularly by microplastics—plastic particles 5 mm or less in diameter. These particles are formed by environmental factors such as weathering and ultraviolet irradiation, thereby making environmental pollution worse. This environmental pollution intensifies human exposure to microplastics via food chains. Despite potential negative effects, few toxicity assessments on microplastics are available. In this study, two sizes of polytetrafluoroethylene (PTFE) microplastics, approximately 5 µm and 10–50 µm, were manufactured and used for single and four-week repeated toxicity and pharmacokinetic studies. Toxicological effects were comprehensively evaluated with clinical signs, body weight, food and water consumption, necropsy findings, and histopathological and clinical-pathological examinations. Blood collected at 15, 30, 60, and 120 min after a single administration of microplastics were analyzed by Raman spectroscopy. In the toxicity evaluation of single and four-week repeated oral administration of PTFE microplastics, no toxic changes were observed. Therefore, the lethal dose 50 (LD₅₀) and no-observed-adverse-effect-level (NOAEL) of PTFE microplastics in ICR mice were established as 2000 mg/kg or more. PTFE microplastics were not detected in blood, so pharmacokinetic parameters could not be calculated. This study provides new insight into the long-term toxicity and pharmacokinetics of PTFE microplastics.

Keywords: microplastics; polytetrafluoroethylene; toxicity evaluation; pharmacokinetics

1. Introduction

Globally, the amount of plastic used is steadily increasing, with production rising from 1.5 million tons in the 1950s to 3.35 billion tons in 2016 [1]. Some plastics are recycled, but most are discarded, often causing environmental pollution. Plastic particles with a size of less than 5 mm are called microplastics [2,3]. These small particles are designated as one of the world's four major environmental issues, along with environmental changes, ozone layer destruction, and marine oxidation [4]. Microplastics are classified as primary

microplastics made for use in personal care products, cosmetics, toothpaste, detergents, sunscreens, and drug vectors [5–7]. Secondary microplastics are formed by environmental factors, such as UV oxidation, light degradation, and physical ablation [5,8–10]. Primary microplastics are mainly spherical in keeping with their uses, and secondary microplastics are mostly fractured or fibrous forms due to weathering and other environmental factors. The latter particles cause environmental pollution worldwide [11,12]. Studies on rivers and seas detect large amounts of microplastics [13–15]. In addition, secondary microplastics are small, making them difficult to remove during sewage treatment [16]. Thus, particles are released into receiving waters and eventually flow into the seas. These microplastics may stick to the gills of aquatic organisms during oxygen exchange or when particles are mistaken for food [17]. Subsequently, microplastics accumulate in these aquatic organisms and can be detected in various ways [18,19]. The consumption of aquatic organisms that have accumulated microplastics might be harmful to humans, making toxicological research essential. Further, many studies report microplastics of various sizes, colors, and types, such as polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET), in easily accessible foods (mineral water, salt, beer, wine, canned foods, milk, seaweed) [20–27]. Exposure to microplastics can occur via inhalation, dermal absorption, or ingestion, with the ingestion route being the most important [28]. In vitro, microplastics show increased accumulation and toxicity through the inhibition of ATP-binding cassette transporter activity in Caco-2 cells [29] and significantly increase the production of ROS in human-derived HDFs, PBMCs, and Raw 264.7 cells [30]. Oxidative stress increased in human cerebral cells (T98G) and epithelial cells (HeLa) after exposure to microplastics [31]. These impacts at the cellular level suggest that microplastics might exhibit toxicity in humans. Experiments at this cell level suggest that microplastics can potentially exhibit influence or toxicity in humans. Recently, in vivo experiments using microplastics are on the rise. In aquatic organisms, PE and PP caused increased mortality and gut clearance times and decreased growth of *Hyalella azteca* [32]. Polystyrene (PS) caused reduced body weight, body length, and body mass index and increased inflammatory cytokine and chemokine gene expression in zebrafish [33]. In oysters, a decrease in the number and diameter of female oocytes, the speed and activity of male sperm, and the growth rate of larval were observed [34]. In experiments using mammals, PE also altered intestinal microbial populations in C57BL/6 mice and cause inflammatory cell infiltration and loosening of glands in the colon [35]. PS caused inflammation of testicles, fibrosis of ovaries, adipose metabolic disorders in the liver, a reduction of mucin secretion in the colon, and a change in the intestinal microbial population in intestinal microorganisms [36–39]. PS is distributed to the liver, kidney, and gastrointestinal tract, and affects energy metabolism, lipid metabolism, oxidative stress, and neurological function [40]. Additionally, our previous study showed that polyethylene microplastics can induce granulomatous inflammation in the lungs after four-week repeated oral administrations [41]. Thus, microplastics may be toxic to various tissues, including reproductive and nervous systems. PTFE is a plastic with a density of 2.0 g/m^3 and 2.3 g/m^3 for amorphous and crystalline portions, respectively [42]. Unlike general plastics, it is used to coat kitchen utensils applied via spraying. Most of these kitchenware coatings can peel off during cooking through heating or friction with utensils [43]. Released PTFE can be incorporated into cooked food and subsequently ingested. Despite this high potential for human exposure, the number of animal experiments using microplastics is still small, and most animal experiments used microplastics composed of polystyrene and polyethylene. PTFE is rarely studied in vivo for toxicity and kinetics in mammals. We manufactured two sizes of PTFE microplastics to confirm whether the manufactured microplastics conform to the commonly used definition of microplastics, under the size of 5 mm. A typical toxicity test was conducted using manufactured microplastics to establish LD_{50} and NOAEL, and a pharmacokinetic experiment was conducted to determine the organs in which microplastics are widely distributed in the body.

2. Materials and Methods

2.1. Preparation of Polytetrafluoroethylene Microplastics

Two sizes of PTFE microplastics (approximately 5 μm and 10–50 μm) were made from PTFE raw materials (TF1641, DyneonTM, Aston, PA, USA). For the preparation of PTFE 10–50 μm particles, PTFE was frozen at $-78\text{ }^{\circ}\text{C}$ with dry ice and ground using a blade-type homogenizer for 4–5 h. Particles were filtered sequentially through 63 μm and 10 μm mesh filters and washed 4–5 times with ethanol. Particles were then dried in an oven at $50\text{ }^{\circ}\text{C}$ for 48 h. For the preparation of approximately 5 μm PTFE particles, 10–50 μm particles of PTFE were dispersed in ethanol and ground with a high-pressure homogenizer 4 times with 600 bar. Then we separated particles sequentially using a 15 μm mesh filter and a 5 μm mesh filter and washed particles with ethanol 4–5 times. Finally, the particles were dried for 48 h in a $50\text{ }^{\circ}\text{C}$ oven.

2.2. Characterization of Polytetrafluoroethylene Microplastics

The average particle size was measured using a Particle Size Analyzer based on light scattering (PSA, ELS-Z2Plus, Otsuka Electronics, Osaka, Japan). This method can be used to obtain the hydrodynamic size of a particle using the Stokes–Einstein relationship by analyzing the fluctuation of scattered light by suspended particles when illuminated with a laser to determine the rate of Brownian motion. The shape of microplastics was confirmed using a 3D-laser profile (Confocal microscopy, Keyence, Itasca, IL, USA) and scanning electron microscopy (SEM, JSM-6701F, JEOL Inc., Akishima, Tokyo, Japan). Finally, chemical identity was confirmed using a Raman microscope (RAMANtouch, Nanophoton, Osaka, Japan) equipped with a 532 nm-laser diode. The morphology of microplastics was examined with a $20\times$ objective lens (Nikon LU Plan Flour $20\times/0.45$), then Raman spectra were collected in the $45.3\text{--}4273.8\text{ cm}^{-1}$ range using 300 lines per mm grating with a 50 μm slit width. Spectra were measured over a 16-bit dynamic range with Peltier cooled charge-coupled device detectors. The laser power was adjusted to 2 mW for each scan to obtain a sufficient signal. The acquisition time and the number of accumulations were adjusted for each measurement to obtain sufficient data for library searching. The spectrometer was calibrated with silicon at a line of 520 cm^{-1} before spectral gaining. Raman spectra were analyzed using the SLOPP Library of Microplastics and the spectral library in KnowItAll software (Bio-Rad Laboratories, Inc., Hercules, CA, USA). Similarities above the Hit Quality Index of 80 were considered satisfactory.

2.3. Animal and Ethics Statement

Five-week-old specific-pathogen-free ICR mice, 128 male and 104 female, were purchased from KOATECH Inc., Pyeongtaek, Gyeonggi-do, Korea. Mice were housed in a standard SPF facility in ventilated IVC cages ($395\text{W} \times 346\text{D} \times 213\text{H}$) at $22 \pm 1\text{ }^{\circ}\text{C}$, relative humidity of $50 \pm 10\%$, a ventilation time of 10–15 h, light for 12 h per day, and illumination of 150–300 lux. All animal care and experimental procedures were approved by the Institutional Animal Care and Use Committee of the Laboratory Animal Center of the DGMIF (IACUC; approval No. DGMIF-21031601-00) and were in accordance with their guidelines.

2.4. Single Oral Dose Toxicity Study

Two groups of 12 male and 12 female mice were acclimatized for 1 week to evaluate the different sizes of PTFE microplastics. Each group of animals was divided into four subgroups (control, low-dose (500 mg/kg), mid-dose (1000 mg/kg), and high-dose (2000 mg/kg)) with three male and three female animals for each subgroup. A single dose of corn oil was administered to control mice, and microplastics suspended in corn oil were administered for each of three microplastic doses. The volume of corn oil was constant at 10 mL/kg. The study was conducted with reference to OECD guideline 423. The observation of clinical signs, the presence of moribund or dead animals, and the measurement of body weight were performed once a day, twice a day, and once a week, respectively, during the two-week observation period. All animals were anesthetized with CO_2 at the end of

the study and exsanguinated through the abdominal aorta. Complete gross postmortem examination was performed on all mice.

2.5. Four-Week Repeated Oral Dose Toxicity Study

Two groups of 40 male and 40 female mice were acclimatized for 1 week to evaluate different sizes of PTFE microplastics. Each group of animals was divided into four subgroups (control, low-dose (500 mg/kg), mid-dose (1000 mg/kg), and high-dose (2000 mg/kg)) with ten male and ten female animals for each subgroup. Four-week repeated administration of corn oil for the control group and microplastics suspended in corn oil for each of three microplastic doses were performed. Animals in the remaining groups received microplastics suspended in corn oil to achieve the above doses for each particle size. The volume of corn oil was constant at 10 mL/kg. This study was conducted with reference to OECD guideline 408. The observation of clinical signs and the presence of moribund or dead animals were recorded once a day and twice a day, respectively. The measurement of body weight, food consumption, and water consumption were all measured once a week. After four weeks, blood was collected from the abdominal aorta under isoflurane (Hana Pharm, Co., Ltd., Seoul, Korea) anesthesia. Blood samples collected from animals were analyzed using a blood cell analyzer (ADVIA 2120i, SIEMENS, Muenchen, Germany) and a serum biochemistry analyzer (TBA 120-FR, Toshiba, Tokyo, Japan). Complete gross postmortem examinations were performed on all animals and tissues. The adrenal glands, brain, cecum, colon, duodenum, epididymis, esophagus, heart, ileum, jejunum, kidney, liver, lungs, ovary, pancreas, parathyroid glands, pituitary gland, rectum, spinal cord, spleen, stomach, testis, thymus, thyroid gland, trachea, and uterus were harvested. Organ weights were recorded for the brain, spleen, heart, kidney, liver, testis, epididymis, and ovary. Tissues were fixed in 10% neutral buffered formalin (BBC Biochemicals, Mount Vernon, WA, USA), except for testes, which were fixed in Davison's fixative followed by storage in 10% neutral buffered formalin. A tissue processor (Thermo Fisher Scientific, Inc., Runcorn, UK) was used to prepare fixed tissues. Four-micrometer sections were cut from paraffin-embedded tissue blocks and mounted onto glass slides. Sections were then stained with hematoxylin and eosin using an autostainer (Dako Coverstainer; Agilent, Santa Clara, CA, USA). Personnel that performed histopathological evaluations were blind to the sources of tissues.

2.6. Pharmacokinetics Study

Pharmacokinetics of PTFE was characterized in 24 male mice acclimatized for 1 week. Animals were divided into 2 groups with social housing of three mice per cage. Animals were administered a single oral dose of 2000 mg/kg PTFE microplastics, followed by blood collection after 15, 30, 60, and 120 min. Groups of animals were administered one of the two sizes of PTFE particles.

2.7. Quantitative Evaluation of Polytetrafluorethylene Microplastics in Blood

Whole blood collected at predetermined times was pooled, and a 10 wt% aqueous KOH solution (20 times sample weight) was added. These samples were incubated at 37 °C for 48 h with shaking at 250 rpm. Sample solutions were filtered stepwise through stainless-steel (47 mm disk, 45 µm pore size) and silicon filters (1 cm × 1 cm, 1 µm pore size) provided by Nanophoton. The Raman microscope used RAMANtouch to assess the number of PTFE microplastics collected on silicon filters.

2.8. Data Analysis

A non-compartmental analysis was performed to calculate pharmacokinetic parameters for PTFE using Phoenix WinNonlin 8.1 software. The area under the plasma concentration–time curve (AUC_{last}) from time zero to infinity (AUC_{∞}) was calculated with linear trapezoidal and standard area extrapolation methods. Terminal half-life ($t_{1/2}$) was calculated as $0.693/\lambda$, where λ represents the terminal slope of the log-linear of larotrectinib

concentration–time profile. Total clearance (CL) for PTFE was calculated as $\text{dose}/\text{AUC}_{\infty}$ and steady-state volume of distribution (V_{ss}) was then calculated as $\text{MRT} \times \text{CL}$. The observed maximum concentration ($C_{\max}$) and time to reach $C_{\max}$ ($T_{\max}$) were obtained directly from individual PTFE plasma concentration–time profiles.

2.9. Human NOAEL Dose

The human NOAEL dose was estimated using the HED (human equivalent dose) converting table for mice. A 2000 mg/kg dose, the assumed NOAEL, was used for the calculation (Equation (1)) because PTFE plasma concentrations were not recorded within the range of 500–2000 mg/kg.

$$\text{Dose}_{\text{human}} (\text{mg/kg}) = \text{Dose}_{\text{mouse}} (\text{mg/kg}) \times (\text{Km}_{\text{mouse}}/\text{Km}_{\text{human}}) \quad (1)$$

2.10. Statistical Analysis

All hematology, serum biochemistry, and body weight data are presented as means $\pm$ standard deviation. The statistical significance of the differences between treated and control animals was evaluated using Student's *t*-tests and one-way analysis of variance with the SAS program (version 9.4, SAS Institute Inc., Cary, NC, USA).

3. Results

3.1. Characterization of Polytetrafluoroethylene Microplastics

PSA, Confocal microscopy, SEM, and Raman microscope analysis were performed to characterize prepared PTFE microplastics and assess the intended size. PSA confirmed the two sizes of microplastics were approximately 5 μm ($6.03 \pm 2.10 \mu\text{m}$) and 10–50 μm ($31.65 \pm 5.64 \mu\text{m}$) (Figure 1a). The actual size of microplastics was measured with confocal microscopy and SEM (Figure 1a). Representative Raman spectra obtained from filtered microparticles identified PTFE based on peaks at 290 cm^{-1} to 1400 cm^{-1} , presenting symmetric stretch CF_2 and C–C peaks at 733 cm^{-1} and 1379 cm^{-1} , and CF_2 twisting and CF_2 bending peaks at 292 cm^{-1} and 384 cm^{-1} , respectively [44]. In addition, lines of medium intensity at 1222 cm^{-1} and 1304 cm^{-1} were ascribed to the antisymmetric stretch peak of CF_2 [45] (Figure 1b). The physical and chemical properties of the particles prepared through these analytical methods were confirmed to be suitable for the conditions of PTFE microplastics.

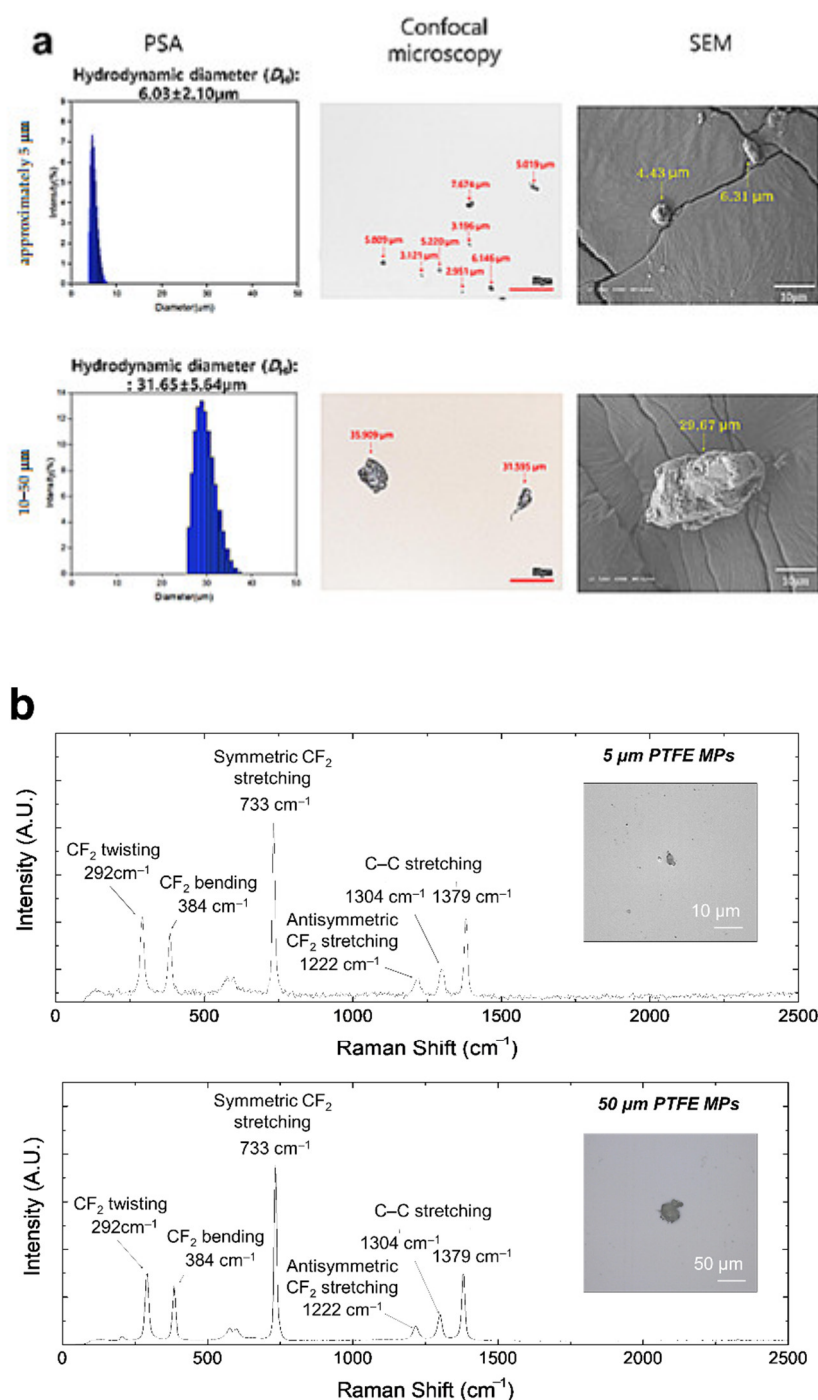


Figure 1. Characterization of PTFE microplastics. (a) Analysis with PSA, confocal microscopy, and scanning electron microscopy, (b) Raman spectra of approximately 5 μm and 10–50 μm -sized PTFE microplastics captured on silicon filters. Inset images show representative PTFE microplastics. Scale bar = 10 μm and 50 μm .

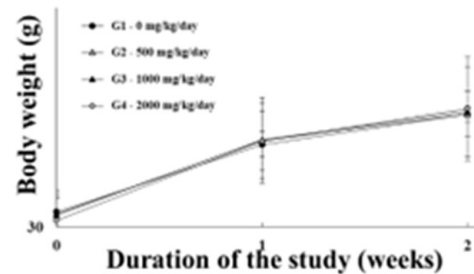
3.2. Toxicity Study

A single-dose toxicity study was performed to identify an approximate lethal dose of PTFE microplastics in two size ranges. No morbidity or death in mice was observed, and no specific clinical symptoms were recorded. Further, no significant weight changes were associated with exposure to microplastics when compared to control animals (Figure 2a–d). At necropsy, macroscopic examinations did not reveal changes associated with PTFE microplastic administration (data not shown). Thus, the approximate lethal dose for both

sizes of PTFE microplastics was 2000 mg/kg or greater. The above LD₅₀ and NOAEL values suggest that the prepared PTFE microplastics show no harm to mice *in vivo* at a dose of less than 2000 mg/kg.

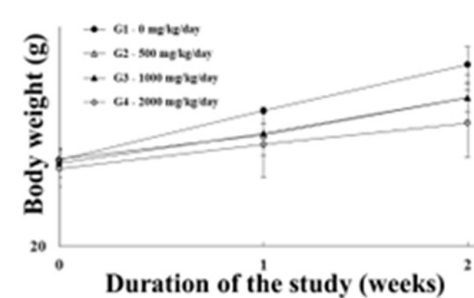
a approximately 5 μ m, male

Dose \ Week	0	1	2
G1 - 0 mg/kg/day	31.1	35.7	37.7
G2 - 500 mg/kg/day	30.9	35.9	37.7
G3 - 1000 mg/kg/day	30.8	36.0	37.9
G4 - 2000 mg/kg/day	30.5	35.9	38.1



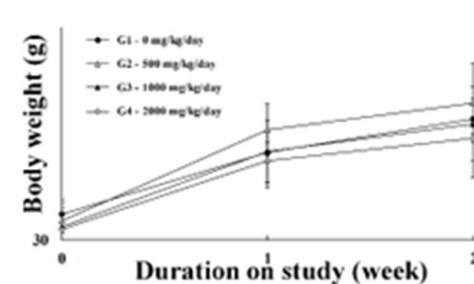
b approximately 5 μ m, female

Dose \ Week	0	1	2
G1 - 0 mg/kg/day	25.9	29.3	32.4
G2 - 500 mg/kg/day	26.0	27.6	30.1
G3 - 1000 mg/kg/day	25.7	27.7	30.1
G4 - 2000 mg/kg/day	25.3	27.0	28.4



c 10–50 μ m, male

Dose \ Week	0	1	2
G1 - 0 mg/kg/day	31.8	36.1	38.5
G2 - 500 mg/kg/day	31.3	37.8	39.6
G3 - 1000 mg/kg/day	30.9	36.2	38.2
G4 - 2000 mg/kg/day	30.7	35.6	37.2



d 10–50 μ m, male

Dose \ Week	0	1	2
G1 - 0 mg/kg/day	25.4	26.8	28.4
G2 - 500 mg/kg/day	25.0	27.7	30.1
G3 - 1000 mg/kg/day	25.1	27.6	28.6
G4 - 2000 mg/kg/day	24.9	26.0	28.9

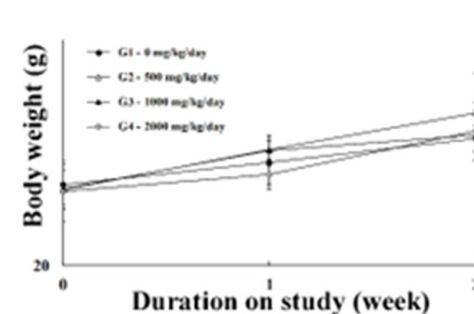
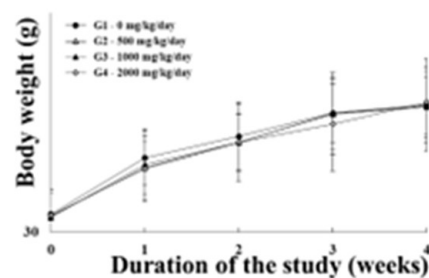


Figure 2. Male and female bodyweight changes after a single dose of approximately 5 μ m (a,b) and 10–50 μ m (c,d) PTFE microplastics.

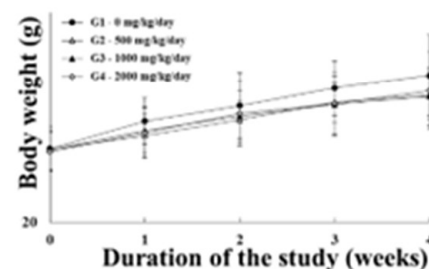
Four-week repeated-dose toxicity study based on the single-dose toxicity study and OECD guideline No. 408 was then used to establish a NOAEL for chronic exposure. No morbidity or death of animals was observed, and no specific clinical signs were recorded. Body and organ weights (Figure 3a–d, Supplementary Table S1), food (Figure 4a–d) and water (Figure 4e–h) consumption, clinical pathology (Table 1), and histopathological changes (Figure 5a–c) due to PTFE administration were not observed. Thus, NOAELs for two sizes of PTFE microplastics were 2000 mg/kg or greater.

a approximately 5 μm , male

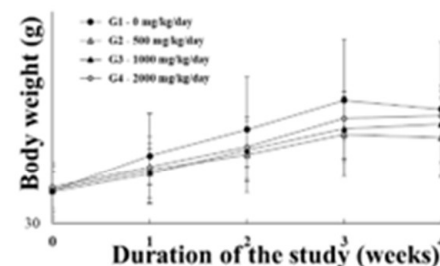
Dose \ Week	0	1	2	3	4
G1 - 0 mg/kg/day	31.2	35.1	36.5	38.1	38.7
G2 - 500 mg/kg/day	31.1	34.4	36.1	38.1	38.6
G3 - 1000 mg/kg/day	31.0	34.6	36.1	38.1	38.6
G4 - 2000 mg/kg/day	31.1	34.3	36.1	37.4	38.9

**b** approximately 5 μm , female

Dose \ Week	0	1	2	3	4
G1 - 0 mg/kg/day	25.3	27.2	28.3	29.6	30.5
G2 - 500 mg/kg/day	25.2	26.2	27.3	28.6	29.1
G3 - 1000 mg/kg/day	25.2	26.5	27.6	28.4	29.0
G4 - 2000 mg/kg/day	25.0	26.4	27.8	28.5	29.4

**c** 10–50 μm , male

Dose \ Week	0	1	2	3	4
G1 - 0 mg/kg/day	32.3	34.8	36.7	38.8	38.1
G2 - 500 mg/kg/day	32.4	33.8	34.9	36.4	36.1
G3 - 1000 mg/kg/day	32.3	33.6	35.2	36.7	37.1
G4 - 2000 mg/kg/day	32.6	34.0	35.4	37.5	37.7

**d** 10–50 μm , female

Dose \ Week	0	1	2	3	4
G1 - 0 mg/kg/day	25.4	26.5	28.5	30.5	29.7
G2 - 500 mg/kg/day	25.6	25.8	26.5	27.8	28.2
G3 - 1000 mg/kg/day	25.5	26.1	27.3	28.8	28.8
G4 - 2000 mg/kg/day	25.7	25.8	26.7	28.5	28.3

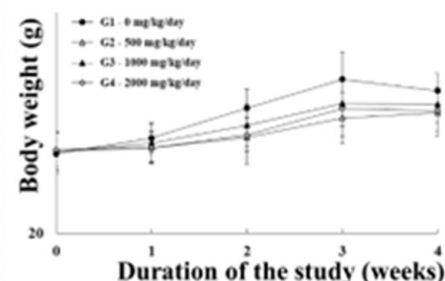


Figure 3. Male and female bodyweight changes after four weeks of repeated dosing with approximately 5 μm (a,b) and 10–50 μm (c,d) PTFE microplastics.

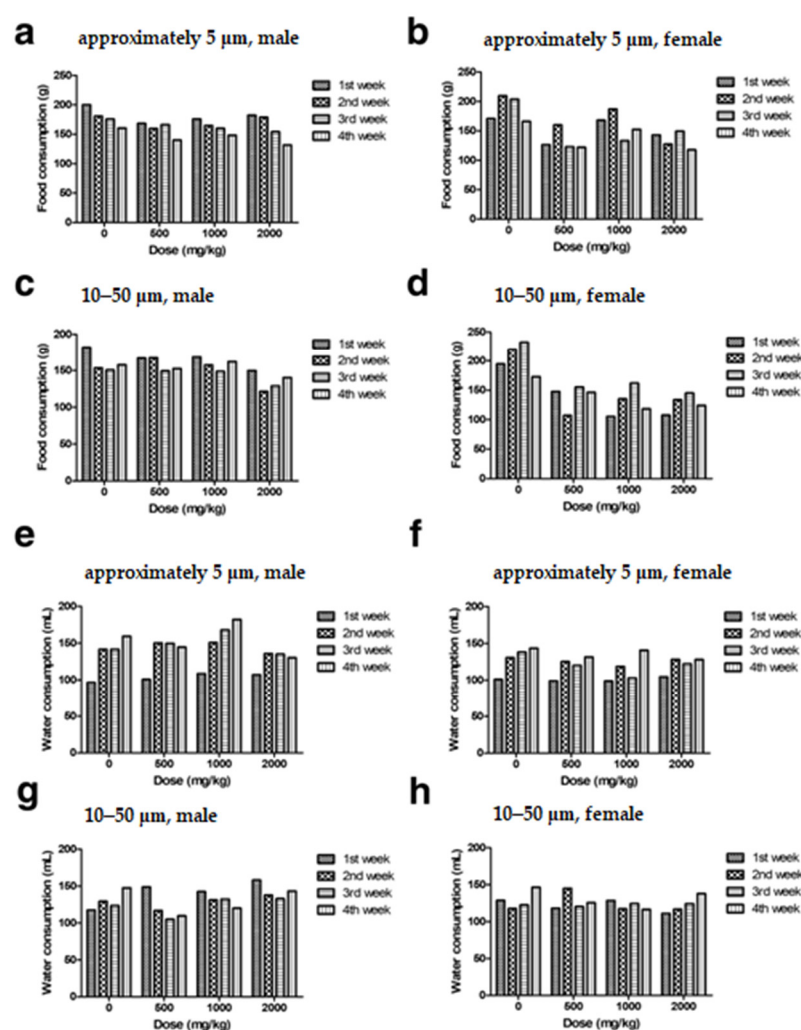


Figure 4. Male and female food and water consumption changes during the four-week repeated-dose toxicity study of approximately 5 μm (a,b,e,f) and 10–50 μm (c,d,g,h) PTFE microplastics.

Table 1. Clinical pathology analysis of the 28-day repeated oral dose toxicity study. Male and female serum biochemistry hematology data of approximately 5 μm (a–d) and 10–50 μm (e–h). The results are expressed as the mean $\pm$ SD. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ vs. 0.

a. Approximately 5 μm , Male, Serum Biochemistry Parameters								
Group/ Dose (mg/kg/Day)	Sodium (mmol/L)	Potassium (mmol/L)	Chloride (mmol/L)	Total Protein (g/dL)	Albumin (g/dL)	Blood Urea Nitrogen (mg/dL)	Creatinine (mg/dL)	Glucose (mg/dL)
G1 0	150.3 $\pm$ 1.9	7.6 $\pm$ 2.0	113.0 $\pm$ 2.7	5.0 $\pm$ 0.3	3.1 $\pm$ 0.3	22.4 $\pm$ 4.4	0.2 $\pm$ 0.0	93.0 $\pm$ 28.9
G2 500	149.7 $\pm$ 1.7	7.7 $\pm$ 1.8	114.8 $\pm$ 3.3	5.1 $\pm$ 0.1	3.3 $\pm$ 0.1	19.2 $\pm$ 4.7	0.2 $\pm$ 0.0	90.1 $\pm$ 22.1
G3 1000	151.7 $\pm$ 0.7	7.3 $\pm$ 1.1	114.7 $\pm$ 1.1	5.2 $\pm$ 0.2	3.2 $\pm$ 0.2	22.6 $\pm$ 4.9	0.2 $\pm$ 0.0	78.6 $\pm$ 15.6
G4 2000	150.7 $\pm$ 2.7	6.9 $\pm$ 1.0	113.9 $\pm$ 4.3	5.3 $\pm$ 0.2 *	3.3 $\pm$ 0.1	23.1 $\pm$ 6.7	0.2 $\pm$ 0.0	93.5 $\pm$ 51.1
Group/ Dose (mg/kg/Day)	Total Bilirubin (mg/dL)	Calcium (mg/dL)	Phosphate (mg/dL)	Total Cholesterol (mg/dL)	Triglyceride (mg/dL)	Aspartate Aminotransferase (U/L)	Alanine Aminotransferase (U/L)	Alkaline Phosphatase (U/L)
G1 0	0.1 $\pm$ 0.0	8.9 $\pm$ 0.4	7.9 $\pm$ 1.1	137.2 $\pm$ 23.0	167.9 $\pm$ 53.6	69.4 $\pm$ 28.2	23.9 $\pm$ 6.5	248.6 $\pm$ 92.5
G2 500	0.1 $\pm$ 0.0	8.9 $\pm$ 0.3	7.1 $\pm$ 1.3	139.9 $\pm$ 20.6	136.6 $\pm$ 40.1	71.8 $\pm$ 35.6	27.1 $\pm$ 8.6	222.6 $\pm$ 90.3
G3 1000	0.1 $\pm$ 0.0	9.0 $\pm$ 0.2	7.8 $\pm$ 0.9	152.7 $\pm$ 23.7	140.5 $\pm$ 45.5	64.8 $\pm$ 9.8	22.9 $\pm$ 3.2	191.6 $\pm$ 65.8
G4 2000	0.1 $\pm$ 0.1	9.2 $\pm$ 0.5	7.5 $\pm$ 0.8	150.8 $\pm$ 26.1	140.7 $\pm$ 47.6	81.9 $\pm$ 53.9	30.4 $\pm$ 11.0	223.0 $\pm$ 72.4

Table 1. Cont.

b. Approximately 5 μm, Female, Serum Biochemistry Parameters								
Group/ Dose (mg/kg/Day)	Sodium (mmol/L)	Potassium (mmol/L)	Chloride (mmol/L)	Total Protein (g/dL)	Albumin (g/dL)	Blood Urea Nitrogen (mg/dL)	Creatinine (mg/dL)	Glucose (mg/dL)
G1 0	148.7 ± 1.4	6.4 ± 1.2	112.7 ± 1.4	5.1 ± 0.2	3.6 ± 0.1	17.7 ± 2.2	0.2 ± 0.0	85.1 ± 21.9
G2 500	150.3 ± 1.3 *	6.4 ± 0.7 *	114.4 ± 1.7	5.0 ± 0.2	3.6 ± 0.2	18.0 ± 3.4	0.2 ± 0.0	76.8 ± 21.5
G3 1000	151.6 ± 1.3 ***	6.5 ± 1.3 *	115.3 ± 3.0	5.0 ± 0.2	3.6 ± 0.2	19.2 ± 2.1	0.2 ± 0.0	74.5 ± 17.6
G4 2000	153.1 ± 1.5 ***	6.3 ± 0.5 ***	116.2 ± 1.6	5.1 ± 0.2	3.5 ± 0.1	18.4 ± 1.7	0.2 ± 0.0	91.2 ± 21.0
Group/ Dose (mg/kg/Day)	Total Bilirubin (mg/dL)	Calcium (mg/dL)	Phosphate (mg/dL)	Total Cholesterol (mg/dL)	Triglyceride (mg/dL)	Aspartate Aminotransferase (U/L)	Alanine Aminotransferase (U/L)	Alkaline Phosphatase (U/L)
G1 0	0.0 ± 0.0	9.1 ± 0.3	7.4 ± 1.0	113.0 ± 19.0	97.9 ± 27.5	88.0 ± 42.6	22.8 ± 5.0	291.1 ± 84.1
G2 500	0.0 ± 0.0	9.1 ± 0.3	7.6 ± 0.8	100.8 ± 15.7	101.7 ± 38.3	91.4 ± 37.6	22.6 ± 4.3	604.4 ± 78.3
G3 1000	0.0 ± 0.0	9.2 ± 0.4	7.5 ± 1.0	106.5 ± 21.1	70.5 ± 22.6 *	106.8 ± 43.1	24.5 ± 4.5	295.7 ± 78.2
G4 2000	0.0 ± 0.0	9.1 ± 0.2	7.8 ± 0.8	120.7 ± 21.7	108.5 ± 30.9	93.5 ± 39.8	24.5 ± 5.9	329.7 ± 99.8
c. Approximately 5 μm, Male, Hematology Parameters								
Group/ Dose (mg/kg/Day)	White blood cell (×10 ³ cells/uL)	Red blood cell (×10 ⁶ cells/uL)	Hemoglobin (g/dL)	Hematocrit (%)	Mean Corpuscular Volume (fL)	Mean Corpuscular Hemoglobin (pg)	Mean Corpuscular Hemoglobin Concentration (g/dL)	Red Cell Distribution Width (%)
G1 0	3.52 ± 1.58	9.23 ± 1.27	14.5 ± 1.7	46.6 ± 6.0	50.5 ± 0.4	15.7 ± 0.3	31.1 ± 0.6	12.5 ± 0.3
G2 500	3.41 ± 0.65	9.25 ± 0.23	13.8 ± 0.1	45.0 ± 0.3	48.7 ± 1.5	15.0 ± 0.3	30.7 ± 0.4	12.3 ± 0.5
G3 1000	4.25 ± 1.23	9.03 ± 0.17	14.0 ± 0.4	45.4 ± 1.0	50.2 ± 0.3	15.5 ± 0.2	30.8 ± 0.4	13.5 ± 0.4
G4 2000	4.90 ± 0.98	8.74 ± 0.17	13.4 ± 0.4	43.1 ± 1.0	49.6 ± 1.0	15.4 ± 0.5	31.0 ± 0.6	12.5 ± 0.4
Group/ Dose (mg/kg/Day)	Hemoglobin Distribution Width (g/dL)	Platelet (×10 ³ cells/uL)	Mean Platelet Volume (fL)	Neutrophil (%)	Lymphocyte (%)	Monocyte (%)	Eosinophil (%)	Basophil (%)
G1 0	2.35 ± 0.14	844 ± 62	5.3 ± 0.2	26.5 ± 1.7	39.5 ± 9.3	3.4 ± 0.9	30.2 ± 7.0	0.2 ± 0.1
G2 500	2.32 ± 0.06 *	1042 ± 60	4.9 ± 0.1	21.7 ± 6.6	60.2 ± 10.3	2.9 ± 1.9	14.9 ± 16.3	0.1 ± 0.1
G3 1000	2.44 ± 0.21	1150 ± 229	4.7 ± 0.3	28.7 ± 3.3	60.9 ± 3.4	3.1 ± 1.0	6.8 ± 3.1	0.1 ± 0.0
G4 2000	2.34 ± 0.12	1146 ± 91	4.8 ± 0.4	18.9 ± 4.4	67.0 ± 3.9	1.7 ± 0.5	11.8 ± 8.5	0.1 ± 0.0
Group/ Dose (mg/kg/Day)	Neutrophil (×10 ³ cells/uL)	Lymphocyte (×10 ³ cells/uL)	Monocyte (×10 ³ cells/uL)	Eosinophil (×10 ³ cells/uL)	Basophil (×10 ³ cells/uL)	Reticulocyte (×10 ⁹ cells/L)	Reticulocyte (%)	
G1 0	0.92 ± 0.40	1.46 ± 0.84	0.11 ± 0.04	1.00 ± 0.39	0.01 ± 0.01	427.3 ± 75.7	4.61 ± 0.18	
G2 500	0.91 ± 0.09	2.58 ± 0.43	0.13 ± 0.07	0.81 ± 1.06	0.00 ± 0.01	312.2 ± 56.5 *	3.37 ± 0.58 *	
G3 1000	1.35 ± 0.29	2.93 ± 0.90	0.15 ± 0.05	0.35 ± 0.25	0.01 ± 0.01	388.4 ± 53.7	4.30 ± 0.52	
G4 2000	1.02 ± 0.25	3.60 ± 0.38	0.10 ± 0.04	0.63 ± 0.43	0.01 ± 0.00	332.6 ± 46.2	3.81 ± 0.61	
d. Approximately 5 μm, Female, Hematology Parameters								
Group/ Dose (mg/kg/Day)	White Blood Cell (×10 ³ cells/uL)	Red Blood Cell (×10 ⁶ cells/uL)	Hemoglobin (g/dL)	Hematocrit (%)	Mean Corpuscular Volume (fL)	Mean Corpuscular Hemoglobin (pg)	Mean Corpuscular Hemoglobin Concentration (g/dL)	Red Cell Distribution Width (%)
G1 0	5.31 ± 2.22	9.47 ± 0.27	15.1 ± 0.3	47.5 ± 1.5	50.1 ± 0.5	15.9 ± 0.2	31.7 ± 0.7	13.3 ± 0.7
G2 500	3.75 ± 0.97	9.26 ± 0.22	14.5 ± 0.3	46.3 ± 0.7	50.0 ± 0.9	15.7 ± 0.5	31.4 ± 0.6	12.8 ± 0.8
G3 1000	7.42 ± 3.21	9.17 ± 0.23	14.5 ± 0.7	45.5 ± 1.9	49.7 ± 1.0	15.8 ± 0.3	31.8 ± 0.5	13.2 ± 0.4
G4 2000	5.18 ± 2.70	9.53 ± 0.35	14.9 ± 0.4	46.9 ± 1.4	49.2 ± 1.1	15.7 ± 0.7	31.8 ± 0.8	13.1 ± 0.2
Group/ Dose (mg/kg/Day)	Hemoglobin Distribution Width (g/dL)	Platelet (×10 ³ Cells/uL)	Mean Platelet Volume (fL)	Neutrophil (%)	Lymphocyte (%)	Monocyte (%)	Eosinophil (%)	Basophil (%)
G1 0	2.41 ± 0.12	872 ± 186	5.1 ± 0.3	15.6 ± 3.5	71.2 ± 8.6	1.9 ± 0.6	10.9 ± 6.5	0.1 ± 0.1
G2 500	2.37 ± 0.10	968 ± 35	5.0 ± 0.2	14.9 ± 2.5	73.7 ± 3.4	1.6 ± 0.3	9.2 ± 5.2	0.1 ± 0.1 *
G3 1000	2.55 ± 0.13	903 ± 94	5.3 ± 0.6	21.6 ± 3.1	64.1 ± 10.0 *	2.2 ± 0.5	11.4 ± 8.1	0.1 ± 0.1
G4 2000	2.49 ± 0.08	849 ± 102	5.7 ± 0.2	18.0 ± 2.7 **	64.0 ± 9.9	1.1 ± 0.5	16.3 ± 8.2	0.3 ± 0.1
Group/ Dose (mg/kg/Day)	Neutrophil (×10 ³ Cells/uL)	Lymphocyte (×10 ³ cells/uL)	Monocyte (×10 ³ Cells/uL)	Eosinophil (×10 ³ Cells/uL)	Basophil (×10 ³ Cells/uL)	Reticulocyte (×10 ⁹ Cells/L)	Reticulocyte (%)	
G1 0	0.96 ± 0.21	4.72 ± 2.31	0.13 ± 0.07	0.71 ± 0.45	0.01 ± 0.01	371.2 ± 82.3	3.91 ± 0.77	
G2 500	0.64 ± 0.16	3.23 ± 0.95	0.07 ± 0.02	0.40 ± 0.20	0.01 ± 0.01	424.0 ± 20.6	4.58 ± 0.26	
G3 1000	1.75 ± 0.25	5.42 ± 2.20	0.19 ± 0.10	0.88 ± 0.51	0.01 ± 0.01	350.8 ± 21.7	3.83 ± 0.27	
G4 2000	1.13 ± 0.57	4.13 ± 2.25	0.07 ± 0.06	0.93 ± 0.58	0.02 ± 0.01	316.7 ± 26.2	3.32 ± 0.19	

Table 1. Cont.

e. 10–50 μm, Male, Serum Biochemistry Parameters								
Group/ Dose (mg/kg/Day)	Sodium (mmol/L)	Potassium (mmol/L)	Chloride (mmol/L)	Total Protein (g/dL)	Albumin (g/dL)	Blood Urea Nitrogen (mg/dL)	Creatinine (mg/dL)	Glucose (mg/dL)
G1 0	148.0 ± 1.1	7.8 ± 1.0	111.2 ± 2.1	5.1 ± 0.3	3.2 ± 0.2	23.2 ± 2.9	0.2 ± 0.0	119.4 ± 41.0
G2 500	148.4 ± 1.2	7.3 ± 1.8	112.3 ± 2.1	5.3 ± 0.2	3.4 ± 0.2	21.8 ± 2.4	0.2 ± 0.0	178.9 ± 36.8
G3 1000	149.2 ± 1.1	7.8 ± 1.2	113.5 ± 1.3	5.1 ± 0.2	3.1 ± 0.2	19.7 ± 3.7	0.2 ± 0.0	159.8 ± 49.5
G4 2000	150.7 ± 1.6	7.3 ± 0.9	112.9 ± 1.8	5.2 ± 0.2	3.3 ± 0.2	26.1 ± 5.7	0.2 ± 0.0	123.7 ± 36.5
Group/ Dose (mg/kg/Day)	Total Bilirubin (mg/dL)	Calcium (mg/dL)	Phosphate (mg/dL)	Total Cholesterol (mg/dL)	Triglyceride (mg/dL)	Aspartate Aminotransferase (U/L)	Alanine Aminotransferase (U/L)	Alkaline Phosphatase (U/L)
G1 0	0.1 ± 0.0	8.5 ± 0.3	8.5 ± 1.1	158.8 ± 24.2	117.5 ± 26.9	81.9 ± 46.1	26.6 ± 8.9	188.5 ± 63.4
G2 500	0.1 ± 0.0	8.6 ± 0.3	7.1 ± 1.5	151.5 ± 18.7	125.5 ± 51.5	64.4 ± 19.6	28.0 ± 12.5	235.6 ± 86.4
G3 1000	0.1 ± 0.0	8.5 ± 0.2	7.5 ± 1.3	146.4 ± 23.0	127.2 ± 78.5	63.3 ± 31.5	21.3 ± 5.4	152.1 ± 53.1
G4 2000	0.1 ± 0.1	8.6 ± 0.3	7.8 ± 1.2	155.0 ± 19.8	108.5 ± 26.5	78.2 ± 24.9	39.3 ± 30.8	200.2 ± 72.5
f. 10–50 μm, Female, Serum Biochemistry Parameters								
Group/ Dose (mg/kg/Day)	Sodium (mmol/L)	Potassium (mmol/L)	Chloride (mmol/L)	Total Protein (g/dL)	Albumin (g/dL)	Blood Urea Nitrogen (mg/dL)	Creatinine (mg/dL)	Glucose (mg/dL)
G1 0	151.8 ± 3.4	6.3 ± 0.9	114.1 ± 2.9	5.0 ± 0.3	3.6 ± 0.2	18.7 ± 1.9	0.2 ± 0.0	115.6 ± 34.8
G2 500	155.9 ± 3.7 *	6.5 ± 0.6	117.9 ± 4.5 *	5.0 ± 0.3	3.5 ± 0.2	16.1 ± 4.3	0.2 ± 0.0	147.4 ± 57.4
G3 1000	159.1 ± 5.0 **	7.2 ± 1.9	120.5 ± 3.3 ***	5.1 ± 0.3	3.7 ± 0.2	19.5 ± 3.3	0.2 ± 0.0	141.0 ± 48.4
G4 2000	152.2 ± 2.7	7.5 ± 2.0	117.1 ± 2.3 *	5.2 ± 0.4	3.6 ± 0.2	14.7 ± 3.2 **	0.2 ± 0.0	172.8 ± 30.5 **
Group/ Dose (mg/kg/Day)	Total Bilirubin (mg/dL)	Calcium (mg/dL)	Phosphate (mg/dL)	Total Cholesterol (mg/dL)	Triglyceride (mg/dL)	Aspartate Aminotransferase (U/L)	Alanine Aminotransferase (U/L)	Alkaline Phosphatase (U/L)
G1 0	0.0 ± 0.0	9.4 ± 0.4	7.9 ± 1.2	105.4 ± 25.6	50.2 ± 14.6	82.1 ± 79.1	45.6 ± 69.4	301.6 ± 111.1
G2 500	0.0 ± 0.0	9.7 ± 0.3	7.9 ± 0.8	113.8 ± 25.6	55.8 ± 19.3	53.8 ± 6.3	23.4 ± 12.8	262.4 ± 35.0
G3 1000	0.0 ± 0.0	10.0 ± 0.5 *	8.1 ± 1.4	114.6 ± 18.1	62.4 ± 27.0	54.2 ± 7.8	22.4 ± 8.6	333.0 ± 88.1
G4 2000	0.0 ± 0.0	9.5 ± 0.4	8.4 ± 1.1	95.6 ± 25.3	34.4 ± 20.4	113.6 ± 115.1	24.6 ± 12.3	261.4 ± 55.2
g. 10–50 μm, Male, Hematology Parameters								
Group/ Dose (mg/kg/Day)	White Blood Cell (×10 ³ cells/uL)	Red Blood Cell (×10 ⁶ cells/uL)	Hemoglobin (g/dL)	Hematocrit (%)	Mean Corpuscular Volume (fL)	Mean Corpuscular Hemoglobin (pg)	Mean Corpuscular Hemoglobin Concentration (g/dL)	Red Cell Distribution Width (%)
G1 0	5.50 ± 1.88	9.25 ± 0.58	14.4 ± 0.9	47.0 ± 3.2	50.8 ± 1.33	15.6 ± 0.3	30.7 ± 0.2	12.9 ± 0.7
G2 500	5.75 ± 0.94	8.93 ± 0.09	13.8 ± 0.3	44.4 ± 1.0	49.7 ± 1.4	15.4 ± 0.4	31.0 ± 0.7	12.9 ± 0.2
G3 1000	6.30 ± 2.32	8.90 ± 0.49	13.6 ± 0.4 *	44.0 ± 1.5	49.4 ± 1.1	15.3 ± 0.4	31.0 ± 0.4	12.9 ± 0.6
G4 2000	4.68 ± 0.59	8.36 ± 1.10	13.3 ± 1.1	42.3 ± 3.9	50.8 ± 2.0	16.0 ± 0.9	31.4 ± 0.6	12.8 ± 0.1
Group/ Dose (mg/kg/Day)	Hemoglobin Distribution Width (g/dL)	Platelet (×10 ³ Cells/uL)	Mean Platelet Volume (fL)	Neutrophil (%)	Lymphocyte (%)	Monocyte (%)	Eosinophil (%)	Basophil (%)
G1 0	2.47 ± 0.21	1047 ± 86	5.1 ± 0.3	17.4 ± 3.1	66.6 ± 4.7	3.4 ± 0.3	12.0 ± 5.6	0.2 ± 0.2
G2 500	2.34 ± 0.12	983 ± 54	4.9 ± 0.7	21.2 ± 6.6	65.3 ± 6.6	3.6 ± 1.2	9.4 ± 8.9	0.2 ± 0.2
G3 1000	2.43 ± 0.06	1080 ± 232	4.9 ± 0.3	17.1 ± 4.3	70.4 ± 3.4	2.2 ± 1.0	9.8 ± 2.5	0.1 ± 0.0
G4 2000	2.39 ± 0.15	1101 ± 167	4.9 ± 0.2	40.8 ± 36.4	41.5 ± 35.4	2.5 ± 1.0	14.9 ± 9.3	0.1 ± 0.0
Group/ Dose (mg/kg/Day)	Neutrophil (×10 ³ Cells/uL)	Lymphocyte (×10 ³ Cells/uL)	Monocyte (×10 ³ Cells/uL)	Eosinophil (×10 ³ Cells/uL)	Basophil (×10 ³ Cells/uL)	Reticulocyte (×10 ⁹ Cells/L)	Reticulocyte (%)	
G1 0	4.33 ± 1.69	0.22 ± 0.06	0.69 ± 0.16	0.03 ± 0.01	0.01 ± 0.01	364.7 ± 78.9	3.92 ± 0.62	
G2 500	1.48 ± 0.35	4.65 ± 1.04	0.26 ± 0.11	0.66 ± 0.59	0.02 ± 0.01	326.9 ± 59.5	3.66 ± 0.70	
G3 1000	1.26 ± 0.31	5.52 ± 2.35	0.16 ± 0.07	0.81 ± 0.51	0.01 ± 0.00	333.6 ± 18.7	3.75 ± 0.28	
G4 2000	1.85 ± 1.55	2.06 ± 1.90	0.12 ± 0.07	0.67 ± 0.36	0.00 ± 0.01	355.9 ± 26.9	4.33 ± 0.86	
h. 10–50μm, Female, Hematology Parameters								
Group/ Dose (mg/kg/Day)	White Blood Cell (×10 ³ Cells/uL)	Red Blood Cell (×10 ⁶ cells/uL)	Hemoglobin (g/dL)	Hematocrit (%)	Mean Corpuscular Volume (fL)	Mean Corpuscular Hemoglobin (pg)	Mean Corpuscular Hemoglobin Concentration (g/dL)	Red Cell Distribution Width (%)
G1 0	4.95 ± 2.22	9.50 ± 0.66	15.1 ± 0.2	47.5 ± 0.7	50.1 ± 2.7	15.9 ± 0.9	31.8 ± 0.1	12.8 ± 1.0
G2 500	7.77 ± 2.80	9.50 ± 0.90	14.8 ± 1.1 *	47.2 ± 3.3 *	49.8 ± 2.2	15.5 ± 0.5	31.2 ± 0.3	12.7 ± 0.6
G3 1000	5.61 ± 0.64	9.04 ± 0.60	14.2 ± 0.9	45.6 ± 3.0	50.4 ± 0.9	15.7 ± 0.1	31.1 ± 0.5	13.6 ± 2.4
G4 2000	3.49 ± 1.89	9.91 ± 0.60	15.6 ± 0.7	49.8 ± 2.6	50.2 ± 1.0	15.7 ± 0.3	31.4 ± 0.5	12.5 ± 0.2

Table 1. Cont.

h. 10–50 μm , Female, Hematology Parameters								
Group/ Dose (mg/kg/Day)	Hemoglobin Distribution Width (g/dL)	Platelet ($\times 10^3$ Cells/uL)	Mean Platelet Volume (fL)	Neutrophil (%)	Lymphocyte (%)	Monocyte (%)	Eosinophil (%)	Basophil (%)
G1 0	2.34 ± 0.02	915 ± 12	5.0 ± 0.2	15.2 ± 3.2	67.5 ± 9.6	1.8 ± 0.4	15.1 ± 8.4	0.1 ± 0.0
G2 500	2.29 ± 0.11	942 ± 78	5.1 ± 0.3	18.3 ± 4.0	68.9 ± 3.1	1.5 ± 0.9	10.7 ± 6.4	0.2 ± 0.1
G3 1000	2.45 ± 0.38	977 ± 193	4.9 ± 0.5	16.3 ± 2.8	74.5 ± 2.0	1.4 ± 0.3	7.1 ± 3.4	0.1 ± 0.0
G4 2000	2.29 ± 0.10	939 ± 212	5.2 ± 0.5	17.4 ± 3.2	69.2 ± 13.0	1.3 ± 0.4	11.5 ± 10.3	0.1 ± 0.1
Group/ Dose (mg/kg/Day)	Neutrophil ($\times 10^3$ Cells/uL)	Lymphocyte ($\times 10^3$ Cells/uL)	Monocyte ($\times 10^3$ Cells/uL)	Eosinophil ($\times 10^3$ Cells/uL)	Basophil ($\times 10^3$ Cells/uL)	Reticulocyte ($\times 10^9$ Cells/L)	Reticulocyte (%)	
G1 0	0.80 ± 0.39	3.75 ± 2.27	0.09 ± 0.04	0.65 ± 0.10	0.00 ± 0.01	396.3 ± 132.9	4.21 ± 1.58	
G2 500	1.57 ± 0.74	5.75 ± 1.99	0.12 ± 0.04	0.78 ± 0.22	0.01 ± 0.01	425.9 ± 153.7	4.49 ± 1.48	
G3 1000	1.05 ± 0.29	4.78 ± 0.81	0.09 ± 0.01	0.44 ± 0.16	0.01 ± 0.01	508.2 ± 397.6	5.82 ± 4.89	
G4 2000	0.79 ± 0.42	3.08 ± 1.82	0.06 ± 0.04	0.54 ± 0.50	0.01 ± 0.01	325.0 ± 34.2	3.29 ± 0.42	

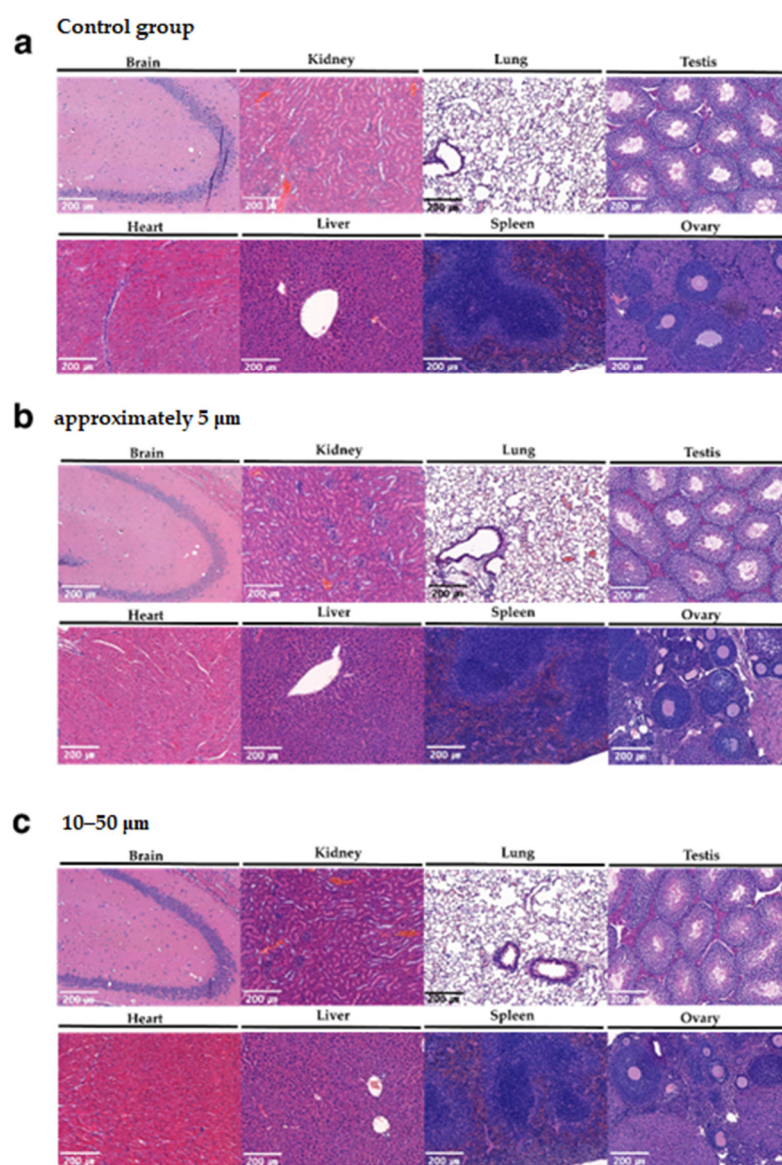


Figure 5. Histopathological evaluation of tissues from mice after four weeks of repeated dosing. Representative images of the brain (hippocampus), heart, kidney, liver, lung, spleen, testis, and ovary of the control mice (a), approximately 5 μm PTFE-treated mice (b) and 10–50 μm PTFE-treated mice (c). Scale bar = 200 μm .

3.3. Pharmacokinetics Study

Pharmacokinetic experiments were performed to determine how PTFE microplastics were distributed in blood and organs after oral administration. The distribution of PTFE microplastics was analyzed at four time points (15, 30, 60, and 120 min) after a single oral dose of microplastics. However, PTFE plasma concentrations were not detected with Raman spectrometry (Figure 6a–c), and pharmacokinetic parameters for PTFE could not be calculated.

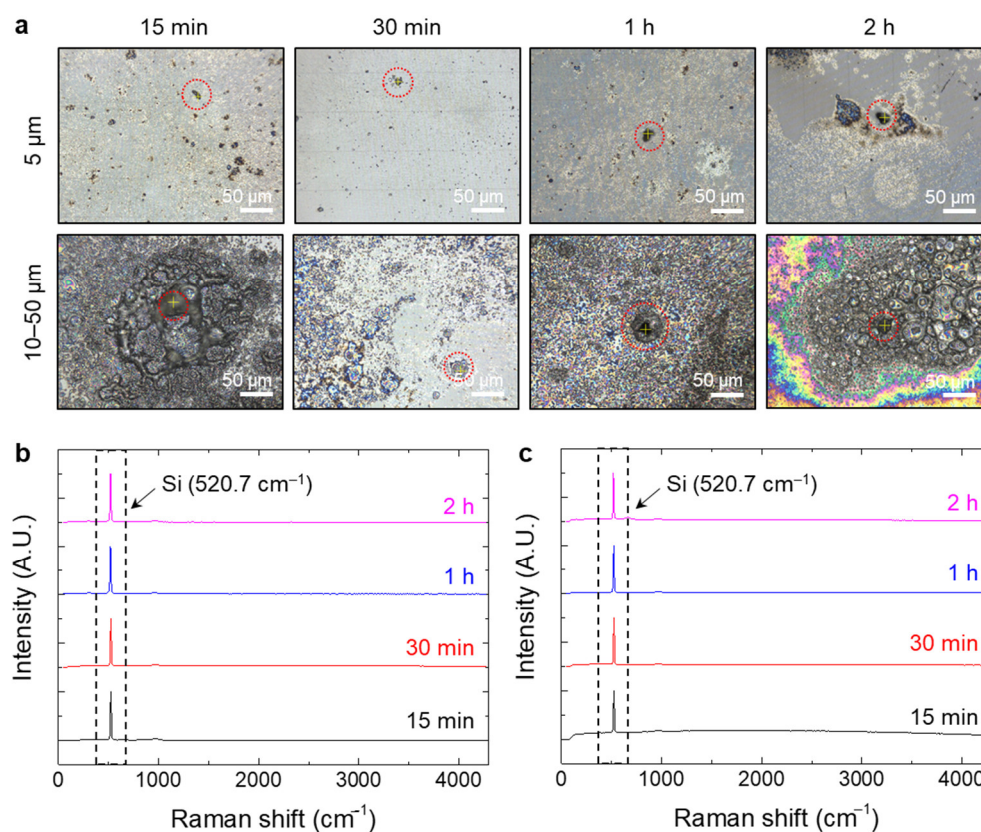


Figure 6. Detection of PTFE microplastics in whole blood. (a) Microscopic images of microparticles captured on silicon filters from blood collected at 15, 30, 60, and 120 min after oral administration of PTFE microplastics (approximately 5 and 10–50 μm). (b,c) PTFE microplastics were not detected on filters. Silicon (Si) peaks are indicated by the arrow. Scale bar = 50 μm.

3.4. Human NOAEL Dose

The human NOAEL dose could be estimated using the HED converting table and Equation (1). Assuming the NOAEL in mice is 2000 mg/kg (i.e., the highest dose in mice pharmacokinetic studies), the human NOAEL was calculated to be 9720 mg per 60 kg.

4. Discussion

Plastic use continues to increase worldwide. Physical properties, diversity, and low prices make the use of plastics attractive [46]. One report indicated that approximately 3% of plastic was recycled worldwide in 2017 and 67.8 million metric tons will be discarded in the environment by 2050, reflecting an increase in plastic use [47]. Discarded plastics are degraded to a size of less than 5 mm, called microplastics, via weathering and ultraviolet rays [48]. Their small size allows microplastics to move easily to contaminate soil, lakes, rivers, and seas [49–54]. In particular, many reports indicate that marine life accumulates microplastics on gills during oxygen exchange or plastics are ingested when mistaken for food [17]. Human exposure may occur when microplastic-loaded aquatic organisms are consumed [55]. Another means of human exposure is encountered when eating cooked

food [56]. Microplastics are reported in tap water, beer, salt, and mineral water, and large amounts are detected in meat or cooked food in Thai markets [57–59]. Thus, the ingestion of contaminated food will cause human exposure to microplastics found in various aquatic organisms.

Many studies indirectly confirm such exposure to microplastics. Microplastics are detected in marine environments and aquatic organisms [60–62]. In vivo, aquatic organisms are often used as experimental models, and microplastics accumulate in zebrafish in the intestines, histopathological changes occur in vacuolization, and the existence of mast cells, the release of mobile cells, and other changes such as an increase in oxidative stress occur [63]. In addition, decreased movement, neurological changes such as seizures, and female reproductive dysfunction are also reported [62]. In experiments using minnows, changes such as decreased movement and increased oxidative stress and immune response are reported [64]. Female and male reproductive dysfunction appeared in oysters [34]. Experiments with mammals, especially rodents, report changes in the reproductive systems of female and male mice, behavioral changes, and liver inflammation [36–38]. Information is thus increasing on the risks associated with microplastics, but many knowledge gaps remain. In particular, toxicity studies have distinct limitations, such as observing only specific physiological systems or very low concentrations. Our work included a comprehensive evaluation of toxicity across all organs for PTFE particles, as recommended by OECD guidelines 408 and 423. In addition, a pharmacokinetic evaluation using Raman spectroscopy was completed to confirm in vivo behavior of PTFE.

Microplastics used in most experiments are spherical. Microplastics in the environment are more fragmented or fibrous [65]. We manufactured two sizes of fragmented microplastics, approximately 5 μm and 10–50 μm . These morphological characteristics were confirmed through PSA, confocal microscopy, and SEM (Figure 1a), and the chemical properties of PTFE were confirmed through Raman spectroscopy (Figure 1b). These analytical results suggest that manufactured particles are suitable for the physical and chemical conditions of the PTFE microplastics. Subsequently, single and four-week repeated-dose toxicity evaluations were performed using these microplastics. The single-dose toxicity test confirmed the LD_{50} of PTFE using doses of 500, 1000, and 2000 mg/kg. During the two-week observation period after a single administration, no deaths or clinical signs of toxicity were recorded (data not shown) and no weight changes (Figure 2a–d) due to PTFE microplastic administration were observed. Further, no changes due to microplastic administration were observed in necropsy. Thus, the LD_{50} for PTFE microplastics was 2000 mg/kg or more for both particle sizes.

Subsequently, no specific clinical sign was recorded during the 4-week observation period, and no significant differences were observed in body weight (Figure 3a–d), organ weight (Supplementary Table S1), or water and food consumption (Figure 4a–h) in the administration groups compared to the control group. As a result of the clinical pathological evaluation (a–h in Table 1), no dose-dependent and simultaneously significant difference was observed, and no degenerative changes such as inflammation, desquamation, or necrosis were observed in the histopathological evaluation (Figure 5a–c). Therefore, NOAEL for four-week repeated oral administration of PTFE microplastics was confirmed to be 2000 mg/kg or higher. The results provide a new understanding of acute and chronic oral exposure to PTFE microplastics.

In addition, Raman spectroscopy analysis of blood after a single dose of 2000 mg/kg showed no PTFE microplastics. The absorption of microplastics through oral administration is known to be very low [66]. In the case of weathered microplastics, if analyzed by Raman spectroscopy, the peak of microplastics may change, resulting in inaccurate results [67]. Additional experiments such as administering microplastics through IV or experiments to visually determine the bio-distribution of microplastics by labeling fluorescent substances on microplastics are necessary to overcome this limitation and directly confirm the kinetics of microplastics in vivo.

Our present study is the first to report single and repeated toxicity, along with pharmacokinetics using high concentrations of PTFE microplastics in mammals. These experiments provide new insight into the biological effects of microplastics. The difference between our previous study on the toxicity of polyethylene microplastics [41] and the results of the present study suggests that there may be differences in biological effects depending on the type of plastic. This hypothesis can be tested with in vivo experiments using other plastics, such as PS, PET, and polyamides.

5. Conclusions

The purpose of this study was to establish LD₅₀ and NOAEL values, which are representative values of the toxicity study for two sizes of PTFE microplastics, and confirm the movement of microplastics in the body. In the single and four-week repeated toxicity study, no significant differences were observed in clinical sign, body weight, organ weight, water and food consumptions, macroscopic examination at necropsy, or clinical and histopathological evaluation. Both single and four-week repeated oral dose toxicity tests suggested LD₅₀ and NOAEL values of more than 2000 mg/kg. A pharmacokinetic experiment using Raman spectroscopy analysis did not detect PTFE in blood, and pharmacokinetic parameters could not be calculated. To overcome the limitations of this experiment, pharmacokinetic evaluation using a different route of administration is required.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/polym14112220/s1>; Table S1: Male and female organ weight in the 28-day repeated-oral-dose toxicity study.

Author Contributions: Conceptualization, M.-S.S. and K.K.; animal study, S.L. (Sijoon Lee); pathological analysis, K.-K.K., S.-E.S. and M.S.; Raman analysis, J.-H.C., K.-Y.S., J.L., S.K., S.L. (Sunjong Lee) and S.Y.Y.; pharmacokinetic analysis, K.-R.L.; writing—original draft preparation, S.L. (Sijoon Lee); writing—review and editing, M.-S.S. and K.K.; visualization, S.L. (Sijoon Lee); supervision, M.-S.S. and K.K. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: This study was approved by the Institutional Animal Care and Use Committee of the Institutional Animal Care and Use Committee of The Laboratory Animal Center of the Daegu-Gyeongbuk Medical Innovation Foundation (IACUC; approval No. DGMIF-21031601-00) and was in accordance with their guidelines.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

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Critical Review

A Critical Review of the Application of Polymer of Low Concern and Regulatory Criteria to Fluoropolymers

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ABSTRACT

Per- and polyfluoroalkyl substances (PFAS) are a group of fluorinated substances that are in the focus of researchers and regulators due to widespread presence in the environment and biota, including humans, of perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA). Fluoropolymers, high molecular weight polymers, have unique properties that constitute a distinct class within the PFAS group. Fluoropolymers have thermal, chemical, photochemical, hydrolytic, oxidative, and biological stability. They have negligible residual monomer and oligomer content and low to no leachables. Fluoropolymers are practically insoluble in water and not subject to long-range transport. With a molecular weight well over 100 000 Da, fluoropolymers cannot cross the cell membrane. Fluoropolymers are not bioavailable or bioaccumulative, as evidenced by toxicology studies on polytetrafluoroethylene (PTFE): acute and subchronic systemic toxicity, irritation, sensitization, local toxicity on implantation, cytotoxicity, in vitro and in vivo genotoxicity, hemolysis, complement activation, and thrombogenicity. Clinical studies of patients receiving permanently implanted PTFE cardiovascular medical devices demonstrate no chronic toxicity or carcinogenicity and no reproductive, developmental, or endocrine toxicity. This paper brings together fluoropolymer toxicity data, human clinical data, and physical, chemical, thermal, and biological data for review and assessment to show that fluoropolymers satisfy widely accepted assessment criteria to be considered as “polymers of low concern” (PLC). This review concludes that fluoropolymers are distinctly different from other polymeric and nonpolymeric PFAS and should be separated from them for hazard assessment or regulatory purposes. Grouping fluoropolymers with all classes of PFAS for “read across” or structure–activity relationship assessment is not scientifically appropriate. *Integr Environ Assess Manag* 2018;14:316–334. © 2018 The Authors. *Integrated Environmental Assessment and Management* published by Wiley Periodicals, Inc. on behalf of Society of Environmental Toxicology & Chemistry (SETAC)

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INTRODUCTION

The carbon–fluorine (C–F) bond is the strongest bond between C and another atom, instilling substances that contain a majority of C–F bonds with stability, inertness, and persistence (Banks et al. 1994). Per- and polyfluoroalkyl substances (PFAS) are a large group of highly fluorinated synthetic substances with diverse properties that have been used in a wide variety of industrial and consumer applications since the 1950s (Buck et al. 2011). Within the group are

distinct substances with different properties: polymers and nonpolymers; solids, liquids, and gases; persistent and nonpersistent substances; highly reactive and inert substances; mobile and insoluble substances; and toxic and nontoxic chemicals.

The PFAS are a large, diverse group of substances that, in some respects, challenge easy distinction for assessment and management. A clearer understanding of the origin of PFAS found in the environment and assessment of their properties is needed to be able to determine which classes of PFAS require management action. Per- and polyfluoroalkyl substances must be assessed taking into account their differences in chemical, physical, thermal, and biological properties. A single, globally harmonized system for PFAS classification has not yet been defined, resulting in a lack of distinction between PFAS. As regulatory frameworks continue to evolve, such as the Regulation (EC) No 1907/2006 of the European

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Parliament and of the Council on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) (EC 2006), more work is needed to distinguish classes of PFAS to ensure that regulations are appropriate in scope and proportionality.

Two long-chain nonpolymer perfluoroalkyl acids (PFAAs), perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) (both PFAS), found widespread in the environment and living systems, led to regulatory assessment and management efforts in several countries (Buck et al. 2011; OECD 2017; USEPA 2017a). Management actions to curtail manufacture of long-chain PFAAs, including PFOS and PFOA, and substances that may degrade to form them (also known as “precursors”) have been taken (EC 2006; ECHA 2015; USEPA 2017a). Both PFOS and PFOA have been determined by regulators to be persistent, bioaccumulative, and toxic (PBT) substances (EC 2006; ECHA 2015). A current concern is the potential for certain side-chain polymer PFAS to degrade in the environment to PFOS and PFOA or lower homologues (Liu and Mejia-Avendaño 2013). In addition, PFOS (a nonpolymeric perfluoroalkyl substance) and related substances have been listed as persistent organic pollutants (POPs) under Annex B of the Stockholm Convention (UNEP 2009), and PFOA and other related substances (UNEP 2011), as well as perfluorohexane sulfonic acid (PFHxS) and related substances are being evaluated for listing (UNEP 2017a). As a result, questions about the health and environmental safety of PFAS as a group have been raised (Scheringer et al. 2014; Blum et al. 2015).

These findings have prompted expanded regulatory interest and concern about PFAS as a group, spurring additional assessment and management actions. The German Environment Agency, Umweltbundesamt (UBA), published a proposal to implement new assessment criteria and procedures for identifying persistent (P), mobile (M), and toxic (T) substances under the European Union REACH chemical registration process (UBA 2017). The UBA has concluded that PM and/or PMT substances constitute “an irreversible threat to sources of drinking water and the quality of drinking water” in Germany. This has prompted the designation of PFAS substances as posing an “equivalent level of concern” under Article 57(f) of REACH and thereby has prompted the need for a new paradigm for chemical assessment and authorization. The Swedish Chemicals Agency, Kemikalieinspektionen (KEMI), announced agreement among 37 government agencies and research institutions in the European Union (EU) to expand cooperation to reduce the risks and increase the knowledge of PFAS, thereby endorsing the UBA view on the hazards posed by all PFAS substances (KEMI Swedish Chemicals Agency 2016). The KEMI announcement indicated that all perfluoroalkyl substances should be considered as extremely persistent in the environment, and many are water soluble, mobile in soil, and likely to contaminate waterways and drinking water supplies. A risk assessment report prepared by KEMI is forthcoming (ChemNews 2016).

The PFAS are divided into 2 primary categories: non-polymers and polymers (Figure 1). Figure 1 shows that these 2 categories are divided into 5 classes of PFAS. The fluoropolymer class of PFAS is the focus of the present

paper. The nonpolymer category includes perfluoroalkyl substances and polyfluoroalkyl substances. The polymer category includes fluoropolymers, perfluoropolyethers, and side-chain fluorinated polymers. Polymers generally have very different physical, chemical, and biological properties than do nonpolymer chemical substances of low molecular weight. Precise criteria that distinguish polymers from nonpolymers have been established (OECD 1993).

There are distinct differences between the 5 classes of PFAS. For example, PFOA, in the class nonpolymer perfluoroalkyl substances, is small, mobile, and persistent; has been assessed and determined to be a PBT chemical (ECHA 2015); and is in the final stage for recommendation of listing as a POP under the Stockholm Convention (UNEP 2017b). Regulatory and industry management actions on PFOA include precursor substances that may degrade to form PFOA (USEPA 2017a). An example in the class of nonpolymer polyfluorinated substances, 8:2 fluorotelomer alcohol, is known to degrade under environmentally relevant conditions to form PFOA (Liu and Mejia-Avendaño 2013). It is therefore a precursor substance to PFOA and subject to regulatory management (Liu and Mejia-Avendaño 2013). Polymers derived from 8:2 fluorotelomer alcohol are examples of the side-chain fluorinated polymers class. These polymers may degrade to form PFOA and therefore are subject to regulatory management. Lastly, perfluoropolyethers class is a complex class of PFAS, which contains O linkages in the polymer backbone.

In the present paper, we address fluoropolymers, a class of PFAS polymers (Figure 1). Fluoropolymers are high molecular weight solid plastics that have been studied extensively.

The present paper brings together fluoropolymer toxicity data, human clinical data, and physical, chemical, thermal, and biological data for review and assessment to show that fluoropolymers satisfy widely accepted assessment criteria to be considered as “polymers of low concern” (PLC) and to show that fluoropolymers are distinctly different enough from other classes of PFAS to not be grouped with them for hazard assessment or regulatory purposes.

PERFORMANCE CHARACTERISTICS AND USES OF FLUOROPOLYMERS

Since the discovery of polytetrafluoroethylene (PTFE) in 1938 (Plunkett 1987), the use of fluoropolymers has grown considerably to take advantage of their unique physical–chemical, thermal, and biological properties. The 4 fluoropolymers addressed in the present paper, polytetrafluoroethylene (PTFE), fluorinated ethylene propylene (FEP), ethylene tetrafluoroethylene (ETFE), and tetrafluoroethylene copolymers with perfluoroalkyl vinyl ethers (e.g., perfluoroalkoxy polymer, PFA), accounted for approximately 70% to 75% of the world fluoropolymer consumption in 2015 (IHS 2016). The representative fluoropolymer discussed in the present paper, PTFE, made up 58% (by weight) of 2015 worldwide fluoropolymer consumption (IHS 2016). Fluoropolymers are high molecular weight plastics with unique properties attributable to the strong C–F bonds, the strongest bond between C and another atom, making

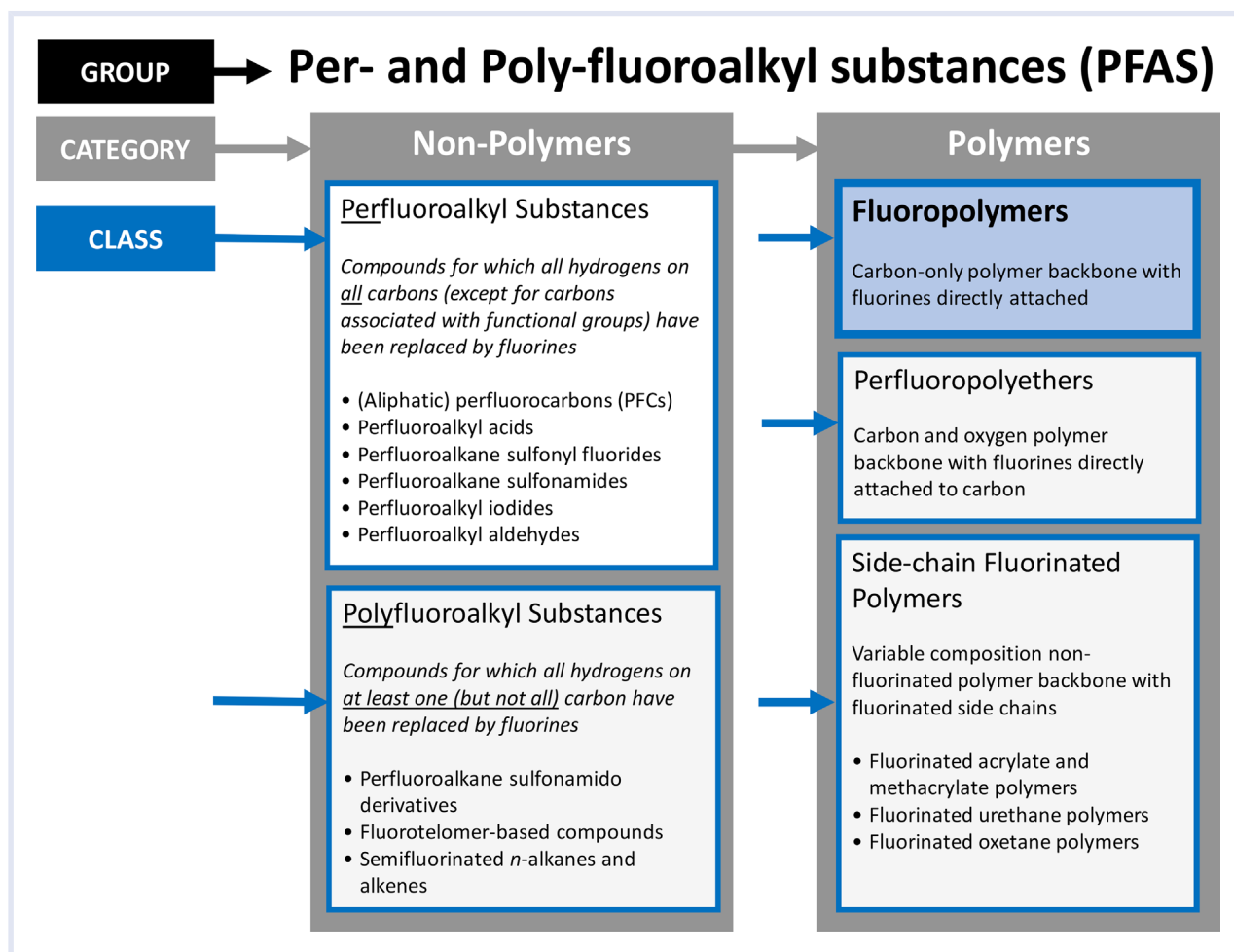


Figure 1. Per- and polyfluoroalkyl substances (PFAS).

them highly stable (Olabisi and Adewale 2015). Carbon atoms alone form the fluoropolymer backbone, each surrounded by an envelope of F atoms. Fluoropolymers are generally very high molecular weight (>100 000 Da); have high thermal, chemical, photochemical, oxidative, hydrolytic, and biological stability; have low flammability, neutral electrical charge, and resistance to degradation; have negligible residual monomers and low molecular weight oligomer content; have limited low molecular weight leachables; and have no reactive functional groups of concern (Gangal and Brothers 2015).

The unique properties of fluoropolymers include durability, mechanical strength, inertness, thermal stability in foreseeable use conditions, and resistance to chemical, biological, and physical degradation (Hougham et al. 1999). Table 1 shows performance characteristics required in various commercial fluoropolymer applications (Gangal and Brothers 2015; Dams and Hintzer 2016). For example, medical devices are successful when they are made from “biocompatible” biomaterials, that is, the material has the ability to perform with an appropriate host response in a specific situation (Williams 1987). The inertness of PTFE allows for its acceptance into the body. Moreover, PTFE flexibility and

durability deliver mechanical integrity for the device’s lifetime. The microstructure of PTFE can be modified to meet specific physiological needs (e.g., porous and open structure to facilitate tissue ingrowth), enhancing its utility in medical devices. In terms of end-use function, PTFE’s inertness, physical properties (Ebnesajjad 2011), and the low level of residual monomer, oligomers, and low molecular weight leachables (Supplemental Data p 32–55) meet the requirements for low levels of contaminants and particulates in manufacturing environments essential for the food and beverage, pharmaceutical, medical, and semiconductor industries (Olabisi and Adewale 2015). Manufacturing applications requiring ultrapure high efficiency particulate air (HEPA) filtration use the finely controlled microporous PTFE membranes. Other components requiring a high degree of contamination control associated with patient care (e.g., dialysis tubing) also find the properties of PTFE essential. Durability in harsh conditions makes PTFE a superior material of choice in aerospace, environmental controls, energy production and storage, and electronics, as well as in technical apparel. The thermal stability of PTFE and FEP fluoropolymers provides improved fire safety risk over other polymers when used in plenums and structural

Table 1. Fluoropolymer functionality and commercial applications

Commercial application	Fluoropolymer characteristics									
	Durable			Inert			Functional			Stable
	Mechanical strength	Low particulation	Resistance to chemicals	Nontoxic, biocompatible, resistant to biological degradation	Flexibility	Friction resistance	Low dielectric constant	Low leachables	Resistance to photolysis, oxidation, hydrolysis	
Aerospace	X	—	X	—	X	X	X	—	X	X
Automotive industry	X	—	X	—	X	X	X	—	X	x
Medical devices	X	X		X	X	X	—	X	X	X
Pharmaceutical manufacture	X	X	X	X	X	—	—	X	—	X
Consumer outdoor apparel	X	—		X	X	—	—	X	—	—
Technical clothing (military, firefighters, first responders, medical personnel)	X	—	X	X	X	X	—	X	X	X
Consumer electronics	X	—	X	—	X	X	X	—	X	X
Wireless communications	X	—	X	—	X	X	X	—	X	X
Satellite navigation systems	X	—	X	—	X	X	X	—	X	X
Semiconductor industry	—	X	X	—	—	—	X	X	—	—
Building construction	X	—	—	X	X	—	X	—	X	X
Energy production and storage	X	X	—	—	—	—	X	X	X	X
Food and beverage production	X	X	X	X	X	X	—	X	X	—
Food protection and packaging	X	X	X	X	X	—	—	X	—	—
Drinking water filtration	—	X	X	X	—	—	—	X	X	—
Environmental protection	—	X	X	X	—	—	—	X	X	X

geometries in aviation and standard building construction (Olabisi and Adewale 2015). In addition, chemical resistance to acids, bases, solvents, and chemical attack, combined with its unique conformable strength, makes PTFE an ideal coating for chemical process equipment, lining for process piping, sealants for gaskets and hoses, and fabricated parts for pumps, gears, and other mechanical parts that need this extreme resistance for functionality (Olabisi and Adewale 2015). The low dielectric constant of PTFE ensures the integrity of high speed–low signal loss systems as employed in the aerospace industry for flight controls, communication, and protection from extreme cold, moisture, and altitude changes (Dams and Hintzer 2016). These are lifesaving applications that are used in satellite systems for navigation, wireless communications, in-flight navigation, and shielding from electronic interference. Civil and military aviation depends on reliable performance of these systems for long service hours with minimal maintenance down times. In addition, PTFE provides reduced friction of moving parts (e.g., cable chains), preventing particulation during automated manufacturing in cleanroom environments (Dams and Hintzer 2016). This friction reduction is also uniquely beneficial in light load bearings, gears, cams, and other mechanical machine parts as well as in weaving fibers, yarns, and greases (Dams and Hintzer 2016).

ASSESSMENT OF POLYMERS

History

Prior to the mid-20th century, regulation of new chemical substances, mixtures, and polymers in general was very limited. National chemical inventories were created with notification requirements for new chemical substances, mixtures, and polymers. In the United States, new chemicals submitted to the US Environmental Protection Agency (USEPA) under the Toxic Substances Control Act (TSCA) (USC 1976) for addition to the US chemical inventory are reviewed for potential physical, chemical, and biological effects (environmental and mammalian), as well as for potential exposure to the environment and human populations. Over time, the USEPA regulatory scientists gained enough knowledge through the review of the thousands of data packages to develop tools to assist in the identification of physical–chemical properties, potential hazard, and potential exposure to assist in and expedite the chemical review and assessment process (Auer et al. 1990; Wagner et al. 1995; USEPA 2012; USEPA 2017b).

The predictive power and reliability of these approaches were tested and refined (Wagner et al. 1995). Over time, it was recognized that many of the physical–chemical properties, such as molecular weight, limit the ability of the chemical to cross the cell membrane and therefore limit its bioavailability. Further examination of general physical–chemical properties and their relationship to hazard potential of a given chemical led to the development of general principles or criteria for the identification of chemicals, including polymers, with low hazard potential.

These criteria were developed for use by USEPA for its hazard evaluation of new polymers. The USEPA made this methodology available to the public to assist submitters interested in developing low hazard polymers (USEPA 1997a). In 1984, the USEPA published the polymer exemption rule to exempt low hazard polymers from certain notification requirements under the new chemicals program (USFR 1984). The polymer exemption rule incorporated the hazard criteria as part of the criteria to determine eligibility for exemption (USEPA 1997a, 2010).

The hazard criteria that support the PLC concept represent an extension of these principles and practices developed for (nonpolymeric) chemicals and rely heavily on physical–chemical properties that determine a chemical's bioavailability. In 1993, the Organisation for Economic Co-operation and Development (OECD) Expert Group on Polymers found that sufficient data existed to create a consensus document identifying the essential data elements to qualify a polymer as a PLC to human health and the environment (OECD 1993). By 2007, the OECD Expert Group on Polymers agreed that, "Polymers of low concern are those deemed to have insignificant environmental and human health impacts" (OECD 2009). Thus, there was agreement within the OECD that polymeric chemicals meeting these criteria have a low hazard potential. However, the integration of the criteria into a risk management framework may differ from country to country according to their individual regulatory mandate.

In a recent report commissioned by the European Commission (EC) (BIO by Deloitte 2015), the following countries agreed on the polymer properties predictive of adverse human health and environmental hazard: Australia, Canada, China, Japan, South Korea, Philippines, New Zealand, Taiwan, and the United States. Further, the report identified the eligibility criteria to be considered a PLC with respect to potential for adverse impact on health and the environment. The report also compiled existing polymer regulations outside the EU and proposed alternative options for EU polymer registration, including defining a category of a PLC and grouping polymers into families.

The PLC criteria are described in the following section. Note that there are some policy components, such as elemental composition, as well as the physical–chemical attributes, in the PLC criteria.

POLYMER OF LOW CONCERN CRITERIA

Here we describe each of the eligibility criteria for PLC and provide an assessment for the representative fluoropolymer PTFE. We will show that fluoropolymers, including PTFE, satisfy the widely accepted assessment criteria to be considered PLCs (Table 2) and therefore are considered to be of low hazard to human health and the environment.

Polymer composition

The polymer composition criterion requires structure and elemental composition of the polymer be described and identified (e.g., by Chemical Abstracts Service [CAS] number).

Table 2. Fluoropolymers and PLC criteria

Assessment criteria ^a	Fluoropolymers			
	PTFE	ETFE	FEP	PFA
	CAS 9002-84-0	CAS 25038-71-5, 68258-85-5	CAS 25067-11-2	CAS 26655-00-5, 31784-04-0
Structure	$\text{-(CF}_2\text{-CF}_2\text{)}_n$	$\text{-(CH}_2\text{-CH}_2\text{)}_n\text{-(CF}_2\text{-CF}_2\text{)}_m$	$\text{-(CF}_2\text{-CF}_2\text{)}_n\text{-(CF}_2\text{-CF(CF}_3\text{))}_m$	$\text{-(CF}_2\text{-CF}_2\text{)}_n\text{-(CF}_2\text{-CF(R}_f\text{))}_m$
Polymer composition (must have C, H, Si, S, F, Cl, Br, or I covalently bound to C)	Yes	Yes	Yes	Yes
Molecular weight	389 000–8 900 000 ^{bc}	—	—	—
(M _n > 1000 Da and oligomer content < 1%)	520 000–45 000 000 ^{bd}	530 000–1 200 000 ^{ef}	241 000–575 000 ^{eg}	200 000–450 000 ^{eh}
Molecular weight distribution MW ÷ number average M _n (M _n and heterogeneity of MW distribution indicate if majority are >1000 or <1000 Da, which could penetrate the cell)	2.3 ⁱ	1.4–2.7 ^f	1.55–2.09 ^g	1.7 ^j
Wt % oligomer (see Figure 2) (<5% for <1000 Da oligomers, <2% for <500 Da oligomers)	Negligible	Negligible	Negligible	Negligible
Ionic character (cationic polymers associated with aquatic toxicity; polycationic with adverse human health effect)	Neutral	Neutral	Neutral	Neutral
RFGs ^k (some highly reactive functional groups associated with adverse human health and ecotoxicology effects, e.g., acrylates, isocyanates, anhydrides, aziridines)	<1 (see section <i>Reactive functional groups and RFG ratio to MW</i>)	<1 (see section <i>Reactive functional groups and RFG ratio to MW</i>)	<1 (see section <i>Reactive functional groups and RFG ratio to MW</i>)	<1 (see section <i>Reactive functional groups and RFG ratio to MW</i>)
FGEW ^k (typical value) (the lower the FGEW, the more reactive the polymer and the higher the potential for health and environmental impact)	>10 ⁵ –10 ⁷	>10 ⁵ –10 ⁶	>10 ⁵	>10 ⁵
Low molecular weight leachables (MW < 1000 Da able to enter cell)	<1 ppm	No active leachables by USP class VI ^l (121 °C)	No active leachables by USP class VI ^l (121 °C)	No active leachables by USP class VI ^l (121 °C)
Residual monomers (monomers have lower MW than polymers; typically more hazardous than polymers)	<1 ppm	<50 ppb	<50 ppb	<50 ppb
Ratio of residual monomers to molecular weight (typical value) (more low MW monomer content per mole increases bioavailability and hazard potential)	~10 ⁻¹³ to 10 ⁻¹⁵	~10 ⁻¹³ to 10 ⁻¹⁴	~10 ⁻¹³	~10 ⁻¹³
Structural similarities to RFG of concern (increases potential risk of adverse effects)	None	None	None	None
Reference standard see also ISO 1133 (ISO 2011), ISO 12086 (ISO 2006)	ASTM D 4894 (ASTM 2015a), D 4895 (ASTM 2015b)	ASTM D 2116 (ASTM 2016a)	ASTM D 3159 (ASTM 2015c)	ASTM D 3307 (ASTM 2016b)

(Continued)

Table 2. (Continued)

Assessment criteria ^a	Fluoropolymers			
	PTFE	ETFE	FEP	PFA
	CAS 9002-84-0	CAS 25038-71-5, 68258-85-5	CAS 25067-11-2	CAS 26655-00-5, 31784-04-0
Physical–chemical properties				
Water solubility (per USP 2011) (water solubility < 10 mg/L showed generally low health concerns; 10 mL/L to 10000 mg/L had potential health concern)	Practically insoluble or insoluble (1 × 10 ⁻⁵ mg/L)	Practically insoluble or insoluble	Practically insoluble or insoluble	Practically insoluble or insoluble
Octanol–water partition coefficient, <i>K</i> _{OW} (higher <i>K</i> _{OW} associated with lipophilicity and a high potential to bioaccumulate or bioconcentrate)	NA	NA	NA	NA
Particle size (median mass aerodynamic diameter, MMAD, should be >5 μm)	100–500 μm (powders)	50–250 μm (powders)	50–250 μm (powders)	50–250 μm (powders)
	—	2–4 mm (pellets)	2–4 mm (pellets)	2–4 mm (pellets)
Stability				
Hydrolysis (breaking into <i>M</i> _n < 1000 Da increases hazard potential)	Stable	Stable	Stable	Stable
Light (hν) (breaking into <i>M</i> _n < 1000 Da increases hazard potential)	Stable	Stable	Stable	Stable
Oxidation (breaking into <i>M</i> _n < 1000 Da increases hazard potential)	Stable	Stable	Stable	Stable
Biodegradation (aerobic and anaerobic) (breaking into <i>M</i> _n < 1000 Da increases hazard potential)	Stable	Stable	Stable	Stable
Thermal stability at normal foreseeable use maximum continuous temp (°C) (breaking into <i>M</i> _n < 1000 Da increases hazard potential)	260	150	200	260
Meets PLC criteria ^a (Y/N)	Yes	Yes	Yes	Yes

ASTM = American Society for Testing and Materials; CAS = Chemical Abstracts Service; Da = dalton; ETFE = ethylene tetrafluoroethylene; FEP = fluorinated ethylene propylene; FGEW = functional group equivalent weight; ISO = International Organization for Standardization; MMAD = median mass aerodynamic diameter; *M*_n = number average molecular weight; MW = molecular weight; MWD = molecular weight distribution; OECD = Organisation for Economic Co-operation and Development; PFA = perfluoroalkoxy polymer; PFPE = perfluoropolyether; PLC = polymer of low concern; PTFE = polytetrafluoroethylene; PVDF = polyvinylidene fluoride; PVF = polyvinyl fluoride; RFG = reactive functional groups; USEPA = US Environmental Protection Agency; USP = US Pharmacopeia.

^aSee OECD 2009 and BIO by Deloitte 2015 for details on characteristics of a “polymer of low concern.”

^bMolecular weight is number average molecular weight.

^cBerry and Peterson 1951; Doban et al. 1956.

^dSuwa et al. 1973.

^eMolecular weight is weight average molecular weight.

^fTuminello et al. 1993.

^gTuminello 1989.

^hPutnam 1986.

ⁱChu et al. 1989.

^jFrick et al. 2012.

^kFor definition of reactive functional group; lists of low-, moderate-, and high-concern functional groups; and FGEW limits, see USEPA Polymer Exemption Guidance Manual (USEPA 1997b), BIO by Deloitte 2015 (p 191–192), and USEPA 2010. See Supplemental Data.

^lIn the USP<88> testing for “class VI,” 2 g of the plastic (e.g., FEP, ETFE, or PFA) were extracted at 121 °C in: 1) 0.9% sodium chloride solution, 2) sesame oil, NF, 3) alcohol saline, and d) polyethylene glycol. The acute systemic toxicity and intracutaneous reactivity tests were conducted with those extracts. The intramuscular implantation was conducted with the plastic. Passing these 3 tests indicates that any leachables were not released in concentrations capable of causing these adverse effects, but does not result in a quantitative concentration of leachables. (See USP 2018.)

Note: The following are not addressed in this paper: PFPEs, side-chain fluorinated polymers, fluoroelastomers, PVF, and PVDF.

Molecular weight, number average molecular weight, MW distribution, and % oligomer <1000 Da

The number average molecular weight (M_n) and oligomer content are the most commonly used criteria for PLC assessment. The EU assessment report (BIO by Deloitte 2015) states that the “most potential health concern polymers have a number average molecular weight, M_n , < 1000 Da and oligomer content >1%.” The higher the oligomeric content, the more likely a polymer is to be a health or ecotoxicological (OECD 2009, p 9). In fact, when comparing the potential health concern of polymers with varying percent oligomer content, “...the distribution of potential health concern polymers showed an increased incidence of higher oligomer content that began at 5% for <1000 Da and 2% for <500 Da oligomeric content” (OECD 2009, p 24).

Molecular weight (MW) is an important predictor of biological effect because very large molecules (>1000–10 000 Da) are too large to penetrate cell membranes (Supplemental Data in Beyer 1993, p 14). Because large molecular weight polymers cannot enter the cell, they cannot react with “target organs,” such as the reproductive system, and are not bioavailable. “Therefore, as the M_n of a polymer increases, a reduced incidence of potential health concern effects might be expected” (OECD 2009, p 20).

An additional PLC consideration is the weight percent oligomers <1000 Da. Oligomers may be composed of, for example, dimers, trimers, and tetramers, meaning they have 2-, 3-, and 4-monomer units, respectively. The EU report (BIO by Deloitte 2015) concluded that most potential health concern polymers have M_n of <1000 Da and oligomer content of >1%: “...the distribution of potential health concern polymers showed an increased incidence of higher oligomer content that began at 5% for <1000 Da and 2% for <500 Da oligomeric content” (OECD 2009, p 24).

Molecular weight distribution (MWD), also known as “polydispersity index,” measures the heterogeneity of size of polymer molecules in a polymer. The MWD is an important parameter for predicting potential biological effects of polymers because although M_n may be a large value, low MW oligomers <1000 Da may be present, which could penetrate the cell.

Electrical charge (ionic character)

Electrical charge or ionic character can be anionic, cationic, amphoteric, or nonionic. Specifically, cationic polymers have been associated with aquatic toxicity (Auer et al. 1990; USEPA 1997a). Polycationic polymers that are water soluble or dispersible are of concern due to adverse human health (inhalation) effects (NICNAS 2016).

Reactive functional groups and RFG ratio to MW

A “reactive functional group” (RFG) is defined as an atom or associated group of atoms in a chemical substance that is intended or can be reasonably anticipated to undergo facile chemical reaction (USFR 2012). Some highly reactive functional groups (or a high ratio of RFGs per mole) have been associated with adverse human health and ecotoxicology (e.g., acrylates,

methacrylates, isocyanates, anhydrides, aziridines) (USEPA 2010). Methods have been demonstrated to identify the functional end groups on fluoropolymers (Pianca et al. 1999).

The functional group equivalent weight (FGEW) is used to determine if the RFGs in a polymer are substantially diluted by polymeric material to allow the polymer to be a PLC (USEPA 1997b). The FGEW of a polymer is defined as the ratio of the M_n to the number of functional groups in the polymer. It is the weight of a polymer that contains 1 formula weight of the functional group. The FGEW is used as an indication of the degree of reactivity of the polymer; the lower the FGEW, the more reactive the polymer and the higher the potential for health and environmental impact (OECD 2009, p 10).

Low MW leachables

Low MW leachables are chemical molecules, either inorganic or organic, that migrate (i.e., leach) out of the polymer. These could be residual monomers or oligomers resulting from incomplete polymerization processes, surface residues, or other chemicals used in the manufacturing processes (e.g., initiators, catalysts, chain transfer agents, surfactants). Chemical analysis, by techniques such as thermal gravimetric analysis (TGA), gas chromatography mass spectrometry (GC-MS), or liquid chromatography mass spectrometry (LC-MS) are used to identify low MW leachables.

Low MW leachables are critically important to the potential for a polymer to affect health and the environment, given that they may be able to migrate out of the polymer and cross cell membranes to potentially react with biomolecules. In a report to the EU (BIO by Deloitte 2015) the polymer policies for 10 countries around the world, including the EU REACH handling of polymers, were reviewed. The report concluded that “Polymers with <1% MW <1000 Da and low water extractivity are not able to cause systemic effects which are toxicologically or ecotoxicologically relevant.”

Monomers, by nature, are reactive. Unreacted monomer left in a polymer may migrate out of the polymer to react with biomolecules to cause potential adverse effects. Regulatory authorities (BIO by Deloitte 2015) and the OECD Expert Group on Polymers (OECD 2009) agree that the residual monomer content of a polymer is critical to determining if it qualifies to be a PLC.

Particle size

Particle size is also a PLC criterion. Particles that are small enough to reach the deep lung upon inhalation are often associated with adverse health effects. Therefore, to qualify as a PLC, median mass aerodynamic diameter (MMAD) of the polymer particle size should be greater than 5 μm .

Structural and elemental composition

In the United States, Chemical Categories of Concern are the result of the review of new chemicals by the USEPA under the TSCA (see <https://www.epa.gov/reviewing-new-chemicals-under-toxic-substances-control-act-tsca/chemical-categories-used-review-new>). New chemicals submitted to the USEPA

under the TSCA for addition to the US chemical inventory are reviewed for potential chemical, physical, and biological effects (environmental and mammalian). The USEPA groups Pre-manufacture Notice (PMN) chemicals with shared chemical and toxicological properties into categories, enabling both PMN submitters and USEPA reviewers to benefit from the accumulated data and past decisional precedents, allowing reviews to be facilitated. The categories describe the molecular structure, boundary conditions such as MW, equivalent weight, the log of the octanol–water partition coefficient, log P, or water solubility, and standard hazard (mammalian and ecological) and (environmental) fate tests to address concerns. The categories include chemicals for which sufficient history has been accumulated so that hazard concerns and testing recommendations vary little from chemical to chemical within the category. (See Supplemental Data, p 30, for details on USEPA's chemical categories.)

Elemental composition

The elemental composition is a factor in the assessment of the eligibility of polymers for reduced notification requirements. The exclusion of polymers under this step is not a conclusion of hazard but a determination that the elemental composition does not fall within the parameters of the polymer set under which this rule was formulated, and consequently, these polymers would have to follow the standard notification and review process. These elemental requirements differ across jurisdictions as covered in the report to the EU on global regulatory approaches to polymer assessment (BIO by Deloitte 2015). For example, in the EU under REACH it is proposed that polymers composed from among these elements, covalently bound to C, have reduced hazard: H, N, O, Si, S, F, Cl, Br, or I (BIO by Deloitte 2015). In contrast, the USEPA Polymer Exemption Rule states that a polymer is eligible for reduced agency review when it has at least 2 of the following elements: C, H, O, N, S, or Si (USFR 1995).

Water and lipid solubility and the octanol–water partition coefficient

Water solubility is the extent to which a compound will dissolve in water. According to the OECD 2009 meeting of the Expert Group on Polymers, polymers with “negligible” water solubility, or those described as “hydrophobic” have been represented with a water solubility of 0.000001 mg/L (1×10^{-6} mg/L; assigned arbitrarily) (OECD 2009). That is equivalent to 1 ppt, a very conservative definition.

Based on the data set studied, the OECD Expert Group on Polymers concluded “A higher proportion of polymers with intermediate water solubility values (10 mL/L–10 000 mg/L) displayed potential health concern. Polymers with water solubility <10 mg/L showed generally low health concerns” (OECD 2009, p 10). Although not a solubility metric, a polymer capable of absorbing its weight in water was associated with increased inhalation cancer risk in rats (OECD 2009).

The octanol–water partition coefficient (K_{OW}) is another criterion to assess chemicals and their environmental and health impact. The K_{OW} is a physical–chemical property at equilibrium to represent the lipophilic or hydrophilic nature

of a chemical, the distribution of a compound in octanol, representing the lipophilic nature, to its solubility in water, representing the aqueous nature. The higher the K_{OW} , the more lipophilic the compound. Typically, a $K_{OW} > 5000$ or a $\log K_{OW} > 5$ means high lipophilicity and, thus, a high potential to bioaccumulate or bioconcentrate. Numerous studies showed that K_{OW} was useful for correlating structural changes of drug chemicals with the change observed in some biological, biochemical, or toxic effect (LaGrega et al. 2010). It has been found to be related to water solubility, soil or sediment adsorption coefficients, and bioconcentration factors for aquatic life. According to the Stockholm Convention, a bioconcentration factor of >5000 and a $\log K_{OW} > 5$ is used as a criterion for bioaccumulation.

Stability

Stability is resistance to physical, chemical, or biological transformation. Loss of stability in the polymer breaks it down into smaller pieces, producing low MW species. As was previously described in the Polymer of Low Concern section under the *Molecular weight, number average molecular weight, MW distribution, and % oligomer < 1000 Da* heading, molecules with $M_n < 1000$ Da are capable of crossing cell membranes, making unstable polymers potentially hazardous to health and the environment.

Abiotic stability

Polymers are stable; monomers are not. Abiotic degradation may involve sunlight, water, or oxygen. Photochemical transformation is a reaction involving the radiation energy of sunlight (ultraviolet radiation) that may break a bond in a molecule to change it to another chemical entity. Hydrolytic degradation of polymers is another potential way to break the polymer bonds, creating smaller oligomers that may be bioavailable. Chemical oxidation is a reaction involving the loss of electrons from 1 atom to another.

Biotic stability: aerobic, anaerobic, and in vivo

Biotic stability is assessed by whether or not the polymer is degraded by microorganisms under oxygenated (aerobic) or anoxic (anaerobic) conditions; in vitro and in vivo stability studies demonstrate this. In vivo biodegradation involves the breaking of the polymer bonds by the action of bacteria, enzymes, and oxidants within the organism.

Thermal stability

Thermal stability of a polymer can be assessed when used as intended under normal, foreseeable use conditions or in extreme temperatures during disposal, such as by incineration. Thermal stability testing may involve Thermal Gravimetric Analysis (TGA), which determines mass loss over time and temperature of a test substance.

ASSESSMENT OF FLUOROPOLYMERS ACCORDING TO PLC CRITERIA

Characteristics of a PLC have been described in the preceding section. These criteria represent the combined

experience and knowledge of global regulatory authorities on factors demonstrated to be predictive of health and environmental hazards of polymers (OECD 2009; BIO by Deloitte 2015). Four fluoropolymers were assessed according to the PLC criteria. The results are summarized in Table 2, and an expanded discussion on specific criteria is provided in the remainder of this section.

Polymer composition

Fluoropolymers satisfy the PLC criterion of polymer composition. Polytetrafluoroethylene is a homopolymer of tetrafluoroethylene (TFE). Polytetrafluoroethylene can be a homopolymer (1 monomer) or it can be a modified homopolymer containing TFE widely and not more than 1% of another fluoromonomer (see ASTM 2015). Polytetrafluoroethylene contains only C and F having a $-\text{CF}_2-$ backbone terminated on both ends of each polymer chain with $-\text{CF}_3$. In unique cases, based on production method and ingredients used, commercial PTFE may have end groups that contain O, H, N, or S, depending on the initiator or chain transfer agent used in polymerization (Pianca et al. 1999). Polytetrafluoroethylene meets the compositional criterion to be a PLC.

Molecular weight, M_n , MWD, and % oligomer < 1000

Fluoropolymers satisfy the PLC criterion of MW, M_n , MWD, and % oligomer < 1000. Fluoropolymers are practically insoluble in water and all organic solvents. Therefore, standard MW methods are not applicable for fluoropolymers like PTFE and have been replaced by standardized indirect methods that use specific gravity and melt flow index to determine MW of PTFE and fluoropolymers (see Supplemental Data, p 27–28). Standard Specific Gravity (SSG) and Melt Flow Rate (MFR) are more conveniently and frequently used with fluoropolymers rather than rheological and dynamic light scattering methods (Chu et al. 1989; Starkweather and Wu 1989; Tuminello 1989; Tuminello et al. 1993). Polytetrafluoroethylene has an M_n of 500 000 to 9 000 000 Da (Berry and Peterson 1951; Doban et al. 1956; Suwa et al. 1973; Putnam 1986; Chu et al. 1989; Tuminello 1989; Tuminello et al. 1993; Frick et al. 2012). Therefore, PTFE, as a very high molecular weight polymer, cannot cross cell membranes, is not bioavailable, and cannot bioaccumulate or be toxic (see Supplemental Data, p 14). High molecular weight fluoropolymers, such as PTFE, therefore meet the PLC criterion for having MW that prevents them from entering the cells. Polytetrafluoroethylene has negligible (<<1%) oligomeric content (Starkweather and Wu 1989), as does FEP (Figure 2.) In summary, fluoropolymers are high molecular weight polymers with narrow MWD and negligible oligomer content.

Reactive functional groups and RFG ratio to MW

Fluoropolymers satisfy the PLC criterion of RFGs and RFG ratio to MW. Polytetrafluoroethylene most typically has a terminal $-\text{CF}_3$ group that is not an RFG. When this is not the case, the most common terminal group is $-\text{COOH}$, which is

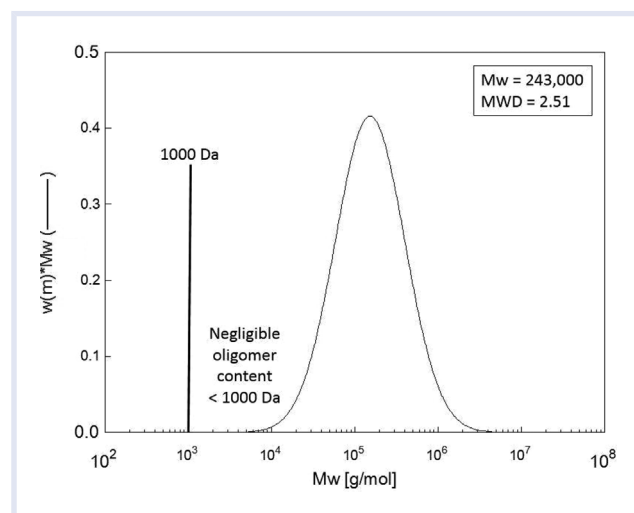


Figure 2. A fluorinated ethylene propylene (FEP) fluoropolymer molecular weight distribution from a rheological study. MW = molecular weight; MWD = molecular weight distribution.

categorized by the USEPA as a low-concern functional group. In unique cases, based on production method and ingredients used, PTFE may have end groups that may contain O, and H, N, or S, depending on the initiator or chain transfer agent used in polymerization. Fluoropolymers have a very high MW, which yields an FGEW on the order of 10^5 or more, well beyond the FGEW threshold of concern.

Low MW leachables

Fluoropolymers satisfy the PLC criterion of low MW leachables. Concentration of leachables from fluoropolymers, particularly PTFE “fine powder” (ASTM [2015] 4895-16 Type I fine powder definition), are typically very low (<1 ppm) (see Supplemental Data). This finding can be explained by the sensitivity of the PTFE polymerization reaction to contamination and is due to the postpolymerization processing steps aggressively exercised to wash out residuals and drive off volatiles. In order to achieve high MW polymerization of TFE, all traces of telogenic H- or Cl-bearing impurities must be removed (Ebnesajjad 2011; Supplemental Data).

In the analysis done on PTFE (see Supplemental Data, p 32), residual TFE monomer was not detected in PTFE resin by headspace GC-MS with a limit of detection of 1 ppm. In addition, publicly available analytical data from independent industry authorities demonstrate that TFE is not detected in finished articles made from fluoropolymers at detection limits down to about 0.01 ppm wt/wt (SPI 2005). Table 3 compares the molecular weight and the 8-h time weighted average (TWA) (American Conference of Governmental Industrial Hygienists [ACGIH], threshold limit value [TLV]), for monomers used to make fluoropolymers (ACGIH 2010). The TWAs are the exposure levels to which a worker could be exposed in an 8-h shift without adverse effects. The monomers have significantly lower MW, have lower TWAs, and are reactive. Note that the fluoropolymers are high MW, have no TWAs, and are inert. Table 3 illustrates that polymers do not have the same health hazards or MWs as their monomers.

Table 3. Fluoropolymer and monomer molecular weight and TLV data

Substance	CAS Nr	Molecular weight	ACGIH TLV 8-h TWA
Monomer: TFE	116-14-3	100	2 ppm
Monomer: Ethylene	74-85-1	28	200 ppm
Monomer: HFP	116-15-4	150	0.1 ppm
Monomer: PPVE	1623-05-8	266	200 ppm (vendor limit)
Polymer: PTFE	9002-84-0	389 000–45 000 000	None
Polymer: ETFE	25038-71-5, 68258-85-5	530 000–1 200 000	None
Polymer: FEP	25067-11-2	241 000–575 000	None
Polymer: PFA	26655-00-5, 31784-04-0	200 000–450 000	None

ACGIH = American Conference of Governmental Industrial Hygienists (ACGIH 2010); CAS = Chemical Abstracts Service; ETFE = ethylene tetrafluoroethylene; FEP = fluorinated ethylene propylene; HFP = hexafluoropropene; PFA = perfluoroalkoxy polymer; PPVE = perfluoropropylvinyl ether; PTFE = polytetrafluoroethylene; TFE = tetrafluoroethylene; TLV = threshold limit value; TWA = time weighted average.

Elemental composition

Fluoropolymers meet the widely accepted elemental composition criterion (BIO by Deloitte 2015). The USEPA, in updating its Polymer Exemption Rule, which applies to new polymers only, changed some review procedures to address certain side-chain fluorinated polymers that may degrade into small, mobile, and persistent substances (USFR 2010). This has contributed to confusion regarding the assessment of fluoropolymers. The exclusion of polymers under this step is not a conclusion of hazard, but a determination that the elemental composition does not fall within the parameters of the polymer set under which this rule was formulated, and consequently, these polymers would have to follow the standard notification and review process.

When USEPA updated the polymer exemption rule in 2010, the agency excluded polymers containing $-\text{CF}_3$ or larger chains that are covalently bound to C. The agency's rationale for the change was "...because the Agency has receiving information which suggests that polymers containing PFAS (perfluoroalkyl sulfonates) or PFAC (perfluoroalkyl carboxylates) may degrade and release fluorochemical residual compounds in the environment. Once released, PFAS or PFAC are expected to persist in the environment, may bioaccumulate, and may be highly toxic..." (USFR 2006).

Although USEPA recognized that PFAS and PFAC chemicals with longer C chain lengths (C7 and longer) may be of greater concern, it stated that there is insufficient evidence at this time, however, to definitively establish a lower C chain length limit to meet the "will not present an unreasonable risk" finding, which is the determination necessary to support an exemption under section 5(h)(4) of TSCA. The USEPA believes that it is possible for polymers containing these other types of perfluoroalkyl moieties to also degrade over time in the environment, thereby releasing the perfluoroalkyl moiety (USFR 2006).

The updated USEPA polymer exemption definition in 2010, summarized in the Objective and Rationale section for the Final Rule, may imply that new fluoropolymers with pendant or terminal $-\text{CF}_3$ groups, such as FEP, do not meet

the polymer exemption eligibility for reduced PMN reporting (USFR 2010). However, the summary definition in USFR (2010) lacks critical context found in the preamble to the Final Rule, which elaborates the conditions that would be necessary to exclude a perfluoro chemical from the polymer exemption:

- The first condition is cited above, "...polymers containing PFAS (perfluoroalkyl sulfonates) or PFAC (perfluoroalkyl carboxylates)..." where the C or S atom is an integral part of the polymer molecule; and
- the second condition notes that, polymers containing fluorotelomers or "...perfluoroalkyl moieties that are covalently bound to either a carbon or sulfur atom where the carbon or sulfur atom is an integral part of the polymer molecule can be attached to the polymers using conventional chemical reactions."

For the PFAS and PFAC as described by USEPA, the agency offers a clarification about the nature of the linkage, stating "How these materials are incorporated into the polymer is immaterial (they may be counter ions, terminal/end capping agents, or part of the polymer backbone)" (USFR 2010). The key characteristic is the presence of a $-\text{CF}_3$ group that is attached to, or forms part of, the polymer backbone and "this link (between the polymer backbone and the $-\text{CF}_3$ group) is susceptible to degradation and cleavage." (USFR 2010). Thus, in USEPA's review, the presence of $-\text{CF}_3$ group is important because it is a structural alert to consider potential degradation products. The USEPA will make a determination whether the potential degradation of the polymer in question presents an unreasonable risk to health and the environment under TSCA. As shown in Table 2, these fluoropolymers are not subject to degradation.

Water and lipid solubility and the octanol–water partition coefficient

Fluoropolymers, such as PTFE, are not soluble in octanol or water. Therefore, it is not possible to measure or calculate a

K_{OW} . Because solubility in octanol is predictive of lipid solubility, PTFE cannot dissolve in cell membrane lipids to gain access to cellular contents, nor is it small enough to enter the cell due to its very high MW. Because PTFE cannot enter the cells, it is not capable of bioaccumulation or bioconcentration in aquatic life.

Stability

Under normal, foreseeable uses, fluoropolymers are stable. Stability is resistance to physical, chemical, or biological transformation. Loss of stability in the polymer breaks it down into smaller pieces, producing low MW species. Molecules with $M_n < 1000$ Da are capable of crossing cell membranes, making unstable polymers potentially hazardous to health and the environment. Fluoropolymers, in general, have exceptional chemical and thermal stability; that is why they are so unique and useful. This is due to very strong C–F bonds that are stable under even extreme conditions (Gangal and Brothers 2015). Polytetrafluoroethylene is inert and chemically resistant to all solvents except molten alkali metals, chlorine trifluoride, and oxygen difluoride. Polytetrafluoroethylene, as a representative fluoropolymer, has the best chemical resistance of all currently known polymers and is insoluble in all known solvents, including water (Drobny 2006).

Abiotic stability

Polymers are stable; monomers are not. Photochemical transformation is a reaction involving the radiation energy of sunlight (ultraviolet radiation) that may break a bond in a molecule to change it to another chemical entity. Although PTFE will rapidly degrade in ionizing radiation (e.g., gamma radiation or high energy electron-beam radiation), it is resistant to photolysis (Drobny 2006). Photoinduced reactions with fluoropolymers do not occur. In addition, hydrolysis is a reaction involving the breaking of a bond in a molecule using water. The fluorine envelope surrounding the C backbone of PTFE is very hydrophobic. Fluoropolymers, such as PTFE, are hydrolytically stable, water resistant, and are not subject to hydrolysis catalyzed degradation (Arkles 1973). Finally, chemical oxidation is a reaction involving the loss of electrons from one atom to another. Because the C–F bond is one of the strongest known, and F is the most electronegative element, the C–F bond is thermodynamically stable, unfavorable to lose electrons (i.e., to oxidize) (Arkles 1973).

Biotic stability: aerobic, anaerobic and in vivo

Fluoropolymers like PTFE are biologically inert and not degraded by microorganisms under oxygenated (aerobic) or anoxic (anaerobic conditions); in vitro and in vivo studies demonstrate this. In vivo degradation involves the breaking of the polymer bonds due to bacteria and other enzymes and oxidants. For example, PTFE hernia patches explanted from patients and examined by scanning electron microscopy, attenuated total reflectance Fourier transform infrared spectroscopy, modulated differential scanning calorimetry, and optical microscope showed no degradation in vivo (King et al. 2013).

Thermal stability

Fluoropolymers, when used as intended under normal, foreseeable use conditions as specified in Table 2 (or “continuous processing temperature”) are thermally stable (Puts et al. 2014). The fluoropolymer industry has provided significant information on appropriate use of fluoropolymers (SPI 2005). Thermal gravimetric analysis determines mass loss over time and temperature of a test substance. Polytetrafluoroethylene is one of the most thermally stable polymers. Polytetrafluoroethylene’s continuous processing temperature is 260 °C (SPI 2005). This means that PTFE could remain for decades at 260 °C and not decompose (SPI 2005 see percent mass lost per hour at maximum continuous processing temperature).

Outside of normal, foreseeable use conditions (also known as “misuse”), when fluoropolymers are held at temperatures above their recommended processing temperatures, they degrade. Upon decomposition, fluoropolymers generate volatile degradation products (SPI 2005). At 450 °C, the decomposition of PTFE “only proceeds at a rate on the order of one percent per hour. It is not until considerably above the polymer first-order transition temperature (329 °C) that substantial decomposition is observed” (Arkles and Bonnett 1974). As the temperatures increase above recommended processing temperatures, the rate of generation rises and may sufficiently degrade the polymer to produce hazardous gaseous byproducts and polymer (particulate) fume fever (SPI 2005). Temperature, availability of O, the physical form of the polymer article, and the residence time at elevated temperature factor into the ultimate nature of the decomposition products (SPI 2005), mainly fluoroalkenes, hydrogen fluoride, oxides of C, and lower molecular weight fluoropolymer particulates. For PTFE, TFE is the principle gaseous product observed at temperatures near 330 °C. See Supplemental Data for additional information regarding overheating PTFE.

PRODUCT-SPECIFIC REGULATORY REQUIREMENTS

Certain product-specific regulations, such as those for medical devices and food contact for the United States and the EU, require the development of additional data beyond what is required to conduct a PLC evaluation. The following text will discuss food contact requirements for the United States and the EU, and medical device requirements.

Data requirements for food, pharmaceutical, and medical device applications

There are country-specific data requirements for fluoropolymer use in food, pharmaceutical, and medical device applications because the intended use of these products has the potential to directly or indirectly introduce the product into the human body. An extensive fluoropolymer data set has been developed by W.L. Gore for these uses. The clinical history of the safe implantation of more than 40 million PTFE medical devices over 40 y, extensive toxicity data, preclinical

data, and chemical extractables and migration testing confirmed that fluoropolymers are not bioavailable. Although the data requirements have evolved over time for contacting food, pharmaceuticals, or use in medical devices, the data (some of which are provided in the present article, the Supplemental Data for the present paper, regulatory submissions, and product literature) confirm the conclusion that fluoropolymers are safe for these intended uses and support the conclusion that fluoropolymers should be considered PLCs.

Polymer of low concern data and US and European Union food contact requirements

In general, the data required to support a PLC determination are helpful, but insufficient to qualify a material for food contact use. Submissions to the US Food and Drug Administration (USFDA) to support new food contact substances require extensive data submissions, including, for example, the nature and amount of nonvolatile extractives (USFDA 2017). Fluoropolymers, however, are not new substances in applications where they come in contact with food and have longstanding acceptance by regulators. In the United States, the USFDA is responsible for regulation of materials that come in contact with food and are considered "indirect food additives," specifically polymers (USFR 2016a). Food storage or food packaging materials, such as the fluoropolymers PTFE, FEP, and PFA, are "perfluorocarbon resins" acceptable for use by application and material type, provided they meet the extractable limits specified in the regulation (USFR 2016b).

Similarly, the European Food Safety Agency (EFSA) provides recommendations to the European Commission (EC) within the EU for the regulation of food contact materials, requirements for their evaluation, and authorization of acceptable uses (EC 2004). Polymer clearance is based in part upon the fact that polymers will not migrate into food due to their high molecular weight. The EU focuses on potential low molecular weight moieties, such as residual monomers and leachables, rather than on the polymer itself. The EU food contact regulation requires that monomers, other starting substances, and additives used to produce food contact polymers should be risk assessed and authorized (EU 2011). The regulation lists authorized substances that are permitted to have food contact (EU 2011). This regulation also sets the specific migration limit (SML), which is the maximum permitted amount of substance in food that has been determined not to pose a risk to human health, specifically for individual chemicals (e.g., monomer) (EU 2011). Note that these limits exist whether or not the substance is present in the food contact material (FCM). The monomers, other starting substances, and additives used to produce fluoropolymers for food contact (e.g., PTFE, FEP, and PFA) have been authorized for food contact uses. Representative SMLs for these monomers, additives, and starting substances relevant for fluoropolymers are given in the Supplemental Data (p 14).

Polymer of low concern data and medical device regulatory requirements

Satisfaction of the PLC criteria is insufficient to satisfy medical device requirements. Formal biocompatibility evaluations are required by the USFDA and other global regulatory authorities to support submissions for approval of medical devices and pharmaceuticals (e.g., combination products, such as drug-eluting stents or prefilled single-dose syringes). The International Organization for Standardization (ISO) 10993 Biocompatibility of Medical Devices standards describe a broad array of biocompatibility tests that require consideration for each new device or significant changes to existing devices (ISO 2009). Over the years, medical devices containing PTFE (or expanded PTFE) have been evaluated using ISO 10993 and US Pharmacopeia (USP) Class VI standards (USP 2011) and have been determined to be biocompatible in their intended uses.

The ISO 10993 standards provide guidance for evaluation of the biological response to a medical device. The USFDA, as well as most international regulatory agencies, recognizes and uses ISO 10993 standards to guide safety evaluations of medical devices submitted for their approval. Requirements to demonstrate the biocompatibility of medical devices are set forth in ISO 10993-1, and regulatory authority-specific requirements (e.g., PMDA 2003; USFDA 2016). In addition, country pharmacopeial organizations also specify testing required for biological reactivity of drugs (e.g., US Pharmacopeia, EU Pharmacopeia, Japan Pharmacopeia). The ISO requirements are categorized by the nature of body contact (e.g., mucosal membrane, circulating blood, tissue, bone, dentin) and duration of contact (<24 h, ≥ 1 d ≤ 30 d, >30 d). Depending on the nature and duration of contact, requirements include cytotoxicity, irritation, sensitization, implantation, acute-subchronic-chronic systemic toxicity, material-mediated pyrogenicity, hemocompatibility (e.g., hemolysis, thrombogenicity, and complement activation), genotoxicity (in vitro and in vivo), carcinogenicity, and developmental toxicity. (See Supplemental Data p 15 for a list of ISO 10993 biocompatibility tests.)

MEETING PLC CRITERIA PRECLUDES A FINDING THAT A CHEMICAL IS OF HIGH CONCERN

Just as regulatory frameworks have mechanisms to identify materials of low concern such as PLCs, they also have mechanisms to identify chemicals of high concern. For example, under REACH, a mechanism exists to identify substances of very high concern (SVHCs). Having demonstrated that fluoropolymers like PTFE should be considered PLCs, we will also demonstrate that these fluoropolymers cannot be SVHCs under REACH, do not meet the PM and PMT criteria proposed by UBA, and do not meet the criteria for listing as a POP under the Stockholm Convention.

Fluoropolymers and EU REACH SVHC, CMR, PBT, vPvB, and endocrine disrupting chemical (EDC) criteria

According to the European Chemicals Agency (ECHA), SVHCs are defined in Article 57 of Regulation (EC) Nr 1907/2006 ("the REACH Regulation") (EC 2006) and include substances that are

- "Carcinogenic, mutagenic or toxic to reproduction (CMR), meeting the criteria for classification in category 1 or 2 in accordance with Directive 67/548/EEC. This directive was replaced in beginning of 2009 by the new EU regulation (EC) No 1272/2008 on classification, labeling and packaging of chemical substances and mixtures, the so-called CLP Regulation. According to the new CLP Regulation these substances shall be classified as 1a or 1b."
- "Persistent, Bioaccumulative and Toxic (PBT) or very Persistent and very Bioaccumulative (vPvB) according to the criteria in Annex XIII of the REACH Regulation."
- "Identified, on a case-by-case basis, from scientific evidence as causing probable serious effects to human health or the environment of an equivalent level of concern as those above (e.g., EDCs)."

Under REACH, polymer substances are not registered, but the monomers they are composed of are registered, and the registration must be supported by data submissions that are tiered on the basis of tonnage (see EC 2006, Annex VII). The REACH definition of polymer includes materials with as few as 3 repeating units. But such a small molecule would not meet common industry standard definitions for fluoropolymers (ASTM 2015). It is highly unlikely that fluoropolymers meeting the PLC criteria would exhibit the criteria of an SVHC under REACH. Fluoropolymer data developed for other regulatory needs support the predictive value of the PLC assessment criteria and demonstrate the low hazard potential of this class of PFAS. Due to their physical-chemical properties, PLCs are not bioavailable to cause toxicity or to bioaccumulate. Toxicity study data on PTFE in the Supplemental Data (p 15–27), for example, demonstrate a lack of toxicity, including genotoxicity. Although fluoropolymers are persistent, they are not bioaccumulative or toxic and therefore do not meet the PBT criteria.

Fluoropolymers and German UBA-proposed PMT criteria

As regulatory frameworks continue to evolve, more work is needed in the area of PFAS classification to ensure that regulations are appropriate in scope and proportionality. Although some well-known PFAS would qualify as PM or PMT substances as proposed by the UBA (2017), fluoropolymers do not possess these characteristics. Although fluoropolymers are highly stable (persistent), they do not meet the criteria to be mobile or toxic. To demonstrate this point, PTFE, a high molecular weight fluoropolymer and a member of the PFAS group, is assessed (in the last 4 paragraphs of this section) according to the proposed UBA criteria (UBA 2017).

Briefly, the changes to PM and/or PMT assessment proposed by UBA address applicability, persistence, mobility, and toxicity. The UBA proposes an initial step involving assessment of the chemical composition of a substance to determine if the substance is within the applicability domain of the proposed new assessment criteria. The UBA notes that currently only identifiable organic and organometallic chemicals are considered, and purely inorganic substances or substances of unknown or variable compositions, complex reaction products, or biological material are excluded (UBA 2017).

With respect to persistence, UBA proposes that the criterion for persistence be the same as in Annex XIII of REACH, which considers degradation half-lives in marine water, fresh- or estuarine water, marine sediment, and soil as part of the PBT/very persistent, very bioaccumulative (vPvB) assessment criteria; these degradation half-life criteria range from 40 to 180 d. The UBA proposes that a substance meets the persistent criterion if the degradation half-life in marine water at pH 6 to 8 and 12 °C is higher than 60 d, the half-life in fresh- or estuarine water at pH 6 to 8 and 12 °C is higher than 40 d, the half-life in marine sediment at pH 6 to 8 and 12 °C is higher than 180 d, the half-life in fresh- or estuarine water sediment at pH 6 to 8 and 12 °C is higher than 120 d, or the half-life in soil at pH 6 to 8 and 12 °C is higher than 120 d.

The UBA proposes that the mobility criterion for a persistent chemical should be determined on the basis of 2 considerations. First, the water solubility of a substance at pH 6 to 8 and 12 °C must be greater than or equal to 150 µg/L, and the log K_{OC} at pH 6 to 8 and 12 °C must be less than or equal to 4.5. The UBA notes that the mobility criterion should be applied only to substances that have fulfilled the criterion for persistence.

Lastly, with respect to toxicity, UBA proposes a 5-part test for involving data to understand if the substance is carcinogenic, germ cell mutagenic, or toxic for reproduction; if there is other evidence of chronic toxicity; and if there is evidence for effects on or via lactation. The derived no adverse effect level (DNEL) must be less than or equal to 9 µg·kg⁻¹·d⁻¹. The UBA notes that the first 2 considerations are the same criteria defined in Annex XIII of REACH as part of the PBT/vPvB assessment criteria regarding human health. The next 2 criteria specifically address concerns for drinking water exposure and are based on Regulation EC No 1272/2008 (EC 2008) and Cramer class II (Cramer et al. 1978) for substances exhibiting moderate or low biological activity, respectively. The DNEL criterion is based on Kalberlah et al. (2014).

Regardless of the arguments concerning the scientific foundation and credibility of the changes proposed by UBA to REACH PM and PMT assessment criteria, the central question with respect to PTFE is whether chemical-specific assessment would lead to an outcome different from that assuming PTFE behaved similarly to other PFAS substances. Polymers, including fluoropolymers, are different from non-polymeric chemicals and may be regulated differently. Because of these differences, it is recognized that some data requirements may not be applicable to polymers (EU 2011). For example, as we have shown, the physical-chemical criteria of PLC are predictive of lack of hazard.

With respect to applicability, PTFE is not a substance currently registered under REACH because it meets the REACH definition of a polymer substance: “a molecule that contains a sequence of at least 3 monomer units, which are covalently bound to at least one other monomer unit or other reactant” (EC 2006). However, because PTFE is an identifiable organic substance, the proposed UBA framework for assessment using the proposed PMT criteria would be applicable. Further, PTFE is highly stable and persistent in the environment. It is resistant to thermal degradation, being stable for decades at temperatures up to 260 °C (SPI 2005); is stable in terms of hydrolysis, oxidation, and light (Brydson 1999); and is stable in terms of anaerobic and aerobic degradation (King et al. 2013). Therefore, PTFE would fulfill the UBA’s proposed persistence criterion.

In contrast, PTFE is practically insoluble in water and, therefore, is not mobile in the environment. Using the descriptive solubility table for the USP (2011), the water solubility of PTFE would be classified as practically insoluble (1×10^{-5} mg/L or 0.01 µg/L) to very slightly soluble (1×10^{-4} mg/L or 0.1 µg/L) (USP 2011). The mobility of PTFE is 1000 to 10000× lower than UBA’s proposed mobility criterion. Therefore, PTFE does not fulfill UBA’s proposed mobility criterion and would not be classified as a PM or PMT substance.

A similar negative finding for PTFE pertains to toxicity. The average molecular weight of PTFE is too large for the polymer to cross a cell membrane, which means it is not bioavailable or toxic. Polytetrafluoroethylene has been tested extensively in the United States and European Union to assess commercial applications for food contact and global medical device regulations (see Supplemental Data for additional details). Results demonstrate the absence of toxicity. Therefore, PTFE does not fulfill UBA’s proposed toxicity criterion and would not be classified as a PM or PMT substance (Table 4).

Fluoropolymers and the Stockholm Convention POP criteria

In addition to country and regional regulations, there are global legally binding instruments, such as the United Nations Environment Programme-administered conventions on chemicals and waste (UNEP 2001), such as the Stockholm Convention on Persistent Organic Pollutants. The Convention aims to eliminate POPs by eliminating their production, reducing their use, or limiting their use through a cradle-to-grave approach. For the listing of new chemicals into the Convention, numeric or other criteria have been set for the screening of proposed compounds. Stockholm Convention Criteria (annex D) are compared to those of the USEPA, EU REACH, and the UBA-proposed PMT (Table 4). Fluoropolymers meet the persistence criterion only, not the bioaccumulative, toxic, or mobile criteria.

Fluoropolymers satisfy widely accepted criteria to be considered PLCs. Their physical-chemical properties prevent bioavailability, bioaccumulation, toxicity, and degradation. They have negligible monomer, oligomer, and leachable content and no reactive functional groups with high toxicity. These comparisons of PLC and various regulatory assessment criteria demonstrate that, in the realm of PFAS, high

molecular weight fluoropolymers like PTFE have vastly different properties than do other PFAS, and therefore, they are truly a separate class of materials that must be assessed on their own merits as has been done here. They also underscore the value of a global regulatory definition of a polymer.

FUTURE WORK

It is important to acknowledge that the manufacture and end-of-life phases of the fluoropolymer life cycle are not the subject of the present paper. The following reflections are provided on how these may be explored in future work. Fluoropolymer manufacture includes fluoromonomers and a wide array of initiators, catalysts, et cetera, including polymer production aids, some of which are fluorosurfactants (non-polymer PFAS) (see Supplemental Data, p 8, for more information about them). Historically, perfluorocarboxylic acids such as PFOA and perfluorononanoic acid (PFNA) were used as polymer production aids in the manufacture of fluoropolymers. They are no longer used by leading global fluoropolymer manufacturers (USEPA 2017a), who are now using alternative substances such as fluorinated polyether carboxylates (see Supplemental Data Table S2). The toxicological and environmental properties (e.g., persistence, bioavailability, and mobility) of these alternatives are very important. Future work should delve into fluoropolymer manufacture and describe the safety, health, and environmental management practices and controls employed; should describe the applicable regulations; and should assess substances used in fluoropolymer manufacture, their human health and environmental attributes, and their mass balance.

At end-of-life when a fluoropolymer has fulfilled its intended use and will be disposed of, the fate of fluoropolymers should be investigated further. Although there are sufficient data to demonstrate that fluoropolymers such as PTFE do not degrade in the environment or release substances of toxicological or environmental concern (Hintzer and Schwertfeger 2014), the downstream, end-of-life process of incineration merits future work. For instance, at temperatures above 450 °C, PTFE begins to degrade, releasing hazardous substances such as hydrofluoric acid. There are published studies on the incineration of fluoropolymers under normal, foreseeable municipal waste incinerator conditions targeting specific analytes (Taylor 2009). Presently, most legislation addresses the release of hydrogen fluoride (HF) as the only critical parameter; limit values are for stack emissions (e.g., EU 2000). Future work should investigate incineration under a range of relevant foreseeable use conditions to determine more comprehensively the substances formed and their amounts. Such an incineration study is underway with results to be published upon completion (W.L. Gore 2017). In addition, the practice of the open burning of fluoropolymers, or for that matter of any polymer, is unacceptable and unsafe. Responsible incineration of fluoropolymers, adhering to regulatory guidelines, at the end of their life cycle is appropriate.

Table 4. Comparison of United States, Stockholm Convention, EU REACH, and German Criteria

Criterion	United States ^a	Stockholm Convention ^b	REACH ^{c,d}	Germany ^{d,e}
Persistence (half-life)				
P	Water, soil, sediment > 60 d	Water >60 d	Marine water > 60 d	Same as REACH
		Soil, sediment >180 d	Estuarine water > 40 d	
			Fresh or estuarine sediment or soil > 120 d	
vP	Water, soil, sediment > 180 d		Marine, fresh, estuarine H ₂ O > 60 d	
			Marine, fresh, or estuarine sediment > 180 d	
			Soil > 180 d	
Bioaccumulation				
B	Aquatic BCF > 1000	Aquatic BCF or BAF > 5000	BCF > 2000	
		Log K _{OW} > 5		
vB	BCF > 5000		BCF > 5000	
Toxicity				
	Fish	Toxic or ecotoxic	Long-term aquatic NOEC or EC10 < 0.01	1) Carcinogenic, germ cell mutagenic, or toxic for reproduction ^d ;
	Low > 10 mg/L	(No numeric criteria)	Classified as carcinogen category 1A or 1B; mutagen 1A or 1B; reproductive toxin 1A, 1B, or 2 ^d	2) other evidence of chronic toxicity ^d ; and
	Moderate 0.1 mg/L–10 mg/L			3) evidence for effects on or via lactation ^d .
	High < 0.1 mg/L			4) DNEL ^f ≤ 9 μg · kg ⁻¹ d ⁻¹
			Specific target organ toxicity (STOT RE 1 or 2) upon repeated (chronic) exposure) ^d	
Long-range transport (potential for)		Long-range transport (potential for): Presence through monitoring or modeled data; t _{1/2} (air): 2 d		
Mobility				Mobility: water solubility at pH 6–8, 12 °C, must be ≥150 μg/L, and the log K _{OC} at pH 6–8, 12 °C must be ≤4.5.

BAF = bioaccumulation factor; BCF = bioconcentration factor; DNEL = derived no adverse effect level; EU = European Union; M = mobile; P = persistent; REACH = Registration, Evaluation, Authorisation and Restriction of Chemicals; STOT RE = specific target organ of toxicity repeat exposure; T = toxic; v = very.

^aUSEPA 1999.

^bUNEP 2001

^cECHA 2014

^dEC 2008

^eUBA 2017

^fBarlow 2005; Kalberlah et al. 2014.

Recycling, reuse, and closed loop systems are alternative options at the end of life. Recent work has shown, on a small scale, the ability to convert fluoropolymers back to their monomers for capture (Schlipf 2014; Invertec 2017).

This approach to a closed loop economy for fluoropolymers merits additional work and discussion, as does the recycling and reuse of melt-processable fluoropolymers, such as FEP.

CONCLUSIONS

The present review has brought together fluoropolymer toxicity data, human clinical data, and physical–chemical characteristics, using PTFE as an example to show that fluoropolymers satisfy the widely accepted regulatory assessment criteria to be considered as PLCs. Fluoropolymers are high molecular weight, have narrow molecular weight distribution, and have negligible oligomer content and organic and inorganic leachables. Data show that fluoropolymers have thermal, chemical, photochemical, hydrolytic, and biological stability. Polytetrafluoroethylene has been extensively tested to comply with US and EU food contact and global medical device regulations (e.g., USFDA, CFDA, Korea MFDS, Japan PMDA), including ISO 10993 biocompatibility testing and preclinical animal testing. Toxicology studies on PTFE demonstrate the absence of acute or subchronic systemic toxicity, irritation, sensitization, local toxicity on implantation, in vitro and in vivo genotoxicity, hemolysis, complement activation, or thrombogenicity. The data presented demonstrate that the fluoropolymer class of PFAS is well defined, meets PLC criteria, and should be considered as distinctly different from other classes of PFAS. The grouping of all PFAS together is not supported by the scientific data.

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Data Accessibility—All data and information used in this manuscript have been made available in tabulated form (Tables 1–4) by the authors and are included in the paper and the Supplemental Data.

SUPPLEMENTAL DATA

The Supplemental Data contains descriptive and more detailed information as highlighted in the paper.

Figure S1. Where does polytetrafluoroethylene (PTFE) come from?

Figure S2. Fluoropolymer primer: polytetrafluoroethylene (PTFE) polymerization scheme.

Figure S3. Fluoropolymer primer: polytetrafluoroethylene (PTFE) finishing scheme.

Figure S2. A fluorinated ethylene propylene (FEP) fluoropolymer molecular weight distribution from a rheological study.

Table S1. Polytetrafluoroethylene (PTFE) polymerization and post polymerization aids

Table S2. Alternative fluoropolymer processing aids: Sources of data

Table S3. Solubility table from USP 34 NF 29 General Notices, Section 5.3.0, p 6

Table S4. European Union (EU) specific migration limits (SMLs) for monomers in representative fluoropolymers

Table S5. Biocompatibility tests, conditions, and acceptance criteria results for expanded polytetrafluoroethylene patch

Table S6. US Environmental Protection Agency's (USEPA's) chemical categories of concern, 2010

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