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DEVELOPMENT OF AN
EMPIRICAL MODEL OF
METHANE EMISSIONS
FROM LANDFILLS

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DEVELOPMENT OF AN EMPIRICAL MODEL OF METHANE EMISSIONS FROM LANDFILLS

Final Report

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ABSTRACT

The U.S. Environmental Protection Agency's (EPA's) Air and Energy Engineering Research Laboratory (AEERL) began a research program in 1990 with the goal of improving global landfill methane (CH_4) emissions estimates. Part of this program is a field study to gather information that can be used to develop an empirical model of CH_4 emissions. The field study is the subject of this report.

Twenty-one U.S. landfills with gas recovery systems were included in the study. Site-specific information includes average CH_4 recovery rate, landfill size, tons of refuse (refuse mass), average age of the refuse, and climate. A correlation analysis showed that refuse mass was positively linearly correlated with landfill depth, volume, area, and well depth. Regression of the CH_4 recovery rate on depth, refuse mass, and volume was significant, but depth was the best predictive variable ($R^2 = 0.53$). Refuse mass was nearly as good ($R^2 = 0.50$). None of the climate variables--precipitation, average temperature, dewpoint--were correlated with the CH_4 recovery rate or with CH_4 recovery per metric ton (Mg) of refuse. A large amount of the variability in CH_4 recovery remains unexplained, and is likely due to between-site differences in landfill construction, operation, and refuse composition. A model for global landfill emissions estimation is proposed.

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INTRODUCTION

BACKGROUND

The U.S. Environmental Protection Agency's (EPA's) Air and Energy Engineering Research Laboratory (AEERL) began a research program in 1990 with the goal of improving global landfill methane (CH_4) emissions estimates (Thorneloe and Peer, 1990). Methane is a greenhouse gas of particular concern because its radiative-forcing potential is thought to be much greater than that of carbon dioxide (CO_2) (Shine et al., 1990). Considerable uncertainty remains about the quantitative emissions of CH_4 from each of its known sources (Khalil and Rasmussen, 1990).

Municipal solid waste (MSW) includes a considerable amount of degradable organic carbon, moisture, and a variety of bacterial species. These bacteria are the primary agents of the decomposition of organic wastes, producing CO_2, CH_4, and trace amounts of other gases. In the presence of oxygen, aerobic bacteria are active and the primary product is CO_2. However, in sanitary landfills, the oxygen is quickly used up and oxygen infiltration is usually very low; in an oxygen-poor environment, anaerobic bacteria are the primary decomposers and methane as well as CO_2 are produced. The MSW deposited in both sanitary landfills and open dumps is a large potential source of methane.

Recent CH_4 budgets attribute approximately 11 percent (Cicerone and Oremland, 1988) and 17 percent (Bingemer and Crutzen, 1987) of global anthropogenic CH_4 to landfill emissions. However, these estimates are based on limited data and assume near optimal conditions for anaerobiosis. The optimal moisture, temperature, pH, and substrate conditions are not likely to be found in sanitary landfills in the United States and Europe, let alone in the open dumps typical of the less-developed countries. One objective of AEERL's research program is to develop a database and a methodology that can be used to reduce the uncertainty of CH_4 emission estimates from landfills on a global basis (Thorneloe and Peer, 1991).

The research program began with a review of currently available models and data (Peer et al., 1991). Several theoretical models and laboratory experiments used to estimate CH_4 production in individual landfills were identified. However, adapting these methodologies for global estimates posed several problems, the worst being that site-specific data would be needed for every country. The few global emissions methodologies that were found were reasonable, but were hampered by a paucity of data. In particular, reliable refuse generation rates and waste composition data were not available for many countries. In addition, many landfill experts believe that climate (particularly as it affects moisture input to the landfill) has an effect on CH_4 generation rates. No currently available model incorporates climate as a controlling variable.

In order to accurately estimate CH_4 generation in landfills on a global basis, a model is needed that is responsive to a wide range of climates, types of waste, and landfilling practices. Understanding the effects of climate on CH_4 production is especially important to climate modelers who are studying feedback effects of global climate change. Therefore, AEERL initiated a field testing program to gather data to:

- Identify key variables that affect CH_4 generation; and
- Develop an empirical model of CH_4 generation based on those variables.

From the literature review, several variables were identified as potentially important: refuse moisture content, refuse composition, refuse age, pH, and a variety of other variables related to landfill characteristics and waste-handling practices. The scope of global landfill emissions estimation, however, limits the number and type of variables that can be considered.

Landfills with gas recovery systems, where landfill gas is collected and measured by the gas recovery operators, offer unique opportunities for studying CH_4 production. If data from these landfills can be verified to be reasonably accurate, and if sufficient information is available about the landfill itself, the landfill gas measurements collected at the site may be used to estimate total CH_4 generation. If sufficient sites are available to provide a representative sample of current U.S. landfills, then an empirical model may be developed. Eventually, this model can be expanded to estimate methane emissions from landfills globally. Gas recovery systems are widely used in Europe, and are becoming more common in other parts of the world. They represent an important source of data for estimating global landfill CH_4 emissions, and may be used to calibrate a model developed from U.S. data.

The first step in developing the field testing program was a pilot study of six U.S. landfills that have CH_4 recovery systems (Campbell et al., 1991). The primary objectives of the pilot study were to determine the types and quality of landfill data available and to assess the feasibility of expanding the study to include other sites. The study included gas sampling and testing. For the six sites visited, the sampling program demonstrated that landfill gas composition, as measured by landfill monitoring equipment, was reasonably accurate.

The results of the pilot study were sufficiently encouraging so that a full-scale field program was begun. However, the field program was limited to acquisition of CH_4 data gathered by on-site monitors. Furthermore, no other sampling or testing was planned. Data acquisition was confined to historical records kept at individual sites.

The limitations of this approach were recognized at the outset:

- Collection efficiencies of the recovery systems are unknown;
- Waste composition data are usually not available for a particular site; and
- It is impossible to fully account for differences in the structure and operating characteristics of landfills.

Given these caveats, a certain amount of unexplainable variability was expected in the final results. Nevertheless, by choosing sites from a wide range of climates, any relationship between climate and CH_4 production might be detected if the effects of site-specific factors (such as refuse age) could be identified and removed.

OBJECTIVES

The objectives of the study described in this report were to:

- Develop a statistical model of annual landfill CH_4 emissions as a function of climate, refuse mass and age, and other physical characteristics (if warranted);
- Compare the performance of the statistical model to a deterministic kinetics-based model of landfill CH_4 production; and,
- Develop a simple model that can be used to estimate global CH_4 emissions from landfills.

It is important to note that CH_4 recovery is being used as a surrogate for CH_4 emissions in this study, thus affording the potential to either underestimate and overestimate emissions. The method may underestimate if gas recovery is not 100 percent efficient; some CH_4 may still be lost through the cap or by lateral gas migration out of the landfill. On the other hand, the method may overestimate if gas recovery circumvents the reoxidation of CH_4 by methanotrophs, methanogens, and sulfate-reducing bacteria. Given that strong arguments can be made for both cases and no quantitative data exist for either, the approach used in this study is to assume that both cases are true but the net effect is zero. If data that refute this assumption become available, adjustments to the model will be made.

The landfills included in this study are described in Section 2. Data acquisition and development, and analytical methods and models are described in Section 3. The results of the analyses are discussed in Section 4. Section 5 presents conclusions.

SECTION 2

LANDFILL CHARACTERISTICS

Data from 25 landfills were obtained for the field study. Brief descriptions of the landfills are presented below. Landfills 1 through 6 were part of a pilot study (Campbell et al., 1991). Only Landfills 23, 24, and 25 were not visited by Radian personnel; data for these three landfills were provided by on-site operators. Data from Landfills 14, 15, 18, and 19 were not used in this report because they either did not maximize gas recovery or they lacked historical refuse/gas recovery data. Therefore, these landfills are not described below. The landfill site visit reports written during this study are provided in Appendix A (excluding Landfills 14, 15, 18, and 19). The site visit reports for Landfills 1 through 6 are provided in the pilot study report (Campbell, et al., 1991) and are, therefore, not reproduced here. Landfill data are given in metric units. A metric/U.S. equivalent conversion chart is provided in Appendix B.

Landfill 1

Landfill 1 is located in Wisconsin and was visited August 6, 1990. The landfill covers about 35 hectares. Refuse was accepted at this site from sometime in the 1950s until June 1989, when the landfill was closed. The site accepted hazardous waste until the early 1980s; the hazardous waste was placed in separate cells from other refuse. The landfill is reportedly covered by a 1.5-meter-thick cap.

Gas recovery began at this site on December 31, 1985. Forty-five wells are in place, 25 along the perimeter of the site (installed in 1985) and 20 on the interior portion of the site (added in 1987). Six wells that are placed over older sections average 12 to 15 meters in depth. The wells installed most recently are 24 to 27 meters deep.

Landfill personnel do not routinely monitor for surface or perimeter gas migration. Problem areas are usually identified by visual inspection of the surface for vegetative stress. Once a problem area is identified, the decision is made by landfill personnel whether or not to install a new well. Except for roadbeds, the entire landfill surface was seeded with grass. The only fissures noted in the landfill surface appeared to be due to water erosion. It is not known, however, if gas is escaping through these fissures.

Landfill 2

Landfill 2 is located in Illinois. It was visited on August 7, 1990. Two closed sections cover about 54 hectares. Refuse was first placed in the older closed section of the landfill in 1968. Refuse acceptance at the newer closed section began in November 1982. The original landfill owners were very inconsistent in cap placement and cap thickness. Cap thickness in the older section varies from 0.15 to 2.4 meters. The clay cap on the newer section has an average thickness of 0.9 meters. The current owner uses visual vegetation inspection and routine surface monitoring to identify areas that need a new or thicker clay cap.

The older section of the landfill produces from 19,000 to 30,000 liters of leachate per week. The leachate and the landfill gas condensate are transported by truck to a local wastewater treatment plant. The newer section of the landfill produces a much smaller quantity of leachate (not quantified, however).

Gas is being recovered from the two closed sections. The current owners installed a flare system in 1988, and converted to turbines in January of 1989. Of a total of 72 wells, 65 are currently on-line. Of the on-line wells, 44 are considered very active and were used in the data analysis. The other on-line wells are very low flow and were installed primarily to control odors. The older section of the landfill has 40 wells in place, and the remainder are on the newer section. Routine gas monitoring reports on permanent probe testing for pressure, percent CH_4, and water levels are prepared by landfill personnel. Wells are added as needed to improve gas recovery.

The landfill operators place a great emphasis on controlling any gas migration problems so as to prevent odor complaints and vegetative stress. A visual inspection of the vegetation growing on the landfill surface revealed only one area with vegetative stress; a well had already been installed to correct the problem, but it was not yet under a vacuum. Gas was bubbling through the water that had collected in the bottom of the well. No odors were detected in any other part of the collection area. The only location at which measurable CH_4 concentrations could be found with a handheld organic vapor analyzer (OVA) was within a new well enclosure. No other significant leaks were found.

Landfill 3

Landfill 3, located in Pennsylvania, was visited on August 9, 1990. The landfill comprises a closed portion, which covers about 51 hectares, and an active portion, which covers about 24 hectares. Refuse acceptance began in 1970 and essentially ceased in 1988 for the portion of the landfill with gas recovery. Hazardous wastes were accepted until 1981, and make up about 1 percent of the total refuse. Refuse is still being added in small amounts to the closed portion as settling occurs. Average clay cap thickness is 0.6 meters.

Gas was originally vented to the atmosphere to control lateral off-site migration. Gas recovery began in January 1988 on the closed portion of the landfill. Gas will be recovered from the active portion at some future date. Two turbines are currently operating full time. A total of 31 wells are on the site, with an average well depth of 30 meters. Landfill personnel report that they are encountering problems on the eastern slope of the recovery area, with organic vapor surface probe readings of 25 to 48 percent as CH_4. One suspected reason for this problem is the fact that this slope has several leachate manholes that are not tied into the gas collection system.

A few areas of the landfill had sparse vegetation, but it could not be concluded that these areas had migration problems because the topsoil applied to the site was of very poor quality, and prior to the site visit there had been a 6-week period with very little rain. A very strong landfill gas odor was detected in at least five separate areas on the eastern slope (even with a brisk wind), but there were no signs of vegetative stress.

Landfill 4

Landfill 4 is located in Florida. The site was visited on August 20, 1990. One area of the landfill is closed; another area is currently accepting refuse. The closed portion covers about 57 hectares. Refuse acceptance in the closed area began in 1971 and ceased in April 1989. The current area was then opened. Portions of the landfill also accepted sludge from a nearby wastewater treatment plant in the past and continue to do so. Construction and demolition debris make up approximately 5.5 to 6 percent of total refuse volume. Final cover on the closed area is 45.7 cm of topsoil, 45.7 cm of clay (rock tailings), and 45.7 cm of sand. This cover is very permeable to rainfall and the permeability also limits the amount of vacuum that can be applied.

The Plant Manager estimated leachate collection up to 5.3×10^6 liters/month, depending on rainfall. Because the cap is so permeable, the amount of leachate produced is greatly affected by rainfall amounts. Leachate from the area currently accepting waste is shipped off site to a wastewater treatment facility along with condensate from the gas collection system. The closed portion of the landfill with gas recovery does not have a true leachate collection system.

Gas is recovered from the closed portion of Landfill 4. One hundred and eleven wells are in place. Average well depth is 21 meters, with depths ranging from 18 to 46 meters. Five turbines were installed and brought on line during March and April of 1989. Official start-up began July 1989. Prior to this time, recovered gas was processed in a gas plant and/or flared. Currently, the facility continuously operates four turbines at 95 percent capacity. The Plant Manager hopes to increase recovery by installing eight new deep wells.

Permanent bore holes have not been installed for routine perimeter gas migration monitoring. Buildings near the perimeter of the site (up to 305 meters from the landfill) are routinely tested for gas levels. On-site personnel indicated that when vegetation stress is identified, they first try to adjust the vacuum on nearby wells. If required, a decision is made as to whether a new well should be added to alleviate the vegetative stress. Soil dehydration due to lateral gas may also result in vegetative stress.

Landfill 5

Landfill 5, located in southern California, was visited on August 23, 1990. Since refuse acceptance began at this site in 1952, refuse has been placed in the pit left from a gravel mining operation. During the 1950s and 1960s, the site primarily received inert waste, but at that time the waste also contained a high proportion of orange trees. The very center portion of the landfill reportedly contains a high proportion of construction and demolition debris. Landfill personnel have no knowledge of hazardous waste being disposed of at this site.

The closed portion of the landfill covers about 32 hectares. The closed portion did not have a final cover in place at the time of the site visit, although a cover was to be installed in the Fall of 1990. The area is currently covered with a permeable silty sand and is not vegetated. Landfill personnel estimate the moisture content of the refuse in place to be 12 percent. Reinjection of condensate to boost moisture in the refuse was permitted by the local authorities until 1985. Landfill personnel note, however, that since this practice ceased, there has not been any appreciable drop in either gas or condensate production. There is no active leachate collection system in place where gas is being collected.

Gas is being recovered from the closed portions of the landfill. Gas collection first began at this site in 1976; the previous owners periodically used an internal combustion engine to produce energy or flared the gas. The closed portion of the landfill has a total of 102 wells, 42 interior and 60 perimeter. Orifice plates are used on each well to measure and control gas flow. The lines connecting the well systems are kept separate and lead to flares on the perimeter of the site. There are three flares at the site, one for each well system and one for backup use only. The interior wells are better producers than the perimeter wells, with high gas flow and higher gas CH_4 content. The depths of the interior wells range from 46 to 76 meters, while the perimeter wells, designed primarily for migration control, are much shallower.

Local regulations often limit customer use of landfill gas. Therefore, there is currently only a sporadic market for gas sales at this facility, and the majority of recovered gas is flared. Operators of this facility are optimistic that gas sales will increase in the future, and predict that as waste acceptance rates increase, gas recovery rates will also increase.

Perimeter gas migration is controlled by the 60 shallow perimeter wells that encircle the closed portion of the landfill. Monthly surface test data typically indicate organic vapor readings below 50 parts per million. No measurable organic vapors levels were detected during the site visit. Vegetation has not been established on any portion of the landfill.

Landfill 6

Landfill 6, located in northern California, was visited on August 24, 1990. Three areas of the landfill (Areas 1, 2, and 3) are now closed. Refuse is currently being placed in another area. The closed areas comprise approximately 40 hectares.

Refuse was first accepted at this site in 1975. Paper waste accounts for approximately 46 percent of the total refuse at the site; garden wastes account for 13 percent, and glass/ceramics and food waste, 10 percent each. The average refuse moisture content is reported to be 23 percent. The final cover on Areas 1 and 2 and part of Area 3 consists of a 1.2-meter-thick clay cap and 0.3 meters of soil, with vegetation established. Parts of Area 3 have not yet been seeded with vegetation.

Gas recovery from the closed portions of the landfill began in August 1988. The current system consists of 68 wells, three internal combustion engines, and a backup flare that is used if one of the engines fails. This flare is constantly burning, and normally runs on propane (with only a small stream of recovered CH_4). On-site personnel indicate that the volume of CH_4 burned in the flare has been steadily decreasing over time.

Condensate collected at the well heads is fed back into the fill area. Condensate collected at the gas recovery plant is combined with the leachate collected from the landfill and transferred to one of two surface collection ponds. The liquid is then allowed to stand until it reaches a solids-to-liquid ratio of 50:50. After testing the mixture's toxicity, it is placed in the landfill if permitted.

Information received from the County Environmental Health group, the party responsible for gas migration testing, showed that there are no areas with any significant gas migration problems. At the time of year testing was performed for this study, all vegetation was dry and in a generally dormant condition. Visual inspection indicated one small area of possible distress during the previous growing season. The cap is full of large cracks, caused by excessive dryness of the soil; however, no leakage from the cracks was detected.

Landfill 7

Landfill 7 is located in North Carolina and was visited on March 14, 1991. The landfill, which was opened in 1972, covers 51 hectares and is divided into three areas based on past and current refuse placement patterns. Closed areas are covered with a 0.61-meter-thick clay cap. This landfill has no active leachate collection system; however, groundwater monitoring wells are located around the perimeter of the property.

The current refuse acceptance rate is approximately 1270 metric tons per day, with at least 36 metric tons being construction and demolition debris. Landfill operators have no knowledge of any commercial hazardous wastes being placed at this site, but asbestos-containing building tiles were accepted until 1985. The building tiles are placed with the construction and demolition debris in areas that are separate from the areas that receive residential garbage.

Gas recovery began at this site in December 1989. The average depth of the 48 existing wells is 12 meters, but as new wells are installed in higher fill areas, they will be drilled 26 to 28 meters deep. The landfill gas is used as boiler fuel and is the main fuel source for a nearby industrial facility. Condensate from the gas stream is sent to the city sewer system. One flare is located by the blower, which is computer-operated to automatically run when demand for steam from the boiler is low. Gas composition measurements are taken daily at a point along the pipe leading to the flare. Percent CH_4 typically runs from 40 to 53 percent, and averages 51 percent. At this point, the gas contains an estimated 2 to 3 percent water by volume.

The city has installed 14 perimeter wells to monitor off-site gas migration. Monitor levels reportedly never exceed 0.05 percent CH_4. Prior to installation of the gas recovery system, there were frequent odor complaints, which have now ceased. Landfill personnel believe that only 65 percent of the available CH_4 is being recovered (based on amount of refuse in place), with the majority of the gas escaping along the steep slopes without being detected at the perimeter migration wells.

Landfill 8

Landfill 8 is located in Georgia. It was visited on March 19, 1991. Refuse was accepted at this 22-hectare site between 1973 and 1987. Waste composition is estimated to be 60 percent commercial, 25 percent residential, and 15 percent construction and demolition debris. Paper reportedly accounts for 50 percent of the landfill refuse. No liquids or sludges were accepted during the life of the landfill. The landfill is covered with a 0.61- to 1.2-meter-thick clay cap and has an established vegetative cover, mostly grasses with some wild flowers. There is no active leachate collection system at this landfill. Leachate is reportedly well contained by the natural clay liner under the landfill.

Gas recovery began at this site in 1986. One hundred and seven wells are in place with plans to reduce the number of wells by approximately half to reduce competition between wells and increase individual well efficiency. Average well depth is 17 meters. Replacement wells (approximately 20 per year) will be drilled deeper than original wells in most cases. There is one flare located by the gas recovery facility. The flare can burn 28 cubic meters per minute, which is not enough to prevent all migration when the system is down. The flare is not used when the plant is operating.

The gas treatment process to produce pipeline quality, high-Btu gas is considered proprietary. Before treatment, the CH_4 content of the landfill gas ranges from 55 to 59 percent. After processing, the gas contains at least 95 percent CH_4. The gas is sold to a local gas company.

Perimeter wells have been installed at 305-meter intervals around the landfill to monitor off-site gas migration. The wells average 9 to 14 meters in depth. They are monitored monthly when the gas recovery plant is in operation, and weekly when it is not operating. When the recovery plant is not operating, the vacuum on the perimeter wells is increased and the vacuum on the interior wells is decreased to prevent off-site migration.

Landfill 9

Landfill 9 is located in Mississippi and was visited on March 19, 1991. The landfill has been operational since 1979 and has 73 hectares available for refuse disposal. The landfill is divided into three cells, two of which (Cell 1 and Cell 2) have been filled. The two filled cells cover approximately 12 hectares and are covered with a 0.61- to 0.91-meter-thick clay cap and have established vegetative cover, mostly grasses and some wild flowers. Cells 1 and 2 do not have active leachate collection systems. Cell 3 does have a system and, ultimately, the gas condensate sumps will be tied into this system.

Landfill personnel estimate that approximately 20 percent of incoming refuse is construction and demolition debris, 60 percent is commercial, and 25 percent residential. Landfill personnel have no knowledge of accepting commercial hazardous waste, gas tanks, or car batteries. Tires are accepted if they have been shredded or cut in half.

A gas recovery system was installed at this landfill in September 1990 in response to migration problems. There are a total of 32 wells, 20 of which are in Cell 1, and 12 in Cell 2. Interior wells are 18 to 21 meters deep and perimeter wells are about 9 meters deep. An additional 15 deep interior wells should be operational by summer 1991. Recovered gas averages 40 percent CH_4; gas from perimeter wells has a lower CH_4 content. There is one flare located on site, which is burning about 17 cubic meters per minute.

Perimeter probes have been installed at 305-meter intervals to monitor off-site gas migration. These probes are tested monthly. The site is flaring the minimum amount of gas necessary to keep the perimeter probes at 0 percent CH_4.

Landfill 10

Landfill 10 was visited on March 21, 1991. It is located in Alabama on approximately 40 hectares, which are divided into two 20-hectare areas based on past and current refuse placement patterns. The landfill has been operational since 1958; however, accepted refuse was burned in place in the early 1960s. Waste acceptance is expected to cease in 2006. Waste is covered daily with soil excavated from an area behind the landfill. A 0.91-meter sandy clay soil cap was placed on the newer area of the landfill in 1985. This landfill does not have a leachate collection system, but has had no off-site leaching problems. However, leachate monitoring wells are maintained at the landfill perimeter and checked twice each year.

Incoming refuse is not segregated. Landfill personnel have no knowledge of liquid, hazardous, or infectious wastes being accepted. Periodic spot inspections of incoming refuse is conducted and actual dumping monitored two or three times per week to ensure that no prohibited waste is entering the landfill. Asbestos was accepted in the past, but is now banned. Tires are still being accepted. In a waste characterization study done for EPA in 1986, approximately 50 percent of total waste was determined to be from household sources, 20 percent from construction and demolition, and 5 percent from industrial processes.

Landfill gas recovery began in 1988. The 96-well system draws gas from approximately 32 hectares of the landfill. The wells are approximately 21 meters in depth, with the bottom 6 meters filled with rock. Gas recovery personnel expect 50 new wells to be drilled in the near future. The recovered gas is treated and sold to a local gas company. The volume of pipeline-quality gas sold is about half the volume of total landfill gas extracted. The other 50% of the landfill gas is unusable water, hydrocarbons, carbon dioxide (CO_2), oxygen (O_2), and nitrogen (N_2).

In 1979, a polyethylene curtain was placed in a 7.6-meter ditch on the perimeter of the landfill to stop CH_4 gas migration. Gas migration is checked once each year at the landfill perimeter. No vegetative stress was observed.

Landfill 11

Landfill 11, located in Georgia, was visited on March 22, 1991. The landfill covers 49 hectares and is divided into two approximately equal areas (Parcel A and Parcel B), based on gas rights; there are no obvious distinctions between the two areas. The landfill began accepting waste in 1962 and is expected to be active until at least 1993.

The landfill has accepted nearly all of the residential and commercial waste from the surrounding county (population 170,000) since the landfill opened. Landfill personnel have no knowledge of hazardous waste placed at the site; however, waste is not routinely inspected for the presence of hazardous waste. Sewage sludge from the local wastewater treatment plant is accepted. Prior to landfilling, the sludge moisture must be reduced such that the sludge will not pass through a paint filter. Construction and demolition debris was accepted until 1986. Medical waste is not accepted. This landfill has no active leachate collection system. However, there are groundwater monitoring wells around the perimeter of the property.

The company that owns the gas rights to Parcel B has not recovered gas from that area since 1989. A brick manufacturing company has been collecting gas from Parcel A since 1985. Parcel A contains 39 wells with average depths of 14 meters. Landfill gas is treated by mechanical refrigeration to remove water. All of the gas collected is used as fuel in a brick kiln. None of the gas is vented or flared.

Gas migration monitoring is not required at this site, and there is no monitoring program in place. Landfill personnel state that vegetative stress on the landfill surface is not a problem.

Landfill 12

Landfill 12 is located in Oregon. It was visited on April 4, 1991. The landfill covers approximately 34 hectares and is divided into two segments: north and south. Filling began in the south area in 1969 and progressed to the northern boundary until 1980. Between 1980 and 1983 waste was placed in a second lift in the south area. The site was closed in 1983.

The landfill is built on land that was formerly a marshy wetland. Since 1983, the final landfill cover has been upgraded to increase slope and water runoff. Currently, the landfill cover consists of an average of 1.8 meters of low-permeability soil. The slope of the landfill averages just over 2 percent, and grass covers the entire surface. No active leachate collection or treatment system exist at this site. However, groundwater monitoring wells are located around the perimeter of the landfill.

The landfill accepted primarily residential and commercial wastes. The landfill's operating permit specifically excluded medical wastes, chemicals, oils, liquids, septic tank pumpings, and nondigested sewage sludge; however, household hazardous wastes were not excluded. Some construction and demolition debris was accepted and placed separately from the general refuse.

Gas recovery began in 1984. Of a total of 78 active wells, 50 are horizontal wells placed in trenches about 1.8 meters below the landfill surface and ranging in depth from 61 to 305 meters. The remaining wells are vertical, with an average depth of 11 meters. A private company operated the gas recovery system from 1984 until 1989, when gas production at the site decreased to the point where gas purification was no longer profitable. Currently, some gas is extracted from the existing well system and used to fuel boilers for the county; however, the system is no longer operating in an optimal fashion.

Perimeter monitoring for gas migration was not practiced at this site.

Landfill 13

Landfill 13 is located in Washington state and was visited on April 5, 1991. The landfill is 50 years old and is scheduled to close in December 1991. The landfill was built on an old gravel mine. The underlying soil is sandy gravel. The bottom of the landfill is about 1.5 meters above the groundwater table and is lined with a layer of demolition refuse. The landfill does not have a leachate collection system. Groundwater contamination from landfill leachate has been documented. The landfill owners are currently building a water treatment plant that will commence operation at the end of 1991. Contaminated water from the underlying aquifer will be extracted, treated, and returned to the ground.

The landfill is divided into two areas. The north area comprises approximately 20 hectares and has been closed since 1988. A 60-mil polyethylene liner was placed on 14 hectares of this section in 1989. The south area comprises approximately 12.1 hectares and refuse is still being accepted in portions of the area. A 0.15-meter cover of sandy dirt is placed over the active area daily. Open burning of refuse was practiced from the time the landfill was opened until the mid-1960s, after which refuse was either shredded or placed directly in the landfill and compacted.

Landfill gas recovery began in the late 1970s. Separate CH_4 gas recovery systems were operated in the north and south areas until March 1991. The landfill operates a total of 71 vertical gas extraction wells, 20 in the south area and 51 in the north area. Eight of the 20 in the south area are located in the active dumping area. Each well is 9 to 15 meters deep. Twenty-five new wells will be installed in the currently active area at landfill closure. Initially, recovered landfill gas was burned by separate flares in each section. The south area flare is currently inoperable and the south area wells are tied into the north area collection system.

Gas migration is measured with 20 gas probes located on the perimeter of the landfill. Very little gas migration has been noted since the flare system was installed. However, substantial amounts of landfill gas were observed bubbling in puddles along the road between the north and south areas.

Landfill 16

Landfill 16 is located in New York and covers 30 hectares. It was visited on April 10, 1991. Waste acceptance at this site began in 1976. All white goods, wood, tires, and construction debris are separated out of incoming refuse. Sewage sludge is accepted and is placed on the south slope of the fill area. Asbestos is also accepted and placed in a separate area of the landfill. There is no final cap on any part of the landfill, but a cap is planned in the near future. Leachate is collected in several ponds around the site.

Gas recovery began at this site in December of 1988. The gas is treated and then used to operate a 3MW turbine generating electricity. Thirty-six wells, spaced 30 to 61 meters apart, are connected to one header. Average well depth is 18 meters; however, wells located on the south side of the fill area, where the county is actively dumping waste, average only 11 meters.

The county is responsible for monitoring off-site gas migration and has installed several perimeter wells. Migration is thought to be minimal.

Landfill 17

Landfill 17, located in Massachusetts, was visited on April 23, 1991. The landfill covers 16 hectares and is divided into two sections, one active and one inactive. A 60-mil synthetic liner is in place under the active section; it extends over the inactive half to also act as a cap. A 0.3-meter-thick clay cap also covers the inactive section. Leachate is collected from the approximately 8 hectares of the landfill that are lined.

The landfill started accepting refuse in 1952, but much of the refuse currently in place was received within the past 10 years. Commercial waste accounts for 85 percent of the refuse, with the remainder being residential waste. The site contains tires, which were accepted by a former owner. Hazardous waste was accepted between 1968 and 1979. Batteries are banned from landfills by State regulation.

A candlestick flare (small, unenclosed flame) was introduced at this site in 1987; however, it was not large enough to handle the amount of landfill gas collected. A new flare system went on-line in February 1990. The current gas control system consists of 41 wells which feed one enclosed flare.

Perimeter wells from the 1987 gas collection system are monitored periodically for CH_4, but show no gas migration from the site. Interior wells appear to be pulling gas toward the center of the site, thereby controlling off-site migration.

Landfill 20

Landfill 20 is located in Michigan. The site visit took place on May 1, 1991. The landfill covers approximately 100 hectares, which are divided into two sections based on past and current refuse placement patterns. The entire landfill is surrounded by a clay dike and a trench to control surface water run-off. Refuse was accepted in the northern 65-hectare section from 1967 to 1985. Refuse was then placed in the southern 31 hectares, which are still being filled. Ten hectares of the northern section have a final cap (a 0.61-meter-thick clay cap and 0.15 meters of topsoil seeded with grass). The remaining 55 hectares--apart from the valley now being filled--have a 0.7-meter-thick clay cap. A final cap will be placed over this area in the near future.

The site contains no active leachate collection system under the oldest refuse in the northern section of the landfill. The southern section and the upper fill areas of the northern section do have a system. Condensate is combined with leachate and sent to leachate collection ponds and aerated. During dry periods, some of the liquid is recirculated in active fill areas and haul roads to reduce dust. The remaining liquid is tanked and trucked off site.

Refuse entering the landfill is classified as general refuse (municipal solid waste), compact general refuse (municipal solid waste), construction and demolition debris (usually includes wood), bulky wastes (white goods) and process residue from a local resource recovery facility, ferrous metal (now recycled), contaminated soil, non-contaminated soil, sand and concrete, asbestos, industrial and wastewater sludge, and ash from a local incinerator. Only incinerator ash is segregated; it is placed in a lined, 2.8-hectare monofill.

Landfill gas collection began in January 1990. Initially, 69 wells collected gas from 73 hectares of refuse. In December 1990, an additional 11 wells were brought on line. Eighty wells are currently distributed over 85 hectares, with the majority being located in the northern section, primarily where refuse is deepest. Average well depth is 17 meters; maximum depth is 20 meters. The gas is currently flared, although there are plans to sell electricity to the local utility company. In order to prevent off-site migration, the amount of gas flared is maximized.

Gas migration is monitored at 31 perimeter probes, which are tested monthly. Landfill personnel indicate that two or three of the probes along the southern boundary of the landfill (near the newly-placed refuse) show slightly elevated CH_4 levels. As new wells are installed along the southern slope, this migration will be controlled. In addition, four leachate collection wells in this area had CH_4 levels so high that flares were attached.

Landfill 21

Landfill 21 is located in Michigan and was visited on May 2, 1991. It began operation in 1971 and is currently divided in three areas based on temporal waste acceptance. The oldest area encompasses 18.6 hectares and accepted waste between September 1971 and the fall of 1978. The second area encompasses 8 hectares and accepted waste between 1982 and 1986. Both of these areas are now closed and are graded to the original contour of the land. The oldest area of the landfill is capped with 0.61 meters of clay and covered with approximately 9 meters of dirt. The second area is capped with 0.61 meters of clay and is scheduled to have a low-density polyethylene liner.

The third area, the only active portion of the landfill, encompasses 16 hectares. Waste is placed in excavated cells to an approximate depth of 20 to 30 meters. The area is lined with 41 mil polyethylene. Asbestos and contaminated soil are the only wastes separated from incoming refuse. Asbestos is kept in a controlled area, separate from all other landfill waste acceptance areas. Contaminated soil is co-disposed with other refuse. Municipal sludge is not accepted. The landfill has an active leachate collection system in all areas except the oldest.

Landfill gas recovery began in February 1990. The landfill gas collection system consists of 56 wells with an average depth of 18 meters. Forty-three wells are in the oldest area and 13 are in the second area.

A flare was installed to control off-site migration, and no CH_4 has since been detected during the monthly inspection of the 20 perimeter probes. No vegetative stress was detected in the closed areas on the perimeter of the landfill.

Landfill 22

Landfill 22 is located in Minnesota and covers 40 hectares. The site was visited on May 3, 1991. Refuse acceptance began in 1970 and ended in 1988. The landfill accepted primarily municipal solid waste. No known commercial hazardous wastes, little construction and demolition debris, and little sludge were accepted. The landfill does not have final closure, but the entire surface is covered with at least 0.61 meters of silty clay, which is 3 to 4.5 meters deep in some areas. The refuse is settling 1.5 to 3 meters per year, and clay is added to control surface water drainage. No active leachate collection system exists at this landfill. The fill area is surrounded by 54 groundwater test wells.

Landfill gas collection began in February 1989. The gas is currently flared, as gas recovery personnel feel that electricity or pipeline-quality gas cannot be produced profitably at this site. The well field has a total of 54 wells; 14 of them are in the east area to prevent off-site migration and are not placed in refuse. The 40 high-flow wells range in depth from 11 to 24 meters.

Off-site gas migration is monitored with 74 perimeter probes that are tested weekly. Because of concerns over the proximity of houses on the east side of the landfill, wells were installed to contain potential migration. The amount of gas recovered from these wells is negligible. Gas migration through the cap is monitored with an organic vapor analyzer. There is reportedly no significant amount of gas escaping to the atmosphere.

Landfill 23

Landfill 23 is located in Colorado and covers 40.5 hectares. Refuse was accepted at this site from the late 1950's until 1986. The majority of refuse was placed between 1981 and 1985. The surface of the landfill has a clay cap 0.6 to 1.5 meters thick.

Gas recovery for electric power generation began in December 1986. A reciprocating engine is used to generate the electricity. The well field consists of 19 high-flow wells and 12 low-flow wells. The average depth of the wells is 19.8 meters, with the minimum and maximum depths corresponding to the refuse fill depths. There is one flare located at the site which is used to burn off landfill gas not consumed for power generation.

Landfill 24

Landfill 24 is located in Texas and covers a total of 109 hectares. Waste acceptance began in 1972 and continues to date. A large portion of the refuse was received between 1983 and 1988, giving an average refuse age of 5.6 years. Refuse composition is estimated to be 55 percent commercial, 10 percent residential, and 35 percent demolition debris. Closed portions are covered with a clay cap 1.5 meters thick.

Gas recovery began in May of 1988. The landfill gas is burned to generate electric power using a turbine. The well field has 23 high-flow wells and 5 low-flow wells. Well depth averages 15 meters.

Landfill 25

Landfill 25 is in Illinois and covers 75 hectares. The landfill began accepting waste in 1970. Average refuse age is 12 years, with most waste accepted between 1973 and 1982. Refuse composition is 60 percent residential, 20 percent commercial, and 20 percent demolition debris. Closed portions of the landfill are covered with a clay cap 0.6 to 3.6 meters thick.

Gas recovery began in July 1988. The landfill gas is burned to generate electric power using two turbines. The system consists of two turbines, 43 high-flow wells, and 30 low-flow wells. There is also one flare located on site used to burn off the landfill gas not used for power generation.

SECTION 3

DATA REDUCTION AND MODEL DEVELOPMENT

All the data in this report, except for the climate data, came from the records kept at individual sites. Therefore, considerable effort was expended in evaluating each set of data, standardizing units, and preparing the data for analysis, as described below. (Note: All data and results tables in the main body of this report are presented in metric units; Appendix C contains select tables in U.S. equivalents.)

DATA QUALITY

Since the data used in this analysis were gathered by site operators to suit their own needs, the quality of the data could not be controlled by the measures that are normally used for actual emissions sampling. The acceptable error for this study is therefore greater than it would be for a controlled testing program. Gas composition estimates calculated by on-site operators were verified by independent sampling for the first six sites (Campbell et al., 1991). The relative accuracy for the percent of CH_4 by volume ranged from 2 to 19% and averaged 10.5% for Landfills 1 through 6. Furthermore, no biases in the on-site data were found. Based on this analysis, the on-site CH_4 data were found to be acceptable for the purposes of this study.

The accuracy of the flow rate data could not be verified directly. Instead, the calibration procedures used by the operators were evaluated. Based on the calibration procedures and instrument types, the flow rate data were judged by Radian personnel to be reasonably accurate. The expected accuracy of the flow monitors was assessed at 10% for the first six sites (Campbell et al., 1991). Due to greater variety of equipment and calibration procedures for the 22 sites, the average error is likely to be somewhat higher. Therefore, the expected accuracy of flow rate data is estimated to be about 15%.

The greatest source of error is the refuse data. The composition is not well documented for most of the sites. The mass of refuse is calculated by several different methods. Refuse is weighed at the gate at a few sites, but not at most. The accuracy of these data cannot be quantified, but the error is certainly greater than for the methane flow rate. Other landfill characteristics, such as depth and volume, are equally uncertain.

Overall, the data quality is good. Certain variables, such as refuse mass, are as good as they can be given that the study required data from existing landfills with gas recovery. The accuracy of other variables might be improved by use of independent gas testing, but the small increase in accuracy is not worth the increased cost, especially given the large (and uncontrollable) uncertainty in refuse mass and composition. The data reduction discussion below elaborates further on the data quality for specific variables.

DATA REDUCTION

Methane Data

The data used to calculate the average CH_4 recovery rate at each landfill were provided in printouts or computer files listing total gas flow, percent CH_4 composition of the total gas flow, and other information applicable to an individual landfill. Data were reported for each gas recovery system, usually in the form of daily averages of hourly recovery rates or of monthly totals of gas flow. Table 1 summarizes the type and units of the gas flow data, the type of percent CH_4 composition, and the time period over which the gas flow data were available for each landfill.

The gas flow data were put into Statistical Analysis System (SAS)™ datasets and summarized to obtain an average CH_4 recovery rate for each landfill. For landfills with multiple turbines or flares, a total gas flow value was calculated by summing over all operating systems. The total gas recovery rates were then converted to cubic meters per minute, and the CH_4 recovery rates were calculated by multiplying the gas recovery rate by the appropriate CH_4 composition percentage.

The resulting CH_4 recovery rate distributions were examined for obvious outliers; however, no statistical outlier screening was performed. Methane data points that were separated by large gaps from the main body of data--sometimes by two or more orders of magnitude--were considered obvious outliers. These data points often occurred at shut down or start up and were considered unrepresentative of the optimum gas recovery operation; therefore, they were excluded from the CH_4 averaging calculations. In addition, some portions of data were excluded for landfills that changed the refuse acceptance rate, wells, acres, or other important variables during the period of record for which gas flow data were received. Thus, only periods of record where the landfill parameter variables remained constant were used to calculate CH_4 averages.

Table 2 shows the average CH_4 recovery rate for each landfill, as well as other summary statistics. The number of measurements available varied a great deal between sites. For example, Landfills 13 and 21 had only 11 data points from a 12-month and 14-month period, respectively. On the other hand,

TABLE 1. SUMMARY OF GAS FLOW DATA OBTAINED FROM THE LANDFILLS

Landfill Number	Gas Flow Data: Type	Gas Flow Data: Units[a]	Methane Composition (data type)	Time Period Covered
1	daily average	CFH	daily percent	5/89 to 5/90
2	daily average	CFH	daily percent	1/89 to 7/90
3	daily average	CFH	daily percent	3/89 to 7/90
4	daily average	CFH	daily percent	7/89 to 9/90
5	daily average	CFM	daily percent	1/90 to 8/90
6	daily average	CFM	daily percent	8/88 to 8/90
7	monthly total	CF	average percent	1/90 to 12/90
8	daily total	CF	daily percent	2/89 to 2/91
9	daily average	CFM	average percent	9/90 to 3/91
10	monthly total	CF	average percent	1/90 to 2/91
11	monthly total	CF	average percent	1/86 to 12/90
12	daily total	CF	average percent	2/87 to 12/87
13	daily average	CFM	daily percent	1/90 to 12/90
16	monthly total	BTU	average percent	1/89 to 3/91
17	point total	CFM	daily percent	2/90 to 3/91
20	daily total	CF	daily percent	1/90 to 4/91
21	daily average	CFM	daily percent	3/90 to 1/91
22	daily average	CFM	average percent	2/89 to 5/90
23	daily total	CF	daily percent	4/90 to 1/91
24	daily total	CF	daily percent	11/89 to 5/91
25	daily total	CF	daily percent	7/90 to 5/91

[a] Units abbreviations:
CFH = cubic feet per hour
CFM = cubic feet per minute
CF = cubic feet
Btu = British thermal units

TABLE 2. SUMMARY STATISTICS FOR METHANE RECOVERY RATES GROUPED BY MEASUREMENT TYPE

Landfill	Measurements		Methane Recovery (m^3/min)						Coefficient of Variation (CV)*
	Type	Number	Average	Median	Standard Deviation	Minimum Value	Maximum Value	Range	
1	daily	194	55.3	55.3	2.12	48.0	61.4	13.4	3.8
2	daily	302	18.0	18.2	1.19	12.3	20.5	8.2	6.6
3	daily	314	40.0	40.3	2.32	30.2	44.6	14.4	6.3
4	daily	85	98.4	98.7	1.33	93.3	101.5	8.2	1.4
5	daily	209	24.8	24.9	1.70	20.5	27.9	7.4	6.8
6	daily	37	16.7	16.8	2.07	12.6	22.6	10.0	12.4
7	monthly	12	9.7	10.2	2.01	4.0	12.0	8.0	20.9
8	daily	626	11.7	12.4	2.46	0.5	17.1	16.6	21.0
9	daily	15	7.7	7.0	1.42	5.7	10.5	4.8	21.2
10	monthly	6	29.3	30.5	3.34	23.4	32.4	9.0	11.4
11	monthly	12	11.3	11.7	1.22	9.1	12.7	3.6	10.8
12	daily	232	8.0	7.7	1.02	5.4	10.4	5.0	12.9
13	daily	11	10.4	11.0	1.50	7.8	11.7	3.9	14.5
16	monthly	15	16.0	16.6	4.13	7.4	21.6	14.2	25.7
17	minute	13	13.8	13.9	1.50	10.1	16.5	6.4	10.8
20	monthly	12	35.0	35.1	4.75	26.5	41.3	14.8	25.5
21	daily	11	27.4	26.5	2.94	24.5	32.9	8.4	10.8
22	daily	51	33.2	31.8	7.84	21.6	60.0	38.4	23.6
23	daily	202	2.2	2.3	0.51	0.3	2.9	2.6	22.9
24	daily	333	17.7	17.9	2.18	3.1	22.1	19.0	12.4
25	daily	331	20.2	20.8	2.80	1.4	24.4	23.0	13.9

*CV = 100 * (Standard Deviation/Mean); a unitless measure of relative variability allowing comparison of variance between samples of various sizes or with very different means.

Landfill 8 had 626 data points from a 25-month period and Landfill 24 had 333 data points from a 1-year period. More confidence can be placed in the reliability of the estimated means for the latter two landfills; however, the gas flow variability is fairly low (as shown by coefficients of variation), so the small number of measurements for some sites is not likely to be as problematic as it would be if flow were highly erratic.

Amount of Refuse in Place

The amount of refuse in place was analyzed by weight for each landfill. As shown in Table 3, which summarizes the methods used by different landfills to estimate landfill parameters, refuse data from some landfills were provided by weight, while data from others were provided by volume. It was preferred that refuse data be provided by weight, particularly if the amount of refuse accepted each year was measured with a scale, as in the case of Landfill 16. For the most part, landfill personnel did not indicate how they arrived at their estimate of refuse weight. In some cases, scales were installed after some refuse had already been placed in the landfill.

The landfills that provided refuse data by volume did so because volume is the parameter used for recordkeeping or permitting purposes, and is often the basis for the landfill's tipping fee. Landfill personnel were able to recommend a conversion factor for volume to weight in most cases. The conversion factor used by personnel at Landfills 21 and 22 was 3.37 m^3/Mg.* For Landfill 21, refuse weight was calculated with this conversion factor using estimates of the daily volume placed in the landfill. For Landfill 13, a conversion factor of 2.81 m^3/Mg was recommended, and weight was again calculated based on an estimate of the daily volume.

For Landfills 3, 10, 11, and 17, landfill personnel were able to provide refuse weight only for recent years; for earlier years, only rough estimates were available. The amount of refuse in place calculated by the methods discussed above is included in Table 4, which shows the various landfill parameters that were used in the statistical analyses.

Refuse Age

As shown in Table 3, the average age of the refuse at each landfill was determined by several methods. The most accurate method was where the quantity of refuse placed in the landfill each year was provided by landfill personnel. If this type of detail was not available, landfill personnel were asked

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*Conversion factors supplied by site operators were usually in the form of yd^3/lb. Metric equivalents are reported here for consistency.

TABLE 3. SUMMARY OF DATA USED TO ESTIMATE LANDFILL PARAMETERS

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	16	17	20	21	22	23	24	25
<u>Refuse Weight</u>:																					
Provided as:																					
Weight	X	X		X	X	X	X	X	X			X		X					X	X	X
Volume													X				X	X			
Other			X							X	X				X	X					
<u>Refuse Age</u>:																					
Weighted Average				X		X						X		X		X		X	X	X	X
Estimated	X	X	X		X		X	X	X	X	X				X		X				
Open/Close Dates Only													X								
<u>Number of Hectares</u>:																					
Entire Landfill	X		X					X				X			X			X			
Distinct Section		X			X	X								X			X				
Other				X			X		X	X	X		X			X					
Not Known																			X	X	X
<u>Landfill Depth</u>:																					
Uniform		X			X	X				X		X	X			X	X	X			
Benched								X	X												
Pyramid-Shaped	X		X	X			X				X			X	X						
Not Known																			X	X	X
<u>Well Depth</u>:																					
Related to Fill Depth		X			X	X			X	X		X	X	X	X	X	X	X	X	X	X
Not Related to Fill Depth	X		X	X			X	X			X										
<u>Number of Wells</u>:																					
Total Used	X		X	X	X	X	X		X	X	X	X		X	X	X	X				
High Flow		X											X					X	X	X	X
Other								X													

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TABLE 4. SUMMARY OF LANDFILL PARAMETERS USED IN THE STATISTICAL ANALYSES

Landfill Identification Code		Refuse Mass (10^6 Mg)	Average Refuse Age (yrs)	Landfill Area (hectares)	Average Landfill Depth (meters)	Average Well Depth (meters)	Number of Wells	Landfill Volume (10^6 m^3)	Average Methane Recovery Rate (m^3/min)	Average Methane Recovery Rate Per Unit Mass (m^3/min/10^6 Mg)	Gas End Use
Number	Letter										
1	A	6.35	8.0	34.80	67.06	13.72	45	23.34	55.3	8.71	ELEC.-TURBINE
2	B	6.12	10.0	54.64	25.91	14.33	44	14.15	18.0	2.94	ELEC.-TURBINE
3	C	7.35	10.0	50.99	66.14	23.47	31	33.73	40.0	5.45	ELEC.-TURBINE
4	D	13.79	9.5	56.66	56.39	21.34	111	31.95	98.4	7.14	ELEC.-TURBINE
5	E	0.89	15.0	32.38	45.72	34.14	102	14.80	24.8	2.28	FLARE
6	F	2.40	7.0	40.31	9.83	9.83	68	3.96	16.7	6.97	ELEC.-IC ENGINE
7	G	2.95	10.0	50.59	18.29	12.19	48	9.25	9.7	3.28	BOILER FUEL
8	H	2.72	10.0	22.26	16.76	16.76	107	3.73	11.7	4.32	HIGH BTU
9	I	1.63	7.0	12.14	15.24	15.24	32	1.85	7.7	4.71	FLARE
10	J	5.26	12.0	32.38	21.34	13.72	96	6.91	29.3	5.57	HIGH BTU
11	K	1.81	10.0	27.92	24.38	13.72	39	6.81	11.3	6.22	BRICK KILN FUEL
12	L	2.78	8.5	34.40	10.67	10.67	78	3.67	8.0	2.87	HIGH BTU
13	M	0.96	7.0	14.17	12.19	12.19	51	1.73	10.4	10.87	FLARE
16	P	3.38	5.5	30.35	27.43	18.29	36	8.33	16.0	4.74	ELEC.-TURBINE
17	Q	5.17	10.0	16.19	18.29	18.29	41	2.96	13.8	2.67	FLARE
20	T	9.71	11.0	72.85	18.29	17.37	69	13.32	35.0	3.61	FLARE
21	U	2.60	13.0	26.71	27.43	18.29	56	7.33	27.4	10.52	FLARE
22	V	3.97	12.0	40.47	24.38	24.38	40	9.87	33.2	8.35	FLARE
23	W	2.87	10.7	40.47	21.34	19.81	19	8.63	2.2	0.78	ELEC.-IC ENGINE
24	X	6.21	5.6	109.27	30.48	15.24	23	33.30	17.7	2.85	ELEC.-TURBINE
25	Y	10.65	12.0	74.87	22.86	21.34	43	17.11	20.2	1.90	ELEC.-TURBINE

to provide a rough estimate of the percent of refuse placed in the landfill during certain time periods. For example, the majority of refuse in Landfill 23 was placed between 1981 and 1985, even though the landfill accepted refuse from 1960 through 1986. Rather than basing average age only on landfill open and closure dates, a weighted refuse age of 10.7 years was used to better reflect average refuse age. Landfill 13 is the only landfill for which only open and closure dates were available; the average age for refuse at this site was set at the median between the two dates. The average age for each landfill resulting from the above calculations is shown in Table 4.

Number of Hectares

Table 3 shows that the parameter for hectares for each landfill can be viewed in three different ways. Some landfills (1, 3, 8, 12, 17, and 22) had gas recovery systems that covered the entire fill area. Others (2, 5, 6, 16, and 21) had gas recovery systems that did not cover the entire fill area, but covered a distinct section of the landfill. For these landfills, the hectares shown in Table 4 are only for the hectares covered by the gas recovery system.

It was more difficult to estimate the hectares for the remaining landfills because the gas recovery system covered a portion of the landfill that was not distinctly separate from other sections of the landfill. For example, Landfill 11 had a second gas recovery system that is no longer operating. The hectares presented in Table 4 for Landfill 11 are only those covered by the currently-operating gas recovery system, for which gas flow data were gathered. It is impossible to determine, however, whether or not gas was migrating from the area where the second system was in place. Another example where the hectares in the gas recovery area were difficult to delineate is Landfill 7, which has some steep slopes that do not have wells. It is possible that some gas is escaping to the atmosphere from these slopes.

Landfill Depth

Landfill depth is included in Table 3 because it may be useful when evaluating hectares and well depth as parameters. Several of the landfills had relatively steep side slopes and were pyramid shaped. Landfills 8 and 9 are tall, but were built in benches so there are no large, steep slopes that may limit well placement. The remaining landfills were uniform in depth so that no well placement problems were caused by landfill design. Again, Table 4 shows the value of this parameter for each landfill.

Well Depth

For most of the landfills visited, well depth is directly related to fill depth. For Landfills 1, 3, 4, 7, 8, and 11, however, this may not be true. Except for Landfill 8, these are the landfills that are pyramid shaped. Landfill 8 is unique because the wells were not drilled by the current operator of the gas recovery system. The current operator plans to drill replacement wells deeper than the existing wells. In fact, in most cases, landfill personnel indicated that future wells will be drilled deeper than existing wells in order to maximize gas recovery. At Landfill 11, some of the older wells were covered with refuse. Landfill 12 is the only landfill visited that had horizontal trench wells in addition to vertical wells--all of the other landfills had only vertical wells. Table 3 shows whether well depth is related to fill depth and Table 4 lists the actual well depths for each landfill.

Number of Wells

The parameter for the number of wells for most landfills is the total number of active wells (excluding abandoned or capped wells). For Landfills 2, 13, 22, 23, 24, and 25, however, only wells considered "high flow" were included in the analysis, as shown in Table 3. The remaining low-flow wells were not included because they were installed to eliminate gas migration, and they produce very little gas. At Landfill 22, for example, wells excluded from the analysis were not even placed in refuse. Landfill 8 is once again unique because the previous operator of the gas recovery system installed more wells than the current operator feels is necessary. Table 4 lists the number of wells for each landfill.

Climate Data

Monthly average temperature and total rainfall data were obtained from the Southeast Regional Climate Center for a cooperative National Weather Service (NWS) station nearest each landfill. The monthly average temperature and total rainfall values were summed and converted to average annual temperature and total annual rainfall values for each year. The annual temperature and rainfall values for the years of refuse acceptance were then averaged for comparison to landfill data for each landfill.

In addition to the daily weather data, the 30-year averages of annual mean temperature (NOAA, 1985), mean dewpoint temperature (NOAA, 1979), and annual rainfall (NOAA, 1985) were obtained for the NWS stations. These 30-year averages of temperature and rainfall are referred to as the 'normal' values.

Table 5 shows the temperature and rainfall averages and the time periods from which they were calculated, as well as the 30-year normals for each landfill. The average annual temperatures calculated from the refuse acceptance time period were usually fairly close to the normals; however, the rainfall normals sometimes varied considerably from the refuse acceptance period averages.

TABLE 5. SUMMARY OF CLIMATIC DATA FOR THE LANDFILLS

Landfill	Weather Average Period	Annual Climate Averages (during refuse acceptance period) Average Temp. (°C)	Maximum Temp. (°C)	Minimum Temp. (°C)	Annual Rainfall (cm)	30-Year Annual Averages Average Temp. (°C)	Average Dewpoint (°C)	Annual Rainfall (cm)
1	1955 to 1989	7.31	13.13	1.49	75.34	7.50	3.33	73.05
2	1968 to 1982	9.28	14.93	3.53	94.34	9.28	3.89	90.47
3	1970 to 1988	12.59	17.58	7.61	109.19	12.39	6.11	105.21
4	1971 to 1988	24.63	29.68	19.58	140.87	23.94	18.33	155.91
5	1951 to 1989	17.29	25.33	9.26	42.16	17.11	10.00	43.23
6	1975 to 1989	16.14	23.94	8.34	47.40	16.17	8.33	45.44
7	1972 to 1989	15.10	21.23	8.97	107.77	15.00	8.89	106.07
8	1973 to 1987	16.43	21.98	10.89	126.29	16.22	10.00	123.47
9	1979 to 1989	17.99	24.42	11.56	148.31	18.11	12.22	134.16
10	1962 to 1989	16.59	22.74	10.43	137.29	16.78	10.56	138.48
11	1962 to 1989	18.06	24.61	11.52	114.02	18.17	11.11	113.94
12	1969 to 1983	12.21	17.68	6.73	125.37	12.17	6.67	122.94
13	1980 to 1988	10.67	16.49	4.86	103.78	11.06	6.67	104.32
16	1976 to 1989	9.31	15.26	3.35	97.64	9.50	2.78	102.01
17	1952 to 1989	8.31	13.14	3.47	122.00	8.22	1.67	120.90
20	1967 to 1989	9.23	14.47	3.99	82.37	9.22	3.89	78.66
21	1971 to 1986	9.13	14.41	3.84	83.24	9.22	3.89	78.66
22	1970 to 1988	7.24	12.46	2.03	73.18	7.06	1.11	66.95
23	1958 to 1986	10.06	17.79	2.32	39.01	10.17	-2.22	38.89
24	1972 to 1989	19.01	24.72	13.29	88.90	18.89	11.11	74.80
25	1970 to 1989	9.53	14.77	4.29	94.62	9.56	3.89	84.68

Dewpoint temperature was included in this analysis because it is a readily available variable that provides a better measure of moisture availability than either temperature or precipitation alone. Better composite variables could be chosen (such as actual evapotranspiration), but calculating these values was beyond the scope of this project.

STATISTICAL ANALYSES

Data Reduction

In order to reduce the number of predictive variables tested, several summary descriptive analyses were performed. The first analysis examined correlations between possible CH_4 recovery rate predictors and CH_4 recovery rates and also between the many landfill parameters. Correlation is a measure of the degree to which variables vary together or a measure of the intensity of association. The resulting correlation coefficient, r, is bounded below by -1.0 and bounded above by +1.0. A correlation coefficient of +1.0 or -1.0 indicates that one variable can be expressed exactly as a linear function of another variable, depending on whether the two variables are directly or inversely related, respectively. When the correlation is small, r is near zero. Correlation is calculated as follows:

$$r_{xy} = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sqrt{(\Sigma x - \bar{x})^2 * \Sigma (y - \bar{y})^2}}$$

where: $\bar{x}$ and $\bar{y}$ are the sample means of x and y.

Table 6 shows the Pearson correlation coefficients between average CH_4 recovery rates and CH_4 recovery rates per unit mass with average and normal weather data, as well as other landfill parameters for the 21 landfills. The significance level of the correlation value is determined by calculating the probability that the true value is equal to zero.

Three CH_4 recovery rate correlations--mass of refuse, landfill volume, and landfill depth--were significant at the 95-percent confidence level. This means that a 5% chance exists that a correlation this high could have happened by chance. A fourth CH_4 recovery rate correlation--number of wells--was significant at the 90-percent confidence level. None of the CH_4recovery rate per unit mass correlations were significant. The correlation coefficients for the significant CH_4 recovery rate correlations show a moderate amount of correlation and reflect expected relationships between the CH_4 recovery rate and some of the landfill parameters.

TABLE 6. CORRELATION COEFFICIENTS OF METHANE FLOW VARIABLES WITH LANDFILL PARAMETERS AND SUMMARIZED WEATHER DATA

	Dependent Variables	
Independent Variables	Average Methane Recovery Rate	Average Methane Recovery Rate per Unit Mass
Average Annual Temperature[a]	0.27	-0.07
Normal Annual Temperature	0.24	-0.06
Average Annual Rainfall[a]	0.14	0.07
Normal Annual Rainfall	0.23	0.10
Mean Age of Refuse[b]	0.13	-0.12
Number of Wells	0.40[c]	0.09
Refuse Mass	0.71[d]	-0.25
Mean Depth of Landfill	0.73[d]	0.18
Volume of Landfill	0.66[d]	-0.06
Mean Well Depth	0.29	-0.19

[a] Average calculated from period of refuse acceptance at each landfill.

[b] Mean age of refuse based on recovery data date.

[c] Correlation coefficient significant at 90 percent confidence level.

[d] Correlation coefficient significant at 95 percent confidence level.

It is likely that many of the landfill parameters are correlated. For example, the amount of refuse placed in a landfill (refuse mass) should correspond to the depth of the landfill. In fact, refuse mass was found to be the only landfill parameter that was significantly correlated with all the other landfill parameters. Table 7 shows the Pearson correlation coefficients between refuse mass and the other landfill parameters. Table 8 shows the Pearson correlation coefficients between the 30-year averages and refuse acceptance period averages for the weather variables.

Scatter Plots of Selected Variables

Visual inspection of data plots is a useful method of identifying functional relationships. Scatter plots* for two correlated variables show the general relationship or trend between the two variables and how well defined that relationship is. Scatter plots for CH_4 recovery rate versus landfill depth, refuse mass, and landfill volume are shown in Figures 1, 2, and 3, respectively.

Although no linear correlations between CH_4 per ton and the independent variables were found, nonlinear relationships are possible. Methane flow per ton was plotted against refuse age (Figure 4), average annual rainfall (Figure 5), and normal annual dewpoint temperature (Figure 6). No functional relationships could be identified from these plots, although the dewpoint temperature plot shows a slight linear trend. Figure 7 shows the location of each site on a grid of temperature and precipitation normals. The sample population is fairly representative of the range of climates within the continental United States; however, the more extreme climates are underrepresented.

MODEL DEVELOPMENT

The final step in this study was to develop the simplest model that could be used to predict CH_4 emissions from landfills. Because information on refuse mass is readily available on a global scale, the preferred method for predicting CH_4 was based on this variable, although other variables were also considered.

Based on the preliminary data analyses (see Table 6), a linear model appeared to be sufficient to model CH_4 recovery rate. The scatter plots of CH_4 per ton did not reveal any obvious functional relationships. However, a linear trend seemed to be present in the climate variable data. The relationship between CH_4 generation and climate is a strongly held belief among gas recovery modelers. Therefore, some regression analysis were also attempted for these variables.

*For clarity, letters are used to identify landfills in plots. See Table 4 to match letters to number identification.

TABLE 7. CORRELATION COEFFICIENTS BETWEEN LANDFILL PARAMETERS AND LANDFILL REFUSE IN PLACE

Independent Variables	Dependent Variable Refuse Mass
Refuse Age	0.38[a]
Number of Hectares	0.54[b]
Landfill Depth	0.58[b]
Well Depth	0.58[b]
Number of Wells	0.37[a]
Landfill Volume	0.69[b]

[a] Correlation coefficient significant at 90 percent confidence level.

[b] Correlation coefficient significant at 95 percent confidence level.

TABLE 8. CORRELATION COEFFICIENTS BETWEEN WEATHER VARIABLES

	Normal Rainfall	Average Rainfall	Normal Temperature	Average Temperature	Normal Dewpoint
Normal Rainfall	1.00[a]				
Average Rainfall	0.98[a]	1.00[a]			
Normal Temperature	0.39[b]	0.36	1.00[a]		
Average Temperature	0.40[b]	0.36	0.99[a]	1.00[a]	
Normal Dewpoint	0.54[a]	0.52[a]	0.94[a]	0.94[a]	1.00[a]

[a] Correlation coefficient significant at 95 percent confidence level

[b] Correlation coefficient significant at 90 percent confidence level

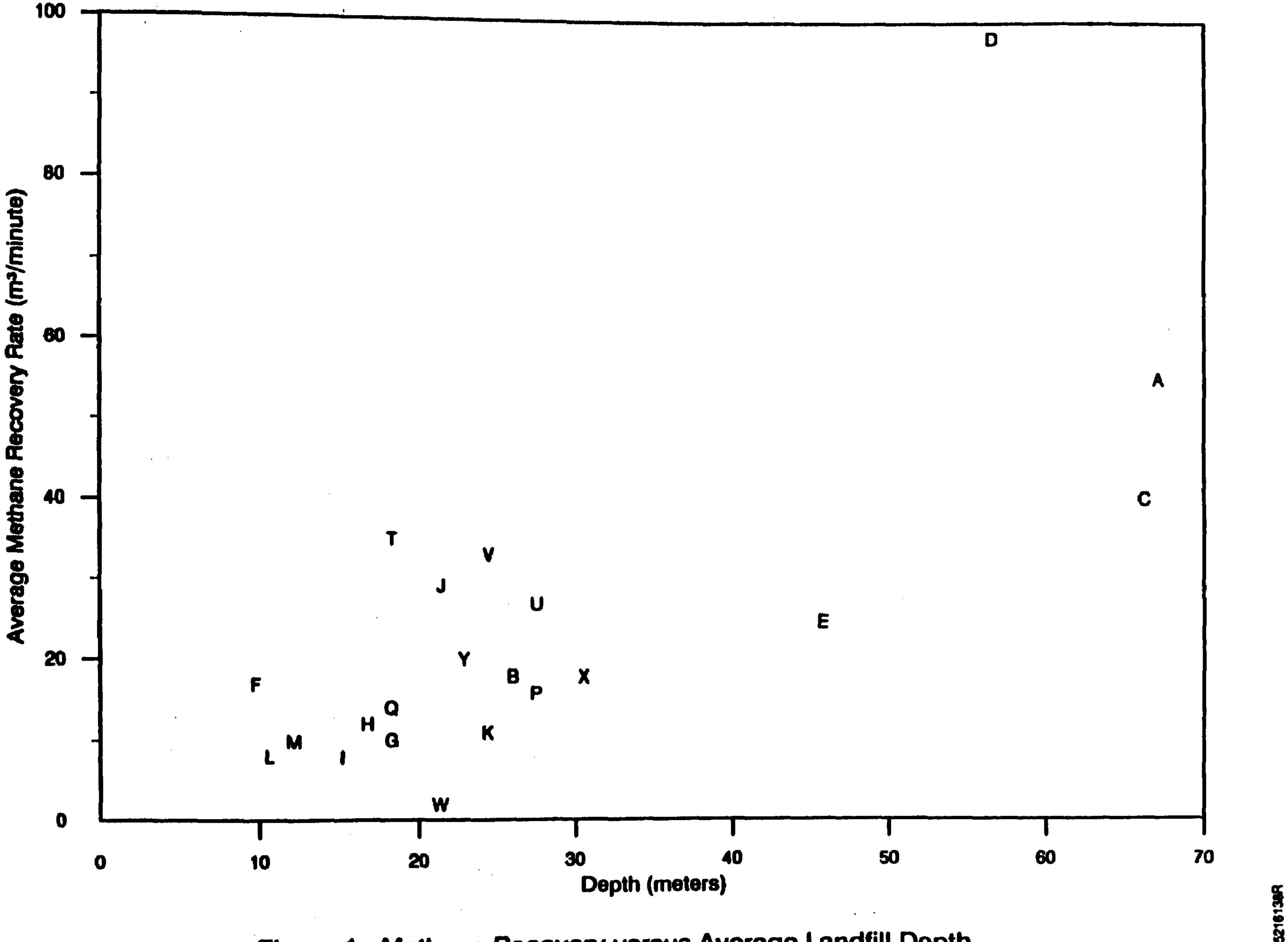

Figure 1. Methane Recovery versus Average Landfill Depth

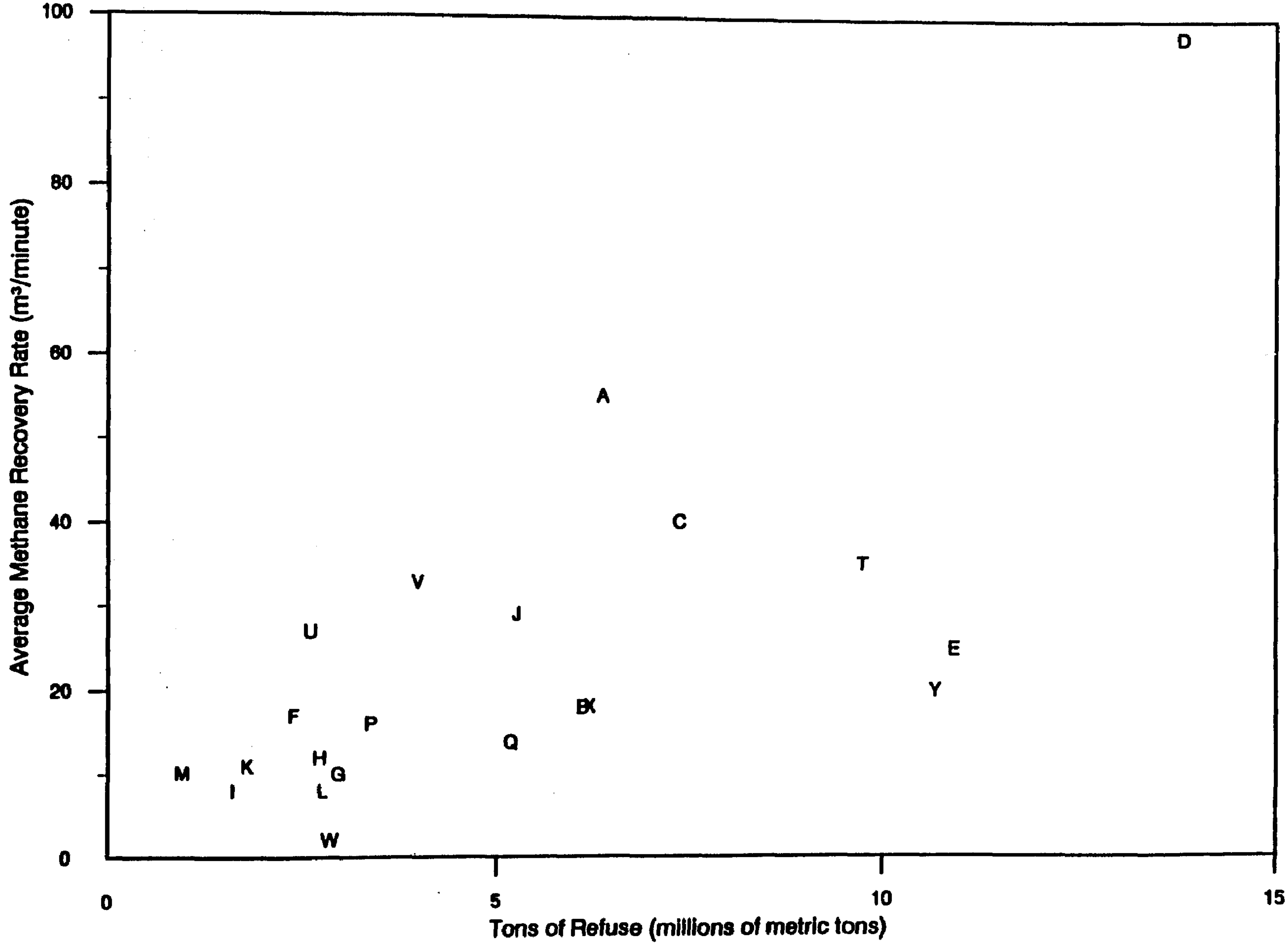

Figure 2. Methane Recovery versus Refuse Mass

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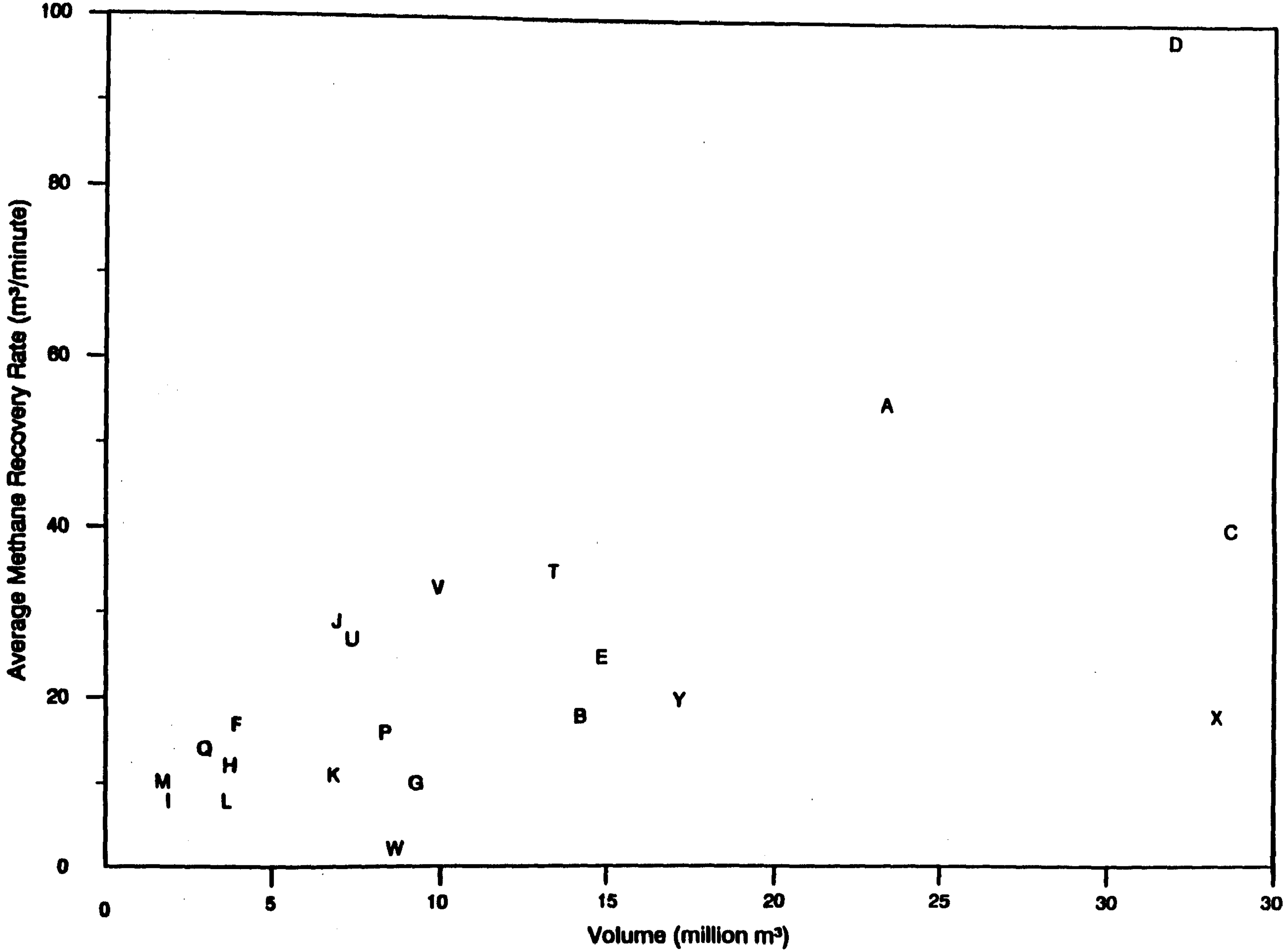

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Figure 3. Methane Recovery versus Landfill Volume

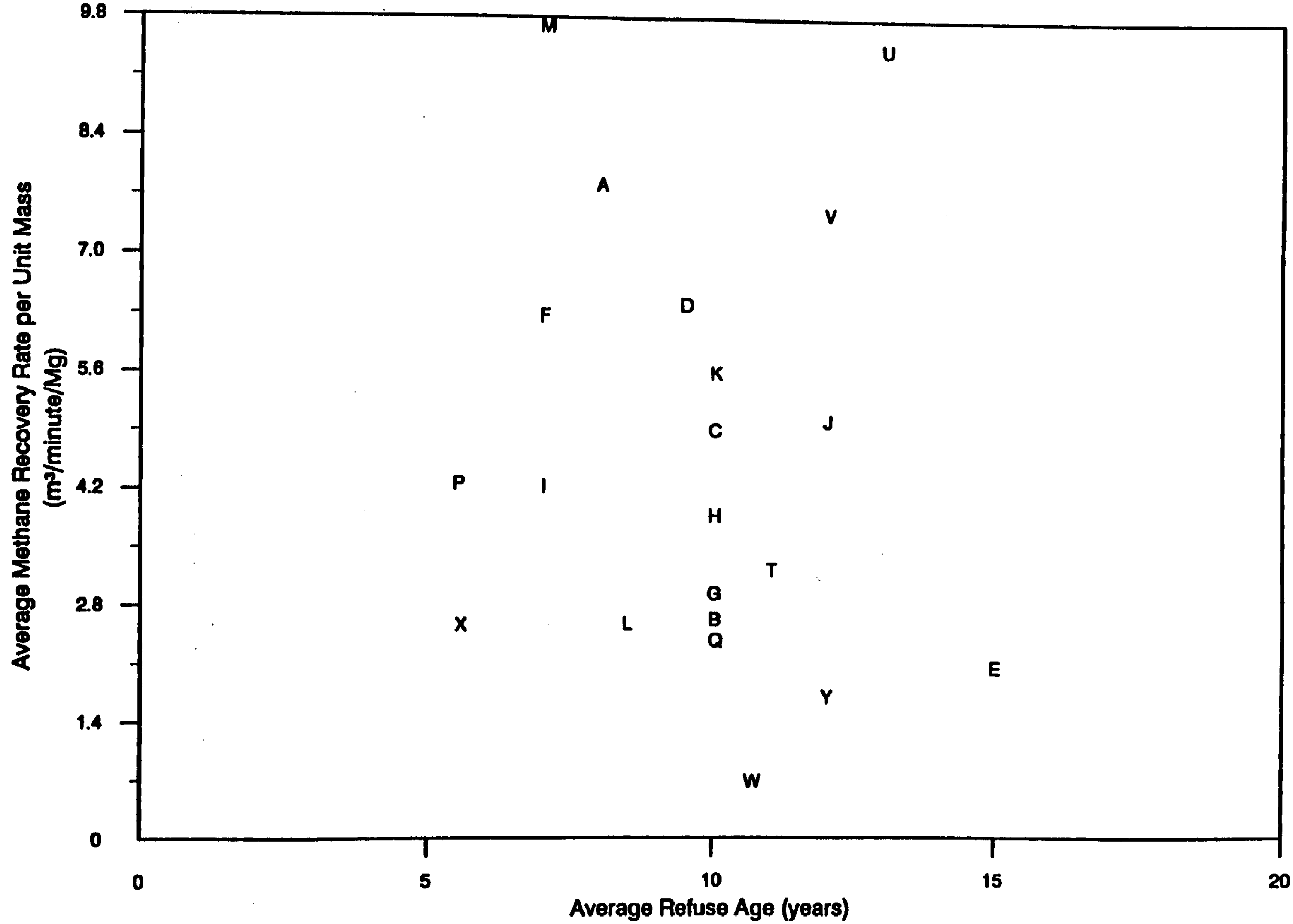

Figure 4. Methane Recovery Rate per Unit Mass versus Refuse Age

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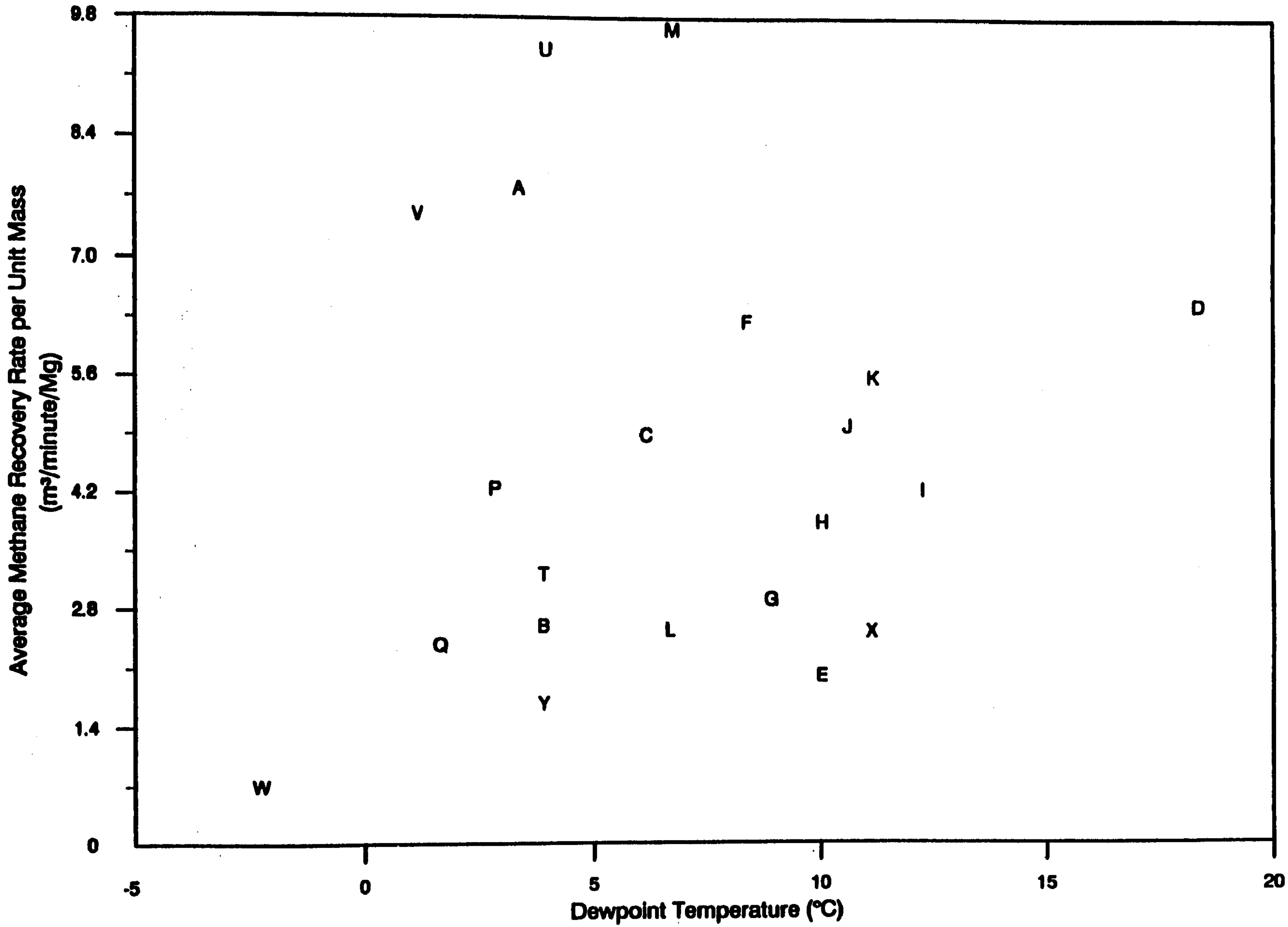

Figure 5. Methane Recovery per Unit Mass versus
Normal Annual Dewpoint Temperature

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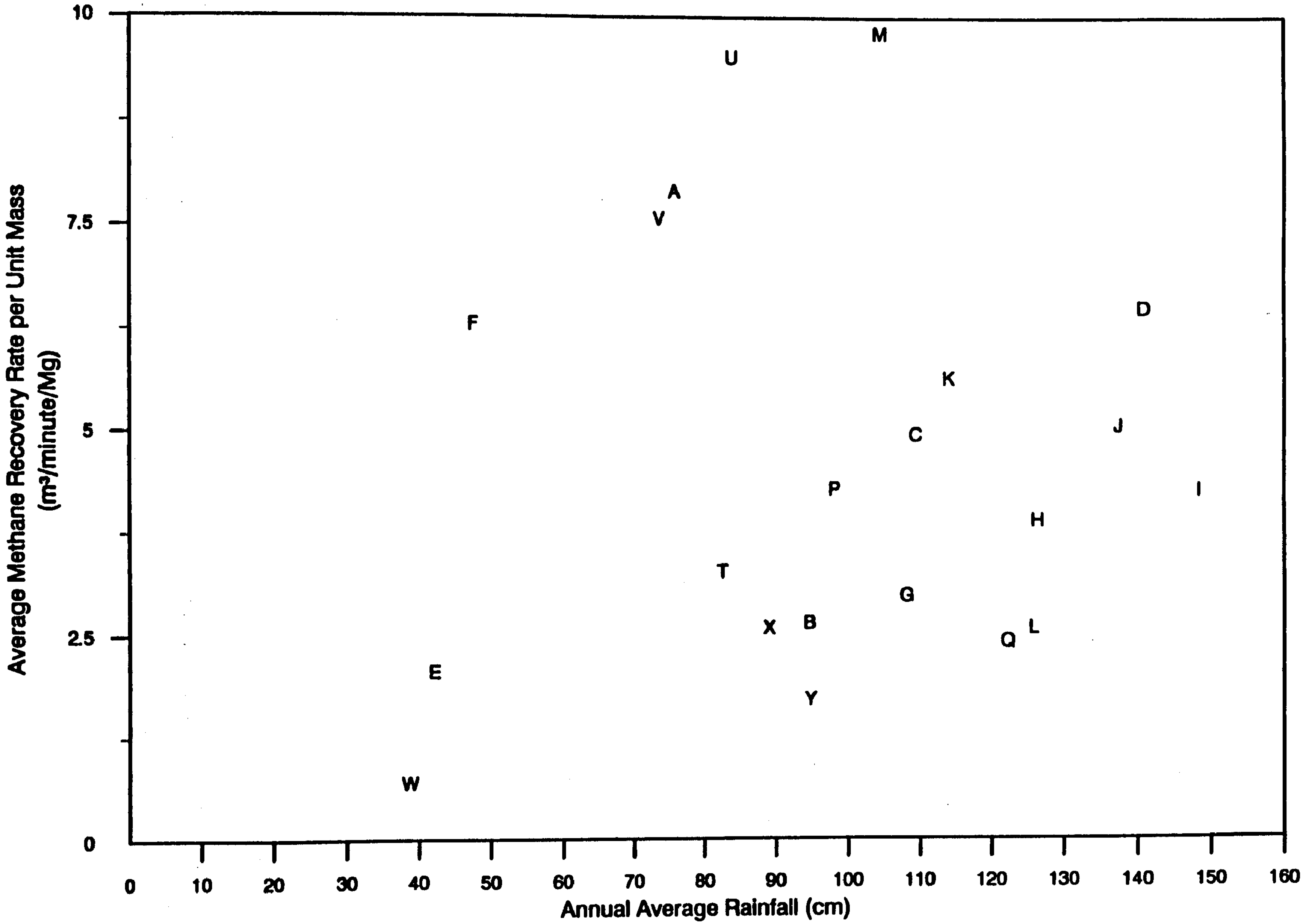

Figure 6. Methane Recovery Rate per Unit Mass versus Annual Average Rainfall

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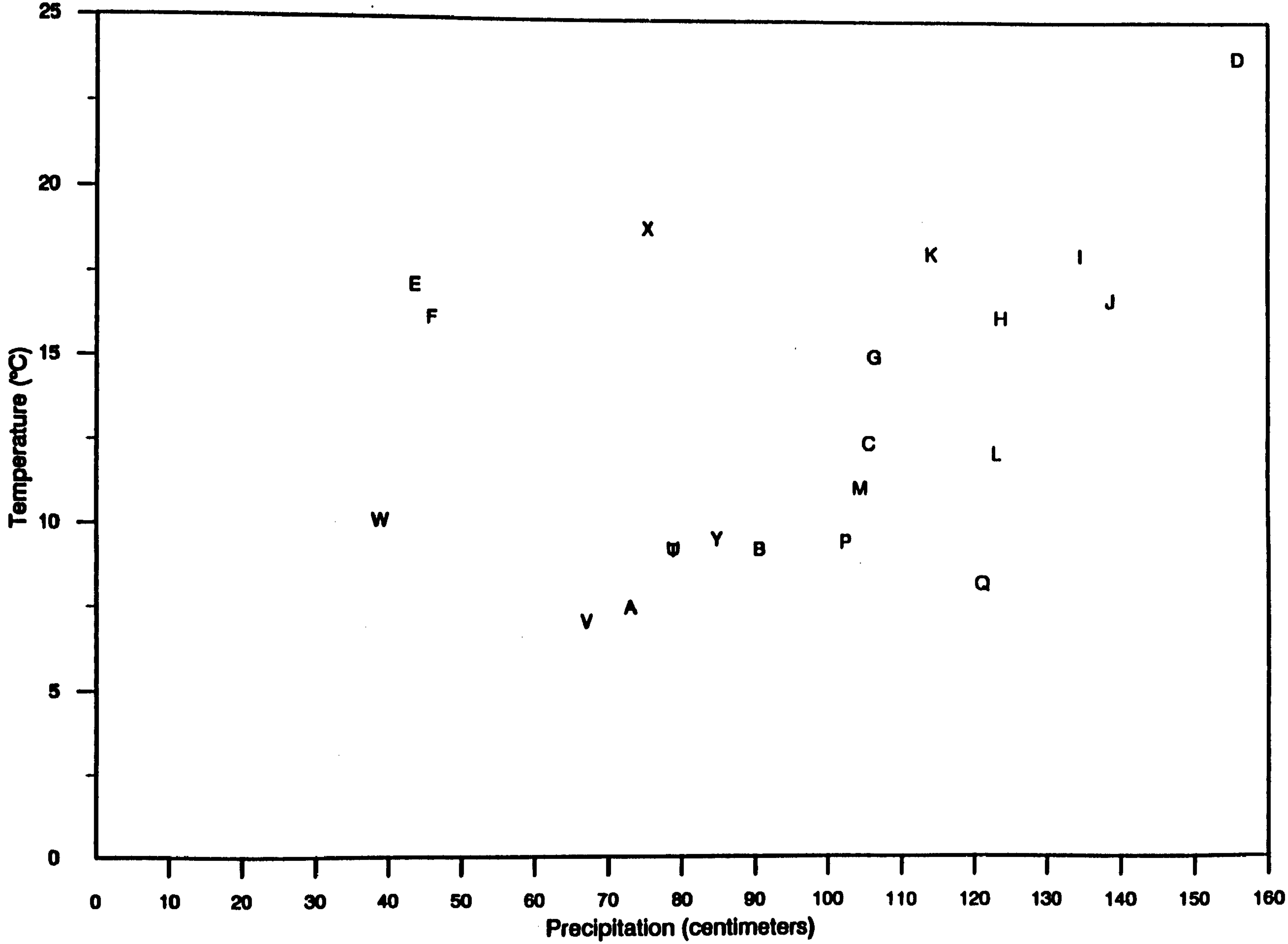

Figure 7. Climatic Normals for the Landfills

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Regression Analysis

The SAS® (Statistical Analysis System) regression procedure (PROC REG) was used to generate regression statistics for various models. Two general models were used--one to predict CH_4 recovery rate, the other to predict CH_4 recovery rate per unit mass. Selection of variables for the regression models was based on the results of the correlation and scatter plots summaries discussed above. In addition, the data distribution of potential regression variables was examined for normality. Although most variables were not normally distributed, the distributions were not so far off as to warrant data transformations.

Landfill Air Emissions Estimation Model

In order to validate the statistical model, its performance was compared to that of the U.S. EPA's Landfill Air Emissions Estimation Model (Pelt et al., 1990), which is a deterministic computer model that was developed for regulatory purposes. Assuming that the refuse has been accepted at the same annual rate over time (i.e., all submasses are of the same size), the model equation is as follows:

$$Q_{CH4} = L_0 R \{\exp(-kc) - \exp(-kt)\}$$

where:

Q_{CH4}	=	methane generation rate at time t, ft^3/yr*
L_0	=	potential methane generation capacity of the refuse, ft^3/Mg refuse
R	=	average annual refuse acceptance rate during active life, Mg/yr
k	=	methane generation rate constant, 1/yr
c	=	time since landfill closure, year (c = 0 for an active landfill)
t	=	time since the initial refuse placement, year

The Landfill Model methodology is based on the Scholl Canyon model (EMCON, 1982) which is a first order decay equation. Because site-specific characteristics are required as model input, the Landfill Model is impractical for use on a global scale.

Two critical input parameters, k and L_0, are not known for individual sites. The CH_4 generation rate constant, k, is assumed to be a function of moisture content, nutrient availability, pH, and temperature. The default value of 0.02 yr^{-1} was used for k. The CH_4 generation potential, L_0, is an estimate of the total amount of CH_4 that will be produced by a given mass of refuse as the refuse

*Conversion chart for metric/U.S. equivalent is provided on page 91.

decomposes. L_0 is partly a function of refuse composition, but it is mitigated by landfill characteristics. The model default is 298 m^3 CH_4/Mg refuse.* Published landfill waste CH_4 recovery potentials for individual sites in the U.S. range from 50 to 162 m^3/Mg (Ham and Barlaz, 1987; Augenstein and Pacey, 1990). The published ranges were included in this study since the model default waste CH_4 potential was designed specifically for regulatory national impacts assessment. Therefore, three sets of model runs were performed using L_0 values of 50, 162, and 298 m^3/Mg in order to determine the sensitivity of the model to L_0 values.

*The model actually uses units of ft^3/Mg, so default L_0 specified in the model is 8120 ft^3 CH_4/Mg refuse. Metric units are used in text for consistency.

SECTION 4

RESULTS AND DISCUSSION

REGRESSION MODELS

Table 9 shows the results of several linear regression models. For most of the models that use a single landfill parameter, the intercept term was found to be insignificant. This was expected because when the mass of refuse is zero, no CH_4 is produced. Therefore, a second regression model was calculated which forced the line through the origin (e.g., a no-intercept model). It should be noted that the R^2 term in a no-intercept model cannot be interpreted in the same manner as in a model with an intercept (Rawlings, 1988); therefore, both intercept and no-intercept models for the same variable are shown for several cases in Table 9.

Landfill and Waste Variables

From the regression model results shown in Table 9, landfill depth appears to be the best predictor of CH_4 emissions ($P = 0.0002$, $R^2 = 0.53$). However, refuse mass is very nearly as good ($P = 0.0003$, $R^2 = 0.50$). Depth and tons were shown to be linearly correlated (Table 7). This is not surprising, as larger landfills tend to be deeper and hold more mass. A bivariate regression of CH_4 emissions on both refuse mass and landfill depth gave a better R^2 than any of the univariate models as show in Table 9. None of the regressions on climate variables were significant and the R^2 values were very low (near zero). Therefore, the best empirical model based on these data for predicting CH_4 recovery is:

$$CH_4 = 2.06 + 0.15$$

where:

CH_4 = methane flow rate (m^3/min);

W = mass of refuse (10^6 Mg); and,

D = landfill depth (m).

However, the purpose of this analysis is to develop a model for predicting CH_4 emission for a large population of landfills. Landfill depth is not known for most landfills, and in many cases, is difficult to estimate. Because waste production data are much more widely available than landfill depth data on a

TABLE 9. LANDFILL REGRESSION SUMMARY

Regression Model*	Prob > F	R^2	b0	b1	b2	Comments
methane = depth	0.0002	0.53	-1.09	9.13E-1	--	intercept not significant
methane = depth	0.0001	--	--	8.84E-1	--	no intercept in model
methane = 10^6 Mg	0.0003	0.50	1.89	4.27	--	intercept not significant
methane = 10^6 Mg	0.0001	--	--	4.52	--	no intercept in model
methane = volume	0.0011	0.44	7.38	1.37E-6	--	intercept not significant
methane = volume	0.0001	--	--	1.73E-6	--	no intercept in model
methane = wells	0.0701	0.16	6.87	3.06E-1	--	model fit & wells borderline; intercept not significant
methane = wells	0.0001	--	--	4.07E-1	--	no intercept in model
methane = depth + 10^6 Mg	0.0001	0.65	-5.96	2.36	0.18	intercept not significant
methane = depth + 10^6 Mg	0.0001	--	--	2.056	0.15	no intercept in model
methane = 10^6 Mg + mean rain	0.0011	0.53	-10.31	4.32	1.22E-1	intercept & mean rain not significant
methane = 10^6 Mg + mean temp	0.0015	0.52	-4.67	4.11	5.61E-1	intercept & mean temp not significant
methane = 10^6 Mg + dewpoint 30	0.0009	0.54	-2.98	3.97	9.49E-1	intercept & dewpoint 30 not significant
methane/Mg = mean rain	0.7688	0.00	4.48	6.19E-3	--	poor model fit; mean rain not significant
methane/Mg = mean temp	0.7607	0.01	6.64	-4.21E-2	--	poor model fit; mean temp not significant
methane/Mg = dewpoint 30	0.6127	0.01	4.61	7.03E-2	--	poor model fit; dewpoint 30 not significant

*Methane = b0 + b1 * variable 1 + b2 * variable 2.

global basis, the no-intercept regression of CH_4 on refuse mass is the better choice of model. This model is:

$$CH_4 = 4.52W$$

where: CH_4 and W are the same as defined above.

Figure 8 shows the regression line for CH_4 recovery rate as a function of refuse mass. The 95-percent confidence interval of the regression coefficient is shown by the dashed lines.

Average refuse age was not shown to have a significant effect on the CH_4 recovery rate. To evaluate the effect of refuse age in more detail, the mass of refuse for each landfill was assigned to three age groups: 1 to 10 years, 11 to 20 years, and greater than 20 years. A multivariate regression of CH_4 recovery rate on refuse mass in the three age groups was calculated. No single age group was significant, although the F value of 4.194 for the overall model was significant (Prob > F = 0.0164). The significance level is higher for the wastes between 11 and 20 years of age, as is shown in Table 10. Although not significant, the somewhat better correlation of CH_4 recovery rates with wastes older than 10 years may be indicative of the generation time. Generation times of 20 to 30 years are generally assumed for landfill gas recovery (Augenstein and Pacey, 1990). This analysis suggests that generation times are at least 20 years if not longer.

Climate Variables

No other variables were found to have any effect on CH_4 production. In particular, no functional model linking CH_4 production to climate variables was found. This does not mean that climate is not important. Given the unexplained variability in the regression of CH_4 recovery on refuse and depth, some aspect of climate may actually play a controlling role. However, as shown in this study, site-specific factors and difficulties in accurately quantifying key parameters confound the problem.

The effects of climate--particularly precipitation--are thought to be significant on gas generation and recovery by many landfill experts (e.g., EMCON, 1982; Augenstein and Pacey, 1990). Although the cover on sanitary landfills is designed to be impermeable, cracks in the cover are common and may allow some infiltration of water. Also, during the period when waste is being deposited in landfills, no barriers to precipitation exist. When the cap is put in place, that moisture will be trapped below the cover.

For these reasons, it was thought that landfills in very wet climates should show greater methane generation than those in dry climates. However, no statistically significant correlations were found in this

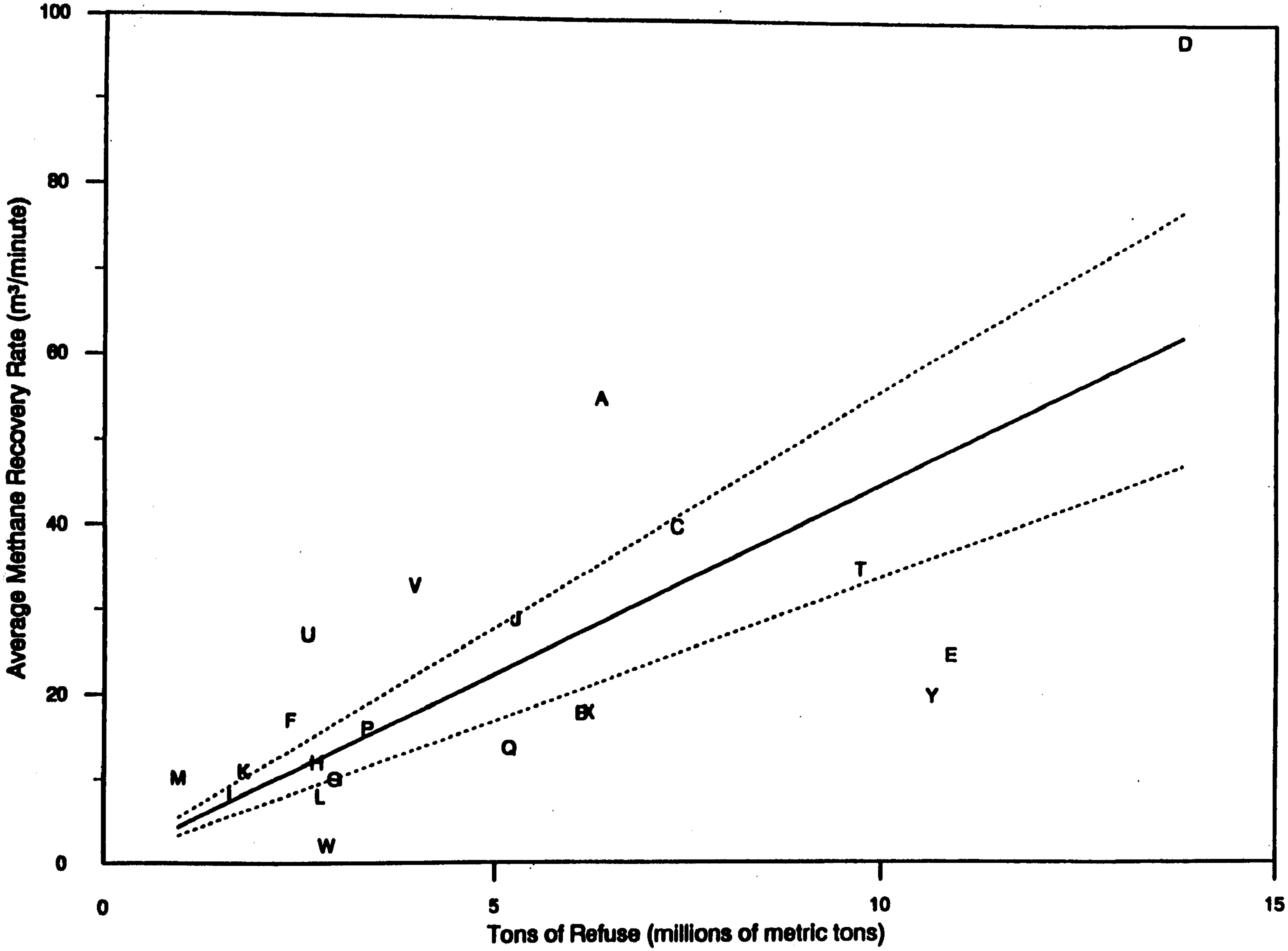

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Figure 8. Methane Recovery Regression with 95% Confidence Interval of Regression Coefficient

TABLE 10. SIGNIFICANCE OF REFUSE AGE

Refuse Age Category (years)	Average Mass of Refuse in Category (10^6 Mg)	Total Mass of Refuse in Category (10^6 Mg)	T*	Prob > |T|**
1-10	2.78	58.28	0.281	0.782
11-20	2.01	42.25	1.598	0.129
>20	3.74	78.52	1.328	0.202

* Student's T value is calculated by dividing the parameter estimate (or slope) for the variable by the standard error. The null hypothesis that the parameter is zero is tested.

**The probability of a T statistic larger than the one actually obtained occuring if the parameter estimate (slope) is actually zero. The smaller the probability, the greater the likelihood that the variable exerts a strong effect on the dependent variable.

study. The high degree of variability in these data makes it impossible to detect any but very strong correlations (such as the effect of refuse mass).

One method for removing any confounding effects in a multivariate analysis is the use of partial regression leverage plots (Rawlings, 1988). The residuals of a regression model measure the discrepancy between the model predictions and the data. The residual for each landfill, i, is calculated by:

$$e_i = Y_i - \hat{Y}_i$$

where:

Y_i	=	the actual value of landfill i, and
$\hat{Y}_i$	=	the predicted value for landfill i.

The residuals from the regression of CH_4 recovery rate on refuse mass and landfill depth were plotted against the residuals from a regression of mean rainfall on refuse mass and depth. The regression of these residuals is not significant (F = 2.496, Prob > F = 0.13); however, this is much closer to significance than the regression of CH_4 recovery rate per ton on mean rain (Prob > F = 0.77, see Table 9). Furthermore, the trend is positive (slope of regression is 0.35) which suggests a positive correlation between methane recovery and annual precipitation. Unless an additional confounding variable can be identified and quantified, no statistically significant relationship between CH_4 recovery and climate can be established with these data. However, a larger data set may allow detection of climate effects even if no other independent variables are included.

EFFECT OF DATA QUALITY ON ANALYSIS

The greatest data uncertainty concerned the refuse itself. As shown in Table 3, refuse mass in place was sometimes difficult to quantify accurately. The best data came from landfills that weighed incoming refuse at the gate (and had done so from the day they opened). However, not all landfills had scales; these sites generally had volume estimates, which had to be converted to mass. Moreover, the quality of recordkeeping varied widely from site to site. Despite these concerns, refuse mass was the most reliable of the site capacity variables.

Landfill depths and acreage (both of which were used to calculate volume) were less reliable. Depth at some sites was quite variable; acreage was unreliable because the topography of sites ranged from very flat to pyramid shaped. Therefore, it is not surprising that landfill volume is a poorer predictive variable (as measured by significance level and R^2 value) than tonnage.

COMPARISON TO LANDFILL MODEL

The results of the Landfill Model runs are shown in Table 11. Also shown are the CH_4 emissions predicted by the regression model and the actual mean CH_4 recovered annually. The year for which the CH_4 values apply is shown in the second column.

The ratio of the predicted value to the true mean for each model run was used to compare model performance. A ratio of 1 shows perfect agreement between the predicted value and the actual value. The ratios are shown in Table 12. The Landfill Model with L_0 of 50 m^3/Mg (Run 1) tends to underpredict (ratio less than 1). When L_0 is set to 162 m^3/Mg, the model gives the best overall result (the mean ratio of 1.07 approximates 1). As this analysis shows, the Landfill Model is very sensitive to L_0. No one value of L_0 is necessarily the best; for some landfills, the closest agreement was given by the default L_0 (sites 1, 4, 11, 13, 21, and 22). The lowest L_0 was best only for two sites (23 and 25). For the remainder of the landfills, the closest agreement is given by an L_0 of 162 m^3/Mg.

The regression model performs reasonably well compared to the Landfill Model. The regression model's mean ratio of 1.39 falls between Landfill Model runs 2 and 3. It also produces slightly more variable results, as shown by comparing CVs (78.8 percent for the Landfill Model, 89.3 percent for the regression model). Thus, the regression model represents the considerable variability of the sample population and should provide a good estimate of the expected CH_4 recovery rate from U.S. landfills as a group.

One particular advantage of using this statistical model is that only one variable is required. Furthermore, it is relatively easy to add new observations and further refine the model, as only average CH_4 recovery and refuse mass are required. The confidence limits of the regression coefficient can be used to bound estimated CH_4 emissions. The upper and lower 95-percent confidence limits are 6.52 and 2.52 m^3 CH_4/min/Mg refuse, respectively.

TABLE 11. ACTUAL AND PREDICTED METHANE VALUES

Site Number	Year	Actual Methane (m^3/min)	Landfill Air Emissions Estimation Model[a] (m^3/min)			Regression Model (m^3/min)
			Run 1	Run 2	Run 3	
1	1989	55.3	8.83	22.08	40.65	28.67
2	1990	18.0	8.73	21.83	40.19	27.71
3	1990	40.0	11.37	28.44	52.35	32.88
4	1990	98.4	21.54	53.90	99.18	60.06
5	1990	24.8	14.34	35.85	66.01	47.81
6	1989	16.7	4.01	10.02	18.45	11.98
7	1990	9.7	4.50	11.25	20.71	14.31
8	1989	11.7	4.37	10.94	20.14	13.36
9	1991	7.7	2.78	6.96	12.82	8.76
10	1990	29.3	7.46	18.66	34.35	24.08
11	1990	11.3	2.57	6.43	11.85	9.53
12	1987	8.0	4.29	10.72	19.73	13.59
13	1990	10.4	1.64	4.10	7.54	5.91
16	1990	16.0	5.28	13.21	24.32	16.15
17	1990	13.8	6.77	16.93	31.16	23.69
20	1990	35.0	14.30	35.77	65.85	42.84
21	1990	27.4	3.98	9.95	18.32	12.85
22	1989	33.2	6.27	15.69	28.88	18.64
23	1990	2.2	3.89	9.72	17.89	13.97
24	1990	17.7	9.47	23.68	43.59	28.06
25	1991	20.2	16.68	41.72	76.78	46.82

[a] Run 1 at L_0 = 50 m^3/Mg

Run 2 at L_0 = 162 m^3/Mg

Run 3 at L_0 = 298 m^3/Mg (model default)

TABLE 12. COMPARISON OF MODEL PERFORMANCES

Site Number	Landfill Air Emissions Estimation Model Run 1 Pred./Actual	 Run 2 Pred./Actual	 Run 3 Pred./Actual	Regression Model Pred./Actual
1	0.16	0.40	0.73	0.52
2	0.48	1.21	2.23	1.55
3	0.28	0.71	1.31	0.83
4	0.22	0.55	1.01	0.62
5	0.58	1.44	2.66	1.95
6	0.24	0.60	1.10	0.73
7	0.46	1.16	2.14	1.50
8	0.37	0.93	1.71	1.15
9	0.36	0.90	1.67	1.15
10	0.25	0.64	1.17	0.83
11	0.23	0.57	1.05	0.85
12	0.54	1.34	2.47	1.72
13	0.16	0.39	0.72	0.57
16	0.33	0.82	1.52	1.02
17	0.49	1.23	2.26	1.73
20	0.41	1.02	1.88	1.24
21	0.15	0.36	0.67	0.47
22	0.19	0.47	0.87	0.57
23	1.74	4.35	8.00	6.32
24	0.54	1.34	2.46	1.60
25	0.82	2.06	3.79	2.34
Mean	0.43	1.07	1.97	1.39
Standard Deviation	0.34	0.85	1.56	1.24

SECTION 5

SUMMARY AND CONCLUSIONS

The research program described in this report and in the pilot study report (Campbell et al., 1991) had as its goal the development of an empirical model of CH_4 emissions from landfills. It was successful in meeting its major objectives, but much remains to be learned. Some of the successes and limitations of the research methodology are discussed below.

EVALUATION OF THE METHODOLOGY

The pilot study included some gas sampling and analysis procedures that were not used in the rest of the program. The cost of gas sampling at each landfill would have limited the number of sites that could have been included in the study. In order to get as large a sample size as possible, only data available from landfill personnel were used. This approach is admittedly subject to error, but the pilot study showed that CH_4 measurements from on-site monitors were reasonably accurate (generally within 10 percent of the reference method). Moreover, no methods could be found to measure the variables that were most subject to error (landfill size, refuse age, and refuse mass in place). Early in the program, an intensive sampling effort involving analysis of core samples from the landfills was considered; however, the expense of this procedure would have severely limited the sites that could be included. Furthermore, the usefulness of the results to a global emissions model was doubtful.

The field program required the cooperation of both landfill operators and gas recovery operators. At some sites, local government officials were also involved. The logistics of arranging and completing site visits consumed a large portion of the project resources. Sites were screened initially by telephone. If the site operator was willing to participate in the program, as much information as possible was obtained prior to visiting the site (the set of information needs is included in Appendix D). In many cases, this information could be used to delete sites from the proposed list.

Initially, 43 landfills were considered for inclusion in the program. These sites were chosen to represent a wide range of climates. Some sites were quickly eliminated because operators did not choose to participate. Others were eliminated for a variety of reasons, such as lack of critical data records, or the fact that the landfill's gas recovery system was either very new, gas recovery was not being optimized, or some gas was not being measured.

Despite this initial screening, four of the 22 landfills visited had to be dropped from the final analysis because of data inadequacies. Three other landfills were added but not visited. For these three sites, the landfill operations were known to the project team, and the operators were also fairly knowledgeable about the program and its objectives; therefore, these data were considered reliable and included in the study.

Given the above limitations, this study was successful and has added to the general knowledge base for landfills. Moreover, the main objective–developing a model for global emissions–was achieved. The strengths and successes of this program include:

- A model was developed that accurately reflects real world variability of landfill CH_4 recovery;
- The model is very simple and easily adapted to global emissions estimation;
- The uncertainty associated with CH_4 recovery was quantified; and,
- The program was cost-effective, allowing maximization of sample size.

The weaknesses of this approach are:

- The model is not mechanistic, and is therefore limited in its usefulness.
- Between-site variability is high, and much of the variability remains unexplained by the model.
- Recovery is used as a surrogate for emissions. The validity of this assumption is unknown.

From here, the research program could take several parallel paths. It would be useful to continue to add sites and refine the model. However, this approach has limited usefulness and should not take priority over other research areas. The limitations on the available data, particularly refuse mass and composition, make it unlikely that this method will ever be successful at quantifying the effects of all the controlling factors. The exception may be climate, but a large number of observations are likely to be required in order to detect any effect. In particular, more observations from the climatic extremes (cool dry and warm wet sites) are needed.

One area that needs further study is the use of CH_4 recovery as a surrogate for emissions. This issue can be addressed by independently measuring total CH_4 gas production and by measuring landfill gas emissions and analyzing gas constituents. A method of measuring total gas production by pressure probes is currently being developed.* An intensive program of measuring landfill gas emissions is needed; multiple samples from multiple sites will be needed in order to fully characterize U.S. landfills.

A GLOBAL MODEL

A factor for estimating global landfill CH_4 emissions can be proposed based on the CH_4 recovery rate per refuse mass regression model. The intercept was not significant (Table 9), so the simpler model (with the line forced through the origin) can be used. The slope for this line is 4.52 m^3 CH_4 per min/10^6 Mg of refuse. If all of the waste is assumed to decay in 25 years, the following emission factor can be calculated:

$$4.5 \ m^3 \ CH_4/min/10^6 \ Mg \ of \ refuse * 60 \ min/hr * 8760 \ hr/yr * 25 \ yr$$

$$= 5.9 \times 10^7 \ m^3 \ CH_4/10^6 \ Mg \ of \ refuse$$

On a global basis, this factor may overestimate CH_4 production for many countries. The composition of wastes from less-developed countries in particular is lower in paper and therefore less likely to produce CH_4. Also, global landfilling practices vary much more than those of the sample population of U.S. sites. On the other hand, if waste decays more slowly than assumed in this study (25 years), then this factor underestimates CH_4 per ton of refuse.

Despite these concerns, the CH_4 potential factor developed in this study should yield more reasonable estimates of global landfill methane emissions than are currently available because the factor is based on actual landfill data rather than theoretical models. By careful consideration of all the mitigating effects, some of which have been discussed in this report,

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*Memorandum from Stan Zison, Pacific Energy, to Susan Thorneloe, U.S. Environmental Protection Agency. April 26, 1991.

is based on actual landfill data rather than theoretical models. By careful consideration of all the mitigating effects, some of which have been discussed in this report, this simple model can be used to quantify and reduce some of the uncertainty in global estimates.

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APPENDIX A

LANDFILL SITE VISIT REPORTS

Data from 25 landfills were obtained for this report. Site visit reports for 12 landfills are included in this appendix. Site visit reports for Landfills 1 through 6 are contained in a pilot study (Campbell et al., 1991). Data from Landfills 14, 15, 18, and 19 were not used in this report because the landfills either did not maximize gas recovery or they lacked historical refuse/gas recovery data; therefore, these landfills are not described in the report or in this appendix. Landfills 23, 24, and 25 were not visited.

The purpose of the site visits was to evaluate the landfill gas collection system and methane (CH_4) gas recovery systems at the landfills, and to obtain historical data on gas flow rates and gas composition, amount of refuse in place, refuse composition and age, as well as information on other characteristics of interest. While on site, the accuracy of instrumentation used to measure gas flow rates, gas composition, and refuse weights or volumes was also evaluated.

The data gathered on CH_4 recovery rates and factors that may influence these rates will be used as inputs for a global model to predict CH_4 emissions from landfills.

LANDFILL 7

Place and Date

State: North Carolina

Date: March 14, 1991

Background Information

The landfill covers 125 acres, and is divided into three areas based on past and current refuse placement patterns. The estimated total amount of refuse in place at this site is 3.25 million tons, with a total capacity of 6 million tons. Area 1 was the first to be filled, from 1972 when the site opened until 1984. There are an estimated 1.8 million tons of refuse in Area 1. Area 2 was filled from 1984 to 1986, and from 1989 to present. Prior to 1988, there was approximately 800,000 tons of refuse in Area 2. Refuse was placed (400,000 tons) in Area 3 from 1987 to 1988.

When the landfill first opened in 1972, approximately 400 tons of refuse were accepted each day. From 1981 until 1986, refuse acceptance increased to 900 tons per day, and since 1986, 1400 tons are brought in each day. Landfill personnel maintain records on the refuse composition, and copies of these records will be sent to Radian personnel. Construction and demolition debris is included in the total tonnages reported here, and of the current acceptance rate of 1400 tons/day, at least 40 tons/day are construction and demolition debris.

Incoming refuse is weighed via a tare system, by which trucks are weighed and assigned a code number. This code number and the corresponding truck weight can then be called up each time the truck passes over the scales at the weigh station, and the weight of the refuse is automatically calculated. The scales are calibrated annually by the North Carolina Department of Agriculture.

The landfill height varies greatly, though eventually all fill areas will be brought up near the maximum height of 110 feet in Area 2. The maximum refuse height in Area 3 is 90 feet, and Area 1 maximum fill height is 50 feet. Some refuse was placed below grade at this site, at depths down to 20 to 30 feet below grade.

There is no knowledge of any commercial hazardous wastes being placed at this site, but asbestos-containing building tiles were accepted until 1985. This material, along with construction and demolition debris, is placed in areas of the landfill that are separate from the areas that receive residential garbage. To assure that no hazardous materials are disposed illegally in the landfill, landfill personnel randomly select one truck each day and inspect the load to make certain that no hazardous wastes were brought to the landfill.

Closed areas are covered with a 2-foot thick clay cap. Only Area 3 has an established vegetative cover. Because more refuse will be placed on Areas 1 and 2 in the future, these areas have not been intentionally vegetated. Some vegetation has invaded the exposed soil, however, such as wild grasses and conifers.

Landfill personnel indicated that the city has plans to install a composting facility at the landfill in the near future. Initially they plan to accept only leaves and grass clippings, but they may eventually install a chipper for tree limbs.

Landfill Gas Collection System

Gas recovery began at this site in December, 1989. There are 48 wells on the landfill, with 24 wells in Area 1, 17 wells in Area 2, and 7 wells in Area 3. The average depth of existing wells is 40 feet, but as new wells are installed in higher fill areas they will be drilled 85 to 90 feet deep. Lateral polyethylene collection lines move the gas from the wells to a blower station, which then sends the gas to a boiler located at a nearby nutrition supplement production facility. The landfill gas is used as boiler fuel and is the main fuel source for this facility. These lines are buried below the surface (primarily to prevent vandalism) and throughout the landfill there are 12 condensate traps on these lines. These traps are placed in low areas along the lines where condensate collects, and the gravel in the bottom of the trap allows the condensate to be filtered back into the landfill.

At the blower station, more condensate is removed from the gas stream (estimated by gas recovery personnel to be 75 gallons/day). This condensate is sent to the city sewer system. The gas stream is not conditioned in any way before being sent to the boiler; this condensate probably forms as the gas cools. Overall, the boiler is estimated to be 81.5% efficient by gas recovery personnel and the boiler manufacturer. Gas recovery personnel indicate that records are maintained on total gas flow as well as steam produced.

There is one flare located by the blower which is computer-operated to automatically run when demand for steam from the boiler is low. For example, when demand is greater than 17,500 lbs/hr, the flare never runs. As demand falls, however, the computer will adjust the amount of landfill gas to be flared proportionally. This system is designed so that the vacuum applied to the wells will not be adversely affected by fluctuations in the steam demand.

Gas Sampling Points

All gas flow and composition measurements are taken at the blower station after lateral lines from landfill Areas 1, 2, and 3 combine to form one gas stream. No measurements are taken on flow from the individual areas, but gas recovery personnel felt that 80% of the 1.8 million cubic feet of gas recovered each day comes from Area 1. Total flow is measured via a differential pressure transducer connected to a pitot tube in a 12-inch pipe where the gas enters the blower. The amount of gas flared is similarly measured in a 4-inch pipe leading to the flare. The pressure transducers send flow rate data to a computer which is located in a separate office (not at the landfill). Gas recovery personnel indicated that there is no strict procedure followed regarding calibration of the pressure transducers, but they estimated that the equipment is calibrated about twice a year. Gas composition measurements are taken daily with a Gas Tech combustibles analyzer at a point along the pipe leading to the flare. Percent methane typically runs from 49 to 53%, and averages 51%. At this point, the gas contains an estimated 2 to 3% water by volume. No details were provided on the frequency of calibration of the gas analyzer.

Leachate Collection

There is no active leachate collection system at this landfill. Around the perimeter of the property there are ground water monitoring wells, however.

Gas Migration

To monitor off-site gas migration, the city has installed 14 perimeter migration wells which are tested monthly with a methane gas monitor (Industrial Scientific Corporation, model number CD212). Landfill personnel indicated that monitored levels never exceed 0.05% methane. Prior to installation of the gas recovery system, there were frequent odor complaints. Gas recovery personnel indicated that the complaints ceased when the recovery system was installed. Discussions with gas recovery personnel indicate, however, that they think they are recovering only 65% of the available methane (based on amount of refuse in place), and that the majority of gas loss occurs along the steep slopes (of Area 3, for example) and escapes to the atmosphere without being detected at the perimeter migration wells.

Information Gathered

No records were gathered the day of the site visit, but discussions were held with landfill personnel and gas recovery personnel about the type of information that is of interest.

Information to be Sent

Landfill personnel were asked to provide information on the refuse tonnage and composition, broken down annually. In addition, a contour map of the landfill showing gas recovery wells was also requested.

LANDFILL 8

Place and Date

State: Georgia

Date: March 19, 1991

Background Information

The landfill is inactive and covers 55 acres. Refuse was accepted from 1973 to 1987. There are an estimated 3 million tons of refuse in the landfill. The waste acceptance rate was approximately the same for each of the 14 years of operation of the landfill. This is equivalent to approximately 215,000 tons of refuse per year or 590 tons daily.

Waste composition is estimated to be 60% commercial and 25% residential. The remaining 15% is construction and demolition debris. A large amount of the commercial waste came from office buildings and includes white office paper. It is estimated that paper accounts for 50% of the landfill refuse. No liquids or sludge were accepted during the life of the landfill.

The landfill was built in benches; the refuse height varies from 30 feet to 75 feet with an average depth of 55 feet. No refuse was placed below grade at this site. The landfill is covered with a clay cap that is 2 to 4 feet thick. The permeability of the clay used in the cap is 10 -6. The landfill has an established vegetative cover, mostly grasses with some wild flowers.

Landfill Gas Collection System

Gas recovery began at this site in 1986. The end-use of gas from this site is high Btu, pipeline quality gas. There are 107 wells connected by 15 lateral lines that lead into the header line. Wells installed by the original gas recovery system owner are being replaced at a rate of about 20 wells per year. There are plans to reduce the number of wells by approximately half so that each well is not in competition with neighboring wells and will perform more efficiently. The average depth of the wells is 55 feet. Replacement wells will be drilled deeper than original wells in most cases. The lateral lines move the gas to the header which transports gas to the recovery plant. These lines are buried below the surface.

The gas treatment process is currently considered proprietary, and will not be discussed in detail here. Before treatment, the CH_4 content of the landfill gas ranges from 55 to 59%. Methanol is used to remove the carbon dioxide (CO_2) from the landfill gas; after processing the remaining gas contains at least 95% CH_4. During processing, there is an estimated 2% CH_4 loss, as some CH_4 is removed along with the CO_2 by the methanol. There is less than 1/2% CO_2 in the final sale gas product. Processed gas must meet the specifications of the gas company that purchases the gas. They require a 950 Btu gas with less than 4% nitrogen. The recovery facility routinely provides gas with a 960 to 970 Btu content. Based on operating records, gas recovery personnel estimate that the recovery plant runs 91% of the time and processes approximately 1.4 million cubic feet of gas per day, although the system has a 3.2 million cubic foot capacity. Gas recovery personnel estimate that they are recovering approximately 75% of the landfill gas produced at this site. This estimate is based on the conditions of the existing well field and the cap.

At the recovery plant, condensate is removed from the gas and collected. The condensate is sent through two oil/water separators before being tanked and trucked off-site. The landfill is currently trying to get a permit to discharge this treated condensate into the city sewer system.

There is one flare located by the gas recovery facility. The flare can burn 1000 CFM, which is not big enough to prevent all migration when the system is down. The flare is not used when the plant is operating.

Gas Sampling Points

Sampling points are located on each lateral line for a total of 15 sampling ports. An Air Data Multimeter (ADM-870) manufactured by Shortridge Instruments Inc. is used to measure flow rate, temperature and pressure. A gas chromatograph located on-site is used to evaluate gas composition. Nitrogen content is routinely checked. Perimeter wells are monitored using an Mine Safety Appliance (MSA 62-S) which indicates percent lower explosive limit (LEL) and percent methane.

Leachate Collection

There is no active leachate collection system at this landfill. Leachate loss from the landfill is reportedly well-contained by the natural clay liner under the landfill.

Gas Migration

To monitor off-site gas migration, perimeter migration wells have been installed at 1000-foot intervals around the landfill and are monitored monthly. When the gas recovery plant is not operating, these perimeter wells are monitored on a weekly basis. The perimeter wells average 30 to 45 feet in depth. If the plant is not running, the vacuum on the perimeter wells is increased to prevent off-site migration, and the vacuum on the interior wells is decreased.

Information Gathered

Daily reports of the amount of gas sold from February 1989 to March 1990 were obtained from gas recovery personnel. Also included in this data is the average carbon dioxide, nitrogen, methane and Btu content of the gas.

LANDFILL 9

Place and Date

State: Mississippi

Date: March 19, 1991

Background Information

The landfill is active and opened in 1979. It is divided into 3 cells, two of which have been filled and are capped. These two cells cover approximately 30 acres of the 180 acres available for refuse disposal. There is an estimated 1.8 million tons of refuse in the landfill. Cell 1 was filled from about 1979 to 1984; cell 2 was filled from 1984 to 1989. Refuse is currently placed in cell 3.

When the landfill first opened in 1979, approximately 1,300 yards/day of refuse was accepted each day. Over the last 3 years that acceptance rate has increased to at least 3,000 yards/day. Incoming trucks are charged a fee based on the size of the truck bed, regardless of whether or not it is full. Gas recovery personnel estimate that there is a total of 1.8 million tons of refuse in place, and indicated that they would provide a conversion factor between yards and tons of refuse. Construction and demolition debris is included in the estimates of amount of waste accepted each day, and accounts for approximately 20% of incoming refuse. The remaining waste is 75% commercial and 25% residential. The landfill personnel have no knowledge of accepting commercial hazardous waste, gas tanks, or car batteries. The landfill will accept tires if they have been shredded or cut in half.

The landfill height varies greatly, as fill was placed in benches, with a maximum interior height of 68 feet. Eventually all interior fill areas will be brought up to this height. Refuse was placed 25 to 30 feet below grade.

Closed areas are covered with a 2 to 3-foot thick clay cap. Cells 1 and 2 have established vegetative cover, mostly grasses and some wild flowers.

Landfill Gas Collection System

Gas recovery began in September 1990. The system was installed in response to migration problems. There are a total of 32 wells; 20 of the wells are in cell 1; and 12 wells are in cell 2. Interior wells are 60 to 70 feet deep and perimeter wells are about 30 feet deep. All wells are tied to lines that lead to a blower, with lines from cells 1 and 2 brought in separately. Fifteen deep interior wells are currently under construction and should be operating by the end of the summer. Nine or ten are located in cell 2.

There is one flare located on-site. It is a 5 burner IT-McGill unit with louvres to adjust the temperature and flame. It also has a fail safe valve that activates if the system shuts down. Vibration isolation valves can control flow rate to the flare. Two 40 hp blowers are alternately used on a weekly basis. The flare is currently burning about 600 CFM. The gas averages 40% CH_4; gas from perimeter wells has a lower CH_4 content. The site is flaring the minimum amount of gas necessary to keep the perimeter wells at 0% methane. The site will maximize gas recovery when untreated, medium Btu gas is sold to a nearby concrete manufacturer at the end of the summer. At that time landfill personnel estimate recovery to be 1000 to 2000 CFM.

Gas Sampling Points

Sampling points to monitor flow are located before and after the gas enters the blower building. Only total flow is measured, the first sampling port is located after the lines from cells 1 and 2 are combined. Gas flow rate, temperature, and pressure are measured with an Air Data Multimeter (ADM-870) manufactured by Shortridge Instruments Inc. Gas composition is not routinely measured. Perimeter gas wells are tested with a Mine Safety Appliance (MSA 62-S) methane meter which measures percent lower explosive limit (LEL) and percent methane.

Leachate Collection

Cells 1 and 2 do not have active leachate collection systems. A leachate collection system is present in cell 3. Ultimately, the gas condensate sumps will be tied into this collection system.

Gas Migration

To monitor off-site gas migration, perimeter migration wells have been installed at 1000-foot intervals. These perimeter wells are 35 to 40 feet deep and are tested monthly.

Information Gathered

Landfill and gas recovery personnel provided weekly flow rate testing data for September 1990 through the present. In addition, a summary of the test results of canister samples analyzed for gas composition was also provided. Maps of the site plan, methane gas pipeline plan and profile, and layout of the gas production lines were also provided.

LANDFILL 10

Place and Date

State: Alabama

Date: March 21, 1991

Background Information

The landfill covers approximately 100 acres and is divided into two areas based on past and current refuse placement patterns. Each area encompasses 50 acres. The two areas are divided by a dirt road leading to the active dumping area. The landfill has been open since 1958. However, the garbage was burned throughout the 1960's. Unburned waste has been placed in the old and new areas since 1971, with each rise overlapping previously filled rises. Waste acceptance in the old area ceased in October 1989, however, the currently active rise may be extended over the old area during 1991. Waste acceptance in the new area ceased in early 1990. The new area currently has a grass cover. Waste acceptance in all areas is expected to cease in the year 2006.

The landfill is permitted to accept approximately 2000 tons of waste per day and there is no total capacity limitation. During 1990, the landfill received about 1200 to 1500 tons per day. The tipping fee was recently raised, and they are currently receiving about 600 tons per day. Landfill personnel estimate the average waste density to be 0.63 tons per cubic yard of air space. An on-site, open-ended, cross sectional survey was performed over a 30-day period to determine the average density of the incoming refuse. The average depth of the landfill is 110 feet. A 2% grade is maintained with the use of lasers attached to the bulldozers.

Waste has been covered daily with soil excavated from an area behind the landfill. A three-foot cap, consisting of sandy clay soil, was placed on the new area in 1985.

The landfill began weighing incoming refuse in 1980 with a computerized scale. Trucks were initially weighed and assigned a code number. This code number and the corresponding truck weight is called up each time the truck passes over the scales. The weight of the incoming refuse is automatically calculated. The scales are calibrated quarterly. In addition, the State Division of Weights and Measurements checks the scale calibration twice a year.

The landfill does not practice waste segregation. There is no knowledge of liquid, hazardous, and infectious wastes being accepted at the landfill. Small quantity generator waste and household hazardous waste are accepted at Subtitle D facilities, however. Tires are still being accepted. Landfill personnel conduct spot inspections of incoming refuse periodically and monitor actual dumping two or three times a week to ensure no prohibited waste is entering the landfill. Asbestos is currently banned from the landfill, however, it was accepted in the past. The landfill maintains a receivables assessment management system (RAMS) to determine waste composition on a monthly basis. Additionally, a waste characterization study was conducted for the U.S. Environmental Protection Agency in 1986. The results of this study indicate approximately 50% of total waste originates from household sources, 25% from commercial sources, 20% from construction and demolition, and 5% from industrial processes. Landfill personnel suggested using these proportions rather than those generated by the RAMS. The primary difference is that in the RAMS household wastes are separated into two categories: refuse (23%) and yard waste (17%).

Landfill Gas Collection System

Landfill gas recovery began in 1988. The methane gas recovery system consists of 96 wells. The wells draw gas from approximately 80 acres of the landfill. Waste continues to be dumped on top of 60 of the 96 wells in operation. The gas recovery personnel have had occasional problems with broken pipe lines and buried wells. The wells are arranged in parallel rows, with 125 feet between each row. The wells are approximately 70 feet in depth, with the bottom 20 feet filled with rock. The collection pipe is perforated, starting 7 feet below the ground surface. A concrete cap covers the pipe end. Gas recovery personnel expect 50 new wells to be drilled in the near future. The average vacuum draw on the wells is 5 inches of H_2O.

The recovered gas stream is treated by a methanol cooling process to remove H_2O, hydrocarbons, CO_2, O_2, and N_2. The refined gas stream is pipeline quality gas, containing less than 3 percent CO_2. The refined gas is sold to the local gas company via a nearby pipeline. The average Btu content is 950. Approximately 30 million cubic feet per month of refined gas is sold to the gas company. Monthly gas records have been maintained since January 1990. The volume of pipeline quality gas sold is about half the volume of total landfill gas extracted.

Gas Sampling Points

A standard gas meter is used to measure methane gas flow to the pipeline. Raw landfill gas recovered before treatment is not measured. Gas recovery personnel claim that the treated gas sales are 50% of raw gas recovered based on periodic monitoring of raw gas methane composition. Gas composition is measured every 15 minutes with a Bendix 7000 gas chromatograph after the gas is treated and before discharge to the pipeline. The gas chromatograph is calibrated daily with a sample gas of known composition. The gas recovery personnel sample raw gas composition in each of the recovery wells on a monthly basis. The raw gas methane content ranges from 50 to 58%. Wells which draw gas with a methane content below 45% are temporarily closed. Excess nitrogen in the raw landfill gas occurs periodically due to the breakage of collection pipes and wells from the expansion of the active dumping area.

Leachate Collection

The landfill does not have a leachate collection system and has had no off-site leaching problems. However, leachate monitoring wells are maintained at the landfill perimeter and checked twice a year.

Gas Migration

A polyethylene curtain was placed in a 25-foot ditch on the perimeter of the landfill in 1979 to stop methane gas migration.

Methane gas migration is checked once a year at the landfill perimeter. An Explosimeter model 214 is used to check for the presence of methane. The Explosimeter is calibrated with 95 percent methane. No vegetative stress was observed.

Information Gathered

The landfill personnel provided daily waste acceptance records from 1988 through 1990. A solid waste landfill survey prepared for the U.S. EPA in November 1986 was also obtained. An aerial photograph of the landfill and surrounding areas was provided for copying back at the office. A seven-month waste composition record from July 1990 to January 1991 was also obtained.

The gas recovery personnel provided a schematic diagram of the gas extraction wells. Methane gas sales records (in cubic feet) for 1990 were also obtained.

LANDFILL 11

Place and Date

State: Georgia

Date: March 22, 1991

Background Information

The landfill covers 120 acres and is divided into two areas based on gas rights. Parcel A covers 69 acres, and Parcel B covers 51 acres. There are no obvious distinctions between the two parcels. Waste is placed in rises which are built progressively over the landfill surface. Each rise overlaps previously filled rises containing older waste. The landfill is active, and it is expected that waste will be accepted for at least two more years. Currently, about 10,000 to 13,000 tons of waste are accepted per month.

The average depth of the landfill is about 80 feet. Except for some excavation to obtain landfill cover, most of the waste has been placed above grade. Less than 10 feet of the waste is placed below grade. The top of the landfill is slightly rounded and the slopes are steep.

The landfill began accepting waste in 1962. The landfill has accepted nearly all of the residential and commercial waste from the surrounding county (population 170,000) since the landfill opened. Prior to 1986, the landfill accepted construction and demolition debris. In 1986, a separate landfill opened and began accepting nearly all of the construction and demolition debris in the county. Therefore, waste placed in Landfill 11 after 1986 does not include construction and demolition debris.

Incoming refuse is weighed via a tare system, by which trucks are weighed and assigned a code number. This code number and the corresponding truck weight can then be called up each time the truck passes over the scales at the weigh station, and the weight of the refuse is automatically calculated. The scales are calibrated monthly by a scale company service technician who uses standard weights to calibrate the scales. The State Department of Agriculture also inspects the scales annually. The weigh station became operational in 1981.

There is no knowledge of hazardous waste placed at the site (however, household wastes and small quantity generator wastes are accepted at Subtitle D landfills). Waste is not routinely inspected for the presence of hazardous wastes.

Medical waste is not accepted at the landfill, but each truck carrying general refuse from the local hospital is scanned with a geiger counter for the presence of radioactivity.

Sewage sludge from the local waste treatment plant is accepted at the landfill. All sewage sludge is tested for moisture content using a paint filter test. Prior to landfilling, the sludge moisture must be reduced such that the sludge will not pass through a paint filter.

As each rise is completed, it is covered with a 2-foot cap of clay and grass is planted. These areas will eventually be covered over with new waste until the landfill reaches capacity. It is estimated that an additional 20 feet of waste will be placed on the landfill before it is permanently closed.

Currently, there are no large-scale recycling or composting programs in the county; however, there have been some wood chipping demonstration projects.

Landfill Gas Collection System

A brick manufacturing company has been collecting gas from Parcel A (69 acres) since 1985. Currently no gas is collected from Parcel B. A separate company has gas rights to Parcel B, but has not recovered gas from the landfill since 1989.

On Parcel A, 39 wells placed about 180 feet apart collect landfill gas. The average depth of each well is about 45 feet. As additional waste is placed on the landfill, pipe extensions are added to the wells so that they will not be covered.

Lateral polyethylene collection lines move the gas from the wells to a blower station which is located at the brick factory. The average vacuum at the main landfill gas header is about 5 inches of water. Landfill gas from the main header is treated by mechanical refrigeration to remove water. The dehydrated gas is then used as fuel in a brick kiln.

About 500 gallons of condensate are collected from the gas each day by the refrigeration system. About half of this condensate is injected back into the landfill, and the rest is evaporated by a boiler.

All of the gas collected is burned in the brick kiln. None of the collected gas is vented or flared. Records of the amount of gas collected have been kept continuously since the gas collection began.

Gas Sampling Points

Total gas flow measurements are taken at the brick factory downstream of the condensate removal system. The gas flow data, therefore, reflects total landfill gas collected minus water. Gas flow is measured with a turbine gas flow meter.

The landfill gas is also monitored for methane at a point downstream of the condensate removal system. Percent methane is measured daily using a hand-held gas monitor. An automatic gas chromatograph is also installed in the gas line downstream of the condensate removal system, but it has not operated reliably. Records on percent methane are not maintained. According to the representative of the brick company, the percent methane is measured daily just to ensure that the gas contains between 50 and 55 percent methane. Lower methane readings indicate breaks in the gas lines which signal to the gas collection personnel that repairs are needed. The brick company representative stated that the landfill gas has averaged 53 percent methane since gas collection began. Other gas constituents, such as CO_2, N_2, and O_2, are not monitored regularly.

Leachate Collection

There is no active leachate collection system at this landfill. Around the perimeter of the property, there are ground-water monitoring wells, however.

Gas Migration

Gas migration monitoring is not required at the site, and there is no monitoring program. Landfill personnel stated that vegetative stress on the landfill surface is not a problem.

Information Gathered

Maps of the landfill as well as a map of the gas collection system were obtained. Monthly records of total gas flow for the period 1985 through 1990 were provided by the brick company. Information was also provided regarding periods when gas collection equipment was not operating continuously.

Landfill personnel provided monthly waste acceptance tonnages for the period 1981 though 1990. No records of waste acceptance were kept prior to 1981. However, landfill personnel suggested that since the landfill served the entire county from 1962 to 1980 (waste was not exported or imported across the county line), waste acceptance prior to 1981 should follow the trend of the county population.

Information to be Sent

A private consulting firm conducted a study of waste composition accepted at the landfill during the past 2 to 3 years. Landfill personnel stated that they would obtain and send a copy of that report.

LANDFILL 12

Place and Date

State: Oregon

Date: April 4, 1991

Background Information

The landfill covers approximately 85 acres and is divided into two segments: a north area and a south area. Filling began in the south area and progressed northward to the northern boundary of the landfill between 1969 and 1980. From 1980 until site closure in 1983, waste was placed in a second lift on the south area. The two areas were initially separated by an east-west drainage ditch, but the ditch is no longer present. The estimated total amount of waste at the site is 3.1 million tons (1.9 million tons in the south area and 1.2 million tons in the north area).

The landfill is built on land that was formerly a marshy wetland with an elevation of 20 to 22 feet. The surface elevations after landfill closure ranged from 45 to 58 feet. Since 1983, the final landfill cover has been upgraded to increase slope and water runoff. Currently the landfill cover consists of an average of 5.8 feet of low permeability soil. The slope of the landfill averages just over 2 percent, and grass covers the entire surface.

A 1986 hydrogeological study of Landfill 12 conducted for the EPA estimated that the net amount of water from precipitation that percolates through the landfill is about 24 inches per year. Boring tests have shown that much of the waste near the bottom of the landfill is water saturated. This is mainly due to the high water table at the site.

The landfill accepted primarily residential and commercial wastes. The landfill operating permit specifically excluded medical wastes, chemicals, oils, liquids, septic tank pumpings, and nondigested sewage sludge (however, household hazardous wastes were not excluded). Some construction and demolition debris was accepted at the landfill, and it was placed in the southern end of the landfill separate from the general refuse. The amount of construction and demolition debris accepted at Landfill 12 is not known; however, a representative of the State environmental agency said that the amount was probably not large since most area construction and demolition debris was taken to a separate landfill.

Landfill Gas Collection System

Landfill gas recovery began at this site in 1984. There are a total of 78 active wells. About 50 of these wells are horizontal wells placed in trenches about 6 feet below the landfill surface. These horizontal trench wells range in length from about 200 to 1,000 feet. The remaining 28 wells are vertical wells with an average depth of 35 feet. The perforation in the vertical wells begins about 3 feet below the landfill surface. The wells and the connecting piping are constructed of PVC. Gas wells cover nearly all of the landfill surface. However, a representative of the landfill said that wells were not located over the section where construction and demolition debris was placed.

From 1984 to 1989, a private company operated the gas recovery system. The landfill gas was conveyed by an internal combustion compressor which was powered by landfill gas. The vacuum pressure at the main landfill gas header was typically 2 to 4 inches of water, while the vacuum at individual wells was about 0.5 inches of water. The total flow of raw landfill gas varied between 300,000 to 800,000 standard cubic feet per day. The gas constituents had the following average composition:

- CH_4 - 53%
- CO_2 - 42%
- N_2 - 4%
- O_2 - 1%
- H_2O - <1%
- Btu's - 530

The raw landfill gas was treated by removing water with a triethylene glycol dehydration system. The dehydrated gas was then treated with selectively permeable membranes to separate the methane from the carbon dioxide. The resulting methane portion of the gas stream (95% methane) was sold as pipeline quality gas via a natural gas pipeline near the landfill. Whenever the gas refining system was not in operation, landfill gas was diverted to a flare.

By 1989, landfill gas production at the landfill decreased to a point where gas purification was no longer profitable. Therefore, the company that had been operating the system ceased operation. Currently, some gas is extracted from the existing well system and used to fuel boilers for the county, but the system is no longer operating in an optimal fashion.

Gas Flow Measuring Points

An 8-inch annubar was installed at the terminus of the landfill gas collection system at a point where it enters the gas purification system. This measured the inlet flow of raw landfill gas in inches of water, and was recorded on a 7-day circle chart.

Grab samples of raw landfill gas were taken once per week; these samples were analyzed by GC for methane, oxygen, and nitrogen. These grab samples were also tested for moisture. An automatic GC was used to continually measure methane, oxygen, and nitrogen in the processed gas stream. Processed gas samples were measured every 9 minutes, 24 hours a day.

The equipment that was used to measure gas flow and composition is no longer present at the site; it was removed when the gas refining operation ceased in 1989.

Leachate Collection

There is no active leachate collection or treatment system at this landfill. However, ground-water monitoring wells are located around the perimeter of the landfill.

Gas Migration

Monitoring at the perimeter of the landfill for gas migration was not practiced at this site.

Information Gathered

The operator of the landfill provided monthly tonnages of waste received at the landfill for the period 1971 through 1983. A study of ground-water impacts at Landfill 12 was also obtained from the State environmental agency. This study contained annual waste acceptance tonnages for the entire life of the landfill (1969 though 1983) as well as a map showing the location of waste placement by year. A study published by the local solid waste authority was obtained which provides a breakdown of typical waste composition in the area.

The company that operated the gas recovery system from 1984 to 1989 provided records of total landfill gas recovered for the period April 1987 to October 1987. They also supplied a schematic diagram showing the placement of wells at the landfill.

Two additional reports were also obtained. One is a 1983 report that projects the amount of recoverable gas from Landfill 12. The other is a 1988 report presenting a risk assessment of the use of a mixture of landfill gas and natural gas in customer homes.

LANDFILL 13

Place and Date

State: Washington

Date: April 5, 1991

Background Information

The landfill is 50 years old and is scheduled to close in December 1991. Open burning of refuse was practiced from the time the landfill opened in the late 1930s until the mid 1960s. After open burning of refuse ceased, the refuse was either shredded or placed directly in the landfill and compacted. A layer of demolition refuse lines the bottom of the landfill.

The landfill was built on an old gravel mine. The underlying soil is sandy gravel. The refuse is approximately 50 feet in height from the prior excavation level. The bottom of the landfill is about 5 feet above the ground water table.

The landfill is divided into two areas. The north section is approximately 50 acres and has been closed since 1988. Refuse acceptance in the north area began in 1980. The cap for the closed portion consists of a synthetic membrane (60-mil polyethylene) which was placed on 35 acres of the north section in 1989. On top of the synthetic membrane is a 1-foot thick earthen cap. The south area is approximately 30 acres and portions of it are still actively accepting refuse. The south area contains the oldest refuse. A 6-inch cover of sandy dirt is placed over the active area daily.

The landfill receives approximately 440,000 to 480,000 cubic yards of refuse annually. The density of the in-place compacted waste is approximately 1200 pounds per cubic yard. The density of incoming uncompacted waste is approximately 600 pounds per cubic yard. Last year, approximately 134,000 tons of refuse were accepted in the landfill. A weigh station was installed at the landfill in 1988. Vehicles are weighed once and assigned a code which is entered in the computer. Each time the vehicle enters the landfill, the code is punched in the computer. Incoming refuse weight is determined automatically. Several studies of estimated waste acceptance and in-place volume have been performed by the landfill's consulting firm and local health district officials. The landfill serves the entire county in which it is located. The county population is approximately 230,000.

Landfill Gas Collection System

The landfill operated separate methane gas recovery systems in the north and south sections of the landfill up until March 1991. Landfill gas recovery began in the late 1970s in the south section and in 1988 in the north section. In the south section, landfill gas was flared using an open candle flare. The south area flare ceased operating in March 1991 and 20 perimeter wells from the south section were tied into the north area collection system. The north area flares landfill gas using an enclosed flare. From

1988 to February 1991, the north flare combusted only landfill gas from the north area of the landfill. When the south area perimeter wells were tied into the north area collection system, the north flare began combusting perimeter gas from the south area.

The landfill operates a total of 81 vertical gas extraction wells. Twenty wells are located in the south area and fifty-one are located in the north area. Eight of the twenty wells in the south area are located in the active dumping area. Each well is approximately 30 to 50 feet in depth. Twenty-five new wells will be installed in the currently active area at landfill closure. The average vacuum pressure on all wells is 34 inches of water column measured at the main header before the blower and 5 inches at each individual well. Condensate is collected from the gas recovery system and pumped via nine pneumatic pumps to a treatment tank. The condensate is filtered with carbon and pH adjusted before discharge to the local sewage treatment plant.

Gas Sampling Points

Gas composition is monitored in each of the gas extraction wells every two weeks using a hand-held gas analyzer. Raw landfill gas methane content averages between 40 and 50% by volume. Gas flow is measured in the main header to the blower on a daily basis. Based on the measurements, landfill personnel reported that the average gas flow rate is 835 cubic feet per minute. Daily flare temperature readings are also recorded. The average flame temperature of the flare was reported to be 1875° F.

Leachate Collection

The landfill does not have a leachate collection system. Ground-water contamination from landfill leachate has been documented. The landfill owners are currently building a water treatment plant which will commence operation at the end of the year. The contaminated water from the underlying aquifer will be extracted, treated, and returned to the ground.

Gas Migration

Gas migration is measured by 20 gas probes located on the perimeter of the landfill. The gas probes were installed in 1979 when methane gas recovery began. Very little gas migration has been detected since the recovery system was installed. However, substantial amounts of landfill gas was observed bubbling in puddles along the road to the active dumping area. The road is located between the north and south areas.

Information Gathered

Landfill personnel provided a topographic diagram of the landfill and a schematic of the gas recovery system. Also provided were monthly records of gas migration probe readings and gas composition measurements taken at individual wells during 1990 and 1991. The landfill's consulting firm sent gas flow rate records for 1990, and the local district health office personnel provided data from several landfill studies on waste composition.

Information to be Sent

Waste acceptance records maintained by the landfill were requested.

LANDFILL 16

Place and Date

State: New York

Date: April 10, 1991

Background Information

The landfill covers 75 acres and refuse averages 80-100 feet deep and 120 feet deep at the highest point. Refuse was placed 20-30 feet below grade. Waste acceptance began in 1976 and the landfill currently has approximately 3,700,000 tons of refuse in place. This tonnage estimate is for municipal solid waste only, and does not include tires, construction and demolition debris, or ash. Approximately 800 tons of refuse are accepted each day, although the amount varies with season. Refuse acceptance may be as high as 1500 tons per day in the spring. Trucks hauling refuse are weighed as they enter and leave the landfill. All white goods, wood, tires, and construction debris are separated out of incoming refuse. Sewage sludge is accepted and is placed on the south slope of the fill area. Asbestos is also accepted and placed in a separate area of the landfill. There is no final cap on any part of the landfill now, but there are plans to add a cap in the near future.

Landfill Gas Collection System

Gas recovery began at this site in December, 1988. There are 36 wells, spaced 100-200 feet apart and connected to one header. The average depth of the wells is 60 feet; however, wells located on the south side only average 37 feet deep where the county is actively dumping waste.

One Solar Centaur T4500 turbine (3 MW) is currently operating. Landfill gas enters the gas plant at 120° F and flows through two inlet scrubbers. The first stage filters the gas and the second stage provides mechanical separation of contaminants in the gas. In this process, the gas is compressed. The gas then flows to a separator and oil knockout which catches impurities and water. The gas then passes through a cooler and water knockout before it enters the turbine.

The single turbine runs on full load continuously with an annual range of 1300 to 1800 scfm. This value changes with temperature as the gas becomes more or less dense. The turbine operates more efficiently when the gas is cooler. The turbine burns approximately 2.1 million cubic feet of gas per day (at 100% capacity). Methane content of the gas is typically 52% by volume.

The recovery system generates 4,000 gallons of condensate every three days. This condensate is tanked and trucked off-site.

Gas Sampling Points

An on-site gas chromatograph (GC) is used to measure gas composition twice a week. Standards are run on the GC every morning. Gas flow is measured with a Kurz Air Velocity Meter (model 4418) flow meter once a week just before the gas enters the turbine (at an orifice plate).

Leachate Collection

Leachate is collected in several leachate ponds around the site. Approximately 35,000 gallons of leachate (and rainwater runoff) are collected daily and tanked and trucked off-site.

Gas Migration

The county is responsible for monitoring gas migration off-site and has installed several perimeter wells. Migration off-site is thought to be minimal.

Information Gathered

A record of the tons of refuse placed by year in the landfill was provided by the County Department of Public Works for 1976 to present. These values are for municipal solid waste only, and do not include tires, construction and demolition debris, or ash. Gas recovery personnel provided a map of the landfill showing well locations, an example of a gas monitoring record for each well, and an example GC printout. Brochures were also provided discussing the gas turbine.

Information to be Sent

Monthly gas flow records were requested from the gas recovery personnel.

LANDFILL 17

Place and Date

State: Massachusetts

Date: April 23, 1991

Background Information

The landfill started accepting waste in 1952 and covers 40 acres. The landfill is rounded in shape with a maximum height of about 80 feet. There are approximately 5.7 million tons of refuse in place. The refuse acceptance rate is about 15,000 tons/month; the landfill operators indicated that much of the refuse in place has been accepted in the past 10 years. The site is divided into two sections, an active and an inactive section. A 60-mil synthetic liner is placed under the active half of the landfill and extends over the inactive half to also act as a cap for the inactive half of the landfill. The liner is under 20 acres and covers the remaining 20 acres. A one-foot thick clay cap also covers the inactive section.

Refuse composition is mostly commercial restaurant/office type waste which accounts for 85% of the refuse. Construction debris accounts for another 5 to 7% of the waste, and the remaining refuse is residential. The site contains tires, which were accepted by the former owner. Most of these are found in the northeast section of the landfill. The site accepted hazardous waste from 1968 to 1979 but does not allow hazardous waste at this landfill any longer. Batteries are banned in landfill by the State and are separated out of incoming trash.

Incoming refuse is weighed via a tare system, by which trucks are weighed and assigned a code number. This code number and the corresponding truck weight can then be called up each time the truck passes over the scales at the weigh station, and the weight of the refuse is automatically calculated. The scales are calibrated annually by a scale company service technician who uses standard weights to calibrate the scales. The State Department of Weights and Measures also inspects the scales annually. Also, hauling trucks pass by a radiation detector as they enter the site.

Once in place, trash is pushed into place with compactors. The operators estimate that the density of waste compacted in place averages 1440 lbs/cubic yard.

Flare System

Flaring began at this site in 1987. This candlestick flare was not large enough for the landfill, so a new system went on-line in February 1990. The current gas control system consists of 41 wells and one enclosed flare manufactured by McGill. The system flares an average 1200 cubic feet per minute (cfm) of landfill gas from the well field. Gas passes from the main header into a knockout tank, through a blower to a second knockout tank, and then to the flare. The blower is manufactured by Aerovent and has a maximum capacity of 2 million cfm.

The gas is very dry and there is generally little to no condensate. When condensate is collected, it is generally after rainfall when moisture has been added to the landfill. The site has never collected any condensate in the second knockout tank.

Gas Sampling Points

All gas flow measurements are taken in the pipe between the blower and the flare. Sampling for flow is taken with an Air Data Multimeter ADM-870. This same device measures vacuum in the system. The sampling point for measuring vacuum is directly before the gas enters the blower. Vacuum averages about 42" of water. Gas composition (percent methane) is measured weekly using a hand-held gas analyzer. Gas composition measurements are taken at the pipe between the blower and the flare.

Leachate Collection

Leachate is collected from that portion of the landfill that is lined -- approximately 20 acres. About one and a half million gallons of leachate are collected annually. This leachate is sent to a public wastewater treatment plant.

Gas Migration

Perimeter wells from the 1987 gas collection system are monitored periodically for methane but show that no gas is migrating from the site. Interior wells appear to be pulling gas toward the center of the site, controlling off-site migration.

Information Gathered

Landfill personnel provided monthly tonnages of waste received for the period February 1990 through April 1991. They also provided an estimate of the amount of total waste in place in the landfill prior to February 1990. Landfill personnel also provided weekly gas extraction reports containing total landfill gas flow rate and methane concentrations for the period February 1990 through April 1991. A landfill map and gas recovery schematic was also provided.

LANDFILL 20

Place and Date

State: Michigan

Date: May 1, 1991

Background Information

The entire landfill covers approximately 247 acres and is divided into two sections based on past and current refuse placement patterns. The entire landfill is surrounded by a clay dike and a trench for surface water run-off. The landfill began accepting refuse in 1967 in the northern 160 acre section. This section was filled until 1985. Refuse was then placed in the southern 77 acre section, which is still actively being filled. One small area in the northern section is being filled to bring it up to the height of the entire section. Refuse is placed in cells; new cells in the northern section were added above older fill areas with a 2-foot thick clay cap and leachate collection system under the new cells. The refuse age in the northern section ranges from 6 to 24 years, with an average age of 15 years (assuming refuse placement was relatively consistent from 1967 to 1985). The oldest refuse in the southern section is approximately 6 years old.

The total refuse height on the northern section is irregular and ranges from 40 to 80 feet. The refuse in the southern section was placed 40 feet below grade and will be 125 feet in height.

Twenty five acres of the northern 160-acre section have a final cap (2-foot thick clay cap, 6 inches of topsoil, and seeded with grass); the remaining 135 acres (apart from the valley now being filled) have a 1-foot thick clay cap. A final cap will be placed over this area in the near future.

Annual waste acceptance figures were estimated by the previous landfill owner for 1967 to 1982 (as tons). A total of 5.62 MM tons of refuse were placed during this period. Records of gate yards accepted from 1982 to 1989 were provided by landfill personnel, and refuse density values will be provided. A total of 16.96 million gate yards were placed from 1982 through 1989. Incoming gate yards were estimated based on the truck bed size, regardless of whether or not it was full.

Scales were installed in 1989, and a tare system is used by which vehicles, their refuse types, and their vehicle weights are coded into a computer. Scales are calibrated annually by the State and quarterly by the scale manufacturer. The refuse entering the landfill is classified as follows:

1. General refuse (municipal solid waste);
2. Construction and demolition debris (usually includes wood);
3. Compact general refuse (MSW);
4. Bulky wastes from local resource recovery facility (i.e., white goods);
5. Process residue from local resource recovery facility;
6. Ferrous metal (now recycled);

7. Non-contaminated dirt;
8. Sand and concrete;
9. Contaminated soil;
10. Asbestos;
11. Industrial and wastewater sludge; and
12. Ash from local incinerator.

The only refuse that is segregated is the incinerator ash, which is placed in a lined, 7-acre monofill.

Landfill Gas Collection System

Landfill gas collection began in January of 1990. The gas is currently flared and landfill personnel have plans to sell electricity to the local utility. Of the 247 acres, wells are distributed over 210 acres. The majority of wells are located in the northern 160 acre section; there are 16 wells in the southern section. Gas was recovered from about 180 acres of refuse (with 69 wells) until December of 1990, when 30 additional acres (with 11 wells) were brought on-line in the southern section.

Wells are primarily located where refuse is deepest. There are currently no wells on the shallow side slopes of the landfill. Well depth varies with refuse depth,, with a maximum well depth of 67 feet and an average depth of 57 feet. The 80 wells are connected to 14 lateral lines which lead to a 16 inch header. Gas first passes through a separator where free liquids fall out, then onto two Hoffman centrifugal blowers, each with a 100 horsepower engine and a capacity of 4 million cubic feet/day (2778 scfm). From the blowers the gas is send to a McGill 5-burner flare with a 99.75% destruction efficiency of total hydrocarbons. The flare has a capacity of 168.6 MM Btu/hr, and currently burns about 4 million cubic feet/day. The flare temperature is maintained at 1850°F. In order to prevent off-site gas migration, the amount of gas flared is maximized.

Gas Sampling Points

Gas flow is read daily from a Daniels Paymeter (Model 2272) at the inlet to the flare. The flow meter is calibrated on an annual basis. Gas composition is also tested daily, and the gas is drawn from the header line before entering the blower. A standard sample gas of known composition is used daily to calibrate the Hach Carle (Series 400 AGC) gas chromatograph. Individual wells and lateral lines are tested twice each week for flow and gas composition. Landfill personnel try to adjust the vacuum on each well so that a nitrogen content of 2% by volume is maintained.

Leachate Collection

There is no active leachate collection system under the oldest refuse in the 160 acre northern section of the landfill. The southern section and the upper fill areas of the northern section have leachate collection systems. Condensate is combined with leachate from these areas and sent to leachate collection ponds and aerated. During dry periods, some of the liquid is recirculated in active fill areas and haul roads to reduce dust. The remaining liquid (38 million gallons per year) is tanked and trucked off-site.

Gas Migration

Gas migration off-site is monitored at 31 perimeter wells that are tested monthly with a Mine Safety Appliances Explosimeter. Landfill personnel indicated that only 2 or 3 of the wells along the southern boundary of the landfill (near the newly-placed refuse) show slightly elevated CH_4 levels. As new wells are installed along the southern slope, this migration will be controlled. In addition, leachate collection wells in this area have high enough CH_4 levels that 4 had to have flares attached until they can be brought into the header line to the blowers.

Information Gathered

Gas recovery personnel provided well boring logs for each well which show total well depth, bottom condition, maximum temperature, date, and soil zone. Refuse information (in tons or gate yards) was provided for 1967 through 1989. Gas recovery personnel also provided monthly gas flow and composition records for January 1990 through April 1991 and a topographic map of the site (1984).

Information to be Sent

Gas recovery personnel were asked to provide refuse tonnages for 1990 and 1991 (and a recommended conversion factor for gate yards) and an up-to-date site map.

LANDFILL 21

Place and Date

State: Michigan

Date: May 2, 1991

Background Information

The landfill began operation in 1971 and is currently divided into three distinct areas based on temporal waste acceptance. The oldest area encompasses 46 acres and accepted waste from September 1971 until the fall of 1978. Area A encompasses 20 acres and accepted waste from 1982 until 1986. Area B is the only active portion of the landfill and encompasses 40 acres. Waste is placed in excavated cells to an approximate depth of 80 to 100 feet. The closed areas are graded to the original contour of the land. The underlying soil is clay with an average depth of 35 feet. The active area is lined with a 41 mil polyethylene liner. The area was covered at the end of each day with six inches of random soil. For the last three months, the active area has been covered at the end of each day with a temporary synthetic fabric which is removed at the beginning of the next business day. The oldest area of the landfill is capped with 2 feet of clay and covered with approximately 30 feet of dirt. Area A is capped with 2 feet of clay and is scheduled to have a low density polyethylene liner. Daily soil covering practices in these areas averaged 10% of the daily refuse accepted.

The oldest area has a thick grass cover. The area will be used as a local park in the near future, with baseball, soccer, and tennis areas planned.

The landfill does not operate a scale to weigh incoming refuse. Waste acceptance rates are measured by "gate" yards (cubic yards). Landfill personnel estimate the landfill will contain approximately 4 million tons of refuse upon closure. Approximately 1.1 million tons of refuse were placed in the oldest area over its active life. Approximately 800,000 tons of refuse were placed in Area A over its active life.

The landfill separates asbestos waste and contaminated soil from other incoming refuse. Asbestos is kept in a controlled area separate from all other landfill waste acceptance areas. No further segregation of wastes is practiced at the landfill. Contaminated soils are co-disposed with other refuse in the active area B only. Approximately 750 yards of contaminated soil are accepted daily. The landfill does not accept municipal sludge.

Landfill Gas Collection System

Landfill gas recovery began in February 1990. An LFG Industries flare is used to destroy the extracted landfill gas. The flare was installed to control off-site gas migration. Two Lamson centrifugal blowers are used to draw the gas from the landfill. Each 100 horsepower blower has a capacity to pull

3200 cubic feet of gas per minute (cfm) and they are operated alternately. Currently the system is operating at 2200 cfm.

The landfill gas recovery system consists of 56 wells. The average depth of the wells is 60 feet. Thirteen of the gas extraction wells are in Area A. The remaining 43 wells are in the oldest area. The average vacuum draw on the entire system is 90 inches of water column. The average methane gas composition is 45%.

Gas condensate is collected and hauled off-site for treatment and disposal. A condensate knock-out tank is located prior to the blower station. An average of less than 100 gallons per day of condensate is collected. The condensate is sampled and TCLP analyzed on a routine basis.

Gas Sampling Points

Temperature, vacuum pressure, methane gas composition, and flow rate are measured once a month at the flare inlet and at each extraction well (well flow rates are not measured). An Air Data Flow Meter is used to measure the gas flow rate at the inlet to the flare (after the blowers). Landfill personnel do not calibrate the gas flow meter.

A Gas Scope is used to measure methane gas content at the inlet to the flare and at each recovery well. The gas scope is calibrated once a month.

Leachate Collection

The older section, which consists of approximately 46 acres, does not have an active leachate collection system. The rest of the landfill does have an active leachate collection system.

Gas Migration

The flare was installed in February 1990 to control off-site gas migration. Since installation of the flare, gas migration off-site is controlled, as evidenced by no detectable CH_4 at the 20 perimeter probes. The gas probes are inspected on a monthly basis. No vegetative stress was detected in the closed areas or on the perimeter of the landfill.

Information Gathered

Two maps of the landfill were received during the site visit (attached). Monthly measurements of vacuum, percent methane, and temperature at the flare inlet and extraction wells, examples of the routine gas condensate TCLP tests, and methane probe monitoring records were provided. Gas flow records from the flare inlet were also provided. Finally, average waste acceptance rates and tonnage in place for areas with gas extraction wells were received from landfill personnel.

LANDFILL 22

Place and Date

State: Minnesota

Date: May 3, 1991

Background Information

The landfill covers 100 acres and refuse acceptance began in 1970. Refuse acceptance ceased in 1988, with the majority of refuse accepted until 1985. The total tons of refuse in place is 4,380,003 tons, with only 260,421 tons accepted from 1986 to closing in 1988. These tonnage estimates are based on gate records of cubic yards brought in and assuming a conversion of 4 yards per ton. The refuse age ranges from 20 years to 3 years, with an average of 13 years.

The landfill accepted primarily municipal solid waste, no known commercial hazardous wastes, little construction and demolition debris, and little sludge. The depth of the fill area ranges from a minimum of 5 to 6 feet at the edges to an average (and maximum) of 80 feet. The landfill does not have final closure, but the entire surface is covered with least 2 feet of silty-clay, which is 10 to 15 feet deep in some areas. The refuse is settling 5 to 10 feet/year, and clay is added to control surface water drainage.

Landfill Gas Collection System

Landfill gas collection began in February of 1989. The gas is currently flared, as gas recovery personnel feel they cannot produce electricity or pipeline quality gas profitably. The well field has a total of 54 wells, but 14 of these wells are in the east area to prevent off-site migration and are not placed in refuse. The 12-inch header line from these wells is brought into a separate blower house on the east side of the property. The two 15 hp, 1100 scfm capacity Lamson blowers run only when nearby perimeter probes detect methane gas migration. The gas from the east side header was originally brought to a separate flare, but the methane content (<10%) and flow of gas from these wells (120 scfm) were too low to maintain the flare. This header is now tied to the header from the high-flow wells before the two lines enter the blower house.

The 40 high-flow wells range in depth from 35 to 80 feet and draw the majority of gas from this landfill. These wells are connected to an 18-inch header which brings the gas first to the blower house and the condensate knockout tank. Gas recovery personnel feel that this site produces a low amount of condensate; they tank and truck approximately 500 gallons/day. The gas then flows to one of two Lamson blowers (each 50 hp with a capacity of 3600 scfm). The blowers always run alternately. The system is currently operating at 1500 scfm with the methane content of the gas averaging 40%. Gas is flared in a John Zink open candle flare with an NAO exterior. There is an ultraviolet sensor to detect the flame and keep the automatic system from cutting the flare off when winds shift the flame.

Gas Sampling Points

Total gas flow from both header lines is measured daily with an Air Data Multimeter model 870 at the inlet and outlet of the main blower house. The Multimeter is calibrated once each year. Gas composition is monitored once each year by an independent laboratory. Gas flow, and composition from the east side header is also measured separately. Wells are tested weekly for temperature, percent methane (with Mine Safety Appliances MSA 625 Explosimeter). Flow is tested less often at the wells.

Leachate Collection

There is no active leachate collection system at this landfill; the fill area is surrounded by 54 ground-water test wells.

Gas Migration

Gas migration off-site is monitored with 74 perimeter probes that are tested on a weekly basis with an MSA 62S Explosimeter. Historical test data on these probes must be viewed with caution because the probes along the northwest edge of the fill area (probes G-5, G-6, and G-7) are actually placed in fill and are not representative of gas migration off-site. Due to concern over the proximity of houses on the east side of the landfill, the east side wells were installed (not on fill) to contain any migration. Gas recovered from these wells is negligible. Gas migration through the cap is monitored weekly with an organic vapor analyzer. Gas recovery personnel indicate that there is no significant amount of gas escaping to the atmosphere.

Information Gathered

Gas recovery personnel provided maps showing well and perimeter probe locations, perimeter probe test results for 1990, well boring logs, and condensate test analyses. Records of refuse (in tons) deposited each year were provided, along with three graphs of estimated methane gas generation rates over time assuming three different production (decomposition) rates. Gas recovery personnel provided test results of flare inlet gas analyses from two independent consultants, and total CH_4 flow data taken at the flare inlet, as well as flow data for wells on the east side of the landfill.

Information to be Sent

Gas recovery personnel were asked to provide the most recent gas flow data.

REFERENCE

Campbell, D., D. Epperson, L. Davis, R. Peer, and W. Gray. 1991. Analysis of Factors Affecting Methane Gas Recovery From Six Landfills. Prepared for Air and Energy Engineering Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA-600/2-91-055 (NTIS PB92-101351).

APPENDIX B

Metric/U.S. Equivalent Chart

Data in the main body of this report are presented in metric units. This conversion table is provided for easy reference.

Metric/U.S. Equivalent Conversion Chart

Multiply	by	To obtain
feet meters	0.3048 3.2808	meters feet
acres hectares	0.4047 2.4710	hectares acres
cubic feet cubic meters	0.0283 35.3145	cubic meters cubic feet
inches centimeters	2.5400 0.3937	centimeters inches
tons (2000 lb) metric tons (Mg)	0.9072 1.1023	metric tons (Mg) tons (2000 lb)
tons per acre Mg per hectare	2.2417 0.4461	Mg per hectare tons per acre
cubic feet per acre cubic meters per hectare	0.0700 14.2913	cubic meters per hectare cubic feet per acre
cubic yards cubic meters	0.7646 1.3079	cubic meters cubic yards
acres acres	4,046.9 43,560	square meters square feet
cubic yards per ton cubic meters per Mg	0.8428 1.1865	cubic meters per Mg cubic yards per ton
cubic feet per ton cubic meters per Mg	0.0312 32.0563	cubic meters per Mg cubic feet per ton
cubic meters of CH_4 (at STP)	713.8	grams CH_4 (at STP)

<u>Temperature</u>

Fahrenheit = (1.8)(Celsius) + 32

Celsius = 0.556 [(Fahrenheit) - 32]

APPENDIX C

Data Summary Tables in U.S. Equivalents

This appendix contains data summary tables in U.S. Equivalents. The corresponding metric table in the main body of the report is referenced.

TABLE C-1. COMPARISON OF SUMMARY STATISTICS FOR METHANE FLOW RATES AT THE LANDFILLS[a]

Landfill	Measurements: Type	Measurements: Number	Methane Recovery (ft^3/min): Average	Median	Standard Deviation	Minimum Value	Maximum Value	Range	Coefficient of Variation (CV)
1	daily	194	1955	1954	75	1696	2169	474	3.8
2	daily	302	637	644	42	435	723	289	6.6
3	daily	314	1415	1424	82	1068	1576	508	6.3
4	daily	85	3477	3489	47	3296	3585	289	1.4
5	daily	209	878	880	60	725	987	262	6.8
6	daily	37	590	592	73	445	800	355	12.4
7	monthly	12	342	359	71	143	423	280	20.9
8	daily	626	415	437	87	18	604	587	21.0
9	daily	15	272	247	50	202	372	170	21.2
10	monthly	6	1036	1077	18	827	1145	318	11.4
11	monthly	12	399	415	43	322	449	127	10.8
12	daily	232	282	273	36	191	366	176	12.9
13	daily	11	368	390	53	276	414	138	14.5
16	monthly	15	567	585	46	260	765	505	25.7
17	minute	13	488	491	53	358	583	225	10.8
20	monthly	12	1237	1240	68	935	1458	522	25.5
21	daily	11	967	937	04	865	1164	299	10.8
22	daily	51	1172	1125	77	764	2121	357	23.6
23	daily	202	79	81	18	11	104	93	22.9
24	daily	333	625	631	77	110	781	677	12.4
25	daily	331	715	734	99	51	862	811	13.9

[a] Corresponds to Table 2.

TABLE C-2. SUMMARY OF LANDFILL PARAMETERS USED IN THE STATISTICAL ANALYSES (U.S. Equivalents)[a]

Landfill Identification Code Number	Landfill Identification Code Letter	Refuse Mass (10^6 tons)	Average Refuse Age (yrs)	Landfill Area (acres)	Average Landfill Depth (feet)	Average Well Depth (feet)	Number of Wells	Landfill Volume (10^6 feet^3)	Average Methane Flow Rate	Average Methane Rate Per Unit Mass (ft^3/min/ 10^6 tons)	Gas End Use
1	A	7.00	8.0	86.0	220.00	45.00	45	824.9	1955	279.29	ELEC.-TURBINE
2	B	6.75	10.0	135.0	85.00	47.00	44	500.3	637	94.37	ELEC.-TURBINE
3	C	8.10	10.0	126.0	217.00	77.00	31	1192.1	1415	174.69	ELEC.-TURBINE
4	D	15.20	9.5	140.0	185.00	70.00	111	1129.2	3477	228.75	ELEC.-TURBINE
5	E	12.00	15.0	80.0	150.00	112.00	102	523.2	878	73.17	FLARE
6	F	2.64	7.0	99.6	32.25	32.25	68	140.0	590	223.49	ELEC.-IC ENGINE
7	G	3.25	10.0	125.0	60.00	40.00	48	327.0	342	105.23	BOILER FUEL
8	H	3.00	10.0	55.0	55.00	55.00	107	131.9	415	138.33	HIGH BTU
9	I	1.80	7.0	30.0	50.00	50.00	32	65.4	272	151.11	FLARE
10	J	5.80	12.0	80.0	70.00	45.00	96	244.2	1036	178.62	HIGH BTU
11	K	2.00	10.0	69.0	80.00	45.00	39	240.7	399	199.50	BRICK KILN FUEL
12	L	3.06	8.5	85.0	35.00	35.00	78	129.7	282	92.16	HIGH BTU
13	M	1.06	7.0	35.0	40.00	40.00	51	61.0	368	348.49	FLARE
16	P	3.73	5.5	75.0	90.00	60.00	36	294.3	567	152.01	ELEC.-TURBINE
17	Q	5.70	10.0	40.0	60.00	60.00	41	104.6	488	85.61	FLARE
20	T	10.70	11.0	180.0	60.00	57.00	69	470.9	1237	115.61	FLARE
21	U	2.87	13.0	66.0	90.00	60.00	56	259.0	967	337.29	FLARE
22	V	4.38	12.0	100.0	80.00	80.00	40	348.8	1172	267.58	FLARE
23	W	3.16	10.7	100.0	70.00	65.00	19	305.2	79	25.00	ELEC.-IC ENGINE
24	X	6.84	5.6	270.0	100.00	50.00	23	1177.2	625	91.37	ELEC.-TURBINE
25	Y	11.74	12.0	185.0	75.00	70.00	43	605.0	715	60.90	ELEC.-TURBINE

[a] Corresponds to Table 4.

TABLE C-3. SUMMARY OF CLIMATIC DATA FOR THE LANDFILLS (U.S. Equivalents)[a]

		Annual Climate Averages (from refuse acceptance period)				30-year Annual Averages		
Landfill	Weather Average Period	Average Temp. (°F)	Maximum Temp. (°F)	Minimum Temp. (°F)	Total Rainfall (inches)	Average Temp. (°F)	Average Dewpoint (°F)	Total Rainfall (inches)
1	1955 to 1989	45.2	55.6	34.7	29.66	45.5	38	28.76
2	1968 to 1982	48.7	58.9	38.4	37.14	48.7	39	35.62
3	1970 to 1988	54.7	63.7	45.7	42.99	54.3	43	41.42
4	1971 to 1988	76.3	85.4	67.2	55.46	75.1	65	61.38
5	1951 to 1989	63.1	77.6	48.7	16.60	62.8	50	17.02
6	1975 to 1989	61.1	75.1	47.0	18.66	61.1	47	17.89
7	1972 to 1989	59.2	70.2	48.1	42.43	59.0	48	41.76
8	1973 to 1987	61.6	71.6	51.6	49.72	61.2	50	48.61
9	1979 to 1989	64.4	76.0	52.8	58.39	64.6	54	52.82
10	1962 to 1989	61.9	72.9	50.8	54.05	62.2	51	54.52
11	1962 to 1989	64.5	76.3	52.7	44.89	64.7	52	44.86
12	1969 to 1983	54.0	63.8	44.1	49.36	53.9	44	48.40
13	1980 to 1988	51.2	61.7	40.8	40.86	51.9	44	41.07
16	1976 to 1989	48.8	59.5	38.0	38.44	49.1	37	40.16
17	1952 to 1989	47.0	55.7	38.3	48.03	46.8	35	47.60
20	1967 to 1989	48.6	58.1	39.2	32.43	48.6	39	30.97
21	1971 to 1986	48.4	57.9	38.9	32.77	48.6	39	30.97
22	1970 to 1988	45.0	54.4	35.7	28.81	44.7	34	26.36
23	1958 to 1986	50.1	64.0	36.2	15.36	50.3	28	15.31
24	1972 to 1989	66.2	76.5	55.9	35.00	66.0	52	29.45
25	1970 to 1989	49.2	58.6	39.7	37.25	49.2	39	33.34

[a] Corresponds to Table 5

APPENDIX D

Landfill Data Sheet

This data sheet was used as a guide by project team members in order to obtain relevant and complete data prior to and during the site visit.

LANDFILL DATA SHEET

Call Made By ______________________ Date Call Made ______________
Landfill Facility Name: ______________________
Address: ______________________
____
____

Contact at Landfill: ______________________ Phone Number: ______________

Please provide the following information for only that portion of your landfill where methane is being recovered. Please provide this information for the period of time that data has been collected. For items such as the number of wells that may have changed over time, please provide the current information.

PRIORITY DATA

Active Landfill? ______________________
Date Waste Acceptance Began ______________________
Date Waste Acceptance Ceased ______________________
Date Methane Recovery Began ______________________
Gas End Use ______________________
Annual Methane Production Rate ______________________
Tons of Refuse in Place ______________________
Age of the Refuse ______________________
Number of Acres ______________________

ADDITIONAL INFORMATION (provide as necessary)

Number of Active Wells (Regular- or High-Flow Wells) ______________________
Number of Low-Flow Wells ______________________
Depth of Active Wells: Minimum ____________ Average ____________ Maximum ____________
Depth of Low-Flow Wells: Minimum ____________ Average ____________ Maximum ____________
Depth of Landfill: Minimum ____________ Average ____________ Maximum ____________
Methane Recovery System (i.e., turbine, IC engine, other): ______________________
Landfill Design (i.e., cell, canyon, trench, or other) ______________________
Cap Composition ______________________ Cap Thickness ____________
Cap Permeability ______________________
No. of Flares (if applicable) ______________________
Acceptance Rate of Waste by Year ______________________
Total Capacity (by weight): ______________________

[If capacity is provided by volume, what is the average refuse density?]

____

Daily Soil Cover Information (does volume number include ALL refuse or soil and refuse?)

____

Results of Routine Testing for Surface or Perimeter Leaks ______________________
Any other data available on:

Refuse Composition? ______________________
Gas Composition? ______________________
Moisture Content of Refuse? ______________________
Compliance Testing of Power Generation or Control Equipment Exhaust?

____

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

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15. SUPPLEMENTARY NOTES AEERL project officer is Susan A. Thorneloe, Mail Drop 63, 919/541-2709.

16. ABSTRACT The report gives results of a field study of 21 U.S. landfills with gas recovery systems, to gather information that can be used to develop an empirical model of methane (CH_4) emissions. Site-specific information includes average CH_4 recovery rate, landfill size, tons of refuse (refuse mass), average age of the refuse, and climate. A correlation analysis showed that refuse mass was positively linearly correlated with landfill depth, volume, area, and well depth. Regression of the CH_4 recovery rate on depth, refuse mass, and volume was significant, but depth was the best predictive variable ($R^2 = 0.53$). Refuse mass was nearly as good ($R^2 = 0.50$). None of the climate variables (precipitation, average temperature, dewpoint) were correlated with the CH_4 recovery rate or with CH_4 recovery per metric ton of refuse. Much of the variability in CH_4 recovery remains unexplained, and is likely due to between-site differences in landfill construction, operation, and refuse composition. A model for global landfill emissions estimation is proposed.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Earth Fills	Stationary Sources	13C
Methane	Gas Recovery	07C
Emission		14G
Mathematical Models		12A
Refuse		

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