Study of the Fate of PFAS through Resource Recovery Facilities

Barr Project No. 23/56-1057.00

Prepared for
Minnesota Resource Recovery Association (MRRA)

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Abbreviations

C&D	construction and demolition
HERC	Hennepin Energy Recovery Center
HFPO-DA	hexafluoropropylene oxide dimer acid
MDH	Minnesota Department of Health
MPCA	Minnesota Pollution Control Agency
MRF	material recovery facilty
MRRA	Minnesota Resource Recovery Association
MSW	municipal solid waste
NMeFOSA	N-methylperfluorooctane sulfonamide
PAC	powder activated carbon
PFAS	per- and poly-fluorinated alkyl substances
PFBA	perfluorobutanoic acid
PFBS	perfluorobutanesulfonic acid
PFDA	perfluorodecanoic acid
PFHxA	perfluorohexanoic acid
PFHsS	perfluorohexanesulfonic acid
PFNA	perfluorononanoic acid
PFOA	perfluorooctanoic acid
PFOS	perfluorooctanesulfonic acid
RAA	Risk Assessment Advice
RDF	refuse-derived fuel

Executive Summary

The Minnesota Resource Recovery Association (MRRA) commissioned a study of per- and poly-fluorinated alkyl substances (PFAS) at Minnesota resource recovery facilities. Barr Engineering Co. (Barr) was hired as a third party to conduct PFAS air emission measurements at three of the MRRA members' facilities, analyze bottom and fly ash samples, and review literature data on PFAS composition of municipal solid waste (MSW) to better understand the fate of PFAS at resource recovery facilities. This project was initiated in response to a request by the Minnesota Pollution Control Agency (MPCA) to provide PFAS air emission data to help the state better understand PFAS emissions from all sources in Minnesota, as part of the MPCA PFAS Monitoring Plan. MRRA expanded this request to include a more comprehensive view of the fate of PFAS by adding ash sampling and estimating the PFAS content of the inlet stream (the MSW).

There are six member companies in the MRRA making up a total of seven resource recovery facilities in Minnesota. Three of the five public resource recovery facilities were chosen from the MRRA member facilities to represent public facilities with a diversity of operating units, pollution controls, size, and sources of solid municipal waste. All the facilities are waste-to-energy operations.

Barr collected PFAS air emission data utilizing US Environmental Protection Agency (EPA) Other Test Method 45 Revision 1 (OTM-45). This was the one test method at the start of this study that was available for characterizing air emissions of 49 PFAS compounds.

The PFAS air emission factors from the three facilities averaged 144 micrograms (ug) of PFAS per ton of MSW. The air emission results are consistent between facilities, ranging from 141 to 147 ug of PFAS/ton MSW. The Minnesota Department of Health has developed inhalation Risk Assessment Advice (RAA) values[1] for six PFAS compounds. When comparing the PFAS concentrations in the flue gas emissions to the RAA values, concentrations for five of the compounds are 10 to 1,000 times less than the MDH RAA values (in ng/m^3), even with no correction for further dispersion and dilution in the atmosphere that would occur after the emissions leave the stack and before they could be exposed to a receptor. For one compound (PFOA) at two facilities, the in-stack concentrations did exceed the RAA values; however, concentrations modeled at the facility fence lines using facility stack heights, test emission rates, and the conservative default dispersion factors in the MPCA's air emissions Risk Assessment Screening Spreadsheet (RASS) were 10 to 100 times below the RAAs.

Results of the measured PFAS air emissions, analysis of the bottom ash and fly ash samples, and published PFAS composition of MSW loading into the resource recovery facilities were used to develop a percent destruction and removal efficiency (DRE, %). The DREs of PFAS for the three resource recovery facilities ranged from 99.6% to 99.97% of total measurable PFAS.

[1] RRA values are one type of MDH "guidance value" that is a concentration that, based on best available science, could be encountered for a specific length of exposure duration and not be likely to pose risk to human health. More detail at https://www.health.state.mn.us/communities/environment/risk/guidance/air/table.html

1 Introduction

Per- and poly-fluorinated alkyl substances (PFAS) are a family of fluorinated chemicals that have been used across numerous industries and incorporated into countless products and building materials for the last 70 years.[2] Common household products and building materials that contain PFAS include non-stick cookware, food packaging, cleaning products, personal care products, adhesives, sealants, and other coatings. As long as PFAS-containing products and building materials remain in use, they will be processed and disposed of at landfills and resource recovery facilities.

The presence of PFAS in various waste streams entering the waste management system has been extensively documented. Studies of PFAS in the waste management system have largely focused on municipal solid waste (MSW) landfills, wastewater treatment plants, and land application of biosolids, largely due to the data availability of those media. Toaymet et al.[3] compiled PFAS loading data from various landfill types, including MSW, MSW ash, construction and demolition (C&D), and hazardous waste landfills. Resource recovery facilities include any waste management process that reclaims materials and/or energy from waste. Although resource recovery facilities have not typically been the subject of those studies, the waste characterization for MSW would be similar to what enters a resource recovery facility.

Many of the unique chemical properties that contributed to the widespread use of PFAS also contribute to the persistence, solubility, and overall mobility of PFAS in the environment.[4] Advances in analytical measurement techniques over the last 10+ years have allowed for the detection and measurement of PFAS concentrations at increasingly lower levels. This has resulted in an increased awareness of the widespread presence of PFAS on a global level and a continuing evaluation of the potential effects of PFAS on human health and the environment.[5] In Minnesota, the Minnesota Pollution Control Agency (MPCA) has documented the presence and "ambient background" of certain PFAS in groundwater in remote areas of Minnesota that have been introduced by general anthropogenic activity in addition to widespread and variable presence of PFAS concentrations in urban areas across the state.[6]

The MPCA issued its PFAS Blueprint in February 2021[7], which included, among other things, an emphasis on understanding municipal waste combustor (also known as and referred to in this report as resource recovery facilities) stack emission contribution to environmental PFAS. The MPCA followed with the PFAS Monitoring Plan in March 2022.[8] The PFAS Monitoring Plan specifically sought certain data from facilities with air permits, including stack emission data.

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[2] Interstate Technology & Regulatory Council (ITRC), 2020. *History and Use of Per- and Polyfluoroalkyl Substances (PFAS) found in the Environment.* August 2020.

[3] Tolaymat, T., Robey, N., Krause, M., Larson, J., Weitz, K., Parvathikar, S., Phelps, L., Linak, W., Burden, S., Speth, T., Krug, J., 2023. *A critical review of perfluoroalkyl and polyfluoroalkyl substances (PFAS) landfill disposal in the United States.* Science of the Total Environment, Vol. 905. December 2023.

[4] ITRC, 2023. *PFAS Technical/Regulatory Guidance Document.* September 2023. Washington, D.C.: Interstate Technology & Regulatory Council, PFAS Team.

[5] Cousins, I., Johansson, J., Salter, M., Sha, B., Scheringer, M., 2022. *Outside the Safe Operating Space of a New Planetary Boundary for Per- and Polyfluoroalkyl Substances (PFAS).* Environ. Sci. Technol. 2022, 56, 16, 11172-11179.

[6] Minnesota Pollution Control Agency (MPCA), 2024a. *PFAS ambient background concentrations.* March 2024 and MPCA 2024b. *PFAS Monitoring Plan: Initial findings and next steps.* April 2024.

[7] https://www.pca.state.mn.us/sites/default/files/p-gen1-22.pdf

[8] https://www.pca.state.mn.us/sites/default/files/p-gen1-22b.pdf

The Minnesota Resource Recovery Association (MRRA) recognized the need to collect critical stack emission data within the context of the incoming fuel source, MSW. The resource recovery facilities within Minnesota do not create or generate PFAS but receive them within the waste stream (as passive receivers). Thus, MRRA commissioned this Fate of PFAS Study through resource recovery facilities and hired Barr Engineering Co. (Barr) as the third-party to conduct the detailed evaluation and study.

Resource recovery facilities operate to thermally process and recover energy from non-recyclable discarded wastes. Temperatures above 850℃ (1,560℉) can initiate the thermal degradation of PFAS in combustion processes.[9] Resource recovery facilities, which typically operate at or above this temperature, can promote the thermal degradation of PFAS. In Minnesota, these facilities process over 1 million tons per year (approximately one-third of MSW generated in Minnesota) and capture the energy for beneficial reuse. These facilities also make available ferrous metal for recovery, which, if otherwise not thermally processed, would not be recycled. Most of these facilities also have additional pre-processing systems that can remove ferrous metals, aluminum, and, in some cases, cardboard, organics, and plastics. These pre-processing systems are integrated into resource recovery facilities to capture recoverable and recyclable materials and leave combustible, non-recyclable materials for energy recovery.

[9] Weitz K. et al. 2024. *Review of per- and poly-fluoroalkyl treatment in combustion-based thermal waste systems in the United States. Science of The Total Environment* 932: 172658.

2 Facilities and Analytical Methods

There are seven resource recovery facilities in Minnesota. Attachment 1 to this report includes a facility matrix summarizing the facility characteristics. Two MRRA member facilities were tested for PFAS in 2022 and 2203. Air emissions, ash samples, and water samples were tested at the Facility #4; ash samples and water samples were tested at Facility #5. Facility #4 and Facility #5 process refuse-derived fuel (RDF), meaning these facilities use mechanical processes to shred the waste and separate out non-combustible materials (e.g., glass, ferrous and non-ferrous metals) prior to combustion. The results of testing at these facilities are summarized in a March 2024 report.[10]

Three additional MRRA member facilities were selected as part of this study to participate in the field stack tests. The facilities in Minnesota are presented in Table 1 below, and the three selected for testing are noted. The selected test facilities provide the best representation of the variety of design and operation of all facilities and previous testing already performed at Facility #4. All operate at or above the temperature (850º C) that is expected to initiate thermal degradation of PFAS. PFAS stack testing is expensive and insight into the conditions that provide environmental reduction of PFAS can be applied across similar facilities, per Minn. R. 7005.0100, Subpart 10a(c)(2)[11].

Table 1 Minnesota resource recovery facilities

Identifier	County	Number of Combustors	MSW/RDF Loading Rate (ton /year)
Fosston*	Polk	2	25,000
Hennepin Energy Recovery Center (HERC)*	Hennepin	2	365,000
Olmsted	Olmsted	3	120,000
Perham*	Ottertail	2	62,000
Pope-Douglas	Pope-Douglas	2	80,000
Xcel Red Wing	Goodhue	2	220,000
Xcel Wilmarth	Blue Earth	2	170,000

*Tested as part of the study addressed in this report

Barr conducted PFAS air emission measurements, analyzed bottom and fly ash samples, and reviewed literature data on PFAS composition of MSW to better understand the fate of PFAS at resource recovery facilities. This approach allows for a comprehensive view of the fate of PFAS. Sampling events were limited to a day or two at each resource recovery facility. Interpretation of the sampling results is limited to the conditions at the time of sampling. The stack testing used EPA Other Test Method 45 Revision 1 (OTM-45) to analyze for 49 PFAS compounds. Evaluation of the sampled bottom ash and fly ash used modified EPA Method 537 to analyze 40 PFAS compounds. The detailed results of the testing are documented in the reports in Attachments 2 through 4.

10 [redacted]. 2024. *PFAS Air Emissions Technical Report,* [redacted]*, [Facility #4] and [Facility #5],* March 27, 2024.

11 Definition of an emission factor includes: "The commissioner shall develop or approve an emission factor using best engineering judgment and based on…the design and operational similarity between the emission units tested and the emission units to which the emission factor is to be applied."

3 Detectable PFAS Analytes

The three resource recovery facilities were sampled during the last quarter of 2024. At each facility, the exhaust gas was sampled from a single combustor. Table 2 provides a summary of the PFAS analytes in the exhaust gas, bottom ash, and fly ash samples that had a PFAS analyte concentration above the method detection limit[12] (indicated by an "X"). All remaining samples and analytes had PFAS concentrations below the method detection limits.

Table 2 Samples with PFAS analyte concentrations above the method detection limit

Analyte	Facility 1			Facility 3			Facility 2		
	Stack	Bottom Ash	Fly Ash	Stack	Bottom Ash	Fly Ash	Stack	Bottom Ash	Fly Ash
Perfluorobutanoic acid (PFBA)[1]	X			X			X		
Perfluoropentanoic acid (PFPeA)	X			X			X		
Perfluorohexanoic acid (PFHxA)[1]	X		X	X	X		X		X
Perfluoroheptanoic acid (PFHpA)				X					
Perfluorooctanoic acid (PFOA)[1]	X			X	X		X		
Perfluorononanoic acid (PFNA)[1]	X			X			X		
Perfluorodecanoic acid (PFDA)[1]	X								
Perfluoroundecanoic acid (PFUnA)									
Perfluorododecanoic acid (PFDoA)									
Perfluorotridecanoic acid (PFTriA)	X								
Perfluorotetradecanoic acid (PFTeA)									
Perfluorobutanesulfonic acid (PFBS)[1]	X						X	X	
Perfluorohexanesulfonic acid (PFHxS)[1]				X					
Perfluoroheptanesulfonic acid (PFHpS)									
Perfluorooctanesulfonic acid (PFOS)	X			X			X		
Perfluorodecanesulfonic acid (PFDS)									
Perfluorooctanesulfonamide (FOSA)				X					
Perfluoropentanesulfonic acid (PFPeS)	X			X					
Perfluorononanesulfonic acid (PFNS)									
N-methylperfluorooctanesulfonamidoacetic acid (NMeFOSAA)									
N-ethylperfluorooctanesulfonamidoacetic acid (NEtFOSAA)									
1H,1H,2H,2H-Perfluorohexane sulfonic acid (4:2 FTS)									
1H,1H,2H,2H-Perfluorooctane sulfonic acid (6:2 FTS)									
1H,1H,2H,2H-Perfluorodecane sulfonic acid (8:2 FTS)									
Hexafluoropropylene Oxide Dimer Acid (HFPO-DA)[1]				X					

[12] Defined by USEPA as the "minimum measured concentration of a substance that can be reported with 99% confidence that the measured concentration is distinguishable from method blank results".

Analyte	Facility 1			Facility 3			Facility 2		
	Stack	Bottom Ash	Fly Ash	Stack	Bottom Ash	Fly Ash	Stack	Bottom Ash	Fly Ash
9-Chlorohexadecafluoro-3-oxanonane-1-sulfonic acid									
11-Chloroeicosafluoro-3-oxaundecane-1-sulfonic acid									
4,8-Dioxa-3H-perfluorononanoic acid (ADONA)									
1H,1H,2H,2H-Perfluorododecane sulfonic acid (10:2 FTS)									
2-(N-ethylperfluoro-1-octanesulfonamido) ethanol							X		
Perfluoro-n-octadecanoic acid (PFODA)									
2-(N-methylperfluoro-1-octanesulfonamido) ethanol				X			X		
N-methylperfluorooctane sulfonamide (NMeFOSA)				X					
N-ethylperfluorooctane sulfonamide (NEtFOSA)							X		
Perfluoro-n-hexadecanoic acid (PFHxDA)									
Perfluorododecanesulfonic acid (PFDoS)									
Nonafluoro-3,6-dioxaheptanoic acid (NFDHA)									
10:2 Fluorotelomer carboxylic acid									
6:2 Fluorotelomer carboxylic acid									
7:3 Fluorotelomer carboxylic acid								X	
6:2 Fluorotelemer unsaturated acid	X						X		
8:2 Fluorotelemer carboxylic acid									
8:2 Fluorotelemer unsaturated acid									
5:3 Fluorotelomer carboxylic acid							X		
3-Perfluoropropylpropanoic acid									
Perfluoro-3-methoxypropanoic acid (PFMPA)	X			X			X		
Perfluoro-4-methoxybutanoic acid (PFMBA)	X			X			X		
Perfluoro-4-ethylcyclohexanesulfonic acid									
Perfluoro (2-ethoxyethane) sulfonic acid (PFEESA)									

1- Compound has Minnesota Department of Health Risk Assessment Advice value (discussed further in Section 4) or a guidance concentration has either been or is potentially being developed.

Dark shading indicates that analyte was not included in Method 537 used to analyze bottom ash and fly ash.

4 Inhalation Risk Assessment Advice Concentrations

Table 3 provides the observed exhaust gas concentrations for six PFAS analytes for which the Minnesota Department of Health (MDH) has developed inhalation Risk Assessment Advice (RAA) values. RAA values are one type of MDH “guidance value” that is a concentration that, based on best available science, could be encountered for a specific length of exposure duration and not be likely to pose risk to human health." The inhalation RAAs are derived from groundwater health values, scaled to be an air equivalent. In Table 3, the RAA values represent ambient air that might be inhaled and the exhaust gas results are actual measured stack concentrations before any ambient dispersion, cooling or dilution has occurred after leaving the stack. Even though a person would not be exposed to stack exhaust gas directly, the comparison of the observed exhaust gas concentrations are approximately 10 to 100 times below the RAA values for all analytes except PFOA.

Table 3 Comparison of exhaust-gas analyte concentrations to the Minnesota Department of Health inhalation Risk Assessment Advice values

Analyte	MDH RAA (ng/m^3)	Exhaust Gas Concentration (ng/m^3)		
		Facility 1	Facility 3	Facility 2
PFBA	10,000	10.3	3.4	12.5
PFHxA	500	0.5	0.5	2.2
PFOA	0.91	4.0	3.0	0.6
PFBS	300	0.8		0.5
PFHxS	34		0.1	
PFOS	3.5	0.3	0.6	0.3

For one compound (PFOA) at two facilities, the in-stack concentrations did exceed the RAA values; however, concentrations modeled at the facility fence lines using facility stack heights, test emission rates, and the conservative default dispersion factors in the MPCA’s air emissions Risk Assessment Screening Spreadsheet (RASS) were 10 to 100 times below the RAAs.

This suggests little or no inhalation health risks are associated with the emitted six PFAS compounds that have RAA values.

5 Emission Rates

The sum of the individual OTM-45 analyte emission rates for the three sampled resource recovery facilities is provided in Table 4. The total PFAS emission rates for the tested facilities range from 1.82 to 26.8 g PFAS/year for 49 analytes. Emission rates were only calculated for analytes with measured concentrations greater than the method detection limit. Björklund *et al*. (2023) reported an emission rate of 4 g PFAS/year for 18 analytes at a Swedish municipal waste combustor (MWC) that processed about 176,000 tons MSW/year of solid waste that is 60% household waste with recyclables and food waste removed and 40% furniture and C&D waste.[13] Xcel Energy (2024) reported an emission rate of 17.4 g PFAS/year for 49 analytes at its Red Wing Unit 2 which processes about 110,000 ton MSW/year.[14] Thus, the PFAS emission rates for the three MRRA-member resource recovery facilities are consistent with those reported by Björklund *et al*. (2023) and Xcel Energy (2024).

Table 4 Total PFAS emission rates for the three MRRA-member resource recovery facilities

Parameter	Units	Facility 1	Facility 3	Facility 2
Emission Rate	g PFAS/year	1.82	4.37	26.8
MSW Loading	ton MSW/year	12,500	31,000	182,500
Emission Factor	µg PFAS/ton MSW	145	141	147

The listed MSW loading rates are half the total MSW capacities listed in Table 1, because only one of the two combustion units was sampled.

To normalize the total PFAS emission rate to the MSW loading, an emission factor was calculated by dividing the emission rate by the MSW loading rate. As shown in Table 4, the emission factors for the three sampled resource recovery facilities were comparable with values ranging from 141 to 147 µg PFAS/ton MSW and yield an average value of 144 µg PFAS/ton MSW. The emission factor obtained from Björklund *et al*. (2023) was 22.7 µg PFAS/ton MSW and from Xcel Energy (2024) was 145 µg PFAS/ton MSW. While the three sampled resource recovery facilities had emission factors that were about 6 times larger than the Björklund *et al*. (2023) values, they were essentially equal to the value reported for the Xcel Energy facility. The lower value from the Björklund study may be due to a difference in the waste mix processed, the amount of PFAS in the incoming waste, the analytical method and analytes targeted, or other factors.

While the measured PFAS emission factors of the four resource recovery facilities are similar, the relative chemical composition of the emissions varies between facilities. Thus, the applicability of a uniform PFAS emission factor for Minnesota resource recovery facilities should be viewed with caution.

[13] Björklund S. *et al*. 2023. Emission of per- and polyfluoroalkyl substances from a waste-to-energy plant—Occurrence in ashes, treated process water, and first observation in flue gas. *Environmental Science & Technology* 57: 10089-10095.
[14] Xcel Energy. 2024. PFAS Air Emissions Technical Report, Northern States Power Company, Red Wing and Wilmarth Facilities.

6 Bottom Ash and Fly Ash Loading Rates

In addition to being emitted with the exhaust gas, PFAS can also be found in the bottom ash and fly ash generated by resource recovery facilities. Table 2 indicates that five analytes had ash concentrations above the method detection limits. A single bottom ash sample at one facility had a PFBS concentration above the reporting limit, while the other two bottom ash samples had non-detectable PFBS concentrations. The sampled bottom ash for another of the facilities and the sampled fly ash for a third did not have any PFAS analyte concentrations above the respective method detection limits.

Residual PFAS is defined as the sum of the mass loading rate of PFAS exiting the resource recovery facility with the exhaust gas, bottom ash, and fly ash (g PFAS/year). The estimated PFAS mass loading rates for bottom ash and fly ash are provided in Table 5, along with the air emissions. The available data suggest that the mass loading of residual (post-combustion) PFAS for the bottom ash is of the same magnitude as the air emissions. The mass loading rate for fly ash is more than 10 times smaller than the mass loading rate for air emissions. Figure 1 suggests that the sum of the mass loading rates for PFAS in the exhaust gas, bottom ash, and fly ash cannot be described by a constant residual PFAS factor. Calculated residual factors ranged from 154 µg PFAS/ton MSW up to 437 µg PFAS/ton MSW. This is a different result from the consistent emission factors for the three MWCs.

Table 5 Mass loading rates of residual PFAS

Mass Loading	Units	Facility 1	Facility 3	Facility 2
Air Emissions	g PFAS/year	1.82	4.37	26.8
Bottom Ash	g PFAS/year	0	3.80	51.7
Fly Ash	g PFAS/year	0.10	0	1.3
Total	g PFAS/year	1.92	8.17	79.8

The solids mass loading rate for the bottom ash is assumed to be 12.5 percent of the loading rate of MSW to the resource recovery facility. The solids mass loading rate for the fly ash is assumed to be 3.75 percent of the MSW loading rate.[15] The test concentration in the ash is multiplied by the MSW loading rate and the assumed percent of MSW loading for that ash.

[15] Björklund S. *et al*. 2023. Emission of per- and polyfluoroalkyl substances from a waste-to-energy plant—Occurrence in ashes, treated process water, and first observation in flue gas. *Environmental Science & Technology* 57: 10089-10095.

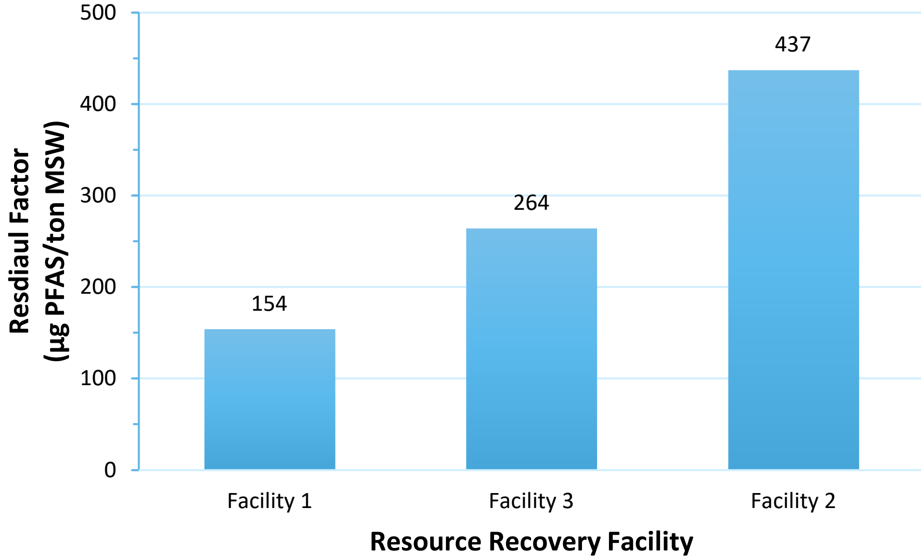

Figure 1 **Residual PFAS factors for the sum of the mass loading rates for exhaust gas, bottom ash, and fly ash at the three sampled resource recovery facilities**

7 Destruction Efficiency

The elevated temperatures generated during MSW combustion is sufficient to promote the thermal degradation of PFAS. The extent of thermal degradation was estimated by calculation of destruction and removal efficiency. The destruction and removal efficiency (*DRE*) for PFAS at the three sampled resource recovery facilities can be estimated from the following equation:

DRE = (Input – Residual) / Input

in which

DRE = the PFAS destruction and removal efficiency of the resource recovery facility (%)
Input = the mass loading rate of PFAS entering the resource recovery facility with the MSW (g PFAS/year)
Residual = the mass loading rate of residual PFAS exiting the resource recovery facility with the exhaust gas, bottom ash, and fly ash (g PFAS/year)

The *Residual* parameter for each resource recovery facility was determined from the sampling results and is provided in Table 5. The *Input* parameter is equal to the MSW loading rate (ton MSW/year) times the PFAS concentration in the MSW entering the resource recovery facility (g PFAS/ton MSW). Higher concentrations of PFAS in the MSW, assuming the same measured residuals, would result in higher DRE. While the operational capacities of the three resource recovery facilities are known, the incoming PFAS concentrations cannot be easily measured. Xcel Energy (2024) estimated that incoming PFAS concentrations could range from 50 to 300 µg PFAS/kg MSW, based on the reported component composition of MSW and on the reported PFAS concentration in some of the MSW components.[16] This range likely underestimates the concentration of PFAS in MSW since the concentrations of PFAS in many MSW components are unknown, and therefore, are unaccounted for in the estimate.

Recently published articles provided an opportunity to update the PFAS concentration estimates developed in the 2024 PFAS Air Emissions Technical Report (2024). When assigning a PFAS concentration to the organic component of MSW, Xcel Energy (2024) relied on the information provided by Choi *et al*. (2019).[17] The analytical methods employed by Choi *et al*. (2019) only measured perfluoroalkyl carboxylic acids and perfluoroalkyl sulfonic acids. The fluorotelomer carboxylic acids and other PFAS analytes associated with paper and food containers were not measured. Because of the limited analyte list, 2024 PFAS Air Emissions Technical Report (2024) could have underestimated the PFAS concentration in MSW. Munoz *et al*. (2022) used an expanded analyte list of 160 compounds when evaluating total PFAS concentrations in MSW compost, including the analytes associated with paper products and food containers.[18] After updating the 2024 PFAS Air Emissions Technical Report (2024) approach with information from Munoz *et al.* (2022) and other studies, the estimated total PFAS concentrations in MSW ranged from 108 to 410 µg PFAS/kg MSW, though this range likely remains an underestimate.

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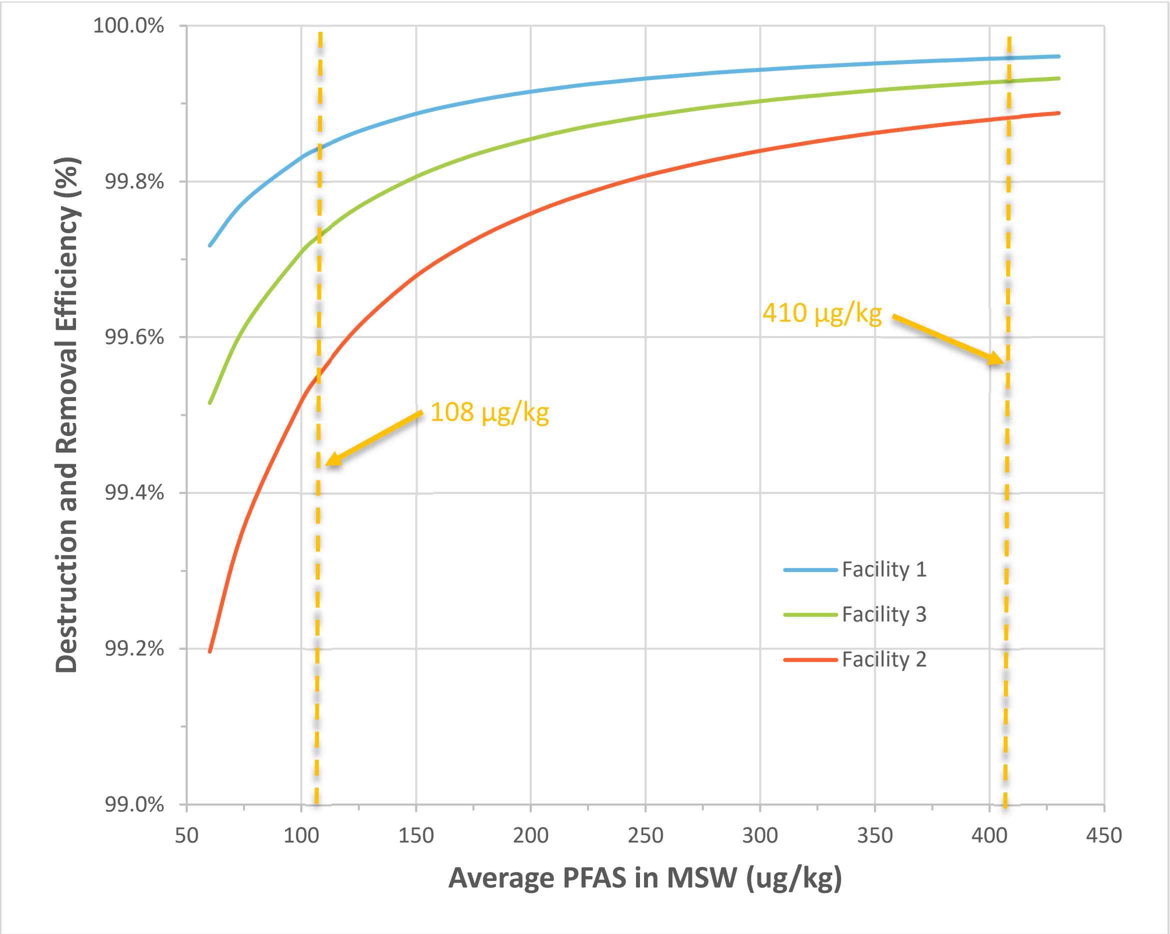
16 [redacted]. 2024. PFAS Air Emissions Technical Report, [redacted], Facility #4 and Facility #5.
17 Choi Y.J. *et al*. 2019. Perfluoroalkyl acid characterization in U.S. municipal organic solid waste composts. *Environmental Science & Technology Letters* 6: 372-377.
18 Munoz G. *et al*. 2022. Target and nontarget screening of PFAS in biosolids, composts, and other organic waste products for land application in France. *Environmental Science & Technology* 56: 6056-6068.

Figure 2 provides the calculated destruction efficiencies as a function of incoming PFAS concentration for the three sampled resource recovery facilities. As the assumed incoming PFAS concentration increases, the destruction and removal efficiency increases for a fixed *Residual* value. Based on the *Residual* values obtained from the PFAS analyte concentrations obtained using OTM-45 and using modified EPA Method 537 (Table 5), calculated PFAS destruction efficiencies can range from at least 99.60 percent to 99.97 percent. The calculated destruction efficiencies are greater for Facilities 1 and 2, because the residual PFAS factors are smaller (Figure 2). The three resource recovery facilities have the calculated ability to reduce the incoming mass loading of PFAS by at least a factor of 100.



The estimated range of PFAS concentrations in MSW is 108 to 410 µg PFAS/ kg MSW.

Figure 2 Calculated PFAS destruction efficiency as a function of the average PFAS concentration in the incoming MSW for the three sampled resource recovery facilities

8 Summary

The fate of PFAS during the combustion of MSW at three resource recovery facilities was evaluated by measuring PFAS concentrations in the exhaust gas, bottom ash, and fly ash. The stack testing used EPA Other Test Method 45 Revision 1 (OTM-45) to analyze for 49 PFAS compounds. Evaluation of the sampled bottom ash and fly ash used modified EPA Method 537 to analyze for 40 PFAS compounds. Only a small number of PFAS analytes were present at concentrations above the respective method detection limits. The literature suggests that a wide variety of PFAS analytes at detectable concentration are found in MSW. The loss of PFAS analyte diversity and concentrations implies that the elevated temperatures generated during MSW combustion are sufficient to promote the thermal degradation of PFAS analytes.

The exhaust gas at the three resource recovery facilities had PFAS analyte concentrations that were 10 to 1,000 times smaller than the MDH's intermediate and chronic inhalation Risk Assessment Advice (RAA) values or conservatively modeled receptor concentrations at the facility fence line that were 10 to 100 times smaller than the RAA values. This suggests that the potential inhalation health risks are minimal for the six PFAS compounds with RAA values.

The measured PFAS emission rates from the three resource recovery facilities ranged from 1.82 to 26.8 g PFAS/year. When the emission rates were normalized to the MSW mass loading rates, the average emission factor was 144 µg PFAS/ton MSW with a range of 141 to 147 µg PFAS/ton MSW. The emission factor was essentially the same for the three resource recovery facilities.

In addition to gas-phase emissions, residual PFAS also exited the resource recovery facilities with the bottom ash and with the fly ash. Only five analytes for modified EPA Method 537 were detected in the ash samples. No PFAS analyte concentrations were above the method detection levels for the bottom ash at one of the facilities and for the fly ash at another. The available data suggest that the mass loading of residual (post-combustion) PFAS for the bottom ash is of the same magnitude as the air emissions. The mass loading rate for fly ash is more than 10 times smaller than the mass loading rate for air emissions.

The summation of the mass loading rates for the gas-phase analytes of OTM-45 and for the solid-phase analytes of modified EPA Method 537 ranged from 1.92 to 79.8 g PFAS/year. These mass loading rates represent the PFAS analytes remaining after combustion of the MSW. The residual mass loading rates are small compared to the estimated mass loading rates of PFAS analytes entering the resource recovery facilities with the MSW.

The elevated temperatures generated during MSW combustion is sufficient to promote the thermal lysis of PFAS. The extent of thermal degradation was estimated by calculation of destruction and removal efficiency. The input mass of PFAS analytes was obtained by multiplying the MSW loading rate by the estimated total PFAS analyte concentration in the MSW. Based on literature values, a conservative estimate of PFAS concentrations in MSW can range from 108 to 410 µg PFAS/kg MSW. The measured mass loading rates of residual PFAS analytes and the estimated input loading rates suggest that destruction and removal efficiencies for the three resource recovery facilities can range from at least 99.6 percent to 99.97 percent.

Although designed to reduce the volume of material sent to landfills, the resource recovery facilities provide the additional benefit of destroying a substantial portion of the PFAS found in municipal solid waste, based on the residual PFAS analyte concentrations measured by EPA Other Test Method 45 Revision 1 (OTM-45) and modified EPA Method 537.

Attachment 1

Minnesota Resource Recovery Association Facility Matrix

Attachment 1

Minnesota Resource Recovery Association PFAS Research Project
Resource Recovery Facility Matrix

Facility	Counties Served	Annual Tonnage (tons/yr)	Annual Ash Tonnage Generation (tons/yr)	Daily Design Capacity (tons/day)	Material Pre-Processing	Combustion Technology	Critical Furnace/Combustion Temperature Values (degrees F)	Air Pollution Control Technology	Other critical operating details
Olmsted County Resource Recovery Facility	Olmsted County, Dodge County	120,000	30,000	400 (Units 1 & 2: 100, Unit 3: 200)	Presently, nothing, but, forthcoming MRF (2026)	Mass burn	1,750+	Ammonia injection for Nox (U3), Hydrated lime scrubber. Fabric filter baghouse. Powder activated carbon injection.	
Hennepin Energy Recovery Center	Hennepin	365,000	75,000	1,212	None	Mass burn	1,800, 1-second off grate	Hydrated lime scrubber. Reverse air baghouse. Carbon injection. Urea	Residential/Industrial MSW (No special waste). Packers, box, transfer
Perham Resource Recovery Facility	Wadena, Ottertail, Becker, Todd, Clay	55,000	10,000-12,000	150 two units combined	Yes	Barlow aerial grate system	1,850-1,950	Dry scrubber hydrated lime, fabric filter baghouse PAC for both units	4.7-5.7 retention to inlet of boiler
Pope-Douglas Resource Recovery Facility	Pope, Douglas, Grant, Stevens, Stearns, Sherburne, Benton	80,000	20,000	220 two units combined	Yes. MRF with metal and plastics recovery	Mass burn - aerial grate system	1,850	Dry reactor hydrated lime, baghouse with PAC	
Polk County Solid Waste Resource Recovery Plant	Beltrami, Clearwater, Hubbard, Mahnomen, Norman, Polk	40,000 across scale - 25,000 processed MSW combusted	3,000 - 4,000	77 two units combined	MRF - extract: Fines as ADC (<3" fraction), OCC, Ferrous, Non-Ferrous, UBC, HPDE-c, HDPE-n, PET, PP and oversized/objectionables (C&D, Electronics, furniture, etc.)	Starved air	1,500-1,550	PAC, Soda Bi-carb, ESP	Unknown - 1987 design docs list as 0.7-1.0 sec @ 1,600-1,800 F is design range. Residential & Non-residential Processable from Self-haul, Direct Collection (Packer), Transfer Trailer (Transfer Stations)
Xcel – Red Wing	Information for facilities not available								
Xcel - Wilmarth									