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Brownfields and Health Risks—Air Dispersion Modeling and Health Risk Assessment at Landfill Redevelopment Sites

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ABSTRACT

Redevelopment of landfill sites in the New Jersey–New York metropolitan area for recreational (golf courses), commercial, and even residential purposes seems to be gaining acceptance among municipal planners and developers. Landfill gas generation, which includes methane and potentially toxic nonmethane compounds usually continues long after closure of the landfill exercise phase. It is therefore prudent to evaluate potential health risks associated with exposure to gas emissions before redevelopment of the landfill sites as recreational, commercial, and, especially, residential properties. Unacceptably high health risks would call for risk management measures such as limiting the development to commercial/recreational rather than residential uses, stringent gas control mechanisms, interior air filtration, etc. A methodology is presented for applying existing models to estimate residual landfill hazardous compounds emissions and to quantify associated health risks. Besides the toxic gas constituents of landfill emissions, other risk-related issues concerning buried waste, landfill leachate, and explosive gases were qualitatively evaluated. Five contiguous located landfill sites in New Jersey intended for residential and recreational redevelopment were used to exemplify the approach.

Keywords: Landfills Emissions Air quality Health hazards Risk analysis

INTRODUCTION

As an important component of the brownfields and urban renewal initiative in the New Jersey–New York (USA) metropolitan area, redevelopment of landfill sites and contaminated/abandoned properties for recreational, commercial, and residential purposes seems increasingly acceptable. Decreasing availability of developable “greenfields” and growing public concern about urban sprawl are forcing developers to look at these alternative sites. In the State of New Jersey, for instance, the Highlands Water Protection and Planning Act virtually bans major development in the 395,000 acres that constitute the core of the northern Highlands region and encourages smart growth in an additional 363,000 acres outside the core. The stated purpose of the Act is to protect the quality of the state’s water supply and preserve open space, but predictably, developers view it as an attempt to choke development. Incidentally, as the Highlands protection bill was nearing passage in the legislature, a golf course was opened at the former site of an abandoned and contaminated quarry in Morris County in northern New Jersey.

Excessive landfill gas emissions can adversely affect public health and well-being. The emissions of concern from most municipal solid waste landfills are mainly methane and nonmethane organic compounds (NMOCs). Methane is not toxic if inhaled but can pose fire and explosion hazards when allowed to accumulate. Also, methane is an asphyxiant and, as a greenhouse gas along with carbon dioxide, contributes to global warming. NMOCs include volatile organic compounds (VOCs), hazardous air pollutants (HAPs), and odorous compounds (e.g., hydrogen sulfide). Certain VOCs and HAPs can cause carcinogenic and noncarcinogenic adverse health effects. VOC emissions also contribute to ozone formation and inhalation of ozone can cause respiratory problems. In an effort to control landfill gas emissions, the US Environmental Protection Agency (USEPA) has adopted New Source Performance Standard (NSPS) 40 CFR (Code of Federal Regulations), Part 60.750, subpart WWW and Emission Guideline (EG) 40 CFR, Part 60.30c. Landfills subject to the NSPS and EG that have a design waste capacity greater than 2.5 million Mg and NMOC emissions exceeding 50 Mg/y are required to install gas control. The NSPS and EG rules do not apply to municipal solid waste landfills that were closed before 8 November 1987. However, most landfills have passive landfill gas collection systems that convey generated landfill gas under barometric pressure gradient to emission stacks from which it is vented to the atmosphere. Active gas collection systems provide a pressure gradient to extract the landfill gas by use of mechanical blowers or compressors.

A properly designed landfill cap or cover system forms a barrier between buried waste and the surface, thereby protecting humans and the environment from exposure to the waste. Also, the landfill leachate collection and control system, which is usually an integral component of a landfill redevelopment project, prevents human contact with the leachate and ensures that leachate is not released into the surrounding environment. However, even when a landfill has been closed, emissions of landfill gas can last for decades, until all nutrients are depleted and both aerobic and anaerobic bacterial activities are negligible (USEPA 2001). Therefore, due diligence demands that the potential health effects of inhalation of residual landfill gas emissions be evaluated before landfill redevelopment for residential, commercial, or recreational purposes. Unacceptably high health risks would call for risk management actions such as eliminating residential units (thereby reducing exposure time and essentially eliminating children from the at-risk population) or introducing stringent...
gas control measures (e.g. active gas venting, high-roof stacks, high-efficiency air filtration systems, etc).

With the use of existing models, a methodology is described herein for estimating airborne contaminant concentrations from residual landfill emissions and for performing a standard risk assessment to evaluate inhalation exposure. The approach was applied to 5 contiguously located landfill sites in New Jersey intended for residential and recreational redevelop-

The health risk assessment was performed in 3 parts. Part 1 describes estimation of landfill gas generation rates based on the USEPA landfill gas model and estimation of air contaminant emissions based on USEPA AP-42 guidance (USEPA 1998). Part 2 describes air dispersion modeling to evaluate atmospheric transport of emitted contaminants and determine receptor exposure point concentrations. The exposure point concentrations provide input for part 3 of the process, quantification of public health risks from inhalation exposure to the contaminant.

**Landfill gas generation and contaminant emission rates**

Municipal solid waste placed in landfills decomposes and produces landfill gas, which consists primarily of methane and carbon dioxide but also contains small percentages of NMOCs. According to the USEPA, landfill gas generation proceeds through 5 stages, starting with an initial aerobic phase during which primary gas production is carbon dioxide, a subsequent anaerobic production of methane, and finally the depletion of bacteria-sustaining nutrients and the ultimate cessation of gas generation (USEPA 1998). The generation of landfill gas is dependent on various factors, such as age, waste composition, moisture content, porosity, density, pH, and temperature. Although landfill gas generation can last several decades, the methane generation potential of landfill waste is usually considered minimal after about 30 y (USEPA 1998).

Estimates of landfill gas generation rates are required for the estimation of hazardous constituent emissions rates and for the design of gas collection, control, and recovery systems. The USEPA requires that the calculation of the maximum expected landfill gas generation rate be performed with Equation 1 or 2 below (NSPS, 40 CFR Part 60.755). Equation 1 was used to estimate the maximum expected gas generation rates. For the landfill sites evaluated, Equation 1 was used to estimate the maximum expected gas generation rate (m3/y); k is methane generation rate constant (y-1); L0 is methane generation potential (m3/Mg solid waste); M is the mass of solid waste in landfill section i; t is age in years of landfill section i (i.e., time since initial placement of refuse); R is the average annual waste acceptance rate (Mg/y); and c is time in years since landfill closure (for active landfill, c = 0).

According to 40 CFR, 60.755, if a collection and control system has been installed, actual flow data can be used instead of or in conjunction with the above equations to project maximum expected gas generation rates. For the landfill sites evaluated, Equation 1 was used to estimate the maximum expected gas generation rate (m3/y), with k = 0.04 y-1 and L0 = 100 m3/Mg (PS & S 2001a, 2001b). The gas generation rate was computed from the initial year of waste acceptance to the year that waste acceptance ceased to 30–40 y beyond. The yearly gas generation rate typically increases to a maximum value and then decreases exponentially to minimal values as time increases. It is noted that the USEPA LandGEM computer model is based on Equation 2 and estimates methane generation rates with the use of average annual refuse acceptance rates, R (USEPA 2001).

Landfill gas survey and sampling are necessary to speciate the NMOC constituents of landfill gas. These include VOCs and HAPs that might be a concern for public health. Landfill gas sampling was conducted with the use of methods recommended in 40 CFR Part 60, Appendix A, and the resulting gas concentrations appropriately corrected for air infiltration (AP-42; USEPA 1998). The landfill gas sampling yielded gas constituent concentrations that were used in the uncontrolled mass emission equation (Eqn. 3) along with the previously estimated landfill gas generation rate (Eqn. 1) to estimate gas constituent emission rates for each identified constituent NMOC of concern (PS & S 2001a, 2001b). Equations 3, which is based on USEPA AP-42 guidance (USEPA 1997, 1998) is

$$M_c = C_c \times 10^{-6} \cdot Q_{p} \cdot M \cdot W \cdot c \cdot 60 \cdot (P / R_{e} T) \quad (3)$$

where $M_c$ is the mass emission rate of the compound (kg/h); $C_c$ is the concentration of the compound (ppmv); $Q_{p}$ is the maximum landfill gas flow rate (L/min); $M \cdot W$ is molecular weight of the compound (kg/kgmol^-1); $P$ is atmospheric pressure (atm); $R_{e}$ is the universal gas constant (L-atm kg^-1 mol^-1 K^-1); and $T$ is temperature (K). Note that landfill emissions are referred to as “controlled” when a gas collection system is installed and the collected gas is combusted through the use of internal combustion engines, flares, or turbines.

The NMOCs of concern are assumed to be those contaminants (among the speciated NMOCs) for which ambient air concentration limits have been listed (USEPA 2003a). The mass emission rates (kg/y) for the NMOCs of concern that were calculated by Equation 3 are shown in Table 1. As described in the following sections, air dispersion modeling of the NMOCs was performed to determine their estimated maximum airborne concentrations within the
vicinity of the landfill sites. The contaminant airborne concentrations represent the receptor exposure point concentrations and were used for the exposure and risk assessment.

**Air dispersion modeling and determination of exposure point concentrations**

Air dispersion modeling was performed to determine the approximate concentrations of contaminants present in the landfill gas emissions at various locations in the vicinity of the landfills. The estimated concentrations were used to quantify potential health risks that might be attributable to exposure to those contaminants. The air dispersion modeling was performed according to the USEPA Industrial Source Complex air dispersion model (ISCST3; version 02035). The ISCST3 model, which is based on the straight-line steady-state Gaussian plume equation for a continuous elevated source, provides options to model emissions from a variety of emission sources, including point sources (e.g., stacks), volume sources, area sources, and open pit sources (e.g., mines; USEPA 1995b). ISCST3 is one of the “preferred” models recommended by USEPA for regulatory modeling exercises (40 CFR Part 51). Although recent USEPA guidance on the use of air dispersion models will result in the eventual adoption of new “next generation” models, such as AERMOD, ISCST3 was used for this study, consistent with current USEPA guidance.

**Air dispersion modeling methodology**

The landfill gas is currently being passively vented at 4 of the 5 landfills evaluated, with equivalent stack diameters of 0.86, 0.94, 0.43, and 0.41 m, respectively. The stack height is 0.91 m at all 4 locations. At the 5th landfill, the landfill gas is currently being flared and combusted for power generation at 4 individual stacks (excluding an emergency generator stack). After completion of the proposed landfill residential and recreational redevelopment projects, active gas venting from individual residences, or other stack locations will replace the current passive/active gas venting from the landfills. The individual active gas venting systems will extract landfill gases from below the foundation with the use of mechanical blowers and vent the gas through a roof-top exhaust, thus minimizing the buildup of landfill gas under the foundations.
or within any occupied interior spaces. Although landfill gas emissions at these closed landfill sites are expected to continue to decrease with time, it was conservatively assumed that the aggregate amount of emissions and resultant exposures would remain approximately the same before and after completion of the proposed development. Therefore, air dispersion modeling was performed on the basis of 4 emission stacks (representing the 4 uncontrolled emissions landfills) with the specified equivalent diameters and 1 equivalent stack representing the controlled emissions landfill. For the controlled emissions landfill site, the stack parameters were determined on the basis of the total cumulative landfill gas flow specified in the Final Operating Permit (NJDEP 2002), assuming average flow velocities and gas exhaust temperatures from the other 4 landfills.

Approximating the 4 individual controlled emissions stacks with 1 equivalent stack located centrally within the landfill was deemed to be sufficiently accurate for the purposes of the dispersion modeling. An emissions release height of 7.6 m was assumed for all stacks, which approximates the roof heights of the residential houses to be constructed. A unit emission rate of 1 g/s (31,500 kg/y) was used for the air dispersion modeling. The modeling results (i.e., contaminant concentrations, µg/m³) were then scaled proportionately to the actual emission rates of the specific contaminants of concern indicated in Table 1. For example, Table 1 shows that the total annual emission for benzene is 440.67 kg/y (on the basis of Eqn. 3). Therefore, if the dispersion model predicts a maximum airborne concentration of 66 µg/m³ (see the Air dispersion modeling results section below) on the basis of a generic gas emission rate of 1 g/s (31,500 kg/y), maximum airborne concentration of benzene could be approximately estimated as (440.67/31,500)·66 (µg/m³) = 0.92 µg/m³. Because the landfill emissions are mostly gaseous, the air dispersion modeling was performed only for airborne concentrations and the ISC particulates deposition option was not activated. Given the anticipated long-term venting of gas emissions, the annual averaging period was selected for estimating exposure concentrations. The model-predicted concentrations represent the combined effects from the 5 emissions sources.

**Air dispersion model inputs**

The ISCST3 model was applied according to the USEPA regulatory default options as required for regulatory air quality analysis (USEPA 1995). In addition, rural dispersion parameters where selected on the basis of the characteristics of the immediate vicinity of the emission sources, and the sources were modeled as point sources. For atmospheric dispersion modeling, meteorological input consists of wind speed, atmospheric stability (which represents the mixing characteristics of the atmosphere), wind direction, and ambient temperature. Five years (1987–1991) of meteorological hourly data from Newark International Airport National Weather Service (NWS) station 14734 with concurrent mixing height data from the Atlantic City station (93755) were used in the analysis. The Newark International Airport NWS station is located very close to the landfill sites and is considered highly representative of meteorological conditions experienced at the site. The receptor grid consists of a polar receptor network centered on the centroid of the polygon formed by connecting the approximate centroidal locations of the 5 landfill sites. For every 10° flow vector, hypothetical receptors were located at 3, 6, 12, 25, 50, 100, 150, 300, 450, 600, 900, 1,200, 1,500, 1,800, 2,100, and 2,400 m downwind of the receptor grid origin, giving a total of 576 receptors.
Table 2. Assumed exposure factors used for the risk assessment. Exposure factors were based on Exposure Factors Handbook (USEPA 1997). If no data is available for the 95th percentile value, the average value is used.

<table>
<thead>
<tr>
<th>Exposure factor</th>
<th>Adult population</th>
<th>Child population</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average value</td>
<td>95th percentile value</td>
</tr>
<tr>
<td>Inhalation rate, IH (m³/h)</td>
<td>0.63</td>
<td>No data</td>
</tr>
<tr>
<td>Exposure time, ET (h/d)</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Body weight, BW (kg)</td>
<td>72</td>
<td>98</td>
</tr>
<tr>
<td>Exposure frequency, EF (d/y)</td>
<td>350</td>
<td>365</td>
</tr>
<tr>
<td>Exposure duration, ED (y)</td>
<td>9</td>
<td>30</td>
</tr>
<tr>
<td>Averaging time, AT (y)</td>
<td>70</td>
<td>75</td>
</tr>
<tr>
<td>Bioavailability, 𝐵ᵣ (dimensionless)</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Air dispersion modeling results

The requested model output consists of the calculated annual average concentrations for unit emissions (1 g/s) at each receptor location. A maximum concentration of 66 µg/m³ was calculated by the model at a distance of approximately 900 m from the receptor grid origin, and this value was conservatively adopted for use in the risk assessment calculations. Figure 1 shows concentration isopleths (µg/m³) superimposed on a location map of the landfill sites vicinity. The average annual concentrations (µg/m³) shown in Table 1 for individual contaminants of concern were calculated by scaling the unit effects in proportion to the average estimated annual emission rate for each contaminant of concern. These concentrations constitute the receptor exposure point concentrations and were used for the risk assessment calculations.

Health risk assessment methods and results

Risk assessment overview—This section evaluates potential public health risks that might be attributable to inhalation of landfill gas emissions by the future residential and nonresidential populations of the proposed landfill redevelopment sites. Only inhalation exposure was evaluated because the proposed landfill cap is assumed to isolate buried waste and contaminants, thereby essentially eliminating the ingestion and dermal exposure pathways. Furthermore, the landfill leachate control and collection system minimizes the risk of human contact with, or environmental exposure to, the landfill leachate. It is noted that a regular preventative maintenance program is necessary to ensure optimal long-term performance of the leachate collection system.

The health risk assessment was performed in accordance with USEPA health risk assessment guidance (USEPA 1989, 1997, 2003b), and the risk calculations were performed with the American Petroleum Institute’s decision support system (API-DSS) software package. Although the proposed landfill redevelopment will be mixed residential and recreational (golf course), the health risk assessment focused on the more critical residential population, which also was the focus of the project scope. For exposure and risk assessment, the 2 main differences between the residential and recreational (or commercial) populations are the exposure time and the necessary inclusion of children in the residential population. Theoretically, recreational or commercial exposure time can be approximated by standard occupational 8- or 10-h work durations, whereas residential exposure time might be regarded as continuous (24 h) in the extreme case scenario. However, for this risk assessment, residential exposure time was assumed to be represented by estimated time spent outdoors (assuming that appropriate indoor air filtration units are incorporated into the building HVAC systems), but the exposure point concentrations were conservatively assumed to be the maximum model-predicted concentrations (regardless of the actual locations of those concentrations). Also, the health risk assessment was based on 2 sets of exposure characteristics that are individually appropriate for the hypothetical child and hypothetical adult residential populations.

In the absence of specific exposure data from the future receptor populations at the landfill redevelopment sites, exposure assumptions were made regarding average body weight, inhalation rate, exposure frequency, etc., on the basis of USEPA default exposure characteristics (Table 2). In addition to the assumed average exposure characteristics, exposure factors corresponding to assumed worst-case exposure scenarios for both child and adult populations were also evaluated. For each exposure factor, the average value was assumed equivalent to the USEPA 50th percentile, whereas the worst-case value was assumed equivalent to the 95th percentile value. If the 95th percentile data were not available for an exposure characteristic, the average value was used instead.

Risk assessment methods—On the basis of the maximum model-predicted airborne concentration for unit emissions, the average annual contaminant concentrations shown in Table 1 were assumed to represent the exposure point concentrations.

Table 2 shows the exposure characteristics that were assumed for the risk assessment. For each contaminant, the absorbed dose (Dₐ) associated with the exposure point concentration (Cₐ) was calculated for the inhalation exposure pathway by Equation 4

\[ Dₐ = Bᵣ Cₐ IH \cdot ET / BW \]  

(4)

Where \( Bᵣ \) is the chemical-specific bioavailability for inhalation, \( IH \) is inhalation rate, \( ET \) is exposure time, and \( BW \) is body weight. The chronic daily intake (CDI), which was used to evaluate potential noncarcinogenic effects, was estimated by Equation 5.
CDI = \( D_b \cdot \frac{EF \cdot ED}{365 \cdot AT} \)  \( \text{(5)} \)

Where \( EF \) is exposure frequency, \( ED \) is exposure duration, and \( AT \) is the averaging time. The lifetime average daily absorbed dose (LADD) was used to evaluate carcinogenic risk and was calculated by Equation 6.

\[
\text{LADD} = \frac{D_b \cdot EF \cdot ED}{365 \cdot AT} \quad \text{(6)}
\]

It should be noted that \( AT \) is equal to the exposure duration for Equation 5, whereas it is equal to life expectancy for Equation 6. The slope factors (SFs) and reference doses (RFDs) that were used to quantify carcinogenic and noncancer health risks are provided in Table 1 and were obtained from the USEPA Integrated Risk Information System Database (USEPA 2003b). The theoretical incremental lifetime cancer risk (ILCR) associated with cumulative contaminant exposure was obtained with Equation 7.

\[
\text{ILCR} = \sum \text{ILCR}_i = \sum (SF_i \cdot \text{LADD}) \quad \text{(7)}
\]

Noncarcinogenic risk was calculated by dividing the CDI for each contaminant by the contaminant RFD to obtain the hazard quotient (HQ), which determines whether exposure is likely to result in noncancerous adverse health effects. By extension, the hazard index (\( HI \), Eqn. 8) determines whether cumulative exposure to several contaminants might cause adverse (noncancerous) health effects and was obtained by summing the HQs associated with each contaminant of concern. If \( HI \leq 1 \), then cumulative exposure to the different contaminants is not expected to cause adverse health effects.

\[
HI = \sum \text{HQ}_i = \sum \left( \frac{\text{CDI}_i}{\text{RFD}_i} \right) \quad \text{(8)}
\]

**Risk assessment results**—The risk estimates for both average and worst-case exposure scenarios are summarized in Table 3. Figure 2 shows calculated \( HI \) values for each air contaminant assuming worst-case exposure conditions for both the hypothetical adult and child receptors. Note that 1,1,2,2-tetrachloroethane and 1,1,2-trichloroethane are not shown in Figure 2 because noncancerous toxicity data were not found for these compounds. Assuming average exposure conditions, the estimated \( HI \) values were 0.04 and 0.07 for

| Table 3. Summary of risk assessment results$^a$ |
|-----------------------------------|--------|--------|--------|--------|
| Risk                             | Adult  | Child  |
| Average estimates                | \(3.6 \times 10^{-2}\) | \(1.8 \times 10^{-6}\) | \(7.2 \times 10^{-2}\) | \(4.8 \times 10^{-6}\) |
| Worst-case estimates             | \(5.3 \times 10^{-2}\) | \(8.9 \times 10^{-6}\) | \(1.0 \times 10^{-1}\) | \(1.3 \times 10^{-5}\) |

$^a$ HI = hazard index; CR = cancer risk.

![Figure 2. Total hazard index by chemical—worst-case estimates.](image)
the adult and child receptor, respectively (Table 3). For the assumed reasonable worst-case exposure scenario (as represented in Table 2), the HI values were 0.05 and 0.1 for the adult and child receptor, respectively. All HI results are <1, which indicates that even under worst-case exposure conditions, the predicted air concentrations are lower than concentrations that would be statistically expected to cause adverse health effects.

Figure 3 shows theoretical cancer risks by contaminant for assumed worst-case exposure conditions for both the hypothetical adult and child receptors. Note that chlorobenzene and 1,1,1-trichloroethane are not shown in Figure 3 because these compounds are not classified as human carcinogens. The average, or best estimate of, incremental lifetime cancer risks were $1.8 \times 10^{-6}$ and $4.8 \times 10^{-6}$ for the adult and child receptors, respectively (Table 3). This indicates that, on the basis of assumed average exposure conditions, the additional risk of cancer attributable to cumulative exposure to the predicted air contaminants are approximately 2 in 1 million and 5 in 1 million for the adult and child receptors, respectively. For upper bound or assumed worst-case exposure conditions, the estimated incremental cancer risks were $8.9 \times 10^{-6}$ and $1.3 \times 10^{-5}$ for the adult and child receptors, respectively, which are equivalent to population cancer risks of approximately 9 in 1 million and 13 in 1 million. The USEPA (1989) regards cancer risks ranging between 1 in 10 million (i.e., $10^{-7}$) and 100 in 1 million (i.e., $10^{-3}$) as within the range of acceptable risk. Both the average and worst-case risk estimates for both adult and child receptor populations were within the USEPA (1989) range of acceptable risk.

**DISCUSSION**

This paper presents a methodology for estimating residual airborne contaminant concentrations at landfill redevelopment sites and evaluating associated public health risks according to standard health risk assessment guidance. Three main steps are involved: Estimation of landfill gas emission rates for the identified contaminants of concern, air dispersion modeling to determine the contaminant exposure point concentrations, and quantification of potential health risks attributable to exposure to those contaminants. The risk assessment focused mostly on inhalation exposure because the landfill cap or cover and leachate collection system isolate the buried waste from human contact, thereby essentially eliminating the ingestion and dermal absorption exposure pathways. To address potential contaminant vapor intrusion into occupied interior spaces, the proposed buildings include active gas venting systems that will extract methane and other landfill gases from below the foundation and vent the gas through roof-top exhausts, thus preventing build up of landfill gas under the foundations or within any occupied interior spaces. In addition, other protective measures will be incorporated into appropriate elements of the development project to protect from potential gas buildup, including but not limited to subfoundation geomembranes (i.e., vapor
barriers); sealed concrete slab floors; and positive-pressure building ventilation systems (including high-capacity fan systems to vent vehicle exhaust gases such as carbon monoxide from garages). On the basis of these measures, air dispersion modeling assumes that the majority of the subsurface gases will be vented through the rooftop stacks and evaluates atmospheric transport of contaminants via these point sources. In addition to indoor vapor intrusion, management of residual risk must be associated with the accumulation of potentially harmful gas in unoccupied confined spaces not serviced by a permanent ventilation system (e.g., utility vaults, pipelines, crawl spaces, manholes, etc.). This risk is inherent to most utility and maintenance work, however, and is not necessarily unique to landfill sites. Strict adherence to proper confined space ventilation and safety procedures by utility and maintenance workers will help minimize this potential worker risk.

The health risk assessment for both the adult and child populations yielded theoretical cancer and noncarcinogenic risk results that fall within limits deemed acceptable by USEPA (1989). On the basis of the project scope, the risk assessment focused on the residential population, which also was regarded as the more critical because it includes children as well as the potential for continuous (24-h) exposure. However, when the exposure time for the adult population was increased to 8 h/d, which approximates the anticipated exposure for recreational activities, the theoretical cancer and noncancer risks were still within USEPA acceptable limits.

Variability and uncertainty in exposure and risk assessments

Variability and uncertainty in health risk assessments arise from natural variability in exposure characteristics among the receptor populations, as well as lack of full knowledge regarding important factors that affect the risk estimates (USEPA 1995a). Variability implies that different individuals within the receptor population will likely be subject to exposures both above and below the exposure levels selected as reference values for use in risk assessment. On the other hand, uncertainty regarding some of the data and assumptions used in the analysis implies that exposures will probably be underestimated or overestimated for individual members of the receptor population. Presenting a range of risk estimates rather than single-point values helps to communicate the potential consequences of variability and uncertainty as described herein. Other measures that were employed to address variability (NRC 1994) included 1) disaggregating and hence minimizing variability by performing the risk assessment separately for the child and adult subpopulations with the use of appropriate exposure characteristics for each subpopulation and 2) use of a statistically reliable average value for the exposure point concentration: The maximum average annual contaminant concentrations according to air dispersion modeling of 5 y of meteorological data were assumed to be reasonable estimates for contaminant exposure point concentrations.

A common approach for quantitatively analyzing uncertainty is the use of uncertainty propagation models, such as Monte Carlo simulation, to produce multiple descriptors of risk. Monte Carlo simulation is a statistical technique in which a quantity is calculated repeatedly with standard computer routines on the basis of randomly selected “what-if” scenarios for each calculation. To perform a Monte Carlo simulation, a probability distribution has to be assigned to each exposure factor or characteristic that has a high level of uncertainty and distribution descriptors (which typically include the mean, standard deviation, maximum, and minimum values of the exposure characteristic) provided. The computer routine then uses random values from each distribution to output multiple estimates of risk (in the form of a probability distribution) corresponding to different statistical levels of confidence. In the absence of site-specific data, Monte Carlo simulations can be performed with assumed probability distributions from guidance sources (USEPA 1997). However, on the basis of the generally favorable risk results, the authors were of the view that a Monte Carlo analysis was not warranted in this case.

Limitations and refinements of ISCST3 air dispersion model

The ISCST3 version that was used for air dispersion modeling does not perform cavity analysis for the near-wake regions of vicinity structures. Evaluation of cavity region effects is required when there is a potential for some portions of the emissions to be trapped in a downwash recirculation cavity behind nearby buildings. Concentrations in these cavities can be high because of the relatively limited mixing air volume. However, because the majority of emissions are from rooftop stacks and the building heights are expected to be fairly uniform, the potential for downwash effects is limited, and a cavity analysis did not have to be performed. For situations in which the buildings are of different heights, cavity effects are anticipated, or both, use of the following models are suggested: 1) The USEPA SCREEN3 air dispersion model calculates concentrations in the cavity region before application of ISCST3 for far-wake regions. However, SCREEN3 is a simple single-stack model and cannot explicitly determine maximum effects from multiple sources. 2) The ISCST3 with plume rise enhancements (ISC-PRIME) is useful in the event of multiple sources and more complicated terrain. The USEPA has incorporated a set of algorithms (PRIME) into the latest version of ISCST3 to evaluate both near-wake and far-wake effects, including cavity region effects. 3) The USEPA AERMOD-PRIME air dispersion model, which is projected to become USEPA’s preferred model for regulatory purposes, can account for building near-wake and far-wake effects, including cavity effects.

CONCLUSIONS

Recreational and residential redevelopment of landfill sites seems to be gaining acceptance, especially in metropolitan regions where developable greenfields are becoming depleted. Health risks are associated with landfill redevelopment, particularly for residential purposes that necessarily involve children and a potential for 24-h exposure. Because a landfill cap system is usually an integral component of any landfill redevelopment, the health risk of most concern is inhalation of landfill gas emissions. Gas emissions from municipal landfills consist mainly of methane and NMOCs. Methane is not toxic if inhaled, but it is an asphyxiant and can pose fire and explosion hazards when allowed to accumulate. NMOCs include VOCs, HAPs, and odorous compounds, some of which can cause carcinogenic and noncarcinogenic adverse health effects.

This paper describes an approach for estimating postdevelopment airborne contaminant concentrations from residual landfill emissions and evaluating associated health risks. The approach was applied to landfill redevelopment sites in New
Jersey, and the numerical risk estimates were within USEPA
guidance risk limits. However, it is emphasized that while the
approach may be applied in the general case, the risk results
may vary depending on the landfill characteristics and site-
specific circumstances. Key assumptions on which the risk
assessment was based include 1) negligible oral and dermal
exposure because of the landfill cap or cover system and
leachate collection system, which limit human (and environ-
mental) exposure to buried waste and minimize off-gassing of
subsurface emissions; 2) contaminant-free indoor air because
of engineered ventilation and subsurface treatments that
prevent buildup of methane and contaminant vapors in
indoor spaces; and 3) air dispersion modeling that does not
need to include cavity region analysis because postdevelop-
ment emissions will be mostly from rooftop stacks and
building heights are expected to be reasonably uniform.

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REFERENCES

support system (DSS) user manual. Washington DC.

[NJDEP] New Jersey Department of Environmental Protection. 2002. MM
Hackensack-Kingsland landfill—Final operating permit. Trenton (NJ): NJDEP,
Bureau of Operating Permits.


Landfill gas passive vent system air permit application. August. Warren (NJ).

DC: Office of Emergency and Remedial Response.


industrial source complex (ISCC3) air dispersion model. Vol 1. Research Triangle
Park (NC): Office of Air Quality Planning and Standards, Emissions Monitoring
and Analysis Division.

models. 40 CFR, part 51 (Appendix W). Washington DC.

Cincinnati (OH): National Center for Exposure Assessment, Office of Research
and Development.

emission factors (AP-42), section 2.4: Municipal solid waste landfills.

[USEPA] US Environmental Protection Agency. 2001. Emission inventory improve-


[USEPA] US Environmental Protection Agency. 2003b. Integrated risk information
system (IRIS) database. Cincinnati (OH): National Center for Exposure
Assessment, Office of Research and Development.