

**METROPOLITAN UNIVERSITY
GRADUATE SCHOOL OF ENVIRONMENTAL AFFAIRS
SAN JUAN, PUERTO RICO**

**LANDFILLS VS. INCINERATORS: IDENTIFICATION AND COMPARISON OF THE
HAZARDS POSED BY THE TOXIC EMISSIONS ASSOCIATED WITH THE DISPOSAL
OF MUNICIPAL SOLID WASTES IN PUERTO RICO.**

Partial requirement for the
Degree of Masters in Science in Environmental Management
In Risk Assessment and Management

By
Francisco J. Pérez Aguiló

December 9, 2010

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THESIS SUBMITTED AS PARTIAL REQUISITE
FOR THE DEGREE

MASTERS IN SCIENCE IN ENVIRONMENTAL MANAGEMENT
IN
RISK ASSESSMENT AND MANAGEMENT


METROPOLITAN UNIVERSITY
SAN JUAN, PUERTO RICO
2010

APPROVED BY:


EDUARDO R. GONZÁLEZ, PE, MBA, MSChE
THESIS COMMITTEE DIRECTOR


JAVIER VÉLEZ AROCHO, M.S.
THESIS COMMITTEE MEMBER


OMAR MUÑIZ DÍAZ, PE, MBA
THESIS COMMITTEE MEMBER


CARLOS M. PADÍN BIBILONI, Ph.D.
DEAN

09/12/10
DAY/MONTH/YEAR

DEDICATION

I dedicate this work to those who *conduct their reason well and seek the truth in science*¹.

¹ Descartes, R (1637)

ACKNOWLEDGEMENTS

Even though a thesis is a one-person job, many people have to pick up the slack resulting from the physical absence of the investigator while he undertakes his thesis, and from the absence of focus to other important matters that often results during this process. So I begin thanking my friend and supervisor Jaime Pabón, who supported me all through this process and encouraged me in this pursuit. Also, thanks to my friend and colleague Antonio Dávila Fussá who relentlessly pushed me to this pursuit when it was the farthest thing from my mind. Thanks also to my family, Mayra, Ector and Maggie, who had to put up the most with my absence, especially to Mayra who even has the spirit to joke about my unlikely, future pursuit of another degree.

This work would not be possible without the early encouragement of Alan Eschenroeder, who taught me so much about risk assessment during our work together in the late 1990s. Also, thanks go to my thesis mentor, Eduardo R. González, who provided all the support required to conduct this study. My risk assessment professor, Omar Muñiz, and my esteemed colleague, Javier Vélez Arocho, both thesis committee members provided the necessary encouragement and shared their wisdom at key moments. Thanks also to Fermin Fontanés, who provided timely, valuable comments.

Finally, I'd like to acknowledge the contribution of Margarita M. Aguiló, my mother, who taught me everything I know, including the value of education, hard work, honesty and perseverance.

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ABSTRACT

This study estimates and compares the mass of Hazardous Air Pollutants (HAPs) emitted by landfills and incinerators. The author utilized the USEPA's quantification of the Arecibo landfill's emissions based on LandGEM Version 3.02, and extrapolated those results for the entire municipal solid waste (MSW) land-filled in Puerto Rico during the year 2008. The study used USEPA's Emission Factors (1995b) for municipal waste combustors to estimate the HAP emissions that would result if all MSW presently land-filled in Puerto Rico was incinerated. HAP emissions data from five incinerators in the United States was also used for validation. A linear relationship of tons of MSW burned to tons per year (tpy) of emissions was used, as in USEPA's Emission Factors. Results indicate that Puerto Rico landfills emitted 106.2 tpy of 26 HAPs during 2008, all of which were volatile organic compounds, eight of which are known carcinogens (11.4 tpy) and seven are possible carcinogens or potential occupational carcinogens (17.1 tpy). Based on the Emission Factors estimates, incinerators would emit 394.2 tpy of eight HAPs, 98.8% of which would be hydrochloric acid (389.5 tpy), five are known carcinogens (0.6 tpy) and one is a potential occupational carcinogen (0.1 tpy). HAP emissions estimates for Puerto Rico using the five incinerators sampled ranged from 39.4 tpy to 1,245.8 tpy, with an average of 493.3 tpy, and similar proportions of HAPs. Even the worst performer of the 5 incinerators sampled would emit fewer known/possible/potential carcinogens (13.3 tpy) than landfills presently do (28.5 tpy).

CHAPTER I

INTRODUCTION

Problem Background

Approximately 9,860 tons of municipal solid wastes (MSW) are generated in Puerto Rico (the Island) every day (ADSPR, 2003). According to the Puerto Rico Solid Waste Authority (ADSPR, from its Spanish acronym), approximately 15.3% of this mass is presently segregated for recycling (ADSPR, 2008). The remaining 8,351 tons per day (tpd) is disposed-off in landfills. During the 100 or so years since the western civilization became a throw-away society (Life, 1955; as cited in Rathje & Murphy, 2001), the MSW stream in Puerto Rico has resulted in approximately 2,000 acres of opened or closed landfills (ADSPR, 2003), for an average rate of 20 new acres of landfill per year.

Landfills are permanent repositories of garbage, where materials slowly decompose over hundreds of years (Rathje & Murphy, 2001). During this time they generate copious amounts of landfill gas, which consists mostly of the greenhouse gases methane and carbon dioxide, with trace amounts of other contaminants, some of which are toxic (USEPA, 2005).

Liquids are also deposited in landfills with the MSW, and as precipitation slowly trickles through the decomposing refuse, landfills discharge out of their bottoms and sides a fluid called leachate with a high biochemical oxygen demand, low pH, contaminated with heavy metals and soluble organic species (Elias-Castells, 2005). Landfill leachate has contaminated many areas in Puerto Rico to the point that four landfills have been selected for the National Priority List (NPL) of contaminated areas (USEPA, 2010). The NPL is the list of national priorities among the known releases or

threatened releases of hazardous substances, pollutants, or contaminants throughout the United States and its territories.

Due to inappropriate siting, uncontrolled leachate discharges to aquifers, and lack of landfill gas collection and treatment, ADSPR determined in 1993 that Puerto Rico landfills were not in compliance with the Resource Conservation and Recovery Act requirements of 1993. In response, ADSPR developed a Master Plan for the management of solid wastes, which was finalized in 1995 (ADSPR, 1995 a; 1995 b). The Master Plan called for the closure of 31 of the existing 60 landfills, the development of seven new regional RCRA Subtitle D landfills, 17 waste transfer stations, and two waste-to-energy (WTE) facilities. The latter would be located at the old sugar mills to bring back to life these historic sources of jobs, now slowly decaying. These infrastructure projects were to be completed and operational by the third quarter of 2000. However, most of them were not developed. Instead, existing landfills were “regionalized” as they began accepting MSW from surrounding municipalities with no means of disposal, assisted by the new transfer stations. The Master Plan also called for a 35% recycling rate by September, 1995, which has yet to reach 20%.

ADSPR developed in 2004 a new Master Plan (ADSPR, 2004) calling for many of the same actions called-for in the previous Master Plan, including WTE facilities, composting facilities and landfills. In 2008, ADSPR developed yet another plan (ADSPR, 2008), which also called for a new compost plant, expansion of some of the existing landfills, a new transfer station, and WTE facilities. Unfortunately these plans remained as plans: No new MSW landfill has been built in Puerto Rico since the Cabo Rojo Landfill in 1994 (USEPA, 2009), and not one WTE facility has been built.

Thus, MSW in Puerto Rico continues to be disposed-off in existing landfills. As of May, 2002, the USEPA believed that only two out of 29 landfills in operation at the time were in compliance with federal regulations (Fernández, 2002). In 2007, this author

prepared a useful-life inventory of all open landfills in Puerto Rico from data in ADSPR files from submittals from the landfills themselves. The results are summarized in Table 1. The cumulative capacity at the time totaled 29,785,444 tons, which at the estimated dumping rate of 3,674,611 tons per year (tpy, see Table 1) yielded 8.1 years of remaining capacity in Island landfills as of 2007, or approximately five years of landfill capacity as of 2010. However, early closing of landfills and other factors considered, the combined landfill capacity for the Island may be less. By the end of the year 2010, 12 additional landfills will be closed as ordered by the USEPA for non-compliance, and seven more will reach capacity (Carl Sodeberg, Director, Caribbean Environmental Protection Division (CEPD), United States Environmental Protection Agency (USEPA) Region 2, pers. comm.), leaving only 12 landfills available beginning the year 2011.

The MSW disposal problem is not unique to Puerto Rico. However, islands impose important limitations upon their inhabitants. Power generation capacity, for instance, has to be greater than in a continent, given that system interconnection is unavailable for reserve capacity. Water availability is also limited due to, among other factors, the scarcity of available land for reservoirs and aquifer recharge. In such an area-limited environment, and considering waste disposal's documented effects upon groundwater (Arbona & Hunter, 1995; Hunter & Arbona, 1995), "zero disposal" of MSW should be the sustainable goal for solid waste management. Although it is not so succinctly stated, it is (Puerto Rico Constitution, Article VI, Section 19; Puerto Rico Law 267 of September 10, 2004; and Puerto Rico Law 310 of September 2, 2000). Source reduction, reuse, and recycling should be fully developed to reduce the MSW stream in such settings. However, until "zero disposal" is achieved, there will be a need for MSW disposal in the Island, and the approach selected for the disposal should take into consideration our areal limitations, our legal framework, and its toxic consequences.

A survey of jurisdictions that have excelled at reducing their MSW draws real-life conclusions about the means to minimize our MSW disposal problems (USEPA, 1994). For instance, all the top performers, those jurisdictions with 50% reduction rate or better, have curbside collection of the recyclable and the compostable portions of their solid residues at the same frequency as collection of their “garbage”. If or when we accomplish our MSW reduction in half, or even in the two-thirds that comprise the recyclable plus the compostable portion of our MSW (ADSPR, 2003; see Figure 1), there remains a residue due for final disposition. Unfortunately, there are not many viable disposal alternatives.

Historically, trash has been dumped out-of-sight in pits, natural or artificial, usually at the edge of town. Trash in dumps was burned periodically for volume reduction, thereby the old term for landfills used in Puerto Rico: “Crematorio”. Smoke generation and toxic emissions were major negative consequences of this practice (Lamieux, 1998). Incinerators came as an alternative. Their controlled burning of wastes was better than open burning, but still contained important amounts of toxic pollutants (USEPA, 1999). WTE facilities were developed to convert the caloric output from the incinerator into energy. The focus on efficient burning resulted in a more complete combustion, or better oxidation of the organics, in accordance with the following formula:



The more efficient the combustion process, fewer contaminants are generated (Elias-Castells, 2005). However, heavy metals and the un-combusted organic substances that remain in the ash residues, including those formed during incomplete combustion can make incinerator ash disposal a problem (USEPA, 1998a).

The more recent stage in the evolution of the incinerator is the Resource Recovery Facility (RRF), which uses technology to reduce not only the volume of MSW,

generate electricity and steam, but also to recover usable materials from the MSW stream and the ash. Some promising RRF technologies don't even have direct combustion of the waste, such as thermolysis, gasification and plasma-arc torches (Elías-Castells, 2005). Just like the decomposers in the biosphere (Husar, 1994), incinerators, or their more appropriate regulatory name Municipal Waste Combustors (MWCs), return energy and materials for anthropogenic (human) consumption: electric power, steam, aggregate for construction, ferrous and non-ferrous metals.

Modern incinerator technologies include the processing of the fly-ash to trap the contaminants it contain and make them unavailable to the environment. For instance, incinerator ash containing 7.5% lead and 0.2% cadmium, encapsulated in a sulfur polymer with additives results in leachable levels below allowable concentrations (USEPA, 1996). The technology to turn ash residues into stable cement-like substances (Keck and Seitz, 2002; Buckley and Pflughoeft-Hassett, 2006) has found many constructive applications (USDOE, 2000; USDOT, 2000). At a minimum, these stabilization technologies allow the solid residue to be disposed in landfills with minimal potential for generation of toxic leachate and occupying a small fraction of the landfill space when compared with the original MSW.

The investment required for incinerators is much larger than for landfills. A facility proposed for Arecibo, Puerto Rico in 1998 for the processing of 2,000 tpd of MSW was estimated a \$300 million (Renova, 2000). In order to finance such facilities, there are two important requirements: assurance of a steady supply of MSW, and a power-purchase agreement with the local utility. To assure a steady supply of MSW, incinerators establish contracts with the appropriate jurisdiction to supply all their MSW to the incinerator. These contracts, which often last 20 years, have been called "put-or-pay" because they contain penalties for non-delivery designed to discourage jurisdictions to find cheaper disposal alternatives after investing in an incinerator facility.

Both, the incinerator and the landfill are widely used around the world as MSW disposal strategies, so their hazards and benefits have been documented. A basic comparison between these technologies indicates that the incinerators fare much better than landfills in the following categories: emission of greenhouse gasses (Solano et al., 2002; USEPA, 2006a), discharge of toxic leachate (Jones-Lee, 1993; USEPA, 1996; USDOE, 2000; USDOT, 2000; Keck and Seitz, 2002; Buckley and Pflughoeft-Hassett, 2006), duration of the impact (Elias-Castells, 2005), materials recovered (landfills have none), power generation (USEPA, 2006a), creation of jobs (USDOT, 2000; RWB, 2001; CEPA, 2003) and land consumption (Renova, 2000). Public perception, however, is an area where incinerators fare far worse than landfills, even though landfills also suffer from the not-in-my-back-yard (NIMBY) syndrome (ANL, 1994; McCarthy, 2004).

The most consistent argument in opposition to the incinerators is their toxic emissions (McCarthy, 2004). This reputation was fueled by earlier versions of the incinerator, where incomplete combustion, inappropriate or non-existent emissions control devices, and other factors yielded large quantities of toxic contaminants in their atmospheric emissions (NYT, 1919; USEPA, 1995b and 1998a). Many of the reports attacking incinerator emissions refer to the Harrisburg, Pennsylvania Incinerator, which began operations in 1972 (USEPA, 1985) and emitted more dioxins than the average U.S. incinerator of its time, by at least two orders of magnitude (USEPA, 1997a). Others refer to the Columbus, Ohio Incinerator, which operated between 1983 and 1994, during which time it emitted a full one third of the dioxin emissions in the U.S. during that period (Lorber et al., 1998).

This study investigates the toxic emissions for existing, modern incinerators, and compares them with the toxic emissions presently emitted from landfills in the Island.

Research Problem

Landfills and incinerators pose hazards to public health and the environment, but which one poses fewer hazards? Groundwater contamination, toxic air emissions, and greenhouse gas emissions are among these potential hazards (Arbona & Hunter, 1995; Ettala, Rahkonen, Rossi, Mangs & Keski-Rahkonen, 1996; Lemieux, 1998; ATSDR, 2001; E.A., 2002; McCarty, 2004; Elias-Castells, 2005; USEPA, 2005). There is ample literature available that characterize the physical and toxicological nature of each of these alternatives (NIOSH, 2007). However, the literature does not compare them directly, or in terms of the risks that each poses to public health and the environment. Prudent decision-makers should weigh both risk and socio-economic benefits (Wilson & Crouch, 2001) before favoring one solid waste management strategy over the other. Yet, it appears that the arguments against incinerators are emotional rather than scientific.

This study identifies and compares the hazards posed by toxic air emissions from these two alternative technologies for MSW disposal. Hazard identification is the first step toward a comparative risk assessment (Lerche & Palelogos, 2001; USEPA, 2004).

Justification of the Study

A study that compares risks associated with these two MSW disposal technologies is justified in a number of ways. First, despite the approximately 10,000 tpd MSW stream in the Island there has not been any new MSW disposal infrastructure developed since the Cabo Rojo Landfill began operating in 1994 (USEPA, 2009). Second, the Island only has five years left of its cumulative, useful landfill capacity (see Table 1). Third, it takes approximately three years to properly site, design, finance, and build a modern incinerator.

A sound decision has to be made about the future of the MSW management for the Island. A comparative risk assessment of each technology's toxic emissions should

settle the emotional debate, and instead provide the grounds for a risk/benefit-based decision-making. By directly comparing the risk posed by toxic emissions from incinerators with the toxic emissions in landfill gas we bring science into an impasse that has committed the Island to a technology (landfills) which's impacts evidently last for a lot longer than a 20 year put-or-pay contract (see landfill closure, Legal Framework section, below).

The Island must work on source reduction, reuse, recycling, and composting: Those are the best mechanisms to achieve efficiency in the development of our resources, to achieve a sustainable development, and to reduce the toxic emissions people breathe. However, whether or not Puerto Rico reduces, reuses, recycles and composts, the disposal of MSW will occupy the land, and will contaminate the air and aquifers for generations unless concrete steps are taken to reduce the land disposal of our solid wastes.

Hypothesis

Toxic emissions from landfills are more massive, and present a greater risk to human health, than toxic emissions from incinerators would.

Goal

In order to bring change to humankind's impacts to our planet, says noted Stanford University biologist Hal Mooney (in Kelsius, 2002) "the challenge we have now is to make our findings clear and compelling to both the general public and policymakers". At the conclusion of this work, the hazards associated with the MSW disposal alternatives (landfills and incinerators) are quantified and qualitatively described. This information is utilized to make inferences about the health effects associated with the exposure of individuals or populations to these substances. These characterized risks could then be communicated in various forums, and submitted to our regulatory agencies and legislative bodies to inform the debate over which technology

should be preferred over the other. The results of this investigation should support a better-informed decision-making. This work establishes the groundwork for a full comparative risk assessment of the MSW disposal technologies.

Objectives

The objectives pursued in order to accomplish this study's goal are:

- A. Estimate the volume of landfill gas generated in Puerto Rico in order to estimate the toxic contaminants emitted to the atmosphere from landfills in Puerto Rico
- B. Estimate the mass of toxic substances that would be emitted from the incineration of MSW in Puerto Rico in order to compare them with those from landfills.
- C. Identify the hazards posed by each toxic substance emitted by landfills and by incinerators, and assess their toxicity.
- D. Compare the technologies to evaluate which emits a greater quantity of toxic atmospheric emissions.

CHAPTER II

LITERATURE REVIEW

Historical Background

On average, for every ton of material that goes to MSW, 71 tons of wastes were generated elsewhere to create those products, such as mine wastes, forest wastes, transportation wastes, and energy wastes (Young & Sachs, 1994). Two important conclusions may be derived from this information: First, that MSW reduction is far more important than the mere MSW that is the subject of this investigation—71 times more important. Second we may conclude that MSW disposal will continue to be a necessity due to the sheer amounts that are generated. Unfortunately, there are not many viable alternatives—particularly in an island setting.

Trash in landfills used to be burned to reduce volume, with smoke generation as a consequence, and as we now know, toxic emissions too (Lemieux, 1998; and USEPA, 1995a and 1997a). Incinerators came as a solution to the open burning. Their emissions were better than open burning, but as history confirms, they still contained significant amounts of toxic pollutants (USEPA, 1998a and 1999). WTE facilities were then developed to capture the caloric output of the incinerator. The focus on efficient burning resulted in a more complete combustion ($\text{organics} + \text{O}_2 = \text{CO}_2 + \text{H}_2\text{O} + \text{heat} + \text{contaminants}$), and therefore fewer toxic emissions (Elias-Castells, 2005).

Modern resource recovery facilities (RRFs), look at MSW as a resource instead of as a problem, are designed to extract as many resources as possible from MSW, have little non-useable residues, and generate emissions that must meet Maximum Achievable Control Technology air emission standards (MACT) standards (Section 112(g) of the Clean Air Act). Ash generation remains an important issue, since it

contains most of the heavy metals that would otherwise be present in the emissions. Additionally, incinerator ash contains organic contaminants, including those formed during incomplete combustion and during the cooling of the emission gasses.

Conceptual or Theoretical Framework

The two main MSW disposal alternatives available today are the sanitary landfill and the incinerator, or municipal waste combustor (MWC), as defined in Subtitle D of the Resource Conservation and Recovery Act (RCRA). Which of the two MSW disposal alternatives pose the least toxic emissions impact? That is the subject of this work.

Sanitary landfill.

The sanitary landfill is the most widely utilized disposal alternative (UNEP, 2002). It is the least expensive alternative when land is not in short supply. Landfills generate no visible emissions, except during fire events, and requires very little manpower and equipment. However, MSW buried in a landfill remains there for hundreds or thousands of years (Rathje & Murphy, 2001). The following are notable exceptions:

1. Methane (CH₄) and Carbon Dioxide (CO₂) will result from the biological decomposition of the organic matter, according to the following formula:

organic substances + microbial activity = heat + CH₄ + CO₂ + contaminants

This “landfill gas” will invisibly ventilate out of crevices, the landfill surface, or a system designed for this purpose (Elías, 2005). CH₄ and CO₂ are important greenhouse gasses, although CO₂ is removed from the atmosphere by photosynthetic organisms (algae and plants), whereas CH₄ is not, and is a greenhouse gas 21 times more potent than CO₂ (USEPA, 1998b, 1998c and 2005b). The methane fraction of this “landfill gas” is sometimes used as fuel, giving it a “recovery” attribute (USEPA, 1998b; USEPA, 2002). Landfill gas generation peaks approximately 30 years after MSW has been deposited in the landfill, and its generation continues for decades or even hundreds of years

(E.A., 1997; ATSDR, 2001; Ferry, 2002; USEPA, 1998c, 2002 and 2005a; Durmusoglu, Yavuz & Tuncay, 2005).

2. Volatile and semi-volatile gases can be present in the MSW stream deposited in landfills. These are also formed during the biochemical reactions that occur within landfills, and they are emitted to the atmosphere in the landfill gas stream (Elias-Castells, 2005). These gasses range in impact from nuisance odors to toxicity (USEPA, 1999; Chian & DeWalle, 1979). The USEPA has compiled a list of typical emissions in landfill gas. Refer to Appendix A for the entire list of landfill-gas contaminants.
3. The liquids deposited in the landfill will find their way to the landfill bottom. Subsequent precipitation will percolate through the layers of MSW deposited, fueling microbial as well as chemical decomposition of the MSW. Liquids moving within the landfill dissolve organic and inorganic contaminants. Landfill leachate, as it is known, is normally toxic (Jones-Lee, 1993; Elías-Castells, 2005). The modern practice is to collect it throughout the bottom of the landfill and re-apply it at the top with or without some treatment. Most Puerto Rico landfills lack such a system (Carl Sodeberg, Director, CEPD, USEPA Region 2, pers. comm.). Even when present, there is always some seepage through the bottom liners, through seams or cracks (USEPA, 2001). This impact decreases once an impermeable cap is placed over a landfill during its proper closure, but it is present during its entire active life. Therefore, it is not surprising that four out of the 13 (30.8%) active superfund sites in Puerto Rico are former landfills: the Barceloneta Landfill, the Fibers Landfill, the Juncos Landfill and the Vega Alta Landfill. Appendix B schematically represents a sanitary landfill.

Due to the above mentioned persistent problems, landfills are long-term environmental liabilities. Landfill closures under Subtitle D of RCRA require at least

three monitoring wells to determine whether landfill leachate contamination is migrating outside the site. Landfill closure requirements also include a final grading to divert runoff away, a gas collection and recovery system, a final capping to keep precipitation off the buried waste, and. The duration of these measures can be as short as 30 years and as long as 100 years (Mark Lichtenstein, Director, USEPA's Environmental Finance Center for EPA Region 2, pers. comm.).

Incinerators.

For economic and regulatory reasons, modern incinerators are designed to extract as many resources as possible from MSW. They use the caloric value from the MSW to generate power at an approximate rate of 0.029 megawatts per ton of MSW, plus they generate steam for industry (Renova, 2000). Materials that survive the process are recovered for sale (recycling), including: ferrous metals (84 pounds per ton {lb/ton} of MSW), non-ferrous metals (eight lb/ton), and glass and ceramics (202 lb/ton) as construction aggregate (Renova, 2000). Appendix C shows a schematic representation of an incinerator.

The process generates CO₂ and water vapor emissions contaminated with organic and inorganic species. The level of contamination depends on the incinerator design: mass burn waterwall, mass burn rotary waterwall, mass burn refractory wall, refuse-derived fuel-fired, fluidized bed, modular starved air, modular excess air, thermolysis/gasification, and plasma arc gasification, to name the most common designs. The emissions control utilized also bears upon the quality of the emissions: electrostatic precipitator, duct sorbent injection, spray dryer, fabric filter, or a sequence thereof, are common emission controls for incinerators (USEPA, 1995b). Pursuant to the Clean Air Act, continuous emission monitoring systems are required of all incinerator facilities for nitrogen oxides (NO_x), carbon monoxide (CO), oxygen (O₂), particulate

matter via opacity meters, and acid gases via monitoring sulfur dioxide (SO₂). Gas temperatures are also monitored in emissions control systems.

The USEPA (1995b) has compiled a list of typical emissions for the various types of incinerators under different scenarios of emissions control. Appendix D lists the typical emissions for modular excess air combustors with and without one of the simplest, most inexpensive emissions control systems: the spray drier with fabric filter.

Incinerators also generate an unusable ash portion, both from the emissions control system, known as “fly ash”, and from the solids that remain un-combusted, known as “bottom ash”. Contaminants captured in the emissions control system are concentrated in the fly ash (Elias-Castells, 2005, p.550). Inorganic contaminants already present in the MSW stream, such as heavy metals, are concentrated in the bottom ash and in the fly ash. The level of contamination of the ash residue varies with the process technology and the emission control mechanisms. These “incinerator solid wastes” occupy a small fraction of the volume of the original MSW, reducing the required landfill capacity needs up to 95% (Renova, 2000). It is important to note that it is the *volume* of the MSW that occupies landfill capacity, not its *weight*. Reducing significantly the volume of the material to be disposed in landfills significantly reduces the disposal problem.

Case studies

Perceived hazard vs. documented risk.

Many communities express concern about the potential implications of incinerator emissions upon their health. However, there is little or no information available to support the speculation about any human health effects associated with MSW incinerator emissions (ATSDR, 1994; Shy, et.al. 1995; and ATSDR, 2002), with the exception of asthma (MDPH, 2008). This may even be true not just for incinerators

but for hazardous waste incinerators. As ATSDR states in its report *Public Health Reviews of Hazardous Waste Thermal Treatment Technologies* (2002):

It is important to note that no other remediation technology has undergone as many stack emission tests, as much ambient air monitoring, or as many health studies as has incineration. It is equally important to note that only one incineration facility, the Caldwell Systems, Inc. hazardous waste incinerator in Caldwell County, N.C., was implicated by the ATSDR-funded studies as the potential cause of adverse health effects in some workers and community members (p. 41).

There is however, a large number of studies indicating that people that live near landfills may have a higher incidence of certain health problems than the population at large (Mallin, 1990; Vrijheid, 2000; ATSDR, 2001 Appendix C; NJDHSS, 2001; Vrijheid, Dolk, Armstrong, and Abramsky 2002, and ATSDR, 2005). True, the subject of some these studies are hazardous waste landfills. However, we must presume that hazardous wastes have been deposited in Puerto Rico's MSW landfills. This presumption has been confirmed for the Barceloneta Landfill, the Fibers Landfill, the Juncos Landfill, and the Vega Alta Landfill—30.8% of all active superfund sites in Puerto Rico. This presumption is substantiated by the fact that there are no hazardous waste landfills in Puerto Rico, despite the large industrial sector in the Island. Furthermore, the cost of disposing of a pound of hazardous waste is approximately \$2.00 if by a licensed company, but only \$0.35 in a non-certified facility (Pedro, Lugo-Rosado & Rojas-Brenes, 2010). Business decisions are customarily economic in nature.

Landfill fire events.

Lemieux (1998) evaluated the emissions from open burning of MSW, such as would occur during a landfill fire event. The results from his experiments indicate that open burning of MSW emits toxic substances at a rate 1,000 to 1,000,000 times greater

than emissions from the average incinerator. Therefore, all but the most insignificant landfill fire event emits more toxic substances than incinerators emit in a year. The USEPA (2000b) states that “currently, the uncontrolled burning of residential waste and accidental fires at landfills are thought to be among the largest sources of dioxins to the environment in the U.S.” Other investigators have reached similar conclusions (Ettala et al., 1996; Ruokojärvi et al., 1995a; 1995b). Each year in the United States, an average of 8,400 landfill fires are reported to the Fire Service (FEMA, 2002).

Vinyl Chloride.

One contaminant that’s emitted copiously in landfill gas (5.2 tpy emitted in Puerto Rico, see Table 2, Table 5 and Table 6) is Vinyl Chloride, a known carcinogen. Kielhorn, Melber and Wahnschaffe (2000) conducted a study of MSW landfills, and found Vinyl Chloride in landfill gas and in groundwater contaminated with landfill leachate. The concentrations found were up to 200 milligrams per cubic meter (mg/m³) in landfill gas and 10 milligrams per liter (mg/L) in leachate. These investigators combined relevant epidemiologic studies from several European countries, and documented an excess (45 times the average) of liver cancer in populations near landfills, primarily due to angiosarcoma. These investigators, as well as the USEPA (2000a), demonstrate a statistically significant elevated risk of liver cancer, primarily angiosarcomas in the liver from exposure to Vinyl Chloride. The average latency for liver angiosarcoma due to Vinyl Chloride is 22 years (Kielhorn et al., 2000), yet it has been documented to be as long as 51 years (Bolt, 2009).

Cancer in Puerto Rico.

Cancer is the second leading cause of death in Puerto Rico after heart disease, and accounted for 16.6% of all deaths in 2004 (Torres-Cintrón, et. al., 2010). Out of 8,953 deaths due to all causes in 2004, of which 1,515 deaths were due to cancer, breast cancer leads with 209 deaths, followed by liver/intrahepatic cancer with 191

deaths (Ortiz-Ortiz et al., 2010). As we shall see below (Results and discussion, Estimates) many of the contaminants from both landfills and incinerators have the liver or kidneys as target organs. Landfills, for instance emit 91.95 tpy of the following HAPs that target the liver or kidneys: Toluene, Xylenes, Tetrachloroethylene, Ethylbenzene, Vinyl Chloride, Trichloroethylene, Acrylonitrile, Ethylidene Dichloride, Methyl Isobutyl Ketone, 1,1,2,2-Tetrachloroethane, Ethyl Chloride, Methyl Chloroform, Methyl Chloride, Carbon Disulfide, Ethylene Dichloride, 1,4-Dichlorobenzene(p), Chlorobenzene, Propylene Dichloride, Vinylidene Chloride, Chloroform, Carbon Tetrachloride, Ethylene Dibromide and Mercury. Incinerators emit 4.63 tpy of the following HAPs that target the liver or kidneys: Mercury, Lead, Arsenic, Cadmium, and 2,3,7,8-Tetrachlorodibenzo-p-Dioxin. Please note that there are no incinerators in operation in Puerto Rico to date, which may presently impact public health, but there are approximately 2,000 acres of open and closed landfills (ADSPR, 2003) emitting these gases.

28% of the NPL (superfund) sites in PR are located in municipalities that have high cancer mortality rates (Torres-Cintrón et al., 2010). We have already established that approximately one third (30.8%) of the contaminated areas in Puerto Rico that have been designated as superfund sites started out as MSW landfills (USEPA, September 10, 2010).

Landfill emissions and pregnancy.

Other investigators found a relation between low birth weight and birth malformations with proximity to landfills. McNamee & Dolk (2001) examined 5,260 landfill sites across Europe, and compared the relative risks for the population of these areas compared to the background. The relative risks for low birth weight increased 6% with proximity to landfills. The relative risks for neural tube defects increased 7% with proximity to landfills. O'Connell (2001) evaluated birth defects and landfill proximity, and found that "overall risk of birth defects was 1% higher in those living within 1.25 miles of

landfills, and the risk of low birth weights was 5% higher. Those living near hazardous waste sites had a 7% higher rate of birth defects. O'Connell also cites a 1998 epidemiology study by the New York State Department of Health of about 38 landfills that "were thought to be leaking methane gas". The study found that women who lived near these sites were four times more likely to contract bladder cancer or leukemia.

As these cases demonstrate, landfill emissions have been documented to pose a threat to human health. This research aims to begin a comprehensive evaluation of toxic emissions from landfills, and weight them against the technologic alternative that is the incinerator.

Legal framework

Federal legislation.

MSW generation, handling and disposal has been formally regulated since the early 1970s. The Federal Government has regulated some of its management since at least 1972, when the Ocean Dumping Act and its amendments banned disposal at sea of solid wastes (33 U.S.C. 1401-1445, 16 U.S.C. 1431-1447f, 33 U.S.C. 2801-2805). In 1976, Congress passed the Resource Conservation and Recovery Act (RCRA, 42 U.S.C. § 3001) in order to protect health, protect the environment, regulate hazardous waste from "cradle to grave", establish guidelines for the disposal of non-hazardous solid waste, promote resource conservation and promote resource recovery systems. Below are some of the highlights of the Federal regulation of solid wastes.

MSW consists mostly of "household waste", which is one category of waste that is exempt from the hazardous waste regulations (RCRA §3001 (i) and 42 U.S.C. §6921). This exemption is important because MSW generally contains small quantities of hazardous substances (i.e. household pesticide, heavy metals and solvents), which now end up in landfills, landfill gas and landfill leachate.

The Comprehensive Environmental Response, Compensation and Liability Act (“CERCLA”) of 1980, also known as “Superfund,” was enacted to deal with the release of ‘hazardous substances’ into the environment. Under CERCLA, persons designated as “potentially responsible parties” or PRPs are liable to the federal government and to private parties for the cost to clean up hazardous substances. PRPs include the current owner or operator of a facility at which a hazardous substance is disposed, the owner or operator of the disposal facility at the time of the disposal, the transporter, and the person who arranged for the disposal or treatment of a hazardous substance at a facility. The latter PRP category includes cities, municipalities or state or agencies (42 U.S.C. §9607).

Liabilities associated with CERCLA can include costs of removal, remediation, damages to natural resources, health effects studies, and other costs of the response, and are retroactive. CERCLA has proven an important deterrent against the manufacture, handling and release of hazardous substances. For instance, about 99% of auto batteries (lead-acid batteries), were recovered in 2007 (USEPA, 2008a), and in 2000 the rate was already 96.4% (USEPA, 2002).

The USEPA establishes the procedure to determine whether a solid waste is considered a hazardous waste, solid waste, or is exempted from regulation (40 CFR Part 261). The USEPA also establishes land disposal restrictions, regulations prohibiting the disposal of hazardous waste on land without prior treatment (40 CFR 268). Under this regulation, materials must be treated to meet land disposal standards prior to placement in a RCRA land disposal unit (landfill, land treatment unit, waste pile, or surface impoundment). Wastes subject to this regulation include solvents, electroplating wastes, heavy metals, and acids.

In 1991 the USEPA regulations governing municipal solid waste disposal by land-filling (Part 258—Criteria for Municipals Solid Waste Landfills, Subpart F—Closure

and Post-closure Care §258.61 Post-closure care requirements) included the following closure requirements to protect against the long-term contamination liability that landfills can pose:

(a) Following closure of each MSWLF unit, the owner or operator must conduct post-closure care. Post-closure care must be conducted for 30 years, except as provided under paragraph (b) of this section, and consist of at least the following:

(1) Maintaining the integrity and effectiveness of any final cover, including making repairs to the cover as necessary to correct the effects of settlement, subsidence, erosion, or other events, and preventing run-on and runoff from eroding or otherwise damaging the final cover;

(2) Maintaining and operating the leachate collection system in accordance with the requirements in § 258.40, if applicable. The Director of an approved State may allow the owner or operator to stop managing leachate if the owner or operator demonstrates that leachate no longer poses a threat to human health and the environment;

(3) Monitoring the ground water in accordance with the requirements of subpart E of this part and maintaining the ground-water monitoring system, if applicable; and

(4) Maintaining and operating the gas monitoring system in accordance with the requirements of § 258.23.

(b) The length of the post-closure care period may be:

(1) Decreased by the Director of an approved State if the owner or operator demonstrates that the reduced period is sufficient to protect

human health and the environment and this demonstration is approved by the Director of an approved State; or

- (2) Increased by the Director of an approved State if the Director of an approved State determines that the lengthened period is necessary to protect human health and the environment.

This regulation by itself demonstrates the long-term liability that landfills pose.

On March 12, 1996 the USEPA published regulations for air emissions of non-methane organic compounds from landfills. 40 CFR Part 60 Subpart CC established emissions guidelines for the largest landfills: those with capacities of greater than or equal to 2.5 million metric tons (2.75 tons). Landfills in this category must submit an initial design capacity report, a yearly emission report, and apply for a title V operating permit. These sources must also install and operate a collection and control system for non-methane organic contaminants (NMOCs).

Landfills in Puerto Rico have only one Federal permit requirement, since the permitting authority for landfills has been delegated to the State government. That permit is the National Pollutant Discharge Elimination System (NPDES) permit, which regulates runoff from landfill sites to surface waters. All Federal standards for landfills are applicable, however, and are enumerated below:

1. Location requirements:
 - A. At least 10,000 feet from an airport runway.
 - B. Not in wetlands, floodable areas.
 - C. At least 200 feet from seismic faults, and not in unstable areas.
 - D. Not in Karst areas (high recharge areas for aquifer).

These and other siting restrictions have been spatially illustrated in the map of areas excluded from siting landfills in the Island. Refer to Appendix D provided by the

USEPA (Carl Soderberg, Director, CEPD, USEPA Region 2, pers. comm.). Landfills and incinerators have different siting requirements.

2. Construction and operation requirements, such as double liners, leachate collection and treatment systems, monitoring wells, storm water runoff control, daily cover, monitoring for hazardous wastes, and security.
3. Closure requirements, such as at least 3 groundwater monitoring wells, final grading such that runoff flows away from landfill, gas collection and recovery systems, final capping, maintenance for approximately 30 years, and financial assurances for this length of time.

Incinerators, on the other hand, have several Federal permitting requirements in Puerto Rico:

1. The NPDES permit to discharge to surface water, as in the case of a landfill.
2. The Air Quality Prevention of Significant Deterioration permit. As its name implies, this permit requires that the facility not adversely deteriorate existing air quality in the region. This implies that background monitoring must be conducted to evaluate existing air quality. Since air quality can be seasonally trendy, approximately one year background monitoring is required.
3. The New Source Performance Standards. This permit requires emissions monitoring for the standards specified in the permit, which include parameters such as: Opacity, particulate matter, cadmium, lead, sulfur oxides, mercury, nitrogen oxides, hydrochloric acid, and others.
4. Congress established the New Source Review (NSR) program as part of the 1977 Clean Air Act Amendments and modified it in the 1990 Amendments. NSR is a preconstruction permitting program that serves two important purposes:

- a. Ensures the maintenance of air quality standards or, where there are not air quality standards, it ensures that air quality does not significantly degrade when factories, industrial boilers, and power plants are modified or added. In areas that do not meet the national ambient air quality standards, NSR assures that new emissions do not slow progress toward cleaner air. In areas that meet the standards, especially pristine areas like national parks, NSR assures that new emissions fall within air quality standards.
 - b. Best Achievable Control Technology regulation ensures that state-of-the-art control technology is installed at new plants or at existing plants that are undergoing a major modification.
5. Title V permit for incinerators that emit or have the potential to emit 100 tpy or more of the following contaminants: Sulfur Oxides, Nitrogen Oxides and Particulate Matter. Title V permit requirements may also be triggered if the sum of all emissions in the category of contaminants called Hazardous Air Pollutants (HAPs) exceeds 25 tpy, or emissions of any single HAP exceeds 10 tpy. We will later discuss in detail HAPs.

Puerto Rico legislation.

At the state government level, there are many requirements for MSW handling facilities, including the Law for the Waste Reduction and Recycling of 1992 and its 2000 version, the Law for the Prevention of Contamination of 2000, and the Law for Sustainable Development of 2004.

Article VI, Section 19 of our Constitution states that the public policy of the Commonwealth of Puerto Rico is to have “the most effective conservation of our natural resources, as well as their greatest development and utilization for the benefit of the community”. The implications of this Article are far reaching in an Island setting, where

areas set aside for MSW disposal—approximately 2,000 acres at the present—compete with areas for aquifer recharge, for agriculture, for wildlife conservation, for recreation, for tourism, and for housing. Consuming an average of 20 acres per year in landfill space hardly qualifies as effective conservation or utilization of our valuable land area. The implications of this Article of our Constitution are also far reaching for an Island with limited mineral resources, yet it buries one thousand pounds of metals every day (see Figure 1; ADSPR, 2003), while it imports equivalent amounts of metals in value-added products, such as structural steel (PRPB, 2008).

The Environmental Public Policy Act, Law 416 of September 22, 2004, requires the evaluation of the environmental impacts, including socioeconomic impacts, before the State issues any permit. This law is the successor to Law 9 of June 18, 1970, which sets the basis for many of the environmental regulations administered by the Environmental Quality Board (EQB), including: The Water Quality Regulation of April, 1990, as amended April, 2010), the Regulation for the Control of Atmospheric Emissions of July, 1995, and the Regulation for the Handling of Non-Hazardous Solid Waste of December 17, 1997. The Regulation for the Presentation, Evaluation and Processing of Environmental Documents is also presently supervised also by the EQB.

The Public Policy for Sustainable Development enacted as Law 267 of September 10, 2004, states that the Government, including its municipalities, in cooperation with interested public and private organizations, is mandated to use every means and practices, including financial assistance and the best practices and available technologies, with the purpose of encouraging and promoting a sustainable development for Puerto Rico Article 5 of said Law includes, as a duty of Government entities, to review their statutory authority and administrative rules to determine whether they contain deficiencies or inconsistencies that would prevent the full compliance with this Law, and to take the necessary steps to resolve them.

The 23-year old principle of “sustainable development” may be summarized as “satisfying the needs of the present without undermining the ability of future generations to satisfy their own needs” (UN, 1987). The United Nations General Assembly Report, commonly known as the Bruntland Report, discusses the need for a “strict liability” on the subject of inter-generational equity. It summarizes the legal principle as follows: “States shall conserve and use the environment and natural resources for the benefit of present and future generations”. It adds that “States shall take all reasonable precautionary measures to limit the risk when carrying out or permitting certain dangerous but beneficial activities”.

A subsequent report (UN, 2002) of the United Nations General Assembly summarizes “the three components of sustainable development—economic development, social development and environmental protection—as interdependent and mutually reinforcing pillars”. The principle of sustainable development, enacted as public policy and law for Puerto Rico, thus embraces the need to evaluate risks and economic benefit of the MSW management strategy it chooses. For an island setting, this principle should apply to the conservation of its limited land resources, the contamination of its potable water supplies (aquifers), and the health impacts of its toxic air emissions.

The Prevention of Contamination Act, Law 310 of September 2, 2000 declares as public policy “the most effective protection and conservation of our natural resources, and their maximum beneficial exploitation for the benefit of the community in general. To achieve this goal, it is necessary to prevent and reduce at the source all sorts of contamination. Contaminants that cannot be prevented will be reused or recycled in a manner protective of the environment; barring these options, it will be disposed using technology approved by the Environmental Quality Board; and as a last recourse, it will be disposed to the environment in accordance to the laws and regulations” (Article 2, Declaration of public policy). Clearly, it is the Island’s law and policy to follow the

hierarchy established by the Federal RCRA for the management of MSW: (1) reduce, (2) reuse, (3) recycle, (4) resource recovery, and (last) land-filling.

The Prevention of Contamination Act also highlights the benefits of following this RCRA hierarchy, when it states: “The efficient execution of this public policy will improve the quality of life, will reduce health problems associated to the contamination, will reduce the risk to adversely impact the food chain, it will protect the flora and fauna, it will benefit the socio-economic sector by reducing cost of disposal and the cost of raw materials for manufacturing...” (Article 2, Declaration of public policy). Clearly, the legislators did not intend for reusable or recyclable materials to be buried under layers of earth, and instead they pursued a vision where these materials would be the building blocks for industrial activity in Puerto Rico.

Article 4 of the law delegates upon the ADSPR the Prevention of Contamination Program, with a simple charter: “The main purpose of the Program is to maintain and protect our environment through the prevention and reduction of contamination at the source in order to create healthy surroundings that will promote an integrated, sustainable development for Puerto Rico”. Evidently, the Prevention of Contamination Act was envisioned as a central strategy for economic development. There is a marked contrast between The Act and the action, since Puerto Rico buries on the ground all the MSW that is not removed from the approximately 10,000 tpd MSW stream as recyclables; presently 15.3% (ADSPR, 2008) is recycled, whereas approximately 33% of the MSW stream is recyclable and approximately 33% is compostable (of biological origin).

Finally, the Reduction and Recycling of Solid Wastes in Puerto Rico Act, Law 70 of September 18, 1992 makes it public policy of the Island to “develop and implement economically viable strategies that will result in the reduction of the volume of solid wastes that require final disposal in order to reduce the use of landfills in the State”.

This Act also gives the ADSPR powers to “stimulate the recovery of recyclable materials through incentives to participating businesses, encourage the participation of private business in the construction and operation of recovery and recycling facilities”, among others. Law 13 of January 20, 1995 amended it to create new economic incentives to promote recycling, and for other purposes, and Law 411 of October 8, 2000 further amended it to establish an itinerary of percent recycling goals, which should have been 35% by 2006. These latest amendments included a requirement for source reduction to any entity that at least employs 10 persons or more.

CHAPTER III

METHODOLOGY

The hazardous air pollutants (HAPs), those listed in Subchapter I, Part A, § 7412 of the Clean Air Act (USEPA, 2008c), are here quantified here for the hypothetical emissions of MSW management in Puerto Rico using incinerators. The samples consisted of data from existing facilities, which was then extrapolated to the entire MSW stream for the Island. HAP emissions data from incinerators was obtained from existing United States facilities through available USEPA databases. All incinerators must monitor their emissions, and report the data to the USEPA. Once that information has been submitted to the Agency, it becomes part of the public record, and can be obtained through various mechanisms, potentially including a Freedom of Information Act request (FOIA, 5 U.S.C. §552, September 6, 1966).

Data from landfill toxic emissions was not so readily available. Although the existing method of MSW disposal in Puerto Rico is exclusively the landfill, there is virtually no actual monitoring information on their emissions. Until recently (USEPA, 1997b) there was no requirement for landfill gas monitoring. Even the 1997 regulation, which imposed gas monitoring to active landfills, was limited to the largest 5% of landfills (greater than 2.5 million metric ton capacity). Therefore, the existing data needed to compare toxic releases from landfills is limited. However, the USEPA has compiled a list of Emission Factors, which consist of averages of the available data of acceptable quality, and are assumed to be representative of long-term averages for each type of facility (USEPA, 1995b and 2008b). Using these Emission Factors and the latest mathematical model to estimate landfill gas emissions, accurate estimates of the HAP emissions from Puerto Rico landfills were drawn.

There are Emission Factors available for incinerators as well. Since these are representative of the long term averages for incinerator emissions, these modeled emissions and their concentrations were also primarily utilized for the discussion, instead of the individual incinerator emissions.

Study area

The study area is Puerto Rico, an archipelago approximately 100 miles long by 35 miles wide that harbors approximately 4 million residents. A central agency (ADSPR) compiles information for the entire Island's waste stream, and MSW characterization studies have been conducted at least twice in the recent past (ADSPR, 1995c; 2003). Managerial and planning decisions are also centralized at the ADSPR, which leads the implementation of the solid waste management for the entire Island.

Since it is the goal of this study to inform the debate over which technology (landfills vs. incinerators) should be preferred, the entire Island was the logical study area delimitation.

Population and sample description

The Arecibo landfill was used as a sample of the HAP emissions generated from the disposal of MSW in Puerto Rico landfills. A LandGEM model of its emissions was completed by the USEPA (2009). Located in the north-central portion of the Island, it serves the sixth largest municipality in the Island (U.S. Census Bureau, 2000), and received the fourth largest waste stream in the Island behind Humacao, Toa Baja and Ponce (ADSPR, 2004). A private company, Landfill Technologies, provides the following services for the Arecibo Landfill: operation, waste screening, waste compaction, stormwater management, and environmental monitoring.

Study period

The data collected by the USEPA (2009) in support of their emissions model of the Arecibo Landfill covered from 1973, the year it opened, through 2006, or a total of 33

years. The ADSPR (2003) study utilized to estimate the Island's MSW mass and characteristics reported the weight and volume of MSW disposed in 31 landfills for one week each during 2003, and the waste composition at 12 selected landfills and 2 transfer stations. Some stations, including the Arecibo landfill, were re-sampled to measure the impact of the holiday MSW stream and other fluctuations. That study's results are expressed as average values (mass) per year, a format which can in turn be expressed as any other time period, such as average daily or average monthly values.

Methodology design

A. To estimate the volume of landfill gas generated in Puerto Rico, in order to estimate the toxic contaminants emitted to the atmosphere from landfills in Puerto Rico.

This study utilized the USEPA's Landfill Gas Emissions Model (LandGEM, Version 3.02) (USEPA, 2005a), prepared for the Arecibo Landfill by the USEPA Region 2. The LandGEM is a tool utilized to estimate emission rates for landfill gas, including: methane, carbon dioxide, non-methane organic compounds, and individual air pollutants. It was designed to be used by the USEPA, landfill owners, and operators to determine if a landfill is subject to the control requirements of the federal New Source Performance Standards (NSPS) for new MSW landfills (40 CFR 60).

LandGEM is based on the following first-order decomposition rate equation for quantifying emissions from the decomposition of MSW in landfills:

$$Q_{CH_4} = \sum_{i=1}^n \sum_{j=0.1}^1 kL_o \left(\frac{M_i}{10} \right) e^{-kt_{ij}}$$

Where,

Q_{CH_4} = annual methane generation in the year of the calculation ($m^3/year$)

i = 1 year time increment

n = (year of the calculation) - (initial year of waste acceptance)

j = 0.1 year time increment

k = methane generation rate (year^{-1})

L_o = potential methane generation capacity in cubic meters per mega-gram (m^3/Mg) of MSW.

M_i = mass of waste accepted in the i^{th} year in Mg

t_{ij} = age of the i^{th} section of waste mass M_i accepted in the i^{th} year (decimal years, e.g., 3.2 years)

The LandGEM generates results in Mg/year and in m^3/year for all three categories of landfill gas: Methane, carbon dioxide, and non-methane organic contaminants.

Values obtained were for the Arecibo Landfill, which accepts an average of 541 tpd, or 6.5% of the 8,301 tpd deposited in Puerto Rico landfills daily (see Table 1). This study extrapolated the values obtained from the LandGEM model for the MSW land-filled in the entire Island through the following equation:

$$\begin{array}{l} \text{Emissions Estimate for all} \\ \text{MSW deposited in Puerto} \\ \text{Rico landfills} \end{array} = \begin{array}{l} \text{LandGEM Results,} \\ \text{Arecibo Landfill} \end{array} \times \frac{8,301 \text{ tpd}}{541 \text{ tpd}}$$

The results from the previous exercise, namely the landfill gas emissions estimate, were used to estimate the toxic contaminants emitted to the atmosphere from landfills in Puerto Rico using the emission factors compiled by the USEPA (1995b). An emissions factor is a representative value obtained from hundreds of actual test results performed on actual emission sources. In the case of landfill emissions, these are expressed as a ratio of a pollutant emitted per volume of landfill gas (i.e. mg/m^3). These factors are averages of all available data of acceptable quality, and are to be representative of long-term averages for all landfill facilities, instead of instantaneous values.

To estimate emissions of non-methane organic contaminants, the following equation was used:

$$Q_P = 1.82 Q_{CH_4} + C_p \div (1 \times 10^6)$$

where:

Q_P = Emission rate of pollutant P, m^3/yr

Q_{CH_4} = CH_4 generation rate, m^3/yr , from LandGEM results (above)

C_P = Concentration of P in landfill gas (emission factor, ppmv)

1.82 = Multiplication factor, assumes that approximately 55% of landfill gas is CH_4 and 45% is CO_2 , N_2 , and other constituents

The LandGEM utilizes the USEPA emission factors (1995b), and generates results for all the landfill gas contaminants (see Appendix A) in Mg/year and in $m^3/year$. These results were converted to tons per year (tpy).

B. To estimate the mass of toxic substances that would be emitted from the incineration of MSW in Puerto Rico, in order to compare them with those from landfills.

Emissions data in Mg/year or in $m^3/year$ from five actual operating incinerators was obtained through EPA databases. Two proven and three promising technologies were sought for outstanding performance, including: mass-burn, refuse-derived fuel, thermolysis, plasma arch and gasification. The latter three, however, were not obtained. Data derived from the Emission Factors (USEPA, 1995b) for MWCs was also used to estimate the Island's emissions for comparison.

The emissions data obtained from these incinerators and from the USEPA (1995b) Emission Factors for MWCs, were scaled for 8,301 tpd, in accordance with the following equation:

$$\begin{array}{l} \text{Emissions from all} \\ \text{Puerto Rico MSW} \\ \text{incinerated} \end{array} = \begin{array}{l} \text{Results for} \\ \text{incinerator Y} \end{array} \times \begin{array}{l} \underline{8,301 \text{ tpd}} \\ \text{tpd MSW} \\ \text{incinerator Y} \end{array}$$

C. To identify the hazard posed by each toxic substance emitted by landfills and by incinerators, and to assess their toxicity.

Risk assessment is a complex, multidisciplinary process in which the net result is an estimate of the “probability of future loss” (Byrd & Cothorn, 2000). For the topic at hand, such future loss could be decreased longevity or a reduced quality of life for the affected population due to cancer or impaired organ functions. USEPA (1989) emphasizes that the term “risk assessor” generally refers to *teams* of individuals from the disciplines of toxicology, chemistry, hydrology and engineering. In that context, this study was but a piece of the puzzle that comprises the risk assessment of the MSW disposal alternatives.

The four steps of the risk assessment process are (USEPA, 1989 and 2004):

1. Hazard identification. Establishes the presence of a “hazard”, which could be toxic substances or specific conditions that have the potential to be harmful to human health or the environment. These substances will be identified from the most recent list published by the National Institute for Occupational Safety and Health (NIOSH 2007), from the results of the LandGEM tool for landfill emissions, and from the FOIA results for the incinerators.
2. Exposure assessment. This is the fundamental information required for estimating the consequences of an exposure. Physical, chemical, carcinogenicity and other relevant information will be derived from the NIOSH (2007) database for each toxic substance. The routes, frequency, and duration of exposure to these contaminants were investigated for each from the Integrated Risk Information System (IRIS), an electronic database containing information on human health effects that may result from exposure to hazardous substances (www.epa.gov/iris).
3. Toxicity assessment. Also called a dose-response assessment, it involves the identification of the types of adverse health effects associated with the chemical

exposure. NIOSH and IRIS will also be the sources of this information for each toxic emission species.

4. Risk characterization. Risk characterization has two parts: A numerical estimate of the risk, and recommendations about the significance of the risk for the benefit of decision-makers. Since a dispersion model is beyond the scope of this study, and would be required to quantify the exposure to the various receptor populations, a numerical estimate of the risk will not be possible in this study. However, this study generated a qualitative risk characterization that describes the significance of the risks posed by each technology. Most importantly, this study quantified the mass of HAPs emitted by each technology. Dispersion models could utilize the results of this study to quantify exposure for specific receptors.
- D. Compare the two technologies to evaluate which one emits a greater quantity of toxic atmospheric emissions.

The comparison was made in two ways: First, the mass of toxic contaminants in tons/year was estimated for each technology, and the sheer mass and volume of toxic contaminant was compared. Then, the toxicity assessment for the contaminants emitted by each technology was qualitatively compared. Inferences were made based upon the duration of impact, and the dispersion characteristics of each MSW disposal technology.

Data analysis

Quantitative hazard identification: I entered into a spreadsheet the emissions data obtained from the LandGEM model for the Arecibo Landfill as tpy emitted. Similarly, the emissions data obtained for MSW incinerators was entered for each incinerator selected. Then, the emissions from each, the Arecibo Landfill, five incinerators and the Emission Factors estimate for MWCs were extrapolated for the average MSW disposal for the Island. The results of this exercise were tabulated, and

expressed as estimated toxic emissions for Puerto Rico in tpy. Numeric and graphic representations of the mass of toxic contaminants presently emitted by landfills in Puerto Rico were compared with the mass of toxic contaminants that would be emitted by incinerators in the Island.

Qualitative hazard comparison: The toxic substances emitted by landfills and incinerators was paired with toxicology information available from authorities such as ATSDR, IRIS, NIOSH and the Occupational Safety and Health Administration (OSHA, 2010). Relevant parameters evaluated include:

- Route of exposure.
- Symptoms caused by each contaminant's intoxication.
- Target organs, where the substance concentrates or acts causing deleterious effects.
- Reference Dose (RfD) and Reference Concentration (RfC). These provide quantitative information for use in risk assessments of health effects. The RfD is an estimate of a daily exposure to the human population that is likely to be without an appreciable risk of deleterious effects during a lifetime. Reference values are sometimes derived for different durations of exposure:
 - acute (less than 24 hours),
 - short-term (between 24 hours and 30 days),
 - and sub-chronic (greater than 30 days, up to approximately 10% of the life span) exposure durations. This parameter is utilized, given the long-term duration of the impacts relevant to this study.
- The inhalation RfC, which considers toxic effects for the respiratory system in addition to systemic effects. This parameter was utilized given its relevance to this study (long term exposure to toxic air emissions).

- Whether the contaminant is a known or suspected carcinogen.
- No-observed-adverse-effect level (NOAEL).
- Lowest-observed-adverse-effect level (LOAEL).
- OSHA's permissible exposure limit (PEL) and NIOSH's recommended exposure limit (REL) are also used for comparison.
- Whether a concentration with an immediate danger to life and health (IDLH) has been established for the substance.

These parameters were utilized to complete the picture of the risks posed by landfill and incinerator HAP emissions. As stated in the Methodology section, this study falls short of being a health risk assessment. This is due to the need for exposure estimates (dose) in order to estimate risk due to chronic inhalation, which would require a dispersion model, meteorological data, etc. to estimate contaminant concentrations around the emission source(s) and at the receptor sites. However, future studies could benefit from the information compiled in this study, and close the gap that presently limits our ability to compare the risks posed by landfills versus incinerators in terms of their toxic emissions.

CHAPTER IV

RESULTS AND DISCUSSION

Information sources

The USEPA is the single most important source of information for this project. Not only do they collect each facility's compliance monitoring results, but they also conduct compliance monitoring independently, and conduct research to fulfill their role of improving air quality in the Nation. Many of the referenced sources are USEPA publications, particularly from the 1990's, when concern about incineration resulted in several important initiatives. Several sources within the USEPA were utilized, and are credited below.

Upon request, the National Emissions Inventory, Emissions Inventory & Analysis Group, Air Quality Assessment Division, Office of Air Quality Planning and Standards, U.S. EPA, Research Triangle Park, NC 27711 provided a table that includes all HAP emissions for all emission sources with a North American Industry Classification System (NAICS) category of 562213 (Solid Waste Combustors and Incinerators) during 2005. A new report for HAP emissions from 2008 was in preparation at the time of my request. They also provided tables with the contact information for the facilities, identification numbers for the various programs USEPA administers, and identification numbers for the States' regulatory programs. These Id numbers were valuable when looking-up more updated information in the USEPA web site, and to validate that the emissions data was in fact for a specific facility. The source of said data is the monitoring results submitted to the USEPA in compliance with the CAA, PSD and State permits under which individual incinerators operate. The table provided by the USEPA contains 10,346 lines of data, each representative of a boiler, a facility, etc. Some of the lines of data

include emissions from other on-site operations, and so some included emissions of contaminants that are foreign to the incinerator operation, and those were excluded.

Another source for incinerator emissions information is the USEPA's Toxic Release Inventory (TRI) program. The Emergency Planning and Community Right-to-Know Act (EPCRA) was enacted in 1986 to provide workers and communities information about toxic chemical releases. Their database contains information on toxic chemical releases reported annually by certain industries. Their Envirofacts Report is available for certain facilities, including most major air emissions sources, and it provides total aggregate releases of TRI chemicals for each facility. Data up to 2009, provided in pounds or grams emitted per year, was available for many facilities during this investigation. See http://www.epa.gov/enviro/html/tris/tris_query.html.

A third source of incinerator emissions information was the USEPA's Emissions Factors (USEPA, 1995b). These factors are representative of long-term averages for all facilities in the source category (i.e., landfills and incinerators). In the case of incinerators and landfills, an emissions factor is simply the average of all data of acceptable quality available to the USEPA that relates the quantity of an emitted pollutant (mg) with the mass (tons) of solid waste land-filled or incinerated. Many sections of its fifth edition (USEPA, 2003) have been updated, including the one for MWCs, in 1998, and for landfills, in 1999. Revisions are underway for the landfill category.

The U.S. EPA's National Center for Environmental Assessment (NCEA) focuses on human health and ecological risk assessment—how pollutants may impact human health and the environment. NCEA conducts research that help extrapolate experimental data into real-world impacts. Their Database of Sources of Environmental Releases of Dioxin-Like Compounds in the U.S. has comparison data from 1995 on dioxin emissions. See <http://cfpub.epa.gov/ncea/CFM/recordisplay.cfm?deid=20797>.

The Enforcement & Compliance History Online (ECHO) site provided information on compliance history for each facility. See <http://www.epa-echo.gov/echo/>. This information was used in the selection of the incinerators sampled.

The Air Facility System contains compliance and enforcement data and permit data for stationary sources regulated under the Clean Air Act. Upon request, a username and password was provided, and emissions data for specific facilities was made available. See <http://www.epa.gov/compliance/data/systems/air/aboutafs.html>.

The one data source for landfill emissions is the Landfill Gas Emissions Model (LandGEM, Version 3.02) (USEPA, 2005), prepared for the Arecibo Landfill in 2009. It is based upon the USEPA's Emissions Factors (USEPA, 1995b and 2003); therefore, its results could be considered averages for the universe of MSW landfills.

The Freedom of Information Act (FOIA) request initially proposed to obtain emissions data for existing facilities proved obsolete, given the level of information available on-line within the EPA web site, and given the outstanding cooperation obtained from EPA personnel upon request.

The study results are presented below under the headings of each objective (A through D) presented in Chapter 1.

Estimates

A. Estimate of landfill gas generated in Puerto Rico and its HAPs components

The USEPA's Caribbean Environmental Protection Division (CEPD) results from the LandGEM model prepared for the Arecibo Landfill may be found in Appendix A. The LandGEM generates results for all three categories of landfill gas: Methane, carbon dioxide, and non-methane organic contaminants. The HAP emission estimates obtained for the Arecibo Landfill, which accepts an average of 260,700 tpy, or 7.09% of the 3,674,611 tpy MSW deposited in Puerto Rico landfills were extrapolated for the entire Island.

Appendix A shows that the Arecibo Landfill emitted in 2008 approximately 618,900,000 cubic feet of landfill gas with an estimated mass of 24,070 tons. This landfill gas consists of approximately 17,640 tons of carbon dioxide, 6,430 tons of methane, and 41.1 tons of non-methane organic compounds. The latter group includes the 7.5 tons of HAPs emitted by the Arecibo Landfill in 2008. Table 2 lists the components of landfill gas and the HAP results in tpy for the Arecibo Landfill in 2008. The values obtained for Arecibo from the LandGEM model were extrapolated to the entire Island's landfilled MSW. The right hand column of Table 2 shows the results of the extrapolation. Puerto Rico landfills generated approximately 8,723,502,160 cubic feet per year of landfill gas using 2008 data. The landfill gas emitted in Puerto Rico during 2008 contained approximately 248,686 tons of carbon dioxide, 90,637 tons of methane, and 106.2 tons of HAPs.

B. Estimate of incinerator HAPs if all MSW in Puerto Rico were incinerated.

One of the criteria for selection of the operating incinerators was that it should have a similar waste stream to the Island's. However, such information was not available within the databases accessed. Questionnaires were then prepared and submitted to eleven selected facilities (see Figure 2). In addition to waste stream characteristics, the questionnaire requested information about the investment, emissions control systems, materials recovery, power generated, employment, and characteristics of the facility's own waste stream. Table 3 summarizes the information obtained from the five facilities that responded to the questionnaires. The response concerning the incoming solid waste characteristics unfortunately was qualified by most incinerators as best-guesses. At least one of the facilities requested confidentiality for their responses, so the facilities are not identified by name in this study, and the completed questionnaires will be withheld.

The five facilities were selected to represent modern, well-operated incinerators with little or no enforcement history. Given that the purpose of this study was to compare emissions from existing landfills with possible incineration technology for the Island, it was reasonable to seek out the best technologies which obviously remained in compliance with their permits. Plasma arch gasification and thermolysis were two technologies that were sought but not found within the U.S. EPA's databases. Therefore, only mass-burn and refuse-derived-fuel technologies were selected.

The incinerators that responded to the questionnaire began operations between 1987 and 1994. Their capital investment ranged from \$18M to \$300M (average = \$106.6M), and their design capacities ranged from 350 tpd to 2,000 tpd (average = 1,117). In 2008 they processed from 275 to 1,650 tpd (average = 717), their operating costs ranged from \$1.2M to \$5.5M for payroll (average = \$3.95M) and from \$0.5 to \$12M for outsourced services and supplies (average = \$6.95M). They employed from 29 to 145 full time equivalents (average = 64) during 2008. On average, processing the MSW in this fashion cost \$20.37 in capital investment (assumes a 20-year useful life), \$15 in payroll costs, and \$27 in outsourced services and supplies, for a total cost of \$62.03 per ton. Although the incinerators did not indicate their sources of revenue, one can assume that they all charge a tipping fee, they all sold excess power, and some of them sold steam and recovered ferrous metals (3.6 to 40 tpd, average = 15.6 tpd), non-ferrous metals (0.4 to 4.5 tpd, average = 1.9 tpd). One of the facilities stated that their refuse-derived fuel is processed by another facility, which recovers the ferrous and non-ferrous metals.

The design characteristics for the facilities selected are summarized in Table 3. Two are mass-burn facilities, two are refractory wall boilers, three are water-wall boilers, and three utilize refuse derived fuel. All five use fabric filters for emissions control, four also use spray dryers and also four have in place good combustion practices. Many

other emission control systems are represented in the mix, including: Cyclones, dry sorbent injection (duct), flue gas recirculation, injection of activated carbon, selective non-catalytic reduction (SNCR) using ammonia injection, and SNCR using urea injection.

Emissions data from the incinerators that responded to the questionnaires was obtained through the various EPA sources mentioned above. Table 4 lists the composition of the HAP emissions for the five incinerators. For instance, MWC-A received 100,375 tons of MSW in 2008, which represents 2.73% of the MSW land-filled in Puerto Rico; therefore, their HAP emissions results for MWC-A were multiplied by 36.61 ($=1 \div 2.73\%$) to estimate the HAP emissions should all the MSW from Puerto Rico were processed with a facility or facilities similar to MWC-A. MWC-A emitted 20.8 tons of HAPs in 2008, of which 0.0000002 tons (0.0003 pounds) consisted of dioxins and furans, and 20.6 tons consisted of hydrochloric acid. Should all of the MSW generated in Puerto Rico be processed using the technology of MWC-A, for instance, 761.9 tons of HAPs would be emitted to the atmosphere, of which 0.000006 tons (0.02 pounds) would consist of dioxins and furans, and 754.1 tons would consist of hydrochloric acid.

As illustrated in Table 4, using incinerators to process all of the Island's MSW would generate anywhere from 39.4 to 1,245.8 tpy of HAPs, with an average of 493.3 tpy. The single largest HAP present in the emissions of the five incinerators evaluated is hydrochloric acid. It comprised anywhere from 99.0 to 99.8% of the HAP mass for the five incinerator emissions, with an average of 99.3%.

Lead is the next most important component of the HAP emissions, comprising an average of 0.038%, with mass ranging from 0.04 to 13.07 (Avg. = 2.73) tpy for all of Puerto Rico's MSW.

Mercury compounds followed in order of concentration in the incinerator's HAP emissions, comprising an average of 0.054% of the emissions for all five incinerator's.

Mercury emission estimates for the Island using the various incinerators as models would range from 0.009 to 1.1 (Avg. = 0.3) tpy.

Cadmium is the fourth most important component of the HAP emissions, comprising an average of 0.011%, with a mass ranging from 0.00 to 0.24 (Avg. = 0.06) tpy for all Puerto Rico's MSW.

Yet another estimate of emissions from processing the entire Island's MSW using incinerators can be obtained from the USEPA's Emissions Factors (USEPA, 1995b and 2003). These USEPA publications provide emissions factors for MWCs under five scenarios: no emissions controls, electrostatic precipitators, spray dryer/electrostatic precipitator, duct sorbent injection/fabric filter, and spray dryer/fabric filter. Each set of emissions control technologies has its own strengths and weaknesses (Elias-Castells, 2005). Furthermore, some of these controls may be installed in series for additional removal of contaminants.

This author selected the spray dryer/fabric filter emissions factors mainly due to the simplicity and effectiveness of this process: Water or partially treated wastewater (for re-use) is sprayed into the emissions, often with additives such as lime (CaCO_3) or caustic soda (NaOH) for pH adjustment and contaminant adsorption. The emissions temperature is decreased to below the temperature of formation for dioxins and other organic pollutants (Lorber et. al., 1998; USEPA, 1997a, 1998a, and 2006b). As water evaporates to steam, the solids that are left behind are trapped, forming a "cake" in the surface of the fabric filters, which further provides filtering and adsorption (Elias-Castells, 2005; and USEPA, 1998a, b, 2008b). Spray dryer/fabric filter is also the most frequently used emissions control technology for incinerators in the United States (USEPA, 2003).

The last column in Table 4 shows the results of the emissions estimate for the Island's MSW using the Emissions Factors (USEPA, 1995b) for incinerators equipped with spray dryer/fabric filter emission control technology. Total HAP emissions were

estimated at 394.3 tpy. The single largest HAP present in the emissions, based on this national average is, again, hydrochloric acid. It comprised 98.8% of the HAP mass (389.5 tpy), followed by Mercury with 4.0 tpy (1.03%), Lead with 0.5 tpy (0.038%), Nickel with 0.09 tpy (0.024%), Arsenic with 0.08 tpy (0.020%), Chromium with 0.06 tpy (0.014%), Cadmium with 0.05 tpy (0.013%), and dioxins & furans with 0.0001 tpy (0.00003%). These are the only HAP contaminants listed in the Emissions Factors (USEPA, 1995b) for MWCs.

Hazards

The inhalation route of exposure is the most direct hazard associated with the HAP emissions from the disposal of MSW in landfills and incinerators, and so, inhalation hazards are the focus of this section. However, the fate of HAP emissions in the environment and their pathways to humans depends upon their individual properties. Whether a particular HAP will be in contact with, or available to humans, hinges on parameters such as vapor density (whether it is heavier or denser than air), its water or fat solubility, and whether or not the HAP persists in the environment or in biological tissue. Therefore, these properties are noted for each HAP characterization.

C. Identify the hazards posed by the HAPs emitted by landfills and incinerators, and assess their toxicity.

As described in the Methodology section, this study falls short of assigning numerical values to the risks to public health and the environment from the HAP emissions of landfills and incinerators. However, simply comparing the mass of HAPs emitted should be a strong indication of the overall risk that landfills and incinerators each pose. Mass is the most important factor in risk assessment for one simple reason: The amount of a toxic substance is always the numerator in the risk factors, such as dose (mg/Kg, milligrams of contaminant per kilogram of body mass) and exposure potential (mg/m³, milligrams of contaminant per volume of air). Take away the mass of

the contaminant and the risk goes to zero. Increase the mass of a contaminant in the environment and the risk increases accordingly.

The four components of the risk assessment (hazard identification, exposure assessment, toxicity assessment and risk characterization; USEPA, 2004) will be discussed below in order to compare the potential risks from HAP emissions from these two solid waste disposal technologies.

Municipal solid waste landfill.

There are 46 non-methane organic contaminants in landfill gas (USEPA 1995b), of which 27 belong to the hazardous air pollutant category (USEPA, 2008c, see Appendix A). The HAPs emitted from landfills in Puerto Rico are quantified in Table 2, following the extrapolation methodology described in Section A of the Methodology Design. A total of 106.2 tons per year of HAPS are emitted at ground level from open and closed landfills throughout the Island as they emit 248,686 tpy of carbon dioxide and 90,637 tpy of methane, for a total of 2,152,063 tons per year of greenhouse gas CO₂-equivalents; (USEPA, 2005b). Of the 106.2 tpy of HAPs, 40.6 tpy (38%) is Toluene, 14.4 tpy (14%) are xylenes, 6.9 tpy (7%) is Tetrachloroethylene (Perchloroethylene), 6.4 tpy (6%) is Hexane, 5.8 tpy (5%) is Methyl Ethyl Ketone (2-Butanone), 5.5 tpy (5%) is Ethyl Benzene, 5.2 tpy (5%) is Vinyl Chloride, 4.2 tpy (4%) is Trichloroethylene, 3.8 tpy (4%) is Acrylonitrile, 2.7 tpy (3%) is Ethylidene Dichloride (1,1-Dichloroethane), 2.2 tpy (2%) is Methyl Isobutyl Ketone (Hexone), 2.1 tpy (2%) is 1,1,2,2-Tetrachloroethane, 1.7 tpy (2%) is Benzene, 0.9 tpy (1%) is Ethyl Chloride (Chloroethane), 0.7 tpy (0.7%) is Methyl Chloroform (1,1,1-Trichloroethane), 0.7 tpy (0.6%) is Methyl Chloride (Chloromethane), 0.5 tpy (0.5%) is Carbon Disulfide, 0.5 tpy (0.4%) is Ethylene Dichloride (1,2-Dichloroethane), 0.3 tpy (0.3%) is 1,4-Dichlorobenzene(p), 0.3 tpy (0.3%) is Carbonyl Sulfide, 0.3 tpy (0.3%) is Chlorobenzene, 0.2 tpy (0.2%) is Propylene Dichloride (1,2-Dichloropropane), 0.2 tpy (0.2%) is Vinylidene Chloride (1,1-

Dichloroethylene), 0.04 tpy (0.04%) is Chloroform, 0.007 tpy (0.007%) is Carbon Tetrachloride, 0.002 tpy (0.002%) is Ethylene Dibromide (Dibromoethane) and 0.0007 tpy (0.0006%) are volatile Mercury Compounds.

Below is a characterization of the 27 HAPs emitted by landfills. They are listed in decreasing order of emissions mass. The characterization sources of information are NIOSH (2007), and the on-line databases of IRIS and (www.epa.gov/iris) ATSDR (www.atsdr.cdc.gov). The Oxford University on-line database (OU, 2010, April 7) was consulted for information not found in the U.S. databases.

1. **Toluene** (40.6 tpy, Chemical Abstracts Service (CAS) No. 108-88-3) is a colorless liquid with a heavier-than-air vapor (vapor density = 3.2) and a benzene-like odor (odor threshold = 0.17 ppm) that is toxic to humans. Routes of exposure are inhalation, dermal contact, and ingestion. Exposure symptoms include Irritation of eyes and nose; lassitude (weakness, exhaustion), confusion, euphoria, dizziness, headache; dilated pupils, lacrimation (discharge of tears); anxiety, muscle fatigue, insomnia; paresthesia (sensation of tingling, pricking, or numbness of a person's skin); dermatitis; liver and kidney damage (LOAEL chronic inhalation = 46 mg/m³). There is inadequate information to assess Toluene's carcinogenic potential; however, exposure may result in increased kidney weight, and neurological effects in occupationally-exposed workers. Target organs are the eyes, skin, respiratory system, central nervous system, gastrointestinal system, blood, liver and kidneys. NIOSH REL = 375 mg/m³. IDLH = 500 ppm. The major use of toluene is as a mixture added to gasoline to improve octane ratings. Automobile emissions are the principal source of toluene to the ambient air. The highest concentrations of toluene usually occur in indoor air from the use of common household products (paints, paint thinners, adhesives, synthetic fragrances and nail polish) and cigarette smoke.

2. **Xylenes** (14.4 tpy, CAS No. 1330-20-7, 108-38-3, 95-47-6 and 106-42-3) are a family of colorless, practically insoluble in water, liquid solvents with a heavier-than-air vapor (vapor density = 3.7) that are toxic to humans. Routes of exposure are inhalation, skin, and ingestion. Exposure symptoms (LOAEL chronic inhalation = 39 mg/m³) include irritation of eyes, skin, nose and throat; dizziness, excitement, drowsiness, incoordination, and staggering gait. There is inadequate information to assess the carcinogenic potential; however, exposure may result in corneal vacuolization; anorexia, nausea, vomiting, abdominal pain; dermatitis, decreased body weight, and increased mortality. Target organs are the eyes, skin, respiratory system, central nervous system, gastrointestinal system, blood, liver and kidneys. NIOSH REL = 655 mg/m³. IDLH = 900 mg/m³. Xylenes are also released into the atmosphere as fugitive emissions from industrial sources, from auto exhaust, and through volatilization from their use as solvents.
3. **Tetrachloroethylene (Perchloroethylene)**, 6.9 tpy, CAS No. 127-18-4) is a colorless liquid with a heavier-than-air vapor (vapor density = 5.8) and a sharp, sweet odor (odor threshold = 1.0 ppm) that is toxic to humans. Routes of exposure are inhalation, dermal contact, ingestion and eyes. Symptoms include irritation of eyes, skin, nose, throat and respiratory system; nausea; flush face and neck; dizziness; incoordination; headache; drowsiness; skin erythema (skin redness); and liver damage. Target organs are the eyes, skin, respiratory system, liver, kidneys and central nervous system. Tetrachloroethylene is a possible human carcinogen and a potential occupational carcinogen. No LOAEL for chronic inhalation or NIOSH REL has been determined (typical of carcinogens). IDLH = 150 mg/m³. Tetrachloroethylene is widely used for dry-cleaning fabrics and metal degreasing operations.

4. **Hexane** (6.4 tpy, CAS No. 110-54-3) is a colorless liquid with a slightly disagreeable odor (odor threshold = 130 ppm) with a heavier-than-air vapor (vapor density = 3) that is toxic to humans. Routes of exposure are inhalation, ingestion and eyes. Symptoms include irritation of eyes and nose; nausea, headache; peripheral neuropathy: numb extremities, muscle weakness; dermatitis; dizziness; and chemical pneumonitis (aspiration liquid). Critical effects are peripheral neuropathy, decreased mean corpuscular volume (size of red blood cel). Target organs are the eyes, skin, respiratory system, central nervous system and peripheral nervous system. There is inadequate information to assess the carcinogenic potential of hexane. NIOSH REL = 180 mg/m³. IDLH = 1,100 ppm. The main use of hexane is as a solvent to extract edible oils from seed and vegetable crops (e.g., soybeans, peanuts, corn). The most probable route of human exposure to hexane is by inhalation. Individuals are most likely to be exposed to hexane in the workplace. Monitoring data indicate that hexane is a widely occurring atmospheric pollutant.
5. **Methyl Ethyl Ketone** (5.8 tpy, CAS No. 78-93-3) is a colorless liquid with a heavier-than-air vapor (vapor density = 2.5) with an Acetone-like odor (odor threshold = 5.4 ppm) that is toxic to humans. Symptoms of exposure include irritation of eyes, skin and nose; headache; dizziness; vomiting; and dermatitis. Target organs are the eyes, skin, respiratory system, and central nervous system. NIOSH REL = 885 mg/m³. IDLH = 3,000 ppm. The primary use of Methyl Ethyl Ketone is as a solvent in processes involving gums, resins, cellulose acetate, and cellulose nitrate. Methyl Ethyl Ketone has been detected in both indoor and outdoor air. Methyl Ethyl Ketone can be produced in outdoor air by the photooxidation of certain air pollutants, such as Butane and other hydrocarbons.

On December 19, 2005 the Environmental Protection Agency removed Methyl Ethyl Ketone from the list of toxic air pollutants. The total number of listed air toxics is now 187.

6. **Ethylbenzene** (5.5 tpy, CAS No. 100-41-4) is a colorless liquid with a heavier-than-air vapor (vapor density = 3.7) and an aromatic odor (odor threshold = 2.3 ppm) that is toxic to humans. Routes of exposure are inhalation, ingestion and eyes. Symptoms include irritation of eyes, skin and mucous membrane; headache; dermatitis; narcosis and coma. Critical effects are liver and kidney toxicity. Target organs are the eyes, skin, respiratory system and central nervous system. There is inadequate information to assess the carcinogenic potential of ethyl benzene. NIOSH REL = 545 mg/m³. IDLH = 800 ppm. Ethylbenzene is mainly used in the manufacture of styrene. Exposure to ethylbenzene occurs from the use of consumer products, gasoline, pesticides, solvents, carpet glues, varnishes, paints, and tobacco smoke.
7. **Vinyl Chloride** (5.2 tpy, CAS No. 75-01-4) is a colorless gas (boiling point = -13.9°C) that is heavier than air (vapor density = 2.2) and has a mild, sweet odor (odor threshold = 3,000 ppm) that is toxic to humans. Routes of exposure are inhalation and eyes. Symptoms include lassitude; abdominal pain, gastrointestinal bleeding; enlarged liver; pallor or cyanosis of extremities. Critical effect is liver cell polymorphism. Target organs are the liver, central nervous system, blood, respiratory system, and lymphatic system. Vinyl Chloride is a known human carcinogen by the inhalation route or exposure, and by analogy, through the oral route of exposure; and a likely human carcinogen by the dermal route. A 1-in-10,000 increase in the risk of cancer is expected for continuous lifetime exposure to 23 µg/m³ of Vinyl Chloride during adulthood. LOAEL = 4 mg/m³. No NIOSH REL or IDLH have been established, typical of carcinogens. Most vinyl chloride is used to

make Polyvinyl Chloride (PVC) plastic and vinyl products. Vinyl Chloride is also a microbial degradation product of Trichloroethylene. Ambient air concentrations of Vinyl Chloride are generally quite low, with exposure occurring from the discharge of exhaust gases from factories that manufacture or process Vinyl Chloride, or evaporation from areas where chemical wastes are stored. Air inside new cars may contain vinyl chloride at higher levels than detected in ambient air because Vinyl Chloride may outgas into the air from the new plastic parts. The half-life of vinyl chloride in air is a few hours.

Additional characteristics of Vinyl Chloride were discussed further under Case studies.

8. **Trichloroethylene** (4.2 tpy, CAS No. 79-01-6) is a colorless liquid with a heavier-than-air vapor (vapor density = 4.5) and negligible water solubility. Routes of exposure are inhalation, dermal contact, ingestion and eyes. Symptoms of exposure include Irritation of eyes and skin; headache, visual disturbance, lassitude, dizziness, tremor, drowsiness, nausea, vomiting; dermatitis; cardiac arrhythmias, paresthesia; and liver injury. Target organs are eyes, skin, respiratory system, heart, liver, kidneys, and central nervous system. Trichloroethylene is a potential occupational carcinogen. LOAEL = 170 mg/m³. No NIOSH REL has been determined (typical of carcinogens). IDLH = 5,370 ppm. The main use of Trichloroethylene is in the vapor degreasing of metal parts. Trichloroethylene is also used as an extraction solvent for greases, oils, fats, waxes, and tars; a chemical intermediate in the production of other chemicals; as a refrigerant; and in consumer products such as typewriter correction fluids, paint removers/strippers, adhesives, spot removers, and rug-cleaning fluids. Trichloroethylene is not a persistent chemical in the atmosphere; its half-life in air is about 7 days.

9. **Acrylonitrile** (3.8 tpy, CAS No. 107-13-1) is a clear, colorless or slightly yellow liquid with a heavier-than-air vapor (vapor density = 1.8), a pungent odor (odor threshold = 47 mg/m³), that is water soluble and toxic to humans. Routes of exposure are inhalation, dermal contact, ingestion and eyes. Symptoms of exposure include irritation eyes, skin; asphyxia; headache; sneezing; nausea, vomiting; lassitude, dizziness; skin vesiculation; and scaling dermatitis. Critical effects of chronic inhalation include degeneration and inflammation of nasal respiratory epithelium; and hyperplasia of mucous secreting cells. Target organs are the eyes, skin, cardiovascular system, liver, kidneys, and the central nervous system. Acrylonitrile is a probable human carcinogen based on limited evidence of carcinogenicity in animals (lung cancer in exposed workers and observation of tumors, generally astrocytomas in the brain). A 1-in-10,000 increase in the risk of cancer is expected for continuous lifetime exposure to 0.002 mg/m³. LOAEL = 1.9 mg/m³. NIOSH REL = 1 ppm. IDLH = 85 ppm. Acrylonitrile is primarily used in the manufacture of acrylic fibers and plastics. Exposure to Acrylonitrile is primarily occupational.
10. **Ethylidene Dichloride (1,1-Dichloroethane, 2.7 tpy, CAS No. 75-34-3)** is colorless aromatic viscous liquid with a heavier-than-air vapor (vapor density = 6.5) that has an odor similar to ether (odor threshold = 120 ppm) that is toxic to humans. Routes of exposure are inhalation, ingestion and eyes. Symptoms include irritation of skin; central nervous system depression; liver, kidney, and lung damage. Target organs are the skin, liver, kidneys, lungs, central nervous system. Ethylidene dichloride is a possible human carcinogen, based on no human data and limited evidence of carcinogenicity in two animal species (rats and mice) as shown by an increased incidence of mammary gland adenocarcinomas and hemangiosarcomas in female rats and an increased incidence of hepatocellular carcinomas and benign uterine polyps in mice. A 1-in-10,000 increase in the risk of cancer is expected for

continuous lifetime exposure to $4 \mu\text{g}/\text{m}^3$. LOAEL has not been determined. NIOSH REL = $400 \text{ mg}/\text{m}^3$. IDLH = 3,000 ppm. Ethylidene Dichloride is primarily used in the manufacture of chemicals such as Vinyl Chloride and 1,1,1-Trichloroethane, and rubber.

11. **Methyl Isobutyl Ketone (Hexone, 2.2 tpy, CAS No. 108-10-1)** is a colorless liquid with a heavier-than-air vapor (vapor density = 3.5) with a pleasant odor (odor threshold = 0.1 ppm) that is toxic to humans. Routes of exposure are inhalation, ingestion and eyes. Symptoms of exposure include irritation of eyes, skin and mucous membrane; headache, narcosis, coma; and dermatitis. Target organs are the eyes, skin, respiratory system, central nervous system, liver and kidneys. Critical effects of chronic inhalation are reduced fetal body weight, skeletal variations, increased fetal death in mice, and skeletal variations in rats. Methyl Isobutyl Ketone is not classifiable as to human carcinogenicity. LOAEL = $3 \text{ mg}/\text{m}^3$. NIOSH REL = $205 \text{ mg}/\text{m}^3$. IDLH = 500 ppm. Methyl Isobutyl Ketone is used as a solvent for gums, resins, paints, varnishes, lacquers, and nitrocellulose, as an alcohol denaturant, in the extraction of rare metals, and as a synthetic flavoring adjuvant. The most probable routes of exposure to Methyl Isobutyl Ketone by the general population are by inhalation and dermal contact during the use of consumer products that contain this compound.

12. **1,1,2,2-Tetrachloroethane (2.1 tpy, CAS No. 79-34-5)** is a colorless to light yellow liquid with a heavier-than-air vapor (vapor density = 5.8) with a chloroform-like odor (odor threshold = 1.5 ppm) that is toxic to humans. Routes of exposure are inhalation, dermal contact, ingestion and eyes. Symptoms of exposure include nausea, vomiting, abdominal pain; tremor fingers; jaundice, hepatitis, liver tenderness; dermatitis; and leukocytosis (increased blood leukocytes). Target organs are the skin, liver, kidneys, central nervous system, and gastrointestinal tract.

Critical effect of chronic inhalation is kidney damage. 1,1,2,2-Tetrachloroethane is a possible human carcinogen, and a potential occupational carcinogen. A 1-in-10,000 increased risk of cancer is expected for continuous lifetime exposure of 20 µg/L. NIOSH REL = 7 mg/m³. IDLH = 100 ppm. 1,1,2,2-tetrachloroethane is no longer available in the U.S. as an end-product; present sources are fugitive emissions when it is generated as a by-product and during chemical production activities. Low levels can be present in both indoor and outdoor air. 1,1,2,2-Tetrachloroethane has been found in trace amounts in these household products: Adhesives, oils, greases, and lubricants. Its half-life in air is about 60 days.

13. **Benzene** (1.7 tpy, CAS No. 71-43-2) is a colorless liquid with high solubility in water and a heavier-than-air vapor (vapor density = 2.7) that has a sweet odor (odor threshold = 1.5 ppm), and is toxic to humans. Routes of exposure are inhalation, dermal contact, ingestion and eyes. Symptoms of exposure include irritation of eyes, skin, nose and respiratory system; dizziness; headache, nausea, staggered gait; anorexia, lassitude (weakness, exhaustion); and dermatitis. Target organs are the eyes, skin, respiratory system, blood, central nervous system and the bone marrow. Critical effects of chronic inhalation are decreased lymphocyte count and bone marrow depression. Benzene is classified as a "known" human carcinogen for all routes of exposure, with a 1-in-10,000 increased risk of cancer expected for a continuous lifetime exposure of 100 µg/L. LOAEL = 0.03 mg/m³. NIOSH REL = 0.1 ppm. IDLH = 500 ppm. Benzene is a constituent in motor fuels; a solvent for fats, waxes, resins, oils, inks, paints, plastics, and rubber; used in the extraction of oils from seeds and nuts, and in certain printing methods. It is also used in the manufacture of detergents, explosives, pharmaceuticals, and dyestuffs. The following sources of Benzene contribute to elevated levels of benzene in the ambient

air: Emissions from burning coal and oil, motor vehicle exhaust, and evaporation from gasoline service stations and in industrial solvents.

14. **Ethyl Chloride (Chloroethane, 0.9 tpy, CAS No. 75-00-3)** is a colorless gas (boiling point = 12.3°C) with an ethereal odor (odor threshold = 4.2 ppm) that is heavier than air (vapor density = 2.2), and is toxic to humans. Routes of exposure are inhalation, dermal contact, ingestion and eyes. Symptoms of exposure include incoordination, inebriation; abdominal cramps; cardiac arrhythmias, and cardiac arrest. Target organs are the liver, kidneys, respiratory system, cardiovascular system, and the central nervous system. Critical effects of chronic inhalation are delayed fetal ossification; liver and kidney damage. Its carcinogenicity has not been assessed under the IRIS Program. The LOAEL and NIOSH REL have not been determined. IDLH = 9,880 mg/m³. Ethyl Chloride is used in the production of ethyl cellulose, as a solvent, refrigerant, and topical anesthetic, in the manufacture of dyes, chemicals and pharmaceuticals, and as a medication to alleviate pain associated with insect burns and stings; exposure may occur from the use of these consumer products.
15. **Methyl Chloroform (1,1,1-Trichloroethane, 0.7 tpy, CAS No. 71-55-6)** is a colorless liquid with a heavier-than-air vapor (vapor density = 4.6) with a mild ether-like odor (odor threshold > 120 ppm) that is toxic to humans. Routes of exposure are inhalation, ingestion and eyes. Symptoms of exposure include eye and skin irritation; headache, lassitude, central nervous system depression, poor equilibrium; dermatitis; and cardiac arrhythmias. Target organs are the eyes, skin, central nervous system, cardiovascular system and the liver. Critical effects of chronic inhalation are liver histopathologic changes. There is inadequate information to assess Methyl Chloroform's carcinogenic potential. LOAEL = 5 mg/m³. NIOSH REL = 1,900 mg/m³. IDLH = 700 ppm. Methyl Chloroform is used as a solvent and degreasing agent and it is an ingredient in consumer products such as household

cleaners, glues, aerosol sprays and typewriter correction. It is also an intermediate in the production of Vinylidene Chloride. Individuals are more likely to be exposed to Methyl Chloroform indoors rather than outdoors because of its widespread use in home and office products.

16. **Methyl Chloride (Chloromethane, 0.7 tpy, CAS No. 74-87-3)** colorless gas (boiling point = $-24\text{ }^{\circ}\text{C}$) with a faint sweet smell (odor threshold = 10 ppm) that is heavier than air (vapor density = 1.74) and is toxic to humans. Routes of exposure are inhalation and ingestion. Symptoms of exposure include dizziness, nausea, vomiting; visual disturbance, stagger, slurred speech, convulsions, and coma. Target organs are the central nervous system, liver, kidneys, and reproductive system. Critical effects of chronic inhalation are cerebellar lesions. Methyl Chloride is most appropriately classified as an agent whose carcinogenic potential cannot be determined (potential occupational carcinogen). LOAEL = 900 mg/m^3 . NIOSH REL not determined as is typical of carcinogens. IDLH = 2,000 ppm). Low levels of Methyl Chloride occur naturally in the environment. Methyl Chloride is used mainly in the production of silicones and in the production of agricultural chemicals, methyl cellulose, quaternary amines, and rubber. Other sources of exposure to Methyl Chloride include cigarette smoke, polystyrene insulation, and aerosol propellants; home burning of wood, coal, or certain plastics; and chlorinated swimming pools.

17. **Carbon Disulfide (0.5 tpy, CAS No. 75-15-0)** is a colorless to light-yellow liquid with a heavier than air vapor (boiling point= $46\text{ }^{\circ}\text{C}$, vapor density = 2.7) with an unpleasant odor (odor threshold = 0.05 mg/m^3). Routes of exposure are inhalation, ingestion, dermal contact and eyes. Symptoms of exposure include dizziness, headache, poor sleep, lassitude, anxiety, anorexia, weight loss; psychosis; polyneuropathy; Parkinson-like syndrome; ocular changes; coronary heart disease; gastritis; kidney, liver injury; eye, skin burns; dermatitis; reproductive effects. Target

organs are the central nervous system, peripheral nervous system, cardiovascular system, eyes, kidneys, liver, skin and reproductive system. The critical effect of chronic inhalation is peripheral nervous system dysfunction. Carbon Disulfide carcinogenicity has not been determined. LOAEL = 0.7 mg/m³. NIOSH REL = 3 mg/m³. IDLH = 500 ppm. Carbon Disulfide is used predominantly in the manufacture of rayon, cellophane, Carbon Tetrachloride, rubber chemicals and pesticides. The main route of exposure to this compound is in the workplace at manufacturing plants that use it.

18. **Ethylene Dichloride (1,2-Dichloroethane)**, 0.5 tpy, CAS No. 107-06-2) is a colorless, oily, heavy liquid that is slightly soluble in water; has a pleasant chloroform-like odor (odor threshold = 6-10 ppm); which may occur also as a heavier-than-air vapor (boiling point = 83 °C, vapor density = 3.4), and is toxic to humans. Routes of exposure are inhalation, ingestion, dermal contact and eyes. Symptoms of exposure include eye irritation, corneal opacity; central nervous system depression; nausea, vomiting; dermatitis; liver, kidney and cardiovascular system damage. Target organs are the eyes, skin, kidneys, liver, central nervous system, and the cardiovascular system. Ethylene Dichloride is a probable human carcinogen based on sufficient evidence of carcinogenicity in animals. LOAEL has not been determined. NIOSH REL = 4 mg/m³. IDLH = 50 ppm. Ethylene Dichloride is primarily used in the production of Vinyl Chloride and other chemicals, in closed systems for various extraction and cleaning purposes in organic synthesis, as a dispersant in rubber and plastics, and as a wetting and penetrating agent. Inhalation of Ethylene Dichloride in the ambient or workplace air is generally the main route of human exposure.
19. **1,4-Dichlorobenzene(p)** (0.3 tpy, CAS No. 106-46-7) is found as colorless or white crystals (melting point = 53 °C, boiling point = 174 °C) with a heavier-than-air vapor

(vapor density = 5.1); it has negligible water solubility; a distinctive odor (odor threshold = 15 ppm); and is toxic to humans. Routes of exposure are inhalation, dermal contact, ingestion and eyes. Symptoms of exposure include eye irritation, swelling periorbital (around the eyes); profuse rhinitis; headache, anorexia, nausea, vomiting; weight loss, jaundice, and cirrhosis. Target organs are the liver, respiratory system, eyes, kidneys, and skin. Critical effects of chronic inhalation are increased liver weights. 1,4-Dichlorobenzene(p) is a possible human carcinogen and a potential occupational carcinogen. No LOAEL or NIOSH REL has been determined, typical of potential carcinogens. IDLH = 900 mg/m³. The general population is mainly exposed to 1,4-Dichlorobenzene through breathing vapors from 1,4-Dichlorobenzene products used in the home, such as mothballs and toilet deodorizer blocks.

20. **Carbonyl Sulfide** (0.3 tpy, CAS No. 463-58-1) is a heavier-than-air gas (boiling point = -50 °C, vapor density = 2.5) with an unpleasant sulfide smell (no odor threshold reported) that is water-soluble and toxic to humans. Routes of exposure are inhalation, dermal contact and eyes. Symptoms of exposure include eye irritation with possible eye damage, irritation of the skin and redness. Target organs are the respiratory system and the eyes. Health effects from inhalation are respiratory system irritation with coughing, wheezing and severe shortness of breath (pulmonary edema), nausea, vomiting, weakness and muscle cramps. There is pathetically little risk information on Carbonyl Sulfide, with most of the aforementioned data obtained from the State of New Jersey Right-to-Know program (DHSS, 2010). No LOAEL, NIOSH REL nor IDLH values have been reported. High concentrations may be fatal. Exposure to the gas rapidly induces olfactory fatigue so that one may underestimate the level at which the gas is present. Carbonyl Sulfide is used as an intermediate in the synthesis of organic sulfur compounds and alkyl carbonates, and occupational

exposure is mainly by inhalation. Carbonyl Sulfide may be released to the atmosphere naturally from volcanoes, marshes, soils, and deciduous and coniferous trees.

21. **Chlorobenzene** (0.3 tpy, CAS No. 108-90-7) is an aromatic (odor threshold = 0.2 – 1.7 ppm), colorless liquid with a heavier-than-air vapor (vapor density = 3.9) with low water solubility, that is toxic to humans. Routes of exposure are inhalation, ingestion and eyes. Symptoms of exposure include eye, skin and nose irritation; drowsiness, incoordination; central nervous system depression. Target organs are the eyes, skin, respiratory system, central nervous system and liver. Critical effects of chronic inhalation are histopathologic changes in the liver. Chlorobenzene is not classifiable as to human carcinogenicity. LOAEL and NIOSH REL have not been determined either. IDLH = 4,600 mg/m³. Chlorobenzene is primarily used as a solvent for pesticide formulations, Diisocyanate manufacture, degreasing automobile parts and for the production of Nitrochlorobenzene. Human exposure to Chlorobenzene appears to be primarily occupational.

22. **Propylene Dichloride (1,2-Dichloropropane)**, 0.2 tpy, CAS No. 78-87-5) is a colorless liquid (boiling point = 95 °C) with a heavier-than-air vapor (vapor density = 3.9) with a chloroform-like odor (odor threshold = 0.25 ppm) that is toxic to humans. Routes of exposure are inhalation, dermal contact, ingestion and eyes. Symptoms of exposure include eye, skin and respiratory system irritation; drowsiness and dizziness. Target organs are the eyes, skin, respiratory system, liver, kidneys, and central nervous system. Critical effect of chronic inhalation is hyperplasia of the nasal mucosa. Propylene Dichloride is a potential occupational carcinogen. LOAEL = 0.0004 mg/m³. NIOSH REL not determined due to its potential carcinogenicity. IDLH = 1,800 mg/m³. Propylene Dichloride is used as a chemical intermediate in the production of chlorinated organic chemicals, as an industrial solvent, in ion exchange

manufacture, in Toluene Diisocyanate production, in photographic film manufacture, for paper coating, and for petroleum catalyst regeneration. Propylene Dichloride has been detected at low levels in ambient air, where it has a half-life ranging from 16 to greater than 23 days.

23. **Vinylidene Chloride (1,1-Dichloroethylene**, 0.2 tpy, CAS No. 75-35-4) is a colorless liquid with a heavier-than-air vapor (vapor density= 3.5) with a mild sweet odor resembling that of chloroform (odor threshold = 190 ppm), that is toxic to humans. Routes of exposure are inhalation, dermal contact, ingestion and eyes. Symptoms of exposure include eye, skin and throat irritation; dizziness, headache, nausea and dyspnea (breathing difficulty). Target organs are the eyes, skin, respiratory system, central nervous system, liver and kidneys. Critical effects of chronic inhalation are liver toxicity (fatty change), kidney disturbance and pneumonitis. Vinylidene Chloride is a possible human carcinogen and a potential occupational carcinogen. LOAEL = 61 mg/m³. The NIOSH REL and IDLH have not been assigned (typical of potential carcinogens). Vinylidene Chloride is used as an intermediate for organic chemical synthesis, in the production of Polyvinylidene Chloride copolymers, which are used in the production of flexible films for food packaging (SARAN® and VELON® wraps), as flame retardant coatings for fiber and carpet backing, and adhesive applications. Air releases, primarily from manufacturing industries, are the greatest source of ambient Vinylidene Chloride.

24. **Chloroform** (0.04 tpy, CAS No. 67-66-3) is a clear, colorless, not very soluble in water, volatile liquid with a heavier-than-air-vapor (vapor density = 4.1), that has a pleasant, non-irritating odor (odor threshold = 85 ppm) and is toxic to humans. Routes of exposure are inhalation, dermal contact, ingestion and eyes. Symptoms of exposure include eye and skin irritation; dizziness, mental dullness, nausea,

confusion; headache, lassitude; and anesthesia. Target organs are the liver, kidneys, heart, eyes, skin and central nervous system. Critical effects of chronic inhalation are enlarged liver and hepatocellular carcinoma. Chloroform is a probable human carcinogen to humans, and is a potential occupational carcinogen. A 1-in-10,000 increase in the risk of cancer is expected for continuous lifetime exposure of $4 \mu\text{g}/\text{m}^3$. LOAEL = $0.000000023 \text{ mg}/\text{m}^3$. NIOSH REL = $9.78 \text{ mg}/\text{m}^3$. IDLH = $2,400 \text{ mg}/\text{m}^3$. Chloroform may be released to the air as a result of its formation in the chlorination of drinking water, wastewater and swimming pools. Other sources include pulp and paper mills, hazardous waste sites, and sanitary landfills.

25. **Carbon tetrachloride** (0.007 tpy, CAS No. 56-23-5) is a colorless liquid (boiling point = $77 \text{ }^\circ\text{C}$) with a heavier-than-air vapor (vapor density = 5.3), a sweet characteristic odor (odor threshold > 10 ppm) that is insoluble in water and is toxic to humans. Routes of exposure are inhalation, dermal contact, ingestion and eyes. Symptoms of exposure include eye and skin irritation; central nervous system depression; nausea, vomiting; drowsiness, dizziness and incoordination. Target organs are the central nervous system, eyes, lungs, liver, kidneys and skin. Critical effects of chronic inhalation are kidney injury, fatty changes in the liver, elevated serum SDH activity. Carbon tetrachloride is a probable human carcinogen via inhalation exposure (tumor type: Pheochromocytoma), and is a potential occupational carcinogen. A 1-in-10,000 increase in the risk of cancer is expected for continuous lifetime exposure to $50 \mu\text{g}/\text{L}$. LOAEL = $0.1 \text{ mg}/\text{m}^3$. NIOSH REL = $12.6 \text{ mg}/\text{m}^3$. IDLH = 200 ppm. Carbon Tetrachloride was produced in large quantities to make refrigerants and propellants for aerosol cans, as a solvent for oils, fats, lacquers, varnishes and rubber waxes, and resins, and as a grain fumigant and a dry cleaning agent. Consumer and fumigant uses have been discontinued and only industrial uses remain. Individuals may be exposed to Carbon Tetrachloride in the

air from accidental releases from production and uses, and from its disposal in landfills where it may evaporate into the air or leach into groundwater. Carbon Tetrachloride is also a common contaminant of indoor air; the sources of exposure appear to be building materials or products, such as cleaning agents, used in the home.

26. **Ethylene Dibromide (1,2-Dibromoethane**, 0.002 tpy, CAS No. 106-93-4) occurs as a liquid with a heavier-than-air vapor (vapor density = 6.5) that is extremely toxic to humans. Routes of exposure are inhalation, dermal contact, ingestion and eyes. Symptoms of exposure include irritated eyes, skin and respiratory system; and dermatitis with vesiculation. Target organs are the eyes, skin, respiratory system, liver, kidneys, reproductive system (testicular atrophy), heart and spleen. Critical effect of chronic inhalation is nasal inflammation. Ethylene Dibromide is considered a probable carcinogen to humans via inhalation exposure (tumor types: adenoma, adenocarcinoma, papillary adenoma, squamous cell carcinoma, and or/papilloma of the nasal cavity; hemangiosarcomas and mesotheliomas), and is a potential occupational carcinogen. A 1-in-10,000 increase in the risk of cancer is expected for continuous lifetime exposure to $0.2 \mu\text{g}/\text{m}^3$. LOAEL = $0.7 \text{ mg}/\text{m}^3$. NIOSH REL = $0.3 \text{ mg}/\text{m}^3$. IDLH = $667 \text{ mg}/\text{m}^3$. Ethylene Dibromide was used in the past as an additive to leaded gasoline, but it is no longer used for this purpose. It was also used as a fumigant to protect against insects, pests, and nematodes in citrus, vegetable, and grain crops, and as a fumigant for turf, particularly on golf courses, but in 1984 it was banned as a soil and grain fumigant. Ethylene Dibromide is currently used in the treatment of felled logs for bark beetles and termites, and for the control of wax moths in beehives. Ethylene Dibromide is also used as an intermediate for dyes, resins, waxes, and gums. Possible sources of emissions to the ambient air are production and processing facilities. Ethylene dibromide reacts with hydroxyl

radicals (OH⁻) in the atmosphere, with a half-life for this reaction of approximately 40 days. In water, its half-life ranges from 2.5 to 13.2 years. In soil it was detected 19 years after it had been applied.

27. **Mercury** (0.0007 tpy, CAS No. 7439-97-6) is a silvery liquid metal (boiling point = 357° C) with negligible water solubility in its metallic state, that is toxic to humans. Routes of exposure are inhalation, skin, ingestion and eyes. Symptoms include irritation of eyes and skin; cough, chest pain, dyspnea, bronchitis, pneumonitis; tremor, insomnia, irritability, indecision, headache, lassitude; stomatitis, salivation; gastrointestinal disturbance, anorexia, weight loss; and proteinuria. Critical effects are hand tremor; increases in memory disturbances; and slight subjective and objective evidence of autonomic dysfunction. Target organs are the eyes, skin, respiratory system, central nervous system and kidneys. Epidemiologic studies failed to show a correlation between exposure to elemental mercury vapor and carcinogenicity. LOAEL = 0.009 mg/m³. NIOSH REL = 0.05 mg/m³. IDLH = 10 mg/m³. Mercury is used in thermometers, barometers, pressure-sensing devices, batteries, lamps, industrial processes, refining, lubrication oils, and dental amalgams.

In summary, there are 26 HAPs in Puerto Rico landfill gas totaling 106.2 tpy, of which 7 are known carcinogens (Vinyl Chloride with 5.2 tpy, Acrylonitrile with 3.8 tpy, Benzene with 1.7 tpy, Ethylene Dichloride with 0.5 tpy, Propylene Dichloride with 0.2 tpy, Chloroform with 0.04 tpy, Carbon tetrachloride with 0.007 tpy, and Ethylene dibromide with 0.002 tpy) and 7 are possible or potential carcinogens (Tetrachloroethylene with 6.9 tpy, Trichloroethylene with 4.2 tpy, Ethylidene Dichloride with 2.7 tpy, 1,1,2,2-Tetrachloroethane with 2.1 tpy, Methyl chloride with 0.7 tpy, 1,4-Dichlorobenzene(p) with 0.3 tpy, and Vinylidene Chloride with 0.2 tpy), for a total of 11.4 tpy of known

carcinogenic HAP emissions and 17.1 tpy of potentially or possibly carcinogenic HAP emission.

Risk assessments have been conducted by the USEPA (1996) for the lifetime inhalation exposure to 8 of the HAPs found in landfill gas. Table 6 shows the concentrations in air at which the likelihood that one person, out of ten thousand equally exposed people would develop cancer if exposed continuously to the specific concentration over seventy years (an assumed lifetime). This would be in addition to those cancer cases that would normally occur in an unexposed population. A parameter associated with this risk assessment is the weight-of-evidence (WoE) for carcinogenicity. This is a system used by the USEPA for characterizing the extent to which the available data support the hypothesis that an agent causes cancer in humans. Under USEPA's guidelines, the weight-of-evidence (WoE) is described by categories A through E: Group A for known human carcinogens through Group E for agents with evidence of non-carcinogenicity. The parameters for which said risk assessment was conducted (WoE and threshold concentrations in parenthesis) are: Vinyl Chloride (A, 0.0048 mg/m³), 1,1,2,2-Tetrachloroethane (C, 0.02 mg/m³), Benzene (A, 0.1 mg/m³), Ethylene Dibromide (B, 0.2 mg/m³), Ethylene Dichloride (B, 4 mg/m³), Chloroform (B, 4 mg/m³), Acrylonitrile (B, 6 mg/m³) and Carbon Tetrachloride (B, 50 mg/m³). A total of 13.3 tpy of these HAPs are emitted from Puerto Rico landfills, based upon year 2008 land-filled MSW.

With the exception of a minute amount (0.001 tpy) of mercury, most of the 106.15 tpy of HAPs in the landfill gas consist of volatile organic compounds, some halogenated, with a heavier-than-air vapor (mean vapor density = 3.8, range = 1.7 – 6.5). Their high density and stability means that these contaminants remain close to the ground, in contact with human receptors. VOCs participate of the atmospheric photochemical reactions and contribute significantly to the formation of ground-level ozone and smog

(Elias-Castells, 2005). Exposure to ground-level ozone can cause serious respiratory illnesses.

Incinerators.

There are 13 contaminants in incinerator emissions (USEPA 1995 B), 8 of which are hazardous air pollutants (USEPA, 2008c, see Appendix D). Should all the MSW presently land-filled in Puerto Rico were processed with incinerators, the HAPs that would be emitted are quantified in Table 4. Depending on which incinerator is selected for the estimate, anywhere from 39.4 (municipal waste combustor C or MWC-C) to 1,245.8 (MWC-D) tpy of HAPs would be emitted, with an average of 493.3 tpy for all five incinerators selected. Using the USEPA's Emission Factors a total of 394.3 tpy of HAPS would be emitted through the smokestack(s) of incinerator(s) burning trash in Puerto Rico, along with 3,619,492 tpy of carbon dioxide. Of the 394.3 tpy, 389.5 tpy (98.8%) would be Hydrochloric acid, 4.0 tpy (1.0%) would be Mercury Compounds, 0.5 tpy (0.1%) would be Lead Compounds, 0.09 tpy (0.02%) would be Nickel Compounds, 0.08 tpy (0.02%) would be Arsenic Compounds, 0.06 tpy (0.01%) would be Chromium Compounds, 0.05 tpy (0.01%) would be Cadmium Compounds, and 0.0001 tpy (0.00003%) would be Dioxins & Furans.

Below is a description of the eight HAPs emitted by incinerators listed in the order of concentration.

1. **Hydrochloric Acid** (389.5 tpy, CAS No. 7647-01-0) is an aqueous solution or a heavier-than-air gas (vapor density = 2.8) that has an irritating, pungent odor (odor threshold = 7 mg/m³) and is toxic to humans. It is corrosive to the eyes, skin, and mucous membranes. Exposure is almost exclusively occupational—during its production and use, and may cause eye, nose, and respiratory system irritation and inflammation. Prolonged exposure or the concentrated acid may cause burns. Long-term occupational exposure to hydrochloric acid (HCl) has been reported to

cause gastritis, chronic bronchitis, dermatitis, and photosensitization. Target organs are the eyes, skin and respiratory system. HCl is not classified as a carcinogen. HCl does not bioaccumulate. LOAEL = 15 mg/m³. NIOSH REL = 7 mg/m³. IDLH = 75 mg/m³. Hydrochloric acid has many uses: in the production of chlorides, for refining ores, for pickling and cleaning of metal products, in electroplating, in removing scale from boilers, for the neutralization (pH) of basic systems, as a laboratory reagent, as a catalyst and solvent in organic syntheses, in the manufacture of fertilizers and dyes, for hydrolyzing starch and proteins in the preparation of various food products, and in the photographic, textile, and rubber industries.

2. **Mercury** (4.0 tpy, CAS No. 7439-97-6) is a silvery liquid metal (boiling point = 357° C) with negligible water solubility in its metallic state, that is toxic to humans. Routes of exposure are inhalation, skin, ingestion and eyes. Symptoms include irritation of eyes and skin; cough, chest pain, dyspnea, bronchitis, pneumonitis; tremor, insomnia, irritability, indecision, headache, lassitude; stomatitis, salivation; gastrointestinal disturbance, anorexia, weight loss; and proteinuria. Critical effects are hand tremor; increases in memory disturbances; and slight subjective and objective evidence of autonomic dysfunction. Target organs are the eyes, skin, respiratory system, central nervous system and kidneys. Epidemiologic studies failed to show a correlation between exposure to elemental mercury vapor and carcinogenicity. LOAEL = 0.009 mg/m³. NIOSH REL = 0.05 mg/m³. IDLH = 10 mg/m³. Although most uses of Mercury have been banned (i.e. paints, gasoline) it is still used in thermometers, barometers, pressure-sensing devices, batteries, lamps, lubrication oils, dental amalgams, and (mercuric chloride) as a disinfectant and pesticide.
3. **Lead** (0.5 tpy, CAS No. 7439-92-1) is a heavy, ductile, solid, soft, bluish-gray metal that is found in small quantities in the earth's crust, and is toxic to humans. Routes

of exposure are inhalation, ingestion and eyes. Symptoms of exposure include lassitude, insomnia; facial pallor; anorexia, weight loss, malnutrition; constipation, abdominal pain, colic; anemia; gingival lead line; tremor; paralysis of wrist and ankles; encephalopathy; kidney disease; irritation of eyes; and hypertension. Target organs are the eyes, gastrointestinal tract, central nervous system, kidneys, blood, gingival tissue. It is a probable human carcinogen based on sufficient evidence of carcinogenicity in animals, which have shown statistically significant increases in renal tumors with dietary and subcutaneous exposure to several soluble lead salts. Short term studies show that lead affects gene expression. Human evidence is inadequate. No LOAEL for chronic inhalation has been determined. NIOSH REL = 0.050 mg/m³. IDLH = 100 mg/m³. Lead is used in the manufacture of batteries, metal products, paints, and ceramic glazes. Exposure to lead can occur from breathing contaminated workplace air or house dust or eating lead-based paint chips or contaminated dirt.

4. **Nickel Compounds** (0.09 tpy, CAS No. 7440-02-0) is an odorless, hard, lustrous, silvery white metal, which is insoluble in water, and is toxic to humans. Routes of exposure are inhalation, ingestion and eyes. Symptoms of exposure include sensitization dermatitis, allergic asthma and pneumonitis. Critical effects are decreased body and organ weights. Target organs are nasal cavities, lungs and skin. It is a probable human carcinogen, and a potential occupational carcinogen. No LOAEL has been estimated. NIOSH REL = 0.015 mg/m³. IDLH = 10 mg/m³. Nickel is a natural element of the earth's crust; therefore, small amounts are found in food, water, soil, and air. Nickel is an essential nutrient, with a daily requirement of 50 µg/kg in the diet.
5. **Arsenic** (0.08 tpy, CAS No. 7440-38-2) is a grey powder that is toxic to humans. Routes of exposure are inhalation, dermal contact, ingestion and eyes. Symptoms of

exposure include ulceration of the nasal septum, dermatitis, gastrointestinal disturbances, peripheral neuropathy, respiratory irritation and hyperpigmentation of skin. Critical effects are keratosis and possible vascular complications. Target organs are the liver, kidneys, skin, lungs and lymphatic system. Arsenic is a known carcinogen and potential occupational carcinogen. An increase in lung cancer mortality was observed in multiple human populations exposed primarily through inhalation. LOAEL = 0.2 mg/m³. NIOSH REL = .002 mg/m³. IDLH = 5 mg/m³. Arsenic is a naturally occurring element found throughout the environment. For most people, food is the major source of exposure. The major use for inorganic arsenic is in wood preservation; arsine, a gas consisting of arsenic and hydrogen, is used in the microelectronics industry and in semiconductor manufacture.

6. **Chromium** (0.06 tpy, CAS No. 16065-83-1 & 18540-29-9) is a very hard silvery grey metal that is toxic to humans in dust form. Routes of exposure are inhalation, ingestion and eyes. Symptoms of exposure include irritation of eyes and skin; and lung fibrosis. Critical effect is nasal septum atrophy. Target organs are eyes, skin, and respiratory system. Cr(VI) is classified as a known human carcinogen by the inhalation route of exposure. LOAEL = 0.000714 mg/m³. NIOSH REL = 0.001 mg/m³. IDLH = 25 mg/m³. Trivalent (Cr III) and hexavalent (Cr VI) Chromium compounds are thought to be the most biologically significant. Cr III is an essential dietary mineral in low doses, since it is essential to normal glucose, protein, and fat metabolism. Cr VI is generally considered 1,000 times more toxic than Cr III. The body can detoxify some amount of chromium VI to chromium III. The metal chromium is used mainly for making steel and other alloys.
7. **Cadmium** (0.05 tpy, CAS No. 7440-43-9) is a grey-white solid that is toxic to humans. Routes of exposure are inhalation and ingestion. Symptoms of exposure include pulmonary edema, dyspnea, cough, chest tightness, substernal (occurring

beneath the sternum) pain; headache; chills, muscle aches; nausea, vomiting, diarrhea; anosmia (loss of the sense of smell), emphysema, proteinuria and mild anemia. Critical effect is significant proteinuria. Target organs are respiratory system, kidneys, prostate and blood. Cadmium is a probable human carcinogen based on limited evidence of carcinogenicity in animals, and a potential occupational carcinogen. LOAEL = 0.02 mg/m³. NIOSH REL has not been determined. IDLH = 9 mg/m³. Cadmium is used to manufacture pigments and batteries and in the metal-plating and plastics industries. The main sources of cadmium in the air are the burning of fossil fuels such as coal or oil and the incineration of municipal waste.

8. **2,3,7,8-Tetrachlorodibenzo-p-dioxin** (0.00003 tpy, CAS No. 1746-01-6 & 5120-73-19) is a colorless solid with no distinguishable odor, is formed as an unintentional by-product of incomplete combustion of fossil fuels, wood and solid wastes; and is toxic to humans. Routes of exposure are inhalation, dermal contact, ingestion, eyes. Symptoms of exposure include eye irritation; allergic dermatitis, chloracne; porphyria; gastrointestinal tract disturbance; and hemorrhage. Critical effects are chloracne, hair loss, loss of body weight, developmental effects, hormonal disruption, and possible reproductive and teratogenic effects. Target organs are the eyes, skin, liver, kidneys, respiratory system, alimentary system (liver); reproductive system; endocrine system; and hematopoietic system. Dioxins and furans are potential occupational carcinogens. The LOAEL and IDLH have not been determined, typical of carcinogens. NIOSH REL = 0.00000004 mg/m³. There are 210 possible isomers of Polychlorodibenzodioxins (PCDD) and Polychlorodibenzofurans (PCDF), but only several have received extensive toxicological testing. The most potent isomer is 2,3,7,8 Tetrachlorodibenzo-p-dioxin, to which other isomers are compared with a toxicity equivalence factor. Most of the exposure of the general population is from food, mainly meat, dairy products, and fish.

In summary, there would be 8 HAPs emitted from Puerto Rico incinerators totaling 394.2 tpy, of which 5 are known carcinogens (Lead with 0.5 tpy, Arsenic with 0.08 tpy, Chromium with 0.06 tpy, Cadmium with 0.005 tpy, and Dioxins & Furans with 0.0001tpy) and 1 is a potential carcinogen (Nickel with 0.09 tpy), for a total of 0.6 tpy of known carcinogen emissions and 0.09 tpy of potentially carcinogenic emission.

Risk assessments have been conducted by the USEPA (1996) for the lifetime inhalation exposure to 3 of the HAPs found in landfill gas. Table 5 shows the concentrations in air at which the likelihood that one person, out of ten thousand equally exposed people would contract cancer if exposed continuously to the specific concentration over seventy years (an assumed lifetime). This would be in addition to those cancer cases that would normally occur in an unexposed population. The parameters for which said risk assessment was conducted for incinerator contaminants (WoE classification, and risk threshold concentrations in parenthesis) are: Arsenic (A, 0.02 mg/m³), Chromium (A, 0.008 mg/m³) and Cadmium (B, 0.06 mg/m³). A total of 0.2 tpy of these HAPs would be emitted from incinerators should all the MSW presently land-filled in Puerto Rico were so processed.

Hydrochloric acid (389.5 tpy) would comprise the overwhelming majority (98.8%) of the HAP emissions (394.2 tpy) should MSW be processed with incinerators in Puerto Rico. The remaining 4.7 tpy consist of the elements Lead, Nickel, Arsenic, Chromium and Cadmium, and a minute amount (0.0001 tpy) of PCDDs and PCDTs. Incinerator emissions are discharged through a smokestack designed to the height necessary to insure that emissions do not result in excessive concentrations of air pollutants in the immediate vicinity of the source as a result of atmospheric downwash, eddies and wakes which may be created by the source itself, nearby structures or nearby terrain obstacles

(USEPA, 2008c). Heavy metals are suspended as particles in the emissions, and deposit by gravitational settling.

Comparison

D. Compare the technologies to evaluate which emits a greater quantity of toxic atmospheric emissions.

The individual incinerators sampled illustrate the range of values that could be emitted by incinerators if all the MSW in Puerto Rico was processed in this fashion. However, estimates using the USEPA's Emission Factors (USEPA, 1995b; 2008b) are mainly utilized during this discussion since they represent averages of the available data of acceptable quality, and are assumed to be representative of long-term averages for each type of facility. Estimates using these Emission Factors for MWCs, and the latest mathematical model to estimate landfill gas emissions, the HAP emissions from landfills and incinerators are compared here.

Table 2 illustrates that Puerto Rico landfills presently emit 106.2 tpy of HAPs, while Table 4 (far right-hand column) illustrates that incinerators would emit on average 394.3 tpy. However, the individual facilities sampled (Table 4), MWC-A through MWC-E, demonstrate that there are incinerator technologies that are able to reduce HAP emissions to a tenth of the Emission Factors estimates. MWC-C would emit 39.4 tpy if it processed all the MSW generated in the Island. That is close to a third (37%) of the HAPs presently emitted by landfills in Puerto Rico. The individual facilities sampled also illustrate that some of these incinerators fail to adequately control their HAP emissions. Should all of the Island's MSW be processed using MWC-D, HAP emissions would be 1,245.8 tpy or eleven times the HAPs presently emitted from Puerto Rico landfills. Figure 4 graphically compares HAP emissions from each of the incinerators sampled, from the Emissions Factor estimates for MWCs, and from landfills.

It is notable that the best and worst emissions, MWC-C and MWC-D respectively, have the same boiler type (water-wall), and both process the refuse to create a refuse-derived fuel (RDF). No further information is available on the RDF process from each facility. Both facilities also list similar emission control systems: Fabric filters and good combustion practices. However, that is where similarities end. The best performer, MWC-C, only has a spray drier in addition to the above mentioned design and operational controls. The worst performer, MWC-D, lists one additional boiler design feature and three additional emissions control features. No further evaluation of the boiler or emissions control systems designs was conducted.

Mass alone is not, however, the most important factor associated with the emission of HAPs from landfills and incinerators. A HAP that burns your eyes at an elevated exposure is not the same as a HAP that causes cancer. Tables 5 and 6 summarize the risk parameters associated with the HAPs emitted from both incinerators and landfills.

Table 5 lists the non-carcinogen inhalation risk parameters identified for the HAPs emitted by landfills and incinerators. The Reference Concentration (RfC) is an estimate of a continuous inhalation exposure to the human population, including sensitive groups, which is likely to be without an appreciable risk of deleterious effects during a lifetime (USEPA, 2010, March 3). The No-Observed Adverse Effect Level (NOAEL) is the highest exposure levels at which there are no biologically significant increases in the frequency or severity of adverse effect between the exposed population and its appropriate control (IRIS, 2010). Similarly, the Lowest Observed Adverse Effect Level (LOAEL) is that for which there are biologically significant increases in frequency or severity of adverse effects (IRIS, 2010). The Recommended Exposure Limits (RELs) are developed by NIOSH (2007) for hazardous substances or conditions in the workplace, and is associated with a time-weighted average concentration for up to a 10-

hour workday during a 40-hour workweek. Permissible Exposure Limits (PELs) are also developed for the workplace by OSHA (2010). The more protective limit between the NIOSH REL and the OSHA PEL should always be used to determine worker safety. Finally, the Immediately Dangerous to Life or Health Concentrations IDLH is also developed by NIOSH (2007) as the maximum concentration from which you could escape within 30 minutes without irreversible health effects.

Not all of the risk parameters were available for all HAPs. However, the order of magnitude of the available ones may be compared to illustrate the general potency of the HAPs that these risk parameters characterize. Toluene is one of the HAPs with all of the selected inhalation risk parameters available. Using it as an example the reader can see that Table 5 is organized with an increasing concentration from left to right. On the left is the RfC, (0.4 mg/m³), a concentration that is likely to be without appreciable effects during a lifetime of exposure, while to the right is the IDLH (1,885 mg/m³), a concentration from which you must escape or face irreversible health effects. The units for all of these contaminants is concentration—mass per volume of air—or the amount of contaminant to which the human population, including sensitive groups, is likely to be exposed. Expose yourself to a tiny amount of Toluene (i.e. 0.4 mg/m³) and statistically-speaking you will suffer no appreciable adverse health effects. You probably are since it is present in car exhaust; your home probably stores paints, paint thinners, adhesives, synthetic fragrances and nail polish that give off toluene; and there are 43.1 million cigarette smokers in the U.S. (AHA, 2010). Expose yourself to a lot (i.e. 1,885 mg/m³) and you probably will never be the same.

The relative extremes of these risk parameters are the RfC and the IDLH. The HAPs emitted by landfills in Puerto Rico and those that would be emitted if the MSW of the Island was processed with incinerators show immense variability in their non-carcinogen parameters. Landfill HAP RfCs range from 0.00000002 to 10 with an

average of 1.1 (all values in this paragraph are in mg/m³), whereas the incinerator HAP RfCs range from 0.000008 to 0.03 with an average of 0.01. Incinerator HAPs have an RfC minimum that is two orders of magnitude higher (less potent) than landfills, yet their maximum is four orders of magnitude lower, and their average is two orders of magnitude lower (more potent) than that of the landfills. Landfill HAP IDLHs range from 2 to 9,880 with an average of 2,796. Incinerator HAP IDLHs range from 2 to 100 with an average of 32. Incinerator HAPs have an IDLH minima that is identical to that of landfills, and their maximum and their average are two orders of magnitude lower (more potent) than that of the landfills. The crucial question is the level of exposure to which the population is exposed, which is directly related to the mass of pollutants that are emitted and how far they are dispersed.

The fourth column in Table 6 includes the weight of evidence estimate (WoE), which is a characterization of the strength of the data supporting the hypothesis that a contaminant causes cancer in humans: Group A is for known human carcinogens, and Group E is for contaminants with evidence of non-carcinogenicity (IRIS). For Table 6, "Known Carcinogens" were selected from those in the WoE groups A and B. "Possible/Potential Carcinogens" were those in the WoE Group C and those that NIOSH considers potential occupational carcinogens. The next column is labeled "1 in 10,000 Concentration" and it represents the concentration at which a 1-in-10,000 increase in the risk of cancer is expected for a continuous lifetime exposure during adulthood. This increase in cancer rate would be in addition to those cancer cases that would normally (2.5 cases per 10,000 people in 1996) occur in an unexposed population. Continuous or chronic exposure is the type of exposure that landfills and incinerators impose upon the receptor population.

Landfills in Puerto Rico emit 11.4 tpy of known carcinogens (5.2 tpy Vinyl Chloride, 3.8 tpy Acrylonitrile, 1.7 tpy Benzene, 0.5 tpy Ethylene Dichloride, 0.2 tpy

Propylene Dichloride, 0.04 tpy Chloroform, 0.007 tpy Carbon Tetrachloride, and 0.002 tpy Ethylene Dibromide) and 17.1 tpy of potential carcinogens (6.9 tpy Tetrachloroethylene, 4.2 tpy Trichloroethylene, 2.7 tpy Ethylidene Dichloride, 2.1 tpy 1,1,2,2-Tetrachloroethane, 0.7 tpy Methyl Chloride, 0.3 tpy 1,4-Dichlorobenzene(p), and 0.2 tpy Vinylidene Chloride). In contrast, incinerators processing all of the MSW presently land-filled in Puerto Rico would emit 0.6 tpy of known carcinogens (0.5 tpy Lead, 0.08 tpy Arsenic, 0.06 tpy Chromium, 0.005 tpy Cadmium, and 0.0001 tpy Dioxins & Furans) and 0.09 tpy of a potential carcinogen (Nickel). Figure 5 graphically compares HAP emissions of known carcinogens from each of the incinerators sampled, from the Emissions Factor estimates for incinerators, and from landfills. Figure 6 graphically compares HAP emissions of possible carcinogens or potential occupational carcinogens from each of the incinerators sampled, from the Emissions Factor estimates for MWCs, and from landfills.

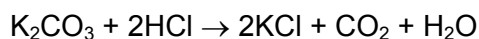
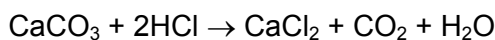
Lifetime Assessment Concentrations are shown in Table 6 to illustrate the potency of the HAP as a carcinogen over a long-term exposure. The lowest concentration (0.0048 µg/L) or higher potency in the list belongs to Vinyl Chloride, a HAP emitted in Puerto Rico landfills at the rate of 5.2 tpy, and a contaminant that targets the liver. The USEPA has conducted lifetime assessments for only eleven of the HAPs emitted from the management of MSW: Eight from HAPs that are emitted by landfills at the rate of 13.3 tpy and three that are emitted by incinerators at the rate of 0.1 tpy.

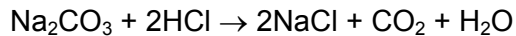
Landfills in Puerto Rico emit 77.6 tpy of non-carcinogen HAPs (40.6 tpy Toluene, 14.4 tpy Xylenes, 6.4 tpy Hexane, 5.8 tpy Methyl Ethyl Ketone, 5.5 tpy Ethylbenzene, 2.2 tpy Methyl Isobutyl Ketone, 0.9 tpy Ethyl Chloride, 0.7 tpy Methyl Chloroform, 0.5 tpy Carbon Disulfide, 0.3 tpy Carbonyl Sulfide, 0.3 tpy Chlorobenzene, and 0.001 tpy Mercury). If all of the MSW presently landfilled in Puerto Rico were processed using incinerators they would emit 393.5 tpy of non-carcinogen HAPs (389.5 tpy Hydrochloric

Acid and 4.0 tpy Mercury). Therefore, incinerators emit five times more non-carcinogenic HAPs than landfills. The largest component by far of these incinerator HAPs is Hydrochloric Acid (HCl).

HCl deserves particular consideration. Potential exposure, according to the USEPA (2010, March 10) is occupational during its production and use. It leaves no residue to be measured in order to assess personal exposure. Acute effects stem from its corrosivity to the eyes, skin, and mucous membranes. Acute inhalation (high doses) may cause coughing, hoarseness, inflammation and ulceration of the respiratory tract, chest pain, and pulmonary edema (fluid accumulation). Drinking it causes corrosion of the mucous membranes, esophagus, and stomach, with nausea, vomiting, and diarrhea. However, "HCl is a natural physiological fluid present as a dilute solution in the stomachs of humans" (Manahan, 1994, p. 679). Contact with the skin can cause severe burns, ulceration, and scarring. Chronic effects (continuous exposure) may cause gastritis, chronic bronchitis, dermatitis, and photosensitization in workers. Prolonged exposure to low concentrations may also cause dental discoloration and erosion. No information is available on the reproductive or developmental effects of hydrochloric acid in humans and no information is available on the carcinogenic effects of hydrochloric acid in humans.

HCL is simply a mineral acid with unlimited solubility in water, which reacts readily with carbonates (CO_3^{2-}) in soil dissolving them, resulting mainly in calcium chloride (CaCl_2), potassium chloride (KCl) or sodium chloride (NaCl); carbon dioxide and water, in accordance with the following equations (from Kolthoff, Sandell, Meehan and Buckenstein; 1969, p. 1101):





Calcium chloride is commonly used as an electrolyte in sports drinks. Potassium chloride is consumed as a sodium-free substitute for table salt (sodium chloride).

All of the above information about HCl is not meant to represent that 389.5 tpy of HCl emissions to the atmosphere would be without impact. HCl will acidify the rain, although it is not considered an acid-rain component. The distinction is made here given that 98.8% of the HAPs in incinerator emissions consist of this non-organic, non-bio-accumulative mineral acid (USEPA, March 10 2010). For the five incinerators sampled, HCl ranged from 98.8% to 99.8% of the HAP emissions, with an average of 99.3%. 99.2% of the landfill emissions (105.4 tpy) consist of a blend of organic solvents and degreasers, four of which are known carcinogens, and six of which are possible/potential carcinogens.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

This study's goal was to inform the debate about solid waste disposal technologies (landfills vs. incinerators) and their potential impacts to public health. Their emission of Hazardous Air Pollutants listed in the Clean Air Act (USEPA, 2008c) was chosen for the comparison. I quantified HAP emissions for the disposal of MSW in Puerto Rico using landfills (presently) and in the hypothetical case where incinerators would process all the MSW that is presently land-filled. The USEPA's LandGEM model results were obtained for the Arecibo landfill, which takes approximately 7% of Puerto Rico's refuse, and its emissions were extrapolated for the stream of MSW land-filled in Puerto Rico. I obtained data for five operating incinerators in the United States for the year 2008, and their emissions were extrapolated for the MSW land-filled in Puerto Rico. The USEPA's Emission Factors for MWCs were also used to estimate the HAP emission for the hypothetical incinerator case, and were used as representative of incinerators.

Accordingly, the following conclusions are drawn from this study's results:

1. The volume of landfill gas generated in Puerto Rico was 8,723,502,160 cubic feet in the year 2008. This landfill gas contained 90,637 tpy of Methane, 248,686 tpy of Carbon Dioxide, for a total of 2,152,063 tons per year of CO₂-equivalent greenhouse gas, and 106.2 tpy of Hazardous Air Pollutants, as defined in the Clean Air Act (USEPA, 2008c). These HAPs are found to consist almost exclusively of volatile organic compounds.
2. Should the entire volume of MSW presently land-filled in the Island be processed using incinerators, the year 2008 emissions would have contained 3,619,492 tpy of Carbon Dioxide and 394.3 tpy of HAPs, 98.8% of the latter would be Hydrochloric

Acid, 1.2% heavy metals, 0.02% Arsenic, and 0.00003% would be Dioxins and Furans.

3. Should Puerto Rico landfills be under the control of a single entity, they would be considered a major emission source under the Clean Air Act.
4. Put-or-pay contracts, required for the financing of incinerators constitute a long-term liability for the host community; lasting approximately twenty years (see Figure 3).
5. The community that hosts a landfill has the long-term liability of the underground storage of slowly decomposing refuse with the ensuing emissions (greenhouse gasses and non-methane organic compounds, including HAPs) and leachate discharges to the ground and groundwater. USEPA regulations (40 CFR Parts 257 and 258, October 9, 1991) require that monitoring and control measures for landfill gas and leachate last for at least thirty years (see Figure 3).

Both solid waste management strategies, landfills and incinerators, generate important amounts of toxic emissions. However,

6. Landfill emissions occur at ground level, where they are close to the human population, cattle and other links to exposure pathways, increasing the potential exposure to the HAP emissions.
7. Incinerator emissions are required to be at a height that minimizes concentrations of air pollutants in the immediate vicinity of the source and that maximize dispersion of potential pollutants (smokestack design, USEPA, 2008 c).

Using USEPA's Emission Factors (1995b) to estimate both landfill and incinerator emissions, which represent average emissions over the long term, the following conclusions were reached:

8. Incinerators would emit 3.7 times more HAPs than landfills do; 394.3 tpy for incinerators v. 106.2 tpy for landfills, or 288.1 additional tpy than Puerto Rico's present method of solid waste disposal (see Figure 4).

9. Incinerators would emit 18 times fewer known carcinogen HAPs than landfills do; 0.6 tpy for incinerators v. 11.4 tpy for landfills, or 10.8 fewer tpy than Puerto Rico's present method of solid waste disposal (see Figure 5).
10. Incinerators would emit 190 times fewer possible carcinogen or potential occupational carcinogen HAPs than landfills do; 0.09 tpy for incinerators v. 17.1 tpy for landfills, or 17.0 fewer tpy than Puerto Rico's present method of solid waste disposal (see Figure 6).

Using emissions data for the year 2008 obtained for the five operating incinerators sampled, the following conclusions were reached:

11. Actual operating facilities can achieve far greater reductions of HAP emissions than the USEPA (1995b) averages. That is the case of MWC-C. If its combustion and emissions-control technology were utilized in the management of all MSW presently land-filled in Puerto Rico, incinerators would emit 37% fewer (67 tpy) reduction in HAP emissions than landfills presently do (106.2 tpy), more than a one-third reduction (see Figure 4).
12. The proportion of Hydrochloric Acid to the total HAP emissions was consistent when the estimate from the USEPA Emissions Factors for MWCs (98.8% HCl) was compared to the estimates from the five incinerators sampled (range = 98.8% to 99.8% HCl).
13. Similarly, the combined HAP emissions of carcinogens and possible or potential occupational carcinogens would also be much lower if all of the MSW presently land-filled in Puerto Rico were processed using MWC-C (0.8 tpy) instead of Puerto Rico's present method of solid waste disposal (28.5 tpy): 27.7 fewer tpy.
14. Actual operating facilities can emit far more HAPs than the USEPA (1995b) averages. If the combustion and emissions-control technology used by MWC-D were utilized in the management of all MSW presently land-filled in Puerto Rico,

incinerators would emit 1,073% more (1,140 tpy) HAP emissions than landfills presently do (106.2 tpy).

15. Even the worst performer in terms of total HAP emissions, out of the incinerators sampled, MWC-D, would emit approximately one half of the carcinogenic and possible or potential carcinogenic HAPs (13.3 tpy) than landfills presently do (28.5 tpy). See Figure 5 for comparison of the known carcinogens and Figure 6 for comparison of the possible carcinogens or potential occupational carcinogens.

In order to achieve its constitutional and legislative goal of sustainable solid waste management and waste minimization, Puerto Rico should imitate the success stories of other jurisdictions. The implementation of curbside collection of the recyclable and the compostable portions of our solid residues at the same frequency as the collection of our trash could achieve a 66% reduction in the materials that must be disposed-off (USEPA, 1994). The remaining portion of MSW, or that which must be disposed, would have an equivalent reduction in HAP emissions and leachate discharges, regardless of the solid waste disposal method utilized.

It is impossible to directly compare the emission of 5.2 tpy of Vinyl Chloride, a contaminant known to cause liver cancer in humans, with 389.5 tpy of Hydrochloric Acid, an irritant. However, only a dispersion model would give us a better idea of the concentrations to which the population (receptors) are presently exposed to landfill gases, and would be exposed to the hypothetical incinerator. Perhaps a programmatic evaluation of solid waste disposal alternatives that includes at least two rounds of public consultations (one to inform of the alternatives under consideration and potential impacts, and the other to inform the results of dispersion models and such) would bring the public on-board with the science involved in the debate, thereby reducing mistrust

and uncertainty. The resulting, empowered public would be on-board with the decision, whichever happens to be the chosen alternative(s).

The following recommendations are derived from the analysis of this study:

Recycle and compost. Approximately one third of the MSW in Puerto Rico consists of recyclable materials such as cardboard and paper (fiber), glass, ferrous and non-ferrous metals, and plastics (see Figure 1). Approximately another third of the MSW in Puerto Rico consists of compostable materials (those of biological origin) such as yard wastes, food wastes, and fiber. These two streams could be processed separately from the MSW stream with an ensuing 66% reduction in the solid waste that must be disposed using either landfills or incinerators. In turn, this could result in a comparable (two thirds) reduction in HAP emissions whichever way the MSW is disposed. A two-third reduction in disposable solid waste would have the benefit of multiplying by three the remaining landfill capacity, or three times our present combined landfill capacity of five years, for a total new combined landfill capacity of fifteen years.

Incinerate. As the above conclusions demonstrate, incinerators can emit two thirds (63%) less HAP emissions than landfills, and could emit twenty seven times less carcinogenic and possible or potentially carcinogenic HAPs than landfills. As the references in the Conceptual Framework of this study illustrate, incinerators can also reduce the volume of MSW that must be disposed by at least 85%. This level of reduction in disposable solid wastes would have the benefit of multiplying by fifteen the remaining landfill capacity of five years, for a total new combined landfill capacity of 33 years. This would put a stop on the approximately 20 acres per year average land consumption of landfills in Puerto Rico.

Recycle, compost and incinerate. Combining the above two recommendations, the waste stream is reduced and processed by recycling, composting and by incineration. The result is a dramatic difference between the present condition in terms

of combined landfill capacity, HAP emissions, and carcinogenic or possible/potentially carcinogenic HAP emission for the Island.

The resulting combined landfill capacity could be estimated by multiplying the presently five-year remaining landfill capacity, times three (reduce, compost), times 6.7 (incinerate), for a total new combined landfill capacity of 100 years.

Using the best incineration technology and the best operation, the reduction in HAP emissions would be just as dramatic: From the existing 106.2 tpy of HAPs, divide by three (from compost and recycling volume reduction) and multiplied by two thirds ($39.4 \div 106.2$) or 37.1% reduction, from incineration), for a total of 13.3 tpy of HAPs. Following these proportions, from the existing 28.5 tpy of carcinogenic, possible or potential carcinogenic HAPs, divide by three (from compost and recycling volume reduction) and multiplied by two thirds (37.1% reduction, from incineration), for a total of 3.5 tpy of carcinogenic, possible or potential carcinogenic HAPs.

LITERATURE CITED

ADSPR (1995a). *Plan of regional infrastructure for recycling and disposal of solid wastes in Puerto Rico*. Administración de Desperdicios Sólidos de Puerto Rico. Prepared by Quiñones, Diez, Silva & Assoc. And Brown & Caldwell. San Juan, P.R.

ADSPR (1995b). *Programmatic environmental impact statement for the Plan of Regional Infrastructure for Recycling and Disposal of Solid Wastes in Puerto Rico*. Administración de Desperdicios Sólidos de Puerto Rico. Prepared by Quiñones, Diez, Silva & Assoc. And Brown & Caldwell. San Juan, P.R.

ADSPR (1995c). *Waste composition study in northwestern Puerto Rico*. Roxana Longoria, Marly Martinez and Christopher Underwood.

ADSPR (2003). *Final report: Waste characterization study*. Prepared by Wehran P.R., Inc. & Shaw EMCON/OWT, Inc.

ADSPR (2004). *Strategic plan for the management of the solid residues in Puerto Rico*. Autoridad de Desperdicios Sólidos de Puerto Rico.

ADSPR (2008). *Dynamic plan for the management of solid waste in Puerto Rico*. Autoridad de Desperdicios Sólidos de Puerto Rico. MP Engineers of Puerto Rico, P.S.C.

AHA (2010). *Cigarette Smoking Statistics*. American Heart Association. Retrieved from: www.americanheart.org.

ANL (1994) *Trash, ash and the phoenix: Waste-to-energy facilities after the Supreme Court decision of May 2, 1994*. Argonne National Laboratory, Washington, D.C. Retrieved from: http://www.osti.gov/bridge/product.biblio.jsp?osti_id=100237.

APA (2010) *Publication manual of the American Psychological Association* (6th ed.). Washington, DC: American Psychological Association.

Arbona, S.I. & Hunter, J.M. (1995). Economic development threatens groundwater in Puerto Rico: Results of a field study. *Journal of Geography* 94(6) 558-569.

ATSDR (1994, January 24). Congressional testimony on the health impacts of incineration, by Barry L. Johnson, Ph.D. Assistant Surgeon General and Assistant Administrator for the Agency for Toxic Substances and Disease Registry, Public Health Service, U. S. Department of Health and Human Services, before the Subcommittee on Human Resources and Intergovernmental Relations, Committee on Government Operations, United States House of Representatives.

ATSDR (2001). *Landfill gas primer: An overview for environmental health professionals*. U. S. Department of Health and Human Services, Agency for Toxic Substance Substances and Disease Registry, Public Health Service, U.S. Department of Health and Human Services, Division of Health Assessment and Consultation.

ATSDR (2002). *Public health review of hazardous waste thermal treatment technologies: A guidance manual for public health assessors*. U. S. Department of Health and Human Services, Agency for Toxic Substances and Disease Registry, Public Health Service, U. S. Department of Health and Human Services, Division of Health Assessment and Consultation.

ATSDR (2005). *Health consultation: Public health evaluation of gas vent sampling data reports, Old Southington Landfill, Southington, Hartford County, Connecticut (EPA Facility ID: CTD980670806)*. U. S. Department of Health and Human Services, Agency for Toxic Substances and Disease Registry, Public Health Service, U.S. Department of Health and Human Services, Division of Health Assessment and Consultation.

Bolt, H.M. (2009). Case report: Extremely long latency time of hepatic angiosarcoma in a vinyl chloride autoclave worker. *Experimental and Clinical Sciences Journal* 8, 30-34.

Buckley, T. & Pflughoeft-Hassett, D.F. (2006). *Review of Florida regulations, standards and practices related to the use of coal combustion products. Final report*. Prepared for: John Sager U.S., Environmental Protection Agency and William Aljoe, U. S. Department of Energy, National Energy Technology Laboratory. Energy & Environmental Research Center University of North Dakota, Grand Forks, ND 58202-9018. 2006-EERC-04-03

Byrd, D.M, & Cothorn, R. (2000). *Introduction to risk analysis: a systematic approach to science-based decision making*. Rockville, Maryland: Government Institutes.

CEPA (2003). *Diversion is good for the economy: Highlights from two independent studies on the economic impacts of diversion in California*. California Environmental Protection Agency, Integrated Waste Management Board. March, 2003.

Chian, E.S.K. & DeWalle, F.B. (1979). *Effect of moisture regimes and temperature on MSW stabilization*. Proceedings of the Fifth Annual Research Symposium, MSW: Land Disposal. EPA-600/9-79-023, 32-40.

Descartes, R (1637). *Discours de la méthode: Pour bien conduire sa raison, et chercher la vérité dans les sciences*.

DHSS (2010). *Right to know hazardous substance fact sheets: Emergency responders quick reference*. Department of Health and Senior Services, State of New Jersey. Retrieved from: <http://web.doh.state.nj.us/rtkhsfs/qrlist.aspx>.

Durmusoglu, E., Yavuz, M. and Tuncay, K. (2005). Landfill settlement with decomposition and gas generation. *Journal of Environmental Engineering* 131(7) 783-784.

EA (1997). *A quick reference guide: Estimating potential methane production, recovery and use from waste*. Environment Australia. ISBN 0 642 19463 7

EA (2002). *Solid residues from municipal waste incinerators in England and Wales: A report on an investigation by the Environment Agency*. Retrieved from

- http://www.seas.columbia.edu/earth/wtert/sofos/UK-env-agency_incin-residue_2002.pdf.
- Elias-Castells, X. (Ed.), (2005). *Tratamiento y Valorización Energética de Residuos*. Madrid: Fundación Universitaria Iberoamericana/Ediciones Díaz de Santos.
- Ettala, M., Rahkonen, P., Rossi, E., Mangs, J. & Keski-Rahkonen, O. (1996). Landfill fires in Finland. *Waste Management & Research* 14:377-384.
- FEMA (2002). *Landfill fires: Their magnitude, characteristics, and mitigation*. Federal Emergency Management Agency, United States Fire Administration, National Fire Data Center (FA-225).
- Fernández, J. (2002). Vertederos que no cumplen con el reglamento federal (Agencia EFE). *El Vocero* (San Juan, P.R.) 22 de mayo de 2002 pg. 40.
- Ferry, S. (2002). Landfill perimeter gas control. *MSW Management* 12(5). Retrieved from <http://www.mswmanagement.com/july-august-2002/landfill-perimeter-gas.aspx>.
- Hunter, J.M. & Arbona, S.I. (1995). Paradise lost: An introduction to the geography of water pollution in Puerto Rico. *Social Science & Medicine* 40(10), 1331-1355. (Pergamon Press, Oxford).
- Husar, R.B. (1994). Ecosystem and the biosphere: Metaphors for human-induced material flows. In: R. U. Ayres & Simonis, U. E. (Eds.), *Industrial Metabolism:*

Restructuring for Sustainable Development. Tokyo: United Nations University Press.

Retrieved from http://capita.wustl.edu/ME449-07/Reports/Ecosystem_Biosphere.pdf

IRIS (2010, March 3). *Glossary*. Integrated Risk Information System, USEPA.

Retrieved from http://www.epa.gov/ncea/iris/help_gloss.htm#n.

Jones-Lee, A. & Lee, F. (1993). *Groundwater pollution by municipal landfills: Leachate composition, detection and water quality significance*. Sardinia '93IV International Landfill Symposiums. Margherita di Pula, Italy. October 11-15, 1993.

Keck, K.N. & Seitz, R.R. (2002) *Potential for subsidence at the low-level radioactive waste disposal area*. Idaho National Engineering and Environmental Laboratory, Prepared for the U.S. Department of Energy, Assistant Secretary for Environmental Management, Under DOE Idaho Operations Office Contract DE-AC07-99ID13727

Kelsius, M. (2002) The state of the planet. *National Geographic* (September, 2002).

Kielhorn, J., Melber, U. & Wahnschaffe, C. (2000). Vinyl chloride: still a cause for concern. *Environmental Health Perspectives* 108(7) 579–588.

Kolthoff, I.M., Sandell, E.B., Meehan, E.J. and Buckenstein, S. (1969). *Quantitative chemical analysis*. Fourth Edition. London: The Macmillan Company.

Lemieux, P.M. (1998) *Evaluation of emissions from the open burning of household waste in barrels*. USEPA Research and Development, National Risk Management Laboratory, Cincinnati, OH 45268. USEPA/600/SR-97/134.

- Lerche, I. & Paleologos, E.K. (2001). *Environmental risk analysis*. New York: McGraw-Hill.
- Lorber, M., Pinsky, P., Gehring, P., Braverman, C., Winters, D. & Sovocool, W. (1998). Relationship between dioxins in soil, air, ash and emissions from a municipal solid waste incinerator emitting large amounts of dioxin. *Chemosphere* 37(9-12), 2173-2197.
- Mallin, K. (1990). Investigation of a bladder cancer cluster in northwestern Illinois. *American Journal of Epidemiology* 132 [Supplement 1] S96-S106.
- Manahan, S.E. (1994). *Environmental Chemistry 6th ed.* Boca Raton: CRC Press.
- McCarthy, T.M.. (2004). Waste incineration and the community. *Waste Management World (Sept.- Oct. 2004)*. London: James & James (Science Publishers). Retrieved from http://www.seas.columbia.edu/earth/wtert/sofos/McCarthy_WTE_experience.pdf
- McNamee, R. and H. Dolk (2001). Does exposure to landfill waste harm the fetus? *British Medical Journal* 323(7309) 351-352.
- MDPH (2008). *Air pollution and pediatric asthma in the Merrimack Valley: Final report*. Bureau of Environmental Health, Environmental Epidemiology Program, Massachusetts Department of Public Health. Prepared for ATSDR.

NIOSH (2007). *NIOSH pocket guide to chemical hazards*. National Institute for Occupational Safety and Health. NIOSH Publication No. 2005-149.

NJDHSS (2001). *Public health assessment: Dover Township Municipal Landfill (CERCLIS Number: NJD980771570) and the Silverton private well contamination investigation (CERCLIS Number: NJD981877780), Dover Township, Ocean County, New Jersey*. Hazardous Site Health Evaluation Program, Consumer and Environmental Health Service, Division of Epidemiology, Environmental and Occupational Health, The New Jersey Department of Health and Senior Services, Under a Cooperative Agreement with The Agency for Toxic Substances and Disease Registry.

NYT (1919). *Favor refuse incinerator: Merchants' Association is opposed to present dumping system*. The New York Times Editorial. Retrieved from <http://query.nytimes.com/mem/archive-free/pdf?res=F10F1EF9395C1B728DDDA80A94DC405B898DF1D3>

O'Connell, K.A. (2001). Birth defects tied to landfill proximity. *Waste Age* 32(10) 28-29.

Ortiz-Ortiz, K.J., Pérez-Irizarry, J., Marín-Centeno, H., Ortiz, A.P., Torres-Berrios, N., Torres-Cintrón, M.,...Figuroa-Vallés, N.R. (2010). Productivity loss in Puerto Rico's labor market due to cancer mortality. *Puerto Rico Health Science Journal* 29(3) 241-249.

OSHA (2010, March 3) *Occupational Safety and Health Administration*. 29 CFR Part 1910 (Occupational Safety and Health Standards) Subpart: Z (Toxic and Hazardous

- Substances) 1910.1028 Appendix B: Substance technical guidelines. Retrieved from <http://www.osha.gov/SLTC>
- OU (2010, April 7). *The physical and theoretical chemistry laboratory*, Oxford University. Chemical and other safety information. Retrieved from <http://msds.chem.ox.ac.uk>
- Pedro, E., Lugo-Rosado, I., and Rojas-Brenes, M. (2010). Regulations and recommendations for appropriate disposal of antineoplastics. *Puerto Rico Health Science Journal* 29(3) 218-222.
- PRPB (2008) *Imports of recorded merchandise by NAICS: FY 1998-2007*. In 2007 Puerto Rico imported \$1,246.3M in structural steel (NAICS 331 and NAICS 332). Puerto Rico Planning Board. From www.jp.gobierno.pr
- Rathje, W. and C. Murphy (2001). *Rubbish! The archaeology of garbage*. New York: Harper Collins Publishers.
- Renova (2000). Siting consultation application, Volume 2: Environmental impact report. May, 2000.
- Ruokojärvi, M. Ettala, P. Rahkonen, J. Tarhanen P. and J. Ruuskanen, (1995a). Polychlorinated dibenzo-p-dioxins and -furans (PCDDs and PCDFs) in municipal waste landfill fires. *Chemosphere* 30(9) 1697-1708.

- Ruokojärvi, P., J. Ruuskanen, M. Ettala, P. Rahkonen and J. Tarhanen (1995b). Formation of polyaromatic hydrocarbons and polychlorinated organic compounds in municipal waste landfill fires. *Chemosphere* 31(8) 3899-3908.
- RWB (2001). *Economic impacts of recycling in Iowa*. R.W. Beck, Inc. for the Iowa Department of Natural Resources.
- Shy, C.M., Degnan, D., Fox, D.L., Mukerjee, S., Hazucha, M.J., Boehlecke, B.A.,...Bromberg, P.A. (1995). Do waste incinerators induce adverse respiratory effects? An air quality and epidemiological study of six communities. *Environmental Health Perspectives* 103 (7-8) 714-724.
- Solano, E., R.D. Dumas, K.W. Harrison, S.R. Ranjithan, M.A. Barlaz, and E.D. Brill (2002). Life-cycle-based solid waste management II: Illustrative applications. *Journal of Environmental Engineering* (October, 2002) 993-1005. DOI: 10.1061/(ASCE)0733-9372(2002)128:10(993)
- Themelis, N.J, Kim, Y.H. & Brady, M.H. (2002) Energy recovery from New York City municipal solid wastes. *Waste Management and Research Vol. 20(3)* 223-233.
- Torres-Cintrón, M., Ortiz, A.P., Pérez-Irizarry, J., Soto-Salgado, M., Figueroa-Vallés, N.R., De La Torre-Feliciano, T.,...Suárez-Pérez, E. (2010) Incidence and mortality of the leading cancer types in Puerto Rico: 1987-2004. *Puerto Rico Health Science Journal* 29(3), 317-329.

UN (1987). *Report of the World Commission on Environment and Development (Brundtland Report)*. United Nations General Assembly.

UN (2002). *Draft plan of implementation of the World Summit on Sustainable Development*, in Extract From: *The future draft report of the main committee of the World Summit on Sustainable Development*. United Nations. Advance unedited version. A/CONF.199/CRP.

UNEP (2002). *Landfill still a necessary and effective practice*. United Nations Environment Programme, Division of Technology, Industry, and Economics.

USDOE (2000). *A comparison of gasification and incineration of hazardous wastes final report*. U.S. Department of Energy, National Energy Technology Laboratory. DCN 99.803931.02.

USDOT (2000). *Recycled materials in European highway environments: Uses, technologies, and policies*. International Technology Exchange Program, U.S. Department of Transportation, Federal Highway Administration. FHWA-PL-00-025.

USEPA (1985). *Summary report on corrosivity studies in co-incineration of sewage sludge and solid waste*. U.S. Environmental Protection Agency, Hazardous Waste Engineering Research Laboratory. EPA 600 S2-85 099.

USEPA (1989). *Risk assessment guidance for superfund, Volume I: Human health evaluation manual (part A) interim final*. U.S. Environmental Protection Agency, Office of Emergency and Remedial Response. EPA/540/1-89/002.

USEPA (1994). *Waste prevention, recycling, and composting options: Lessons from 30 communities*. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response. EPA 530-R-92-015

USEPA (1995a). *Decision maker's guide to solid waste management: Volume II*. U.S. Environmental Protection Agency, Office of Solid Waste. EPA 530-R-95-023.

USEPA (1995b) *Compilation of air pollutant emission factors – Volume 1: Stationary point and area sources (AP-42 Fifth Edition)*. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Office of Air and Radiation, Research Triangle Park, NC 27711. January, 1995. Section 2.4 MSW Landfill updated November, 1998. Section 2.1 Refuse Combustion updated October, 1996.

USEPA (1996) *Stabilization/solidification processes for mixed waste*. U.S. Environmental Protection Agency, Center for Remediation Technology and Tools, Radiation Protection Division, Office of Radiation and Indoor Air. EPA 402-R-96-014.

USEPA (1997a). *Locating and estimating air emissions from sources of dioxins and furans*. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Office of Air and Radiation, Research Triangle Park, NC 27711. EPA-454/R-97-003.

USEPA (1997b). *Approval and promulgation of State air quality plans for designated facilities and pollutants, New Mexico; control of landfill gas emissions from existing*

municipal solid waste landfills; correction for same, Louisiana. Federal Register Vol. 62, No. 203, October 21, 1997.

USEPA (1998a). *The inventory of sources of dioxin in the United States.* U.S. Environmental Protection Agency, Exposure Analysis and Risk Characterization Group, National Center for Environmental Assessment, Office of Research and Development, USEPA, Washington, D.C. April 1998. This document is for review purposes only, and carries a disclaimer that it does not represent Agency policy. USEPA600/P-98/002Aa.

USEPA (1998b). *Inventory of U.S. greenhouse gas emissions and sinks: 1990-1996.* Office of Policy, Planning and Evaluation (2122). USEPA 236-R-98-006.

USEPA (1998c). *Greenhouse gas emissions from management of selected materials in MSW.* Solid Waste and Emergency Response (5306W), Washington D.C. USEPA 530-R-98-013.

USEPA (1999). *1990 emissions inventory of forty potential section 112(k) pollutants, supporting data for EPA's section 112(k) regulatory strategy: Final report.* Emission Factors and Inventory Group (MD-14), Emissions, Monitoring and Analysis Division, USEPA, Research Triangle Park, North Carolina 27711.

USEPA (2000a). *Toxicological review of vinyl chloride (CAS No. 75-01-4) in support of summary information on the Integrated Risk Information System (IRIS).* U.S. Environmental Protection Agency Washington. EPA/635R-00/004.

- USEPA (2000b). Questions and answers about dioxins. U.S. Environmental Protection Agency, National Center for Environmental Assessment. July 2000. <http://www.epa.gov/ncea/pdfs/dioxin/dioxin%20questions%20and%20answers.pdf>
- USEPA (2001). *RCRA financial assurance for closure and post-Closure*. Office of Inspector General, U.S. Environmental Protection Agency. Report No. 2001-P-007.
- USEPA (2002). *MSW in the United States: 2000 facts and figures*. U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response. EPA530-R-02-001.
- USEPA (2003). *Emission factor documentation for AP-42 section 2.1: Refuse combustion*. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Office of Air and Radiation, Research Triangle Park, North Carolina 27711.
- USEPA (2004). *Risk assessment guidance for superfund, Volume I: Human health evaluation manual (Part E) supplemental guidance for dermal risk assessment*. U.S. Environmental Protection Agency, Office of Superfund Remediation and Technology Innovation Response. EPA/540/R/99/005. OSWER 9285.7-02EP, PB99-963312.
- USEPA (2005a). *LandGEM landfill gas emissions model, Version 3.02*. U.S. Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory and Clean Air Technology Center, Research Triangle Park, North Carolina. EPA-600/R-05/047.

USEPA (2005b). *Metrics for expressing greenhouse gas emissions: Carbon equivalents and carbon dioxide equivalents*. U.S. Environmental Protection Agency, Office of Transportation and Air Quality. EPA420-F-05-002.

USEPA (2006a). *Solid waste management and greenhouse gasses: A life-cycle assessment of emissions and sinks, 3rd Edition*. U.S. Environmental Protection Agency. EPA530-R-02-006.

USEPA (2006b). *An inventory of sources and environmental release of dioxin-like compounds in the United States for the years 1987, 1995, and 2000*. U.S. Environmental Protection Agency, National Center for Environmental Assessment, Office of Research and Development. Washington, DC 20460. EPA/600/P-03/002F

USEPA (2008a). *MSW generation, recycling and disposal in the United States: Facts and Figures for 2007*. U.S. Environmental Protection Agency. EPA530-R-08-010.

USEPA (2008b). *Background information document for updating AP-42 Section 2.4 for estimating emissions from MSW landfills*. U.S. Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory and Clean Air Technology Center, Research Triangle Park, North Carolina. EPA/600/R-08-116.

USEPA (2008c). Clean Air Act, as amended in 2008. Title 42 Chapter 85—Air pollution and control.

USEPA (2009). *LandGEM landfill gas emissions model, Version 3.02. for the Arecibo Landfill*. U.S. Environmental Protection Agency, Caribbean Environmental Protection Division (CEPD), U.S. Environmental Protection Agency, Region 2.

USEPA (2010, March 3). *Glossary of terms, 1996 national-scale air toxics assessment*. U.S. Environmental Protection Agency, Technology Transfer Network, Air Technical Web Site. Retrieved from <http://www.epa.gov/ttnatw01/nata/gloss.html>

USEPA (2010, March 10). *Health effects notebook for hazardous air pollutants*. U.S. Environmental Protection Agency, Technology Transfer Network, Air Technical Web Site. Retrieved from <http://www.epa.gov/airtoxics/hlthef/hapindex.html>

USEPA (2010, September 10). *Region 2 cleanup site lists, Puerto Rico sites*. Retrieved from http://www.epa.gov/region02/cleanup/sites/prtoc_sitename.htm.

Vrijheid, M (2000). Health effects of residence near hazardous waste landfill sites: A review of epidemiologic literature. *Environmental Health Perspectives* 108(Supplement I), 101-112.

Vrijheid, M, Dolk, H., Armstrong, B. and Abramsky, L. (2002). Chromosomal congenital anomalies and residence near hazardous waste landfill sites. *The Lancet* 359(9303), 320-322. London. January 26, 2002.

Wilson, R. and Crouch, E.A.C. (2001). *Risk-benefit analysis*. Cambridge: Harvard University Press.

Young, J.E. and Sachs, A. (1994). *The next efficiency revolution: Creating a sustainable materials economy*. Washington, D.C.: Worldwatch Institute, 1994.

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Table 1

Puerto Rico landfills as of 2007: Municipal solid waste (MSW) deposit rate and useful life.

Landfill	MSW Deposit Rate		Useful Life (years)	Time to Closure (years)	% of the Total	Total Capacity (tons)
	Tons/ week	Tons/ year				
Humacao	12,951	673,452	15	15	18.4%	10,101,780
Toa Baja	9,496	493,792	0.6-0.7	1	13.5%	493,792
Ponce MSW	8,500	442,000	6.9-8.6	8	12.1%	3,536,000
Arecibo	3,791	197,132	10.2-12.7	12	5.4%	2,365,584
Juncos	3,753	195,156	0.7-0.9	2	5.3%	390,312
Yauco	3,136	163,072	1-1.3	2	4.4%	326,144
Salinas	2,906	151,112	16.4-20.6	20	4.1%	3,022,240
Aguadilla	2,697	140,244	0.31-0.39	1	3.8%	140,244
Carolina	2,255	117,260	7.3-9	9	3.2%	1,055,340
Fajardo	2,167	112,684	3-3.8	3	3.1%	338,052
Toa Alta	1,965	102,180	6.5-8.4	8	2.8%	817,440
Peñuelas	1,951	101,452	17.8	17	2.8%	1,724,684
Juana Diaz	1,827	95,004	3.9-4.9	4	2.6%	380,016
Vega Baja	1,516	78,832	0.17-0.22	1	2.2%	78,832
Mayaguez	1,516	78,832	14.5	14	2.2%	1,103,648
Santa Isabel	1,260	65,520	3.5-4.4	0	1.8%	0
Añasco	1,076	55,952	3.7-4.7	4	1.5%	223,808
Guaynabo	1,061	55,172	1	1	1.5%	55,172
Cabo Rojo	962	50,024	10.5-13.2	13	1.4%	650,312
Guayama	821	42,692	20.7-25.9	25	1.2%	1,067,300
Moca	771	40,092	6.2-7.7	7	1.1%	280,644
Isabela	567	29,484	2.3-2.9	2	0.8%	58,968
Cayey	558	29,016	5.8-7.2	7	0.8%	203,112
Arroyo	536	27,872	1.6-2	2	0.8%	55,744
Barranquitas	492	25,584	1-1.25	1	0.7%	25,584
Florida	487	25,324	7.9-9.9	0	0.7%	0
Yabucoa	399	20,748	0	0	0.6%	0
Lajas	356	18,512	26-32.4	32	0.5%	592,384
Hormigueros	271	14,092	12.1-15.2	15	0.4%	211,380
Jayuya	206	10,712	18.8-23.4	23	0.3%	246,376
Vieques	123	6,396	29-36.3	36	0.2%	230,256
Culebra	99	5,148	2.2-2.7	2	0.1%	10,296
Total (tpw)	70,472	3,674,611	Total Landfill Capacity (tons)		29,785,444	
Total (tpd)	10,067	Total capacity÷deposition rate			8.1 years	

Source: Autoridad de Desperdicios Sólidos, Compiled by the author.

Table 2.

Landfill gas and hazardous air pollutant (HAP) estimates for the Arecibo Landfill and for Puerto Rico using 2008 MSW deposit rate

CAS Number	Chemical Name	Arecibo Landfill	Puerto Rico
74-82-8	Methane	6,430	90,637
124-38-9	Carbon Dioxide	17,643	248,686
79-34-5	1,1,2,2-Tetrachloroethane	0.1	2.1
106-46-7	1,4-Dichlorobenzene(p)	0.02	0.3
107-13-1	Acrylonitrile	0.3	3.8
71-43-2	Benzene	0.1	1.7
75-15-0	Carbon disulfide	0.04	0.5
56-23-5	Carbon tetrachloride	0.0005	0.007
463-58-1	Carbonyl sulfide	0.02	0.3
108-90-7	Chlorobenzene	0.02	0.3
67-66-3	Chloroform	0.003	0.04
100-41-4	Ethyl benzene	0.4	5.5
75-00-3	Ethyl chloride (Chloroethane)	0.07	0.9
106-93-4	Ethylene dibromide (Dibromoethane)	0.0002	0.002
107-06-2	Ethylene dichloride (1,2-Dichloroethane)	0.03	0.5
75-34-3	Ethylidene dichloride	0.2	2.7
110-54-3	Hexane	0.5	6.4
7439-97-6	Mercury Compounds	0.00005	0.0007
74-87-3	Methyl chloride (Chloromethane)	0.05	0.7
71-55-6	Methyl chloroform	0.05	0.7
78-93-3	Methyl ethyl ketone (2-Butanone)	0.4	5.8
108-10-1	Methyl isobutyl ketone (Hexone)	0.2	2.2
78-87-5	Propylene dichloride	0.02	0.2
127-18-4	Tetrachloroethylene (Perchloroethylene)	0.5	6.9
108-88-3	Toluene	2.9	40.6
79-01-6	Trichloroethylene	0.3	4.2
75-01-4	Vinyl chloride	0.4	5.2
75-35-4	Vinylidene chloride	0.02	0.2
1330-20-7	Xylenes (isomers and mixture)	1.0	14.4
Total HAP emissions:		7.5	106.2

All emissions figures in tons per year (tpy). Significant digits were removed for clarity.

Table 3

Summary of responses from the incinerators (municipal waste combustors) that responded to the questionnaire.

	M u n i c i p a l W a s t e C o m b u s t o r				
	A	B	C	D	E
1. Facility Characteristics					
Year Started	1990	1994	1989	1987	1987
Investment	\$300M	\$125M	\$45M	\$18M	\$45M
Design Capacity (tpd)	2,000	1,836	1,000	400	350
Tpd during 2008	605	1,650	772	282	275
Design					
Excess Air		x	x		
Fluidized Bed				x	
Mass Burn		x			x
Refractory Wall		x		x	
Refuse-Derived Fuel	x		x	x	
Water-wall		x	x	x	
Emissions Control					
Cyclones	x			x	
Dry Sorbent Injection				x	
Fabric Filters	x	x	x	x	x
Flue gas recirculation		x			
Good Combustion Practices	x	x	x	x	
Injection Activated Carbon		x		x	
SNCR - ammonia injection		x			x
SNCR - urea injection		x		x	
Spray Drier	x	x	x		x
Wet Scrubbing (centrifugal)					
Annual Impacts					
Payroll	n/r	\$5.5M	\$4.5M	\$1.2M	\$4.6M
FTE jobs	145	53	44	29	50
Outsourced	\$12M	n/r	\$7.8M	\$0.5M	\$7.5M

Table 3 (Continued)

Summary of responses from the incinerators (municipal waste combustors) that responded to the questionnaire.

	M u n i c i p a l W a s t e C o m b u s t o r				
	A	B	C	D	E
2. Input Characteristics					
Plastic	9%	23%	11%	17%	14%
Fiber	50%	30%	28%	40%	21%
Glass	5%	5%	3%	5%	0.1%
Metals	5%	5%	5%	5%	3%
Yard Waste	5%	12%	5%	5%	20%
Moisture Content	22%	12%	n/r	5%	n/a
Rejected Materials	15%	n/r	*	23%	**
By volume? By weight?	weight	n/r	n/r	weight	weight
3. Output Characteristics					
Excess Power (MW-hrs)	51	50	160,000	78,641	7,500
Steam Sold ppy	0	0	0	0	0
Recovered Ferrous (tpd)	13	40	0	5.6	3.6
Recovered Non-Ferr. (tpd)	4.5	0.75	0	0	0.36
Facility waste as % MSW	18%	n/r	28%	n/r	27%
Haz? Non haz? Special?	n/r	n/r	special	non-haz	non-haz
Emissions Temperature °F	290	280	300	270	305
Scrubber Salts: WW? SW?	SW	None	SW	n/a	SW

Notes

* RDF is processed by at a separate facility, which recovers ferrous and non-ferrous metals. Figures not available.

**Combined ash was treated using cement to meet non-hazardous classification and reused at one of their landfills.

Table 4.

HAP emissions estimates from MWCs sampled and from Emission Factors for all MSW landfilled in Puerto Rico in 2008.

	A		B		C		D		E		Emission Factors for MSW w/Spray Drier/Fabric Filter
MWC/AP-42→	MWC	PR	MWC	PR	MWC	PR	MWC	PR	MWC	PR	
tpy Rec'd 2008→	100,375		602,250		281,780		220,825		102,930		
MWC + PR MSW)→	2.7%		16.4%		7.7%		6.0%		2.8%		
Emissions Multiplier→	36.61		6.10		13.04		16.64		35.70		
Contaminant Name	MWC	PR	MWC	PR	MWC	PR	MWC	PR	MWC	PR	
Hydrochloric acid	20.6	754.1	41.6	253.8	3.0	39.1	74.0	1,231.4	4.6	164.6	389.5
Lead Compounds	0.001	0.04	0.03	0.2	0.02	0.3	0.8	13.1	0.003	0.1	0.5
Hexachlorobenzene	0.2	7.4									
Mercury Compounds	0.005	0.2	0.05	0.3	0.001	0.01	0.07	1.1	0.0003	0.009	4.0
Cadmium Compounds	0.001	0.03	0.002	0.01	0.0008	0.01	0.01	0.2	0.004	0.1	0.05
Manganese Compounds									0.003	0.1	
Polycyclic Organic Matter											
Formaldehyde	0.0002	0.007									
Arsenic Compounds	0.0000002	0.000006	0.0009	0.005							0.08
1,3-Butadiene	0.00002	0.0007									
Benzene	0.000020	0.0007									
Beryllium Compounds			0.000006	0.0004							
Dioxins & Furans	0.0000002	0.000006							0.000004	0.0001	0.0001
Naphthalene	0.000002	0.00008									
Nickel Compounds	0.0000004	0.00002									0.09
Chromium Compounds	0.00000001	0.0000004									0.06
Total	20.8	761.9	41.7	254.3	3.0	39.4	74.9	1,245.8	4.6	164.9	394.3

Notes:

All Emissions and MSW Figures in tons per year. Emission Factors in kilograms per megagram of MSW.

Estimates based upon the estimated 3,674,611 tpy MSW land-filled in the Island (see Table 1).

Decimal places reduced to the first non-zero to illustrate order of magnitude. Calculations with all significant figures.

Table 5

*Inhalation risk parameters for landfill and incinerator HAP emissions— non carcinogenicity.
(mg/m³)*

Chemical Name*	RfC	NOAEL	LOAEL	REL	PEL	IDLH
Toluene	0.4	46	332	375	754	1,885
Xylenes	0.1	39	61	435	435	3,900
Tetrachloroethylene	-	-	102	Ca	685	1,020
Hexane	0.7	-	204	180	1,800	3,880
Methyl ethyl ketone	5	-	-	590	590	8,850
Ethylbenzene	1	434	-	435	435	3,470
Vinyl chloride	0.1	2.5	4	Ca	2.6	Ca
Trichloroethylene	0.6	-	170	Ca	537	5,370
Acrylonitrile	0.002	-	43	2	4.3	182
Ethylidene dichloride	0.5	-	-	400	400	1,200
Methyl isobutyl ketone	0.08	1,026	-	205	410	2,050
1,1,2,2-Tetrachloroethane	-	-	890	7	35	690
Benzene	0.03	1.7	-	0.32	3.2	1,600
Ethyl chloride	10	4,000	-	-	2,600	9,880
Methyl chloroform	5	1,553	-	1,900	1,900	3,800
Methyl chloride	0.09	94.6	107	Ca	207	4,140
Ethylene dichloride	0.4	-	8.5	4	202	2,000
Carbon disulfide	0.7	-	-	3	62	1,550
1,4-Dichlorobenzene(p)	0.8	75	-	Ca	450	900
Chlorobenzene	0.02	-	-	-	350	4,600
Carbonyl sulfide	-	-	-	-	-	-
Propylene dichloride	0.0004	-	69.3	Ca	350	1,800
Vinylidene chloride	0.2	20	61	CA	-	Ca
Chloroform	0.00000002	-	122	9.78	240	2,400
Carbon tetrachloride	0.1	-	31.5	12.6	63	1,260
Ethylene dibromide	0.0002	-	0.7	0.3	133	667
Hydrochloric Acid	0.02	-	15	7	7	75
Mercury	0.0003	-	0.025	0.01	0.01	2
Lead	-	-	-	0.1	0.05	100
Nickel	0.03	-	-	0.015	1	10
Arsenic	0.00003	-	0.2	0.002	0.01	5
Chromium	0.000008	-	0.000714	0.001	0.5	25
Cadmium	-	-	0.02	Ca	0.2	9
Dioxins & Furans	-	-	-	0.00000004	-	Ca

Ca = Potential or possible carcinogen; often not assigned a lower risk limit.

IDLH = Immediately Dangerous to Life or Health Concentrations (NIOSH).

LOAEL = Lowest observed adverse effect level.

NOAEL = No observed adverse effect level.

PEL = Permissible exposure limit.

REL = Recommended Exposure Limit (NIOSH).

RfC = Reference concentration.

Table 6

Inhalation risk parameters for landfill and incinerator HAP emissions – carcinogenicity
(mg/m^3)

Chemical Name	MWCs (tpy)*	Landfills (tpy)*	WoE**	1 in 10,000 Concentration ($\mu g/m^3$)***	Known Carcinogen	Possible/Potential Carcinogen
Toluene		40.6	D	-		
Xylenes		14.4	D	-		
Tetrachloroethylene		6.9	C	-		X
Hexane		6.4	D	-		
Methyl Ethyl Ketone		5.8	D	-		
Ethylbenzene		5.5	D	-		
Vinyl Chloride		5.2	A	0.0048	X	
Trichloroethylene		4.2	-	-		X
Acrylonitrile		3.8	B1	6	X	
Ethylidene Dichloride		2.7	C	-		X
Methyl Isobutyl Ketone		2.2	D	-		
1,1,2,2-Tetrachloroethane		2.1	C	0.02		X
Benzene		1.7	A	0.1	X	
Ethyl Chloride		0.9	-	-		
Methyl Chloroform		0.7	D	-		
Methyl Chloride		0.7	D	-		X
Ethylene Dichloride		0.5	B2	4	X	
Carbon Disulfide		0.5	-	-		
1,4-Dichlorobenzene(p)		0.3	C	-		X
Chlorobenzene		0.3	D	-		
Carbonyl Sulfide		0.3	-	-		
Propylene Dichloride		0.2	B2	-	X	
Vinylidene Chloride		0.2	C	-		X
Chloroform		0.04	B2	4	X	
Carbon Tetrachloride		0.007	B2	50	X	
Ethylene Dibromide		0.002	B2	0.2	X	
Mercury	4.0	0.001	D	-		
Hydrochloric Acid	389.5		-	-		
Lead	0.5		B2	-	X	
Nickel	0.09		-	-		X
Arsenic	0.08		A	0.02	X	
Chromium	0.06		A	0.008	X	
Cadmium	0.005		B1	0.06	X	
Dioxins & Furans	0.0001		B2	-	X	
Total	394.3	106.2				

- Data not available in the NIOSH, IRIS or EPA databases.

* Estimates for Puerto Rico (tpy) using the USEPA's Emissions Factors.

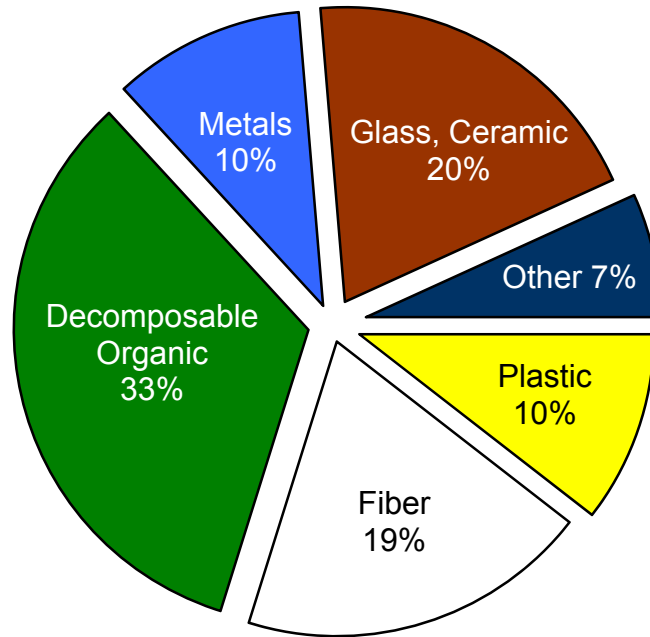
**Weight of Evidence Assessment.

***Concentration that will increase the likelihood of cancer 1/10,000 over a lifetime of exposure.

FIGURES

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Municipal solid waste composition in Puerto Rico.

	%	tpd	Recy- clable	Orga- nic	Energy value	tpd	%	Practical Use Category
Type 1 PET	1.1%	108	X		X	1,035	10%	Plastic
Type 2 HDPE	2.9%	286	X		X			
Types 3-7	6.5%	641	X		X			
High Qual. Paper	1.3%	128	X	X	X	1,903	19%	Fiber
Low Qual. Paper	8.7%	858	X	X	X			
Cardboard	9.3%	917	X	X	X			
Ferrous Metals	9.4%	927	X			1,035	10%	Metals
Non-Ferr. Metals	1.1%	108	X					
Yard Waste	20.4%	2,011		X	X	3,283	33%	Decomposable
Organic	12.9%	1,272		X	X			
Constr. Debris	17.1%	1,686	X			1,923	20%	Glass/ceramic
Glass	2.4%	237	X					
Hazardous	0.5%	49			X	670	7%	Other
Other	6.3%	621						
Totals	100%	9,849	5,896	5,186	6,270	9,849	100%	

Figure 1.

MSW composition in Puerto Rico and their practical-use categories.

Source: ADSPR (2003).

name of facility here

I. Facility Characteristics

a. Year facility placed in operation _____ Aprox. Investment \$ _____ M.

b. Design capacity (TpD) _____. Average TpD processed during 2008 _____.

c. Design & Operation: Mark all that apply.

Design:

Emissions Control:

- Coal/RDF co-fired
- Excess Air
- Fluidized Bed
- Mass burn
- Modular
- Refractory Wall
- Refuse-derived Fuel
- Rotary Waterwall
- Starved Air
- Waterwall

- Activated Carbon Filters
- Cyclones
- Electrified Gravel Beds
- Electrostatic Precipitators
- Dry Sorbent Injection (Duct)
- Dry Sorbent Injection (Furnace)
- Fabric Filters
- Flue gas recirculation
- Good Combustion Practices
- Injection of activated carbon
- Injection of sodium sulfide
- Low excess air

- Natural gas reburning.
- SCR - ammonia injection
- SNCR - urea/methanol injection
- SNCR - ammonia injection
- SNCR - urea injection
- Spray Dryer
- Staged combustion
- Venturi Scrubbers
- Wet Scrubbing (centrifugal)
- Wet Scrubbing (spray towers)
- Wet Scrubbing (venturi)

d. Annual Impacts:

Payroll \$ _____ M. Full time equivalent jobs _____ Outsourced \$ _____ M.

Please, include outsourced expenses such as services, chemicals, & supplies.

II. Input Characteristics

a. Estimated percent composition of MSW:

%Plastic 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40

%Fiber 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40

%Glass 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40

%Metals 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40

%Yard waste 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40

%Moisture content 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33

%Rejected material 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 by volume or by weight
(please select one unit)

III. Output Characteristics

a. Excess Power (MW-hrs) _____ b. Steam sold _____
(please provide units) Daily? Annually?

c. Recovered Materials (avg. tpd): Ferrous Metals _____ Non-ferrous Metals _____

Construction Aggregate _____ Other _____

d. Facility's solid waste as % of the incoming MSW _____

Disposed-of as which type of waste? Hazardous Non-Hazardous Special
(please select one)

e. Typical Emissions Temperature _____ °F °C

f. Other facility wastes:

Are scrubber salts disposed-of as a wastewater? Solid waste? (please select one)

Thank You ☼ Francisco J. Perez ☼ Masters Thesis ☼ Facilities Questionnaire

Figure 2.

Questionnaires submitted to eleven incinerators.

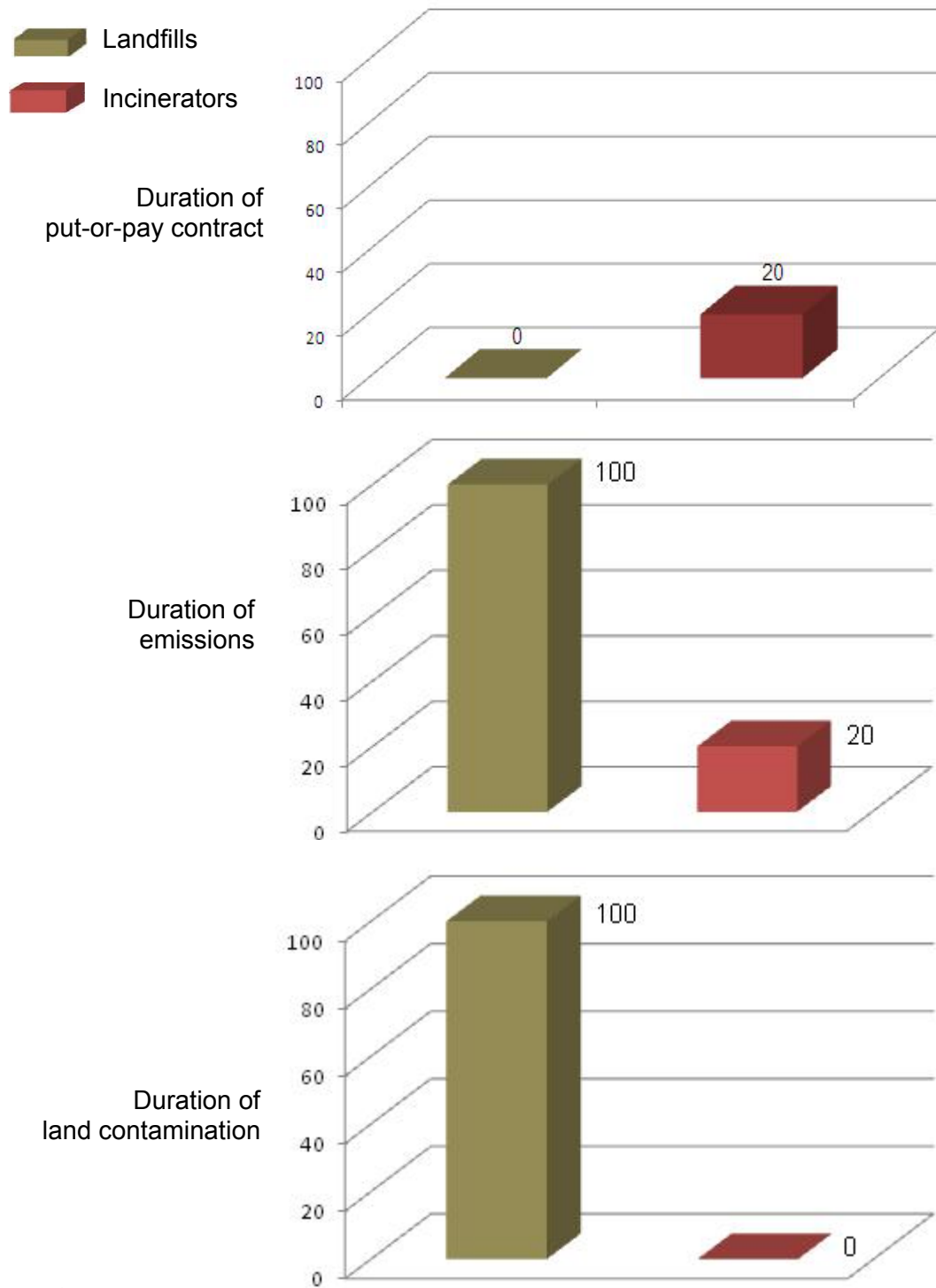


Figure 3.

Comparison (in years) of long-term liabilities: Landfills v. incinerators.

A one-hundred year limit was artificially added to the duration of the emissions and land contamination, both of which are expected to be much lengthier.

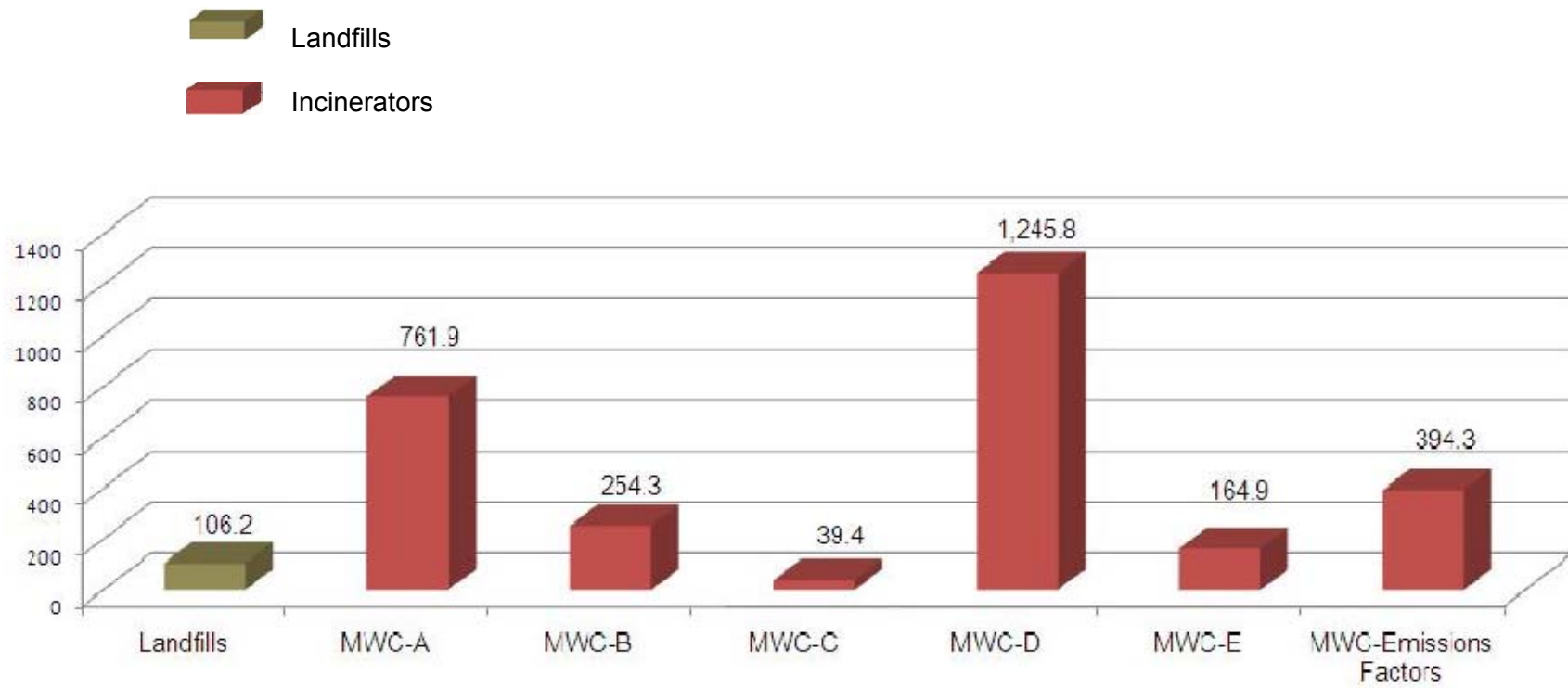


Figure 4.

Comparison (in tpy) of HAP emissions in Puerto Rico: Landfills v. incinerators.

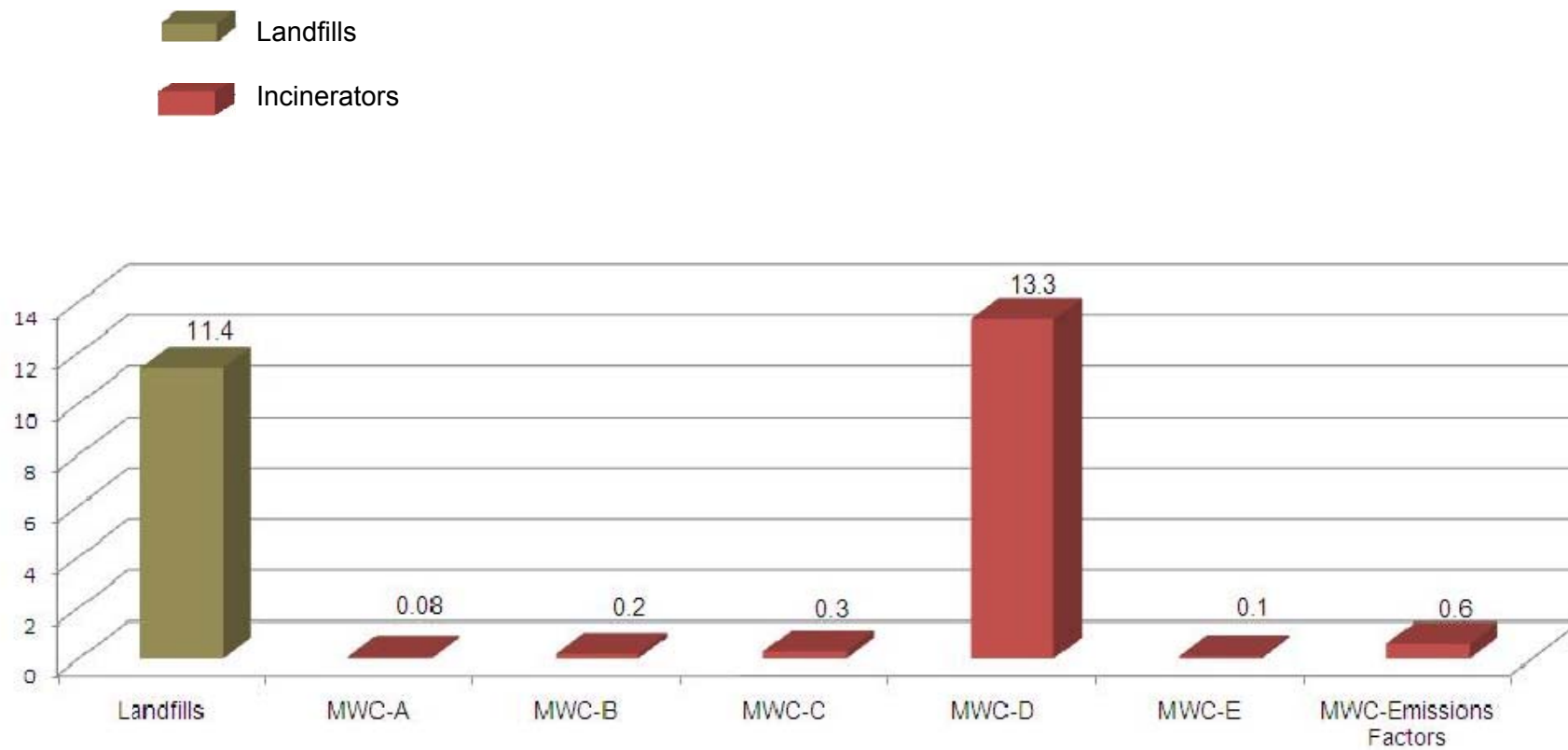


Figure 5

Comparison (in tpy) of known carcinogenic HAP emissions in Puerto Rico: Landfills v. incinerators.

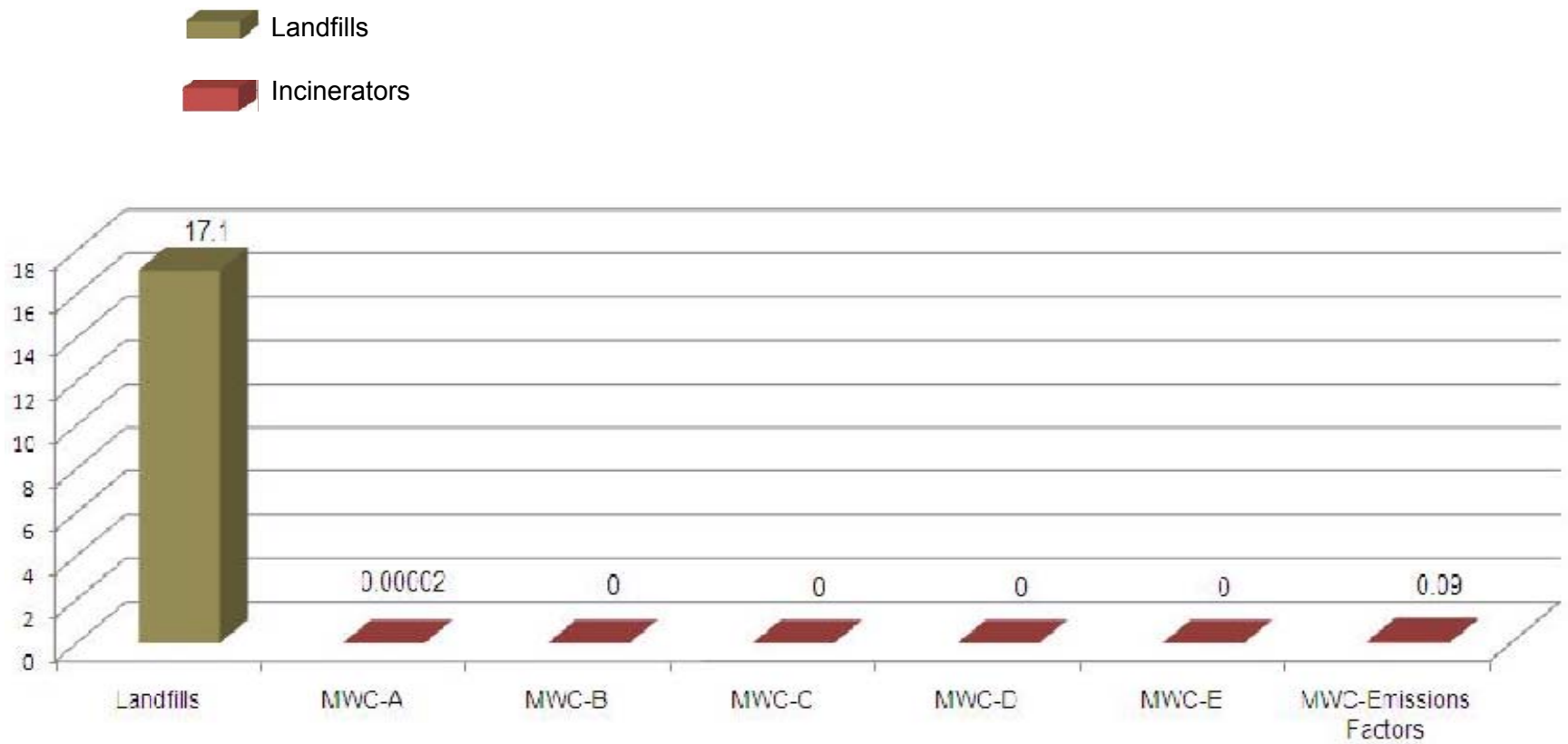


Figure 6

Comparison (in tpy) of potential/possible carcinogenic HAP emissions in Puerto Rico: Landfills v. incinerators.

APPENDICES

Appendix A
Typical contaminants of landfill gas
Source: Default concentrations (USEPA 1995b)

Pollutant	Default Concentration (ppmv)
1,1,1-Trichloroethane (methyl chloroform) ^a	0.48
1,1,2,2-Tetrachloroethane ^a	1.11
1,1-Dichloroethane (ethylidene dichloride) ^a	2.35
1,1-Dichloroethene (vinylidene chloride) ^a	0.20
1,2-Dichloroethane (ethylene dichloride) ^a	0.41
1,2-Dichloropropane (propylene dichloride) ^a	0.18
2-Propanol (isopropyl alcohol)	50.10
Acetone	7.01
Acrylonitrile ^a	6.33
Benzene	1.91
Bromodichloromethane	3.13
Butane	5.03
Carbon disulfide ^a	0.58
Carbon monoxide ^b	141.0
Carbon tetrachloride ^a	0.004
Carbonyl sulfide ^a	0.49
Chlorobenzene ^a	0.25
Chlorodifluoromethane	1.3
Chloroethane (ethyl chloride) ^a	1.25
Chloroform ^a	0.03
Chloromethane	1.21
Dichlorobenzene ^c	0.21
Dichlorodifluoromethane	15.7
Dichlorofluoromethane	2.62
Dichloromethane (methylene chloride) ^a	14.30
Dimethyl sulfide (methyl sulfide)	7.82

USEPA NOTES:

This is not an all-inclusive list of potential landfill gas constituents, only those for which test data were available at multiple sites.

^a Hazardous Air Pollutant listed in Title III of the 1990 Clean Air Act Amendments.

^b Carbon monoxide is not a typical constituent of LFG, but does exist in instances involving landfill (underground) combustion. Therefore, this default value should be used with caution. Of 18 sites where CO was measured, only 2 showed detectable levels of CO.

^c Source tests did not indicate whether this compound was the para- or ortho- isomer. The para- isomer is a Title III-listed HAP.

^d No data were available to speciate total Hg into the elemental and organic forms.
 ppmv = parts per million based on volume of landfill gas.

Appendix A (continued)
Typical Contaminants of Landfill Gas.
Source: Default concentrations (USEPA 1995b)

Pollutant	Default Concentration (ppmv)
Ethane	889.0
Ethanol	27.20
Ethyl mercaptan (ethanethiol)	2.28
Ethylbenzene ^a	4.61
Ethylene dibromide	0.001
Fluorotrichloromethane	0.76
Hexane ^a	6.57
Hydrogen sulfide	35.5
Mercury (total) ^{a,d}	0.000292
Methyl ethyl ketone ^a	7.09
Methyl isobutyl ketone ^a	1.87
Methyl mercaptan	2.49
Non-Methane Organic Compound (as hexane)	595.0
Pentane	3.29
Perchloroethylene (tetrachloroethylene) ^a	3.73
Propane	11.10
t-1,2-dichloroethene	2.84
Trichloroethylene (trichloroethene) ^a	2.82
Vinyl chloride ^a	7.34
Xylenes ^a	12.10

USEPA NOTES:

This is not an all-inclusive list of potential landfill gas constituents, only those for which test data were available at multiple sites.

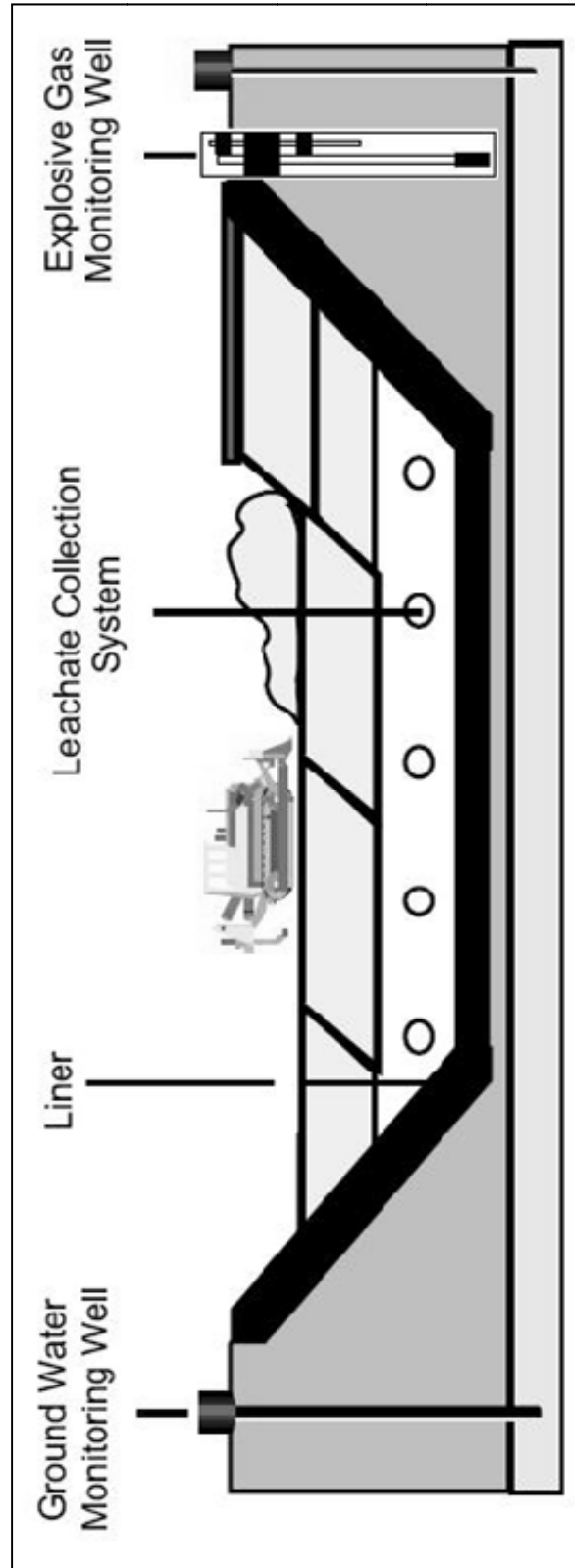
^a Hazardous Air Pollutant listed in Title III of the 1990 Clean Air Act Amendments.

^b Carbon monoxide is not a typical constituent of LFG, but does exist in instances involving landfill (underground) combustion. Therefore, this default value should be used with caution. Of 18 sites where CO was measured, only 2 showed detectable levels of CO.

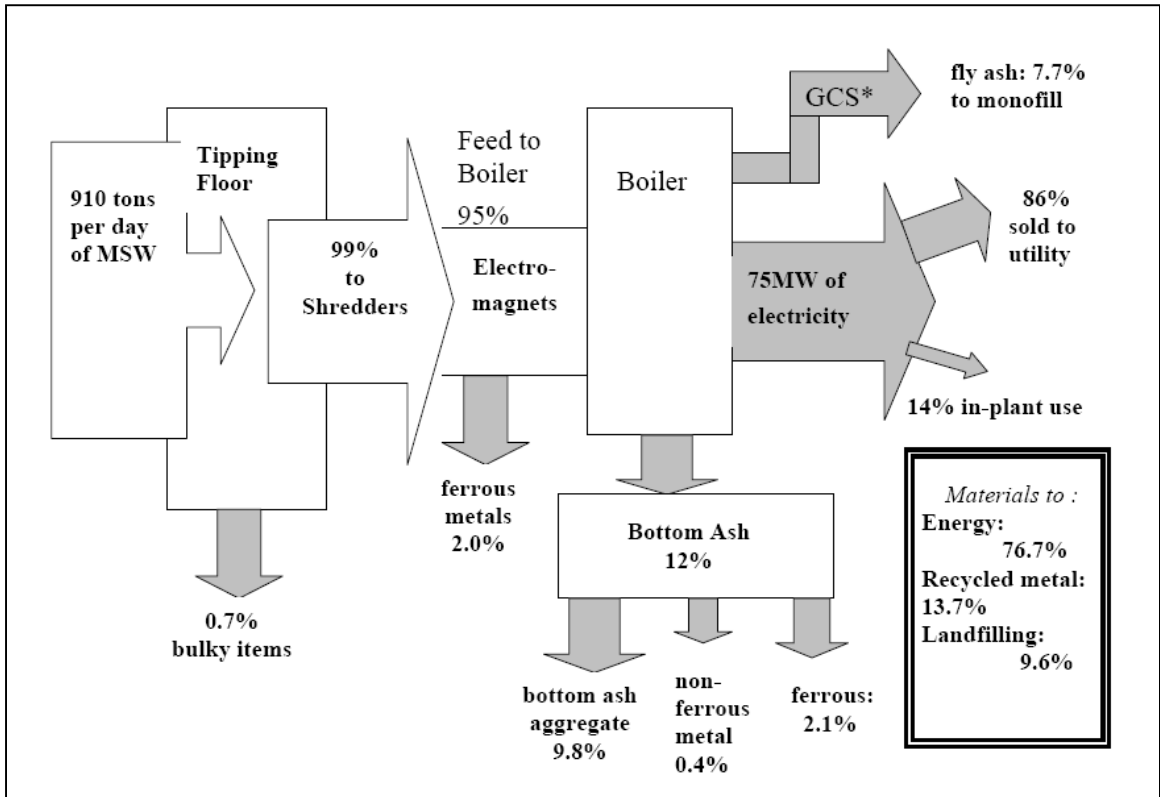
^c Source tests did not indicate whether this compound was the para- or ortho- isomer. The para- isomer is a Title III-listed HAP.

^d No data were available to speciate total Hg into the elemental and organic forms.
 ppmv = parts per million based on volume of landfill gas.

Appendix B
Sanitary landfill schematic
Source: USEPA (2008c)



Appendix C
Incinerator schematic for a 910 tpd facility
Source: Themelis et al. (2002).



Appendix D

Typical Emissions for incinerators with and without emissions control.

Source: Emissions (USEPA 1995b).

Pollutant	Emissions Control Technology	
	Uncontrolled Emissions (kg/Mg)	Spray Drier/ Fabric Filter Emissions (kg/Mg)
Arsenic ^b	0.00214	0.0000212
Cadmium ^b	0.00545	0.0000136
CDD/CDF ^c	0.000000835	0.0000000331
CO ₂	985	*
CO ^d	0.232	*
Cromium ^b	0.00449	0.0000150
HCl ^b	3.20	0.106
Mercury ^b	0.0028	0.0011
Nickel ^b	0.00393	0.0000258
NOx ^d	1.83	*
Lead ^b	0.107	0.000131
Particulate Matter ^a	12.6	0.0311
SO ₂	1.73	0.277

USEPA NOTES:

All factors in kg/Mg refuse combusted.

CO₂ emitted from incinerators may not increase total atmospheric CO₂ because emissions may be offset by the uptake of CO₂ by regrowing biomass.

Emission factors should be used for estimating long-term, not short-term emission levels. This particularly applies to pollutants measured with a continuous emission monitoring system (e.g., SO₂).

kg/Mg = kg of emissions per Mega gram (1,000,000 grams, 1.102311 tons or 1.0 metric tons) of solid waste combusted.

* = Same as "uncontrolled" for these pollutants.

^a PM = Filterable particulate matter, as measured with EPA Reference Method 5.

^b Hazardous air pollutants listed in the Clean Air Act.

^c CDD/CDF = total tetra- through octa-chlorinated dibenzo-p-dioxin/chlorinated dibenzofurans. 2,3,7,8-tetrachlorodibenzo-p-dioxin, and dibenzofurans are hazardous air pollutants listed in 1990 Clean Air Act.

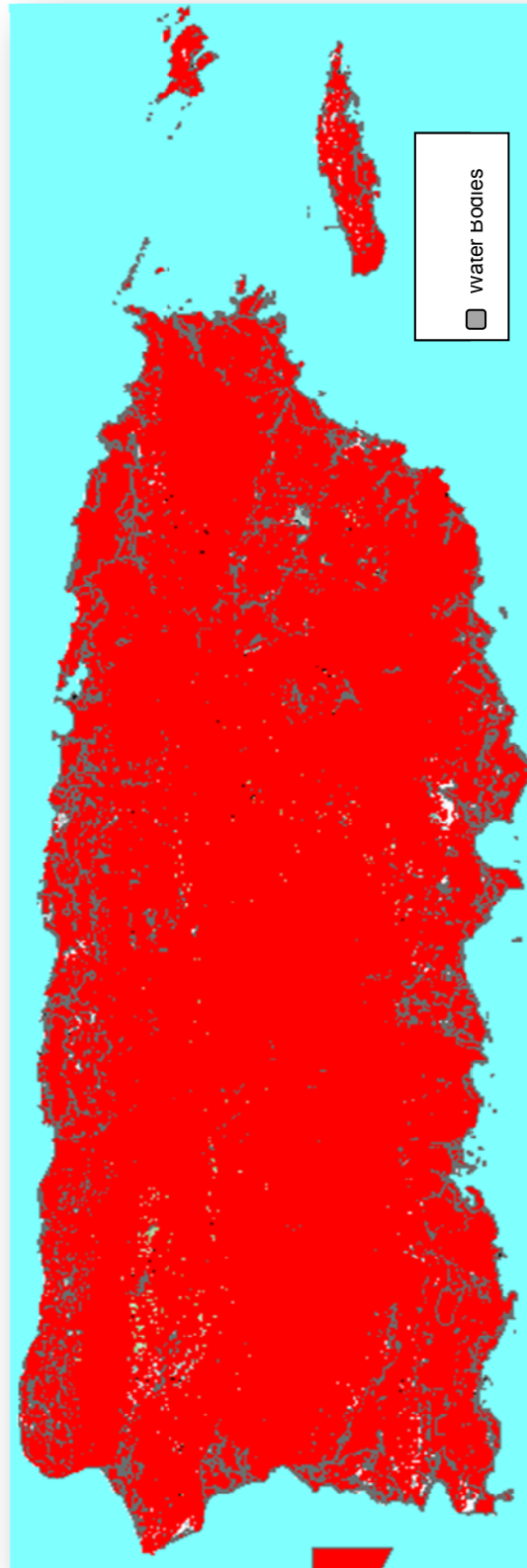
^d Control of NOx and CO is not tied to traditional acid gas/PM control devices.

^e Calculated assuming a dry carbon content of 26.8% for feed refuse.

Appendix E

Excluded areas from sitting sanitary landfills.

Source: Carl Sodeberg, Director, CEPD, USEPA Region 2, pers. comm.



Appendix F

LandGEM Input and Results

Source: USEPA (2009).

USER INPUTS

Landfill Name or Identifier: ARECIBO MUNICIPAL LANDFILL

Clear ALL Non-Parameter Inputs/Selections

1: PROVIDE LANDFILL CHARACTERISTICS

Landfill Open Year	1973	
Landfill Closure Year		
Have Model Calculate Closure Year?	<input checked="" type="checkbox"/> Yes ; <input type="checkbox"/> No	
Waste Design Capacity	4,000,000	megagrams ▼

Restore Default Model Parameters

2: DETERMINE MODEL PARAMETERS

Methane Generation Rate, k ($year^{-1}$)	Inventory Conventional - 0.04 ▼
Potential Methane Generation Capacity, L_0 (m^3/Mg)	Inventory Conventional - 100 ▼
NMOC Concentration ($ppmv$ as hexane)	User-specified ▼
	User-specified value: 595
Methane Content ($\%$ by volume)	CAA - 50% by volume ▼

3: SELECT GASES/POLLUTANTS

Gas / Pollutant #1	Total landfill gas ▼	User-specified pollutant parameters are currently being used by model.
Gas / Pollutant #2	Methane ▼	Edit Existing or Add New Pollutant Parameters
Gas / Pollutant #3	Carbon dioxide ▼	Restore Default Pollutant Parameters
Gas / Pollutant #4	NMOC ▼	

Description/Comments:

4: ENTER WASTE ACCEPTANCE RATES

Input Units: Mg/year ▼

Year	Input Units (Mg/year)	Calculated Units (short tons/year)
1973	36,290	39,919
1974	36,280	39,908
1975	36,330	39,963
1976	36,200	39,820
1977	36,300	39,930
1978	36,300	39,930
1979	36,300	39,930
1980	36,300	39,930
1981	36,300	39,930
1982	36,300	39,930
1983	36,300	39,930
1984	36,200	39,820
1985	59,200	65,120
1986	59,200	65,120
1987	59,200	65,120
1988	59,200	65,120
1989	59,200	65,120
1990	59,200	65,120
1991	59,200	65,120
1992	59,200	65,120
1993	59,200	65,120
1994	113,800	125,180
1995	115,000	126,500
1996	116,000	127,600
1997	116,000	127,600
1998	118,000	129,800
1999	118,000	129,800
2000	118,000	129,800
2001	118,000	129,800
2002	148,000	162,800
2003	173,000	180,300
2004	251,000	276,100
2005	251,000	276,100
2006	237,000	260,700

**Appendix F (continued).
LandGEM Input and Results
Source: USEPA (2009).**

INVENTORY

Landfill Name or Identifier: ARECIBO MUNICIPAL LANDFILL

Enter year of emissions inventory:

Gas / Pollutant	Emission Rate				
	(Mg/year)	(m ³ /year)	(av ft ³ /min)	(ft ³ /year)	(short tons/year)
Total landfill gas	2.189E+04	1.752E+07	1.177E+03	6.109E+08	2.407E+04
Methane	5.846E+03	8.762E+06	5.887E+02	3.094E+08	6.430E+03
Carbon dioxide	1.604E+04	8.762E+06	5.887E+02	3.094E+08	1.764E+04
NMOC	3.738E+01	1.043E+04	7.006E-01	3.682E+05	4.111E+01
1,1,1-Trichloroethane (methyl chloroform) - HAP	4.688E-02	8.412E+00	5.652E-04	2.971E+02	5.134E-02
1,1,2,2-Tetrachloroethane - HAP/VOC	1.346E-01	1.928E+01	1.295E-03	6.808E+02	1.480E-01
1,1-Dichloroethane (ethylene dichloride) - HAP/VOC	1.731E-01	4.206E+01	2.826E-03	1.485E+03	1.004E-01
1,1-Dichloroethane (vinylidene chloride) - HAP/VOC	1.413E-02	3.505E+00	2.355E-04	1.238E+02	1.555E-02
1,2-Dichloroethane (ethylene dichloride) - HAP/VOC	2.957E-02	7.185E+00	4.828E-04	2.537E+02	3.253E-02
1,2-Dichloropropane (propylene dichloride) - HAP/VOC	1.482E-02	3.154E+00	2.119E-04	1.114E+02	1.631E-02
2-Propanol (isopropyl alcohol) - VOC	2.191E+00	8.762E+02	5.887E-02	3.094E+04	2.410E+00
Acetone	2.963E-01	1.227E+02	8.242E-03	4.332E+03	3.260E-01
Acrylonitrile - HAP/VOC	2.437E 01	1.104E+02	7.418E 03	3.899E+03	2.680E 01
Benzene - No or Unknown Co-disposal - HAP/VOC	1.082E-01	3.330E+01	2.237E-03	1.176E+03	1.190E-01
Benzene - Co-disposal - HAP/VOC	6.263E-01	1.928E+02	1.295E-02	6.808E+03	6.889E-01
Bromodichloromethane - VOC	3.702E 01	5.433E+01	3.650E 03	1.919E+03	4.072E 01
Butane - VOC	2.110E-01	0.762E+01	5.007E-03	3.094E+03	2.330E-01
Carbon disulfide - HAP/VOC	3.218E-02	1.016E+01	6.829E-04	3.590E+02	3.540E-02
Carbon monoxide	2.858E+00	2.453E+03	1.648E-01	8.664E+04	3.144E+00
Carbon tetrachloride - HAP/VOC	4.485E-04	7.010E-02	4.710E-06	2.476E+00	4.934E-04
Carbonyl sulfide - HAP/VOC	2.145E-02	8.587E+00	5.770E-04	3.033E+02	2.360E-02
Chlorobenzene - HAP/VOC	2.051E-02	4.381E+00	2.944E-04	1.547E+02	2.256E-02
Chlorodifluoromethane	8.194E-02	2.278E+01	1.531E-03	8.045E+02	9.013E-02
Chloroethane (ethyl chloride) - HAP/VOC	6.114E-02	2.278E+01	1.531E-03	8.045E+02	6.725E-02
Chloroform - HAP/VOC	2.611E-03	5.257E-01	3.532E-05	1.857E+01	2.872E-03
Chloromethane - VOC	4.416E-02	2.103E+01	1.413E-03	7.427E+02	4.858E-02
Dichlorobenzene - (HAP for para isomer/VOC)	2.250E-02	3.080E+00	2.473E-04	1.300E+02	2.475E-02
Dichlorodifluoromethane	1.410E+00	2.804E+02	1.884E-02	9.902E+03	1.551E+00
Dichlorofluoromethane - VOC	1.950E-01	4.556E+01	3.061E-03	1.609E+03	2.146E-01
Dichloromethane (methylene chloride) - HAP	8.668E-01	2.453E+02	1.648E-02	8.664E+03	9.535E-01
Dimethyl sulfide (methyl sulfide) - VOC	3.532E-01	1.367E+02	9.184E-03	4.827E+03	3.886E-01
Ethane	1.951E+01	1.560E+04	1.048E+00	5.508E+05	2.146E+01
Ethanol - VOC	9.069E-01	4.732E+02	3.179E-02	1.671E+04	9.976E-01
Ethyl mercaptan (ethanethiol) - VOC	1.042E-01	4.031E+01	2.708E-03	1.423E+03	1.146E-01
Ethylbenzene - HAP/VOC	3.559E-01	8.061E+01	5.416E-03	2.847E+03	3.915E-01
Ethylene dibromide - HAP/VOC	1.369E-04	1.752E-02	1.177E-06	6.189E-01	1.506E-04
Fluorotrichloromethane - VOC	7.610E-02	1.332E+01	8.949E-04	4.704E+02	8.371E-02
Hexane - HAP/VOC	4.146E-01	1.157E+02	7.771E-03	4.085E+03	4.560E-01
Hydrogen sulfide	8.943E-01	6.309E+02	4.239E-02	2.220E+04	9.837E-01
Mercury (total) - HAP	4.241E 05	5.082E 03	3.415E 07	1.795E 01	4.665E 05
Methyl ethyl ketone - HAP/VOC	3.732E-01	1.244E+02	8.360E-03	4.394E+03	4.105E-01
Methyl isobutyl ketone - HAP/VOC	1.387E-01	3.330E+01	2.237E-03	1.176E+03	1.526E-01
Methyl mercaptan - VOC	8.767E-02	4.381E+01	2.944E-03	1.547E+03	9.644E-02
Pentane - VOC	1.735E-01	5.783E+01	3.886E-03	2.042E+03	1.909E-01
Perchloroethylene (tetrachloroethylene) - HAP	4.472E-01	6.484E+01	4.357E-03	2.290E+03	4.920E-01
Propane - VOC	3.535E-01	1.928E+02	1.295E-02	6.808E+03	3.889E-01
t-1,2-Dichloroethene - VOC	1.978E-01	4.907E+01	3.297E-03	1.733E+03	2.176E-01
Toluene - No or Unknown Co-disposal - HAP/VOC	2.619E+00	6.835E+02	4.592E-02	2.414E+04	2.881E+00
Toluene - Co-disposal - HAP/VOC	1.142E+01	2.979E+03	2.002E-01	1.052E+05	1.256E+01
Trichloroethylene (trichloroethene) - HAP/VOC	2.682E-01	4.907E+01	3.297E-03	1.733E+03	2.950E-01
Vinyl chloride - HAP/VOC	3.326E 01	1.279E+02	8.596E 03	4.518E+03	3.858E 01
Xylenes - HAP/VOC	9.286E-01	2.103E+02	1.413E-02	7.427E+03	1.021E+00