Assured PFAS Separation

An alternative method of PFAS treatment as leachate disposal costs rise due to increasing regulations.

White Paper

Acknowledgement

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Their contributions were essential in ensuring the technical accuracy and robustness of this work.

Executive Summary

Growing concerns around the presence of Per- and Polyfluoroalkyl Substances (PFAS), and their potential harmful health effects are driving unprecedented changes in how landfill leachate is managed. Increasingly, landfills are being cut off from historical outlets as publicly owned treatment works (POTWs) are under increasing pressure to reduce PFAS loading in their discharge of wastewater and biosolids. Conventional wastewater biological treatment and disinfection do not reduce influent PFAS concentrations in the discharge. With PFAS regulatory change widely expected by the solid waste industry, landfill managers must consider alternatives for PFAS management, including on-site treatment.

Thermal evaporation is an established technique for onsite leachate treatment in which heat is used to reduce the volume of leachate at a landfill. The fate of PFAS during evaporative treatment has been a question from regulators and landfill managers, including how much measurable PFAS remains in the residual and, more concerning, how much escapes with water vapor. By design and validated through mass balance testing, the Heartland Concentrator™ is an efficient PFAS separation technology, highly effective at concentrating PFAS in the raw feed into liquid residuals without significant losses to the vapor stream. Design features of the Heartland Concentrator™, including its method of evaporation, operational temperatures, and high-efficiency mist elimination, make the technology an effective solution to retain PFAS compounds in landfills and keep them out of the environment.

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The ability to concentrate and isolate PFAS compounds from complex leachate streams mitigates environmental risks, returns clean water vapor to the environment, and offers a zero liquid discharge (ZLD) solution. The small volume of concentrated residuals can be safely retained in the landfill or treated by PFAS destruction technologies.

Through an in-depth review of the regulatory landscape, site sampling, and PFAS data analysis, this paper aims to shed light on the behavior of PFAS through a concentration process and establish the viability of leachate evaporation as a tool for assured landfill leachate PFAS separation and sequestration.

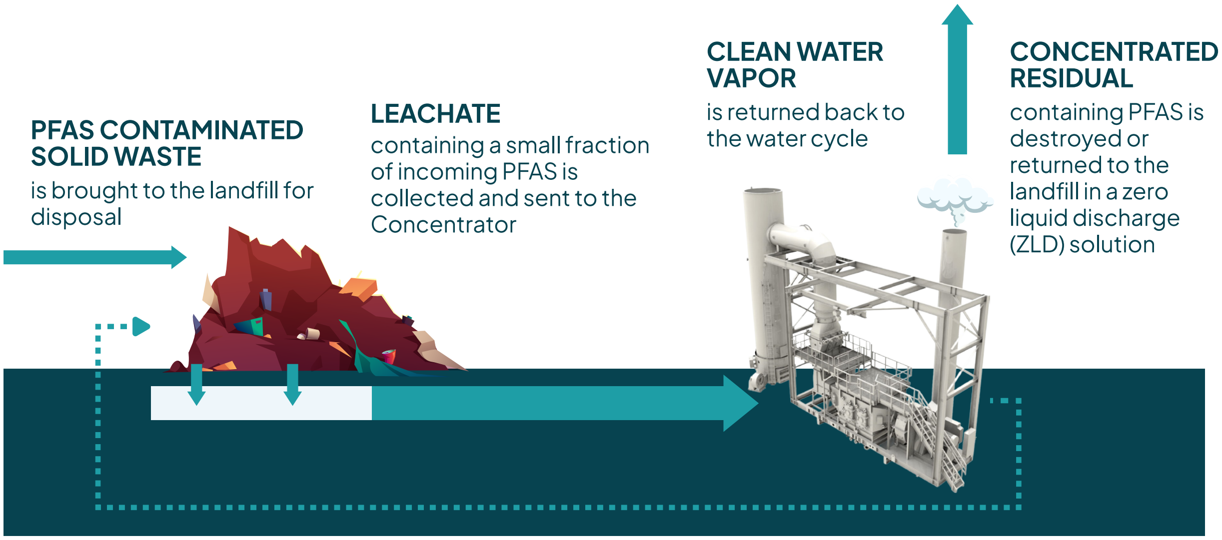


Figure 1. Zero Liquid Discharge Leachate Evaporation Solution for PFAS Separation

Harmful Effects of PFAS

PFAS stands for Per- and Polyfluoroalkyl Substances, a group of man-made chemicals that have been widely used in various industrial and consumer products since the 1940s. Dubbed "forever chemicals", a key characteristic of PFAS composition is their exceptionally strong carbon-fluorine bond, making PFAS highly resistant to degradation and leading to wide-spread use in products ranging from nonstick cookware, water-repellent clothing, or firefighting foams.

Because of the extreme duration of time it takes for PFAS to break down, these chemicals bioaccumulate in the environment, becoming concentrated in soil, water, and food. While production and use of certain PFAS compounds, most notably PFOS and PFOA, have been phased out in the US since the early 2000s, their presence in international products and resistance to degradation means they remain in our environment.

While research is still ongoing, it is understood that exposure to certain PFAS may lead to adverse health outcomes. Regulatory agencies and health experts are concerned about toxicology research that indicate numerous harmful effects, including developmental delays in infants, thyroid hormone disruption, liver damage, immune system effects, increased risk of certain cancers, and reproductive and hormonal effects.[i]

Toxicology research is driving timely federal and state regulations, including the development of maximum contaminant levels (MCLs) in drinking water and other regulations to address PFAS in the environment. Notably, the Environmental Protection Agency (EPA) has developed efforts to address PFAS, including instituting the PFAS Strategic Roadmap as well as designating certain PFAS as hazardous substances under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA).

The chart below illustrates interaction between several key components of the PFAS cycle.

Critical Elements of the PFAS Cycle

1. Agricultural runoff
2. Drinking water
3. Landfills
4. Industrial facilities
5. Wastewater treatment plants

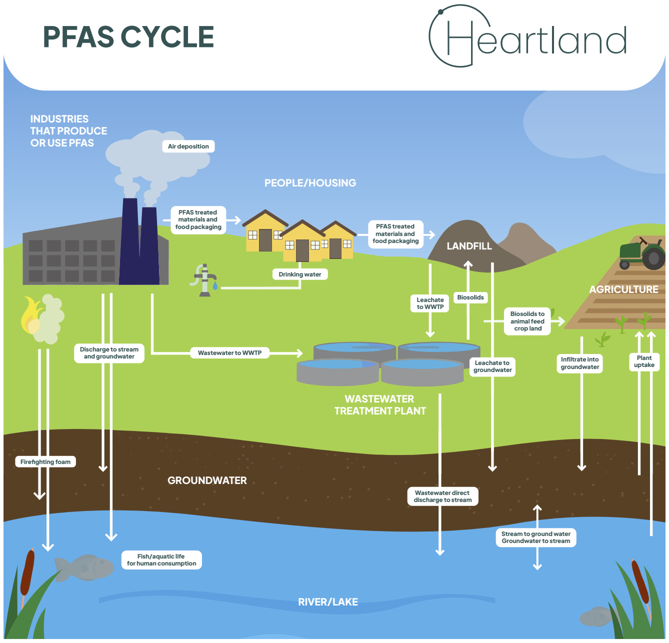


Figure 2. PFAS Cycle in our Environment [ii]

PFAS in Landfills and Leachate Treatment

Landfills are depositories for consumer products, food, and other wastes containing trace concentrations of these chemicals. While landfills do not generate PFAS, they are an important repository for safely sequestering PFAS from the environment. According to the EPA, "Most modern MSW landfills, when constructed and operated with appropriate controls (e.g., a flexible membrane liner system and leachate and LFG collection and management systems), can also help contain PFAS." [iii]

Leachate is an aqueous substance that results from liquids, largely generated by rainfall, percolating through solid waste in a landfill. The resulting fluid is concentrated with organic and inorganic substances, including PFAS. Proper collection and management of leachate is a critical aspect of landfill operations. Leachate treatment costs are often some of the landfill's largest annual expenses.

POTWs are increasingly concerned by changing discharge regulations at the state and local level. Challenges include nutrient loading limits, ammonia levels, and the presence of contaminants such as PFAS. Across the country, there is a growing trend of sewage treatment plants rejecting leachate. Once cut off, landfills often experience an increase in operational costs as much as 3–5× or more due to longer hauling distances and increased disposal fees.

Landfills unable to dispose of leachate via POTWs see OpEx costs rise 3–5×.

As landfills look to reduce their cost and risk associated with leachate management, high PFAS concentrations in leachate are becoming a major concern.

Landfill owners and operators should consider proven onsite methods to treat leachate and retain PFAS within the landfill, thereby eliminating risk associated with offsite transportation and disposal of PFAS at POTWs or other offsite facilities. Onsite treatment creates a closed loop system that keeps PFAS from leaving the landfill site. The EPA notes that PFAS management options such as recirculation and solidification can control the migration of PFAS into the environment. [iii]

One such established method of cost-effective leachate management is thermal evaporation. Through an evaporative process, the leachate volume is dramatically reduced and leachate contaminants, including PFAS, are concentrated into a small volume of residual. The residual is returned to the landfill or destroyed while clean water vapor is released back to the water cycle.

Benefits of Evaporation

Proven PFAS Sequestration – Testing has demonstrated that PFAS is retained in Heartland's concentrated residual.

Volume Reduction – Unlike other PFAS treatment technologies, evaporation reduces the volume of landfill leachate, generally by more than 95%.

Clean Water Returned to the Environment – During the evaporative process, clean water vapor is released to the atmosphere and returned to the environment.

Zero Liquid Discharge Solution (ZLD) – Leachate contaminants, including PFAS, are retained in the residual and returned to the landfill. By retaining the concentrate safely in the landfill, no liquid is released to the environment in a true ZLD solution.

ESG Leadership – By eliminating the need for trucking leachate for off-site disposal, a landfill takes trucks off the road, eliminates harmful emissions, and reduces the environmental risk of spills or leakage.

PFAS Regulation and Enforcement on the Rise

In October 2021, the EPA announced the PFAS Strategic Roadmap[iv]: EPA's Commitment to Action 2021 – 2024, making it clear that the agency sees addressing PFAS contamination a top priority. The Strategic Roadmap outlines three central directives to addressing PFAS.

1. Research to increase understanding of PFAS exposures and toxicities, human health and ecological effects, and effective interventions that incorporate the best available science.
2. Restrict PFAS from entering air, land, and water at levels that can adversely impact human health and the environment.
3. Remediate PFAS contamination to protect human health and ecological systems.

Central to EPA's approach to PFAS is to ensure science-based decision making in the development of PFAS regulations and establishing PFAS standards. The EPA will invest in scientific research to increase understanding of exposure levels at which PFAS poses risk to human health and the environment. Additionally, the EPA will develop methods to test, measure, remove, and destroy PFAS.

Protecting communities from exposure to PFAS is one of the top enforcement priorities in the National Enforcement and Compliance Initiatives: FY 2024–2027

The EPA has stated that protecting communities from exposure to PFAS is one of the top enforcement priorities in the 2024–2027 National Enforcement and Compliance Initiatives[v] [vi]. Addressing PFAS was listed among other top priorities, including climate change, coal ash, air toxins, drinking water contamination, and chemical accidents. The PFAS initiative will focus on implementing the Strategic Roadmap and holding responsible those who manufactured PFAS and/or used PFAS in the manufacturing process, federal facilities that released PFAS, and other industrial parties who significantly contributed to the release of PFAS into the environment. The initiative seeks to ensure these entities properly identify and characterize contamination, control ongoing releases, and comply with both existing and future environmental requirements.

Multiple regulatory and legislative actions are in process as part of the EPA's strategic roadmap. Several of those most likely to impact leachate treatment are listed below.

Safe Water Drinking Act (SWDA)

As PFAS effects become understood throughout society, federal and state regulators have begun efforts to mitigate the impact on human health. The Safe Water Drinking Act (SWDA), administered through the EPA, protects public drinking water through the development and supervision of MCLs (maximum contaminant levels). In April 2024, the EPA enacted a 4 parts per trillion (ppt) MCL for PFOA and PFOS, and a hazard index of 1 for PFNA, PFHxS, PFBS, and HFPO DA[vii]. This rule will require many municipalities and community water systems to implement additional water treatment technologies to abide by the regulation. MCLs and initiatives taken to address drinking water foreshadow potential approaches that will be taken to regulate and remediate wastewater.

Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)

The Comprehensive Environmental Response, Compensation, and Liability Act of 1970 (CERCLA) manages superfund site identification and gives the EPA the authority to define liable responsibility for proper contamination cleanup. In April 2024, CERCLA designated PFOA and PFOS as hazardous substances. The EPA is currently considering adding seven additional PFAS to the list of hazardous substances: PFBS, HFPO-DA (also known as GenX), PFNA, PFHxS, PFDA, PFHxA, and PFBA.[viii] This would introduce liability for both past and future PFAS discharges from specific sites.

Resource Conservation and Recovery Act (RCRA)

The Resource Conservation and Recovery Act of 1976 (RCRA) governs the disposal of solid and hazardous waste, setting cradle-to-grave standards for treatment, storage, and disposal. In February 2024, the EPA issued a proposal to the Office of Management and Budget (OMB) to list nine PFAS compounds (PFOA, PFOS, PFBS, HFPO DA, PFNA, PFHxS, PFDA, PFBA, and PFHxA) as hazardous constituents under RCRA. This rule would likely have substantial impacts on how landfill leachate is managed onsite and would impact transportation and offsite disposal methods through Best Available Treatment (BAT).

Regulatory Updates

CERCLA: Final rulemaking designating PFOA and PFOS as hazardous substances finalized April 2024

RCRA: Final rule expected in July 2025.

Effluent Guidelines Program Plan 15

In January 2023, US EPA's Office of Water communicated its intent to update the Effluent Guidelines Program Plan 15 and develop new effluent limitation guidelines (ELGs) and pretreatment standards for landfill leachate due to the presence of PFAS. ELGs are national, technology-based regulations developed to control industrial wastewater discharges to surface waters and into POTWs. ELGs are intended to represent the greatest pollutant reductions through technology that are economically achievable for an industry. The new PFAS ELGs and pretreatment standards will apply to all landfills that treat and discharge leachate under an NPDES permit and those that discharge to a POTW or other regulated facility for treatment and disposal.

With looming lawsuit filings and regulatory delays, various states have initiated state-based legislation to target point source discharges of PFAS into the environment as well as potential management of landfill leachate.

Summary of PFAS Compounds in Proposed Regulations

Table 1 summarizes PFAS compounds in proposed federal regulations under CERCLA, RCRA, and the SWDA, as well as relevant state-based air limits, further discussed in the ambient air and dispersal modeling sections. The science-based approach of selecting these PFAS compounds and developing regulatory standards (e.g., MCLs) involved evaluating best-available literature on adverse health effects. While certain stakeholders argue that PFAS should be regulated as a chemical class, peer-reviewed studies show differing health effects of individual PFAS, suggesting regulations should be based on the specific risks posed by individual PFAS. For example, EPA's health advisory level for PFOS is 0.02 ppt, 100,000 times lower than the health advisory level for PFBS of 2,000 ppt. Utilizing health effects of individual PFAS provides a science-based framework for developing PFAS regulations and will support more efficient development of treatment technology.

PFAS	SDWA	CERCLA	RCRA	State-Based Air Limit
PFOA	MCL: 4 ppt MCLG: 0 ppt	Hazardous Substance	Proposed hazardous constituent	MI, NY, MN, TX, NH
PFOS	MCL: 4 ppt MCLG: 0 ppt	Hazardous Substance	Proposed hazardous constituent	MI, MN, TX
PFNA	MCL: 10 ppt MCLG: 10ppt Hazardous Index Applicable *	ANPRM (Intent to Propose)	Proposed hazardous constituent	-
PFHxS	MCL: 10 ppt MCLG: 10 ppt Hazardous Index Applicable *	ANPRM (Intent to Propose)	Proposed hazardous constituent	MN
PFBS	Hazardous Index Applicable *	ANPRM (Intent to Propose)	Proposed hazardous constituent	MN
HFPO-DA	MCL: 10 ppt MCLG: 10 ppt Hazardous Index Applicable *	ANPRM (Intent to Propose)	Proposed hazardous constituent	NJ
PFBA	-	ANPRM (Intent to Propose)	Proposed hazardous constituent	MN
PFHxA	-	ANPRM (Intent to Propose)	Proposed hazardous constituent	MN
PFDA	-	ANPRM (Intent to Propose)	Proposed hazardous constituent	-

* Hazard Index for any mixture of two or more of the following PFAS: PFNA, PFHxS, HFPO-DA, and PFBS.
Table 1 PFAS Compounds in Proposed Regulations Under RCRA, CERCLA and the SDWA

The Heartland Concentrator™

Onsite evaporation of landfill leachate has long been an effective alternative to offsite disposal. With recent testing, Heartland demonstrates that the same proven process also sequesters the PFAS in landfill leachate into a concentrated residual that can be effectively retained in the landfill. Operators can dramatically reduce the volume of leachate, take trucks off the road, and lock-in disposal certainty while simultaneously sequestering PFAS. Testing has been conducted using EPA Method 1633, which analyzes 40 PFAS compounds. Heartland believes that the sequestration observed on these measurable compounds would apply to many of the other compounds.

The Heartland Concentrator™ is a direct-contact evaporator where hot gases are mixed with wastewater in a proprietary process. Figure 3 is a simplified flow diagram of the process.

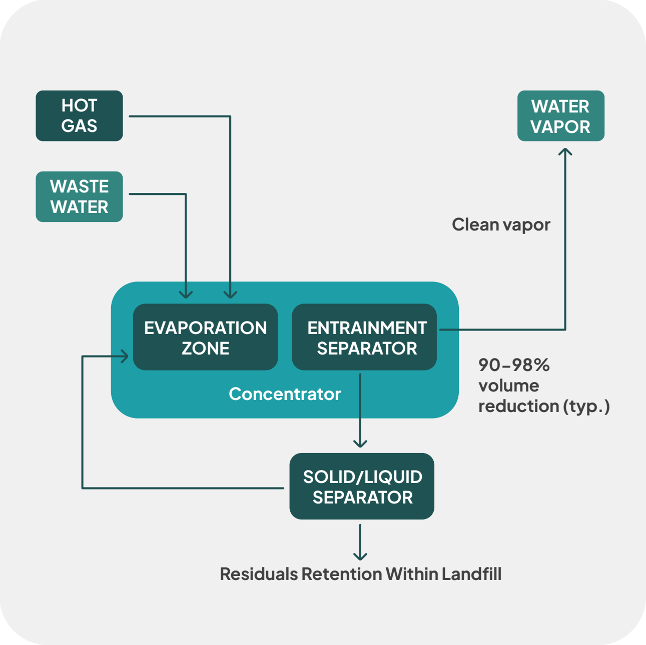


Figure 3. Concentrator Process Flow Diagram (PFD)

Heartland's patented, innovative evaporator does not rely on heat exchangers prone to fouling, but rather directly contacts hot gas with leachate inside a compact evaporation zone. An in-line proprietary and high-efficiency entrainment separator (mist eliminator) removes particulate matter (PM) and water droplets as the cooled exhaust gas is discharged to atmosphere. Concentrated water is returned to the evaporation zone as part of the continuous evaporative process.

The evaporation zone is a compact area where hot gas (typically 600–1,000°F) is contacted with wastewater, facilitating mass and heat transfer (evaporation of water). The flowing gas, which has become saturated with water vapor and entrained liquid droplets, exits this zone at close to the adiabatic saturation temperature (AST) for the mixed gas and liquid phases. Heartland's unique and proprietary design allows use of waste heat from various sources to evaporate wastewater, including a flare configuration using direct combustion of landfill gas (LFG) or natural gas, or a CoVAP™ configuration using exhaust from engines or turbines.

Physical and Chemical Properties Driving PFAS Behavior in the Concentrator

Due to their chemical structure, most PFAS can exist in either an ionic form or an acid form. The chemical form of a given PFAS (ionic versus acid) is pH dependent and determines its physical and chemical properties, including speciation between liquid and vapor phases. Above a pH of 5, dominant PFAS in leachate exist nearly entirely in the dissociated ionic form.

In ionic form, PFAS compounds are characterized by high aqueous phase solubility and negligible volatility.

For two common PFAS, PFOA and PFOS, the following chart demonstrates how these compounds exist in ionic form at the typical operating pH of the Heartland Concentrator™. These physical properties coupled with the design of the Heartland Concentrator™ result in high retention of PFAS in the system's residuals, as further discussed below.

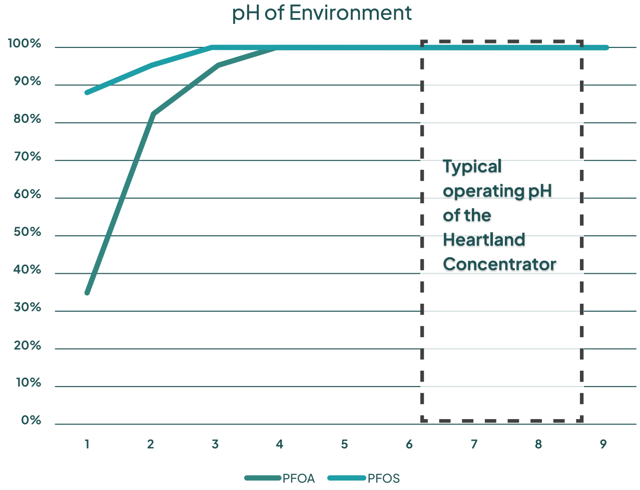


Figure 4. PFOA & PFAS Ionic vs Acid Form [ix]

Innovative Design Drives Efficient PFAS Separation

Several design elements of the Heartland Concentrator™ enable an efficient process for separation of PFAS into a small-volume residuals stream. An important component is Heartland's propriety controls system ensures a highly controlled process that precisely controls airflow velocity and temperature and liquid pH.

Evaporation Zone and Operational Temperature

The Heartland Concentrator™ employs a direct-contact, adiabatic evaporation process in which large "macro-droplets" are reduced to smaller droplets in a highly wetted evaporation zone. By design, this approach to evaporation avoids spray drying, a process that involves rapidly drying a liquid or slurry at high temperatures to form a dry particle. Exiting the evaporation zone, the hot gas and liquids are in thermodynamic equilibrium near the adiabatic saturation temperature (AST) of the hot gas. The Concentrator operates at an AST in the range of 130–160°F, resulting in efficient evaporation while simultaneously maintaining temperatures significantly below the boiling point of PFAS compounds, avoiding PFAS volatilization.

Concentrated liquids exiting the evaporation zone are directed into an integral sump and recirculated back to the evaporation zone. A small slip stream containing concentrated PFAS and other contaminants is purged from the sump at a controlled rate into a residuals storage container pending onsite disposal in the landfill or further

By maintaining a wetted environment in the evaporation zone, PFAS are retained in liquid droplets, minimizing volatilization to the vapor phase by providing a "home" for the compounds to reside.

treatment for PFAS destruction. In certain cases, clarified liquid from the residuals container can be recycled to the Concentrator for further evaporation.

High Efficiency Mist Elimination

A portion of the liquid exiting the evaporation zone is entrained as droplets in the gas stream. These droplets exiting the evaporation zone may contain small amounts of dissolved organic and inorganic compounds, including PFAS. The Concentrator includes a three-stage, high efficiency mist elimination system to remove droplets from the gas stream prior to atmospheric discharge as depicted in Figure 5. Hot gas velocity is designed and controlled to stay within an optimum range for droplet removal.

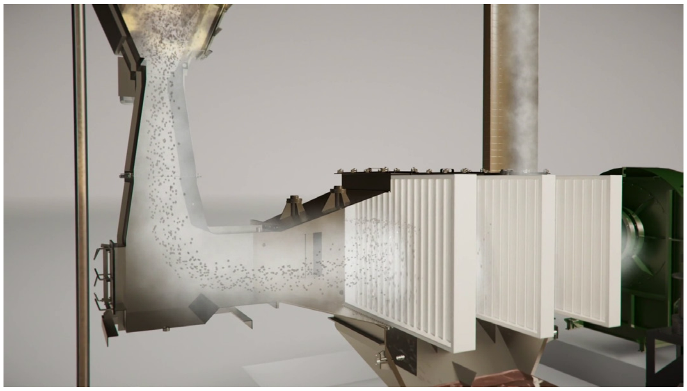


Figure 5. Conceptual Depiction of Mist Eliminator Droplet Removal

By removing water droplets from the gas stream prior to atmospheric discharge, the Concentrator avoids potential airborne PFAS emissions. Additionally, the Concentrator does not form dry PM, thereby avoiding PFAS airborne emissions that may otherwise be associated with dry particles.

Each stage of the mist elimination system sequentially removes smaller droplets, resulting in >99% overall removal of the droplet volume at the exit of the final stage.

Operational pH and Suspended Solids

The Heartland Concentrator™ operates in a pH range of 6.5 to 8.5. Within this range, PFAS are generally in their non-volatile ionic form, and therefore remain in the concentrated liquid residuals generated by the system. Furthermore, the residuals produced from evaporation of landfill leachate often contain elevated concentrations of organic total suspended solids (TSS). Heartland's sampling indicates that PFAS have an affinity for these organic substances, likely through adsorption or electrostatic interactions, further driving PFAS retention in the residuals. The small volume of residuals containing the concentrated PFAS is purged from the system and disposed onsite where it is retained in the landfill.

Testing Data from Two Landfills Confirms Efficient PFAS Separation

Heartland conducted studies at two different municipal solid waste (MSW) landfills sites in the Eastern US, each employing a Type 4 Heartland Concentrator™. A mass balance approach was used to determine the amount (lb/hr) of PFAS in the feed and residuals from the Heartland system. The purpose of these studies was to validate theoretical predictions that PFAS entering the system in raw leachate would be retained in the residuals existing the system. At Site 1, combustion of LFG was used as the energy source, while Site 2 utilized natural gas as the energy source. Concentrated leachate residuals were safely, and in compliance with regulations, returned to the landfill at both Sites.

Heartland personnel collected multiple grab samples from both the raw leachate entering the systems and the concentrated residuals exiting the systems. Prior to sample collection, each system was operated at steady state conditions for several hours to ensure the samples were representative. Duplicate samples were collected as a quality control measure. Samples were collected using standardized best practices for PFAS field sampling, which include provisions for proper equipment, containers, and prevention of sample contamination. Samples were properly shipped under chain of custody procedures to a third-party laboratory for analysis by EPA Method 1633. This method has been specifically developed for various challenging matrices, including landfill leachate.

The laboratory testing protocol for the raw leachate and residual samples involved collecting representative aliquots of the samples and extracting the PFAS from those aliquots, thereby inherently measuring PFAS in both the dissolved and suspended solid phases.

Target Compounds – A Focus on Regulated PFAS

To establish a target list of PFAS compounds, Heartland referenced federal and state PFAS regulations, including CERCLA, RCRA, the SDWA, and state-based air regulations (see Air Dispersion Modeling Section below). As summarized in Table 1, these PFAS include PFOA, PFOS, PFNA, PFHxS, PFBS, HFPO DA (Gen X), PFBA, PFHxA, and PFDA.

The target list of PFAS are prevalent in landfill leachate. In addition to these regulated compounds, fluorotelomer carboxylic acids (FTCAs) are often present in landfill leachate. FTCAs are not regulated in the PFAS regulations referenced above, and were therefore not targeted during this study. However, Heartland anticipates that it will expand testing for these compounds in the future.

Mass Balance Approach

The Heartland Concentrator™ is equipped with highly accurate flowmeters to measure the system's feed and residuals flowrates. These flowrate measurements, along PFAS concentrations provided by a 3rd party laboratory were used to calculate the mass of the target PFAS compounds entering in the raw feed and in the concentrated residuals using the following equations, respectivel

EQUATION 1:

$$Mass\left(\frac{lb}{hr}\right)_{PFAS\ Feed} = Concentration\left(\frac{ng}{l}\right)_{PFAS\ Feed}\ x\ Flow\left(\frac{gal}{min}\right)_{Feed}\ x\,(5.0E\text{-}10).$$

EQUATION 2:

$$Mass\left(\frac{lb}{hr}\right)_{PFAS\ Residuals} = Concentration\left(\frac{ng}{l}\right)_{PFAS\ Res.}\ x\ Flow\left(\frac{gal}{min}\right)_{Res.}\ x\,(5.0E\text{-}10).$$

Note. The factor of 5.0 E-10 is used to convert units to lbs/hr.

Case Study 1 – Results

The leachate feed rate for Site 1 was 52,700 gallons per day (gpd) (2,208 gallons per hour), and the residuals production rate was 2,140 gpd (89 gallons per hour), resulting in an overall volume reduction of 95.9% for this site. Table 2 summarizes feed and residuals concentrations and mass flowrates for the target list of PFAS compounds entering and exiting the system during the case study.

Table 2 – PFAS in Concentrator Feed and Residuals – Case Study 1					
PFAS Acronym	**CAS No.**	**PFAS Concentration**		**PFAS Mass Balance**	
		Feed (ng/L)	**Residuals (ng/L)**	**Feed (lb/hr)**	**Residuals (lb/hr)**
PFOA	335–67–1	1,145	28,950	0.000021	0.0000215
PFOS	1763–23–1	219	7,025	0.000004	0.0000053
PFBS	375–73–5	466	11,550	0.000009	0.000009
PFHxS	355–46–4	908	23,650	0.000017	0.000018
PFNA	375–95–1	58	1,735	0.000001	0.000001
PFBA	375–22–4	1,505	35,700	0.000028	0.000027
PFHxA	307–24–4	1,995	43,650	0.000037	0.000032
HFPO-DA	13252–13–6	<2.85	<475	<0.000001	<0.000001
PFDA	335–76–2	10	337	0.0000002	0.0000001
	Total	**6,305**	**152,597**	**0.000115**	**0.000113**

Table 2 – Case Study 1: PFAS in Concentrator (Feed and Residual)

The PFAS mass balance for Case Study 1 revealed a mere 1.7% difference between the mass of PFAS entering in the raw leachate and the mass of PFAS exiting in the system residuals, confirming that vast majority entering the system was present in the system residuals. When considering inherent error in analytical measurement, the feed and residuals PFAS mass as summarized in Table 2 were essentially identical, indicating the retainment of PFAS in the liquid residual.

Case Study 2 – Results

The leachate feed rate for Site 2 was 25,000 gpd (1,042 gallons per hour), and the residuals production rate was 1,455 gpd (61 gallons per hour), resulting in a volume reduction of 94.2%. Table 3 summarizes feed and residuals concentrations and mass flowrates for the target list of PFAS compounds entering and exiting the system during the case study[x].

Consistent with Case Study 1, the PFAS mass balance revealed a minor difference of only 0.8% between the mass of PFAS entering in the raw leachate and exiting in the residuals. These results further demonstrated that PFAS are effectively separated and concentrated into the system residuals.

Table 3 – PFAS in Concentrator Feed and Residuals – Case Study 2

PFAS Acronym	CAS No.	PFAS Concentration		PFAS Mass Balance	
		Feed (ng/L)	Residuals (ng/L)	Feed (lb/hr)	Residuals (lb/hr)
PFOA	335-67-1	1,900	34,380	0.000017	0.000017
PFOS	1763-23-1	330	5,660	0.000003	0.000003
PFBS	375-73-5	10,000	174,580	0.000087	0.000088
PFHxS	355-46-4	1,100	20,070	0.000010	0.00001
PFNA	375-95-1	99	1,890	0.0000009	0.000001
PFBA	375-22-4	1,500	35,850	0.000013	0.000018
PFHxA	307-24-4	8,500	125,910	0.000074	0.000064
HFPO-DA	13252-13-6	<200	1,600	<0.000002	0.000000
PFDA	335-76-2	70	1,330	0.0000006	0.0000007
	Total	**23,499**	**401,270**	**0.000204**	**0.000203**

Table 3 – Case Study 2: PFAS in Concentrator (Feed and Residual)

Air Dispersion Modeling

AERMOD ambient air modeling was conducted to assess potential PFAS air emissions from a typical Heartland Concentrator™ installed at a MSW landfill leachate facility. The objective of modeling was to determine if potential PFAS emissions from the Concentrator's exhaust stack would comply with Michigan Department of Environment, Great Lakes, and Energy (EGLE) Air Quality Division's screening levels in Rules 225-233. The state of Michigan was selected for performing the analysis based on its robust ambient air regulatory program, including stringent ambient air emission screening levels for PFAS compounds.

Multiple scenarios were evaluated, including:

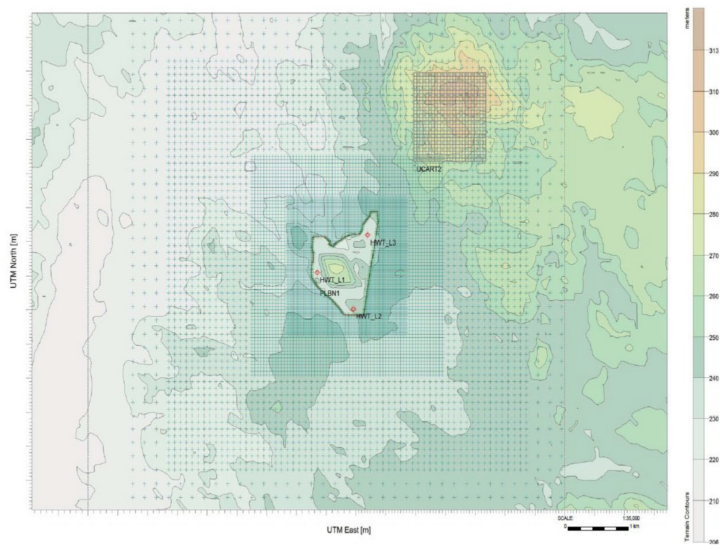
- Three (3) actual landfill facilities in Michigan (referred to as "Model Facility Locations")
- Seven (7) theoretical onsite evaporator locations
- Two PFAS data profiles at each evaporator location, corresponding to PFAS data from Case Studies 1 and 2.

Modeling Methodology

AERMOD is the current regulatory air dispersion model preferred by the U.S. EPA for determining near-field ambient concentrations (or "ambient impacts") resulting at ground level from emissions of air contaminants. AERMOD is a sophisticated executable air emission model that incorporates various aspects of actual meteorological data and site- specific terrain elements into determination of how air emissions will concentrate at various distances away from an emission source.

Three Michigan landfill sites were selected to develop hypothetical AERMOD modeling scenarios which capture variations in site layout, meteorological data, and terrain. Model Facility 1 was located in west Michigan, Model Facility 2 in southwest Michigan, and Model Facility 3 in mid-Michigan.

Onsite evaporator locations were selected based on landfill gas tie-in points, proximity to property boundaries, and prevailing wind directions. It was determined that Model Facility 1 should examine three locations and derive results for each one. Similarly, Model Facility 3 examined three (3) locations. However, given the layout of Model Facility 2, only one (1) location was appropriate for this facility. An example model layout for Model Facility 1 is shown in Figure 6, including the receptor grid and local topography. The modeled evaporator locations are designated as "HWT_L".



Comments:

- 3 exhaust stack locations shown
- Receptor grid 7.2km x 7.2km
- 25-m spacing property line & 1st tier
- Elevated terrain
- Western Michigan

Figure 6. Model Facility 1 Layout

For each Model Facility, the most recent two years of available meteorological data (2022–2023) were used to derive results. It is anticipated that in using two years of data, a wide variety of weather events would occur and give a thorough representation of wind speeds, wind direction, precipitation, etc. Meteorological data was pre-processed by Michigan EGLE-AQD to meet U.S. EPA's quality assurance requirements.

Finally, each model was conducted using a 25–meter spacing for receptor locations along the property boundary, and out to a distance of 600 to 1,000 meters from the sources, depending on the site. Outward from the 25–m spaced receptors, additional receptors were placed at 50–m, 100–m and 200–m spacing until a large enough and dense enough overall receptor grid was made that would ensure the maximum impacts were captured for all averaging periods (1–hour, 8–hour, 24–hour and annual). Elevated terrain was imported for each receptor by pre-processing with AERMAP and utilizing National Elevation Data (NED) GeoTIFF files with a 10–meter resolution.

Exhaust Stack Parameters and PFAS Inputs for Modeling Basis

AERMOD dispersion modeling for each of the three Model Facility Locations was based on an assumed evaporator processing rate of 50,000 gallon per day (GPD) of leachate. Each of the nine target PFAS compounds were modeled in the analysis. The PFAS data profiles (i.e., ng/l concentrations) from both Case Study Sites 1 and 2, summarized in Tables 2 and 3 above, were used as PFAS inputs for each evaporator location. In total, 14 scenarios were evaluated (7 evaporator locations across the 3 Model Facility Locations, 2 PFAS data profiles per location corresponding to Case Study Sites 1 and 2).

To account for sampling variability and accuracy, it was assumed that for each individual PFAS compound, 10% of the mass in the feed to the Concentrator was present in the vapor exhaust from the system. This assumption is conservative, considering the mass balance estimates (see Table 2 and 3) indicated significantly less PFAS was actually present in the exhaust stack.

The exhaust stack was modeled as a Point source in AERMOD, with the parameters shown in Table 4.

Stack Parameter Input	Value
Stack Height	40 feet
Stack Diameter	48 inches
Temperature	166 F
Exhaust Flow	40,100 acfm
Exhaust Velocity	53.2 feet/sec

Table 4 – Evaporator Exhaust Stack - Model Input Parameters

Modeling Results

For the nine target PFAS compounds, ground-level ambient air concentrations (ug/m3) were calculated for each Concentrator location at the 3 Model Facility Locations. The highest impacts per averaging period were determined for comparison to the Michigan EGLE AQD Initial Threshold Screening Levels (ITSLs) for the nine compounds. Michigan ITSLs (i.e. allowed ground level ambient concentrations) for the nine PFAS compounds all have averaging periods of either 24–hours or Annual. Therefore, the Concentrator location resulting in the highest 24–hour impact and Annual impact per facility was utilized to produce pollutant-specific ambient impacts for each respective pollutant for both PFAS Case Study data sets. The maximum pollutant-specific impact for each Model Facility Location was then compared to their respective Michigan EGLE ITSL.

Table 5 summarizes modeling results for Model Facility 1, including a comparison of ambient impacts with respect the Michigan screening levels for allowable concentrations, which includes known ITSLs (PFOA and PFOS) and other ITSLs that the EGLE AQD had developed for a recent air permit application but, as of yet, are not included in the AQD ITSL Listings provided on the AQD's Air Toxics webpage:

(https://www.michigan.gov/egle/about/organization/air-quality/air-toxics).

Model Facility No. 1 (Western Michigan) Estimated Ground Level Air Impacts for PFAS
Michigan Rule 225 PFAS Compliance Demonstration Using AERMOD

Compound		Max Emission Rate (all data)[1]	Ambient Air Standard (MIEGLE AQD Initial Threshold Screening Level ITSL)[2]		Ambient Air Modeled Impact (Max Ground Level Concentration)[3]	
		lb/hr	24-hr	Annual	24-hr	Annual
			µg/m³	µg/m³	µg/m³	µg/m³
Perfluorobutanoic acid	PFBA	0.0000028	-	10	-	0.00000036
Perfluorohexanoic acid	PFHxA	0.0000148	-	2	-	0.0000019
Perfluorooctanoic acid	PFOA	0.0000033	0.0001	-	0.000007	-
Perfluorononanoic acid	PFNA	0.0000017	0.01	-	0.0000003	-
Perfluorodecanoic acid	PFDA	0.0000012	-	0.05	-	0.00000002
Perfluorobutanesulfonic acid	PFBS	0.0000174	1.05	-	0.000035	-
Perfluorohexanesulfonic acid	PFHxS	0.0000019	0.03	-	0.000004	-
Perfluorooctanesulfonic acid	PFOS	0.0000006	0.004	-	0.000001	-
Hexafluoropropylene oxide dimer acid	HFPO-DA	0.00E+00	-	0.27	-	0.00E+00

[1] Based on assumption that 10% of the inlet PFAS mass to the evaporator exits the exhaust stack (Non Detect = 0.00 lb/hr).

[2] ITSLs for PFOA and PFOS are included in the AQD ITSL listing on the AQD's Air Toxics webpage. The other ITSLs listed in this table were developed for a recent air permit application, but, as of yet, are not included in the AQD Air Toxics webpage.

[3] This table displays the maximum impact results of 3 modeled locations and 2 PFAS data sets.

[4] All Results highlighted in light blue are compliant with Michigan Rule 225.

Table 5 - Model Facility No. 1 (Western Michigan) – Maximum Estimated Ground Level Air Impacts for PFAS Michigan Rule 225 PFAS Compliance Demonstration Using AERMOD

Although not included in this report, similar tables were created for Model Facilities 2 and 3. Table 6 was developed to provide an overall comparison of worst-case modeled emissions of each of the nine PFAS compounds versus not only Michigan screening levels, but other known screening levels set forth by other regulatory agencies. The impacts in Table 6 are the maximum ground level concentration results across all modeled Facilities, evaporator locations, and PFAS emission rates. For the sake of this table, the most stringent of any allowed PFAS standard was provided in the table and results compared.

The highest ambient impact of any PFAS compound versus a Michigan allowed concentration was found to be PFOA, corresponding to the Case Study 1 emission profile located at Model Facility No. 2. This impact was 0.0000093 µg/m3, which is about 9% of the Michigan ITSL for PFOA of 0.0001 µg/m3. All other impacts were less than 1% of the state limits, with most being several orders of magnitude below the limits as shown in Table 6.

Compliance Analysis Results for Maximum Evaluated Emission Rates Compared to Various State Agency Allowed PFAS Air Concentrations

Compound		Max Hourly Emission Rate	Most Stringent State Ambient Air Standard	Most Stringent State Ambient Air Standard	Most Stringent State Ambient Air Standard	Ambient Air Modeled Impact	Ambient Air Modeled Impact	Ambient Air Modeled Impact	% of Standard	% of Standard	% of Standard
		(lb/hr)[1]	1 hr (µg/m³)	24 hr (µg/m³)	Annual (µg/m³)	1 hr (µg/m³)	24 hr (µg/m³)	Annual (µg/m³)	1 hr	24 hr	Annual
Perfluorobutanoic acid	PFBA	0.0000028	-	10	10	-	0.0000078	0.0000004	-	0.0001%	0.000004%
Perfluorohexanoic acid	PFHxA	0.000015	-	0.5	0.5	-	0.000042	0.0000023	-	0.008%	0.0005%
Perfluorooctanoic acid	PFOA	0.0000033	0.05	0.0001	0.005	0.00002	0.0000093	0.0000005	0.05%	9.3%	0.01%
Perfluorononanoic acid	PFNA	0.0000002	-	0.01	-	-	0.0000005	-	-	0.005%	-
Perfluorodecanoic acid	PFDA	0.000017	-	-	0.05	-	-	0.00000002	-	-	0.00004%
Perfluorobutanesulfonic acid	PFBS	0.000017	-	0.03	0.03	-	0.000049	0.0000027	-	0.16%	0.01%
Perfluorohexanesulfonic acid	PFHxS	0.0000019	-	0.03	0.034	-	0.00000054	0.0000003	-	0.02%	0.0009%
Perfluorooctanesulfonic acid	PFOS	0.0000006	0.1	0.0004	0.01	0.000004	0.0000016	0.0000001	0.004%	0.40%	0.0009%
Hexafluoropropylene oxide dimer acid	HFPO-DA	0.00E+00	-	-	0.27	--	--	0.00E+00	-	-	0.00%

[1] Hourly emission rates are based on the highest rate from either Case Study 1 or 2, 50,000 GPD treatment basis.

[2] All Results highlighted in light blue are compliant with the most stringent State standard.

Michigan

Minnesota

Texas

Table 6. Compliance Analysis Results for Maximum Evaluated Emission Rates Compared to Various State Agency Allowed PFAS Air Concentrations

Though each Concentrator installation will vary by site-specific factors (location, release height, topography, and meteorology), these modeling results use conservative inputs, providing high confidence that ambient air impacts from an adiabatic leachate evaporation system fall well below the strictest state-based air concentration limits. Regular review of regulatory requirements, PFAS science, and modeling techniques is advised to ensure continued compliance.

Ambient Air Sampling

In addition to the dispersion modeling described above, actual ambient air samples were collected from Case Study Site 1, downwind at multiple distances from the evaporator system. Samples were collected using an ORBO-1500 XAD-2 media sampler provided by Eurofins. Ambient air was collected by drawing air through the media sampler using 5-liter per minute sampling pump over an approximate 24-hr period. The sample was measured for OTM-45 parameters. All concentrations were below detection limits for each of the OTM-45 parameters. Results for compounds having state air limits or screening levels are displayed in Table 7

Ambient Air Sampling Results and State Screening Levels								
Compound		**Unit**	**PFBA**	**PFHxA**	**PFOA**	**PFBS**	**PFHxS**	**PFOS**
Results - 50 ft. / 500 ft. Down Wind		µg/m^3	ND / ND [1] (<0.00039)	ND / ND (<0.000034)	ND / ND (<0.00003)	ND / ND (<0.00001)	ND / ND (<0.000036)	ND / ND (<0.000021)
State Ambient Air Screening Level/Standard								
Compound			**PFBA**	**PFHxA**	**PFOA**	**PFBS**	**PFHxS**	**PFOS**
Michigan	24-hr	µg/m^3	N/A	N/A	0.0001	N/A	N/A	0.0004
New York	Annual	µg/m^3	N/A	N/A	0.0053	N/A	N/A	N/A
Minnesota	24-hr	µg/m^3	10.0	0.5	0.1	0.030	0.034	0.011
	Annual	µg/m^3	10.0	0.5	0.1	0.030	0.034	0.011
Texas	1-hr	µg/m^3	N/A	N/A	0.050	N/A	N/A	0.010
	Annual	µg/m^3	N/A	N/A	0.005	N/A	N/A	0.010
[1] ND / ND - Non-Detect for both 50' and 500' samples.								
[2] All Results highlighted in light blue are compliant with the most stringent State standard.								

Table 7. PFAS Ambient Sampling Results Comparison to State Ambient Air Limits/Screening Levels

Landfill Gas Considerations

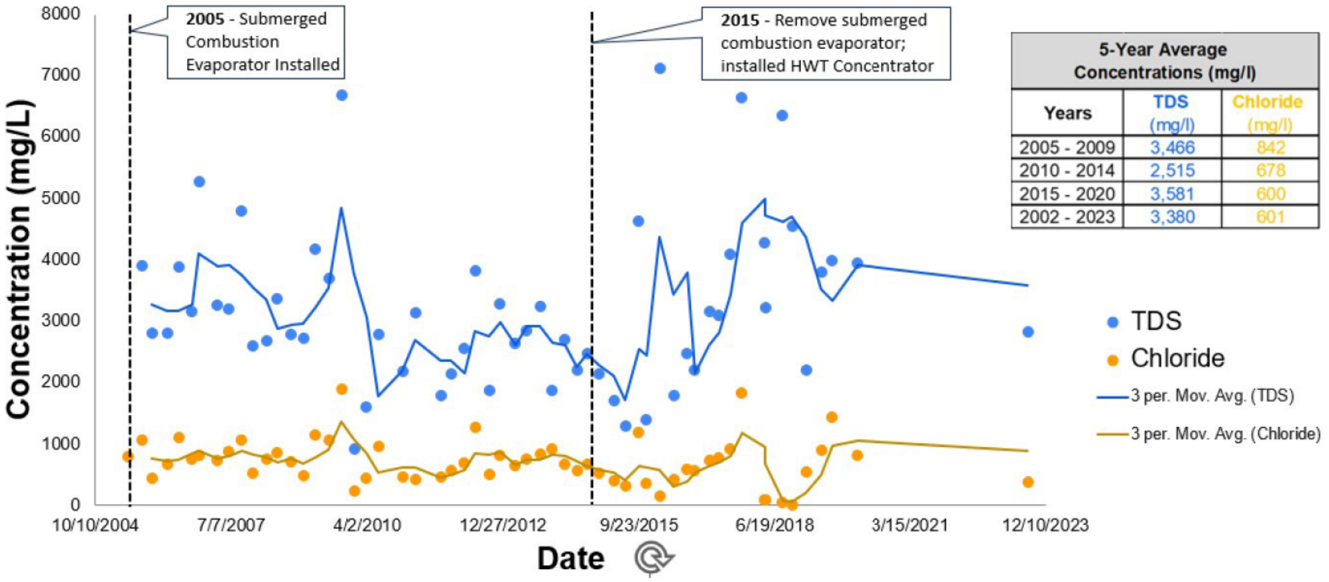
Most MSW landfills have a gas collection system to draw landfill gas (a mixture of methane and CO_2) from the landfill and combust the gas in one or more flares. Recent studies indicate landfill gas may be a pathway for emissions of certain PFAS from a landfill, predominately fluorotelomer alcohols (FTOHs). FTOHs are neutral PFAS that have been detected in landfill gas samples and are precursors to perfluorinated carboxylic acids. Landfill gas flares are subject to environmental regulations, including destruction efficiency requirements to limit emissions of certain parameters. Additional research is required to determine the fate of PFAS in landfill gas flares, including how much PFAS is fully destroyed in the flare versus broken down into smaller PFAS compounds.

Landfill gas is an energy source used at some Concentrator sites treating landfill leachate. At these sites, the Concentrator utilizes an enclosed flare to combust landfill gas, producing hot combustion gases used in the evaporation process. Without a Concentrator, the same landfill site would typically utilize an open flare (also called candlestick flare) to treat the landfill gas. As such, potential PFAS emissions associated with flaring of landfill gas are not exacerbated through the Concentrator process. In fact, enclosed flares have longer residence time than open flares, which may result in higher destruction of PFAS present in the landfill gas.

Residuals Management

A Concentrator installed at a MSW landfill typically reduces the volume of onsite leachate by 90 to 98%, generating a relatively small volume of residuals with total solids concentrations in the range of 100,000 to 300,000 mg/l. For example, a typical size Concentrator treating 50,000 gallons per day, operating at 95% volume reduction, would produce 2,500 gallons per day of concentrated residuals. This small volume residuals stream containing PFAS, and other concentrated parameters can be recycled and contained within the landfill. Literature indicates landfills retain a large majority of PFAS entering the landfill[xi][xii]. This onsite treatment approach can thus create a closed-loop system that avoids PFAS from leaving the landfill site, and is consistent with recent EPA guidance which notes, "Other leachate management options can control the migration of PFAS into the environment, including recirculation and solidification, which return PFAS to the landfill."[xiii]

A 20-year study at one evaporator site showed recirculation of residuals did not appreciably cycle up dissolved parameters in the leachate generated by the landfill. Figure 7 displays leachate data over an approximate 20-year period for an MSW landfill generating approximately 25,000 gallons per day of leachate and producing approximately 1,000 GPD of residuals. Thermal evaporators have been in operation at the site from 2005 to present. Chlorides and total dissolved solids (TDS) concentrations in the leachate collected from the landfill are shown in Figure 7, including 5-year averages from 2005 to 2023. While the chart displays periods of variability likely driven by variation in rainfall and/or mix of MSW received, no appreciable increasing trend was observed for chlorides or TDS. PFAS data was not available for this study, as most landfills have only recently begun monitoring for PFAS; however, PFAS is expected to show similar trends as TDS and chlorides.



5-Year Average Concentrations (mg/l)		
Years	TDS (mg/l)	Chloride (mg/l)
2005 - 2009	3,466	842
2010 - 2014	2,515	678
2015 - 2020	3,581	600
2002 - 2023	3,380	601

Figure 7. Chloride and Total Dissolve Solids Concentrations in Leachate Over 20 Years of Evaporator Residuals Recirculation

Stabilization & Destruction

Additional management options for evaporator residuals include solidification/stabilization and PFAS destruction. These alternatives may be employed at the discretion of a landfill operator, or if required by future regulations. A stabilization bench study was conducted utilizing residuals samples from two MSW leachate evaporator projects. A proprietary, Portland cement-based stabilization product was applied to the residuals in an approximate 1:1 weight ratio, which resulted in a stabilized residual that passed the paint-filter test. The stabilized residuals samples were then analyzed for PFAS using the synthetic precipitation leaching procedure (SPLP) to simulate natural leaching that may occur in a landfill. Results are displayed on Table 8 which indicate approximately 95 to 97% of the PFAS mass was retained in the stabilized residuals.

Another option for management of evaporator residuals is destructive treatment. Several technologies are emerging for destruction of PFAS, including but not limited to, supercritical water oxidation, pyrolysis/gasification, hydrothermal alkaline treatment, electrical oxidation, and plasma treatment. Each of these technologies are energy intensive and are most efficient when employed to smaller volume/higher concentration streams. Concentrated evaporator residuals are therefore well suited to pair with destruction technologies.

PFAS Retention in Evaporator Residuals – Site A and Site B						
	Site A			Site B		
Parameter	Evaporator Residuals (pre-stabilization)	SPLP Leachate Concentration	% PFAS Retained (Post-Stabilization)	Evaporator Residuals (pre-stabilization)	SPLP Leachate Concentration	% PFAS Retained (Post-Stabilization)
	ng/l	ng/l	%	ng/l	ng/l	%
Perfluorobutanesulfonic acid (PFBS)	35,000	67	96.2%	27,000	44	96.7%
Perfluorobutanoic acid (PFBA)	57,000	130	95.4%	33,000	52	96.8%
Perfluorodecanoic acid (PFDA)	900	2.4	94.7%	1,200	ND	>99%
Perfluorohexanesulfonic acid (PFHxS)	1,300	11	83.1%	3,900	3.1	98.4%
Perfluorohexanoic acid (PFHxA)	27,000	62	95.4%	58,000	100	96.6%
Perfluorononanoic acid (PFNA)	500	2.3	90.8%	670	ND	>99%
Perfluorooctanesulfonic acid (PFOS)	5,900	24	91.9%	2,400	1.6	98.7%
Perfluorooctanoic acid (PFOA)	2,400	38	68.3%	21,000	34	96.8%
HFPO-DA (GEN X)	180	ND	ND	ND	ND	ND
Total	**130,180**	**337**	**94.8%**	**147,170**	**235**	**96.8%**
Note – Sites A and B were different project locations than Case Study 1 and 2 locations described above						

Table 8. Evaporator Residuals Stabilization/Solidification Testing

Conclusion: Leachate Evaporation for Assured PFAS Separation

Leachate evaporation is a highly effective and promising approach for assured PFAS separation and management. The ability to concentrate and isolate PFAS compounds from complex leachate streams mitigates environmental risks, returns clean water to the environment, and creates a concentrated waste stream suitable for disposal in a landfill or treatment by PFAS destruction technologies as they enter the market. Studies demonstrate the design of the Heartland Concentrator, including its evaporation technique, operational temperatures, and high-efficiency mist elimination, make the technology an effective solution to retain PFAS compounds in landfills and out of the environment.

As industries and regulators strive to combat PFAS-related challenges, leachate evaporation stands out as an existing, economical, and viable strategy that aligns with both technical and environmental objectives.

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[iii] Interim Guidance on the Destruction and Disposal of Perfluoroalkyl and Polyfluoroalkyl Substances and Materials Containing Perfluoroalkyl and Polyfluoroalkyl Substances. US EPA. Version 2, 84. 2024.

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[viii] Designation of Perfluorooctanoic Acid (PFOA) and Perfluorooctanesulfonic Acid (PFOS) as CERCLA Hazardous Substances. US EPA. Federal Register 87 FR 54415. EPA-821-R-22-004. 2024.

[ix] Per- and Polyfluoroalkyl Substances Technical and Regulatory Guidance. The Interstate Technology & Regulatory Council: PFAS Team. June 2022.

[x] Two samples were tested from the concentrated residual. Table 3 PFAS results are the average between PFAS measured in both samples.

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