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2024 PFAS Testing at the Clean Harbors Aragonite Hazardous Waste Combustor

by **Stephen Zemba and Matthew Estabrooks**

The results of a research study testing PFAS destruction at the Clean Harbors Aragonite facility in Utah.

High-temperature incineration has for decades been an approved method for managing hazardous wastes, especially high organic content wastes that liberate heat and help sustain combustion. Resource Conservation and Recovery Act (RCRA) regulations require facilities to demonstrate >99.99% destruction and recovery efficiency (DRE) of principal organic hazardous constituents (POHCs) such as benzene that are difficult to destroy.¹ Additionally, >99.9999% destruction is required for wastes containing chlorinated dibenzo(p)dioxins and furans (PCDD/Fs).¹ The “four nines” (99.99) and “six nines” (99.9999) DRE criteria are typical goals of certification tests conducted by hazardous waste combustion (HWC) facilities.

Concerns arose over the ability of HWC to destroy PFAS, which have strong C-F bonds and are popularly called “forever chemicals”.^{2,3} In 2022, Congress placed a moratorium on the U.S. Department of War (DoW; formerly the U.S. Department of Defense, DoD) practice of incinerating PFAS-containing wastes.⁴ In response, some members of the HWC industry have conducted PFAS stack testing using the OTM-45 developed by the U.S. Environmental Protection Agency (EPA).

Not surprisingly, initial tests at the Clean Harbors, Inc. Aragonite (Utah) facility focused on DRE demonstrations of compounds such as perfluorooctanoic acid (PFOA), perfluorooctane sulfonic acid (PFOS), and other PFAS of concern.⁵ Additional concerns over the difficulties of mineralizing PFAS motivated EPA to research so-called products of incomplete destruction (PIDs) and to develop the OTM-50 stack test method designed specifically to measure PFAS PIDs, which were included along with DRE evaluation in a subsequent stack test at Veolia’s Port Arthur (Texas) facility.⁶ These tests have been sufficient to convince the DoW to lift the morato-

rium on incineration at permitted facilities combusting with sufficiently high temperatures.⁷

PFAS stack testing at the Clean Harbors Aragonite facility exemplifies the evolving focus on PFAS destruction. Tests in 2021 and 2022 were able to demonstrate six nine DREs of principal PFAS using EPA’s OTM-45 stack test method.⁵ The DRE tests did not examine PIDs, however, and also could not differentiate truly destroyed PFAS vs. uncombusted PFAS potentially captured by air pollution control equipment. Subsequently, a much more detailed stack testing and process sampling campaign was conducted at the Aragonite facility in November 2024, designed specifically to differentiate the destruction and removal components of DREs, and also to look for PFAS PIDs and the ability to destroy very short-chain PFAS.⁸

The November 2024 PFAS Testing at the Aragonite facility was a collaborative effort between Clean Harbors, EPA, and DoW, along with the participation of numerous consulting firms. The project resulted in the publication of an EPA (2025) research report,⁸ which contains details on the methodologies and results. A summary of the test design and results follows.

2024 Aragonite Testing

The 2024 Aragonite testing campaign occurred over three days, with three stack test runs conducted for each of three conditions:

- A:** Normal waste feeds supplemented by legacy aqueous film forming foam (AFFF with percentage levels of PFAS) and PFAS spiking of nine compounds with existing federal or state regulations;

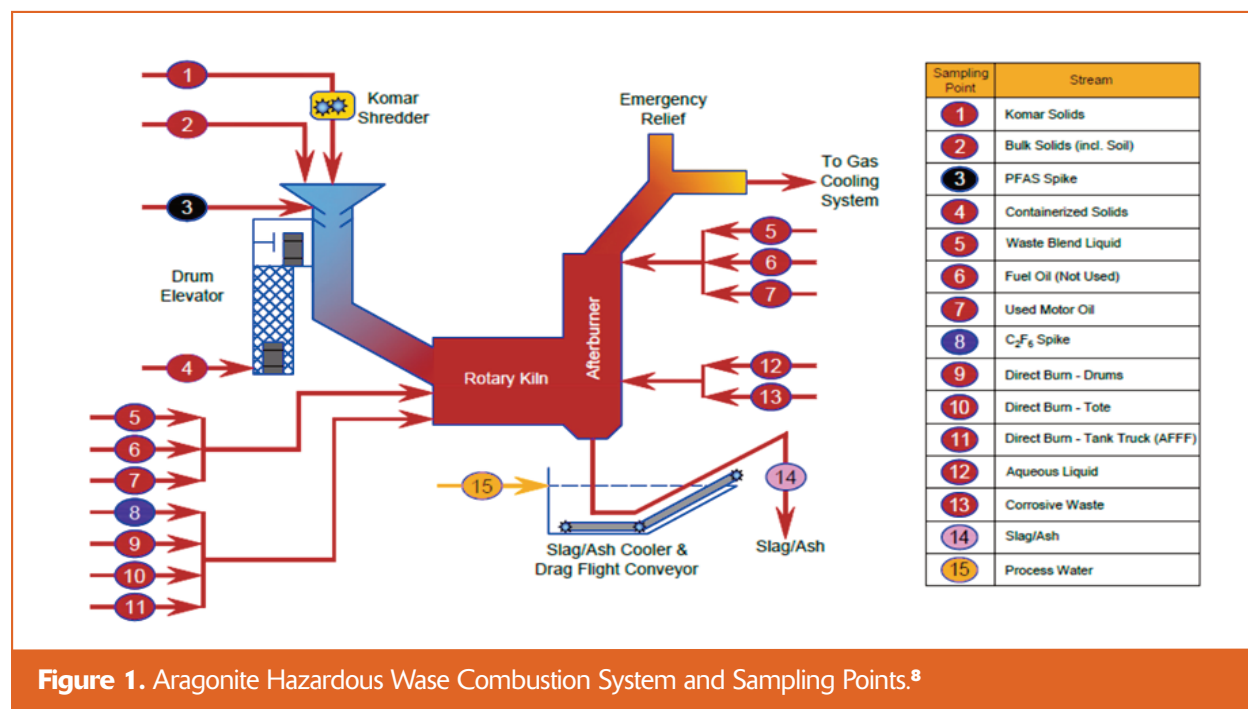


Figure 1. Aragonite Hazardous Waste Combustion System and Sampling Points.⁸

- B:** Normal waste feeds only (control case); and
C: Normal waste feeds supplemented by hexafluoroethane (C₂F₆) spiking.

PFAS spiking into the waste stream feeds was necessary in order to achieve enough sensitivity to demonstrate the high (up to six nine) DREs. Combustion temperatures in the sequential kiln and afterburner were maintained between 950 and 1,196 °C and over 1,100 °C, respectively, during testing. PFAS materials were injected with the normal mix of waste streams through specific ports, as illustrated in Figure 1.

PFAS DREs were estimated from characterization of PFAS inputs to the system (in all wastes where possible, per Figure 1) and measurement of stack emissions. Input characterization was based on EPA Method 1633 sampling results and waste/material feed rates. Stack emissions were measured using four different methods, as summarized in Table 1. Isokinetic methods OTM-45 and Method 0010, were used respectively to measure (a) a list of PFAS similar to Method 1633 and (b) potential semivolatile PFAS PIDs. These methods were used only for Condition A, which was designed to quantify DREs and DEs (see further below). Methods OTM-50 and ASTM D-6348-12 were applied specifically to measure volatile PFAS PIDs in all sampling runs. OTM-50 collects a non-isokinetic canister-based sample for lab analysis, while ASTM D-6348-12 is a “real time” Fourier Transform Infrared Spectroscopy measurement.

The Condition A DRE/DE stack test runs were supplemented by sampling of a number of ancillary liquid and solid streams associated with the incineration process, including kiln slag and process water (Figure 1) and inputs and outputs of the air pollution control equipment (see Figure 2). These process samples were also analyzed for PFAS using Method 1633. Calculation of DEs, as differentiated from DREs, considered the PFAS inputs and outputs to the system via the process samples in addition to the waste feed inputs and stack emissions used for calculating DREs. The “R” or

removal portion of the DRE thus represents the net amounts of PFAS from the wastes that are captured but not destroyed. PFAS mass balances were constructed based on PFAS sampling in waste feed inputs to the combustion system, process/residuals, and stack emissions; however, fluorine mass balances were not attempted because of the abundance of non-PFAS fluorine in wastes processed by the facility, brine, and other process/residual streams.

Pre-test calculations were made to determine the spiking rates necessary to provide the ability to estimate six nines DEs/DREs given analytical reporting limits of the OTM-45 stack emission measurements. Table 2 provides a color-coded tabular summary of the calculated DEs and DREs for the nine PFAS spiked in Condition A testing. Salient findings include:

- Four nines DREs (>99.99% destruction/removal) were achieved for all but one of the 27 PFAS runs (right side of Table 2).
- Six nines DREs (>99.9999% destruction/removal) were achieved for 18 of the 27 PFAS runs (left side of Table 2); and
- DEs were in general found to be about an order of magnitude smaller than DREs. DEs greater than six nines were found for PFNA and PFDA in Run 3, while DEs greater than four nines were found in 20 of the 27 cases.

Finding DEs about an order of magnitude smaller than DREs indicates some limited transfer of undestroyed PFAS to process residuals, meaning that all PFAS are not destroyed by the high temperature incineration process, but large percentages are destroyed. The lower DREs for HFPO-DA (a GenX-related compound) were not expected and hence were explored in a follow-up investigation. Though no definitive explanation was found, HFPO-DA detected in the OTM-45 stack testing was probably an artifactual result due to its presence in the proof blank train (this same compound has been detected in other PFAS stack tests).

Table 1. Stack Emission Sampling Methods

Test Condition	OTM-45 49 LC PFAS (9)	Method 0010 PFAS LC PIDs (10)	OTM-50 30 SC PFAS (11)	ASTM D-6348-12 C ₂ F ₆ and CF ₄ (12)
A	X	X	X	X
B	---	---	X	X
C	---	---	X	X

LC = Long-chain, SC = Short-chain, PIDs = Products of Incomplete Destruction

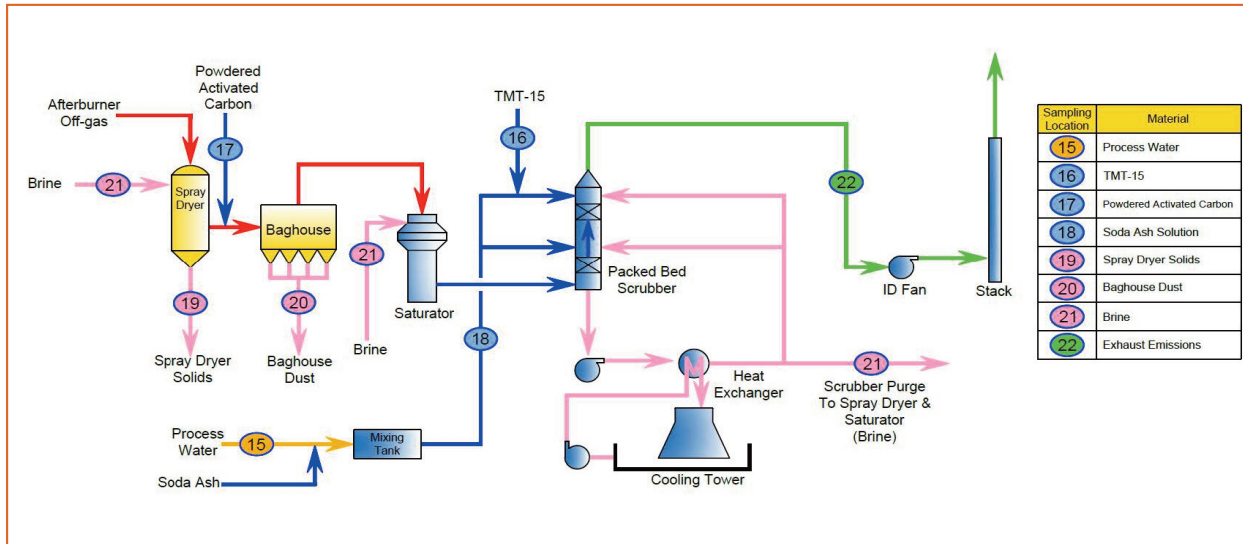


Figure 2. Emission Control System Process Stream Sampling Points.⁸

Table 2. Estimated DEs and DREs for Target PFAS.⁹⁻¹²

DE Run			PFAS	DRE Run		
1	2	3		1	2	3
			Perfluorobutanoic Acid (PFBA)	[Yellow]		
			Perfluorohexanoic Acid (PFHxA)	[Yellow]		
			Perfluorooctanoic Acid (PFOA)	[Green]		
			Perfluorononanoic Acid (PFNA)	[Yellow]		
			Perfluorodecanoic Acid (PFDA)	[Green]		
			Perfluorobutane Sulfonic Acid (PFBA)	[Yellow]		
			Perfluorohexane Sulfonic Acid (PFHxS)	[Green]		
			Perfluorooctane Sulfonic Acid (PFOS)	[Green]		
			Hexafluoropropylene Oxide Dimer Acid (HFPO-DA)	[Purple]	[Pink]	[Purple]

Key to DEs and DREs

[Pink]	>99.9%	[Purple]	>99.99%
[Yellow]	>99.999%	[Green]	>99.9999%

Figure 3 depicts the distribution of PFAS mass flow rates found in waste inputs, stack emissions, and process samples for one of the three Condition A test runs. Bars in Figure 3 reflect total measured PFAS levels (summed across compounds). The logarithmic scale reflects order of magnitude differences, illustrating the dominance of the PFAS feed rates introduced by AFFF and spiking (although there were measurable, albeit much lower, PFAS levels in other wastes routinely processed at the facility). Interestingly, the largest mass flow in process outputs was found in the slag waste from the rotary kiln, which exceeded the stack (exhaust) emission rate, and in large part explains the lower values of the DEs

compared with DREs. It is also worthy to note that all waste and process samples—including materials such as the activated carbon injected in the air pollution control system—had measurable PFAS flow rates (albeit in many cases at low values, reflective of the sensitivity of PFAS analytical methods).

The PFAS mass flows in Figure 3 reflect the results of Method 1633 and OTM-45 tests. No fluorinated PFAS were detected as PIDs via Method 0010, though reporting limits of this method are roughly a thousand times greater than those of OTM-45).

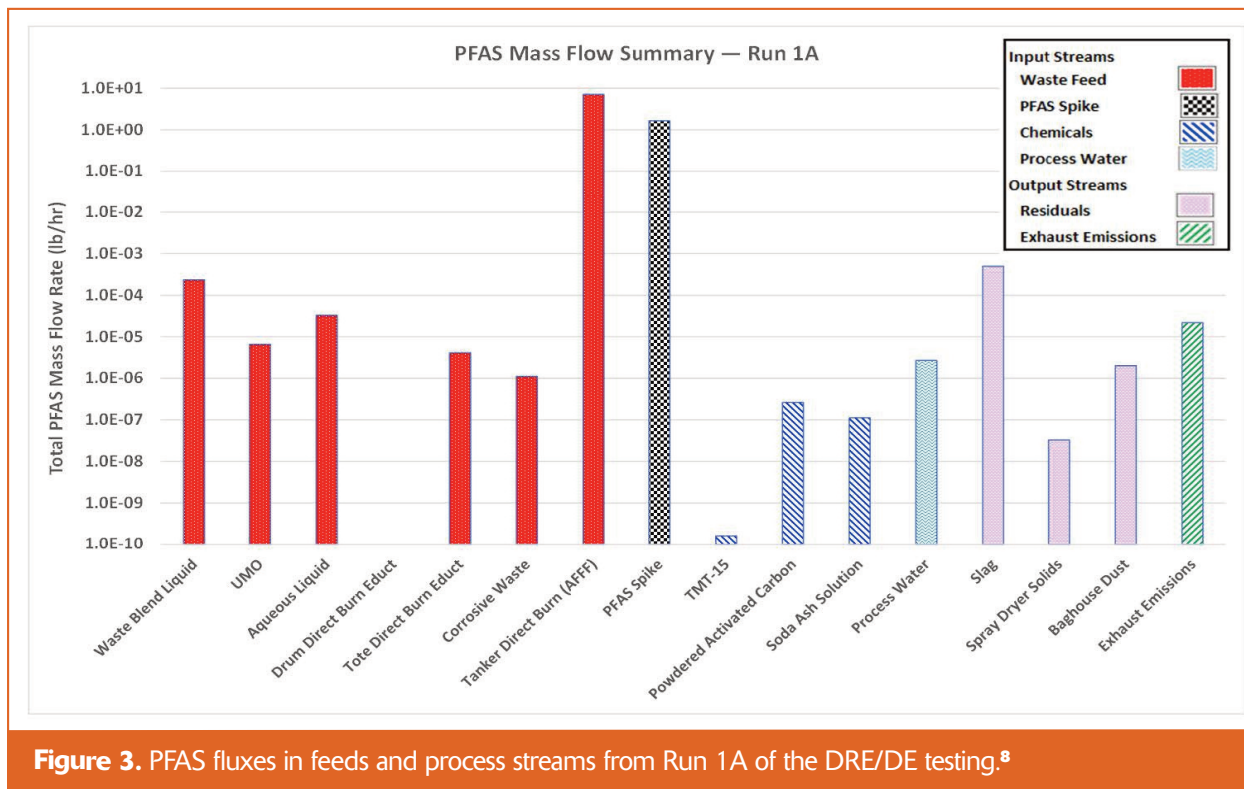


Figure 3. PFAS fluxes in feeds and process streams from Run 1A of the DRE/DE testing.⁸

Test Condition C involved the purposeful spiking of C_2F_6 , a short-chain perfluoroalkane difficult to destroy. It is possible that destruction testing of C_2F_6 may evolve as an economical surrogate method of certifying continued ability to destroy PFAS in general at combustion facilities. Three measurements of C_2F_6 were made during the testing during all test conditions. OTM-50 samples were collected and analyzed by both the facility and EPA, and FTIR monitoring was used to look for C_2F_6 and carbon tetrafluoride (CF_4). There were no detections in either the facility's OTM-50 or the FTIR sampling, but low levels of several short-chain PIDs were detected in EPA's OTM-50 sampling (which achieved lower reporting limits). The detected compounds did not include C_2F_6 . Based on mass emission rates of the measured short-chain PIDs, the average C_2F_6 DE exceeded six nines (>99.9999%) in the Condition C spiking tests.

The Aragonite study also implemented EPA's AERSCREEN model to predict the concentrations of PFAS in ambient air that would result from a continuous release of PFAS from the stack of the Aragonite facility at the emission rates measured during the DRE/DE test. The modeled PFAS concentrations were found to be two to eight orders of magnitude smaller than guideline concentrations and standards that have been established in some states (no federal guidelines are available for comparison). A refined dispersion modeling study would likely indicate lower ambient impacts, and hence a greater margin of safety with respect to ambient air guidelines/standards.

Concluding Remarks

The EPA Research Study of PFAS destruction and removal at the Aragonite hazardous waste incinerator has demonstrated high PFAS destruction efficiencies, supporting EPA's current view of incineration as one of the three most protective means of disposal/management of PFAS-containing wastes. Compared with Subtitle C landfilling and deep well injection (the other technologies viewed as most protective), incineration is the only destructive technology.¹³

Key findings from the study include:

- High temperature incineration destroys PFAS, resulting in low concentrations in exhaust emissions, mostly below 25.0 nanogram per cubic meter (ng/m³), and process residues, below 100 nanogram per gram (ng/g).
 - ▶ DRE values ranging from 99.999% to greater than 99.9999% were achieved for all spiked PFAS except HFPO-DA, which ranged from 99.95% to 99.998%. As described in Appendix K of the EPA Research Report, the DRE values for HFPO-DA are likely biased low due to external contamination.
 - ▶ DE values ranging from 99.94% to greater than 99.9999% were achieved for nine PFAS spiking compounds.
- No fluorinated semi-volatile, nonpolar compounds were identified by EPA Method 0010 sampling and analysis.

- The DE values for C2F6 ranged from greater than >99.9998% to >99.9999% based on the difference between the spiking rate and PIDs detected in EPA's OTM-50 stack tests. **em**

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References

1. U.S. Environmental Protection Agency (1999). 40 CFR Part 63, Subpart EEE. National Emission Standards for Hazardous Air Pollutants from Hazardous Waste Combustors. <https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-63/subpart-EEE>.
2. Bennington College (2020). First in the Nation Testing Reveals Toxic Contamination in Soil and Water Near Norlite Incinerator; Data Indicates That Incineration Does not Destroy PFAS Chemicals and Should Be Halted. Press release dated April 27, 2020. Accessed at: <https://www.bennington.edu/sites/default/files/sources/docs/Norlite%20News%20Release%20%5Bdb%20final%20updated%5D.pdf>.
3. New York State Department of Environmental Conservation (2021). Norlite Environmental Sampling Report, New York State Department of Environmental Conservation March 2021. Accessed at: https://dec.ny.gov/docs/materials_minerals_pdf/norlitesamplingfull0321.pdf.
4. U.S. Department of Defense. Incineration Moratorium, Report to Congress, February 2024. <https://www.acq.osd.mil/eie/eer/ecc/pfas/docs/reports/Incineration-Moratorium.pdf>.
5. Crisenberry, M. (2023). Clean Harbors Aragonite PFAS Test Results. Webinar "PFAS Destruction: Updates on Two Technologies (webinar), Northeast Waste Management Officials' Association, August 10, 2023. Presentation slides accessed at: https://www.newmoa.org/wp-content/uploads/2023/07/CleanHarbors_August2023.pdf.
6. Veolia North America (2025). PFAS Destruction at Veolia's Port Arthur Incinerator. Accessed at: <https://info.veolianorthamerica.com/hubfs/offers/reports/vna/pfas/pfas-destruction-testing-veolia-port-arthur-incinerator-study.pdf>.
7. U.S. Department of War, Updated Interim Guidance on Destruction or Disposal of Materials Containing Per and Polyfluoroalkyl Substances in the United States, February 20, 2026. https://www.acq.osd.mil/eie/eer/pfas/docs/policies/Updated%20Interim%20Guidance%20on%20D_D%20of%20PFAS.pdf.
8. U.S. Environmental Protection Agency (2025). PFAS Destruction by a Hazardous Waste Incinerator: Testing Results. U.S. EPA Office of Research and Development, Washington, DC, 2025. https://cfpub.epa.gov/si/si_public_file_download.cfm?p_download_id=552166&Lab=CEMM.
9. U.S. Environmental Protection Agency. OTM-45 (2021). Other Test Method 45 (OTM-45) Measurement of Selected Per- and Polyfluorinated Alkyl Substances from Stationary Sources. Accessed at: https://www.epa.gov/sites/default/files/2021-01/documents/otm_45_semivolatile_pfas_1-13-21.pdf.
10. U.S. Environmental Protection Agency. OTM-50 (2025). Other Test Method 50 (OTM-50) Sampling and Analysis of Volatile Fluorinated Compounds from Stationary Sources Using Passivated Stainless-Steel Canister. Accessed at: <https://www.epa.gov/system/files/documents/2025-01/otm-50-release-1-r1.pdf>.
11. U.S. Environmental Protection Agency. Method 0010 (1986). SW-846 Test Method 0010: Modified Method 5 Sampling Train. Accessed at: <https://www.epa.gov/hw-sw846/sw-846-test-method-0010-modified-method-5-sampling-train>.
12. ASTM D6348-12 (2020). Standard Test Method for Determination of Gaseous Compounds by Extractive Direct Interface Fourier Transform Infrared (FTIR) Spectroscopy. Accessed at: <https://webstore.ansi.org/standards/astm/astmd6348122020>.
13. U.S. Environmental Protection Agency. (2024). Interim Guidance on the Destruction and Disposal of Perfluoroalkyl and Polyfluoroalkyl Substances and Materials Containing Perfluoroalkyl and Polyfluoroalkyl Substances—Version 2 (2024). Accessed at: <https://www.epa.gov/system/files/documents/2024-04/2024-interim-guidance-on-pfas-destruction-and-disposal.pdf>.

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