KRAFT PULPING

Evaluation of the U.S. EPA–recommended approach to predicting air emissions from pulp and paper industry landfills

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ABSTRACT

There is growing indication that the pulp and paper industry will be required to comply with Clean Air Act (Title V) requirements to estimate emissions of bulk gases and hazardous air pollutants (HAPs) from landfills. One method for estimating such emissions involves the use of the Landfill Air Emissions Estimation Model (LAEEM), which was developed and calibrated specifically for municipal solid waste (MSW) landfills. There is concern about the applicability of LAEEM because the materials placed in industry landfills are considered to be different from those in MSW landfills; as a result, emissions will likely be lower than model predictions.

This study examined the basis of LAEEM and its calibration, and explored alternative predictive approaches. The authors concluded that LAEEM, when defined in terms of the default AP-42 factors, does not accurately represent uncontrolled methane and HAP emissions from industry landfills. It does not account for the attenuating effects of biodegradation and adsorption, nor does it account for the potentially slower migration of landfill gas through a fully saturated landfill zone or the oxidation of methane migrating through landfill covers. With adjusted calibration factors that are based on field observations, LAEEM may provide more realistic estimates of methane and HAP emissions from industry landfills.

Application:

This paper examines the suitability of applying the LAEEM model and the AP-42 emission factors to the prediction of bulk gas and HAPs from pulp and paper landfills. This research will be of interest to those who wish to estimate pulp and paper industry landfill or greenhouse gas emissions.

THE PULP AND PAPER INDUSTRY will be required to comply with Clean Air Act (Title V) requirements to estimate emissions of bulk gases and hazardous air pollutants (HAPs) from landfills. The U.S. Environmental Protection Agency (EPA) has proposed to use the Landfill Air Emissions Estimation Model (LAEEM) for this purpose. This model was developed as a rapid method for screening potential methane and HAP emissions from municipal solid waste (MSW) landfills. The rate of methane generation is predicted from a simplified first-order rate expression governing the degradation of organic matter by anaerobic microorganisms.

To compute the total quantity of emissions, the estimated methane volume is summed with volumes of carbon dioxide, nonmethane organic carbon (NMOC) compounds, and HAPs, the quantities of which are estimated from a series of assumptions. Collectively, these are referred to as *uncontrolled landfill gas emissions.* Site-specific data may be used to calibrate the parameters that are used to estimate emissions or, in their absence, default values may be drawn from New Source Performance Standards (NSPSs) and emission guidelines or from the EPA compilation of air pollution emission factors [AP-42] *(1).* Where landfill gas emissions are controlled, the uncontrolled landfill gas emissions are corrected with a collection system efficiency, which is based on emission factors that account for the controls placed on the gas collection and transportation system.

There is concern over the ability of LAEEM to estimate such emissions from industry landfills because the model is based on data gathered for MSW landfills. Compared with MSW landfills, the contents of pulp and paper industry landfills are expected to decompose at lower rates and ultimately to release lower amounts of methane and NMOCs (a) because they are either deficient in nutrients (especially nitrogen) or are inorganic and (b) due to their higher degree of saturation. Similarly, the default landfill emission factors given by AP-42 are based largely on data from MSW landfills. Consequently, the extrapolation of MSW landfill emission data to industry landfills may not be appropriate.

We investigated the suitability of applying LAEEM and the AP-42 landfill emission factors to the prediction of bulk gas and HAP emissions from pulp and paper industry landfills and to explore alternative predictive approaches. This paper reports on the findings from the work.

EPA LANDFILL AIR EMISSIONS ESTIMATION MODEL

Basis of model

The EPA Landfill Air Emissions Estimation Model (LAEEM) is a PC-based automated estimation tool for calculating uncontrolled gas emissions from municipal solid waste (MSW) landfills. LAEEM was developed for EPA by Radian Corp. *(2)* in response to the requirements of Sections III(b)

Source	k, year^{-1}	L_0, m^3 CH$_4$/Mg waste
EPA AP-42 *(5)*	0.04	100
EPA CAA *(2)*	0.05	170
Huitric and Soni *(6)*	0.03–0.04	39.9–125.7

I. Comparison of default and measured values for k and L_0

Component	Percent by weight	Moisture, %
Organics		
Paper	34.0	6
Yard waste	18.5	60
Food wastes	9.0	70
Plastics	7.0	2
Cardboard	6.0	5
Textiles	2.0	10
Wood	2.0	20
Leather	0.5	10
Rubber	0.5	2
Subtotal: 79.5%		
Inorganics		
Glass	8.0	2
Tin cans	6.0	3
Other metals	3.0	3
Dirt, ash	3.0	-
Aluminum	0.5	2
Subtotal: 20.5%		

II. Typical composition and moisture content of a U.S. MSW landfill (8)

and III(d) of the Clean Air Act (CAA) to control gas emissions from MSW landfills. The model was intended to serve as a quick method for screening potential methane and HAP emissions from MSW landfills to determine the applicability of the control requirements of the CAA regulations. This role is reflected in the model's simplicity, since it is based on the assumption that gases are generated from the first-order decay of organic materials—a concept that has been widely used in the past to model methane generation from MSW landfills. With the assumption that landfill gas acts as a carrier for NMOCs and HAPs, emission estimates of these compounds are made from the total landfill gas flow rate, based on the further assumption that landfill gas is primarily an equal mixture of methane and carbon dioxide. AP-42 emission factors were subsequently introduced to the model to provide guidance for estimating emissions for inventory purposes and control equipment design.

EPA's approach was to use the most simplified model available that is consistent with fundamental principles *(3)*. The model selected as the basis for LAEEM was the Scholl Canyon model, named after the Scholl Canyon Landfill in Los Angeles, CA *(4)*. It is a first-order, single-stage model in which kinetic rate coefficients are empirically adjusted to reflect changes in refuse moisture content and other landfill conditions. The Scholl Canyon model assumes that the gas production rate is at its peak upon initial waste placement and that anaerobic conditions are established immediately. Gas production is then assumed to decrease exponentially as a first-order decay. The model allows for division of the landfill into modules (annual refuse accumulations) to account for different ages of the refuse accumulated over time. Assuming that the refuse has been accepted at the same annual rate over time (i.e., all modules are the same), the following fundamental model equation is derived:

$$Q_{CH_4} = L_0 R\,(e^{-kc} - e^{-kt}) \qquad (1)$$

where

Q_{CH_4} = the methane released up to time t, m^3/year
L_0 = the lifetime methane generation potential capacity of the refuse, m^3/Mg
R = the average annual refuse acceptance rate during active life, Mg/year
k = the first-order decay or methane generation rate coefficient, year^{-1}
c = the time since landfill closure, year
t = the time since the initial refuse placement, year.

Model parameters

The solution of Eq. 1 requires information for several parameters. Site-specific data are generally available for R, c, and t. When waste acceptance rate data are poor, R can be determined by dividing the mass of refuse in place by the landfill age. Also, nondegradable wastes should be subtracted from the accepted mass to prevent overestimation of methane generation. The accuracy of methane (and therefore total gas) generation estimates greatly depends on the values assigned to the two landfill-specific parameters: k, the first-order decay rate coefficient, and L_0, the lifetime methane generation potential. Estimation of these two parameters has been relatively controversial because of the limited database upon which recommended default values were based. Values for k and L_0 are preferably estimated from gas generation data, but these are not likely to be available over the requisite long periods of time.

The LAEEM model may be used with site-specific data for all the information needed to generate emission estimates, or it can be used with two different sets of default values, as discussed in the following section. One set of default values (the CAA defaults) is used for estimating the emissions to determine the applicability of the CAA

regulations for MSW landfill emissions, specifically the New Source Performance Standards (NSPSs) for new MSW landfills and the emission guidelines for existing MSW landfills. The CAA default values provide emission estimates that would reflect the expected maximum emissions and would generally be used only to determine the applicability of the regulations to a landfill. To estimate the actual emissions in the absence of site-specific data, a second set of default values (the AP-42 defaults) is provided in the model. The AP-42 default values in the model are based on emission factors from the EPA's compilation of emission factors, AP-42 *(5).* The AP-42 default values provide emission estimates that should reflect typical landfill emissions and are the values suggested for use in developing estimates for state inventories.

First-order decay rate coefficient, **k.** The coefficient k is an estimate of the methane generation rate in a specific landfill; the higher the value of k, the faster the methane generation rate from each module decreases with time. Although the value of k is known to be a function of solid waste moisture content, nutrient availability, pH, and temperature, there is no mechanistic attempt to express the sensitivity of k to these variables in the model. Estimates of k are, therefore, empirical. In the absence of site-specific data, the two default options for k recommended by EPA are 0.05 year^{-1} for the CAA option and 0.04 year^{-1} for the AP-42 option (**Table I**).

Methane generation potential, **L_0** The theoretical value of L_0 depends solely on the type of solid waste and is based on an empirical formula representing the chemical composition of the solid waste components. The higher the cellulose content, the greater the value of L_0. In the absence of landfill-specific data, the two default L_0 values recommended by EPA are 170 m^3/Mg of waste for the CAA option and 100 m^3/Mg of waste for the AP-42 default option. (Table I).

Recently, an opportunity to test the validity of the default values for k and L_0 arose at MSW landfills operated by the Los Angeles County Sanitation Districts. These landfills were among the first in the United States to install landfill gas recovery systems and now have over 20 years of gas generation data. Site-specific k and L_0 parameters were estimated using a simple spreadsheet first-order model that is virtually identical to LAEEM *(6).* As shown in Table I, the calculated values of k and L_0 were somewhat lower than the AP-42 default values, suggesting that perhaps the default values are conservative.

Nonmethanogenic organic compounds and hazardous air pollutants. LAEEM uses a selection of emission factors in concert with the total gas flow rate to estimate the mass of NMOC and HAP emissions. In the absence of site-specific data based on landfill gas analysis, EPA recommends three default total NMOC concentrations (expressed as hexane equivalents) for use in the model *(2):* one for the CAA default option (4,000 ppmv) and two for the AP-42 default option [one for co-disposal (2,240 ppmv) and one for non-co-disposal (595 ppmv)]. These factors were developed from gas concentrations at MSW landfills. For individual NMOCs and HAPs (where HAPs are a subset of NMOCs), EPA recommends default concentrations for 46 compounds that may be used in LAEEM when site-specific data are not available *(2).*

Other model features. Although other assumptions in the LAEEM model may cause it to overestimate gas emission rates, the effect is the same regardless of the intended application of the model, i.e., MSW or pulp and paper landfills. These assumptions include:

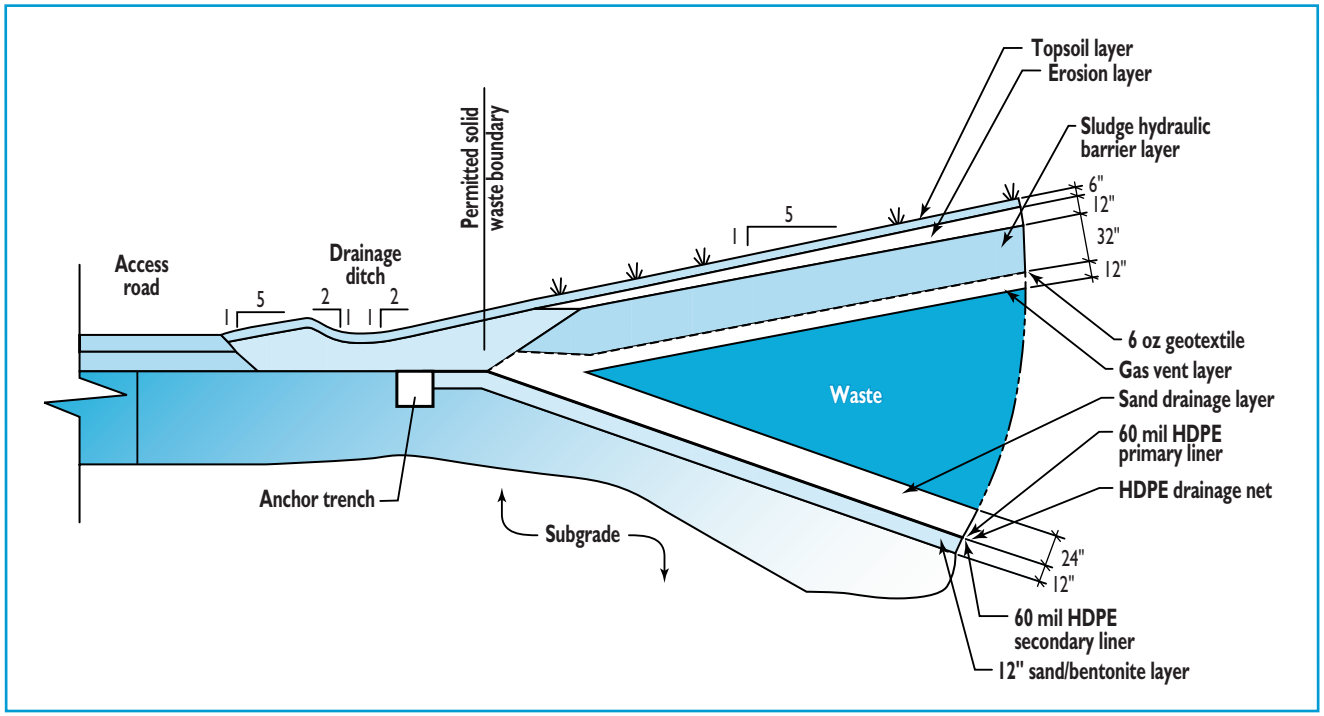
- **Environmental factors.** Nutrient availability is assumed to be the only limiting factor on bacterial activity in a landfill *(7).* Other factors that limit gas production rates, such as moisture content, temperature, pH, and nature of landfill contents, are not considered.
- **Impact of landfill cover.** The model does not allow for changes in landfill cover depth or biological and/or chemical reactions that might take place in the cover material or the landfill itself. All of these parameters can attenuate or reduce uncontrolled landfill gas emissions.
- **Gas production rate.** The model assumes that maximum gas production occurs shortly after landfill closure. This may be true of landfills in warm-climate areas, but in cold-climate areas, maximum methane production rates may be greatly attenuated and/or delayed.
- **Air emissions.** The prediction of NMOC or HAP emissions is not based on fate modeling approaches that are typically used in the wastewater treatment field. Rather, NMOC and HAP emissions are estimated assuming that methane acts as a transport gas for the NMOCs and HAPs *(3).*

IMPLICATIONS OF USING LAEEM IN THE PULP AND PAPER INDUSTRY

A simple comparison of the composition of MSW and pulp and paper industry landfills is useful in understanding the limitations of applying LAEEM to industry landfills.

Characteristics of municipal solid waste landfills

The typical composition and moisture content of MSW landfilled in the United States has been reported by Tchobanoglous *et al. (8),* as shown in **Table II.** Using these data, a compos-



ite moisture content of about 21% can be calculated. MSW landfills are designed and operated to exclude external water from precipitation and runoff. These landfills are also operated to achieve high in-place densities, typically 37–44 lb/ft^3. MSW landfills are unsaturated, with void space that facilitates gas flow.

Characteristics of solid wastes disposed of in pulp and paper industry landfills

NCASI has collected data that characterize pulp and paper industry landfills and the materials placed in them. **Figure 1** and **Tables III–V** *(9–11)* summarize some of this information. Table III indicates the type and proportions of treatment residuals currently being placed in company landfills. Figure 1 and Table III present industry-wide statistics regarding the types and proportions of materials placed in industry landfills. Table IV presents wastewater treatment residuals properties prior to landfilling. The properties of landfilled residuals may change over time in response to precipitation, landfill design, consolidation, biological activity, etc. Table V presents some statistics on overall amounts of material landfilled by the industry nationally, but inferences as to the makeup of a "typical" or "representative" landfill cannot be drawn from the tables.

While the tables and figure present data on the characteristics of pulp and paper industry solid wastes managed by landfilling and of the landfills themselves, a review of data on the specific contents of a limited number of landfills indicates that differences between facilities in amount and type of production, power generation and energy recovery operations, regulatory requirements, and beneficial use opportunities yield wide variations in landfill characteristics with regard to design, type of materials contained, and relative quantities of each type of material present in any particular industry landfill.

MSW landfills probably have much more heterogeneous content than pulp and paper industry landfills, but ironically, there may be less variation in composition between MSW landfills than there is between pulp and paper industry landfills. It is therefore difficult to make specific and direct comparisons of pulp and paper industry landfills to MSW landfills. However, it is possible to make general statements about how differences between the types of materials in MSW landfills and those in pulp and paper industry landfills would lead to differences in the ways in which landfill gas and associated compounds are generated and emitted. The behavior of any specific pulp and paper industry landfill would, of course, depend on the particular characteristics of that landfill.

Landfill gas generation potential—estimation of k and L_0

MSW landfills contain a high proportion of yard wastes (18.5%, Table II), which are rich in nitrogen. This and other nitrogen-rich material in MSW

Property	Range	Median value
Solids concentration, %	8–75	35
Porosity, %	73–86	80
Density (wet basis), lb/ft^3	48–72	69
Ash content, %	10–75	53

IV. Properties of wastewater treatment residuals sent to pulp and paper industry landfills (NCASI) (9, 10)

Landfill characteristic	Range	Median value
Capacity, acre	1.5–500	28
Current use, acre	0.4–200	11
Final depth, ft	5–180	30
Final volume, yd^3	1,000–1,300,000	12,000

V. Pulp and paper industry landfill characteristics (11)

provide sufficient nutrients, at least in parts of the landfill, to support vigorous anaerobic biodegradation of the organics present in the landfill. Pulp and paper industry landfills do not normally contain these materials. While secondary wastewater treatment residuals from pulp and paper mills may have carbon-to-nitrogen ratios that favor biodegradation of organic material, only 1% of the residuals sent to company landfills are such biosolids.

Table III indicates that 56% of landfilled wastewater treatment residuals are a combination of residuals from primary and secondary wastewater treatment, with the majority of the combination usually being from primary treatment. Thirty-eight percent of landfilled residuals are primary residuals alone. Primary residuals contain only 0.27% nitrogen, and even combined primary and secondary residuals contain only 0.85% nitrogen (median values) *(12)*. These data show that wastewater treatment residuals placed in pulp and paper industry landfills tend to be deficient in the nitrogen needed to support anaerobic degradation.

The contention that nitrogen deficiency suppresses gas generation is supported by results of laboratory anaerobic digestion tests on pulp and paper wastewater treatment residuals. Digester gas generation rates were observed to be 0.4–0.55 m^3/kg volatile solids destroyed *(13)*. This is about half the value for typical municipal wastewater treatment plant residuals. For a median residual solids content of 35% (Table IV), L_0 can be calculated from these data to be 44–88 m^3/Mg wet residuals. This is one-third to two-thirds of the AP-42 default value for L_0 derived by EPA for MSW landfills.

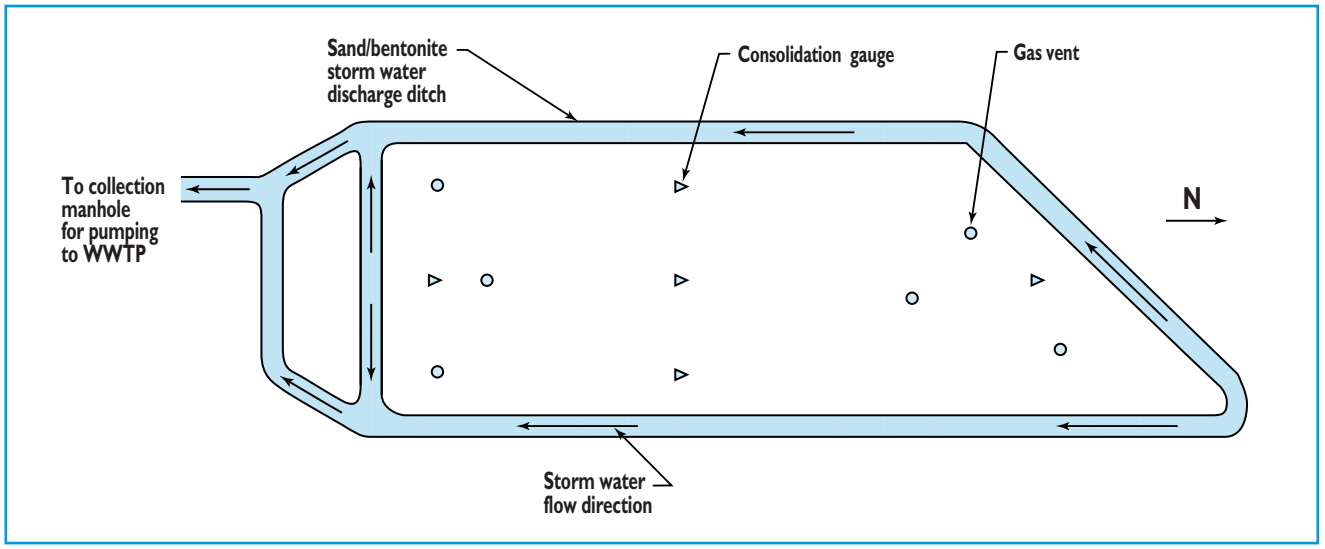
HAPs in one or more leachates	No. of samples	No. of nondetects	HAP CONCENTRATION, µg/L Median[a]	Maximum
Benzene	18	17	ND[b] (10)	1.6
Chlorobenzene	18	17	ND (5)	5.4
Chloroform	18	17	ND (5)	24
1,1-Dichloroethane	13	12	ND (3)	9.2
1,2-Dichloroethane	18	17	ND (5)	5.9
t-1,2-Dichloroethylene	13	12	ND (3)	19
Ethylbenzene	13	11	ND (3)	2.1
Methyl ethyl ketone	13	11	ND (100)	2917
Tetrachloroethylene	13	12	ND (3)	3.4
Toluene	18	7	35	820
Trichloroethylene	18	17	ND (5)	2600
Trichlorofluoromethane	12	11	ND (3)	6.6
Xylene	12	11	ND (3)	23

a Where nondetect values are identified as medians, the value in parentheses is the lowest detection level reported.
b Nondetect

VI. Typical HAP concentrations in pulp and paper industry landfill leachates (14)

Some landfills may contain only combustion ash residues (coal ash, wood ash, and treatment residuals ash), which constitute over 30% of the materials placed in industry landfills (Fig. 1), or mixtures of ash and causticizing materials (lime mud, green liquor dregs, and lime slaker grits). These materials are predominantly inorganic and are therefore unlikely to biodegrade and produce significant quantities of landfill gas. Additionally, these materials have pH values that are typically outside those required for biological activity—and well outside those amenable to methanogenic activity.

The remaining "Miscellaneous" portion shown in Fig. 1, which is sometimes placed in industry landfills, contains varying amounts of organic material. But most of the organic content is cellulose or bark, both of which are deficient in nitrogen and other nutrients. Thus, materials placed in pulp and paper industry landfills are either deficient in nutrients (especially nitrogen) to support anaerobic decomposition or they are inorganic and not subject to anaerobic decomposition to produce landfill gas. Taken together, these observations indicate that the potential for pulp and paper industry landfills to produce gas is lower than it is for MSW landfills. This conclusion is corroborated by the observation that, as of this writing, there are no commercial (i.e., for-profit) landfill gas collection systems installed at any U.S. pulp and paper industry landfills, whereas such systems are frequently found at MSW landfills.



2. Gas emission predictions using LAEEM

Using the default MSW landfill-based values for k and L_0 in LAEEM will likely lead to an overestimation of landfill gas generation rates from industry landfills. Field and laboratory experiments could be done to confirm this conclusion. NCASI plans to initiate laboratory studies in 1999.

Estimates of HAP emissions

Much of the data on NMOCs and HAPs that were used to derive default parameters in LAEEM were based on a limited database; these data were collected primarily at Californian landfills. These landfills were nearly all MSW landfills, with a few co-disposal landfills included in the database. There were sufficient air pollutants present in these test sites to warrant the inclusion of default emission factors for 46 air pollutants in LAEEM.

In comparison, **Table VI** lists concentrations of HAPs that were measured in 22 pulp and paper industry landfill leachates *(14).* The data denote the median and maximum values found for each leachate constituent for which analyses were performed. Data are presented only for those constituents that were found to be above detectable levels in one or more leachates. The range of values for some constituents is large; this is thought to be related to differences in solid waste composition and age, landfill design, or sample collection techniques. The data contain a large number of nondetect values. These values represent instances where analyses were conducted and the compound was either not found or not quantified. The data were ranked by the limit of detection when identifying median and maximum values.

More than 30 HAPs were found, but only 13 HAPs were detected in one or more leachates. Ten of the 30 HAPs were detected only once, suggesting that their presence is not typical of industry leachates. Although no direct inference is possible regarding the concentration of HAPs in landfill gas from leachate data, the absence of many of the AP-42 HAPs in pulp and paper industry leachate suggests that there will be fewer HAPs in industry landfill gases. Of the 13 HAPs shown in Table VI, all but toluene were at below-detectable limits in the leachate for all but 1 of the samples measured. Ten of the 13 HAPs occurred at relatively low levels, even at the maximum concentration observed, and so will correspond to low levels in the vapor phase. Of the remaining three, the Henry's law coefficient for methyl ethyl ketone is relatively low, so low vapor concentrations might also be expected for this compound. However, the Henry's law coefficients for toluene and trichloroethylene are relatively high, and significant vapor concentrations might be expected, particularly for the location where trichloroethylene was found. As an aside, in the relatively anaerobic environment of a landfill, trichloroethylene can degrade, via the well-established sequential dehalogenation process, to vinyl chloride, which is of greater environmental concern than trichloroethylene.

On the whole, based on these data, the likelihood of significant HAP emissions in industry landfill gas is very low. Thus, use of the default HAP concentrations in LAEEM will likely overpredict HAP emissions from most industry landfills. Measurement of HAPs in industry landfill gases would likely verify this supposition.

Loss of methane by oxidation in landfill covers

Over the past 5 years, research has demonstrated the feasibility of methanotrophic bacteria oxidizing methane in landfill gas emissions. The reported extent of removal has varied from the lower levels of 10–20% *(15),* to almost complete removal *(16),* as well as values in between *(17).* Methanotrophic bacteria oxidize methane to carbon dioxide by using the methane

monooxygenase (MMO) enzyme system.

Kjeldsen *et al. (16)* also demonstrated that trichloroethylene is removed in soil covers by invoking the cometabolic degradation mechanisms of the methanotrophic bacteria, which may, in part, address the emissions reported here. Work by other investigators [Refs. 2–7 in *(17)*] has shown that methanotrophic methane oxidation in aerated cover soils can be a major natural control on methane emissions. For industry landfills, where landfill gas is generally not recovered but is allowed to migrate through the cover as uncontrolled emissions, a portion of the total gas volume may be reduced by the amount of methane oxidation that can occur in the cover with corresponding reductions in NMOC and HAP emissions. LAEEM does not account for methane oxidation and may therefore overpredict emissions by this amount.

Factor affecting HAP movement	Included in LAEEM	Significance for pulp and paper industry landfills
Volatilization	No	Generates HAPs from liquid phase. Data are generally unavailable, except for leachate.
Convection	Yes	Results from landfill decomposition. Sweeps HAPs from landfill into atmosphere.
Diffusion	No	Causes HAP releases, even from nondecomposing landfills.
Adsorption	No	The organic content of industry landfill materials may provide a significant retardant to HAP releases.
Biochemical transformation	No	Microbial degradation can greatly reduce HAP emissions.

VII. Significance of factors affecting HAP movement

ALTERNATIVE APPROACHES TO ESTIMATING GASEOUS EMISSIONS FROM LANDFILLS

The recent data shown in Table I, which illustrate the potential overconservatism of default values for the major model parameters k and L_0, suggest that alternative values of k and L_0 warrant investigation. Using typical dimensions for an industry landfill from Table V, the effect of using k and L_0 with half the default AP-42 values assigned to LAEEM is illustrated in **Fig. 2.** Two curves are shown, indicating the gas emission rates relative to the maximum emission rate predicted using the default AP-42 k and L_0 values, where each curve corresponds to the gas velocity associated with different pairs of values for k and L_0 over a 60-year life of the landfill. The upper curve, simulating the response for the AP-42 default values, shows a much larger peak gas velocity than that achieved by the lower curve, which is simulating the response for the reduced k and L_0 values. This suggests that a large reduction in methane generation rates (and corresponding HAP emissions) may be achievable with the adjustment of k and L_0 values.

HAP emissions from landfills are influenced by the following factors, each of which has the potential to significantly affect the rate of emissions:

- The rate of volatilization from liquid into gas
- The rate of methane and carbon dioxide gas convection, measured as vertical velocity
- The rate of molecular diffusion of gas constituents from high concentration areas within the landfill into the atmosphere
- The rates of adsorption of HAPs onto solid materials within the landfill
- The microbial transformation of HAPs within the landfill into other chemical compounds.

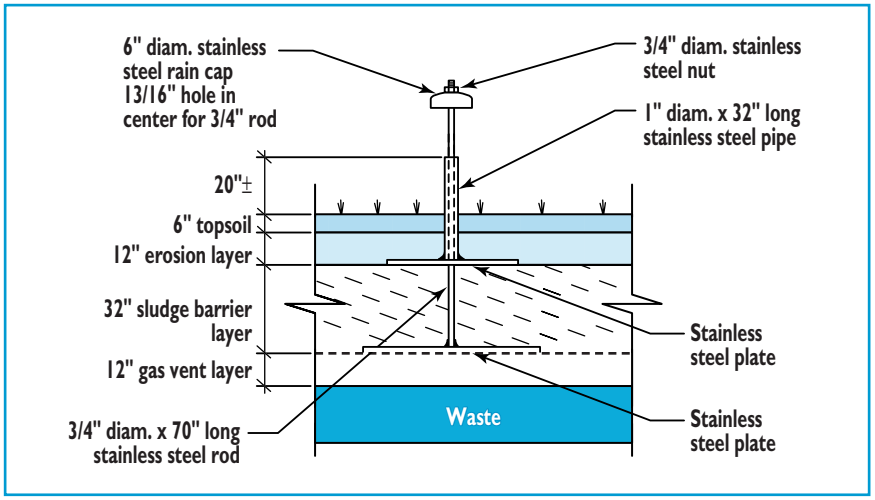
The significance that each factor has on HAP movement within pulp and paper landfills is summarized in **Table VII.** The EPA LAEEM model takes into account only one of these factors, the convection resulting from landfill decomposition. An assessment of the importance of each of the other factors in predicting HAP emissions has been performed and is presented *(18)*. Briefly, a variety of alternative modeling approaches are possible that allow for the incorporation of the above factors, in addition to the convective effect included in LAEEM, to predict HAP emissions.

To estimate HAP emissions from pulp and paper landfills, where lateral subsurface movement beyond the boundaries of the landfill is not of primary concern, the simplest approach is to consider only the vertical movement of gases. A mass balance through a typical cross-sectional element through the landfill yields a partial differential equation; a steady-state simplification of this equation yields:

$$D\frac{d^2c}{dz^2} - v\frac{dc}{dz} - \phi k_b c = 0 \qquad (2)$$

where

D = the effective diffusion coefficient, m^2/year
c = the HAP concentration in the gas phase, mg/m^3
v = the vertical component of gas velocity, m/year
z = the vertical distance, m
ϕ = the landfill porosity, V/V
k_b = the biodegradation rate coefficient, $year^{-1}$.



3. The influence of biodegradation on HAP emissions

HAP concentrations are assumed to be sufficiently low so that they may be modeled in accordance with first-order removal kinetics.

Solution of Eq. 2 yields the concentration profiles for the HAP through the landfill and the landfill surface. The effect of convection in the short term is to increase the emission rate and to decrease it in the long term. Biodegradation decreases both short- and long-term emissions, although HAPs may be formed as by-products of biodegradation. The sensitivity of HAP emission rate to changes in HAP biodegradation rate can be examined by isolating the biodegradation of organics in the landfill through simulating the diffusion of HAPs from a closed, nondecomposing landfill. Many HAPs that were previously thought to be nonbiodegradable have been shown to be degraded to various degrees in research related to groundwater and soil remediation *(19–22)*. Unfortunately, these observations have not been demonstrated in landfill biodegradation research investigations at this time.

Figure 3 shows the dependence of the total HAP emission rate on values of biodegradation rate coefficients ranging from 0 to 250 year^{-1}, the range of values expected for AP-42–listed HAPs, relative to the maximum emission rate expected for the case of no biodegradation. Biodegradation rate coefficients are taken from various sources in the literature *(23–27)*. The simulation illustrates the degree to which emissions are reduced with increasing biodegradability of the HAPs.

SUMMARY AND CONCLUSIONS

Summary

LAEEM is derived from a simplified first-order decomposition model, using default decomposition rates, methane generation potential, and HAP gas concentrations obtained from studies of municipal solid waste landfills. Field studies have shown that even for municipal solid waste, there is significant variation in the values of these parameters, and the user of LAEEM for MSW landfills would therefore be well advised to consider determining actual values through a field calibration study.

Compared with MSW landfills, pulp and paper industry landfills are expected to decompose at lower rates, and ultimately to release lower amounts of methane and nonmethane organic compounds per unit volume of solid waste, because of their higher moisture content and different solid fraction compositions.

Although gas composition data for pulp and paper industry landfills are not readily available, the absence of a number of HAP compounds in industry landfill leachate suggests that the usage of LAEEM default HAP gas concentrations would seem both inappropriate and inaccurate. Because industry landfills are filled with a more homogenous set of materials than MSW landfills, many of the HAP compounds may be absent in industry landfill gas.

The slower rate of decomposition expected in industry landfills would likely downplay the predominance of convection as a transport mechanism for the HAP gas compounds that are present. Although diffusion can still serve as a means to release the HAP gases, the saturated conditions present in many industry landfills would greatly retard gas emissions. The combined effects of adsorption and biodegradation could also serve to reduce the HAP gas emissions.

Conclusions

The following conclusions may be drawn:

- Based on the above analyses, the EPA Landfill Air Estimation Model (LAEEM), using the default AP-42 constants for k and L_0, is not likely to be an accurate representation of methane and HAP emissions from pulp and paper industry landfills.
- The EPA LAEEM, with adjusted k and L_0 values based on field data, may provide more realistic estimates of methane emissions from pulp and paper industry landfills.
- The EPA LAEEM, even with adjusted k and L_0 values, will probably still not provide a realistic estimate of HAP emissions from pulp and paper industry landfills. This is because LAEEM does not account for the attenuating effects of biodegradation and adsorption, nor does it account for the potentially slower migration of landfill gas through a fully saturated landfill zone.

Recommendations

The following recommendations are made:

- Field studies should be conducted to determine k and L_0 values for actual pulp and paper industry landfills.
- Field HAP emission measurements should be conducted at representative pulp and paper industry landfills.
- Additional chemical analyses should be performed on pulp and paper industry landfills to identify potential HAPs in landfill gas.
- A more accurate HAP emission model, using field-calibrated k, L_0, and HAP emission factors, should be developed. **TJ**

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