Implementing OTM-45 Testing at Waste-to-Energy Facilities: Lessons Learned

May 21, 2025

USWAG PFAS Workshop

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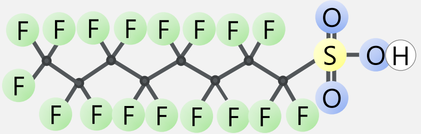
What Are PFAS? Per- and Polyfluoroalkyl Substances

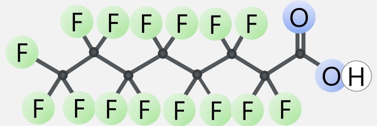
Used in the Production of...

PFAS Non-polymer Examples

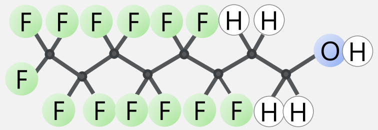
Perfluorosulfonic Acids (PFSAs)
e.g., PFOS



Perfluorocarboxylic Acids (PFCAs)
e.g., PFOA

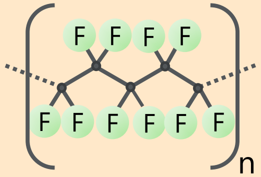


Fluorotelomers (FTs)
e.g., 6:2 FTOH

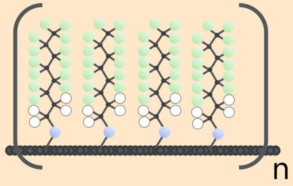


PFAS Polymer Examples

Fluoropolymers
e.g., PTFE for non-stick pans



Fluorinated Side-Chain Polymers
e.g., textile finishes



May Degrade to...

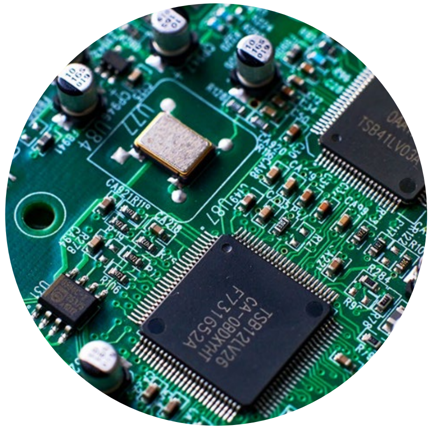
Examples of Products that Contain/Involve the Use of PFAS

Firefighting Foam

Textiles with stain resistant/ water resistant finishes

Processing Aid for Plastic

Electronics



Cleaning Products/ Floor Finishes

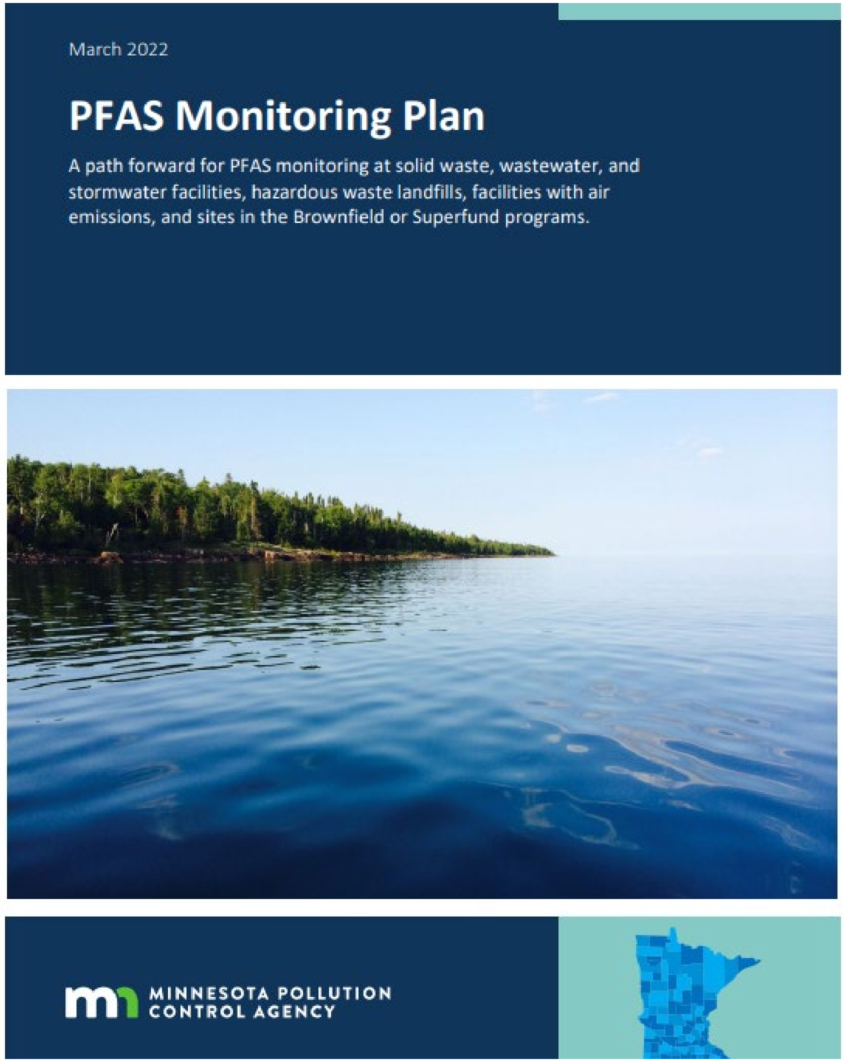
Metal Plating

Fragrances and PCPs

Anti-fog Sprays

Minnesota's "Voluntary " PFAS Monitoring Plan

- Released in 2022 and designed to:
    1. Gather information to craft effective policies;
    2. Identify areas of concern (due to PFAS concentrations or exposure routes) that need quick action; and
    3. Gather data to support source reduction and pollution prevention.
- Air Program
    - Monitoring Options: Continuous Emissions Monitoring, Stack Test, Mass Balance, Emission Factor, or Stack Test,
    - No clear criteria or regulatory outcomes
    - PFAS (9) Compounds for which MDH prioritized development of inhalation risk-based values
- Company was interested in being out front and leading the development of sampling, analysis and interpretation of PFAS in air emissions at RDF/WTE facilities



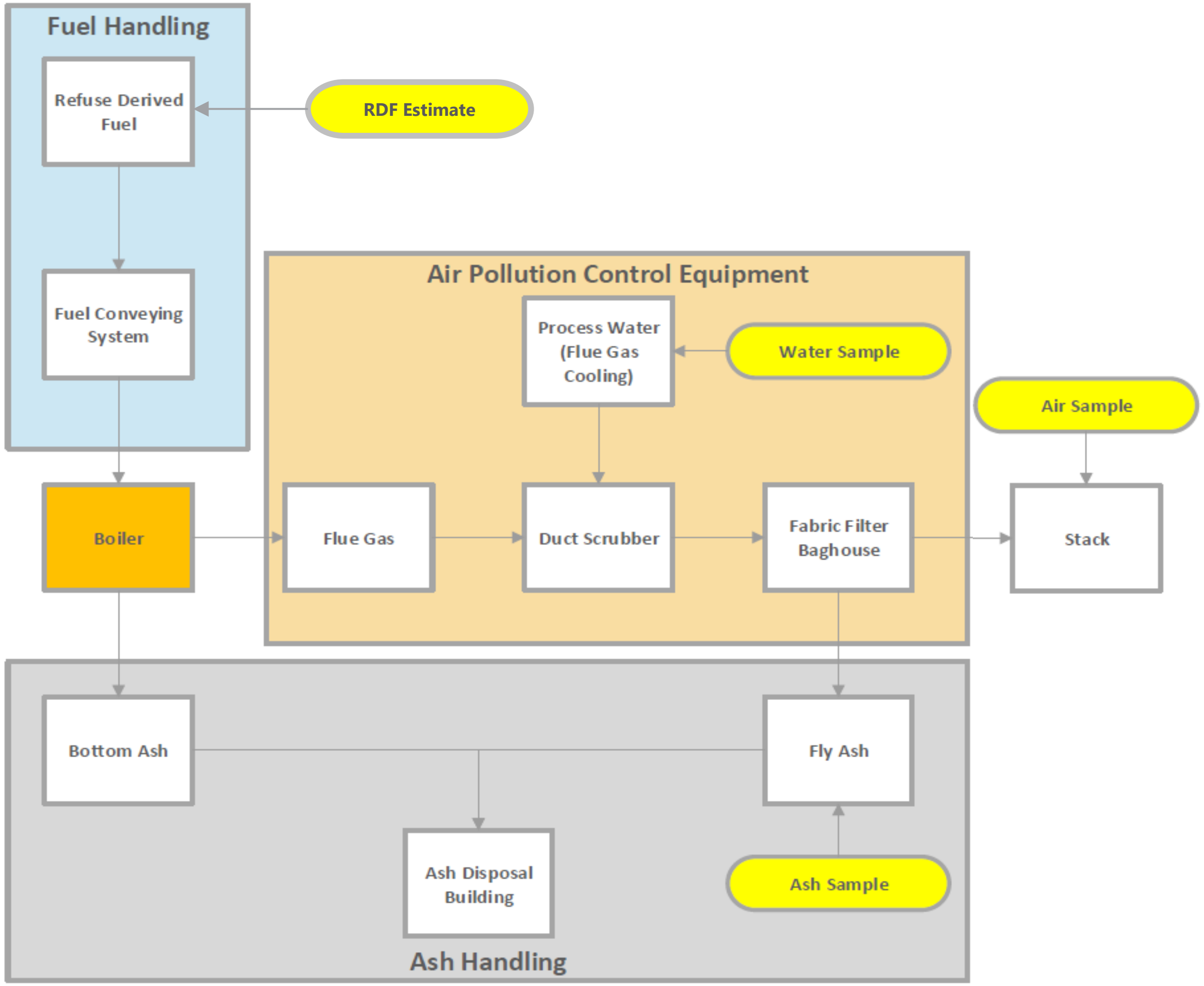
PFAS Sampling and Analysis Plan Overview at RDF Facilities

- A testing plan was developed to inform and support PFAS stack emissions testing at Municipal Solid Waste (MSW) Incineration Facilities since very little information was available regarding PFAS stack emissions from municipal solid waste derived fuel.
- The facilities of interest here are referred to as Refuse-Derived Fuel (RDF) generating plants

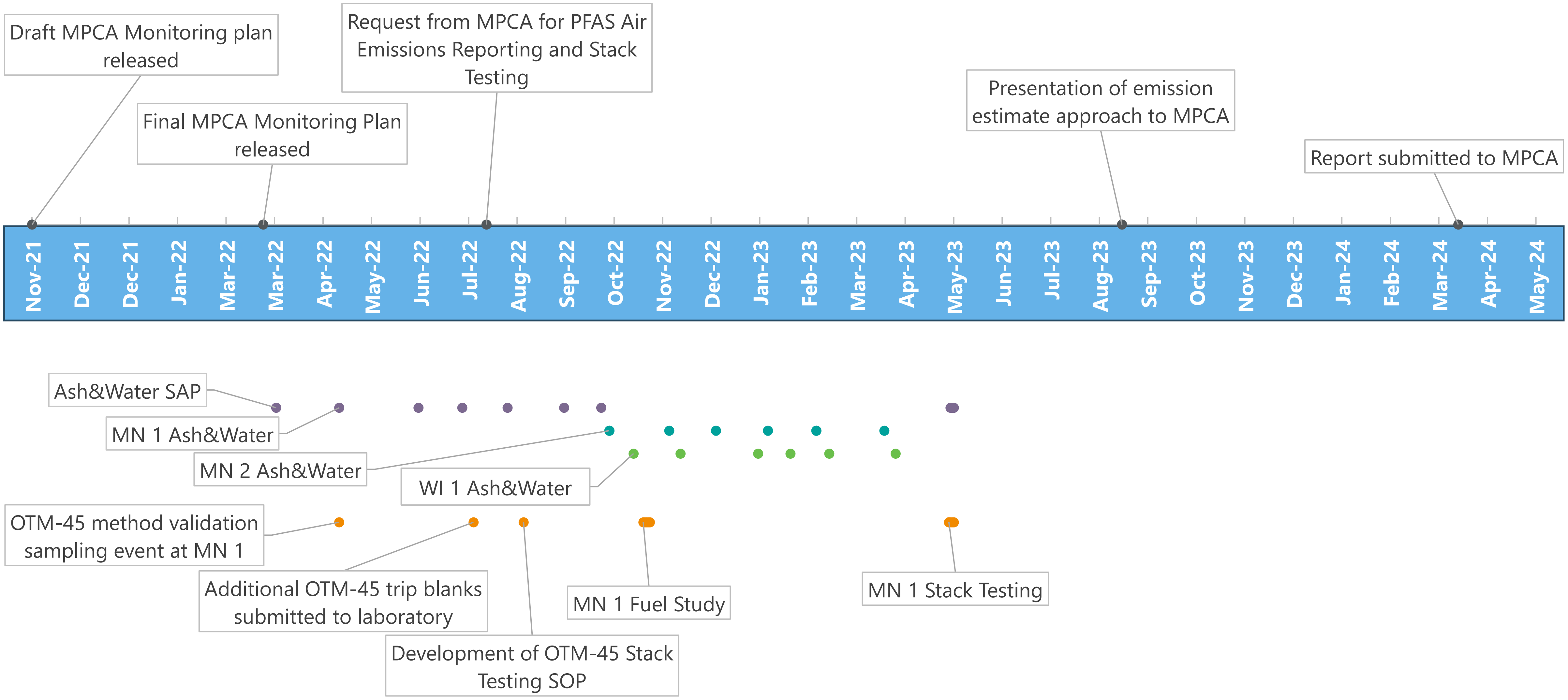
MN 1 and MN 2 Plants

- Incineration is a known technology for destroying PFAS (US DOD, 2023; Wang *et al.*, 2022).
- PFAS destruction efficiency as high as 99.9999% has been documented for certain incineration conditions (>980°C and with residence times >2 seconds)
- MN RDF plants convert over 380,000 tons per year of RDF to produce renewable electricity serving about 20,000 homes.
  - MN 1: Max Temp 1,400°C;
    2.9 sec Residence Time at > 950°C
  - MN 2: Max Temp 1,200°C;
    3.2 sec Residence Time at > 900°C

RDF Incineration Inputs and Stack Outputs



Project Timeline



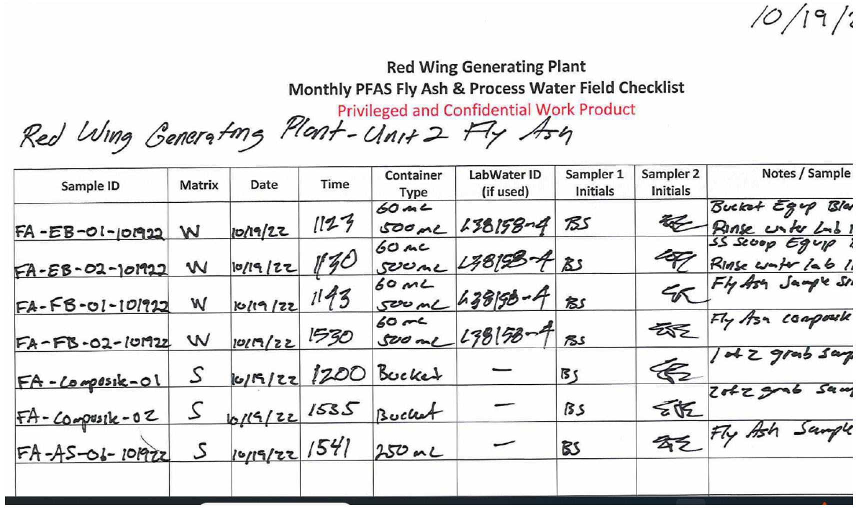
Sampling and Analysis Plan Development

Goals

- Understand Potential Sources of PFAS in RDF facilities
- Evaluate variability of PFAS with time and between facilities
- Support Air Emissions estimates

Sample Collection

- Fly ash sampling
- Process Water sampling
- Composites and grabs
- Equipment used
  - Plastic pails and scoop
  - Stainless steel scoops
  - Laboratory provided “PFAS-free” sample containers
- Clean hands/dirty hands
  - Minimize risk of contamination during sampling
- PPE used



10/19/2

Red Wing Generating Plant
Monthly PFAS Fly Ash & Process Water Field Checklist
Privileged and Confidential Work Product

Red Wing Generating Plant - Unit 2 Fly Ash

Sample ID	Matrix	Date	Time	Container Type	LabWater ID (if used)	Sampler 1 Initials	Sampler 2 Initials	Notes / Sample
FA-EB-01-101922	W	10/19/22	1123	60 mL 500 mL	L38158-4	BS	[illegible]	Bucket Equip Bla Rinse water Lab
FA-EB-02-101922	W	10/19/22	1130	60 mL 500 mL	L38158-4	BS	[illegible]	SS Scoop Equip Rinse water lab
FA-FB-01-101922	W	10/19/22	1143	60 mL 500 mL	L38158-A	BS	[illegible]	Fly Ash Sample Sn
FA-FB-02-101922	W	10/19/22	1530	60 mL 500 mL	L38158-4	BS	[illegible]	Fly Ash composite
FA-Composite-01	S	10/19/22	1200	Bucket	—	BS	[illegible]	1 of 2 grab samp
FA-Composite-02	S	10/19/22	1535	Bucket	—	BS	[illegible]	2 of 2 grab sam
FA-AS-01-101922	S	10/19/22	1541	250 mL	—	BS	[illegible]	Fly Ash Sample

Fly Ash Sampling

- Monthly Sampling for 6 months at 3 facilities
- Completed field sampling logs as sampling progressed during the day
- Collected quality control/assurance samples for all media
- Health and Safety considerations
  - fly ash handling, inhalation, contaminating clothing
  - LOTO – required plant operator involvement to stop and lock out conveyor system. Visual and radio comms

Process Water Sampling

- In addition to fly samples, process water samples were also collected
- Process water is used in the air pollution control systems and analysis completed to correlate with the ash and air sampling (what, if any, PFAS contribution to emissions was from process water)

Sample Analysis

- Analytical Method-Ash and Water
  - Analyzed by EPA Draft 1633
  - Instructed labs to use five grams in the extraction procedure vs. 0.5 grams to gain the lowest possible detection limits
  - Split samples were collected and sent to two different labs
  - EPA Draft 1633 was still in EPA's multi-lab validation process at the time of this study
  - Both labs were part of the multi-lab validation program

	B	C	D	E	F	G	H	I	J
1	SAMPLENAME	LABSAMPID	MATRIX	SAMPDATE	PREPDATE	ANADATE	BATCH	METHODCODE	METHODNAME
2	FA-EB-01-052423-	10654681001	Water	05/24/2023 10:45:00	06/14/2023 14:17:00	06/19/2023 15:15:00	890545	1633 W	EPA 1633 DRA
3	FA-EB-01-052423-	10654681001	Water	05/24/2023 10:45:00	06/14/2023 14:17:00	06/19/2023 15:15:00	890545	1633 W	EPA 1633 DRA
4	FA-EB-01-052423-	10654681001	Water	05/24/2023 10:45:00	06/14/2023 14:17:00	06/19/2023 15:15:00	890545	1633 W	EPA 1633 DRA
5	FA-EB-01-052423-	10654681001	Water	05/24/2023 10:45:00	06/14/2023 14:17:00	06/19/2023 15:15:00	890545	1633 W	EPA 1633 DRA
6	FA-EB-01-052423-	10654681001	Water	05/24/2023 10:45:00	06/14/2023 14:17:00	06/19/2023 15:15:00	890545	1633 W	EPA 1633 DRA
7	FA-EB-01-052423-	10654681001	Water	05/24/2023 10:45:00	06/14/2023 14:17:00	06/19/2023 15:15:00	890545	1633 W	EPA 1633 DRA
8	FA-EB-01-052423-	10654681001	Water	05/24/2023 10:45:00	06/14/2023 14:17:00	06/19/2023 15:15:00	890545	1633 W	EPA 1633 DRA
9	FA-EB-01-052423-	10654681001	Water	05/24/2023 10:45:00	06/14/2023 14:17:00	06/19/2023 15:15:00	890545	1633 W	EPA 1633 DRA
10	FA-EB-01-052423-	10654681001	Water	05/24/2023 10:45:00	06/14/2023 14:17:00	06/19/2023 15:15:00	890545	1633 W	EPA 1633 DRA
11	FA-EB-01-052423-	10654681001	Water	05/24/2023 10:45:00	06/14/2023 14:17:00	06/19/2023 15:15:00	890545	1633 W	EPA 1633 DRA
12	FA-EB-01-052423-	10654681001	Water	05/24/2023 10:45:00	06/14/2023 14:17:00	06/19/2023 15:15:00	890545	1633 W	EPA 1633 DRA
13	FA-EB-01-052423-	10654681001	Water	05/24/2023 10:45:00	06/14/2023 14:17:00	06/19/2023 15:15:00	890545	1633 W	EPA 1633 DRA
14	FA-EB-01-052423-	10654681001	Water	05/24/2023 10:45:00	06/14/2023 14:17:00	06/19/2023 15:15:00	890545	1633 W	EPA 1633 DRA
15	FA-EB-01-052423-	10654681001	Water	05/24/2023 10:45:00	06/14/2023 14:17:00	06/19/2023 15:15:00	890545	1633 W	EPA 1633 DRA
16	FA-EB-01-052423-	10654681001	Water	05/24/2023 10:45:00	06/14/2023 14:17:00	06/19/2023 15:15:00	890545	1633 W	EPA 1633 DRA
17	FA-EB-01-052423-	10654681001	Water	05/24/2023 10:45:00	06/14/2023 14:17:00	06/19/2023 15:15:00	890545	1633 W	EPA 1633 DRA
18	FA-EB-01-052423-	10654681001	Water	05/24/2023 10:45:00	06/14/2023 14:17:00	06/19/2023 15:15:00	890545	1633 W	EPA 1633 DRA
19	FA-EB-01-052423-	10654681001	Water	05/24/2023 10:45:00	06/14/2023 14:17:00	06/19/2023 15:15:00	890545	1633 W	EPA 1633 DRA
20	FA-EB-01-052423-	10654681001	Water	05/24/2023 10:45:00	06/14/2023 14:17:00	06/19/2023 15:15:00	890545	1633 W	EPA 1633 DRA
21	FA-EB-01-052423-	10654681001	Water	05/24/2023 10:45:00	06/14/2023 14:17:00	06/19/2023 15:15:00	890545	1633 W	EPA 1633 DRA
22	FA-EB-01-052423-	10654681001	Water	05/24/2023 10:45:00	06/14/2023 14:17:00	06/19/2023 15:15:00	890545	1633 W	EPA 1633 DRA
23	FA-EB-01-052423-	10654681001	Water	05/24/2023 10:45:00	06/14/2023 14:17:00	06/19/2023 15:15:00	890545	1633 W	EPA 1633 DRA
24	FA-EB-01-052423-	10654681001	Water	05/24/2023 10:45:00	06/14/2023 14:17:00	06/19/2023 15:15:00	890545	1633 W	EPA 1633 DRA
25	FA-EB-01-052423-	10654681001	Water	05/24/2023 10:45:00	06/14/2023 14:17:00	06/19/2023 15:15:00	890545	1633 W	EPA 1633 DRA
26	FA-EB-01-052423-	10654681001	Water	05/24/2023 10:45:00	06/14/2023 14:17:00	06/19/2023 15:15:00	890545	1633 W	EPA 1633 DRA

	A	B	C	D	E	F	G	H	I
1	SAMPLE_NO	AXYS_ID	ANALYSIS_DATE	ANALYSIS	COMPOUND	CAS_NO	IUPAC_NO	COELUTIONS	LAB_FLAG
2	FA-FB-01-030123-S	L38925-1	16-May-23 01:29:51	FC_LC	PFBA	45048-62-2			U
3	FA-FB-01-030123-S	L38925-1	16-May-23 01:29:51	FC_LC	PFPeA	45167-47-3			U
4	FA-FB-01-030123-S	L38925-1	16-May-23 01:29:51	FC_LC	PFHxA	92612-52-7			U
5	FA-FB-01-030123-S	L38925-1	16-May-23 01:29:51	FC_LC	PFHpA	120885-29-2			U
6	FA-FB-01-030123-S	L38925-1	16-May-23 01:29:51	FC_LC	PFOA	45285-51-6			U
7	FA-FB-01-030123-S	L38925-1	16-May-23 01:29:51	FC_LC	PFNA	72007-68-2			U
8	FA-FB-01-030123-S	L38925-1	16-May-23 01:29:51	FC_LC	PFDA	73829-36-4			U
9	FA-FB-01-030123-S	L38925-1	16-May-23 01:29:51	FC_LC	PFUnA	196859-54-8			U
10	FA-FB-01-030123-S	L38925-1	16-May-23 01:29:51	FC_LC	PFDoA	171978-95-3			U
11	FA-FB-01-030123-S	L38925-1	16-May-23 01:29:51	FC_LC	PFTrDA	862374-87-6			U
12	FA-FB-01-030123-S	L38925-1	16-May-23 01:29:51	FC_LC	PFTeDA	365971-87-5			U
13	FA-FB-01-030123-S	L38925-1	16-May-23 01:29:51	FC_LC	PFBS	45187-15-3			U
14	FA-FB-01-030123-S	L38925-1	16-May-23 01:29:51	FC_LC	PFPeS	175905-36-9			U
15	FA-FB-01-030123-S	L38925-1	16-May-23 01:29:51	FC_LC	PFHxS	108427-53-8			U
16	FA-FB-01-030123-S	L38925-1	16-May-23 01:29:51	FC_LC	PFHpS	146689-46-5			U
17	FA-FB-01-030123-S	L38925-1	16-May-23 01:29:51	FC_LC	PFOS	45298-90-6			U
18	FA-FB-01-030123-S	L38925-1	16-May-23 01:29:51	FC_LC	PFNS	474511-07-4			U
19	FA-FB-01-030123-S	L38925-1	16-May-23 01:29:51	FC_LC	PFDS	126105-34-8			U
20	FA-FB-01-030123-S	L38925-1	16-May-23 01:29:51	FC_LC	PFDoS	343629-43-6			U
21	FA-FB-01-030123-S	L38925-1	16-May-23 01:29:51	FC_LC	4:2 FTS	414911-30-1			U
22	FA-FB-01-030123-S	L38925-1	16-May-23 01:29:51	FC_LC	6:2 FTS	425670-75-3			U
23	FA-FB-01-030123-S	L38925-1	16-May-23 01:29:51	FC_LC	8:2 FTS	481071-78-7			U

Fly Ash And Water Results

Results

- Process Water—Detections all well below MN drinking water guidance values, at or below EPA MCLs
- Fly Ash concentrations were consistently at all facilities low:
  - 0 to 2 analytes detected;
  - Concentrations < 1 ng/g;   below MN residential soil reference values; less than or consistent with ambient background soil concentrations
- Suggests near complete destruction of PFAS in RDF
- Indicates that RDF variability did not affect Fly Ash emissions
- Suggests that emission factors measured for MN 1 could be applied to other facilities

Challenges

- Method revisions and incomplete validation
- Delays - Availability of certified “PFAS-Free” sample bottles and containers
- TAT – 3-6 months
- Hold times at lab
- Lab matrix spikes and surrogate recoveries

SAP Implementation – Lead Up to Stack Testing

- Plant operational data
  - Combustion temperatures
  - Residence time
  - Stack temperatures
- Estimated PFAS concentration in RDF
- OTM-45 validation testing
- PFAS specific stack testing standard operating procedure

Do Not Distribute Beyond USWAG

GRADIENT

Fuel Characterization Study and Estimates of PFAS Inputs

- Critical input for estimates of Destruction and Removal Efficiency (%DRE)
- Literature values are underestimates due to reliance on extractable targeted PFAS analyses
- Microwave popcorn bag example shows how poorly extractable target PFAS compares to total organic fluorine
- MN 1 estimate based on Fuel Characterization study and updated literature values for consumer products and compostable materials is still an underestimate of total PFAS
- Incineration is more efficient than extraction

Table 2.1 Estimate of PFAS in MSW

Source	Analytes	PFAS in MSW Prior to Incineration (g PFAS/US ton MSW)
Carpet Fibers in MSW (SWANA, 2021)	PFOA	0.001 to 0.004
Coventry Landfill Estimate (Sanborn Head, 2019)	PFAS	0.01
Kremen (2020) Estimate	PFAS	0.009
Estimates for 1 microwave popcorn bag per ton MSW based on Schultes et al. (2019)	TOF	0.004 to 0.016
	TOF as PFHxA	0.006 to 0.023
	PFAS (extractable)	0.00003 to 0.0026
MN 1 Estimate	PFAS	0.044 to 0.28

Notes:
MSW = Municipal Solid Waste; PFAS = Per- and Polyfluoroalkyl Substances; PFHxA = Perfluorohexanoic Acid; PFOA = Perfluorooctanoic Acid; TOF = Total Organic Fluorine.
Schultes *et al*. (2019) report the concentrations of total fluorine (TF) and total targeted PFAS in microwave popcorn bag samples to be 3.14 to 13.06 ug TF/cm2 (analyzed by combustion ion chromatography) and 0.02 to 2.22 ug targeted extractable PFAS/cm2. The surface area of a microwave popcorn bag is about 1,350 cm2/bag. In 2018, approximately 257,460,000 single use microwave popcorn bags were sold in the United States (Reilly, 2018) and approximately 292,400,000 US tons of MSW was generated (US EPA, 2023). These number yield an estimate of approximately 0.9 microwave popcorn bags per US ton of MSW. That number would suggest the there is 0.004 to 0.016 g TF per US ton of MSW from microwave popcorn bags alone. Assuming that the vast majority of that TF is in the form of, or will eventually breakdown to PFHxA,1 which contains 11 fluorine atoms per molecule, then the "total PFAS" present would be 0.006 to 0.023 g/US ton MSW

OTM-45 Community Validation

- OTM-45 Rev.0 released January 2021, Rev.1 released July 2024
- Sampling train designed to capture particulate and semi-volatile PFAS
- Analysis modeled after EPA Methods; 49 analytes C4 or larger; LC/MS/MS; uses pre-sampling, pre-extraction, and pre-analysis isotopes

Issues discovered during validation sampling

- PFBA Interferences on XAD-2 resin cartridges
- Blank detections
- Poor standard recoveries from XAD-2 for some analytes

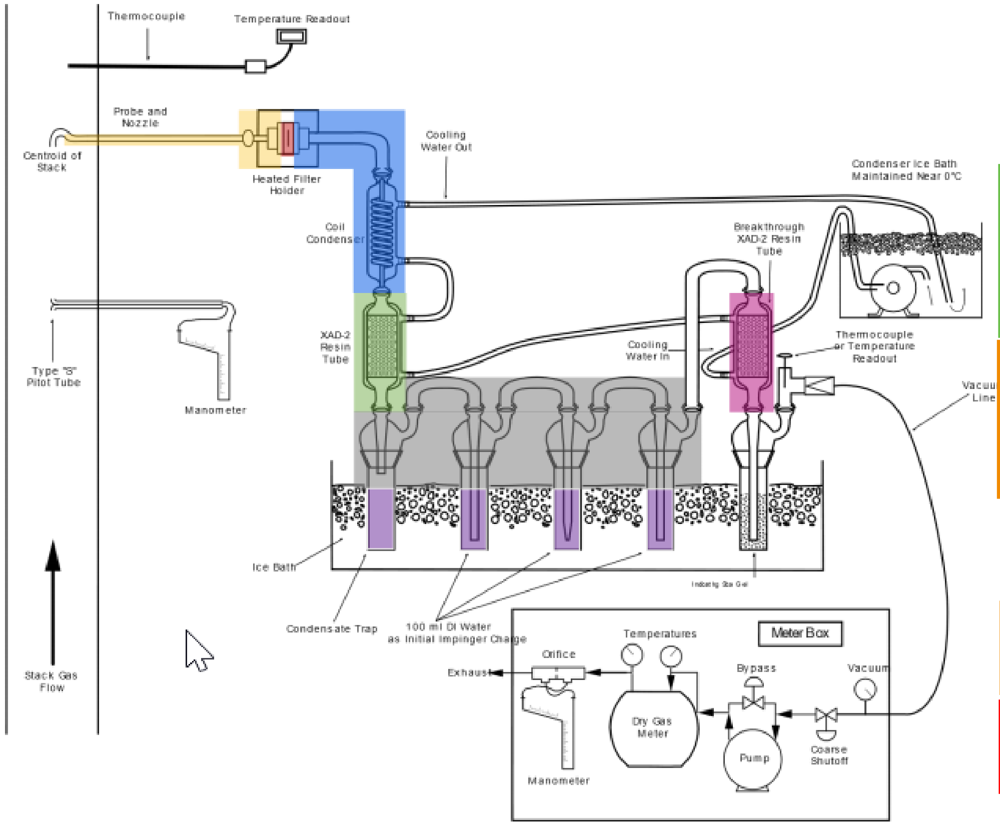


Figure OTM-45-1. Sampling Train

OTM 45 Visual Container Guide

- 1: #1 Filter; #2 Front Half Rinse
- 2: #3 XAD-2; #4 Back half Rinse
- 3: #5 Condensate and Impinger Water
- 2: #6 Impinger Rinse
- 4: #7 Breakthrough XAD-2

PFBA Interferences and False Positives

PFBA Concentrations in XAD-2 Resin Samples (ng/Sample)

Sample Name	Initial [PFBA]	Updated [PFBA]
XAD-2 Resin Blank	ND	ND
Field Proof Blank Cont. 3,4,6 (Primary XAD-2)	44.7	ND
Field Proof Blank Cont. 7 (Secondary XAD-2)	39.7	ND
Field Train Blank Cont. 3,4,6 (Primary XAD-2)	110	ND
Field Train Blank Cont. 7 (Secondary XAD-2)	53.7	ND
Ambient Train Cont. 3,4,6 (Primary XAD-2)	17.4	17.4
Ambient Train Cont. 7 (Secondary XAD-2)	51.2	ND
Sealed XAD-2 Cartridge Trip Blank (Aug 2022)	64	ND

- MPCA (2022) indicated the PFBA was the highest concentration PFAS in Ambient Air
- Initial concerns for Ambient Air contamination in foil sealed cartridges
- Glass sealed cartridge Trip Blank led to re-examination of lab reports and lab data

Blank Detections

OTM-45 method requires multiple blanks for Quality Control:

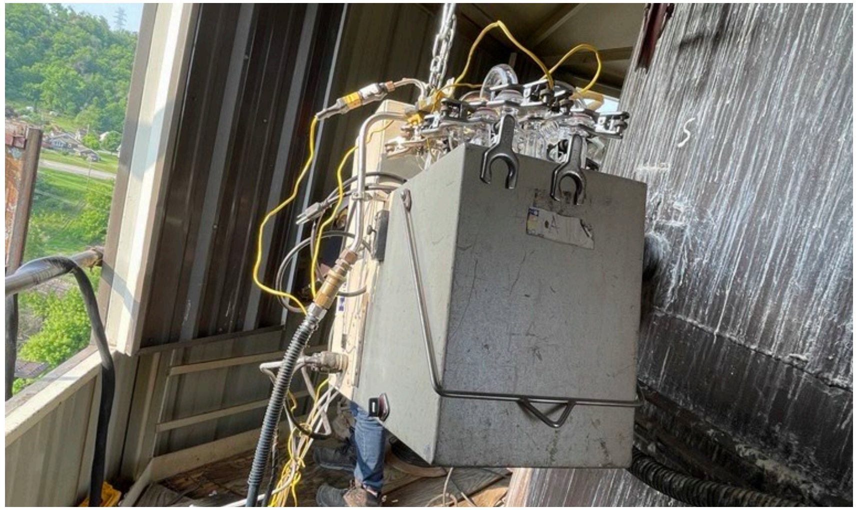
- Laboratory: XAD-2 Batch, Filter Batch, Laboratory Sample Media Blanks, Laboratory Fortified Media Blank
- Sampler: Train Blank, Field Sampling Media, Sample Train Proof Blank, ~~Sample Train Field Blank~~

Issues Identified

- PFOA, PFHxA and PFOS on XAD-2 fractions of Train Proof Blank and Field blank
- PFBA in DI water carried through to every impinger samples

Recommendations

- Take all possible steps to eliminate contamination: new , clean glassware; Clean Hands/Dirty Hands techniques; Certified PFAS-Free materials
- Qualify Samples if
  - Media blanks are >3x the MDL
  - Train Proof or Field Blanks are >10% of sample concentrations.
- Evaluate effects on detection limits and emission estimates

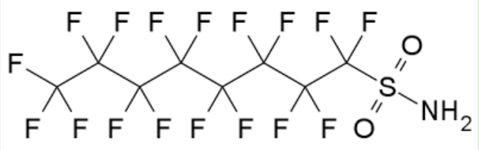


Poor Isotope Recoveries from Solids for FOSA derivatives and long-chain PFCAs

Isotope Dilution method:

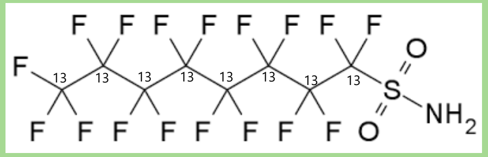
- Samples spiked with isotopic standard prior to extraction (EIS).
- Analytes a quantified based on ratio with isotope standard
- EIS recoveries:
  - 25 to 150% required
  - <25% generally acceptable if signal-to-noise ratio is >10:1
  - <10% and/or signal to noise ratio may result in **rejected data** and require re-analysis
- Poor recoveries EIS standards for **FOSA derivatives and long chain PFCAs (≥C12)** were identified for some Fly Ash samples and XAD-2 Samples
- Issue also recognized during Method 1633 multi-lab validation for solid matrices
- Re-analysis not always an option
- If this issue is confirmed by other stack testers, the stack testing community and regulators may need to consider whether this method can be reliably used to measure emissions for these

Analyte [Mol wt. 499]



Perfluorooctanesulfonamide (FOSA)

Extracted Internal Standard [Mol wt. 507]



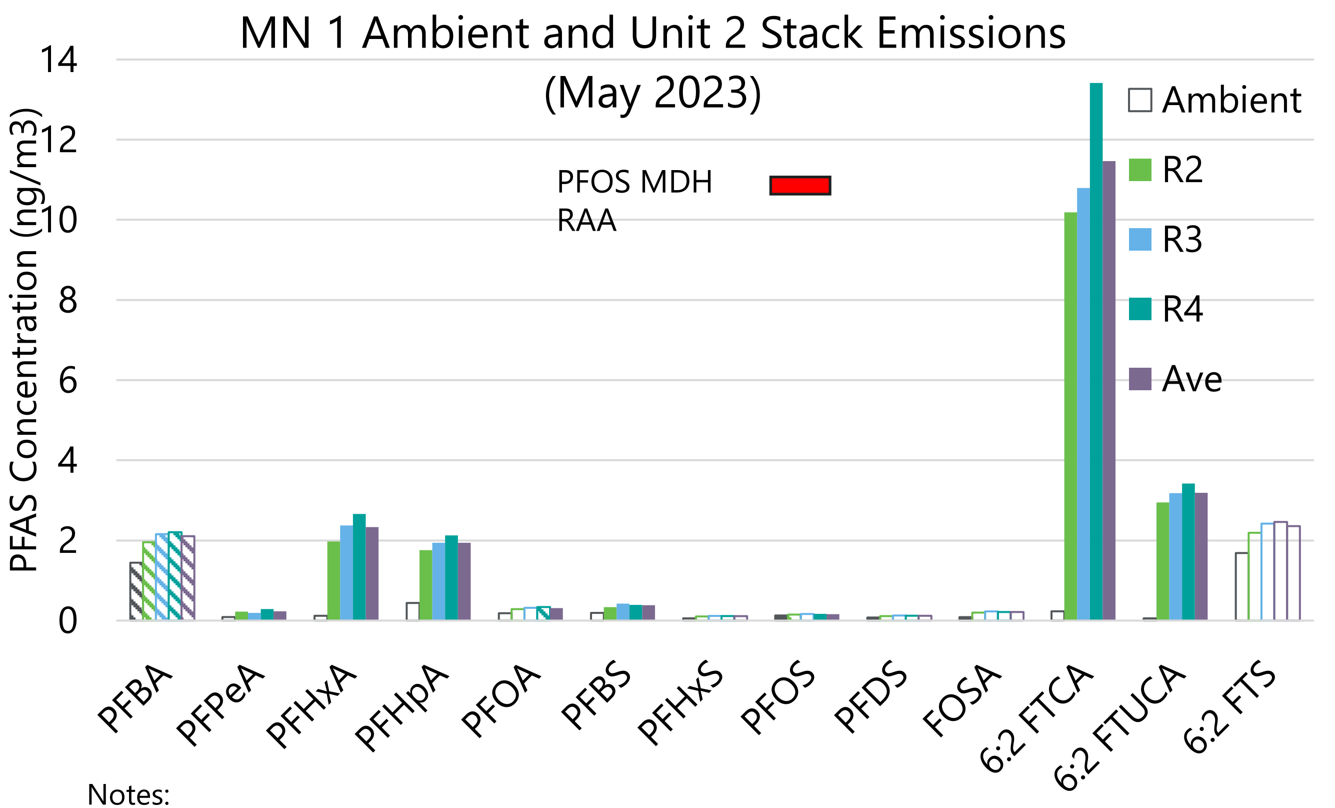
Perfluoro-1-[$^{13}C_8$]octanesulfonamide

Data Quality Recommendations for OTM-45 Testing

- Do not skimp on the blank collection
- Request the level 4 reports and invest in independent data validation—Interferences and false positives are real possibilities
- Evaluate whether problematic analytes (FOSA derivatives and long chain PCFAs) are critical to your program.

Results of May 2023 Ambient Air and MN 1 Unit 2 Stack Test

- Concentrations of all analytes with MDH Inhalation Risk Assessment Advice values, are at least 100-fold below criteria indicating that chronic exposure to these concentrations are likely to pose little or no risk the human health
- Minimal impact from FOSA in process water
- PFHxA and PFHpA were primarily detected in Front Half samples consistent with Fly Ash detections
- Ambient Air Concentrations were low
- Detected analytes consistent with consumer product uses.



Notes:
Detects = filled bars; Non-detects = unfilled bars; Blanks impacted = striped bars; Only analytes with detects are shown or MDH RAA values; Non-detects are include at the detection limit. Blank impact values are shown at reported concentration.
MDH RAA values: PFBA = 10,000 ng/m^3; PFHxA = 500 ng/m^3; PFOA = 63 ng/m^3; PFBS = 300 ng/m^3; PFHxS = 34 ng/m^3; PFOS = 11 ng/m^3.
PFAS (9) = nine compounds included in the Minnesota Pollution Control Agency (MPCA) PFAS Monitoring Plan (PFOA, PFOS, PFBA, PFHxS, PFHxA, HFPA-DA, PFNA, and PFDA;

Estimates of PFAS Emission Factors (g/US ton MSW) and Annual Emissions

MN 1 Emission Factors

$$\left(\frac{ng\ analyte}{m^3}\right)\left(\frac{m^3}{dscf}\right)\left(\frac{min}{hr}\right)\left(\frac{g}{ng}\right)\left(\frac{dscf}{min}\right)\left(\frac{hr}{US\ ton\ MSW}\right)=\frac{g\ analyte}{US\ ton\ MSW}$$

Average amount of analyte (ng) and average sample volume (m^3) from the 3 Runs of the stack test

Gas flow rate during the 3 Runs of the stack test

Average rate of MSW consumption during the 3 Runs of the stack test

MN 1 Annual Emissions

$$\left(\frac{g\ analyte}{US\ ton\ MSW}\right)\left(\frac{US\ ton\ MSW}{yr}\right)=\frac{g\ analyte}{yr}$$

Analyte	Ave (ng/m^3)	Qualifier	Emissions Factor (g/US ton MSW)	Emissions Estimates (g/yr) MN 1: 210,000 US ton MSW/yr	MN 1: 230,000 US ton MSW/yr	MN 2: 170,000 US ton MSW/yr	MN 2: 190,000 US ton MSW/yr
PFBA	2.11	**ADL**	1.49E-05	3.12	3.42	2.53	2.83
PFPeA	0.23	**ADL**	1.64E-06	0.34	0.38	0.28	0.31
PFHxA	2.34	**ADL**	1.64E-05	3.45	3.78	2.80	3.12
PFHpA	1.94	**ADL**	1.37E-05	2.88	3.16	2.33	2.61
PFOA	0.31	**DDL**	2.22E-06	0.47	0.51	0.38	0.42
PFNA	0.21	BDL	1.51E-06	0.32	0.35	0.26	0.29
PFDA	0.13	BDL	9.37E-07	0.20	0.22	0.16	0.18
PFBS	0.39	**ADL**	2.72E-06	0.57	0.63	0.46	0.52
PFHxS	0.11	BDL	7.82E-07	0.16	0.18	0.13	0.15
PFOS	0.16	**DDL**	1.13E-06	0.24	0.26	0.19	0.22
HFPO-DA	2.97	BDL	2.09E-05	4.40	4.82	3.56	3.98
6:2 FTUCA	3.19	**ADL**	2.25E-05	4.72	5.17	3.82	4.27
6:2 FTCA	11.46	**ADL**	8.08E-05	16.97	18.58	13.73	15.35
Total PFAS [ADL&DLL]	22.13		1.56E-04	32.8	35.9	26.5	29.6
Total PFAS [ADL,DLL& BDL]	39.03		2.75E-04	57.8	63.4	46.8	52.3
Total PFAS (9) [ADL&DLL]	5.30		3.74E-05	7.9	8.6	6.4	7.1
Total PFAS (9) [ADL,DLL& BDL]	8.72		6.16E-05	12.9	14.2	10.5	11.7

Notes:

Using OTM-45 rev.1 reporting guidance. BDL = Below Detection Limit; DLL = Detection Limit Limited; ADL = Above Detection Limit; Non-detects = MDL; Blank impacted results included at the reported value; PFAS (9) = nine compounds included in the Minnesota Pollution Control Agency (MPCA) PFAS Monitoring Plan (PFOA, PFOS, PFBA, PFHxS, PFHxA, HFPA-DA, PFNA, and

Estimated Destruction Efficiency

- DRE (%) = ((Input-Output)/Input) x 100
- The calculated DRE ranges from 99.645% and 99.987%
- Underestimate due to uncertainties associated with Input terms

Factor	Description	Value	Unit
$\text{Input}_{\text{average}}$	Estimated Amount of PFAS per US ton of MSW (fuel), based on average concentration reported in literature	44	mg PFAS/US ton MSW
$\text{Input}_{\text{high}}$	Estimated Amount of PFAS per US ton of MSW (fuel), based on high concentrations reported in literature	280	mg PFAS/US ton MSW
Output	PFAS Emissions Factor (amount of PFAS emitted per US ton MSW incinerated) [ADL&DLL]	0.156	mg PFAS/US ton MSW
Output	PFAS (9) Emissions Factor (amount of PFAS emitted per US ton MSW incinerated) blanks included [ADL&DLL]	0.037	mg PFAS (9)/US ton MSW

Notes:
MSW = Municipal Solid Waste; PFAS = Per- and Polyfluoroalkyl Substances

Putting Emission Estimates in Context: Other Emission Estimates

Other Waste Incinerators

- MN 1: 7.9 to 8.6 g/yr PFAS (9); 30 to 35 g/yr Total PFAS
- Swedish WTE Facility (Björklund *et al.*, 2023) : 4 to 5 g/yr Total PFAS
- Hazardous waste incinerator burning AFFF(EA and Montrose, 2021): 10 g/yr Total PFAS

  DRE >99.999% for spiked AFFF

Industrial Releases

- Toxic Release Inventory (2021) for Midwest[a] Regions reports:
  - Stack Releases = 508 g/yr PFOA;
  - Fugitive Releases = 1,140 g/yr PFOA.
- Estimates are likely to increase as more PFAS analytes are added to TRI list and with removal of the de minimis exemption

(a) Midwest region includes Wisconsin, Minnesota, Michigan, Ohio, Indiana, Illinois, Iowa, North Dakota, and South Dakota. Of these states only companies in Wisconsin, Minnesota, Michigan, Ohio and Indiana reported PFAS emissions in the 2021 TRI.

Putting Emission Estimates in Context: Precipitation

- WTE plant air emissions are 10,000 to 100,000-fold lower than estimated wet deposition

Source	Location	Time Frame	Analytes	Wet deposition Yearly Flux (ng/m^2/yr)	Wet deposition Est.Yearly Flux in MN (g/yr)
This Report	MN 1+MN 2				14.2 to 15.7 PFAS (9) 59.3 to 65.5 Total PFAS
Gewurtz et al. (2019)	3 locations on the Great Lakes	monthly from 2006 to 2018[a]	PFAAs		528,000 PFAS (9)
Pfotenhauer et al. (2022)	8 National Trends Network sites in Wisconsin	weekly during summer of 2022[b]	34 PFAS	Spooner: 1,175 PFAS (9) Marinette: 2,690 PFAS (9)	257,000 to 589,000 PFAS (9)
				Spooner: 1,890 total PFAS Marinette: 4,320 total PFAS	413,000 to 944,000 total PFAS

(a) Gewurtz *et al*. (2019) observed a downward trend in many PFAS prior to 2010, therefore only data from 2010 to 2018 were used to calculate the median concentration in precipitation from the 3 locations (n = 240). The median concentrations were 0.35 ng/L, PFOA and 0.86 ng/L PFOS. The sum of the median concentrations for the PFAS (9), excluding HFPO-DA which was not analyzed in this study, was 3.31 ng/L. The State of Minnesota receives approximately 729 mm of precipitation per year over an area of 218,587 km^2 (does not include Lake Superior) for a volume of 1.59 x 10^{14} L precipitation per year. This would contribute 56,300 g/yr PFOA (0.35 ng/L*1.59 x 10^{14} L /10^9 ng/g), 137,000 g/yr PFOS, and 528,000 g/yr PFAS (9) to the state, respectively.

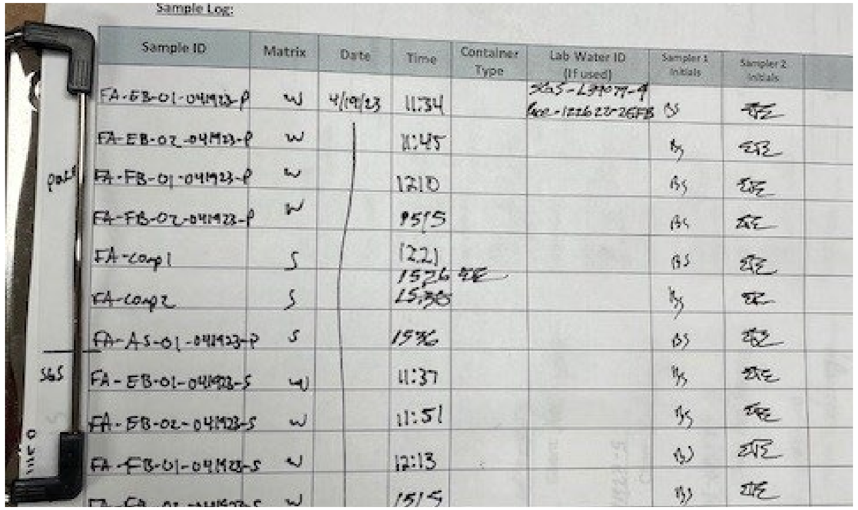
(b) Pfotenhauer *et al*. (2022) assumes that the data collected from April to November 2022 can represent the whole year and may be an under or over estimate if there is significant seasonality in PFAS wet deposition. Some differences between locations were also observed during the study. Marinette had higher concentrations of HFPO-DA and fluorotelomers compared to the other sites which may be relat

Conclusions

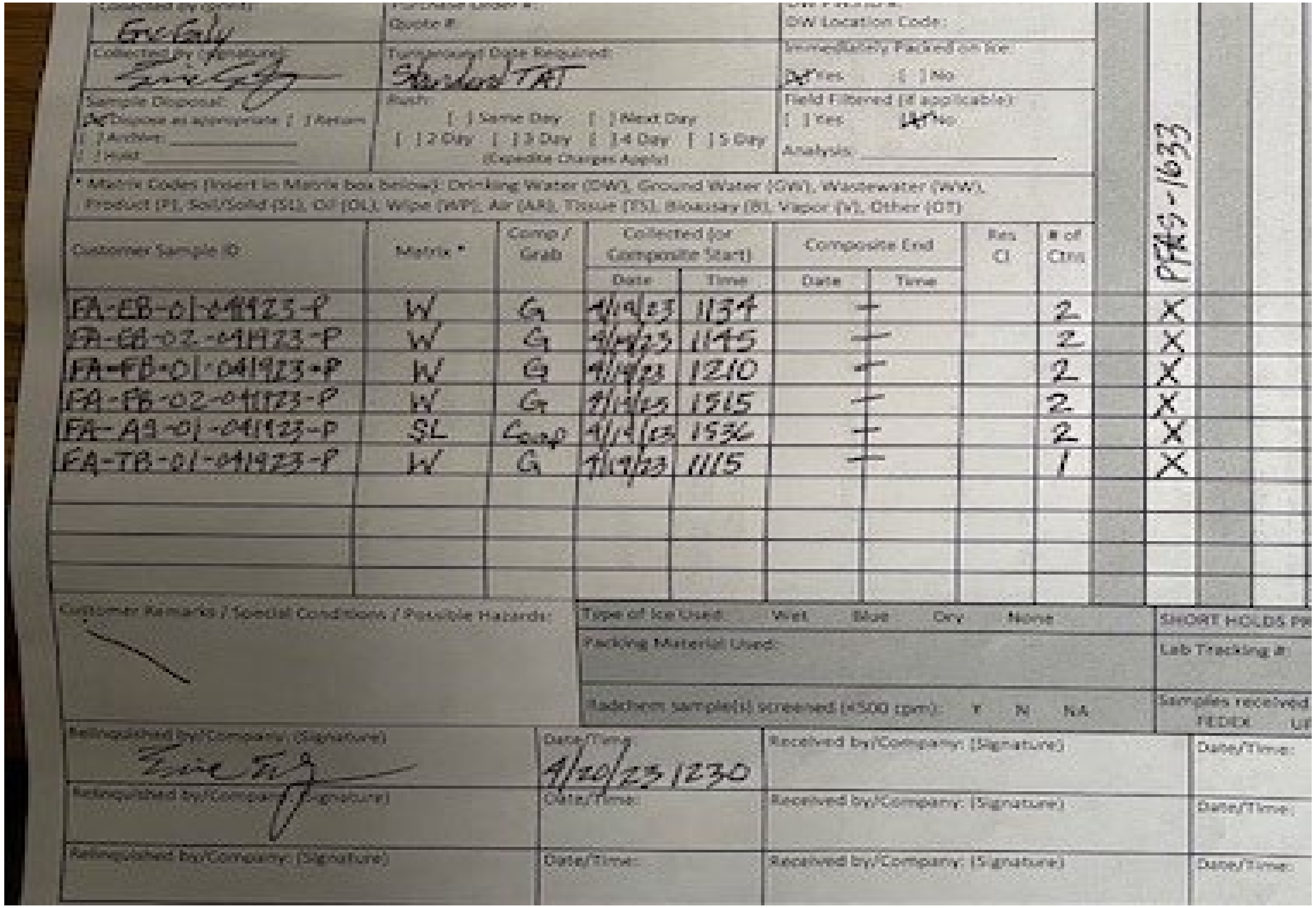
- The first measurement of PFAS stack emissions from a Waste-to-Energy facility in the US
  - PFAS Stack emission testing (OTM-45) is difficult to implement at low concentration sources, but adherence to a PFAS specific SOP can yield reliable emissions estimates.
  - Projects benefit from attention to data quality assurance and control processes during this period of continued method development and validation. Interferences, false positives and contamination are all legitimate concerns
  - Waste Incineration clearly results in the destruction of PFAS in MSW. Conservative estimates of DRE range from 99.645% and 99.987%
  - Measurements of Stack gas concentrations are well below Minnesota Dept. of Health RAA and are unlikely to be a risk to human health
  - Total Emissions of PFAS are consistent with available literature and low relative to other atmospheric sources
  - Emission of PFAS from MSW incineration is expected to decrease as increased scrutiny of PFAS use in consumer products leads to less PFAS in MSW.

Fly Ash Sampling

- Completed field sampling logs as sampling progressed during the day
- Collected and analyzed quality control/assurance samples for all media
  - Equipment rinse (pails and scoops)
  - Field blanks collected at each sample location
  - Duplicate samples
  - Trip blanks (“PFAS-free water” from the laboratories)



Fly Ash Sampling



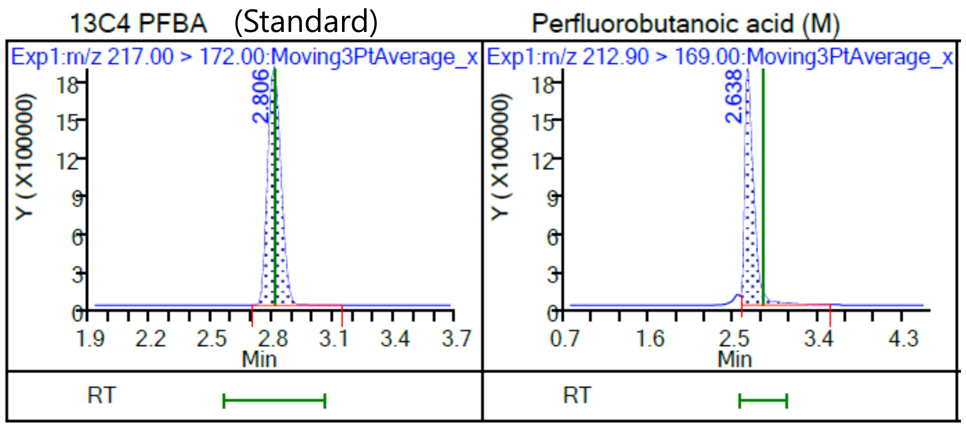
Customer Sample ID	Matrix *	Comp / Grab	Collected (or Composite Start) Date	Collected (or Composite Start) Time	Composite End Date	Composite End Time	Res Cl	# of Ctns	PFAS-1633
FA-EB-01-041923-P	W	G	4/19/23	1134	—			2	X
FA-EB-02-041923-P	W	G	4/19/23	1145	—			2	X
FA-FB-01-041923-P	W	G	4/19/23	1210	—			2	X
FA-FB-02-041923-P	W	G	4/19/23	1515	—			2	X
FA-AS-01-041923-P	SL	Comp	4/19/23	1536	—			2	X
FA-TB-01-041923-P	W	G	4/19/23	1115	—			1	X

- In some cases, to collect one fly ash sample, six samples were sent in for analysis

Air Sampling – Chromatograms for PFBA (from Level 4 lab report, Rev. 0)

Ambient Train Cont. 7

Secondary XAD-2

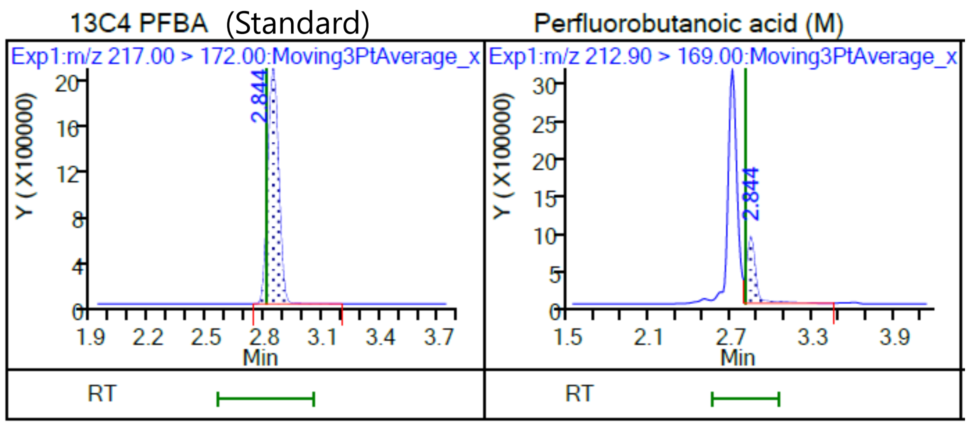


p. 733

- Standard (left) shows that PFBA elutes at ~2.8 min (green vertical line)
- Integration for PFBA in sample (right) **incorrectly includes** earlier peak ~2.6, which is due to the interferent
- RT 0.168 min shift > 0.10 min RT criteria

Ambient Train Cont. 3,4,6

Primary XAD-2



p. 664

- Standard (left) shows that PFBA elutes at ~2.8 min (green vertical line)
- Integration for PFBA in sample (right) **correctly excludes** earlier peak ~2.6, which is due to the interferent