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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 – 1150 °C.
- Oxygen in Exhaust: 6–13 % (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 $\geq \text{C}_4$ PFAS detected despite near-complete fluorine recovery (97–101 %). 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 $\geq \text{C}_4$ 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 mm x 45 mm (outer diameter x 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 °C, 1140 °C, and 1165 °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 °C and outlet of 1100 °C. The system operated with a flow rate of 200 mL/min of Ar and O₂. 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 % H₂O₂, and examined using ion chromatography (AQF-2100H by Nittoseiko Analytech Co., Ltd). An internal standard of Br 8 ug/mL was employed, along with a mobile phase of 2.7 mmol/L Na₂CO₃/0.3 mmol/L NaHCO₃ for a flowrate of 1.5 mL/min. Injection volume was 20 μL 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

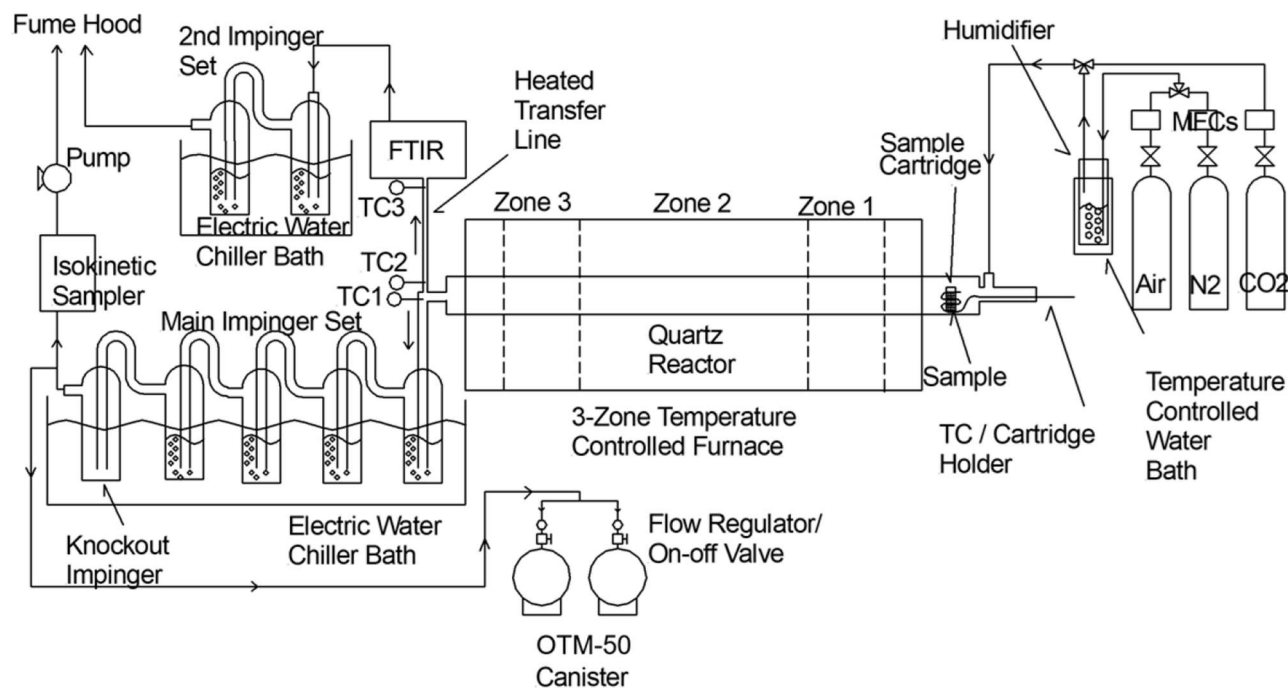
Experiments were conducted decomposing PTFE using a system setup designed by University of Dayton Research Institute (UDRI), as illustrated in Fig. 1A and 1B. The same system was developed and employed in a recent bench-scale incineration study of polychlorotrifluoroethylene (PCTFE) [8]. Carrier gases, 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

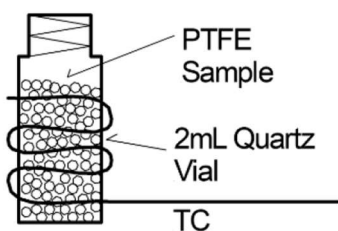
temperature-controlled furnace (Thermcraft, SST-3.00-0-30-3C-D2155-BE). The effective heated length, defined as the region maintaining temperatures within $\pm 5\%$ of the target temperature, was 27 in. Temperature was measured using a K-type thermocouple (KMQXL-125U-48, OMEGA) connected to a temperature 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

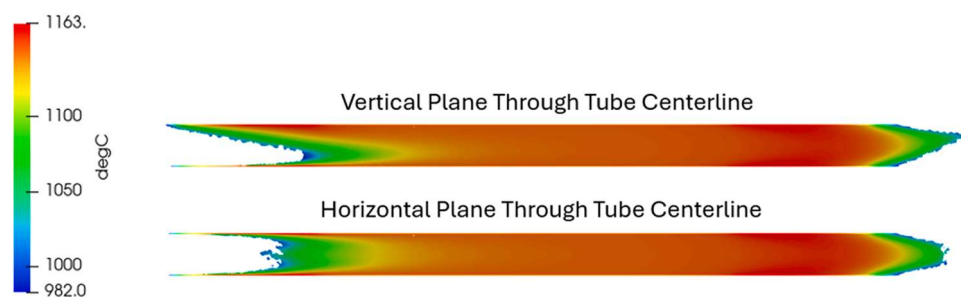


Fig. 2. Gas achieving $T > 982\text{ }^{\circ}\text{C}$ and axial velocity $> 0\text{ m/s}$ for vertical and horizontal planes.

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 QLS 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-dioxanonane	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.

CRedit 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

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.jfluchem.2026.110603](https://doi.org/10.1016/j.jfluchem.2026.110603).

Data availability

Data will be made available on request.

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