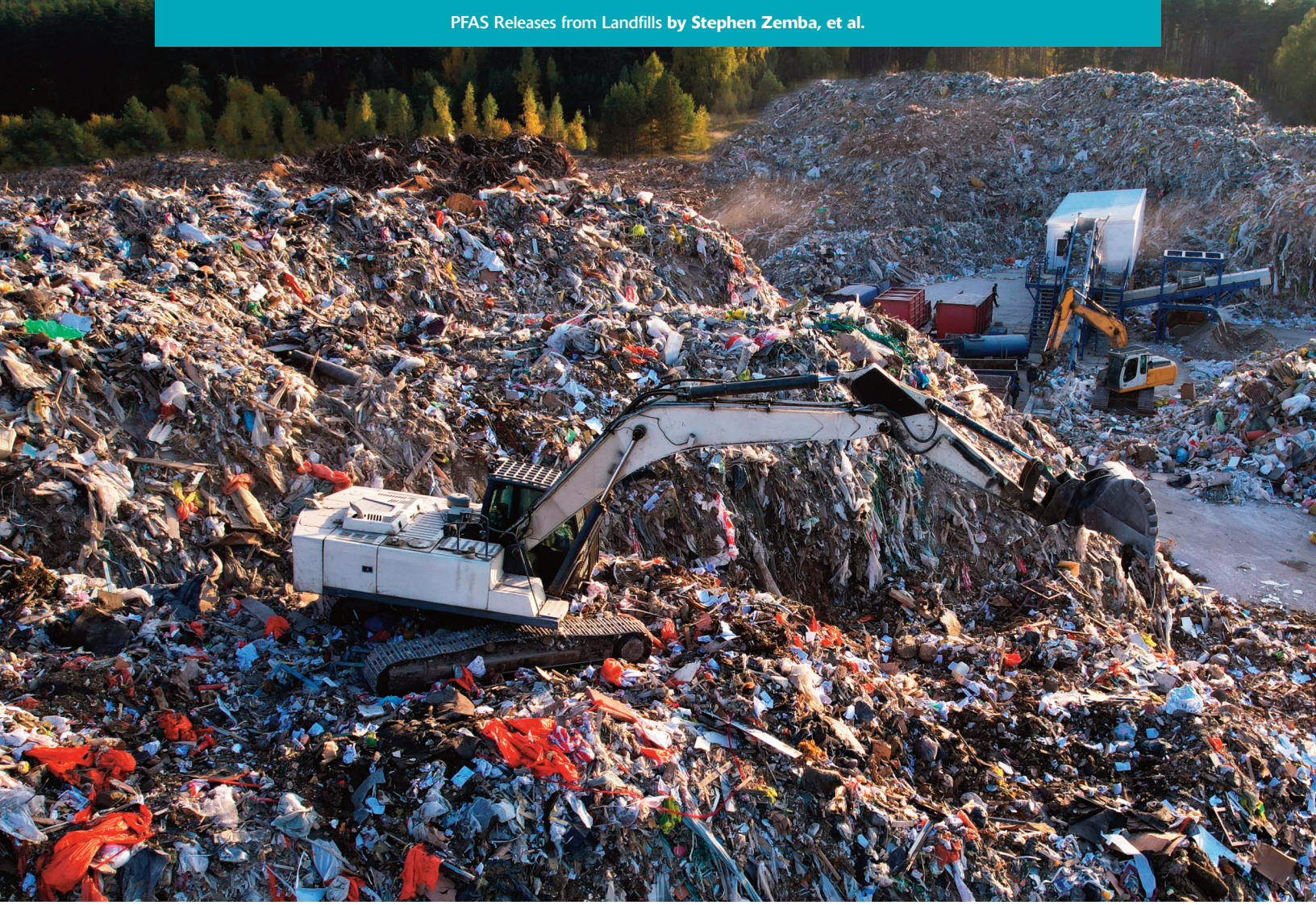

PFAS Releases from Landfills:
Consideration of Air Emissions in Mass Balances

by Stephen Zemba, Matthew Estabrooks, and Meghan Close

A look at the presence and management of PFAS emissions from landfills.

Landfills have received considerable attention in the past few years with respect to per- and poly-fluoroalkyl substances (PFAS), a class of widely-used chemicals increasingly suspected to pose human health risks. A national study of leachate identified PFAS at concentrations above drinking water guidelines.[1] The discovery of PFAS at elevated levels in landfill leachate was not in retrospect surprising given the presence of PFAS in the myriad products and wastes that end up in landfills.[2] Although the landfill industry claims to receive, and not to generate, PFAS from their operations,[3] they are nevertheless the potential conduit for PFAS transformations and releases to the environment, and the U.S. Environmental Protection Agency (EPA) is investigating effluent guidelines for landfill leachate that will in many cases require PFAS treatment and removal.[4]

Although leachate treatment for PFAS will increase waste disposal costs, it also represents an opportunity to lower PFAS releases to the environment. Landfills already appear to be beneficial at sequestering some PFAS. A study of PFAS in select wastes at a Vermont landfill found the influx of long-chain PFAS to be many times larger than the leachate outflux (see Figure 1[5]). Leachate treatment followed by destruction or stabilization of captured PFAS could further enhance the effectiveness of PFAS management by landfills, though releases of short-chain PFAS may be challenging to address.

PFAS flux balances at landfills, however, are not limited to compound-specific waste inflows and leachate outflows. PFAS transformations must also be considered. One of the consequences of EPA's provisional drinking water health advisories for PFOA and PFOS,[6] as well as the 2010/2015 PFOA Stewardship Program,[7] was the phased stoppage of use of these two principal PFAS by U.S. manufacturers. These long-chain perfluorinated compounds (PFCs) were largely replaced by either shorter-chain PFCs or precursor (polyfluoroalkyl) compounds. Precursor PFAS have been shown to degrade—to different PFAS—in anaerobic environments. In a national leachate study, 5:3-fluorotelomer carboxylic acid, which is a breakdown product of the precursor 6:2-fluorotelomer alcohol (FTOH),[8] was the PFAS found at the highest concentrations.[1] The PFAS mass balance is also complicated by volatile PFAS that partition to landfill gas. To date, PFAS air emissions have not been a focus at landfills, but are likely to receive increased attention as data continue to emerge.

PFAS Air Emissions

A national study of PFAS measurements in landfill gas is finding the presence of FTOHs, fluorinated sulfonamides (FOSAs) and sulfonamidoethanols (FOSEs), collectively "volatile PFAS."[9] Similar compounds have been detected at a recent study at three Florida landfills.[10] These compounds are not on the analyte lists of EPA's OTM 45 and OTM 50 stack testing methods,[11,12] and so have not received much regulatory attention thus far. FTOHs dominate the volatile PFAS at a reported median concentration of 50 µg/m^3,

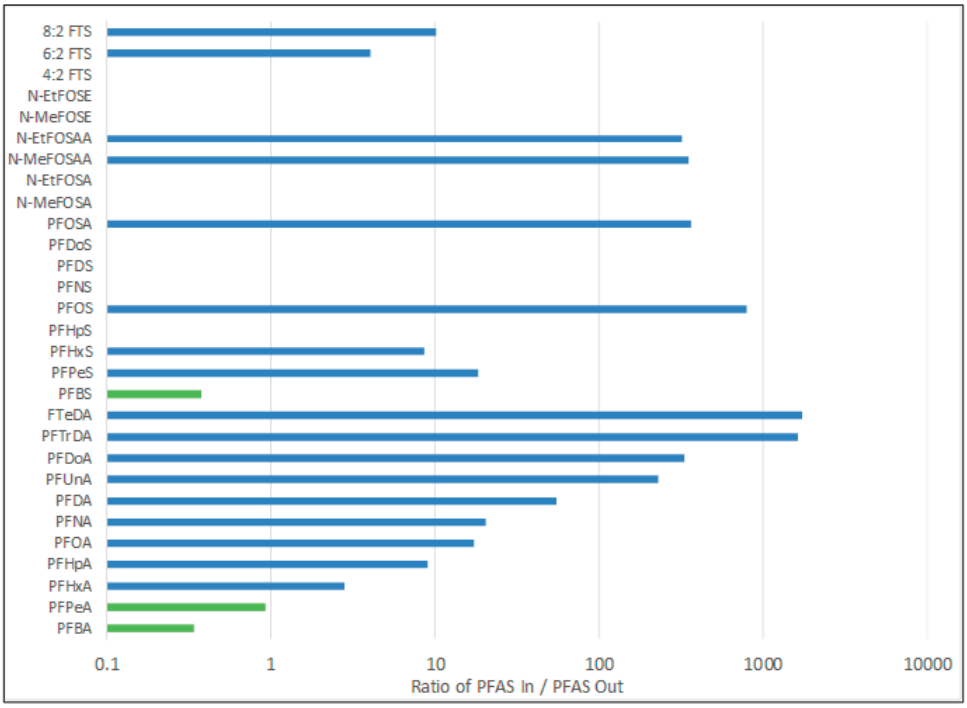

Figure 1. Ratios of PFAS influx:outflux rates in a study at a Vermont landfill.[5]
Note: Ratios greater than 1 (blue bars) indicate PFAS influxes in wastes greater than PFAS outfluxes in leachate.

though the variability across landfills spans several orders of magnitude.[9]

The presence of PFAS in landfill gas (LFG) in several studies implies that landfills emit PFAS to ambient air, and elevated concentrations of these compounds have been detected at locations downwind of both landfills and wastewater treatment plants.[13-15] Estimates of the magnitude of emissions of volatile PFAS, however, are uncertain. Modern sanitary landfills typically employ landfill gas collection systems, but these systems do not generally collect 100% of generated LFG. Fugitive LFG emissions vary according to stages of landfill cell development, with active cells typically collecting smaller fractions than closed cells. EPA provides a default LFG collection efficiency of 75%,[16] but most landfills probably achieve higher overall collection rates. Based on estimates of landfill gas emissions that Sanborn Head has developed for clients using LandGEM,[17] well-designed modern landfills probably release only ~10–20% of generated landfill gas as fugitive emissions. Preliminary research data indicate that FTOHs are not attenuated in soil,[9] and hence fugitive PFAS emission rates likely follow fugitive LFG releases.

Collected LFG is typically treated by combustion, either in flares or energy recovery devices such as internal combustion (IC) engines or turbines. EPA lists default AP42 destruction efficiencies for halogenated organic compounds to be 98% (flares), 93% (engines), and 99.7% (turbines), though these values vary considerably among devices.[16] Stable PFAS with strong carbon-fluorine bonds are potentially difficult to destroy, and hence PFAS emissions from combustion devices are possible. Products of incomplete combustion (PICs) are likely released as well. EPA has developed PFAS stack testing Methods OTM 45[11] and OTM 50,[12] which are designed to measure PFAS at downstream and upstream locations of combustion devices, respectively.

As these methods have not been publicly applied at landfills, the fate of PFAS in combustion systems is at this time unknown. Some data are anticipated soon from an in-progress study to measure PFAS emissions from two sources.[18] One test involves emissions from an IC energy recovery engine, and data will be able to compare polar PFAS emissions using OTM 45 against the volatile PFAS flux measured in the landfill gas feed. The OTM 45 analyte list, however, does not include either volatile PFAS or potential products of incomplete combustion (PICs). Hence, the test will be limited to estimates of stable polar PFAS formed during combustion. A second test of a landfill gas flare is extending OTM 45 to quantify FTOHs and other nonpolar PFAS, as well as using OTM 50 to measure short-chain products of incomplete combustion such as CF_4 and C_2F_6. These tests are expected to provide some information on PFAS emissions, but given variability and likely data gaps, considerably more testing will be required throughout the landfill industry in order to better understand PFAS emissions.

Additional landfill sources may also require assessment. There is a recent trend to convert collected LFG into pipeline quality renewable natural gas (RNG), though the fate of PFAS in RNG systems has not to our knowledge been studied. Leachate evaporation systems also burn LFG, and hence represent another potential source of PFAS emissions.

Recognizing the presence of PFAS in landfill gas, three recent studies have attempted to estimate the overall

significance of PFAS emissions from landfills. Based on data collected at landfills across the United States, Barlaz, et al.[9] estimate that the aggregate environmental flux from landfill gas emissions is about two times greater than PFAS released in landfill leachate. Tolaymat, et al.[19] estimate landfill gas emissions of PFAS are 60% of the national leachate flux. Focusing on three Florida landfills, Lin, et al.[10] conservatively estimate the PFAS mass flux in landfill gas to be comparable to or greater than the mass leaving in landfill leachate. These studies, though uncertain and based on limited data, indicate that aggregate PFAS emissions to air from U.S. landfills in aggregate are within a factor of two of PFAS released in leachate. However, there is likely considerable variability in the emissions from individual landfills, as reported PFAS concentrations in LFG among landfills vary over 2–3 orders of magnitude. Tools to measure emissions are developing in practice. In addition to OTM 45 and OTM 50, unpublished OTM 55 is under development to measure non-polar semi-volatile PFAS,[20] and research methods[9] allow for quantification of volatile PFAS in landfill gas.

Impacts of PFAS Air Emissions

Evaluating the human health and environmental impacts due to PFAS emissions from landfills is difficult. Toxicity data and guideline concentrations have not yet been developed for volatile PFAS. Traditional modeling analyses can at least be used to estimate concentrations in ambient air that potentially result from landfill emissions. Modeling analyses for air toxics typically start with concentrations in LFG. Combined with estimates of LFG generation rates and capture efficiency, and assumed destruction efficiencies of combustion equipment, LFG emissions can be estimated and used as inputs to dispersion modeling to estimate ambient air impacts of PFAS. Since all of the emission estimates are based on PFAS concentrations in LFG, it is useful to define a dilution factor *DF* as:

$$DF = \text{Dilution Factor} = \frac{\text{Concentration of PFAS in Landfill Gas}}{\text{Concentration of PFAS in Ambient Air Due to LFG Emissions}}$$

DF values can be estimated from previous air toxics modeling studies. As defined, *DF* applies to PFAS in raw LFG released in fugitive emissions and the portion not modified or destroyed in combustion treatment. Products of incomplete combustion potentially measured in stack emissions require separate consideration. Table 1 provides values of *DF* from modeling studies that we have conducted for landfill clients. The goal in these studies was demonstration of compliance with regulatory standards or target risk limits. Values of *DF* range considerably based on landfill/source configurations, LFG generation, collection and destruction rates, distances to fence lines and receptors, local topography, meteorological data, and other landfill-specific considerations. The broad ranges in *DF* values likely reflect variability among landfills. The median *DF* values are of a few million for each of the fugitive, IC engine, and flare sources, which suggests that the effects of the diffused nature of the fugitive emissions (as spread out over a landfill surface) compensates for the assumed destruction in LFG treatment devices (IC engines and flares).

The values of *DF* can be used to estimate the order of magnitude impacts to ambient air. For example, a PFAS concentration of 50 µg/m^3 in LFG and a *DF* of 2,000,000 indicate a PFAS impact of 0.000025 µg/m^3 in ambient air. This value is within the range of reported ambient background measurements of 8:2-FTOH (one of the PFAS found at the highest concentration in most LFG samples from completed studies), and many orders of magnitude smaller than the 1,800 µg/m^3 toxicity-based screening-level derived from an acute exposure study in rats.[21]

This study also found that a small amount (~0.1%) of 8:2-FTOH metabolized to perfluorooctanoic acid (PFOA). EPA has not issued inhalation toxicity values for any PFAS, but has developed oral toxicity data for PFOA. Conjecturally, a PFOA exposure rate 7×10^{-9} µg/kg-d can be estimated assuming a 0.1% conversion of the 0.000025 µg/m^3 ambient air concentration in conjunction with standard adult risk assessment assumptions of a 20 m^3/day inhalation rate and a 70 kg body weight. This exposure estimate is several orders of magnitude lower than EPA's current reference dose of 3×10^{-5} µg/kg-d,[22] which suggests that there may be no significant risks to human health. However, this conjectural estimate is tempered by the need for more study of 8:2-FTOH (and other volatile PFAS) toxicity.

Table 1. Dilution Factors (*DF*s) Obtained in Dispersion Modeling Studies.

Emission Source	Number of Studies	Dilution Factors Min.	Max.	Median
Fugitive	11	30,000	9,600,000	2,000,000
C Engine	2	160,000,000	220,000,000	190,000,000
Flare	8	46,000,000	260,000,000	73,000,000

Landfill-specific conditions may also need to be considered, as emissions may vary considerably among landfills, and site-specific factors may affect the degree of their atmospheric dilution.

Summary

Volatile PFAS have been identified in landfill gas, consistent with studies made over a decade ago that identified elevated concentrations of FTOHs, FOSAs, and FOSEs downwind of landfills and wastewater treatment plants. This preliminary analysis suggests impacts from LFG emissions are in the range of reported background measurements in ambient air. Landfill managers may wish to conduct site-specific studies due to variability and uncertainty factors. **em**

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In Next Month's Issue…

Environmental Justice

Now that many new environmental justice (EJ) state and federal drivers have had few years to take hold, what effects are we seeing on industry, state and local governments, tribes, and communities? The April 2025 issue will examine key EJ drivers and discuss progress and continuing challenges.