AN ANALYSIS OF THE FACTORS AFFECTING LANDFILL GAS COMPOSITION AND PRODUCTION AND LEACHATE CHARACTERISTICS AT THE VANCOUVER LANDFILL SITE AT BURNS BOG

By

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ABSTRACT

Landfill gas represents either a significant contributor to the build-up of greenhouse gases in the troposphere when released, or a potential energy source when recovered. An analysis of variation in landfill gas production and composition (%CH_4, %CO_2) in response to variations in ambient temperature, precipitation, barometric pressure and refuse age was carried out at the Vancouver Landfill Site at Burns Bog, located in Delta, B.C.. Results indicate that precipitation is a predominant factor, as illustrated in the relationship between cumulative precipitation 14 days prior to sampling and CH_4 generation (mean r^2=0.88). This finding suggests that a time lag is in effect wherein the moisture acts to enhance the anaerobic nature of the niche, increase the mixing and availability of carbon rich organic matter and nutrients, directly stimulate bacterial growth and dilute metabolic inhibitors, leading to increased CH_4 production. Ambient temperature displayed only a moderate correlation with CH_4 production (mean r^2=0.41), likely due to the establishment of a relatively consistent microclimate within the waste matrix. High gas temperatures were observed to correspond with periods of peak CH_4 production. Fluctuations in barometric pressure were not seen to have an effect on landfill gas production at the p=0.05 level of significance. Refuse age showed some relationship to CH_4 production, but results of this were inconclusive. Regression equations were calculated to predict CH_4 production from the sample gas ports and gas collection lines. Total annual CH_4 production from this site was calculated to be 44.76 kT, which equates to approximately 3% of the total CH_4 produced by landfills in Canada. Results suggest that the potential does exist for the optimization of waste degradation within the matrix. The production ratio of CH_4:CO_2 showed a strong relationship to cumulative precipitation 7-days prior to sampling (r^2=0.85), with the relatively high ratio following periods of heavy rainfall. It is likely that conditions of low hydraulic retention time cause the CO_2 to be dissolved from the matrix and flushed downward with the movement of the leachate. It is also possible that the CO_2 acts as an end-product inhibitor during acetate and propionate degradation; its decreased partial pressures after periods of heavy rainfall would thus favour enhanced CH_4

ABSTRACT (CONT'D)

production. Leachate parameters displayed high variability. COD concentrations were observed to decrease following heavy rainfall. Loadings of both NH_4^+-N and acetic acid were observed to increase with higher precipitation inputs, most likely due to the increased mobilization of the substances. Both NH_4^+-N and acetic acid loadings were found to increase significantly with increasing CH_4 production. Once again, it is likely that the "washing" of the matrix following periods of heavy rainfall (and increased CH_4 production) is responsible for this observation.

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CHAPTER 1 - INTRODUCTION

Municipal solid waste disposal is among the most consequential and expensive challenges facing communities today. As the volume of waste materials generated continues to increase, augmenting pressures accompany decisions regarding land use and environmental management. Despite recent efforts to increase participation in composting and recycling of refuse, landfill disposal remains the end point for the majority of our discarded materials. It is likely that landfills will continue to play this significant role in the disposal of solid wastes, because in many cases they enjoy an economic advantage over alternative means of disposal, while providing an adequate service. Until recently landfill siting, construction and operation were simplistic in nature as little or no attention was paid to the environmental impact of the products of waste decomposition. With the incorporation of leachate collection and treatment systems, landfill gas control systems and regular monitoring of parameters at the site, engineered landfills have become highly regulated "bioreactors".

The environmental impact of landfill sites is a waste management concern which has significant implications. With respect to greenhouse gas emissions, an average tonne of landfilled municipal solid waste eventually produces 174 kg of CO_2, 63 kg of CH_4 and numerous trace gases as products of the waste decomposition process (MacViro Consultants Inc., 1991). The global warming potential of CH_4 (calculated using residence times and radiative forcing effects) is estimated to be approximately 25 times that of CO_2. Consequently, as the highest anthropogenic source of CH_4 to the atmosphere, landfill sites have attracted much attention on the global warming issue. However, when collected, landfill gas can be utilized in energy-from-waste conversions; the generation of heat and/or electricity from landfill gas is within the realms of present technology. Landfill gas utilization acts to significantly decrease greenhouse gas emissions, while displacing the fossil fuels which would otherwise be used as the energy source.

The leachate produced by the action of moisture percolating through the waste matrix must also be collected and treated in order to reduce the impact of the landfill on the surrounding ecosystems. If ignored, the leachate could potentially contaminate both groundwater and surface water supplies through ammonia toxicity, exertion of oxygen demand through nitrification, or by providing nutrients for eutrophication. A number of effective methods for the treatment of landfill leachate have been developed, and are presently in use.

It has recently been recognized that potential benefits may accompany landfill management strategies which aim at the optimization of the decomposition process. An understanding of the degradation of waste materials within the landfill matrix is therefore necessary. These processes have often been compared to those occurring in a soil profile, due to the similarity in the characteristics of the matrix, the most important being the microbial processes occurring within. The optimization of the microbial degradation of refuse could result in a more rapid volume reduction of the wastes, reduced leachate treatment requirements, reduced post-closure care costs, earlier site re-use and greater energy recovery potential.

The primary objective of this study was to determine the effects of precipitation, ambient temperature, barometric pressure and refuse age on the production of CH_4 from the Vancouver Landfill Site at Burns Bog. An additional objective involved the calculation of regression equations to estimate the production of CH_4 from the individual gas ports, taking into consideration the variables which were found to affect the process. An investigation into the overall production of CH_4 from the site was undertaken, in order to determine the landfill gas production volumes from the site as a whole. An additional objective included the attempt at detecting C_2H_4 in the landfill gas, as its toxic effects on vegetation are well documented. Leachate parameters of interest (chemical oxygen demand, total organic carbon, pH, volatile fatty acids and NH_4^+-N) were investigated in order to highlight any discernible patterns in relation to both climate variables, and CH_4 production. The final objective of this research was to discuss the results from the aforementioned investigations with respect to the process of waste decomposition within the landfill site.

CHAPTER 2 - LITERATURE REVIEW

2.1 Refuse Decomposition

Present knowledge of the degradative reactions within the landfill environment is generally inferred from the examination of the major end-products, those being CH_4, CO_2, and volatile fatty acids (Rees, 1980). By use of these inferences, Pohland (1976) was able to describe the potential of a sanitary landfill to go through five distinct phases in the process of stabilization:

Phase 1 - initial adjustment (aerobic)
Phase 2 - transition (anaerobic)
Phase 3 - acid formation (anaerobic)
Phase 4 - methane fermentation (anaerobic)
Phase 5 - final maturation (anaerobic)

It is important to note that the duration and intensity of each phase will vary with the changing conditions of each distinct site.

2.1.1 - INITIAL ADJUSTMENT PHASE

Aerobic biological activity begins to degrade the organic fraction of refuse immediately after it is deposited in the landfill (Miller, 1988). Free O_2 trapped in the waste matrix is quickly exhausted, and CO_2 is formed in approximate concentration to the amount of O_2 consumed (Figure 2.1.1) (Saint-Fort, 1992). During the first few days after refuse placement, temperatures of the compacted waste will rise, followed by a gradual decline back to ambient temperatures. When refuse density is relatively high (~590 kg/m^3), this primary aerobic stage of decomposition will last only a few days. However, if adequate refuse emplacement density is not achieved, this stage may persist. In this situation, the landfilled area will be characterized by the unpleasant odour of organic matter decomposition, high temperatures, and rising carboxylic acid concentrations in the leachate as a result of incomplete metabolic degradation by bacteria.

2.1.2 - TRANSITION PHASE

As O_2 is rapidly depleted by the degradative processes, the reduced conditions encourage the transition to facultative anaerobic microbial stabilization. Primary electron acceptors now shift from free oxygen to nitrates and sulfates, and complex organics are degraded into simpler organic materials (Figure 2.1.1). This phase is typified by increased concentrations of carboxylic acids in the leachate, rising production of CO_2, and a duration in the order of several months in a well managed site.

2.1.3 - ACID FORMATION PHASE

Intermediary volatile fatty acids become the main product during this phase as hydrolysis and fermentation of the waste and leachate constituents continue (Figure 2.1.1). The formation of these organic acids leads to a lowered pH, which in turn triggers the mobilization and possible complexation of metal species (Saint-Fort, 1992). Soil, surface and groundwater contamination is a concern related to this phase of the refuse decomposition process.

2.1.4 - METHANE FERMENTATION PHASE

The organic acids, alcohols, new cells, and energy produced in the Acid Formation Phase are utilized by methanogenic bacterial populations to produce predominantly CH_4 and CO_2 (Figure 2.1.1). An increase in pH to approximately neutral levels is achieved at this stage. Temperatures within the landfill matrix become stabilized at approximately 40°C, this parameter being dependent, however, on conditions specific to the niche. Decomposition is usually more rapid under thermophilic conditions than under mesophilic conditions. Interactions of metal species involving complexation and precipitation reactions with reduced elements such as sulphides and organic ligands take place. The establishment of strictly anaerobic methane-producing bacteria acts to decrease the production of high strength leachate, resulting in a significantly reduced potential environmental impact. This phase may persist for a time period in the order of 20 years.

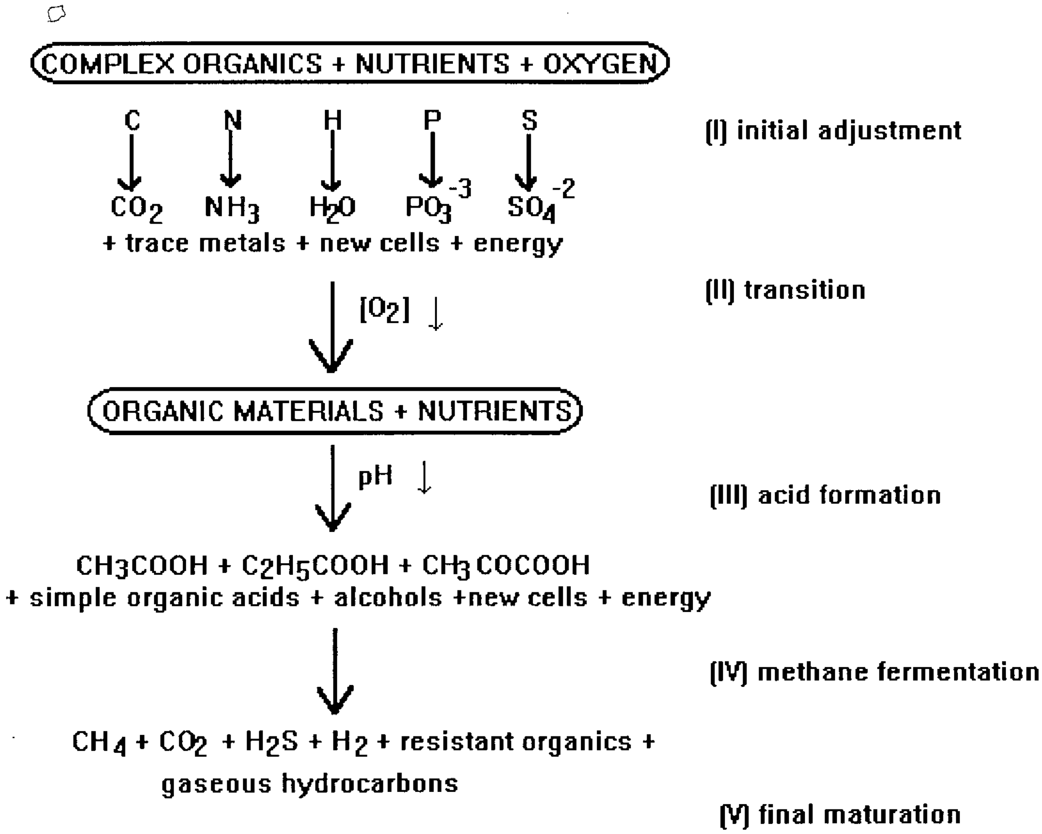

FIGURE 2.1.1: General scheme of the decomposition process in a landfill (modified from Saint-Fort, 1992)

2.1.5 - FINAL MATURATION PHASE

Little is known about the processes related to the long-term stabilization of landfills, but it is hypothesized to go through a relatively dormant stage characterized by biological stabilization of the remaining organic carbon and a gradual decline in the production of gases. Oxygen and oxidized species may reappear, resulting in further degradation of biologically inert material, with the possible production of humic-like substances (Saint-Fort, 1992). There is ambiguity and lack of scientific data with respect to this phase of landfill stabilization.

2.2 The Importance of Microbes

Little is known regarding the microbiology of landfill sites, as the biochemical pathways of refuse degradation are difficult to study. The sequence of the degradative events occurring in a landfill can be tentatively constructed from previous studies, and by analogy with other methanogenic ecosystems (Archer *et al.*, 1988). The heterogeneous nature of refuse, and the resultant problems related to sampling have most likely discouraged microbial examination in the past.

The two main bacterial populations involved in refuse degradation are the acetogens and the methanogens. Relatively little is known about the former population, other than the fact that their anaerobic degradation of volatile fatty acids is energetically unfavourable, and will therefore not proceed unless coupled to a methanogenic reaction. The anaerobic degradation of propionic acid by the acetogen Syntrophobacter wolinii is shown in Figure 2.2.1.

	$\Delta G°$ (kJ/mol)
$CH_3CH_2COO^- + 3H_2O$ ------> $HCO_3^- + CH_3COO^- + H^+ + 3H_2$	+76.1
$HCO_3^- + 4H_2 + H^+$ --------> $CH_4 + 3H_20$	-135.6
SUM: $4CH_3CH_2COO^- + 3H_20$ ----> $HCO_3^- + 4CH_3COO^- + 3CH_4 + H^+$	-102.4

FIGURE 2.2.1: Acetogenesis coupled with methanogenesis using a propionic acid substrate (Archer *et al.*, 1988)

The acetic acid produced may be further metabolized by acetotrophic methanogens such as Methanothrix soehngenii and Methanosarcina barkeri. The mutualistic association between acetogens and methanogens is illustrated in the above reaction. The requirements of each member species in this association must be satisfied in order for methanogenesis to proceed. These bacterial populations require a reducing environment (low Eh), neutral pH, and a range of nutrients. Little attention has been paid to their nutrient requirements due to the common belief that the "landfill will provide". It may be argued however, that the extreme heterogeneity of refuse within the landfill will most likely lead to pockets of deficiency and variability in nutrient availability (Archer *et al.*, 1988).

Some potential for the enhancement of landfill gas production lies in the optimization of microbiological processes. Although certain methods to influence the behaviour of these microorganisms have met with success (control of water content, leachate recirculation, refuse density), much uncertainty surrounds this issue. The microbiology and biochemistry involved in waste degradation must be considered when making landfill management decisions.

2.3 Gas Production

2.3.1 - PRODUCTION PATTERNS

The composition of the gas produced in the degradative reactions is a function of the types of microorganisms predominating during the successive stages (Lisk, 1991). Various attempts have been made to decipher the gas composition patterns during municipal refuse decomposition, but the most prominent appears to be the illustration by Farquhar and Rovers (1973) (Figure 2.3.1). Under this scheme, the four phases of landfill gas production are designated as I/Aerobic, II/Anaerobic Non-Methanogenic, III/Anaerobic Methanogenic Unsteady and IV/Anaerobic Methanogenic Steady.

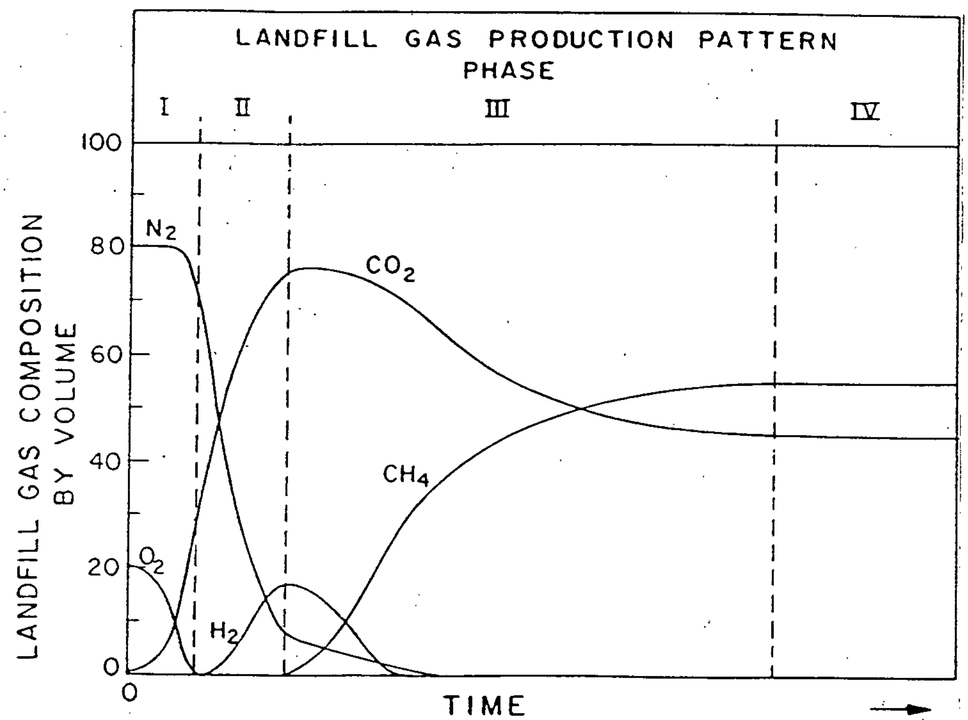

FIGURE 2.3.1: Gas production pattern in a landfill (adapted from Farquhar and Rovers, 1973)

The predominant patterns in gas production include a rapid depletion of O_2 in Phase I, a CO_2 "bloom" during Phase II, and a stabilization of CH_4 and CO_2 production during the latter part of Phase III and Phase IV (Figure 2.3.1). The literature reports some variation with respect to the completion time for the first three phases, ranging from 180 days (Ramaswamy, 1970) to 500 days (Beluche, 1968). In general, one may assume that in the case of older sites (>5 years) the reactions will be of the Phase IV type. At this stage in the process, composition of the gases and rates of production remain steady for the prevailing conditions. Typical values ranging from 50-70% CH_4 and 30-50% CO_2 are expected in the final phase. Some fluctuations are still possible; changes in environmental conditions, nutrient depletion, or the accumulation of inhibitory materials may lead to variation in gas production (Farquhar *et al.*, 1973).

2.3.2 - METHANE BALANCE

A methane balance can provide a useful framework when attempting to evaluate landfill methane emissions. Bogner and Spokas (1993) created a simplified mass balance for analysis of this landfill process (Figure 2.3.2). The balance is partitioned as follows:

CH_4 generated= Σ(CH_4 emitted+CH_4 recovered+CH_4 oxidized+CH_4 migrated)+ΔCH_4 stored

This balance provides a means of cohesion between the processes of generation, transport, and microbial oxidation of CH_4.

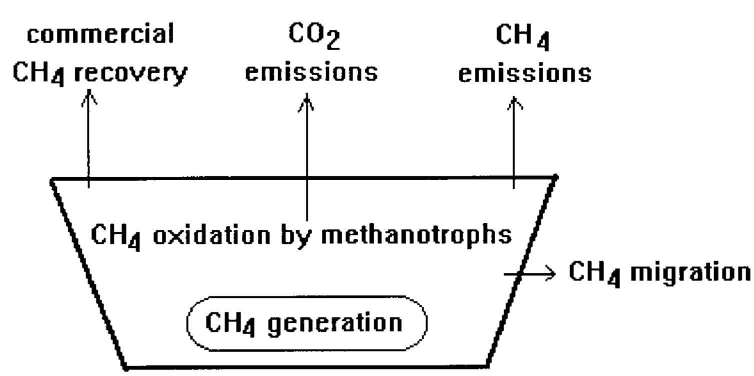

FIGURE 2.3.2: Simplified CH_4 balance for a landfill site (modified from Bogner and Spokas, 1992)

2.3.3 - QUANTIFICATION OF GAS PRODUCTION

For the purposes of collection, management and utilization of CH_4 in landfill gas, attempts at its quantification have been made. These attempts vary broadly in both calculations and results. Using the proposal of Pirt (1978), the theoretical yield of CH_4 and CO_2 from glucose is as follows:

$$1\text{kg } C_6H_{12}O_6 \text{--->} 0.25\text{kg } CH_4 + 0.69\text{kg } CO_2 + 0.056\text{kg dry biomass} + 632 \text{ kJ heat}$$

The result is equivalent to 0.7 m^3 gas at standard temperature and pressure. Another approach, such as that put forward by Saint-Fort (1992), can be used to forecast the theoretical maximum yield of CH_4 per tonne of dry refuse assuming pure anaerobic conditions:

gas composition	=50% CH_4 and 50% CO_2
MW of carbon	=12 g/mol
1 mole of gas	=22.4 L at STP
dry weight of refuse	=50% organic carbon

and assuming that 80% of the organic carbon is converted to gas.....

therefore, 1 g of organic carbon will be expected to produce:

$$(0.80 \times 0.50) \times 1 \text{ mol}/12\text{g} \times 22.4 \text{ L/mol } CH_4 = 0.75 \text{ L } CH_4$$

since the dry weight of refuse is assumed to be 50% organic carbon, consequently:

$$1 \text{ g of waste will produce} = 0.75 \text{ L } CH_4 \times 0.50 = 0.38 \text{ L of } CH_4$$

It is important to note, however, that observed yields tend to be approximately 28% of the theoretical maximum yield (Hoeks, 1983). This is most likely attributable to a failure to optimize environmental conditions for the methanogenic bacterial populations.

2.4 Leachate Production

As water percolates downwards through the waste matrix organic and inorganic constituents are dissolved, and when the field capacity of the refuse is exceeded leachate is produced. Mechanisms contributing to leachate enrichment are described by Saint-Fort (1992) to include the following principal transformations:

- transformation of complex organics to more soluble end-products (e.g. acetic acid, alcohols)
- chemical reduction reactions (e.g. Fe(III)--->Fe(II) and Mn(IV)--->Mn(II)) to more water soluble forms
- transport of fine solid materials
- movement of inherently soluble organic and inorganic compounds (e.g. organics with hydrophilic functional groups)

A variety of parameters are known to govern leachate production, those including climatic conditions, site hydrology, particle size, refuse compaction, composition of the refuse, and the degree of stabilization of the wastes.

2.4.1 - LANDFILL WATER BALANCE

A simple water balance equation may be used in some cases to estimate the volume of leachate produced at a specific site (Atwater, 1994):

$$L = \Sigma(P+GW+SW+M) - \Sigma(E+RU+SR)$$

where: P=precipitation GW=groundwater inputs SW=surface water inputs
M=refuse moisture E=evaporation/evapotranspiration
RU=refuse uptake SR=surface runoff

Variables such as groundwater inputs, surface water inputs, surface runoff and evapotranspiration can be regulated to some degree. These estimations remain somewhat problematic due to heterogeneity of the composition of the deposited wastes, and the dynamic changes occurring during the stabilization process.

2.4.2 - LEACHATE CONSTITUENTS

The variation in leachate characteristics is so large that attempts to define a "typical" composition are problematic. This wide range in chemical compositions and physical characteristics in leachate constituents may be attributable to a number of factors including dilution effects, sampling points, landfill age, hydrogeology of the site and soil attenuation (Saint-Fort, 1992). A compilation of typical leachate characteristics from various sites was put together by Lisk (1991), as shown in Table 2.4.1. Results found by Williams *et al.* (1987) indicated that the organic strength of the leachate will progressively decrease as biogas generation increases.

The chemical oxygen demand (COD) concentration in leachate is an indirect measure of the organic matter present, and thus decreases with landfill age due to the biodegradeable nature of the organics (Sawyer *et al.*, 1978). The biochemical oxygen demand (BOD) parameter reflects the biodegradability of the organic matter in the leachate. Low BOD:COD ratios (<0.1) suggest the presence of refractory humic-like substances, which render the leachate relatively difficult to treat by biological processes.

The total organic carbon (TOC) is a measure of the organic carbon present in the leachate. A high COD:TOC ratios reflects the unoxidized state of organic carbon in the leachate; a situation common in younger landfill sites (i.e. - 6 months to 3 years of age). In older landfill sites, the COD:TOC ratio is commonly less than 2.0.

The presence of NH_4^+-N at appreciable levels in the leachate suggests that there is sufficient available nitrogen to sustain a high reactivity of the methanogenic microorganisms within the refuse matrix. Adverse effects may accompany high NH_4^+-N concentrations in the leachate. This cation can replace toxic metal ions on soil exchange sites, thus releasing them and causing the potential for groundwater contamination (Baedecker *et al.*, 1979). This potential action is only a concern when high metal concentrations exist in the surrounding soil.

Free volatile fatty acids typically appear at highest concentration in the leachates of newly deposited refuse. These substances are readily fermented, but initially enhance solution of heavy metals (Lisk, 1991). Volatile amines, ethanol, hydrocarbons, esters and terpenes may also be present during the acidification stage of refuse degradation. In large landfills, concentrations of volatile fatty acids tend to be relatively low, as the freshly deposited refuse represents a small proportion of total wastes deposited.

In addition to the potential risks mentioned above, groundwater and surface water contamination problems such as ammonia toxicity, exertion of oxygen demand through nitrification, and nutrient loadings leading to eutrophication can be the result of leachate introduction (Johnston *et al.*, 1985). It is for these reasons that leachate collection and treatment must be performed in order to reduce the impact of the landfill on its surrounding ecosystems.

2.5 Leachate Treatment

Landfill leachate may be described as a wastewater with characteristics which are highly variable both on the spatial and temporal scales. Specific to "older" landfills, leachates tend to be high in NH_3-N, low in biodegradable carbon and have pH readings in the neutral range (Chian *et al.*, 1985). A number of treatment methods have been developed to lessen the environmental impact of landfill leachates.

TABLE 2.4.1: Composition of leachates from refuse landfills (adapted from Lisk, 1991).

PARAMETER	CONCENTRATION RANGE (mg/L)	PARAMETER	CONCENTRATION RANGE (mg/L)
pH	6.2-7.4	Mg	12-480
COD	66-11600	K	20-650
BOD	2-8000	Ca	165-1150
TOC	21-4400	Cr	0.05-0.14
NH_3-N	5-730	Mn	0.32-26.5
NO_3-N	0.2-4.9	Fe	0.09-380
organic N	0-155	Ni	0.05-0.16
$H_2PO_4^-$	0.02-3.4	Cu	0.01-0.15
Cl^-	70-2777	Zn	0.05-0.95
SO_4^{-2}	55-456	Cd	0.005-0.01
Na	43-2500	Pb	0.05-0.22

2.5.1 - NATURAL ATTENUATION

When utilizing the natural attenuation method of purifying leachate, the assumption is made that the passage of leachate through the unsaturated zone below the landfill will remove some of the undesired constituents, and dilution upon reaching the groundwater will further decrease concentrations to an acceptable level (James, 1977). This treatment alternative relies on a number of mechanisms of attenuation by soil constituents.

The first involves the filtration and adsorption of particulates in the leachate by the random pore structure of the soil profile. Filtration will be improved with finer soils. Adsorption of pollutants onto clay particles is beneficial, but is highly dependent on the pH of the immediate environment, and the adsorption capacity of the particular clay.

Isomorphous substitution in clay materials leads to their relatively high cation exchange capacity, which in turn can decrease pollutant concentrations in the leachate via ion exchange. Previous studies have found that K, NH_4^+, Mg and Fe can be moderately attenuated through ion exchange, while Pb, Cd, Hg and Zn were strongly attenuated (Bagchi, 1987).

Dilution of potential pollutants is accomplished through the processes of diffusion and dispersion as the leachate reaches the groundwater, and the former equilibrates with the latter. However, it is important to note that the ideal stratigraphy for this process may only occasionally exist. Much remains to be learned about natural attenuation methods of leachate treatment; it is probable that a full reliance on this system will result in some degradation of groundwater quality (Bagchi, 1987).

2.5.2 - TREATMENT WITH DOMESTIC WASTEWATERS

When landfill location is suitable, leachate can be discharged directly into the sewer system for combined treatment at a conventional sewage treatment plant. Economic advantages accompany this treatment method, as it utilizes an already existing infrastructure. Potential problems relate to the possible low acidity, high organic and inorganic concentrations, and low nutrient concentrations of the leachate. Problems such as these may be overcome through the addition of lime, the addition of nutrients, and the regulation of inputs to ensure that the domestic sewage:leachate ratio remains above 20:1 (Saint-Fort, 1992).

2.5.3 - BIOLOGICAL TREATMENT

The aerobic biodegradation of leachates utilizes carbohydrates, fatty acids, amino acids and humic materials, and accomplishes the nitrification of NH_3. The remaining organic matter tends to be fulvic acid type substances. After sufficient retention times, COD and BOD stabilization may reach 97-99%, along with the effective removal of heavy metals (Lisk, 1991). Nutrients must be added to attain these results. Additional disadvantages to the aerobic digestion of leachates include the need for O_2, and the relatively large amounts of sludge waste produced.

Anaerobic digestion is more economically feasible than the aerobic process, as there are no high energy requirements associated with aeration of the system. The production of CH_4 by anaerobic digestion is an advantage, due to its energy recovery potential. Disadvantages accompanying this method include a relatively long start-up period, greater sensitivity to variable organic loads and toxic substances and relatively high remaining toxicity due to NH_3 (Lisk, 1991). For these reasons, anaerobic digestion is often inappropriate for the treatment of mature leachates.

2.6 Fate of Landfill Gas

2.6.1 - GAS MIGRATION

Elementary science dictates that all fluids (both gases and liquids) may migrate from one place to another through porous media at a rate controlled by the permeability of the medium and the intensity of the driving force (Abaci *et al.*, 1993). Subsequently, when conditions are suitable, landfill gas migration occurs leading to concerns of explosive hazards and off-site soil gas contamination (Hodgson *et al.*, 1992). Risk of explosion occurs when CH_4 concentrations are diluted to their explosive range of 5-15% (Hanson, 1994).

Areas of interconnected porosity within and around the landfill site, and discontinuities such as joints, fractures and fault zones act as avenues for gas migration. When faced with unconsolidated materials such as sand and gravel, gas movement is achieved via pore spaces between individual sediment grains. Permeability characteristics vary greatly both between and within sites; texture and structure of the geologic formations will dictate the porosity of the media. The saturation level of the medium will also affect the migration patterns of the gas. If the material is completely saturated with water, gas may be transported only by slow diffusion (Williams *et al.*, 1991). Gas permeability will be at a maximum when the matrix is completely unsaturated with water (Abaci *et al.*, 1993).

The driving forces controlling migration of the gas through and beyond the landfill site are the concentration gradient and the pressure gradient. The concentration gradient causes the gas to diffuse through the materials from areas of high concentration to areas of low concentration (Mohsen *et al.*, 1980). The pressure gradient drives convective flow of the gas through the medium, and is caused by either a confining barrier, or by changes in groundwater level, atmospheric pressure or gas production.

Migration pathways of the gaseous products of waste decomposition can be controlled. Site location, design, and management considerations can be made in order to diminish this concern and hence further decrease the environmental impact of landfill sites.

2.6.2 - EFFECTS ON SOILS

One potential adverse effect of landfill gas is its tendency to cause alterations in soil properties (Wong *et al.*, 1989). This concern is frequently overlooked, as the potential problem is relatively obscure. Methane migrating to the aerobic rhizosphere of plants can be detrimental in one of two ways; it may displace O_2 directly, or it may lead to the depletion of O_2 sources by the action of methane-oxidizing bacteria (Abaci *et al.*, 1993). In either case, the death of vegetation is imminent.

Elevated levels of nitrogen compounds (mainly in the form of NO_3-N and NH_4^+-N) and frequently trace metal contents such as Mn, Fe, Cu and Zn have been detected in landfill gas-affected soils (Leone *et al.*, 1982). Changes in soil properties similar to these have been documented in soils contaminated by leaking natural gas, the main component of which is CH_4 (Garner, 1971).

2.6.3 - EFFECTS ON PLANTS

Due to the altered soil properties, and the direct effect of the presence of gases potentially toxic to plants (C_2H_4), revegetation of the cover material at landfills can be somewhat of a challenge. Studies have shown a strong negative correlation between the establishment of plant cover and landfill gas concentration in the soil (Wong *et al.*, 1989).

The presence of high levels of C_2H_4 in the rhizosphere of soils is known to inhibit root development of plants, thus making their establishment problematic.

Various measures can be taken to minimize the inhibitory effects of landfill gas on vegetation. The installation of gas venting mechanisms acts to obviate the diffusion of the gas into the rhizosphere, and consequently appears to be the most successful approach to preventing phytotoxicity (Spreull *et al.*, 1987). Alternative solutions include the construction of either clay or synthetic barriers below the root zone to prevent the upward migration of the gas. In the situation where nutrient deficiencies exist (due to the replacement of the soil profile with fill) supplemental fertilization and irrigation may be necessary (Flower *et al.*, 1981). Application of digested municipal wastewater sludge is one option which acts to provide nitrogen, organic matter, and increased water holding capacity to the profile. This method has proven advantageous in a number of projects, including the successful revegetation of the Coquitlam Landfill with the Nutrifor product, which is predominantly digested sludge from the Annacis Island Treatment Plant (Hanson, 1994).

2.6.4 - LANDFILL GAS AND THE GREENHOUSE EFFECT

The build-up of greenhouse gases in the troposphere, and the proposed consequence of global warming is of paramount concern among some environmentalists. As the highest anthropogenic source of CH_4 to the atmosphere (Table 2.6.1), landfill sites have become a focus of interest with respect to greenhouse gas build-up. The data reported by the Environmental Protection Service (1990) showed that municipal solid waste landfills were responsible for 37.61% of anthropogenic emissions, thus being significantly greater than oil and gas operations (29.44%) and domestic animals (17.53%). It is interesting to note that these emissions are only a fraction of those originating from natural sources, predominantly wetlands.

Methane has been reported to have a Global Warming Potential (calculated using residence times and radiative forcing) of somewhere between 5-41 times that of CO_2. Using the low end of this range, the United Nations International Panel on Climate Change calculated that each tonne of municipal waste landfilled produces the equivalent to 489 kg of CO_2 (MacViro Consultants, 1991). When put in these terms, it appears as though landfill sites have the potential to act as a significant contributor in the greenhouse gas issue. Various estimates (and methods for attaining them) for annual landfill CH_4 emission rates are displayed in Table 2.6.2. One must note that the highest value is more than seven times the lowest estimate; variation in the assumptions causes this large discrepancy.

Methane emission data from landfill sites may be interpreted to paint a bleak image of our state of environmental health, especially considering the impact of population growth on

TABLE 2.6.1: Summary of CH_4 emissions in Canada (from Canadian Environmental Protection Service, 1990)

	ANNUAL EMISSIONS (kt of CH_4)	% OF TOTAL
anthropogenic		
municipal landfills	1405	37.61
oil and gas operations	1100	29.44
domestic animals	655	17.53
manure	345	9.23
sewage treatment	-	-
natural gas distribution	18	0.48
coal mining	143	3.83
fuel combustion	32	0.86
prescribed fires	38	1.02
subtotal	**3736**	**100.00**
natural		
wetlands	24000	
wild fires	980	
wild animals	100	
subtotal	**25080**	
TOTAL (ALL SOURCES)	**28816**	

our primary waste management strategy. However, the direct emission of gases from landfill sites represents a worse case scenario. Proper management and utilization practices can greatly reduce the atmospheric constituent of the ecological footprint caused by landfill sites, as outlined in the next section.

TABLE 2.6.2: Published estimates for landfill CH_4 emission rates

SOURCE	ESTIMATE (Tg/yr)	METHOD/ASSUMPTIONS
Bingemer and Crutzen (1987)	30-70	-used current estimates for refuse composition -assumed 20% degradable organic C with 80% conversion -assumed all CH_4 vented -assumed steady-state generation -yield of 0.1 kg CH_4/kg refuse
Orlich (1990)	33	-used per capita refuse generation estimates -used net CH_4 emission of either 0.086 kg CH_4/kg refuse (developed countries) or 0.030 kg CH_4/kg refuse (developing countries)
Richards (1989)	9-18	-used refuse estimates proportional to GDP -assumed 80% landfilled -assumed steady state CH_4 generation of 0.036 kg CH_4/kg refuse

2.6.5 - GAS UTILIZATION

Various technologies exist for the utilization of landfill gas, some of which are relatively widespread in the United States and gaining increased participation in Canada. The main categories for landfill gas utilization projects include the following (MacViro Consultants Inc., 1991):

- electric power generation
- heat recovery in the form of either low or medium BTU gas
- cogeneration (the simultaneous generation of power and heat)
- natural gas substitution (through upgrading to high BTU gas)
- alternative fuel for vehicles

Typically, the landfill gas is collected under vacuum from vertical gas extraction wells, in a piped collection system leading to a gas pump/compressor set-up.

The economics of a landfill gas utilization system have been studied and requirements determining their feasibility include an active fill area of at least 16 ha with a depth of 12 m, a minimum of 1 million tonnes of refuse in place, and a nearby willing user of the gas (Bogardus, 1987). Additional site specific criteria, along with the nature of the energy market must be taken into account when assessing feasibility.

When landfill gas utilization is underway, optimization of CH_4 production would result in a number of advantages (Rees, 1980):

-decreased fatty acid concentration in the leachate
-reduction in leachate treatment costs
-more rapid completion of landfill reactions
-the relatively fast and safe reclamation of landfills
-increase in the economic attractiveness of CH_4 utilization

Failure to achieve the rapid stabilization of organic wastes could most likely result in slow CH_4 production over a number of decades. Production would be insufficient for utilization, but most likely fast enough to cause environmental problems.

Many uncertainties presently exist concerning options for energy from waste possibilities. However, changes in our conceptions of environmental issues, market trends in energy prices and new opportunities for electricity production may improve the overall prospects for these projects.

2.7 Factors Affecting Waste Decomposition

Both numerous and diverse are the factors which affect microbial activity, and hence waste decomposition in landfill sites. Many of these factors are significant both independently and through their interactions with other variables. A simplistic overview of the factors affecting waste decomposition are shown in Figure 2.7.1, and explained individually in this section.

2.7.1 - WASTE COMPOSITION

The degradation processes within the landfill matrix are effected by the composition of the materials deposited therein. The results of research conducted by Ramaswamy (1970) showed that rates of methanogenesis could be altered by changing the amounts of nitrogen, phosphorus and potassium in the refuse mixture. It was also shown that carbonaceous materials yield a greater amount of gas than proteinaceous materials, but do so at a slower rate. The estimation of refuse empirical formulae have been attempted, with some results

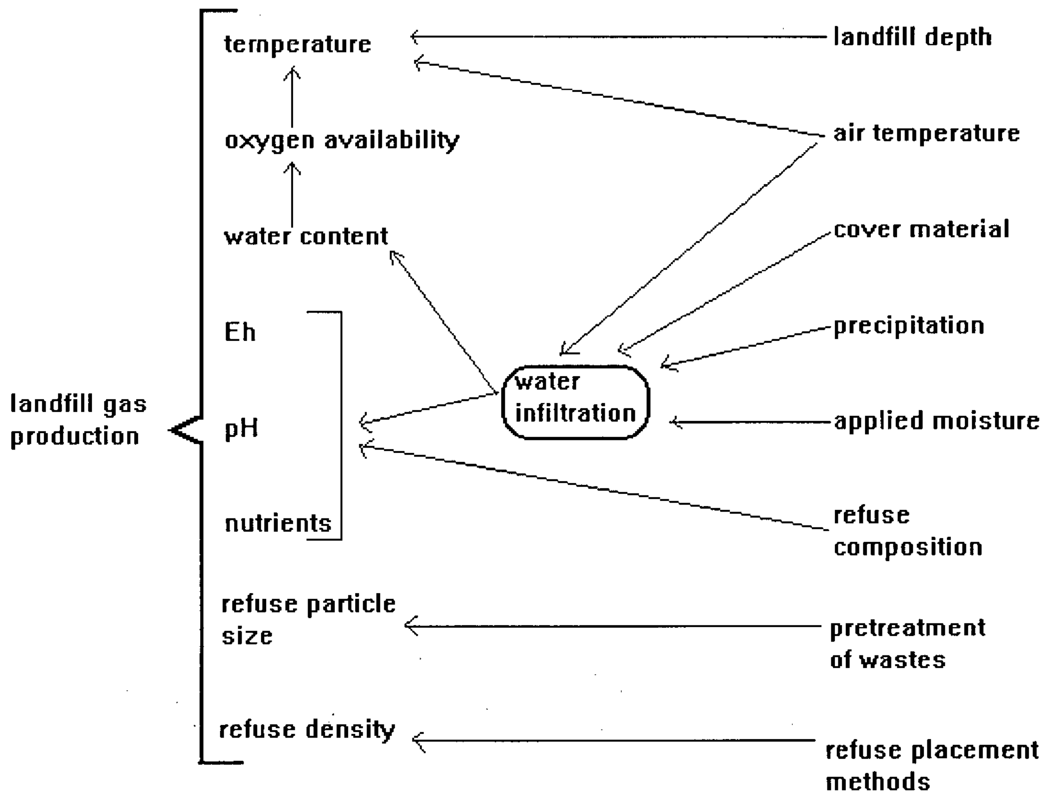

FIGURE 2.7.1: Factors affecting gas production in a landfill site (modified from Farquhar and Rovers, 1973)

shown below in Table 2.7.1. The variation in stoichiometric ratios is most likely a result of the wide range of waste composition estimates used. The moisture content and physical state of the waste materials are additional parameters which will affect the rate of their degradation.

Many attempts have been made to determine the composition of the refuse being deposited at a specific site, but the fact remains that the variability caused by income, season, recycling participation, composting efforts and lifestyle is significant. In addition,

TABLE 2.7.1: Documented refuse empirical formulae

REFERENCE	EMPIRICAL FORMULA
Rees (1980)	$C_{54}H_{87}O_{33}N_1$
Tchobanoglous (1977)	$C_{57}H_{84}O_{39}N_1$
Gibs (1982)	$C_{84}H_{120}O_{53}N_1$
Emcon Assoc. (1980)	$C_{99}H_{149}O_{59}N_1$

methodology for determining the percentage composition of incoming wastes at a landfill tends to be rather primitive, and filled with sources of error. This fact must be kept in mind when interpreting waste composition data.

A table of estimates was compiled by CH_2M Hill Engineering (1993) which displays the composition estimates for the municipal solid wastes disposed of in the Greater Vancouver Regional District (Table 2.7.2). Paper products make up the largest portion of the deposited waste materials (38.6%), with other significant products being metals (11.0%), food (10.1%) and "other" (21.3%), which includes miscellaneous refuse. Projected composition changes include a significant increase in the proportion of plastics deposited, a slight increase in the percentage of paper, and a slight decrease in the deposition of yard, food, glass and metal wastes. These changes are expected as a result of increased computer use, increased manufacturing of plastic products, and increased participation in composting and recycling.

TABLE 2.7.2: Composition of disposed refuse in the Greater Vancouver Regional District (from CH2M Hill, 1993)

ITEM	% OF TOTAL WASTES
food	10.1
paper	38.6
metal	11.0
plastics	8.4
glass	3.5
yard	7.1
miscellaneous	21.3

2.7.2 - REFUSE EMPLACEMENT

Landfilling practices can have significant effects on the decomposition of refuse, and consequently on the production of leachate and gas at a site. Pulverisation of waste materials prior to its disposal was found to increase the reactivity and gas production rates in an experiment carried out by DeWalle and Chian (1979). The decrease in mean diameter of the waste aggregates resulted in a larger surface area of substrate being available for microbial attack (Rees, 1980). The rapid release of carbon from pulverized waste materials offers significant potential advantages for the rapid stabilization of the landfill environment, although work is required to control the fermentation on the field scale.

Refuse compaction is an additional management option which is important for the enhancement of degradative reactions. High compaction drives a system of limited moisture content closer to field capacity, while bringing the refuse into close contact with nutrients and microorganisms (Buivid *et al.*, 1981). Total gas yields will be expected to be enhanced, as greater density by preconsolidation will increase the total mass per unit volume of the refuse (Schumacher, 1983). It is common practice for landfill operators to attempt to achieve a density of approximately 590 kg/m^3.

2.7.3 - NUTRIENT AVAILABILITY

While the extent is somewhat limited, studies of the nutritional requirements for optimal waste decomposition do exist. The key conditions necessary for microbial cell growth in the landfill environment include: sufficient levels of soluble phosphate, ammonia nitrogen, organic nitrogen, potassium, sulphate, and a C:N ratio in the range of 16:1 (Pacey *et al.*, 1986). Phosphorus deficiency has recently been found to be a concern within the waste matrix. The results of investigations by Ramaswamy (1970) indicated that maximum gas production occurred in refuse where the percentages of N, P, and K were 1.86%, 0.31%, and 0.23% respectively. To overcome nutrient deficiencies, the most popular amendments include sewage sludge, digestor effluent, animal wastes and agricultural wastes.

Although sulphate is an essential element for methanogenic bacteria, if present in excess amounts it tends to have an inhibitory effect on CH_4 production. This is due the competition between sulphate reducers and methanogens for H_2 gas, and the potential toxicity to methanogens caused by the production of sulphides (Jones, 1983).

2.7.4 - ALKALINITY AND pH

One of the requirements for optimal CH_4 generation by methanogens is a pH value within the range of 7.0-7.2. Researchers have found that conditions below pH 6.0 will cause a cease in CH_4 production altogether (Pacey *et al.,* 1986). Low pH values during the initial stages of decomposition are commonly caused by the production of fatty acids and CO_2. The mineralization of substrate and conversion of CO_2 to HCO_3^- triggers an increase in buffering capacity of the system. With the increase in alkalinity, the pH levels reach a point favourable to methanogenesis; the increased activity of methanogens results in high consumption of organic acids, thus raising the pH even further.

The addition of a buffer such as $CaCO_3^-$ is one solution for controlling pH levels in the field. The most practical application method is the layering of dry buffer material with the refuse during emplacement.

2.7.5 - REDOX POTENTIAL

The oxidation-reduction potential of the landfill environment must be well into the negative range (-200 mV) for CH_4 production to occur. It has been stated that even a lower redox potential of approximately -330 mV is ideal for the initiation of CH_4 production (Zehnder, 1978). After this initiation, increases in Eh values were shown to decrease methanogen activity. Much uncertainty surrounds this issue, as the measurement of redox potentials are problematic in a matrix as complex as a landfill where several different uncoupled levels may occur in the same environment.

2.7.6 - AMBIENT TEMPERATURE

The temperature attained within the landfill matrix will be determined by the balance between the rates of heat production and addition (solar energy) and the rate of heat loss to the surrounding soil and atmosphere (Lisk, 1991). Although landfill temperature appears to be primarily influenced by the internal temperature regime created by microbial activity, some effects of ambient temperature on the system have been documented. Studies done at the Aveley landfill site (Rees, 1980) showed that ambient temperature affected microbial activity in the top 3.5 m of the fill. In a southern Ontario landfill, some fluctuations in landfill temperature with seasonal variations were documented (Rovers *et al.*, 1972). In addition to the direct effects of fluctuating ambient temperature, air temperature acts as a partial determinant of refuse temperature, and may therefore influence infiltration and evaporation (Lisk, 1991).

The practicality of managing the temperature regime within a landfill is limited (Pacey *et al.,* 1986). The fact remains that a deeper fill will be less affected by ambient temperatures, as the microniches create their own temperature regimes. The implementation of temperature management techniques would serve only to prevent wide temperature swings, not to ensure the existence of favourable methanogenesis temperatures throughout the refuse environment.

2.7.7.- MOISTURE

The infiltration of water into the waste matrix is central to the modification of all the other parameters which directly affect microbial activity (Rees, 1980). A high moisture content improves the mixing and general availability of nutrients and carbon rich organic matter, and also stimulates bacterial growth directly, while diluting metabolic inhibitors. Theoretically, these effects should lead to increased rates of CH_4 production.

Methanogenic bacteria are the key factor for complete anaerobic digestion of wastes, and are often deficient in fresh refuse due to their oxygen sensitivity (Rees, 1980). Thus their growth is particularly favoured by high water content. Maximum CH_4 production has been found to occur when the refuse moisture content was in the range of 60-80% wet weight (Ramaswamy *et al.*, 1970). Other researchers (Rovers *et al.*(1973), DeWalle *et al.*(1979)) have found similar results, as shown in Figure 2.7.2. The landfill environment must be brought to field capacity in order to gain the full advantage of high moisture levels (Pacey *et al.*, 1986). The aforementioned distribution of nutrients, bacteria and alkalinity causes the decomposition matrix to gain the benefits of mass transfer.

Due to the interest in high moisture content for optimal degradation, some work has been done to decipher the effects of precipitation on the landfill system. The general consensus is that CH_4 production increases after periods of heavy rainfall (or rainfall simulations) as found in both field and laboratory studies (Farquhar *et al.*, 1973; Gurijala *et*

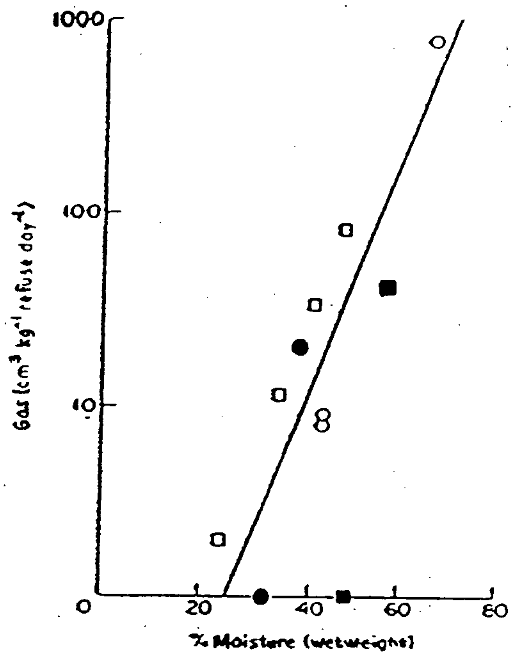

FIGURE 2.7.2: Effects of moisture content on landfill gas production (•Merz and Stone, 1968; °Merz, 1964; ■Rovers and Farquhar, 1973; □DeWalle and Chian, 1979)

al., 1993). A correlation coefficient of 0.55 was found in a comparison of cumulative 3-day precipitation and CH_4 production (McBean *et al.*, 1980). This value suggests a relationship, but is not exclusively convincing. The response of a landfill to precipitation will vary greatly in relation to site specific conditions.

Concerning the composition of the gas following periods of heavy rainfall, studies have indicated that the percentage of CH_4 in the gas mixture tends to increase (Farquhar *et al.*, 1973; Rees, 1980) (Figure 2.7.3). This finding suggests that conditions following moisture addition drive the degradative reactions to produce more CH_4 in relation to CO_2. Hansson (1982) found that the presence of CO_2 inhibited acetate and propionate degradation; rates were 4 times faster at low pCO_2 compared to 1 atm CO_2. The decreased partial pressure of CO_2 following periods of heavy rainfall would thus favour enhanced CH_4 production. Another possibility is simply the dissolution of CO_2 and subsequent downward movement in the leachate following high moisture input. This question does not seem to be addressed extensively in the literature.

Although the beneficial effects of moisture on waste degradation are well documented, excessive infiltration has been found to cause a decrease in CH_4 production (Farquhar *et al.*,

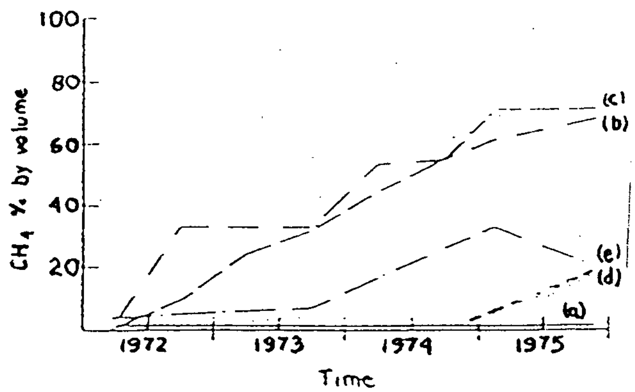

FIGURE 2.7.3: Effects of water content on the % CH_4 produced by a) dry refuse; b) & c) daily liquid application; d) & e) initially saturated (from Leckie *et al.*, 1979)

1973). It was concluded that these events took place due to the inhibition of methanogens caused by increased BOD, COD, TDS levels, along with decreases in refuse temperature and pH levels. It is also possible that viable bacterial cells were washed out by the excessive infiltration.

Where moisture addition is favourable in the landfill, moisture content can be increased by management of rain and surface water infiltration, the introduction of liquid wastes, spray irrigation or leachate recycling. However, accompanying moisture addition is the concern of increased leachate volumes, which must be treated in order to avoid groundwater contamination.

2.7.8 - BAROMETRIC PRESSURE

Exchanges between ambient air and landfill gases will be affected by atmospheric pressure (Lisk, 1991). As conditions change from a high to a low barometric pressure system, a resultant "pumping" action has been known to occur, causing the increased release of landfill gas from the waste matrix. In contrast, the periods of high barometric pressure seem to repress the venting of landfill gas.

2.7.9 - LANDFILL AGE

In older landfill sites, the easily degradable substances have been broken down, leaving mainly the more refractory compounds such as humic and fulvic acids, and soluble salts. This "inactivation stage" is characterized by a drop in methanogenic productivity, as microbes no longer have the readily decomposable materials as substrates.

As the landfill site ages, concentrations of organic and inorganic constituents in the leachates generally decrease. The ratios of COD:TOC, BOD:TOC and VS:FS (volatile solids to fixed solids) have been found to decrease as the landfill ages, an example of this being the change in COD:TOC ratios from approximately 3.3 for the relatively new landfill to 1.2 for the older site (Lisk, 1991). Measurement of these ratios are beneficial when making decisions regarding the most efficient treatment methods.

CHAPTER 3 - SITE DESCRIPTION

3.1 Location

The City of Vancouver Landfill Site is located approximately 16 km south of Vancouver at Burns Bog, in the Municipality of Delta (Figure 3.1.1). The landfill is located on a 635 ha property in the southwest corner of the Bog, with a permitted landfilling area of 405 ha. The remaining area is designated for the operation of roadways, landscaping, buffers, ponds and ditches (Figure 3.1.2).

FIGURE 3.1.2: Aerial view of the Vancouver Landfill Site at Burns Bog

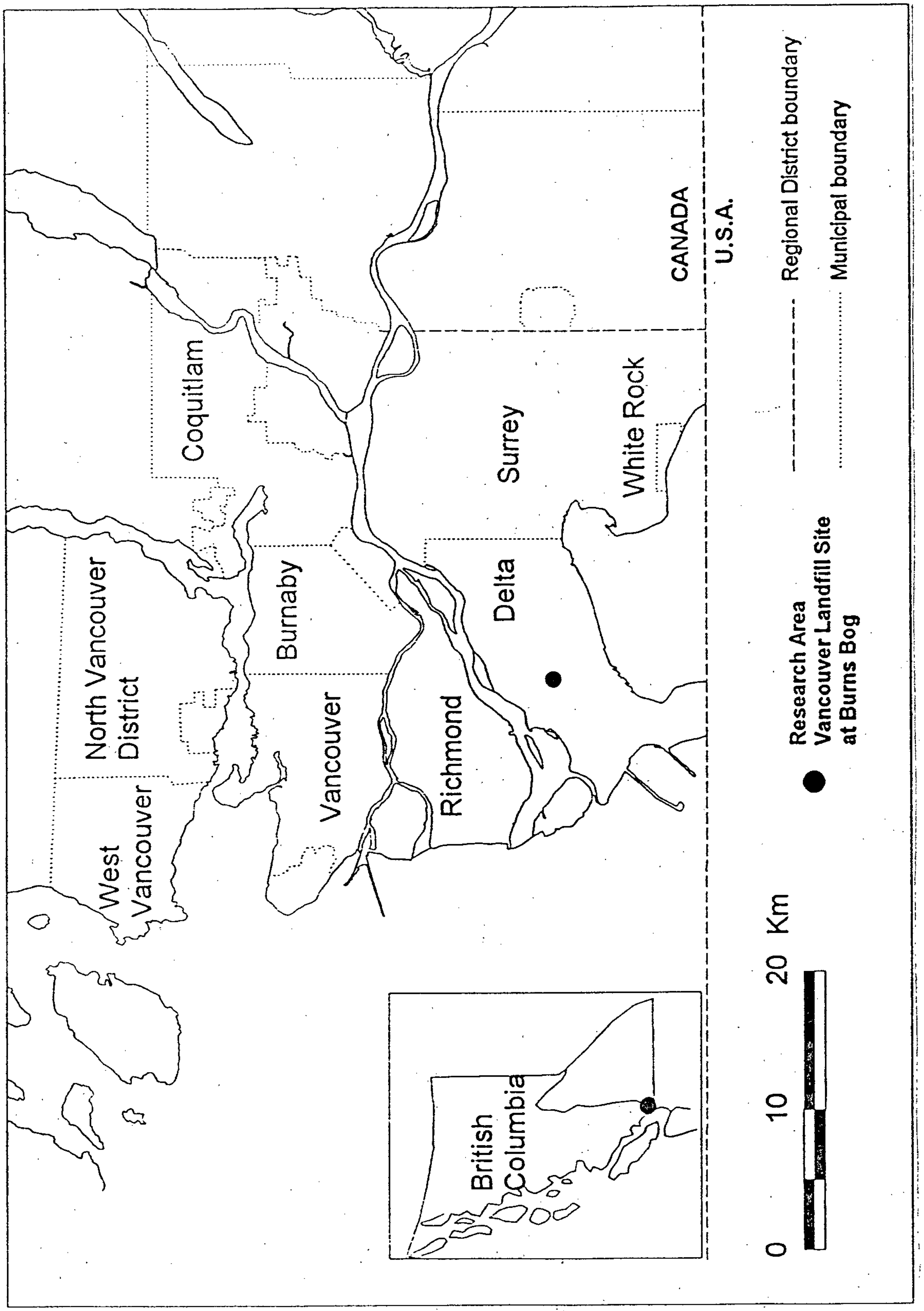

FIGURE 3.1.1: Map showing the location of the City of Vancouver Landfill Site at Burns Bog

3.2 Burns Bog

3.2.1 - TOPOGRAPHY

Burns Bog, within which the City of Vancouver Landfill Site is located, is an ombrotrophic raised bog which is oval in shape and measures approximately 9 km in the east-west direction and 5.5 km in the north-south direction. The highest point of the bog exists at an elevation of approximately 5 m above mean sea level, and the surface slopes gently to an elevation of 2 m at the perimeter. The estimated area covered by the bog is about 27 km^2 (Piteau Associates, 1994).

Soils mapping of the Langley-Vancouver area was carried out by Luttmerding (1980), and results indicate that the Vancouver Landfill Site is located on both Triggs and Lumbum soil deposits. The Triggs is a very poorly drained organic soil with a typical depth of 1.6 m. This soil is characterized by a relatively undecomposed sphagnum moss layer, a high water table, a poor load bearing capacity (very compressible), and is very acidic. The Lumbum soil is also a poorly drained organic soil with a typical depth of approximately 1.6 m. It consists of partially decomposed organic matter, with high acidity and low bearing capacity.

Groundwater levels in the Bog range from 0.2 m to 1.0 m below ground during the summer period. The general direction of groundwater flow is towards the southeast. Soil auger testing conducted by Piteau Associates (1994) indicated that a mat of fibrous to partially decomposed fibrous peat material overlies well decomposed amorphous peat in all areas.

3.2.2 - VEGETATION

Bogs are dynamic systems, and as a result the plant community of Burns Bog has undergone a number of species changes before reaching its present dominant heathland type. Sphagnum heathland characterizes the central portion of the area, while a significant community of pine woodland occupies the area where the landfill is situated, south of the central core. A mixture of deciduous and coniferous forest is found on the perimeter of the bog. In general, the area is a repository for vegetations which are characteristic of the muskeg portions of a Boreal realm. These plants require high moisture inputs and consequently thrive in a bog environment (Piteau Associates, 1994).

3.2.3 - CLIMATE

The climate of south-coastal British Columbia is characterized by warm rainy winters and relatively cool summers. The average annual air temperature measured from the nearby Vancouver International Airport is 9.9°C, and the average annual total precipitation is 1167 mm, based on normalized data from the 1953-1990 time period (Environment Canada, 1995). The majority of the precipitation events occur between October and March. Within the bog itself, average annual precipitation is likely to range from approximately 1020 mm in the southwest to 1150 mm in the northeast (Piteau Associates, 1994). The Thornthwaite method (Thornthwaite, 1948) was utilized by Piteau Associates (1994) to estimate an annual evapotranspiration loss of 639 mm from the bog surface.

3.2.4 - SURFACE DRAINAGE

The majority of recharge to the bog is achieved from surface infiltration of precipitation. Drainage from the raised bog flows radially out from the highest point via subsurface flow in the more permeable fibrous peat zone. When moisture input exceeds the field capacity of the subsurface soils, water will either pond temporarily in surface depressions, or flow in the linear direction (Piteau Associates, 1994).

3.2.5 - WATER USAGE

To date, no licenses have been issued to authorize the use of water within the bog, although domestic withdrawals may be taking place as they require no license. Surface water licenses have been issued to the Agricultural Management Corporation for the uses of irrigation, flood picking and frost protection of cranberry fields, in the areas located south and east of the principal bog area.

The surface water of the bog is an important resource as a landing area for certain bird species. The combination of the protected area, the sphagnum moss and the shallow water surfaces are critical components for the optimum nesting areas for the sandhill crane population of the Lower Fraser Valley (Gehauber, 1993).

3.2.6 - LANDFILLING IN A BOG

When landfilling practices are carried out in a controlled, slow and methodical manner, landfilling onto peat bogs can be performed successfully. The placement of a load on the peat must be carried out at a rate which allows time for sufficient water in the peat layer to migrate into adjacent zones. Loading in this fashion results in the compression and consolidation of the peat and underlying soft clayey silty soils, and a slight increase in the strength of these materials. In contrast, if rapid placement of wastes causes a fast loading of the peat with heavy silty sediments, the resulting buildup in pore pressures within the peat can cause shearing and failure of these soils (Piteau Associates, 1994).

The placement of a suitably thick layer of moderately permeable material at the base of the fill has been proven to be an effective method of distributing the weight of the fill over a wide area, and can consequently minimize the buildup of pore water pressures in the underlying soils.

3.3 Landfilling Practices

3.3.1 - REGIONS SERVED

The Vancouver Landfill Site at Burns Bog began municipal solid waste deposition at the southwest corner of the site in 1965. The landfill is designated as the western regional disposal facility in the District's postcollection system, and receives municipal solid waste from Vancouver, U.B.C., University Endowment Lands, Delta, Richmond, White Rock, and a southern part of Surrey (CH_2M Hill Engineering Ltd., 1993).

In 1992, the Vancouver Landfill handled 471000 tonnes of municipal solid waste. In addition to this, the landfill receives approximately 150000 tonnes of demolition waste annually. The establishment also maintains drop-off recycling programs for the collection of several materials.

3.3.2 - METHODS OF EMPLACEMENT

The landfilling method utilized at the site is an "area fill" with the waste materials being deposited in strips running in the north-south direction. These "cells" are approximately 300m by 800m in size, although this has varied over time. Each cell provides enough area for approximately 3 years of landfilling. When a cell is completed, refuse is then deposited in a newly constructed cell on the east side of the completed one.

The cross-section of an individual landfill cell is shown in Figure 3.3.1. The area is first prepared by the removal of vegetation, followed by the placement of the "mattress" layer of demolition wastes. This layer is intended to act as a firebreak between the refuse and the underlying peat, to evenly distribute loads over the native soil to prevent shearing (see Section 3.2.6), and to provide a relatively porous layer to allow leachate to reach the underdrains. Deposition of refuse is then carried out on the working face of the cell, which is restricted to narrow dimensions. After waste materials have been deposited and compacted, a daily cover of 15 cm of sand is used to prevent the off-site migration of wastes by rodents, birds and wind.

After the three lifts have been completed and the cell is classified as "full", the area is covered with a 1 m layer of clayey peat material. Natural revegetation is encouraged, and the final cover is then seeded with grass.

3.4 Pollution Control Measures

3.4.1 - LEACHATE COLLECTION AND TREATMENT

The landfill site is enclosed by a double ditch drainage system. The outside ditch ("clean" water) acts to prevent surface water from entering the site from the surrounding areas. This water eventually drains to Crescent Slough and the Fraser River. The inside ditch contains leachate which has drained from the peat layer below the fill, along with precipitation and surface runoff. The inner ditch prevents this mixture from leaving the site. This liquid is then pumped to the Annacis Island Treatment Plant, where it is treated along with the sewage.

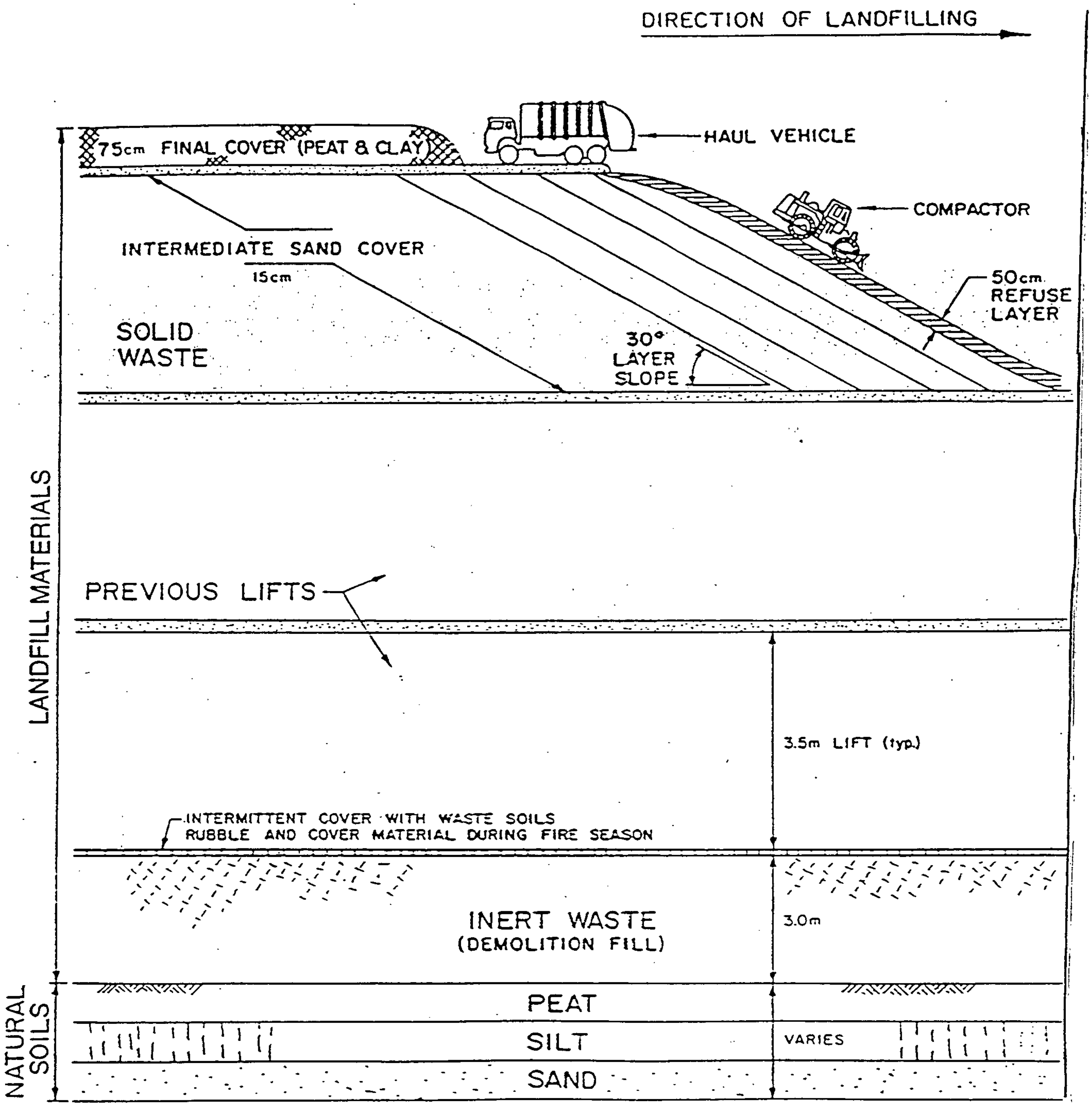

FIGURE 3.3.1: Landfilling practices at the Vancouver Landfill Site are shown above (CH_2M Hill Ltd., 1993)

The results of the 1983 hydrogeological assessment of the landfill showed that estimated daily leachate quantity pumped to Annacis Island was 1692 m^3 (CH_2M Hill Engineering Ltd., 1993). The study also indicated that the leachate has the potential to escape from the bottom of the landfill at an estimated rate of 22 L/m^2/year. However, no effects of migrating leachate on the underlying sand layer were detected at the time of the study.

Groundwater monitoring is performed via 12 shallow wells located in the peat layer, and 12 deep wells located in the underlying sand layer. This system is in place to provide the earliest information on groundwater movement, storage and contamination. Groundwater is sampled 3 times per year for a series of 20 metals, nonmetals, and other general parameters (Twarog, 1994). Natural background levels of the bog are moderately high in a number of parameters including chloride, iron, manganese, and chemical oxygen demand (COD).

The surface water monitoring system consists of 8 monitoring points, located in the outside surface water ditch along the east, west and south borders of the site. Surface water samples are collected three times each year, and tested for the same water quality parameters as the groundwater.

A hydrogeological assessment of the Vancouver landfill site (1983) concluded that with the inclusion of the double ditch system, bottom peat drainage layer and low permeability peat and silt-clay underlying layer, this site is suitable for landfilling (Piteau Associates, 1994).

3.4.2 - GAS COLLECTION AND UTILIZATION

A landfill gas control system was installed at the site in 1992 in response to odour complaints from nearby neighbours. The system consists of roughly 200 perforated PVC gas ports, each protruding into the fill to a depth of approximately 8 m, with a radius of influence in the range of 16-20 m (Figure 3.4.1) (Evans, 1995). The gas ports are connected by a network of PVC pipes which draw the gas by vacuum to the blower/flare facility. Here the gas is incinerated in enclosed flares with controlled temperature and retention time in order to neutralize harmful components.

The results of a 1992 air quality study indicated that the total reduced sulphur and volatile organic compounds were below background levels in the vicinity of the landfill site. Total hydrocarbon levels were higher than normally expected, and this could most likely be attributed to the landfill (CH_2M Hill Engineering Ltd., 1993).

FIGURE 3.4.1: One individual gas port as a fundamental part of the gas collection system at Burns Bog

The 1992 Annual Report stated that approximately 42480 L/min of landfill gas were being burned in the onsite enclosed flares. The system operates under 1 inch of water column at the individual gas ports in order to prevent the intrusion of ambient air into the landfill. This system has been successful in controlling offsite odours.

An estimation of average landfill gas generation was conducted by CH_2M Hill Engineering Ltd. (1992). This analysis indicated that the potential average landfill gas generation rate was 152931 L/min, with a potential future peak of approximately 206740 L/min. The report states that these estimations are not intended to suggest that the difference between the gas produced and the gas captured is currently escaping to the atmosphere, or is even capable of being collected. Additional detailed analysis is needed in order to determine what is occurring.

At the present time, approximately 1% of the recovered landfill gas is being used for energy recovery. The gas is utilized in a domestic hot water heater, a forced air heater and overhead infrared heaters in the onsite maintenance building.

CHAPTER 4 - MATERIALS AND METHODS

4.1 Preliminary Sampling

During the months of July and August of 1994 preliminary sampling was carried out in order to become familiar with the gas collection system and site layout, to develop the most effective sampling technique, and to pick out a number of ports which were consistent producers of landfill gas. Samples were collected in approximately 15cm x 15cm Teflon bags with on/off valves from 35 ports spanning the active gas collection area of the site. Samples were then brought to the Environmental Engineering lab at UBC for analysis using the Fisher-Hamilton Model 29 Gas Partitioner. This instrument is designed for the quantitative determination of substances which are gaseous at room temperature. Samples were introduced through injection using a 1mL Hamilton Gastight syringe (#1001), and were then swept through two chromatographic columns:

-column #1 - molecular sieve 5A
-approximately 60cm in length
-separates out CO_2, H_2S

-column #2 -chromosorb 101
-approximately 120cm in length
-separates out O_2, N_2, CH_4, CO

Helium is used as the carrier gas for this instrument, and the high sensitivity is obtained by the use of a specially designed thermal conductivity cell employing 4 matched Gow Mac W2 hot wire filaments (Fisher-Hamilton Manual, 1988).

Despite the fact that the lab analysis was carried out on the day of sampling, some diffusion of gases into and out of the Teflon bags seemed to be occurring, indicated by the presence of O_2 in the samples. It was therefore decided that with the permission of E.H. Hanson and Associates Engineering Limited, the mobile Landtec Gem 500 Autoanalyzer would be used to take in-field measurements of landfill gas composition. Sampling technique was then carried out as described in the following sections of this Chapter.

4.2 Sampling Design

4.2.1 - SPATIAL LAYOUT

Eleven gas ports spanning the site were chosen based on consistency in landfill gas production during the preliminary sampling stage. The general location of these individual gas ports are shown below in Figure 4.2.1. Leachate samples were collected from the pumping station of the leachate collection ditch which is located on the southwest corner of the site (Figure 4.2.1).

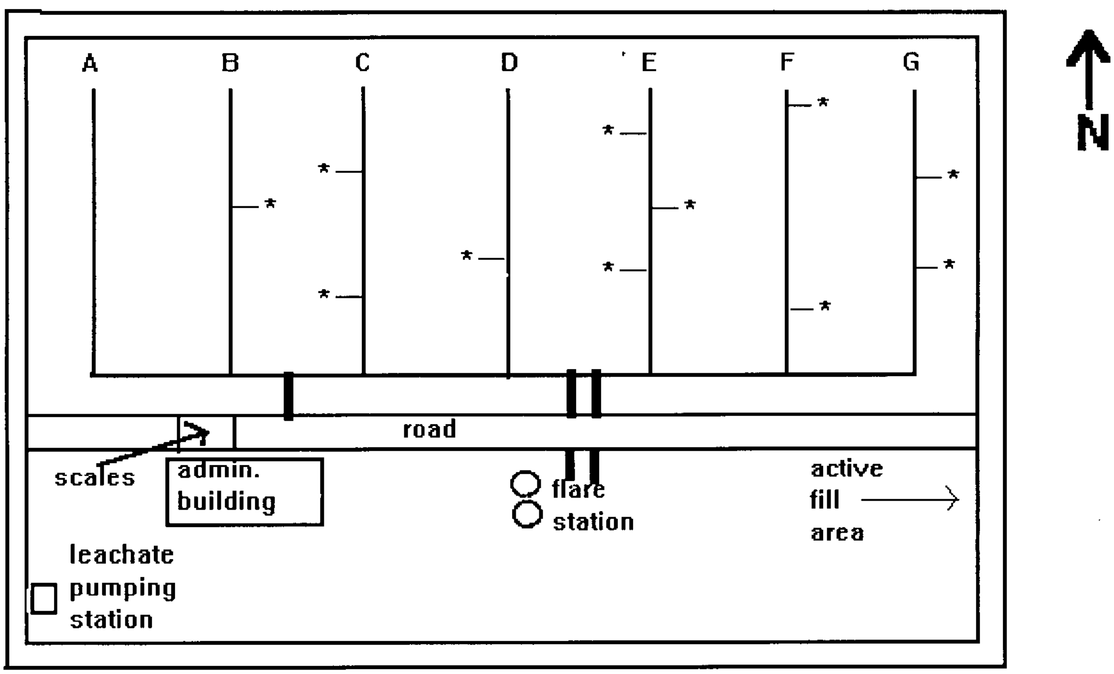

FIGURE 4.2.1: Simplified layout of the gas collection area at the Vancouver Landfill Site at Burns Bog. (*) denotes those gas ports which were sampled

4.2.2 - SAMPLING TIMELINE

The first sampling session was carried out on November 21, 1994, and sampling was repeated once every 3 weeks, until 12 sessions had been completed (July 10, 1995). In addition to this, a 10-day period of daily sampling was carried out from May 29, 1995 until June 7, 1995, in order to determine any short-term effects of the measured variables.

4.3 Field Analysis

4.3.1 - GAS TEMPERATURE

The temperature of the gas being produced at the individual sampling locations was determined by the insertion of a temperature probe into the sampling valve at each gas port. After waiting for temperatures to stabilize (up to 20 seconds), the reading was made from the probe and temperature in °C was recorded.

4.3.2 - GAS COMPOSITION

Gas composition measurements were taken in the field using the Landtec Gem 500 Autoanalyzer (Figure 4.3.1). This instrument is a portable infrared gas analyzer designed specifically for sampling landfill gas mixtures. Gas is drawn from the sampling valve on the gas port into the instrument via an integral pump. The gas mixture then flows through an infrared bench consisting of a light beam transmitted between two mirrors in an optical chamber. The light source is passed through the gas molecules, and the frequency of this determines the presence and volume of CH_4 and CO_2 in the mixture. The gas then flows through a galvonic cell consisting of two gold electrodes between which a current is passed (Landtec, 1993). This apparatus determines the volume of O_2 present in the mixture. The instrument then sums these values and the balance is assumed to be N_2. The percentages by volume of CH_4, CO_2, O_2 and "balance" are then displayed on the instrument's screen. The range and resolution of the Landtec sensor are shown below in Table 4.3.1.

TABLE 4.3.1: Sensor range and % resolution (imperial) for the Landtec Gem 500 are shown below

GAS	SENSOR RANGE	% RESOLUTION
CH_4	0-100%	0.1
CO_2	0-50%	0.1
O_2	0-25%	0.1

4.3.3 - GAS PORT FLOW MEASUREMENTS

After the valve controlling the gas extraction vacuum at the individual port (see Figure 3.4.1, Chapter 3 - Site Description) had been closed for a period of 5 minutes, flow

FIGURE 4.3.1: Landtec Gem 500 portable gas analyzer used in the study

measurements were taken from the sampling valve using Gilmont Compact Flowmeters. These instruments are manufactured from tapered precision bore tubing to give maximum precision attainable for spherical float rotameters. Two sizes were used depending on flow rates:

-size 5 was used for high flow rates (range=2000-77000 mL/min; accuracy of $^+/-2\%$)

-size 12 was used for low flow rates (range=20-2100 mL/min; accuracy of $^+/-5\%$)

These flowmeters were disassembled, washed with ethanol, allowed to dry and then reassembled following each sampling session. The conversion of these flowmeter values into landfill gas flow rates was achieved using the Gilmont Flowmeter analysis software. Details of these calculations can be found in Appendix A.

4.3.4 - IN-LINE FLOW MEASUREMENTS

Measurements of the in-line flow of landfill gas were taken from the four active gas collector lines leading to the flare station (D,E,F & G; see Figure 4.2.1). To achieve this, a Dwyer Pitot Tube was inserted into the collector line through a drilled hole of approximately

0.8 cm diameter. The pitot tube consists of an impact tube (receiving total pressure input) fastened concentrically inside a second tube of slightly larger diameter (receiving static pressure input) (Figure 4.3.2). The air space between the inner and outer tubes permits the transfer of pressure through connecting tubing to the low pressure side of the manometer (Dwyer Instruments Inc., 1983). The total pressure tube was connected from the sampling valve (approximately 15cm upflow) to the high pressure side of the manometer. As a result, velocity pressure was indicated directly on the manometer.

Calculations were carried out to convert the velocity pressure readings to volume flow of the landfill gas through the lines (see Appendix A).

4.3.5 - TEFLON BAG GAS SAMPLES

Landfill gas samples from each of the main header lines were collected in order to detect the presence of C_2H_4. Nalgene 0.64cm internal diameter polyvinyl chloride (PVC) tubing was secured over the sampling valve of the gas collection line, and the gas was extracted by a hand held pump from the valve into the Teflon bag. Samples were transported back to the lab for gas chromatography analysis.

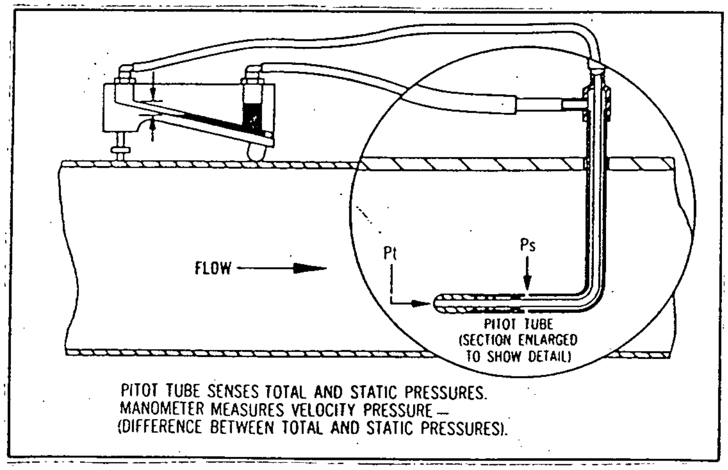

FIGURE 4.3.2: Pitot tube inserted in a gas line for velocity pressure measurement (Dwyer Inst. Inc., 1983)

4.3.6 - LEACHATE SAMPLE COLLECTION

During each sampling session, a leachate sample was collected from the sampling discharge pipe at the pumping station of the inner leachate collection ditch. The sample was collected in a 125 mL high density polyethylene (HDPE) container. Upon returning to the lab, leachate samples were preserved by acidification with 0.25 mL H_2SO_4, and stored at 4°C.

Leachate flowmeter data was provided by the City of Vancouver Solid Waste Management Department. These values represent the total outflow of leachate from the site on a daily basis. This information was used in conjunction with the concentrations of the parameters of interest, in order to determine the loadings of the parameters in the leachate.

4.4 Laboratory Analysis

4.4.1 - pH

Prior to the acidification of the leachate sample with H_2SO_4, a pH reading was taken directly from the leachate using the pHM62 Standard pH Meter.

4.4.2 - CHEMICAL OXYGEN DEMAND

The analysis of the chemical oxygen demand (COD) of the leachate samples was carried out using the closed reflux calorimetric technique as adapted for UBC from the 18th Edition of "Standard Methods".

4.4.3 - TOTAL ORGANIC CARBON

The total organic carbon (TOC) of the leachate samples were measured using the Shimadzu Total Organic Carbon Analyzer TOC-500. Samples were automatically injected into the instrument via the Automatic Sample Injector ASI-502. Total organic carbon measurements were calculated as the difference between the total carbon and the total inorganic carbon in the sample.

4.4.4 - VOLATILE FATTY ACIDS

The separation of aqueous-free carboxylic acids from the leachate mixture was accomplished using the Hewlett-Packard 5880A Series Gas Chromatograph, in conjunction with the Supelco 751G column. Using this 60/80 Carbopack C/0.3% Carbowax 20M/0.1%

H_3PO_4 system, the free C2-C5 carboxylic acids separate readily. This column is approximately 90cm in length, and utilizes helium as a carrier gas at a flow rate of 20 mL/min (Supelco Inc., 1988).

4.4.5 - AMMONIUM NITROGEN

Leachate samples were passed through Whatman #3 filters (11.0 cm diameter) prior to analysis for NH_4^+-N. The samples were then tested using the "LACHAT" automated ion analyzer according to method No. 10-107-06-2-D in "Methods Manual for the QuikChem Automated Ion Analyzer".

4.4.6 - ETHYLENE GAS

In order to determine the presence of C_2H_4 in the landfill gas samples, the Hewlett-Packard 5880A Series Gas Chromatograph was used in conjunction with the 5880A Series GC terminal. The column used for this process was the Porapak Q, which is a stainless steel column approximately 90cm in length. The detector used was the FID, and helium was used as the carrier gas. Samples were injected into the port using a 10uL Hamilton Gastight syringe.

4.5 Climate Station

A climate station was set up on the active gas collection area of the site in order to measure the climate variables over the course of the study period. The station consisted of a tipping bucket apparatus, a temperature probe and a data logger, all powered by a deep discharge marine battery. Measurements of daily average temperature in °C and total daily precipitation in mm were recorded. The numbers were checked regularly with the data obtained at the Vancouver International Airport by Environment Canada, in order to ensure that the Burns Bog climate data was within the reasonable range.

4.6 Statistical Analysis

In addition to the basic descriptive statistics done on the data (median, mean, standard error of the mean, standard deviation), a number of analyses were performed in order to determine the significance of the effects of the individual variables on landfill gas production and composition. Further statistical analyses were carried out in order to predict CH_4 production from each of the individual sampled gas ports and collector lines through the regression of fitted parameters. All statistics were performed using Microsoft Excel version 5.0. The p=0.05 level of confidence was used in all cases, with the exception of the gas collection line analyses, in which the p=0.1 level was utilized.

4.6.1 - SIMPLE LINEAR REGRESSION

Regression analysis was carried out on six independent variables (7 & 14-day cumulative precipitation, barometric pressure, 3 & 7-day average ambient temperature, gas temperature) in order to determine whether or not they had a significant relationship with CH_4 generation at each of the gas ports. The same parameters were tested for significance with respect to the landfill gas sampled in the four main gas collection lines. Regression analysis was also performed on the ratio of CH_4:CO_2 production in response to 3-day, 7-day and 14-day cumulative precipitation. With respect to the leachate, analyses were carried out to determine the strength of the relationship between the COD, NH_4^+-N and acetic acid loadings to the 14-day cumulative precipitation. Final regression analyses were carried out in order to detect a relationship between the leachate parameters and the CH_4 production. An analysis of variance (ANOVA) was carried out for each of the relationships at the p=0.05 level of significance. When less than 0.05, the significance F-values were used to reject the null hypothesis, and conclude that the relationship was significant.

4.6.2 - MULTIPLE LINEAR REGRESSION

Multiple linear regression analysis was carried out in an attempt to predict the production of CH_4 from each of the individual wells, and the volume of CH_4 moving through the active gas collector lines. The independent variables used included 14-day cumulative precipitation, gas temperature (in the case of the ports only) and 3-day average ambient temperature. These variables were chosen due to their relatively high significance values from the simple linear regression analysis.

4.6.3 - COEFFICIENTS OF VARIATION

For each of the above relationships, the coefficient of variation (r^2) was calculated in order to quantify the percent of the variation in the dependent variable which was attributable to its linear relationship with the independent variable.

CHAPTER 5 - RESULTS AND DISCUSSION

Investigations were undertaken to determine the relative influence of the factors affecting CH_4 production from the gas ports, the consequence of heavy rainfall on gas composition ratios, the effects of barometric pressure on landfill gas production, the estimated total annual production of CH_4 from the site, the existence of C_2H_4 in the landfill gas, and the characteristics of the leachate composition and production. The results of this investigation are outlined below.

5.1 Methane Production from Gas Ports

Trends in the production of CH_4 from the individual gas ports in response to various factors were analyzed, and are reported in this section. Of the 11 gas ports sampled, 8 showed consistent gas production over the data collection period. The data from these ports are used to represent the findings in this section. The other 3 gas ports showed highly erratic production, with long periods of no gas production whatsoever. This situation is most likely due to blockages, freezing and leakage. Data from these 3 inconsistent ports can be found in Appendix B.

5.1.1 - CUMULATIVE PRECIPITATION

The most significant factor affecting CH_4 production from the individual gas ports was found to be the cumulative precipitation from the 14 days prior to sampling. The results from ports C14 and D23 are shown to illustrate this (Figures 5.1.1 and 5.1.2). Graphs from the other 6 ports can be found in Appendix C. In all cases, the periods of high moisture input coincided with peak CH_4 production. The strength of this relationship is displayed by the high coefficients of variation (r^2), which represent the percent of the variation in the CH_4 production which can be attributed to its relationship with the 14-day cumulative precipitation. The mean r^2 value from the 8 gas ports is 0.88. The F-value and the significance F-value for each relationship is also displayed on each figure. In all cases the latter is less than 0.05, suggesting that the relationship is significant at the p=0.05 confidence level.

In the cases of the relatively high CH_4 producing wells (D23, E20, E7) (see Table 5.1.1) the relationship was best described by a linear equation, in contrast to the exponential relationship found from the relatively low production wells (C14, F29, G5, G9). This observation may be attributed to the fact that periods of intense rainfall caused a shift in gas composition, leading to higher CH_4 production in relation to CO_2 (see section 5.2). In the cases of the low production wells, this increased output of CH_4 was very significant in relation to the low production during dry periods. However, in the case of the high production wells, the shift in gas composition following periods of intense rainfall did not significantly alter the output of CH_4 in relation to the high production during the dry periods. Although port F6 displayed relatively low CH_4 production, its relationship was best described by the linear equation characteristic of the high production wells. The weight of the significance of this relationship is extremely high (7.38×10^{-7} is far below the 0.05 used for the significance level), suggesting that in this case, the effects of increased moisture input to the system override the shift in CH_4:CO_2 production ratios. This is a likely explanation for the linear relationship between CH_4 production from port F6 with 14-day cumulative precipitation.

TABLE 5.1.1: Mean CH_4 production from sampled gas ports

GAS PORT	MEAN CH_4 PRODUCTION (L/min)
C14	9.54
D23	61.37
E20	71.02
E7	36.38
F6	11.92
F29	0.09
G5	3.95
G9	9.48

The strong influence of this moisture input on CH_4 production can be attributed to a number of factors. Firstly, the cross-section of a landfill cell (Figure 3.3.1) shows that the age of the refuse increases with increasing depth of burial. Hence the area of high organic content is situated at the top of the fill, where both the relatively undecomposed refuse, and the biomass growing on the surface of the cell are located. In many cases the area of active methanogenesis is located far below the surface. The movement of organic matter from the top of the fill to the area of active refuse degradation would be accomplished by the infiltration of moisture, and its downward movement through the matrix. The re-introduction of organic matter to the area of microbial activity would significantly increase the availability of carbon to be used as a substrate in the decomposition reactions. It is likely that the carbon substrate is a limiting factor in areas where only the refractory humic substances persist, and in areas with inherently low available organic matter.

Secondly, the increase in mixing and general availability of nutrients is a result of the downward movement of water through the wastes. It is possible that nutrient deficiencies exist in discrete areas of the fill. The increased availability of nutrients in these "microniches" as a result of moisture addition could enhance the methanogenic process. Aside from acting in nutrient transport, moisture addition can also lead to the direct stimulation of bacterial growth, thus replenishing populations of methanogens. Water is also utilized in the degradation reactions, specifically in the acetogenesis stage where it is necessary for the transformation of propionate to acetate. This reaction is coupled to methanogenesis, so theoretically, if H_2O was limiting CH_4 production would be expected to decrease. Due to the high moisture levels characteristic of refuse this situation is unlikely, but nonetheless warrants consideration. Finally, the dilution of metabolic inhibitors within the waste matrix would further act to enhance the efforts of the microbial populations. Theoretically, all of these effects should lead to increased rates of CH_4 production.

5.1.2 - DISPLACEMENT CONSIDERATIONS

The possibility exists that the increase in gas production from an area of the fill following periods of heavy rainfall is predominantly a function of the displacement of gas by the incoming liquid. An investigation into the response of total leachate production at the site to periods of heavy rainfall was undertaken in order to determine the rate of movement of

H_2O through the fill, the moisture storage capacity of the fill, and the resultant contribution of displacement to the increased gas production observed in relation to 14-day cumulative precipitation.

A comparison between total daily precipitation and daily leachate outflow indicated that leachate production volumes respond quickly to precipitation inputs (Figures 5.1.3-5.1.6). In general, periods of peak rainfall were immediately followed by an increase in leachate production from the site as a whole. Some capacity for moisture storage within the fill did seem to occur (days 327-331 and days 340-347), although the extent of this appeared to be limited. During the period of days 94-100 no increase in leachate flow accompanied the heavy rainfall. This pattern is in contrast to that found during the majority of the sampling period. It is possible that this situation was a result of high evaporation and evapotranspiration influences, and increased moisture uptake following the proceeding dry 13 day period.

The rapid movement of precipitation through the fill, and the resultant quick response in leachate production following rainfall events as indicated by Figures 5.1.3-5.1.6 suggests that the effects of displacement of gas by the incoming moisture would be occurring directly following heavy precipitation.

In further investigation of the relative influence of displacement effects, a comparison was made between the precipitation loading within the radius of influence of each gas port, to the production of landfill gas at that area. The results of this investigation for ports C14, D23, E20 and E7 are shown in Figures 5.1.7-5.1.10 respectively, and the results for the remaining wells can be found in Appendix C. A sample calculation for the determination of precipitation loadings can be found in Appendix A. The results indicate that high gas production frequently occurs following several days of little or no rainfall. Although the beneficial effects of 14-day cumulative rainfall on methanogenesis are evident (see previous sections), the lack of moisture addition immediately prior to sampling did not appear to hamper CH_4 production.

The investigation of both leachate production response to precipitation events, and the effects of moisture loadings on landfill gas production collectively indicate that displacement does not appear to be the predominant factor driving the aforementioned observed increase in CH_4 production following periods of high 14-day cumulative precipitation.

5.1.3 - AMBIENT TEMPERATURE

The correlation between ambient temperature and CH_4 production was most prominent when comparing the production to the average ambient temperature 3 days prior to sampling. Gas ports E20 and E7 are used to display this finding (Figures 5.1.11-5.1.12). Graphs from the other 6 ports can be found in Appendix C.. This relationship displayed a mean r^2 value of 0.41, and consequently is much less notable than the relationship between cumulative precipitation and CH_4 production. The relationships found in 5 of the 8 wells were significant at the $p=0.05$ level of confidence.

In contrast to what may be intuitively expected, these results show that the CH_4 production decreased as the ambient temperature increased. While many associate methanogenesis with warm temperatures, these findings can be explained by taking a number of factors into consideration. First, one must consider the fact that the climate in southwestern British Columbia generally follows the pattern of high temperatures being associated with periods of low rainfall. Considering the significant effect of moisture input on CH_4 production (see section 5.1.1), it is then logical to expect that periods of high ambient temperatures (and low precipitation) would be associated with relatively low CH_4 production. An additional explanation of the lack of association between high ambient temperature and high CH_4 production is the fact that the landfill temperature itself appears to be primarily influenced by the internal temperature regime created by the microbial activity. This overall temperature attained will be determined by the balance between the rates of heat production and addition, and the rate of heat loss to the surrounding soil and atmosphere. Because there exists a relatively large buffer zone between the active gas producing area of the fill and the atmosphere, this heat loss appears to be negligible.

5.1.4 - GAS TEMPERATURE

Results showed that both the median and mean CH_4 production values from the sampled population as a whole were directly related to the median and mean gas temperature values found within the population (Figures 5.1.13 and 5.1.14). Peak methane production corresponded with high gas temperatures. The coefficients of variation were r^2=0.75 for the median values, and r^2=0.69 for the mean values, indicating a strong relationship between the variables. The results of the analysis of variance showed that these relationships were significant at the p=0.05 level of confidence. This finding indicates that those ports which displayed the highest CH_4 production over the sampling period also displayed the highest recorded gas temperatures. Therefore, when making comparisons between the entire sampled population of ports, the warmest gas temperatures were consistently found at the ports with the highest CH_4 production values. This finding concurs with the knowledge that methanogenesis is a highly exothermic process, creating internal temperature regimes of up to 45°C.

When examining the relationship between CH_4 production and gas temperature at each of the individual ports, no significance was indicated. This is most likely due to the influence of external factors on the gas temperature at each of the ports. For example, a cooling effect was indicated by the significant relationship between the gas temperature at the individual ports and the ambient temperature the day of sampling (mean r^2=0.69). Ports F6 and F29 are used to illustrate this finding (Figures 5.1.15-5.1.16). The results found from the remaining 6 ports can be found in Appendix C. This cooling of the gas most likely occurs as it reaches the surface and travels above ground through the collection system.

The effects of cumulative precipitation 14 days prior to sampling on the temperature of the landfill gas was also found to be significant at the p=0.05 level of confidence at 6 of the 8 ports (mean r^2=0.44). Ports G5 and G9 are used to illustrate this finding (Figures 5.1.17-5.1.18). The periods of high precipitation corresponded with low gas temperatures, suggesting that the infiltration of moisture into the waste matrix had a cooling effect on the landfill gas. It may therefore be concluded that although the high landfill gas temperatures were generally an indication of peak CH_4 production, caution must be exercised when interpreting the relationship as external factors such as ambient temperature and precipitation do have some influence on the measured landfill gas temperature in this experiment.

5.1.5 - REFUSE AGE

A direct relationship between estimated refuse age and CH_4 production was not evident from the gas ports sampled (Table 5.1.2). The ports displaying the highest rates of CH_4 production (E20, D23, E7) contain refuse which was estimated to be deposited between 1978 and 1986. This finding suggests that in the case of this specific site, the latter period of stage III gas production (anaerobic methanogenic unsteady - see section 2.3.1) is not being achieved until 10-15 years after refuse emplacement.

TABLE 5.1.2: Estimated age of the buried refuse and mean CH_4 production at each sample port (modified from Lovegrove, 1987)

GAS PORT	ESTIMATED DATE OF REFUSE EMPLACEMENT	MEAN CH_4 PRODUCTION (L/min)
C14	1970-1975	9.54
D23	1978-1982	61.37
E20	1983-1986	71.02
E7	1983-1986	36.38
F6	1986-1988	11.92
F29	1986-1988	0.09
G5	1988-1990	3.95
G9	1988-1990	9.48

The relatively low mean CH_4 production from port C14 may indicate that the decomposition of the refuse buried there is in the latter period of stage IV gas production (anaerobic methanogenic steady). Results suggest that the production of CH_4 is tapering off in this specific area, and only refractory substances are remaining. This situation is probable if the refuse was buried there 20-25 years ago. Concerning ports G5 and G9, it is possible that they represent the other end of landfill gas production timeline. Because the refuse was buried in these areas relatively recently, it is possible that the gas production is still in the earlier phases of stage III (anaerobic methanogenic unsteady), and therefore peak CH_4 production has not yet been achieved. The extremely low CH_4 production from port F29 cannot be explained by the age of the refuse buried there. This situation is possibly a function of decreased moisture infiltration to the matrix, low substrate availability to the active gas producing area of the fill, or perhaps the existence of a partial blockage or a low permeability region within the gas port itself.

Questions arise as to the accuracy of extrapolations from the relationships displayed in Table 5.1.2 to the other wells on the gas collection lines. When comparing the CH_4 production values from the ports to those from the lines (Table 5.4.2), some consistency is evident. For example, the highest production from the ports is clearly found to be from wells D23, E20 and E7. In accordance, the D and E-lines display the highest production, as compared to the F and G-lines. However, comparisons between the F and G-lines, and the corresponding ports indicate no distinct similarities. Hence these extrapolations cannot be made with confidence.

Estimating the age of buried refuse is highly problematic, and wrought with sources of error. A significant amount of backfilling has taken place over the course of the landfilling operations at this site, which adds to the confusion surrounding these estimations. Although it is interesting to speculate on the relationships displayed in Table 5.1.2, the lack of certainty with respect to these correlations makes it necessary to omit refuse age as a significant contributing factor to the patterns in CH_4 generation observed during this study.

Table 5.1.3 displays a summary of the findings with respect to the factors found to affect CH_4 production at the sample gas ports in this study. Cumulative precipitation was found to have the most consistent and significant relationship with CH_4 production. Gas temperature and ambient temperature were also found to have significant correlations to CH_4 production, but to a lesser extent.

5.1.6 -PREDICTING CH_4 PRODUCTION

By utilizing those factors which were found to affect CH_4 production, a multiple linear regression equation was calculated for each gas port (Table 5.1.4). The variables included in each equation are as follows:

TABLE 5.1.3: Summary of factors found to affect CH_4 production at sample gas ports

FACTOR	MEAN r^2	% FREQUENCY OF SIGNIFICANCE
14-day cumulative precipitation	0.88	100
3-day mean ambient temperature	0.41	63
median gas temperature	0.75	88

x_1 = 14-day cumulative precipitation (mm)

x_2 = 3-day average ambient temperature (°C)

x_3 = gas temperature (°C)

It is important to note that as these predictive equations may be useful for estimating CH_4 production, they are extremely site specific and extrapolations to other CH_4 producing sites would most likely be inaccurate.

TABLE 5.1.4: Predictive regression equations for CH_4 production from sampled gas ports

PORT	PREDICTED CH_4 PROD. (L/MIN)	r^2	F_{sig}
C14	$y=0.14x_1+0.02x_2-0.24x_3+5.89$	0.93	$5.0x10^{-5} <0.05$ ∴SIG
D23	$y=0.45x_1+0.75x_2-0.24x_3+39.17$	0.91	$1.4X10^{-4}<0.05$ ∴SIG
E20	$y=0.28x_1+0.17x_2-1.00x_3+92.29$	0.79	$4.7X10^{-3}<0.05$ ∴SIG
E7	$y=0.37x_1+0.13x_2-0.14x_3+22.2$	0.98	$6.0X10^{-7}<0.05$ ∴SIG
F6	$y=0.15x_1+0.27x_2-0.13x_3+4.57$	0.95	$1.4x10^{-5}<0.05$ ∴SIG
F29	$y=0.004x_1+0.002x_2+0.003x_3-0.13$	0.91	$1.3x10^{-4}<0.05$ ∴SIG
G5	$y=0.13x_1-0.06x_2+0.16x_3-4.13$	0.96	$7.2x10^{-6}<0.05$ ∴SIG
G9	$y=0.32x_1+0.29x_2+0.12x_3-9.32$	0.92	$1.2x10^{-4}<0.05$ ∴SIG

When comparing the equations between ports certain discrepancies become evident. For example, gas temperature is seen to correlate negatively with CH_4 production (as indicated by the negative x_3 value) in all cases except for the last 3 sample ports. Potentially, the interaction between the cooling effect of moisture infiltration and low ambient temperatures is not correlating as strongly to high CH_4 production as it is in the first 5 sample ports. With respect to 3-day average ambient temperature, the variable (x_2) is positive in all cases except for port G5. The variation in these equations may be a result of the differing interactions between the variables at each specific port. It is also possible that the different inherent characteristics at each sample area (infiltration rates, refuse density, refuse characteristics) are affecting their patterns of CH_4 production. Due to the discrepancies which are observed when comparing the influence of the factors between regression equations, skepticism regarding the value of these predictive equations is warranted.

5.2 Gas Composition Ratios

An investigation of the patterns in landfill gas composition from the sample ports revealed a significant relationship involving the ratio of CH_4:CO_2 production in response to 7-day cumulative precipitation. This ratio was seen to increase dramatically following periods of intense rainfall. Ports E20 and E7 are shown to illustrate this relationship (Figures 5.2.1 and 5.2.2). The mean coefficient of variation for the 8 gas ports shown is 0.85, suggesting that a strong relationship exists between these variables. In all cases, the analysis of variance concluded significance at the p=0.05 level of significance.

The effects of intense rainfall and decreased hydraulic retention time on the composition of landfill gas is not well documented. The increase in the ratio of CH_4:CO_2 production following periods of heavy rainfall can most likely be attributed to the dissolution of CO_2 and downward movement with the leachate. In addition, it is possible that CO_2 acts as an end-product inhibitor during acetate and propionate degradation; its decreased partial pressures after periods of heavy rainfall would thus favour enhanced CH_4 production.

5.3 Barometric Pressure

The effects of barometric pressure on landfill gas production at the Burns Bog site were found to be negligible. The relationship was only proven to be significant at ports E7 and F6 (Figures 5.3.1 and 5.3.2), and showed no significant relationship with landfill gas production at the remaining gas ports. In the cases where it was significant, landfill gas production was observed to decrease with increasing barometric pressure. This finding concurs with the expectation that a "pumping" action has been known to occur as conditions change from a high to a low pressure system, due to the exchange between ambient air and landfill gases. In contrast, the periods of high barometric pressure have been found to repress the venting of landfill gas.

These results suggest that barometric pressure was not a significant factor affecting landfill gas production from the sample ports at the study site. It is important to note that these measurements were taken during a period when the gas collection system was not running at the site. However, residual effects of the vacuum system were most likely exerting some influence. Any effects of barometric pressure fluctuations on landfill gas production at the Burns Bog site would undoubtedly be overrun by the influence of the vacuum extraction of the gas by the collection system.

5.4 Total Landfill Gas Production

In-line flow measurements from the active gas collection lines used in conjunction with gas composition measurements revealed some patterns in the gross landfill gas production at the site. These patterns were less distinct than those observed from the individual gas production wells, most likely due to the mixing of gases from the relatively large land area, which can include variety with respect to the age of the refuse buried, and the moisture holding capacity of the soil and waste materials. For this reason, relationships between the landfill gas in the 4 active collection lines studied (D,E,F and G) were analyzed at the $p=0.1$ level of significance.

5.4.1 - CUMULATIVE PRECIPITATION

In 3 of the 4 collection lines, the effects of 14-day cumulative precipitation displayed a significant relationship to CH_4 production. The E-line of the collection system is used to illustrate this finding (Figure 5.4.1). The relationships found in the remaining lines can be found in Appendix C. The relatively low mean coefficient of variation (r^2=0.38) suggests that this relationship does not explain the majority of the variation in CH_4 production, but does however replicate to some degree the patterns in CH_4 production found at the individual gas ports.

5.4.2 - AMBIENT TEMPERATURE

The mean ambient temperature 3 days prior to sampling did not appear to significantly correlate with CH_4 production in 3 of the 4 gas collection lines. The low mean value for the coefficient of variation (r^2=0.15) suggests that this relationship does not explain much of the variation in CH_4 production from these areas. Ambient temperature can, however, be negatively correlated with precipitation at this particular site. For this reason it is included in the next section as a factor which may aid in the prediction of CH_4 produced at this site.

5.4.3 - PREDICTING CH_4 PRODUCTION FROM THE LINES

Multiple linear regression equations were calculated for each gas line using the aforementioned factors (Table 5.4.1). The variables included in each equation are as follows:

x_1 = 14-day cumulative precipitation (mm)

x_2 = 3-day average ambient temperature (°C)

TABLE 5.4.1: Predictive regression equations for CH_4 production from sampled gas lines

LINE	PREDICTED CH_4 PROD. (L/MIN)	r^2	SIGNIFICANCE (p=0.1)
D-LINE	$y=24.86x_1+25.55x_2+22216.67$	0.31	significant
E-LINE	$y=41.69x_1+36.50x_2+21393.70$	0.59	significant
F-LINE	$y=34.97x_1+19279.06$ *	0.25	significant
G-LINE	$y=29.68x_1+25.47x_2+20334.62$	0.49	significant

* no x_2 value is included in this equation as the variable was not significant independently, and had no significant interaction with the other variable

The relatively low r^2 values suggest that much of the variation in the CH_4 present in the lines is a result of factors which were not monitored in this experiment. Hence the prediction of the CH_4 from the collection lines using these regression equations could be highly problematic.

5.4.4 - TOTAL ANNUAL CH_4 PRODUCTION

The mean CH_4 production in the D,E,F, and G areas was calculated from the header line data and is presented in Table 5.4.2. The total annual CH_4 production from the active gas collection area of the site is represented as the sum of the mean annual CH_4 flows from each of the four lines Assuming that CH_4 production from the A-line area is negligible, and that the minimal amount produced in the B and C-line areas is utilized by the administration building, this total CH_4 production value is an estimate for the production from the entire area serviced by the gas collection system at the Burns Bog site.

TABLE 5.4.2 : Annual CH_4 production from both the gas collection lines, and the total area serviced by the gas collection system are displayed

AREA	MEAN CH_4 FLOW (L/min)	ANNUAL CH_4 PRODUCTION (L/year)	ANNUAL CH_4 PRODUCTION (m^3/year)
D-LINE	23580	1.239×10^{10}	1.239×10^{7}
E-LINE	23630	1.242×10^{10}	1.242×10^{7}
F-LINE	21634	1.137×10^{10}	1.137×10^{7}
G-LINE	21922	1.152×10^{10}	1.152×10^{7}
TOTAL	**90766**	$\mathbf{4.771 \times 10^{10}}$	$\mathbf{4.771 \times 10^{7}}$

Beyond the landfilling area serviced by the gas collection system lies an additional area of buried refuse which has not yet been tied to the existing gas collection system. This portion of the site is nearly up to the design height, and the final cover has been placed. It has been estimated by E.H. Hanson Engineering Group Ltd. (1995) that an additional 8.00×10^6 m^3 CH_4 is presently being generated by this area annually. When factoring in this additional landfill gas producing area, the estimate of total CH_4 production from this site according to the data collected is 5.57×10^7 m^3 CH_4 each year. This value equates to a production of 44.76 kT CH_4/year, or 0.0033 T CH_4/T refuse/year on a mass basis (see Appendix A for calculations). Assuming that this production will occur for approximately 20 years, the net CH_4 production is calculated to be 0.066 T CH_4/T refuse. This estimate lies between those calculated by Orlich and Richards (Table 2.6.2).

When comparing the total annual production of CH_4 from this site (44.76 kT CH_4/year) to the summary of emissions displayed in Table 2.6.1, one may note that the CH_4 produced at the City of Vancouver Landfill Site at Burns Bog is approximately equal to 3% of the total emissions from municipal landfill sites in Canada. Assuming a Canadian population of 28 million, and a Burns Bog site contributing population of approximately 0.7 million, it is observed that approximately 2.5% of the Canadian population is depositing wastes to this site. Hence, the estimates suggest that 2.5% of the population is producing 3.0% of the total CH_4 originating from landfill disposal of municipal solid wastes. A number of factors may be contributing to the slightly higher CH_4 production on a per capita basis, including the relatively high standard of living in the region (and resultant increase in consumption), and the rainy climate (leading to enhanced methanogenesis). An additional point of interest includes the fact that this one landfill site alone appears to produce more CH_4 than the independent contributions from natural gas distribution, fuel combustion and prescribed fires in Canada.

The collection and flaring of landfill gas at the Burns Bog site represents a significant improvement with respect to greenhouse gas emissions. It is estimated that a given volume of CH_4 recovered and burned has an equivalent net effect of lowering CO_2 to the atmosphere by approximately 2 to 15 times the same volume (MacViro Consultants Inc., 1991). With respect to the City of Vancouver landfill site, using a reduction in the order of 8 times by volume, this equates to a reduction in the order of 4.46×10^8 m^3 CO_2 equivalents each year (see Appendix A for calculations). This value represents a significant decrease in the environmental impact of this site as a whole, and highlights the benefits additional to odour control which accompany landfill gas collection systems.

Further potential reductions in greenhouse gas emissions from this site are achievable by the introduction of energy recovery operations. E.H. Hanson Engineering Group Ltd.

(1995) proposed that a further reduction of 2.92 x 10^8 m^3 CO_2 each year is possible by utilizing the landfill gas from the Burns Bog site as fuel in the cement kilns at Tilbury Cement (see Section 6.3.3). It is the displacement of the fuels presently used in this operation which would accrue these benefits. Options such as this must be explored in order to continue to reduce the emission of greenhouse gases from the City of Vancouver Landfill Site.

5.5 Detection of C_2H_4

No C_2H_4 was detected in the gas samples collected. This may be a result of exchanges of gases between the Teflon bag and the ambient environment. It is also possible that C_2H_4 simply was not present at any detectable levels in the landfill gas. This is a beneficial situation, as C_2H_4 is potentially toxic to plants, thus rendering the revegetation of reclaimed landfill sites highly problematic. In the case of the City of Vancouver landfill site, plant toxicity as a result of high C_2H_4 levels is not likely to be a problem faced during revegetation efforts.

5.6 Leachate Characteristics

The characteristics of the leachate measured over the 12 sampling sessions are shown in Tables 5.6.1. and 5.6.2. Neutral pH values characterized the leachate analyzed, with a mean pH value of 7.4, and very little fluctuation over time. The chemical oxygen demand (COD) concentration values appeared to be relatively high when compared to the literature. This finding suggests that a significant amount of organic matter is present in the leachate, despite the age of the landfill.

The trends in both the COD concentration and COD loading in the leachate were analyzed in order to determine any decipherable patterns. The COD concentration was shown to significantly decrease in response to increasing 14-day cumulative precipitation readings (Figure 5.6.1). Although the total COD loading (calculated using COD concentration in the leachate and leachate volume flow data) did not display a significant relationship with 14-day cumulative precipitation at the $p=0.05$ level of significance (Figure 5.6.2), a trend toward higher loading with higher precipitation inputs is visible. It is likely that this is due to the fact that more COD is mobilized following high precipitation inputs. However, upon observing this relationship one may conclude that the total COD loading in the leachate does appear to "drop off" with the higher cumulative precipitation readings (>60mm precipitation). This finding, in addition to the aforementioned significant decrease in COD concentration following high 14-day cumulative precipitation, supports the claim that dilution effects may be occurring.

The low mean COD:TOC ratio of 1.10 concurs with the assumption that older sites generally have a value for this ratio of less than 2.0. Higher COD:TOC ratios generally reflect the unoxidized state of organic carbon in the leachate; a situation common in younger landfill sites.

The NH_4^+-N loadings in the leachate were calculated using sample concentrations and leachate volume flow data, and results were used to investigate the effects of precipitation on this parameter. The significant relationship was found to be between leachate NH_4^+-N

TABLE 5.6.1: Leachate characteristics measured over the study period (all units are mg/L except pH and COD:TOC)

SAMPLING SESSION	pH	COD	TOC	COD:TOC	NH_4^+-N
1	7.69	550.00	786.60	0.70	158.22
2	7.24	477.78	696.10	0.69	170.74
3	7.36	400.00	632.20	0.63	164.53
4	7.20	382.67	527.60	0.73	181.05
5	7.36	517.20	797.00	0.65	177.94
6	7.32	711.11	484.00	1.47	187.63
7	7.40	519.07	516.58	1.00	193.62
8	7.50	419.64	333.25	1.26	134.28
9	7.77	608.77	502.92	1.21	250.82
10	7.43	647.80	298.59	2.17	249.04
11	7.45	561.91	559.23	1.00	205.42
12	7.50	595.24	515.24	1.16	215.92
MEAN	**7.44**	**532.60**	**554.11**	**1.06**	**190.77**
MEDIAN	**7.42**	**534.54**	**522.09**	**1.00**	**184.34**
STD. DEV.	**0.17**	**101.03**	**155.08**	**0.45**	**34.99**

loadings and 14-day cumulative precipitation (Figure 5.6.3). The loadings were observed to increase with higher precipitation inputs. As the existence of NH_4^+-N indicates protein degradation, this finding suggests that the increased precipitation inputs are causing the displacement of these products of refuse degradation, and their downward movement with the leachate. However, even during the periods of the highest observed NH_4^+-N loadings, these values were not high enough to suggest that problems may arise as a result of the cation displacing heavy metals from soil exchange sites.

Concentrations of volatile fatty acids detected in the leachate samples were low (Table 5.6.2). This concurs with previous findings, and with the understanding that free volatile fatty acids are readily fermented, and subsequently only appear in high concentrations in the leachates of newly deposited refuse. Under the assumption that precipitation drains through a landfill evenly, one can expect that in larger landfills (such as Burns Bog) the concentration of volatile fatty acids in the mixed leachate will be low, as the newly deposited refuse will represent an ever smaller proportion of the old. The patterns in acetic acid concentration in response to precipitation inputs were investigated, and no significant relationship was found. A general trend of decreasing acetic acid concentration with increasing precipitation inputs was, however, evident (Figure 5.6.4). This finding suggests that dilution effects may be a factor. When investigating the acetic acid loading on the sampling day in response to 14-day cumulative precipitation, a significant relationship was detected (Figure 5.6.5). Loadings were seen to increase with greater precipitation inputs. This is most likely due to the increased mobilization of the acid substances following high moisture inputs. This finding is in contrast to what may be expected, as the acetic acid acts as a direct substrate for methanogenesis, and therefore it would be expected that the loadings would decrease during periods of high methanogenic activity. This finding suggests that the increased mobilization of acetic acid is outweighing the effects of its increased utilization as a substrate. It is also possible that the intermediary reactions wherein propionic acid and H_2O are converted to, predominantly, acetic acid and CH_4 are being enhanced by the precipitation inputs (see Section 2.2).

The concentration ranges of the majority of the leachate parameters are highly variable. The composition of the leachate is dependent on many factors (see Section 2.4.2), and consequently both temporal and spatial variation is characteristic.

TABLE 5.6.2: Volatile fatty acid concentrations of the leachate samples are shown below (all units are mg/L)

SAMPLING SESSION	ACETIC ACID	PROPIONIC ACID	ISO-BUTYRIC ACID	BUTYRIC ACID
1	34.45	0	0	0
2	26.64	0	0	0
3	33.58	0	0	0
4	35.74	6.76	0	0
5	39.38	5.97	0	0
6	38.06	0	4.24	3.06
7	32.20	0	0	0
8	31.00	0	0	0
9	36.22	0	0	0
10	31.02	0	0	0
11	33.76	0	0	0
12	36.37	0	0	0
MEAN	**34.04**	**1.06**	**0.35**	**0.26**
MEDIAN	**34.11**	**0**	**0**	**0**
STD. DEV.	**3.50**	**2.48**	**1.22**	**0.88**

5.7 Leachate and Gas Production Relationships

Final investigations involved highlighting any discernible patterns between the leachate loadings and the CH_4 production. No significant relationship was detected between the total CH_4 production from the 8 sampling wells and the COD load in the leachate on the day of sampling (Figure 5.7.1). A downward trend in the COD load with increasing CH_4 production was observed, but this relationship was not significant at the $p=0.05$ level. This finding may be due to the contrasting influences of an increase in carbon substrate utilization during periods of high methanogenesis (causing decreased COD loadings), and an increased mobilization of the substances following heavy rainfall.

Significant direct relationships were detected between CH_4 production from the sampling ports and both NH_4^+-N and acetic acid loadings in the leachate (Figures 5.7.2 and 5.7.3). In the case of the NH_4^+-N, it is likely that the relationship was observed due to the additive influences of increased "washing" of the substance from the landfill profile following heavy rainfall, and the increased rate of protein degradation during periods of rapid decomposition activity. With respect to the relationship between acetic acid loadings and CH_4 production, it is once again likely that the enhanced mobilization of the substance is driving this relationship. As mentioned in the previous section, one may also speculate as to the increased utilization of propionic acid as a substrate during periods of increased methanogenic activity, and the resultant rise in the production of acetic acid as an intermediary compound.

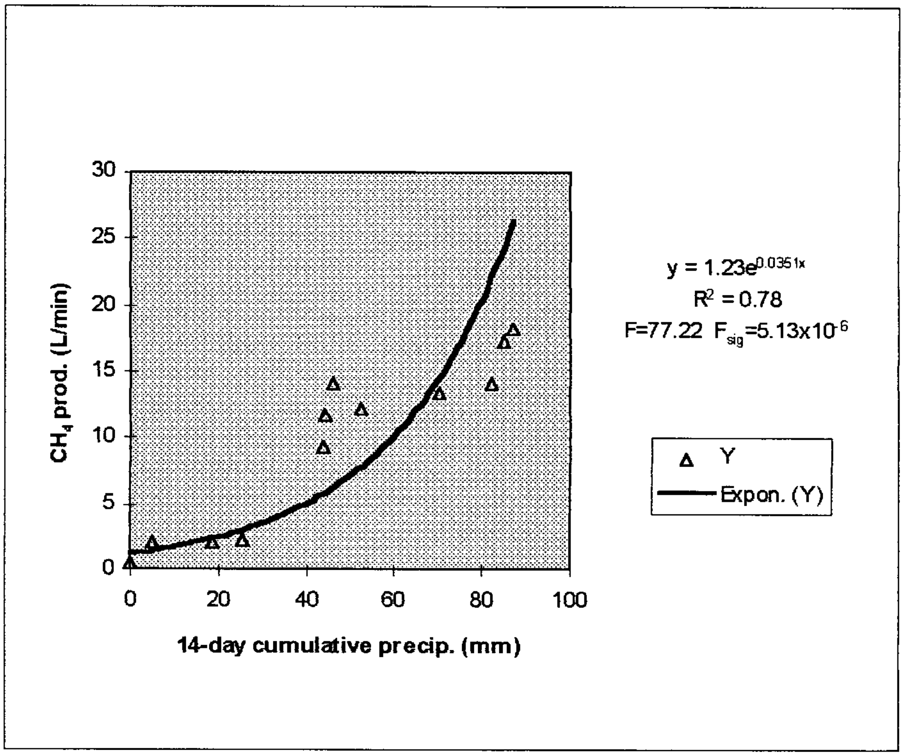

FIGURE 5.1.1: CH_4 production in response to 14-day cumulative precipitation (PORT C14)

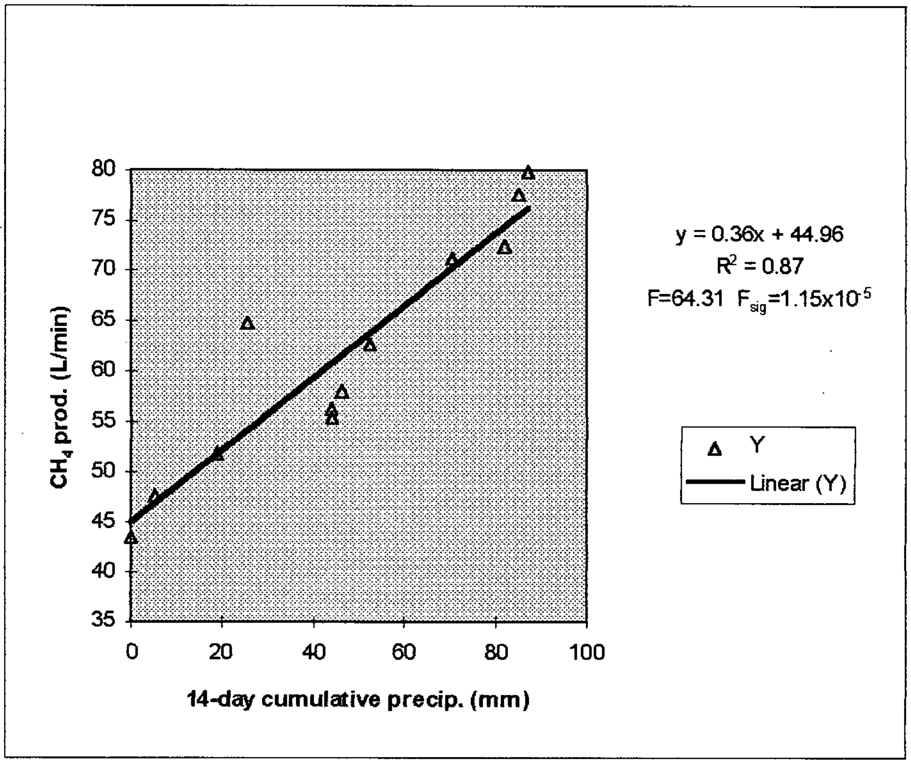

FIGURE 5.1.1: CH_4 production in response to 14-day cumulative precipitation (PORT D23)

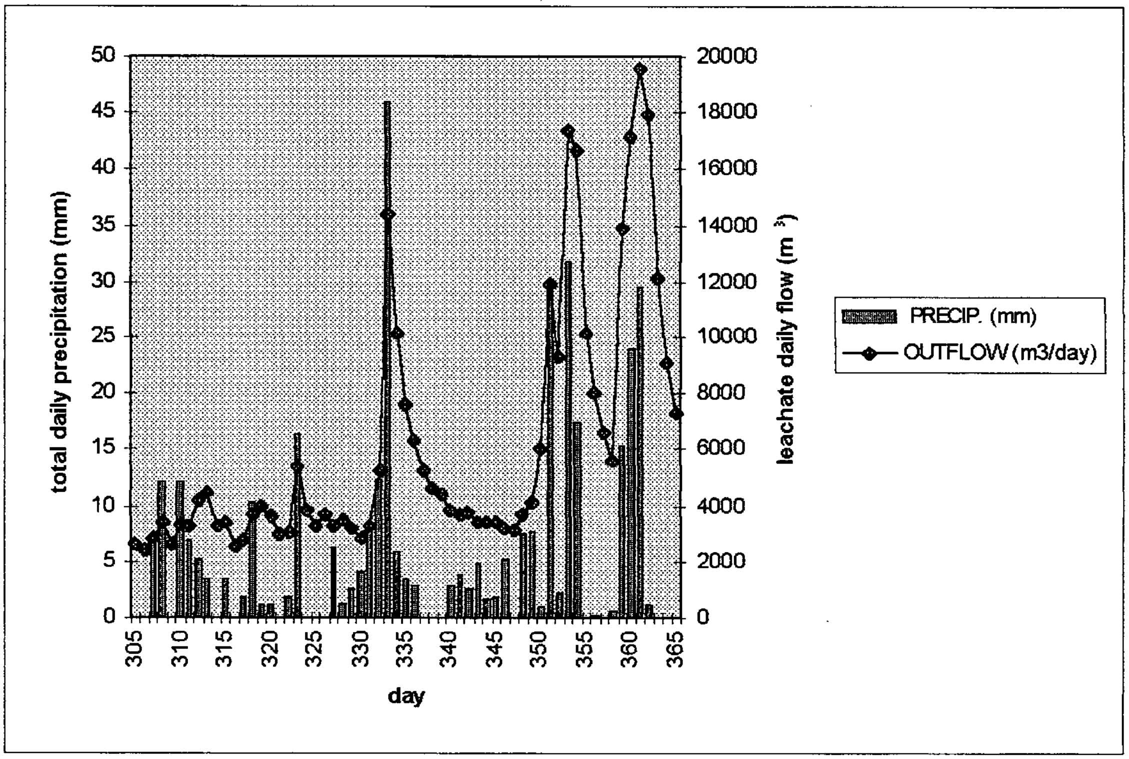

FIGURE 5.1.3: Total leachate production in response to precipitation - November and December 1994

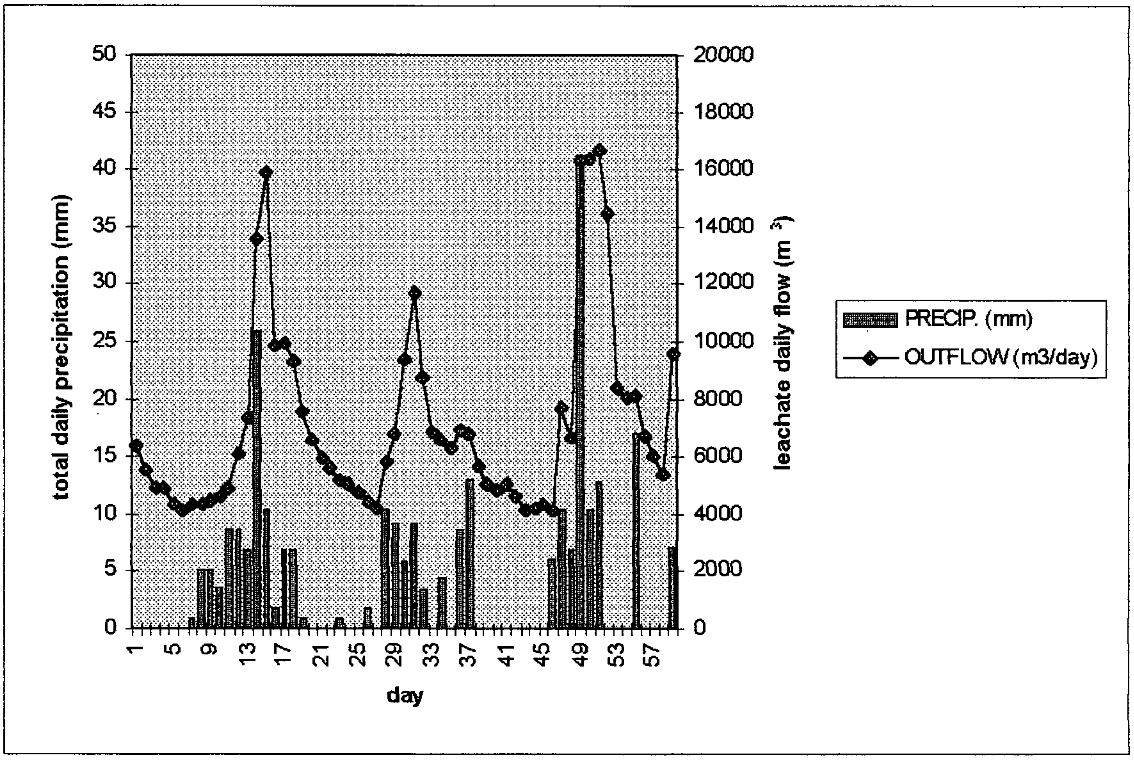

FIGURE 5.1.4: Total leachate production in response to precipitation - January and February 1995

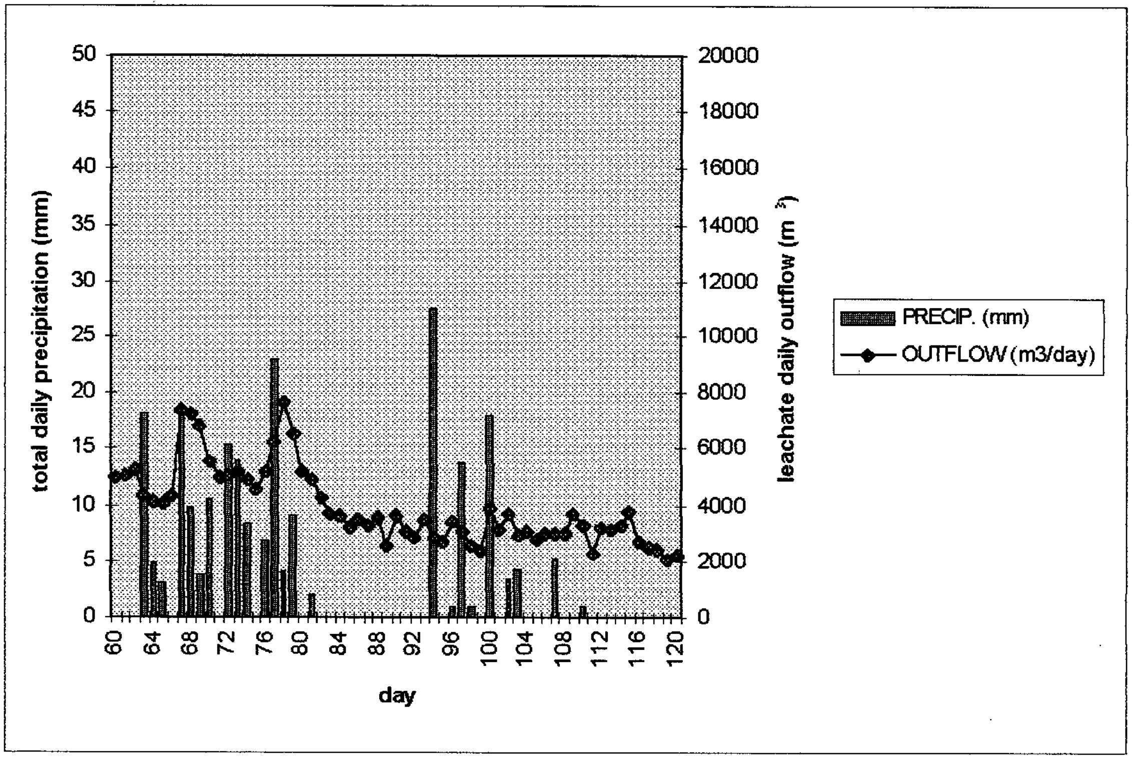

FIGURE 5.1.5: Total leachate production in response to precipitation - March and April 1995

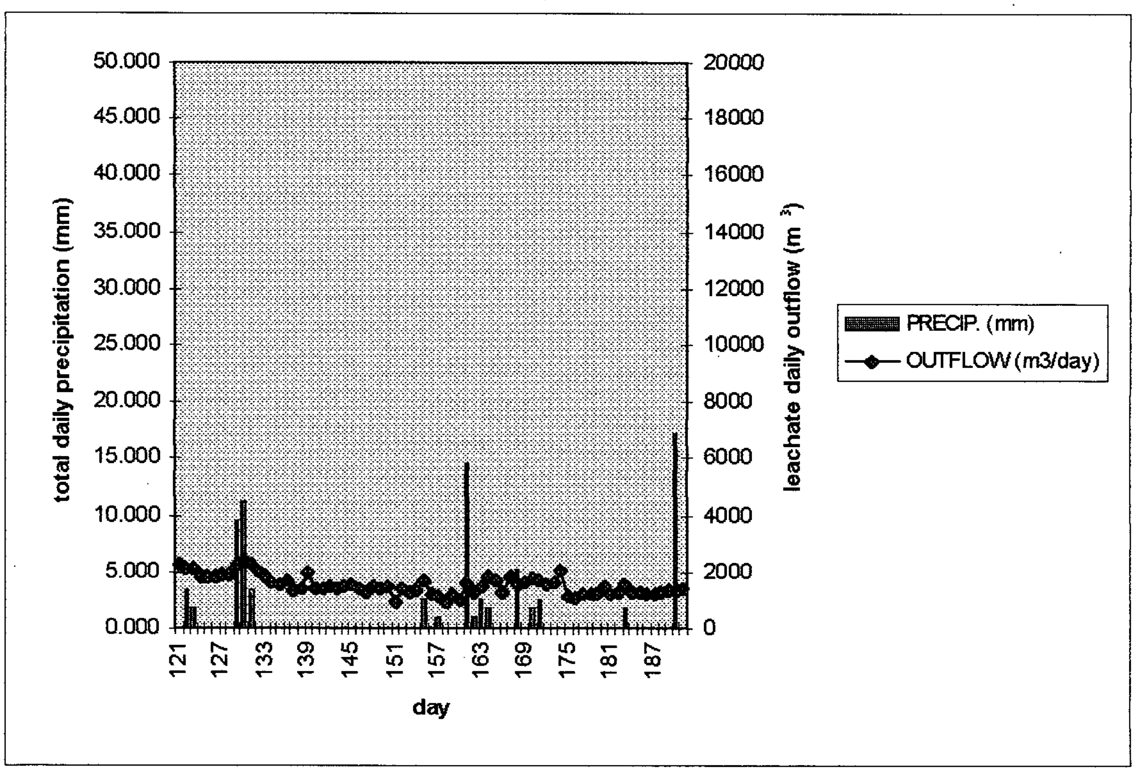

FIGURE 5.1.6: Total leachate production in response to precipitation - May, June and July 1995

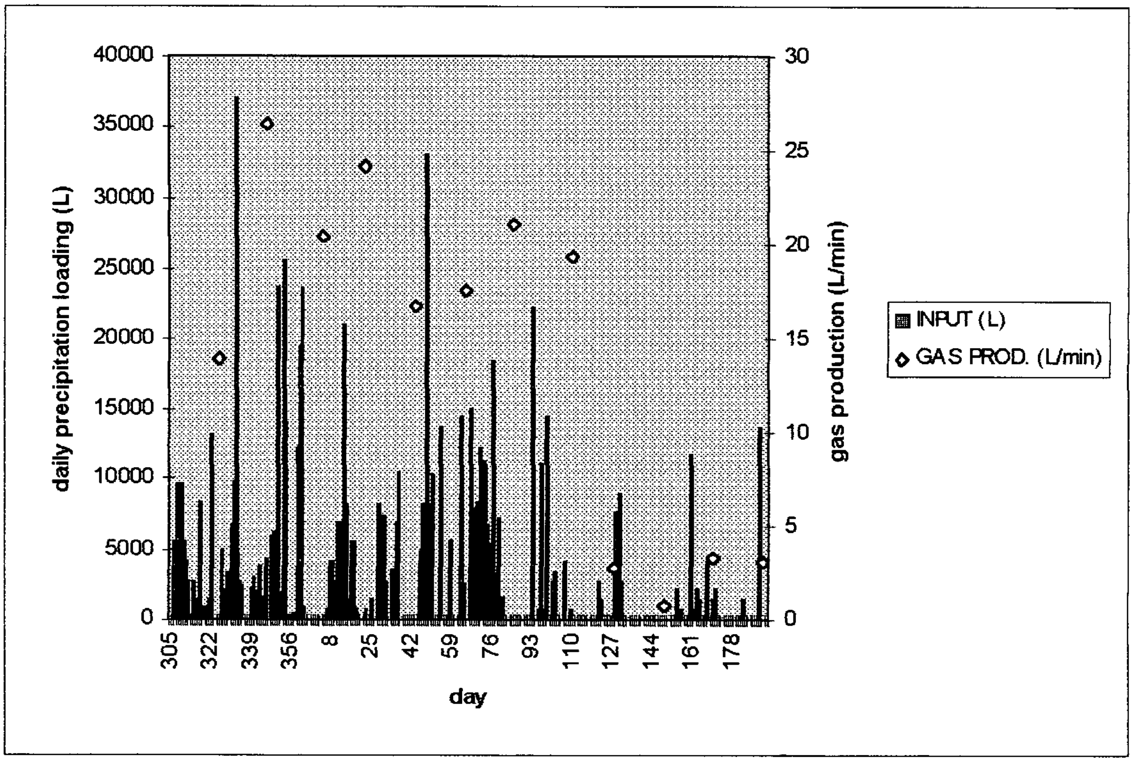

FIGURE 5.1.7: Landfill gas production in response to precipitation loadings - PORT C14

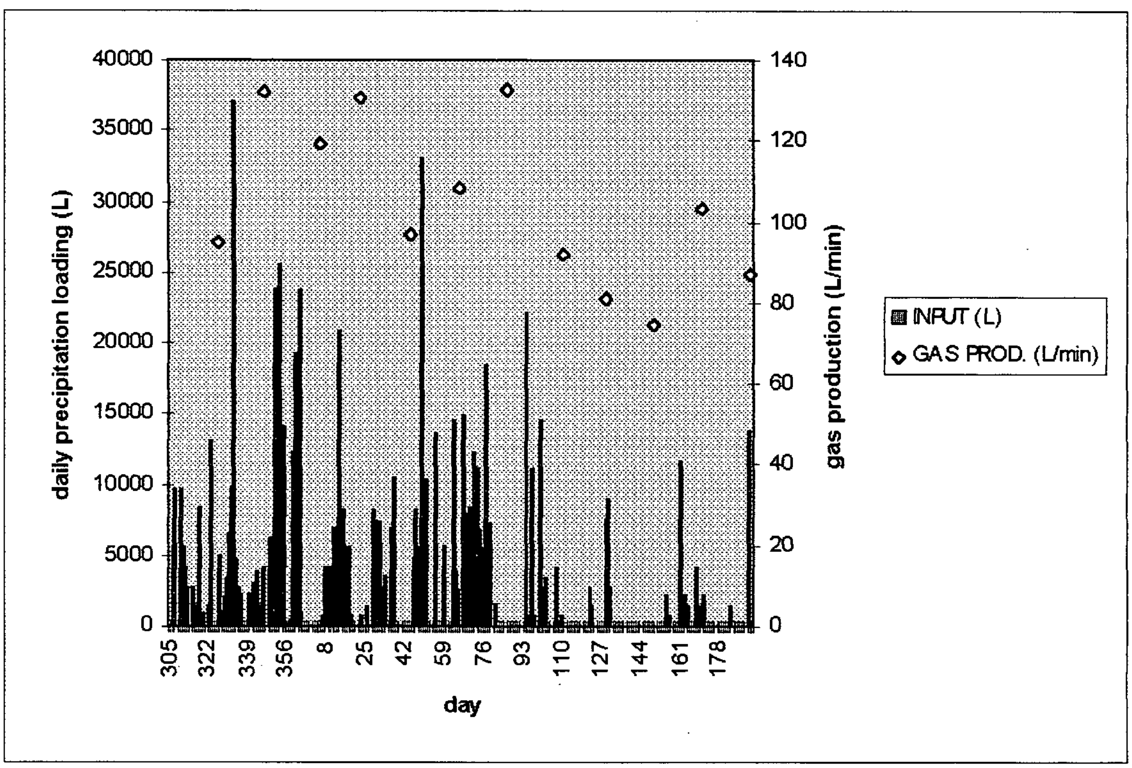

FIGURE 5.1.8: Landfill gas production in response to precipitation loadings - PORT D23

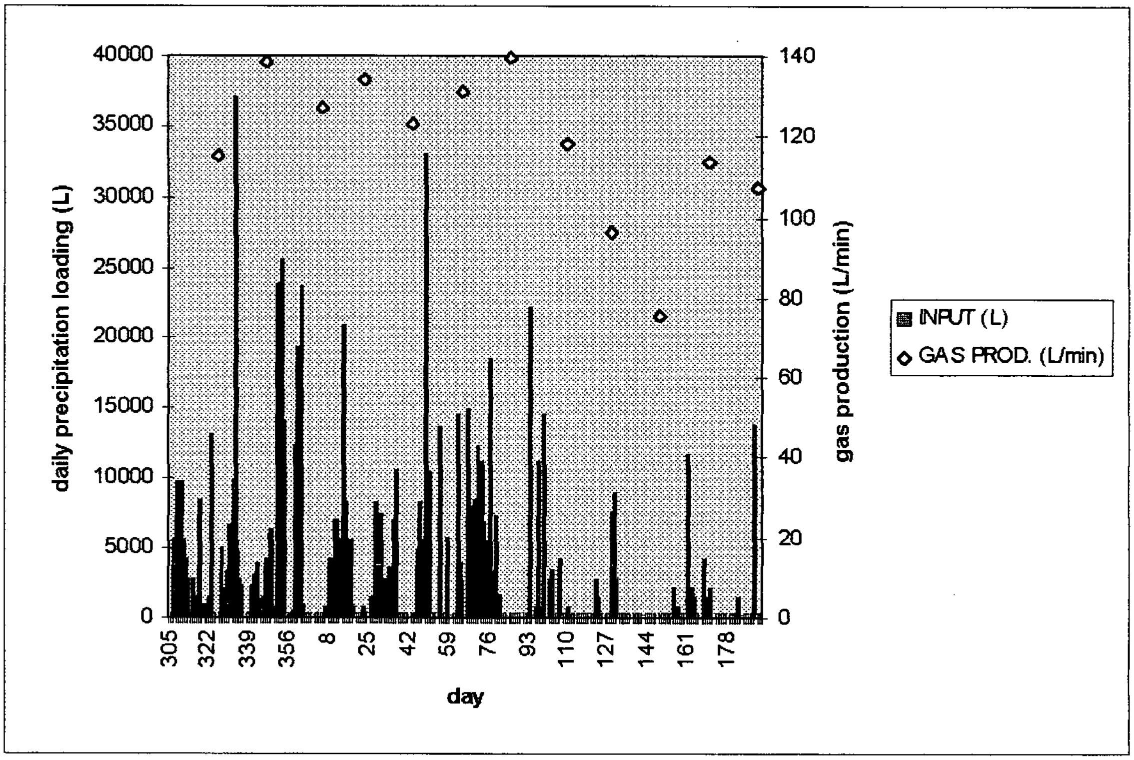

FIGURE 5.1.9: Landfill gas production in response to precipitation loadings - PORT E20

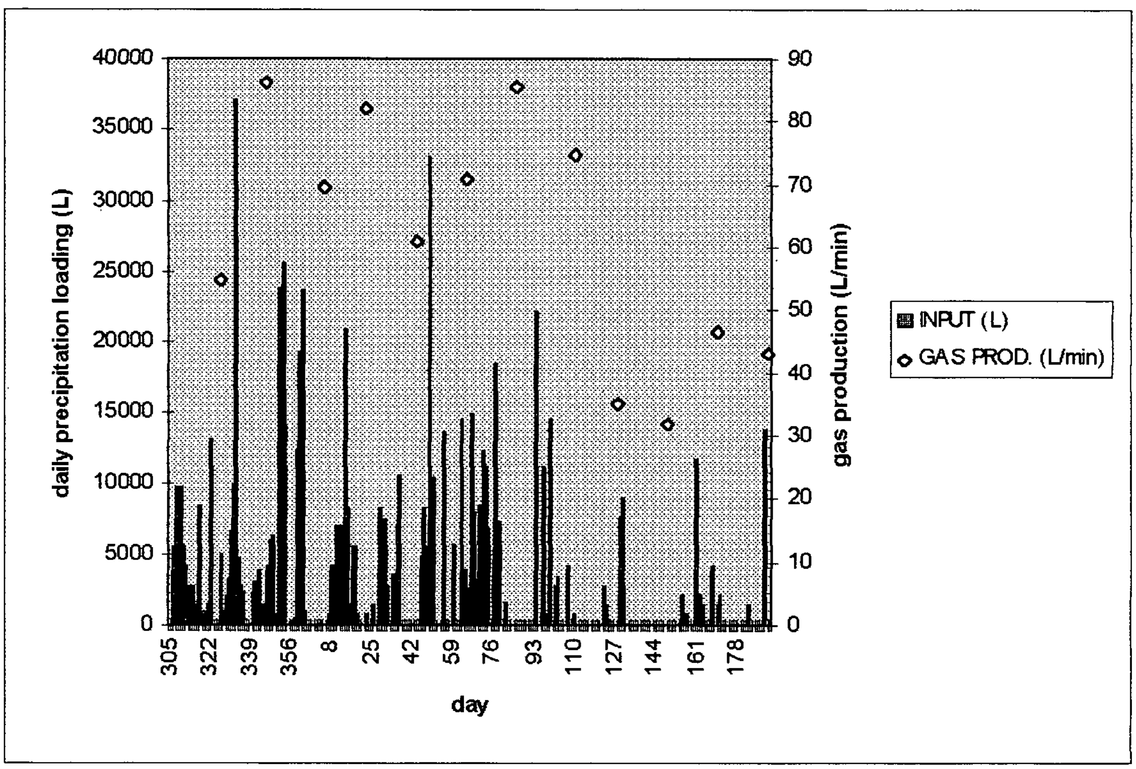

FIGURE 5.1.10: Landfill gas production in response to precipitation loadings - PORT E7

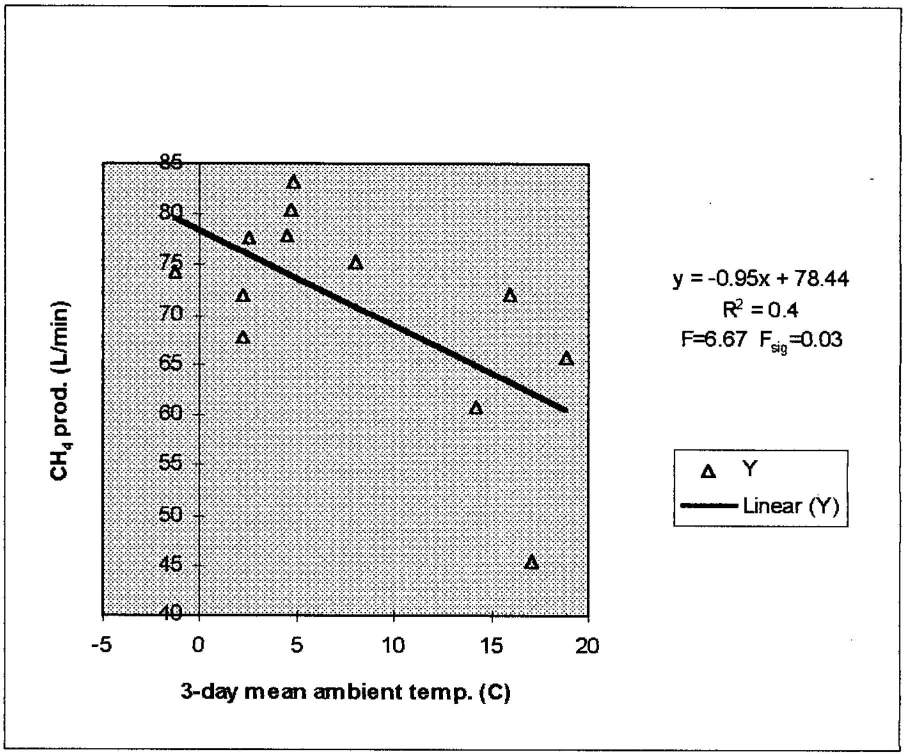

FIGURE 5.1.11: CH_4 production in response to 3-day mean ambient temperature - PORT E20

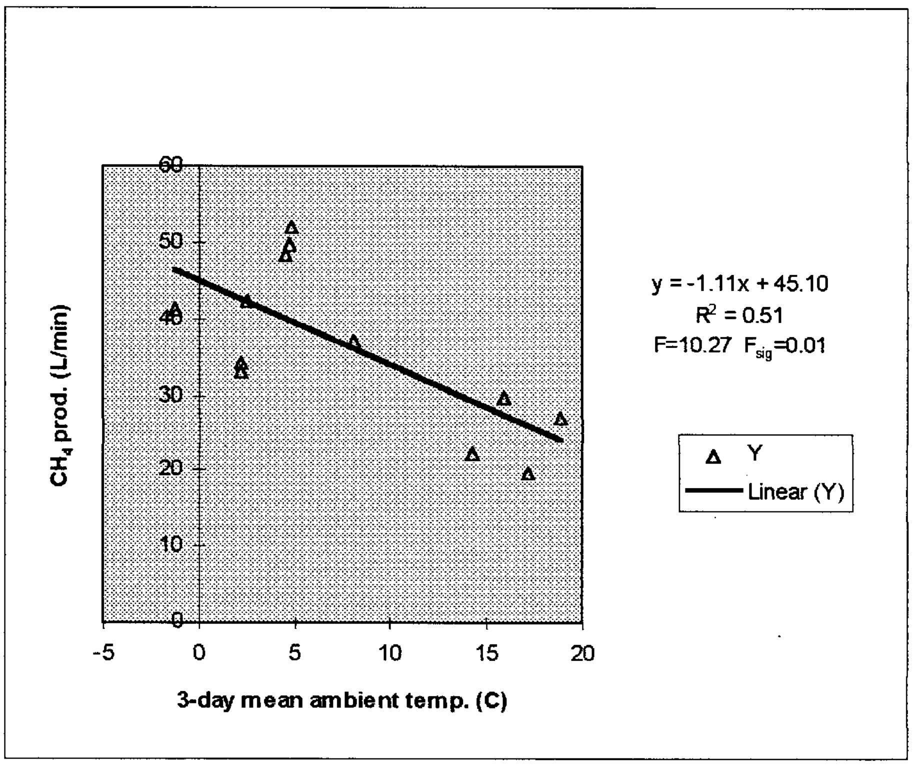

FIGURE 5.1.12: CH_4 production in response to 3-day mean ambient temperature - PORT E7

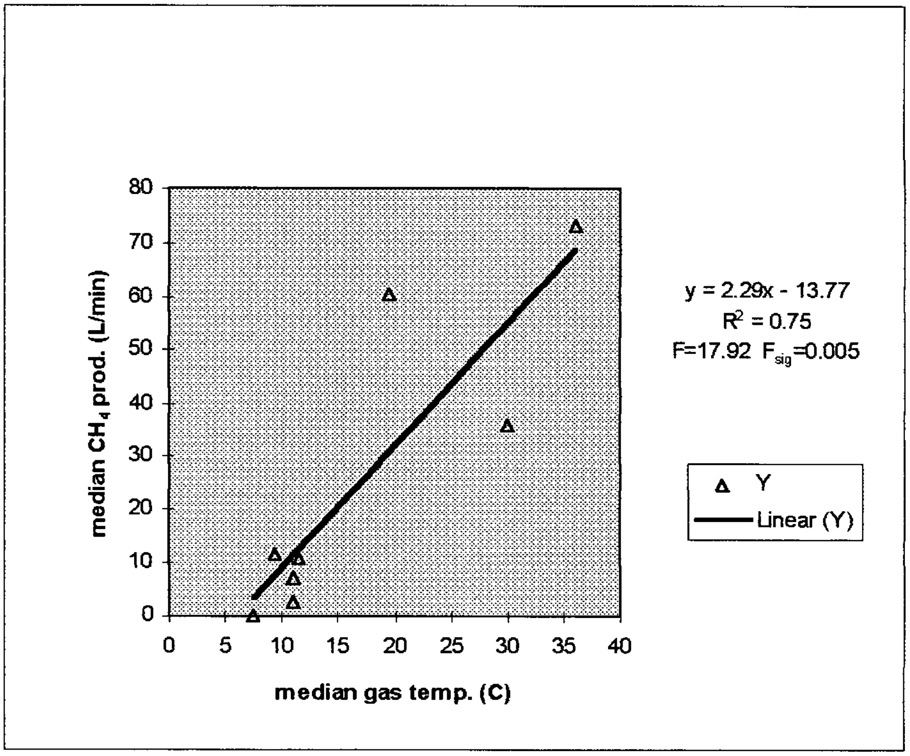

FIGURE 5.1.13: Median CH_4 production of each port in relation to median gas temperature of each port

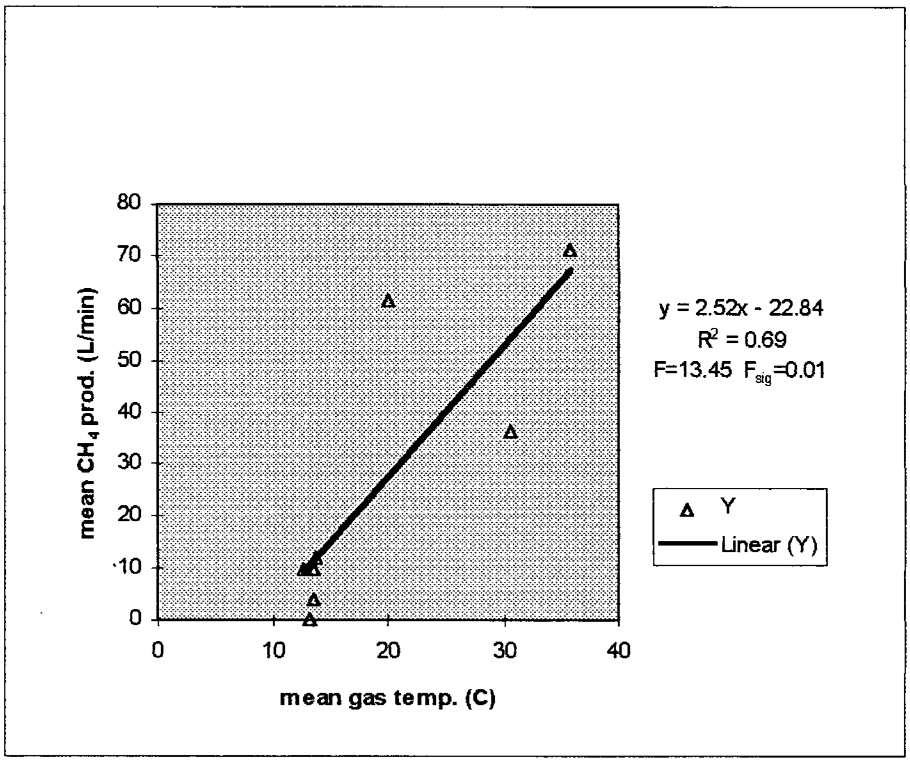

FIGURE 5.1.14: Mean CH_4 production of each port in relation to mean gas temperature of each port

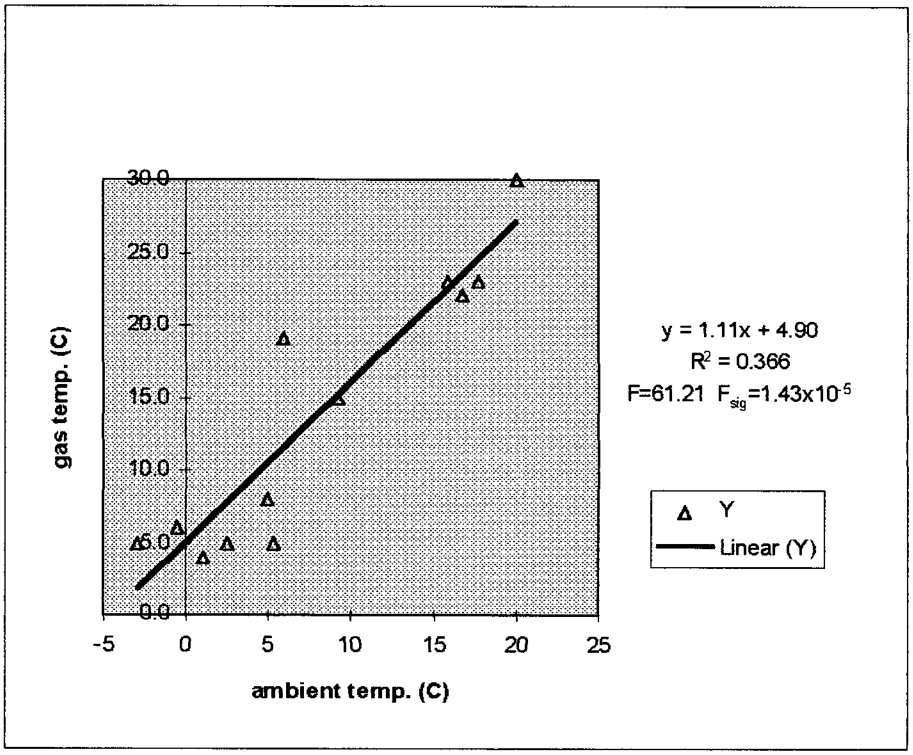

FIGURE 5.1.15: Landfill gas temperature in response to ambient temperature the day of sampling - PORT F6

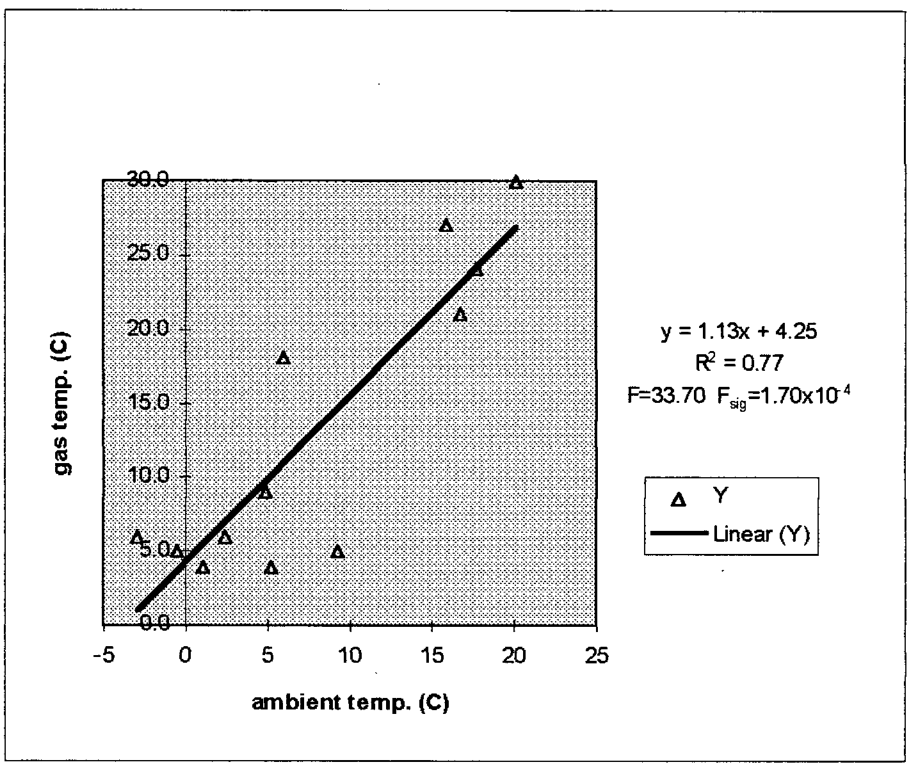

FIGURE 5.1.16: Landfill gas temperature in response to ambient temperature the day of sampling - PORT F29

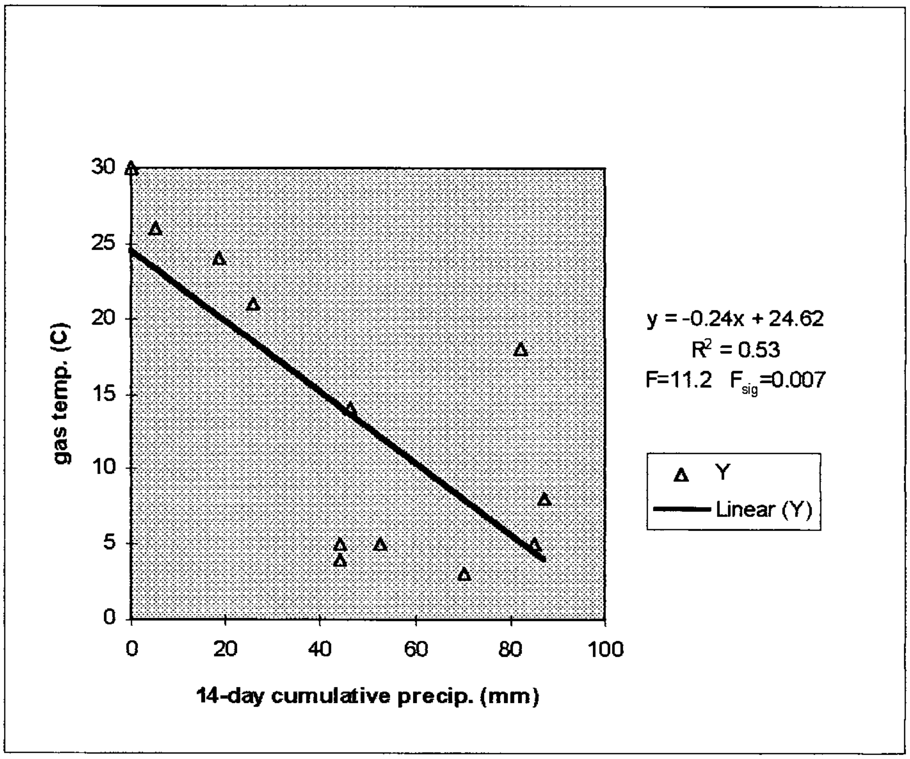

FIGURE 5.1.17: Landfill gas temperature in response to 14-day cumulative precipitation - PORT G5

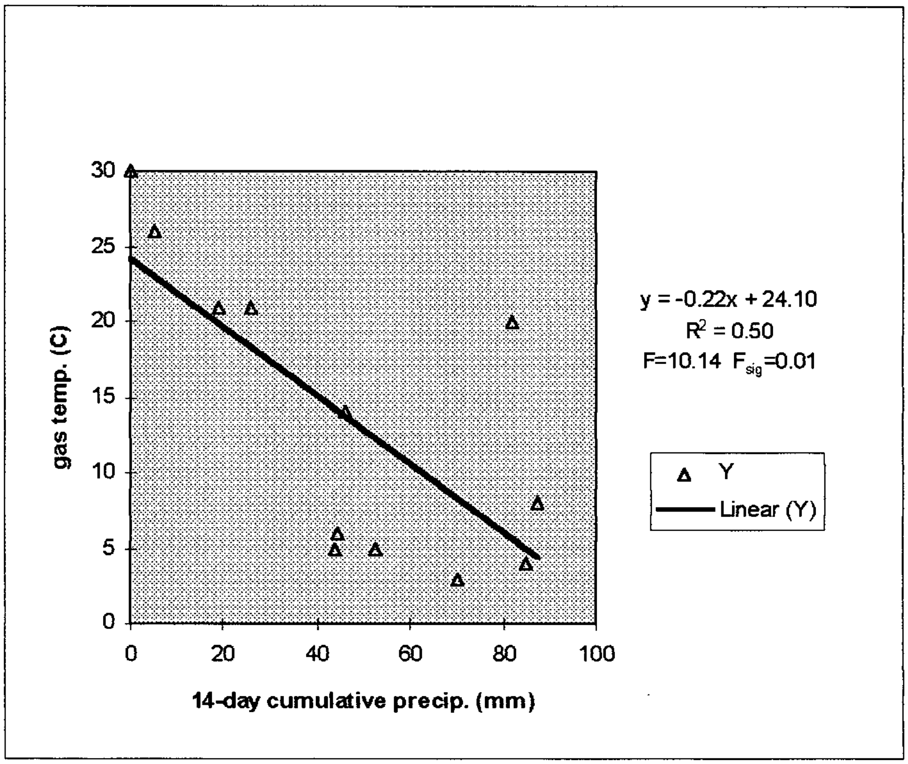

FIGURE 5.1.18 Landfill gas temperature in response to 14-day cumulative precipitation - PORT G9

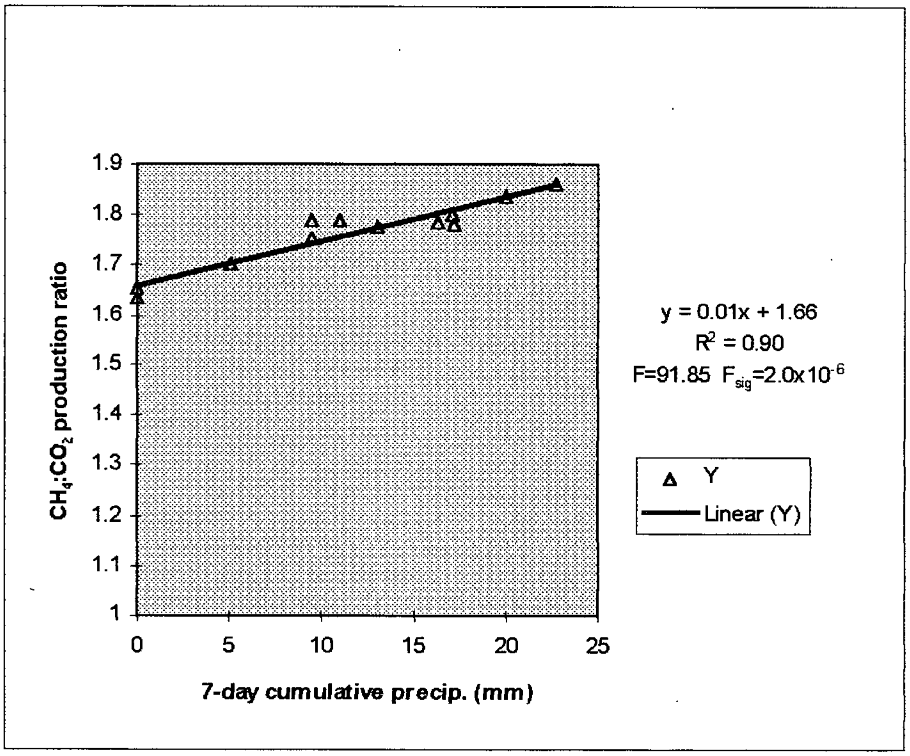

FIGURE 5.2.1: The effects of 7-day cumulative precipitation on CH_4:CO_2 production ratios - PORT E20

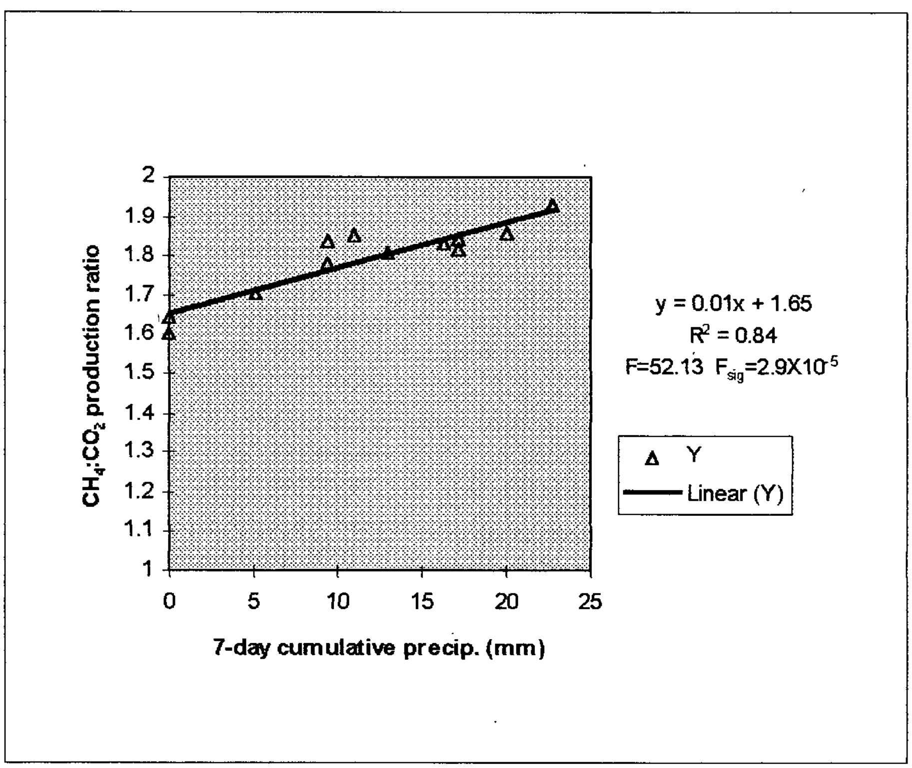

FIGURE 5.2.2: The effects of 7-day cumulative precipitation on CH_4:CO_2 production ratios - PORT E7

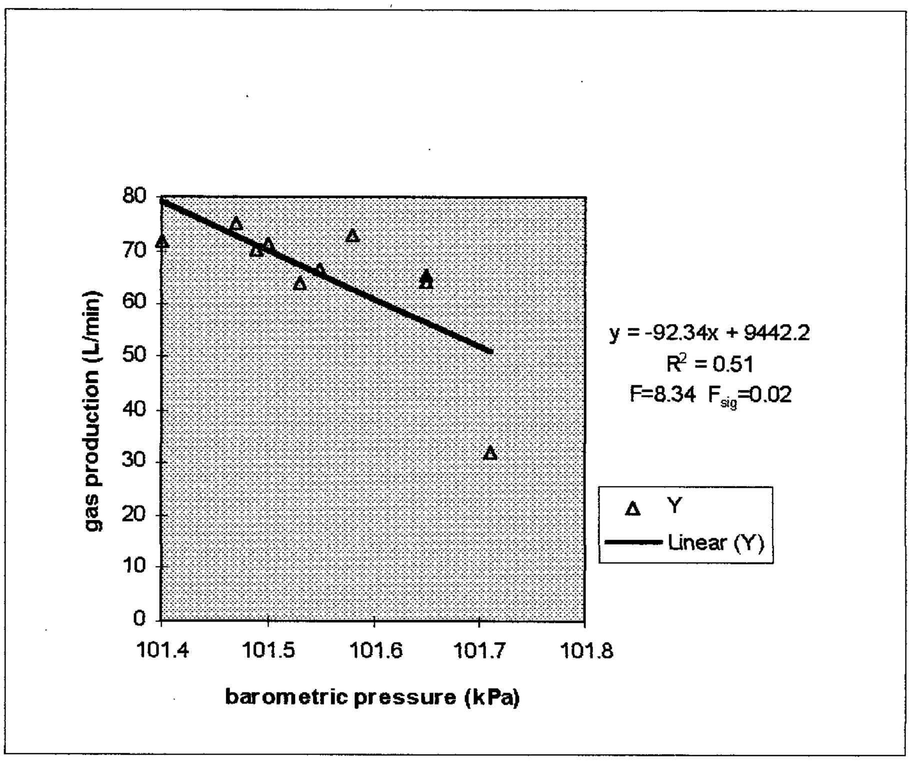

FIGURE 5.3.1: The effects of increasing barometric pressure on landfill gas production - PORT E7

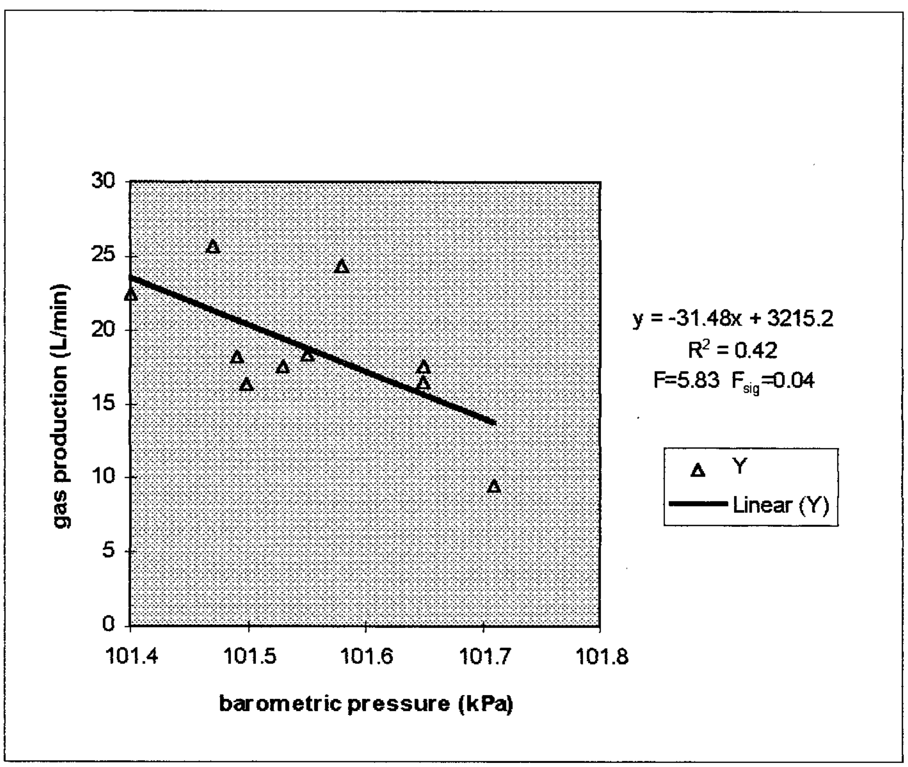

FIGURE 5.3.2: The effects of increasing barometric pressure on landfill gas production - PORT F6

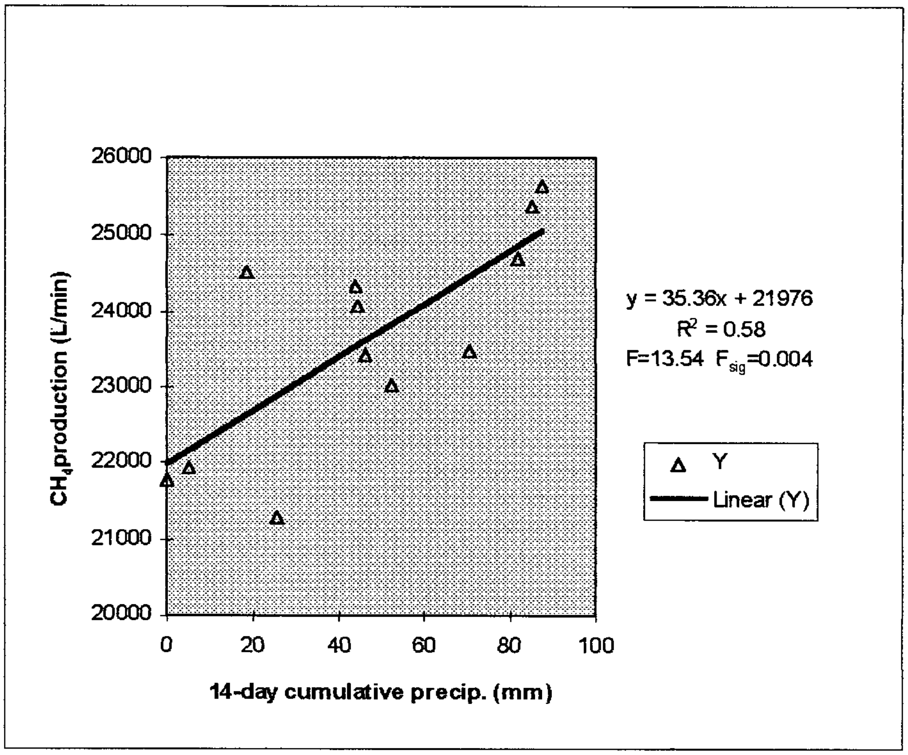

FIGURE 5.4.1: Total CH_4 production in response to 14-day cumulative precipitation - E-LINE

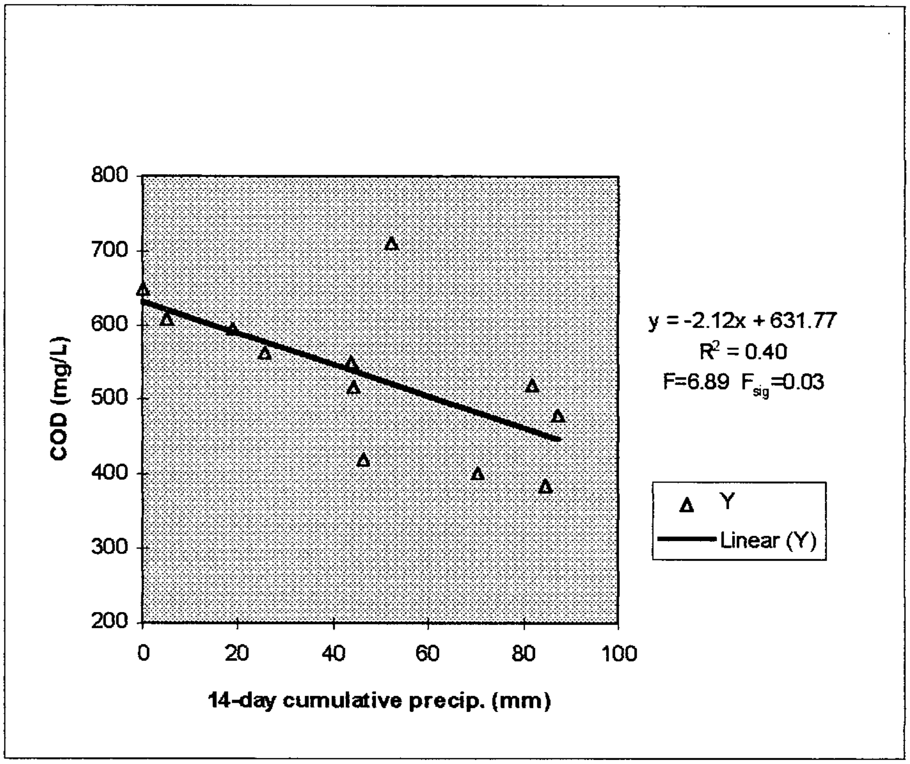

FIGURE 5.6.1: Leachate COD concentration in response to 14-day cumulative precipitation

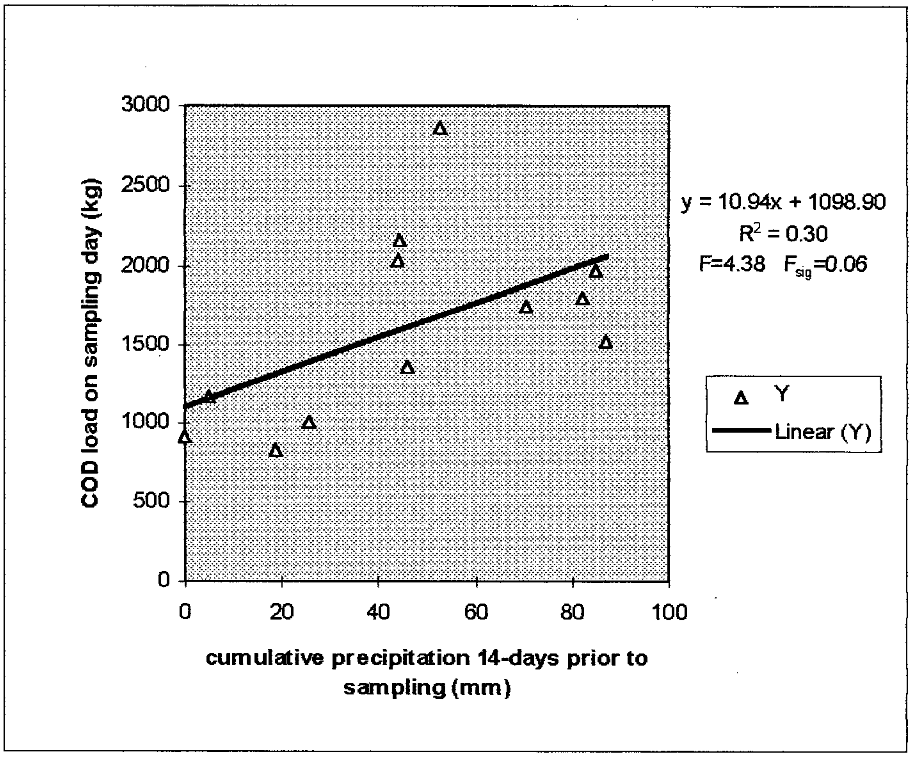

FIGURE 5.6.2: COD loading on sampling day in response to 14-day cumulative precipitation

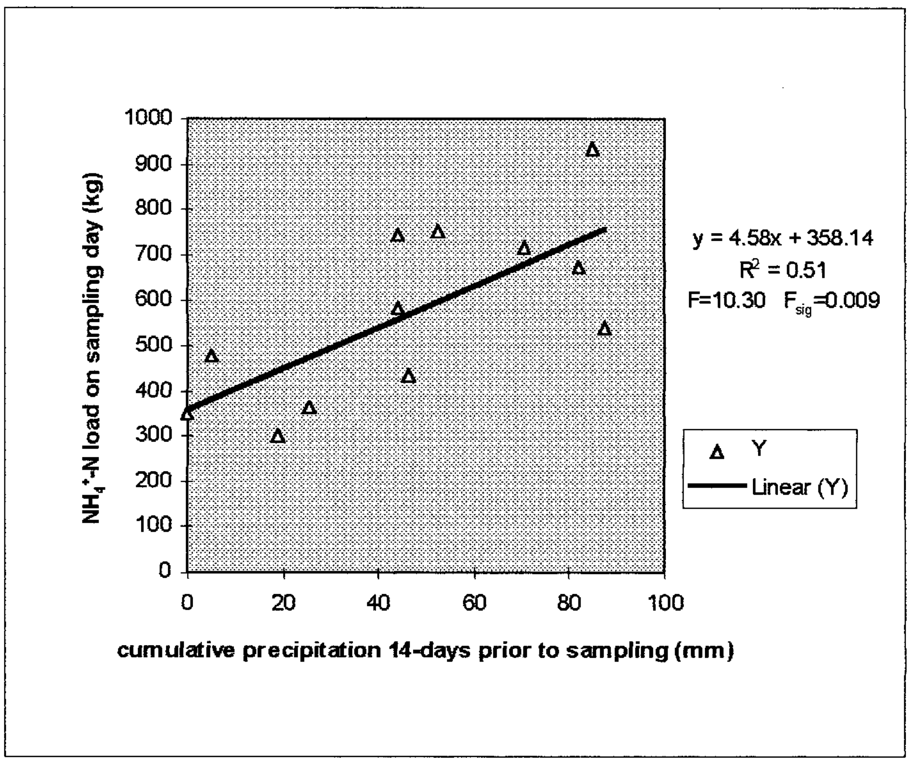

FIGURE 5.6.3: NH_4^+-N loading on sampling day in response to 14-day cumulative precipitation

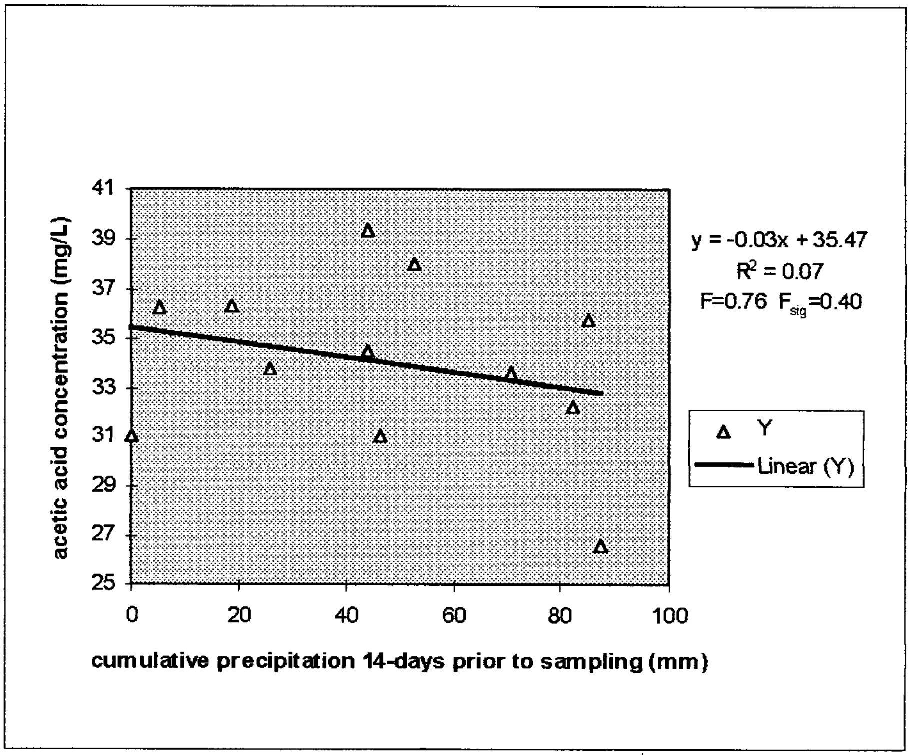

FIGURE 5.6.4: Acetic acid concentration in response to 14-day cumulative precipitation

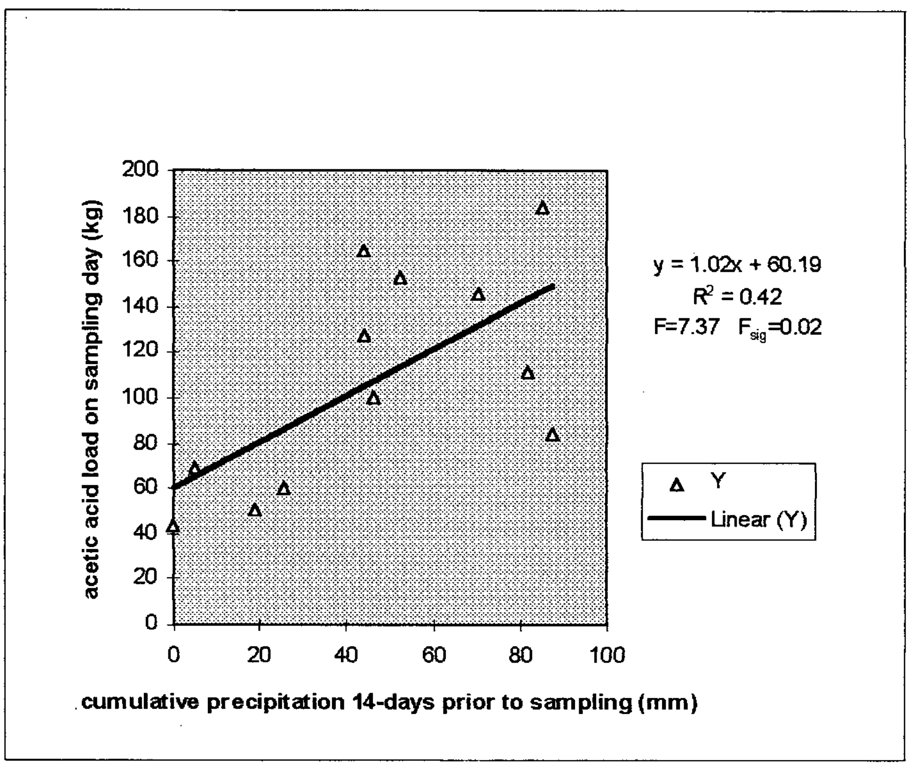

FIGURE 5.6.5: Acetic acid loading on sampling day in response to 14-day cumulative precipitation

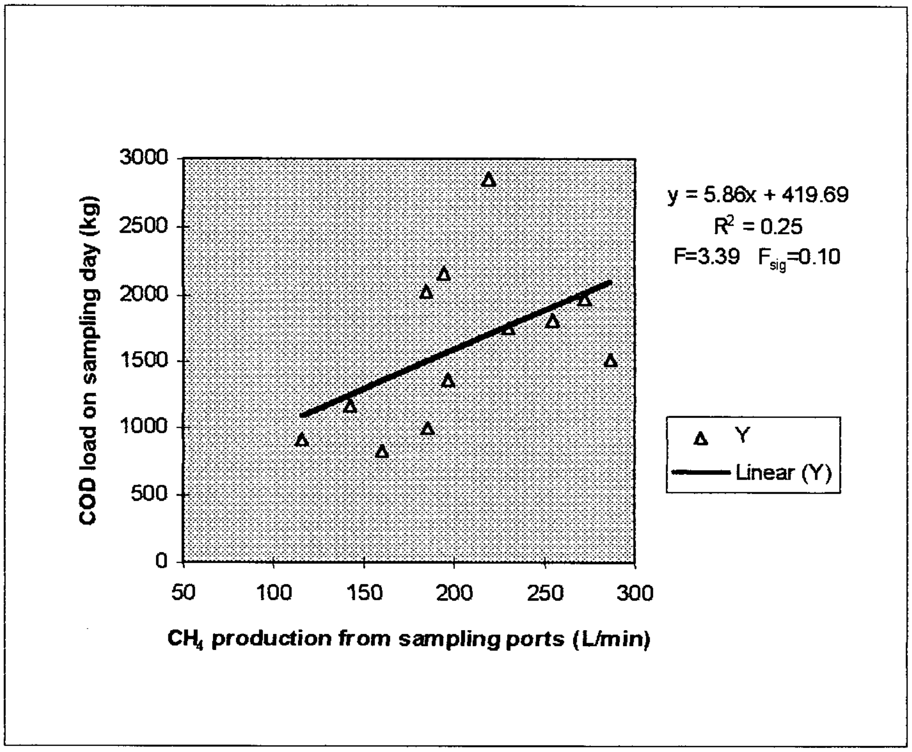

FIGURE 5.7.1: COD load on sampling day in response to CH_4 production from ports

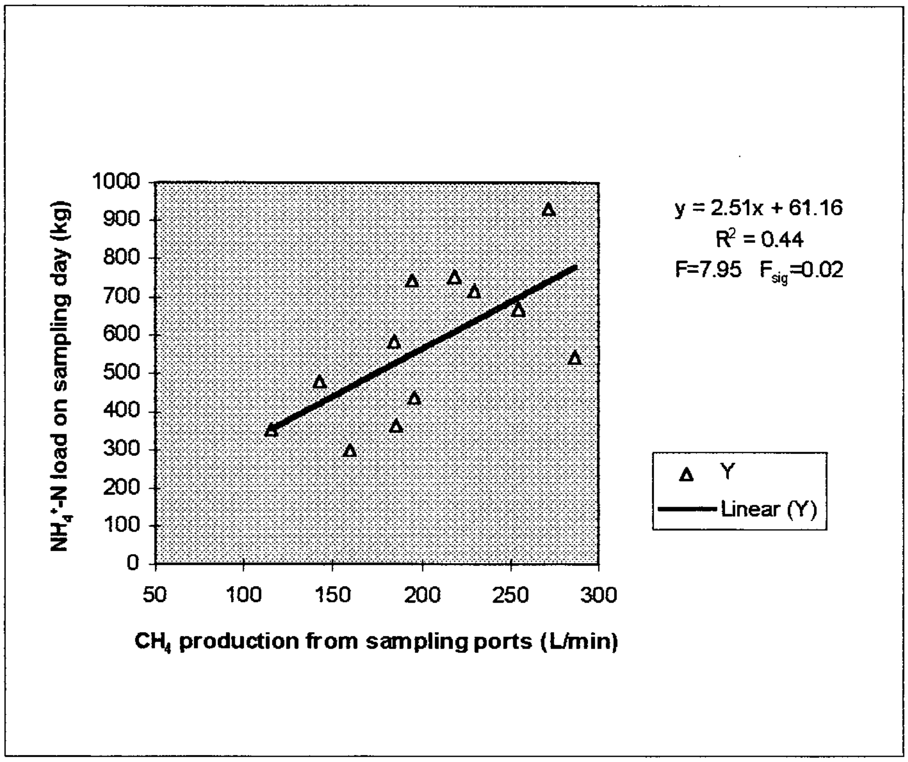

FIGURE 5.7.2: NH_4^+-N load on sampling day in response to CH_4 production from ports

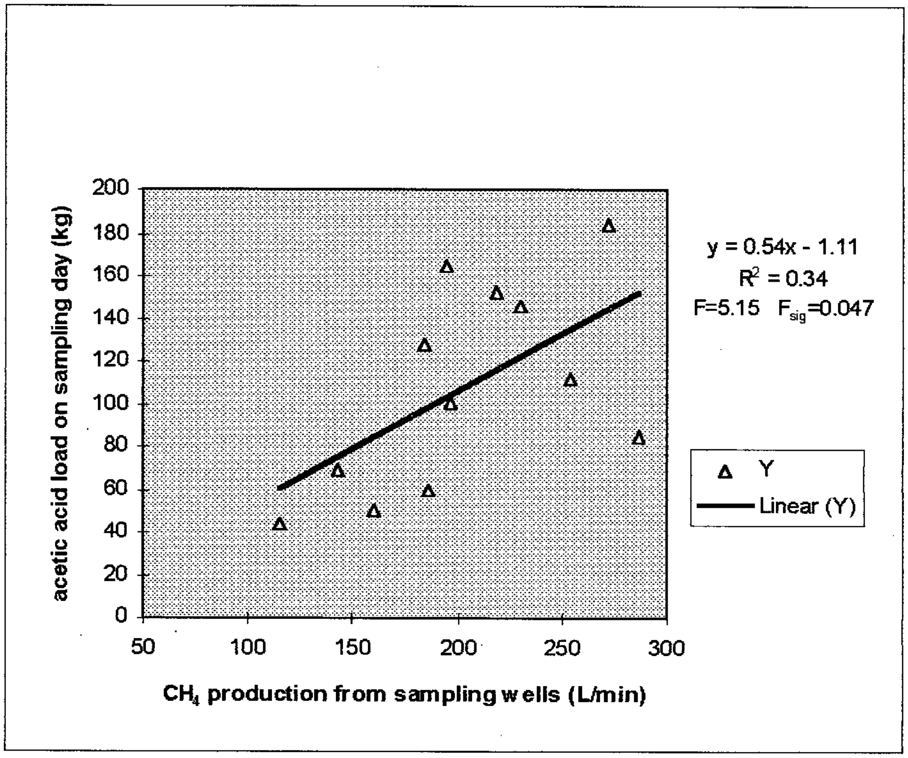

FIGURE 5.7.3: Acetic acid load on sampling day in response to CH_4 production from ports

CHAPTER 6 - IMPLICATIONS AND PERSPECTIVES

This section is provided in order to determine the potential for utilization of the findings of this study. Applications to both the research site, and extrapolations to other sites are considered. The feasibility of some suggestions may be questionable, and for this reason the following chapter should be viewed as a presentation of ideas, rather than a proposal of applications.

6.1 Optimizing Decomposition

In many instances several decades are required for landfill stabilization. Leachate quality may be poor and gas production often occurs at a slow and ill-defined rate. Alternately, the operation and management of a municipal solid waste landfill as a controlled bioreactor can lead to efficient and predictable CH_4 production (enabling its utilization), reduced odour problems and improved leachate quality. This acceleration of the decomposition of wastes to CH_4 has been alternately termed "controlled landfilling" or "accelerated stabilization". The potential benefits of these management practices include a greater volume reduction of buried wastes (and consequent site life extension), reduced leachate treatment requirements, reduced post-closure care costs, earlier site re-use and greater energy recovery potential. Since moisture content, refuse temperature and refuse density are major factors controlling the decomposition process, management practices which optimize these parameters will be discussed.

6.1.1 - MOISTURE ADDITION

The saturation of refuse within the landfill matrix is essential if CH_4 production is to be optimized. The enhancement of the anaerobic nature of the niche within the waste materials, along with the replenishing of nutrients and carbon rich organic matter to the active bacterial populations are likely to be the key benefits of moisture addition to the system. Leachate recirculation represents one method of attaining these increased moisture levels. After two decades of study involving leachate recirculation at experimental landfill sites, Pohland (1980) concluded that collecting and recirculating leachate hastens organic-pollutant degradation and cuts the landfill's stabilization period - where leakage poses the greatest threat - from decades to a few years.

Although the Vancouver Landfill Site at Burns Bog receives high precipitation inputs, the results of this study did indicate a significant enhancement of CH_4 production following precipitation events. Hence, an additional increase in CH_4 production may accompany further moisture inputs. In more arid regions, the benefits of moisture addition to landfilled areas would most likely be of a much higher magnitude. The aforementioned advantages accompanying leachate recirculation may make it a viable option in these regions of low annual precipitation inputs.

6.1.2 - TEMPERATURE CONTROL

The thermal regime of a landfill is a function of the combination of the specific temperature of the refuse mixture, the heats of reaction, solar radiation, and heat losses to the surrounding air and soil. The optimum temperature for CH_4 production from domestic refuse is 40°C; a temperature which can rarely be sustained for a lengthly period of time in temperate regions. However, when managed as a bioreactive landfill, this temperature can be maintained if an insulating layer of refuse is utilized. Rees and Granger (1982) found that when a 4m layer of insulating refuse was in place above the reactive zone of the fill, a greater reactivity and efficiency of CH_4 fermentation was achieved, indicated by the low concentrations of organic acids and SO_4^{2-} in the leachate. These characteristics, coupled with the high NH_4^+-N concentration, contribute to a neutral pH value which favors methanogenesis.

Augenstein *et al.* (1993) suggest that the interior of a landfill heats up as CH_4 generation occurs at an accelerated rate. Later, the generation in the interior may stop as high temperatures exceed the limit tolerable by methanogens. Consequently, they suggest that temperature control of landfills should entail early warming and later cooling. It is suggested that the warming could be accomplished by air injection, and the cooling by leachate recirculation. The feasibility of application of these techniques at the Burns Bog site are questionable due to the high energy requirements, but nonetheless may be worthy of some consideration.

6.1.3 - REFUSE COMPACTION

The compaction of refuse is important to the optimization of CH_4 production as it brings the refuse into intimate contact with water, nutrients and microorganisms, and causes a system of limited moisture to be closer to an optimum field capacity. Accepted theory states that water is squeezed out of the dry refuse at high densities, thus being made available to microorganisms. However, when high precipitation inputs are characteristic, loosely packed refuse may have some advantage, as high initial densities may impede water entry. Reaction rates will increase when the refuse is placed at lower densities, and water infiltration can occur.

The placement of refuse into bales is another option to be explored. The results of studies conducted by Rees (1980) indicated that the leachate quality of fermenting baled refuse was higher than that of fermenting unbaled pulverized refuse. The feasibility of this method of waste placement for the Burns Bog Site is questionable, due to the sheer volume of refuse received daily.

Landfill management practices can be modified to optimize the decomposition of the buried waste materials. Although the effects of certain parameters have not always been clear in previous research, accelerated CH_4 production and refuse volume reduction have been demonstrated. Moisture addition, temperature management and compaction densities should be investigated at the Vancouver Landfill Site at Burns Bog, in order to determine the feasibility of these practices at optimizing the landfill system.

6.2 On-Site Leachate Treatment

Benefits may accompany some form of preliminary on-site leachate treatment aimed at reducing the toxicity of the leachate at the Vancouver Landfill Site at Burns Bog. The focus of concern at this site is the high NH_3-N concentration in the leachate. Investigation into the feasibility of on-site leachate treatment at the Burns Bog Site has occurred, and should continue to be considered. Potential options for on-site treatment of leachate are outlined below.

6.2.1 - AEROBIC DIGESTION

The aerobic biodegradation of leachates involves the utilization of carbohydrates, followed by fatty acids, amino acids and finally humic materials. Nitrification of NH_3 is also accomplished. At appropriate organic loading levels, COD and BOD stabilization can be highly effective. A downfall to this technique is that essential nutrients may be limiting, in which case the addition of phosphorus may be necessary. Due to the increased age of the Burns Bog site, it is quite likely that these nutrient deficiencies may be present, thus rendering this method less attractive.

6.2.2 - CHEMICAL/PHYSICAL METHODS

Older landfills such as the study area typically produce leachates in which the easily oxidized organics are largely absent, and the remaining refractory compounds may be less amenable to decomposition by the above mentioned aerobic and anaerobic digestion processes. In this case, physical/chemical treatment methods have proven to be successful (Lisk, 1991). Within this method, lime, alumina, $FeCl_3$, $FeSO_4$, or polymers are often used for chemical precipitation. The elimination of colour, suspended solids, NH_4^+-N and heavy metals is relatively successful. The disadvantages accompanying this method are the relatively low COD reduction (~40%), and the considerable amounts of residual sediments produced.

Reverse osmosis involving the active passage of leachate through a membrane successfully filters out inorganic ions and organic matter. In order for this method to be effective, lime must be added to attain a pH of 12, and later adjusted to pH of 3-6 with H_2SO_4 in order to remove colloidal matter and $CaSO_4$ respectively, to prevent membrane clogging (Lisk, 1991). Once again, a significant disadvantage resulting from the process is the high volume of residuals produced.

The utilization of activated carbon, either in columns or as a powdered additive, is effective at the removal of organic matter from older leachates. The obvious disadvantage of this method on a scale such as the Burns Bog Site is the extremely high consumption of powdered charcoal. The use of ion exchange resins as a polishing step is effective at removing considerable quantities of both organic anions and inorganic ions, but have been found to be relatively uneconomical.

6.3 Energy from Waste Options

At this point, it is agreed upon that landfill sites produce large quantities of CH_4 over time. The results of this study, in conjunction with those from the past indicate that the Vancouver Landfill Site at Burns Bog is no exception to this rule; CH_4 generation is actively occurring at this site, with the estimated production reaching 44.76 kT CH_4 annually (see Section 5.4.4). This value equates to 3% of the total annual CH_4 emissions from municipal landfill sites in Canada. Considering the fact that this site serves approximately 2.5% of the national population, one may conclude that on a per capita basis, the City of Vancouver Landfill Site is a significant producer of anthropogenic CH_4.

Although a reduction in the order of 4.46×10^8 m^3 CO_2/year is achieved by the present gas collection system, further benefits accompany energy from waste alternatives. Aside from the aforementioned greenhouse gas equivalent reductions achieved by the conversion of CH_4 to CO_2, a reduction in the consumption of fossil fuels necessary to produce an equivalent amount of energy results. The tremendous increase in emphasis on energy conservation, and the encouragement of the utilization of renewable resources makes the energy from waste (EFW) potential of landfill gas from the Burns Bog Site worthy of consideration.

6.3.1 - MOTOR VEHICLE FUEL

The transport of solid wastes from residential areas to the landfill site, and the operation of equipment during refuse placement require a substantial amount of fuel. This entire demand could be met by energy derived from the landfill gas produced on-site, by converting this resource into either compressed natural gas or liquid natural gas. The use of compressed natural gas as a fuel source is the most well known means of conversion for vehicle use, and the technology is well established (E.H. Hanson Engineering Group Ltd., 1995). Disadvantages accompanying this method include longer fill time, shorter travel distance per tank, and low transportability of the fuel.

The liquefaction of CH_4 is obtained at -162°C. Small, self contained, skid mounted machines are available which will liquefy the gas. Following the process, the mixture is then transportable in insulated tanks, which can be stored for approximately 7 days before significant venting takes place by gasification (E.H. Hanson Engineering Group Ltd., 1989). The use of liquid CH_4 gas as a motor vehicle fuel for use in City truck fleets, where there are competent personnel to look after the vehicles, may be worthy of detailed economic evaluation.

6.3.2 - GENERATION OF ELECTRICITY

The generation of electricity from Burns Bog landfill gas for sale to BC Hydro has been considered previously, and at that time (mid 1980s) was found to be of marginal economic payback. The key criteria for consideration regarding electrical power generation from landfill gas include the conversion efficiency, the cost/kW installed, the operation costs, and emissions (MacViro Consultants Inc., 1991). The pricing structure in use by BC Hydro is a significant factor when assessing the economic feasibility of such a process, considering the high initial, operating and maintenance costs associated with this type of project.

6.3.3 - USE AT TILBURY CEMENT LTD.

A proposal has recently been submitted by E.H. Hanson Engineering Group Ltd. to beneficially use the gas from the City of Vancouver Landfill Site as an alternative fuel source in the cement kilns at Tilbury Cement. The landfill gas would be dried in a glycol tower, transported via pipeline to Tilbury Cement and mixed with natural gas prior to being utilized in the kilns. This fuel mixture would be less expensive than the fossil fuels presently used. Proposed estimates of the further reductions in greenhouse gas emissions accompanying this energy from waste alternative are in the order of 2.92×10^8 m^3 CO_2/year. Negotiations regarding the feasibility of the project are still underway.

6.4 Ecological Risk Assessment

Controversy continues to surround the expenditure of public funds on the "remediation" of sites which appear to pose a threat to the environment. As regulatory criteria are designed to protect the environment 100% of the time, cases do often exist wherein the recommended clean-up steps are excessive. A relatively new, but well established method of quantifying the risks of a specific site to its surroundings is the ecological risk assessment (ERA) approach, which acts to estimate the likelihood of undesired effects on ecosystems, or valued ecosystem components (Zapf-Gilje *et al.*, 1994). This quantitative, defensible scientific approach allows the incorporation of uncertainty into analysis, and could potentially assist in maximizing the net benefit of dollars spent on landfill siting, design, operation and decommissioning.

The individual steps in the ERA framework include problem formulation, exposure assessment, toxicity/effects assessment, risk characterization and risk management. During the problem formulation stage, the assessor acts to develop a focused understanding of the specific system (e.g. landfill site), by investigating the stressors (components of landfill gas or leachate), the pathways (wind direction, groundwater flow) and the receptors (vegetation, nearby residents). The magnitude and extent of contact between the stressors and the receptors is next quantified in the exposure assessment phase. Both modeling and monitoring are utilized in this phase to characterize the environmental distribution of the contaminants, and the probability of contact between these substances and the receptors. Next, toxicity/effects assessment is used to determine the relationship between the stressor and "effect endpoints", which in the case of humans, are associated with the specified probability of an adverse effect such as birth defects or cancer. The characterization of the risk involves the integration of exposure and effects assessment to estimate the probability and magnitude of the effects. The characterization output often includes:

1) statement of the probability that effects will/will not exceed some benchmark
2) statement of the expected effect magnitude
3) comparison of the performance of several management scenarios in terms of the probability of effects

Finally, the results of the assessment can be considered as quantitative information for use when seeking an optimum balance between the expenditure of resources and risk reduction. The results may also be used to optimize monitoring programs, by identifying which components of the ecosystem are at risk.

Risk assessment has the potential to be a viable tool for the operation and decommissioning practices at the Vancouver Landfill Site at Burns Bog, and for the siting and planning of future sites of municipal solid waste disposal. A risk assessment approach could aid the decision making process regarding leachate treatment and landfill gas management solutions. In doing so, regulators could ensure the protection of the surrounding ecosystem, and the effective expenditure of environmental dollars.

6.5 Waste Management Strategies

The specific future problems associated with municipal solid waste handling cannot be accurately predicted. The only situation which may be anticipated with confidence is the growth in population (and subsequently wastes) which will continue to occur in the Lower Fraser Basin as we approach the year 2000. Increased production of waste materials, in conjunction with heightened competition for available land will augment existing pressures on waste management decision makers. Creative thinking and well developed problem solving skills will be essential tools if we are to attempt to discern which waste management practices are the most sustainable. It is well accepted by the public that the reduction of waste materials produced is the most important step, but uncertainty lies in the proportion of people that are willing to make personal sacrifices (reduced consumption, decreased packaging) to this end. The immediate prospects for waste reduction are limited, so we must focus our efforts on long-term strategies including the reformulation of materials out of which our products and packages are made. Waste reduction calls for a new way of thinking.

Despite trends towards composting, incineration and recycling, landfilling remains to be our primary method for the management of municipal solid wastes. Due to both technical and economic constraints, landfill sites will most likely continue to hold this status for quite some time. Consequently, increased attention should be paid to the processes occurring within the landfill matrix, and their effects on the surrounding environment. A full understanding of the decomposition process will be necessary in order to optimize the resource potential of municipal solid wastes.

CHAPTER 7 - SUMMARY AND CONCLUSIONS

One principal objective of this research was to determine the effects of external variables on the production of CH_4 from the Vancouver Landfill Site at Burns Bog. The results indicated that precipitation had the most prominent effect, with cumulative precipitation from 14 days prior to sampling showing the strongest relationship to CH_4 production at the individual gas wells. The strong influence of moisture input can be attributed to the increased downward movement of carbon-rich organic matter from the surface of the fill to the deeper regions, the enhancement of the anaerobic nature of the niche, the increase in mixing and availability of nutrients, the direct stimulation of bacterial growth and the dilution of metabolic inhibitors. The average ambient temperature from the 3 days prior to sampling and the temperature of the landfill gas were both shown to correlate with the CH_4 production, but these relationships were less significant than those detected with the precipitation. Fluctuations in barometric pressure showed no significant effect on landfill gas production, most likely caused by the residual effects of the active gas collection system at the site.

Regression equations were calculated to predict CH_4 production at the individual gas wells and collector lines using the specific precipitation, ambient temperature and gas temperature information. It is intended that these equations may be useful in the estimation of CH_4 production from these areas. These calculations are extremely site specific and extrapolations to other CH_4 producing sites would most likely be inaccurate.

A notable finding from this research was the observed significant effect of cumulative precipitation 7 days prior to sampling on the ratio of CH_4:CO_2 production. The dramatic increase in the ratio following periods of heavy rainfall suggests that the decreased hydraulic retention time caused the dissolution of CO_2, followed by its downward movement in the leachate. It is also possible that the CO_2 acts as an end-product inhibitor during acetate and propionate degradation, hence its decreased partial pressures after periods of heavy rainfall would thus favour enhanced CH_4 production. Future research in this area is necessary to determine the processes occurring.

The total annual CH_4 production from the Vancouver Landfill Site at Burns Bog was calculated from the data to be approximately 44.76 kT CH_4/year, representing approximately 3% of the total CH_4 produced from landfill sites in Canada. It is important to recognize the significant reduction in the actual emissions from the site brought about by the introduction of the gas collection and flaring system. These reductions equate to approximately 4.46×10^8 m^3 CO_2 equivalents each year. Further reductions would accompany the utilization of this landfill gas in energy from waste alternatives. Although the environmental impact of the Vancouver Landfill Site at Burns Bog has been the focus of concern to bog conservationists in the past, it has been stated that the conversion of each hectare of bog to a landfill (with adequate gas collection) actually reduces greenhouse gas emissions to the atmosphere, due to the extremely high natural production of CH_4 from bogged areas (Hanson, 1995).

The concentration ranges of the leachate parameters were found to be highly variable. Loadings of COD, NH_4^+-N and acetic acid were observed to increase with higher precipitation inputs. It is likely that the increased mobilization and resultant "washing" of the fill following heavy rainfall was a driving force behind this finding. It is also possible that the increased methanogenic activity following high moisture inputs was leading to an enhanced production of the intermediary products of waste degradation. Because the leachate composition is dependent on many factors such as refuse composition, site hydrogeology, and moisture inputs, both temporal and spatial variation is characteristic.

Significant relationships between leachate parameters and CH_4 production were observed. Both NH_4^+-N and acetic acid loadings displayed significant direct relationships to CH_4 production from the sample ports. In the former case, it is likely that the increased rate of protein degradation during periods of enhanced decomposition were displaying some influence. In the case of the acetic acid loadings, it is possible that the increased utilization of propionic acid as a substrate for methanogenic activity led to a resultant rise in the production of acetic acid as an intermediary compound. In both cases, it must once again be noted that the increased mobilization and downward movement of the substances remains the most likely cause of the increased loadings following heavy rainfall.

The findings of this research suggest that potential does exist for the optimization of waste decomposition in landfill sites. The system mimics microbial degradation of substances within a soil profile through the chemical, physical and biological processes occurring within. It is the requirements of the bacterial populations indigenous to the landfill matrix which must be kept in mind in order to maintain a high level of degradation activity. In this study, moisture input was found to be the most significant factor affecting waste decomposition. Future research efforts at the Vancouver Landfill Site at Burns Bog may be most beneficial if focused on the water balance of the system, and potential interventions therein. The effects of intense rainfall on the ratio of CH_4:CO_2 production should also be investigated further, as a distinct effect was observed at the site, and the potential implications to gas recovery and leachate treatment may be worthy of future research efforts.

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APPENDIX A - SAMPLE CALCULATIONS

1 - FLOW CALCULATIONS - PITOT TUBE MEASUREMENTS

the following parameters will be used for an example:

- gas composition.......CH_4=65% CO_2=29% N_2=6%
- ambient temperature (T) = 1.0°C
- barometric pressure (P_b) = 103.11 kPa
- pitot tube measurement (h_v) = 3.4 inches water column
- cross-sectional area of the collector line (A) = 0.1963ft^2

calculating the density (d) of the gas mixture under the specific conditions:

$d=(1.325)(P_b)/(T)(1.6683\ lbft^{-3})$

$d=(1.325)(30.45\ inches\ H_20)/(493.8\ K)(1.6683\ lbft^{-3})$

$d=0.04898\ lbft^{-3}$

calculating the velocity (v) of the gas mixture:

$v= 1096.7\ [h_v/d]^{0.5}$

$v= 1096.7[3.4\ inches\ H_20/0.04898\ lbft^{-3}]^{0.5}$

$v= 9137.30058\ ft^3min^{-1}$

converting this to the volume flow (q) of the mixture through the line:

$q= Av$

$q= (0.1963\ ft^3)(9137.30058\ ft^3min^{-1})$

$q= 1793.652104\ ft^3min^{-1}$

$q= 50797.30377\ Lmin^{-1}$

2 - PRECIPITATION LOADINGS

assuming a 16m radius of influence of each gas port
assuming no significant surface runoff, evaporation or evapotranspiration effects
P - precipitation reading in mm:
SA - surface area of area of influence of each port
PI - precipitation input (m^3)

$PI= (SA)(P)(0.001m/mm)$

$PI= (\pi\ r^2)(P)(0.001)$

$PI= (0.804)(P)$

3 - TOTAL CH_4 PRODUCTION FROM THE SITE

assuming the production from the A area is negligible
assuming the minimal production from the B and C areas is utilized at the administration building
TP= total production

$TP = 4.77 \times 10^7\ m^3\ CH_4/year + 8.00 \times 10^6\ m^3\ CH_4/year$

$TP = 5.57 \times 10^7\ m^3\ CH_4/year$

hence the total mass of CH_4 produced annually at the site:

$M = (5.57 \times 10^7\ m^3\ CH_4/year) \times (803.6\ g\ CH_4/m^3)$

$M = 4.476 \times 10^{10}\ g\ CH_4/year$

$M = 44.76\ kT\ CH_4/year$

assuming 85714.39 T refuse/ha (CH_2M Hill Engineering)
with a present landfilled area of approximately 158 ha:

refuse mass= (85714.39 T refuse/ha) x (158 ha)
refuse mass= 13542857.14 T refuse
refuse mass= 13542.86 kT refuse

∴ CH_4 produced per T refuse per year:

$= (44.76\ kT\ CH_4/year) / (13542.86\ kT\ refuse)$

$= 0.0033\ kT\ CH_4/year/kT\ refuse$

4 - REDUCTIONS ACHIEVED BY FLARING OF THE GAS

assuming an 8X reduction by volume in CO_2 equivalents:

reductions= $(5.57 \times 10^7\ m^3\ CH_4/year) \times 8$

reductions= $4.46 \times 10^8\ m^3\ CO_2/year$

APPENDIX B - DATA FROM INCONSISTENT WELLS

METHANE PRODUCTION FROM INCONSISTENT WELLS (L/MIN)

PORT	SAMPLING SESSION					
	1	**2**	**3**	**4**	**5**	**6**
B15	13.42	11.18	0	0	0	0.41
C25	6.04	0	0	0.08	13.14	0
E18	1.44	7.26	27.86	0	0	0

PORT	SAMPLING SESSION					
	7	**8**	**9**	**10**	**11**	**12**
B15	0	0	1.90	0.40	0	0
C25	0	19.65	0	0	7.30	0.59
E18	11.75	0	0	0	0	2.69

APPENDIX C - ADDITIONAL GRAPHS

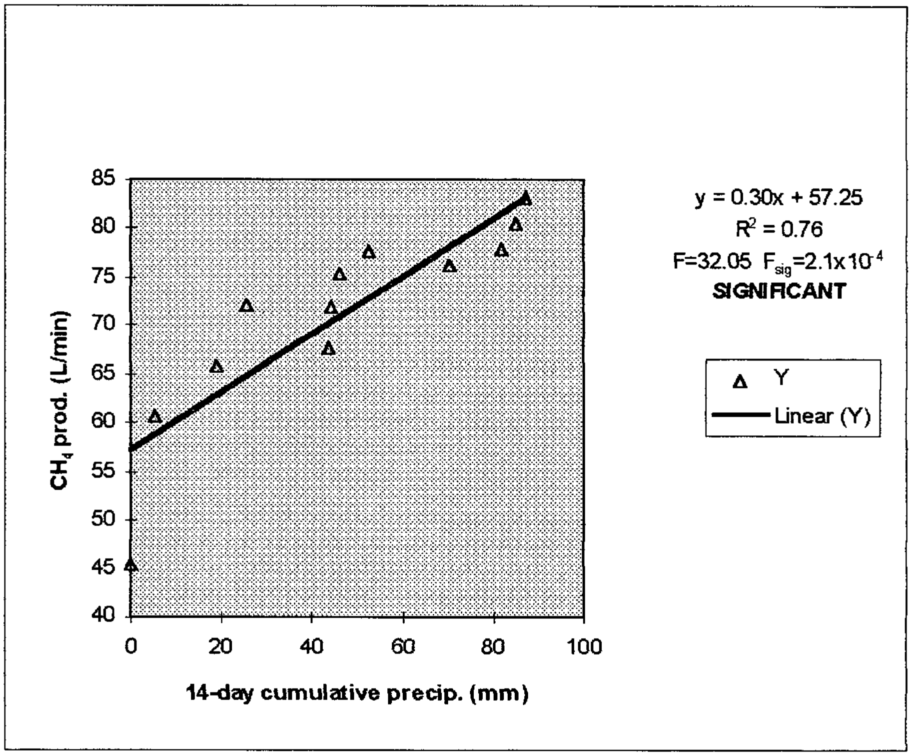

FIGURE C-1.1: CH_4 production in response to 14-day cumulative precipitation - PORT E20

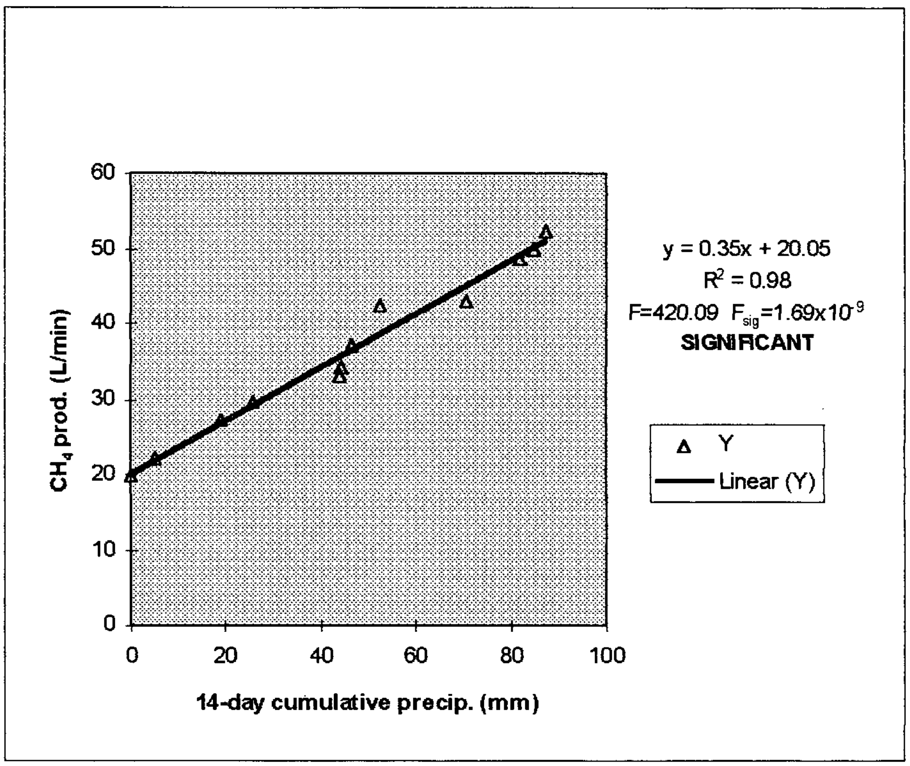

FIGURE C-1.2: CH_4 production in response to 14-day cumulative precipitation - PORT E7

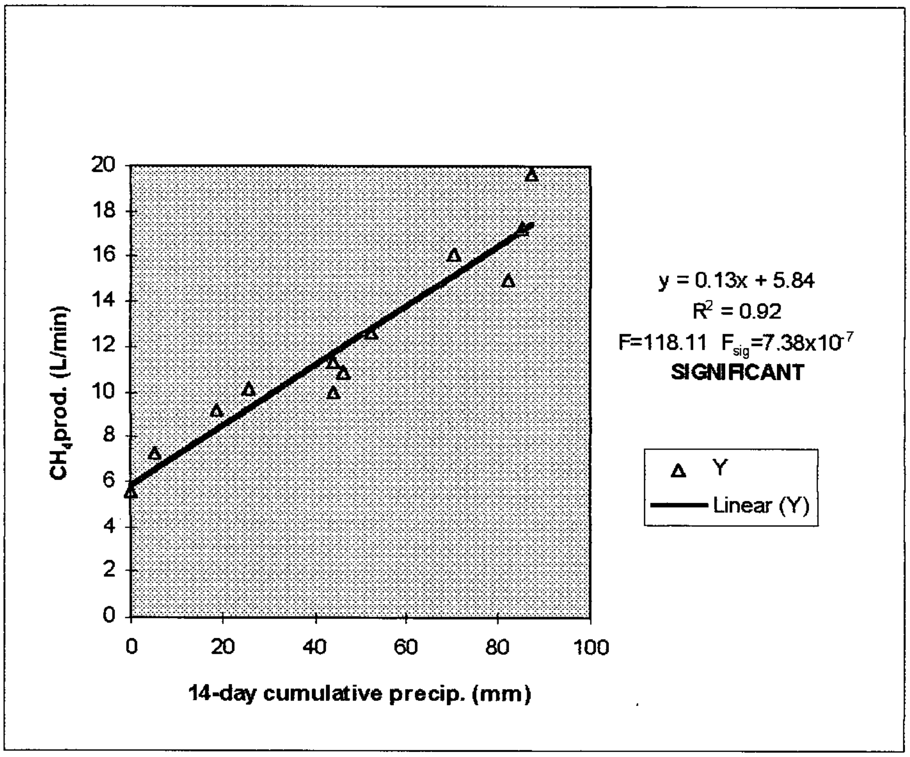

FIGURE C-1.3: CH_4 production in response to 14-day cumulative precipitation - PORT F6

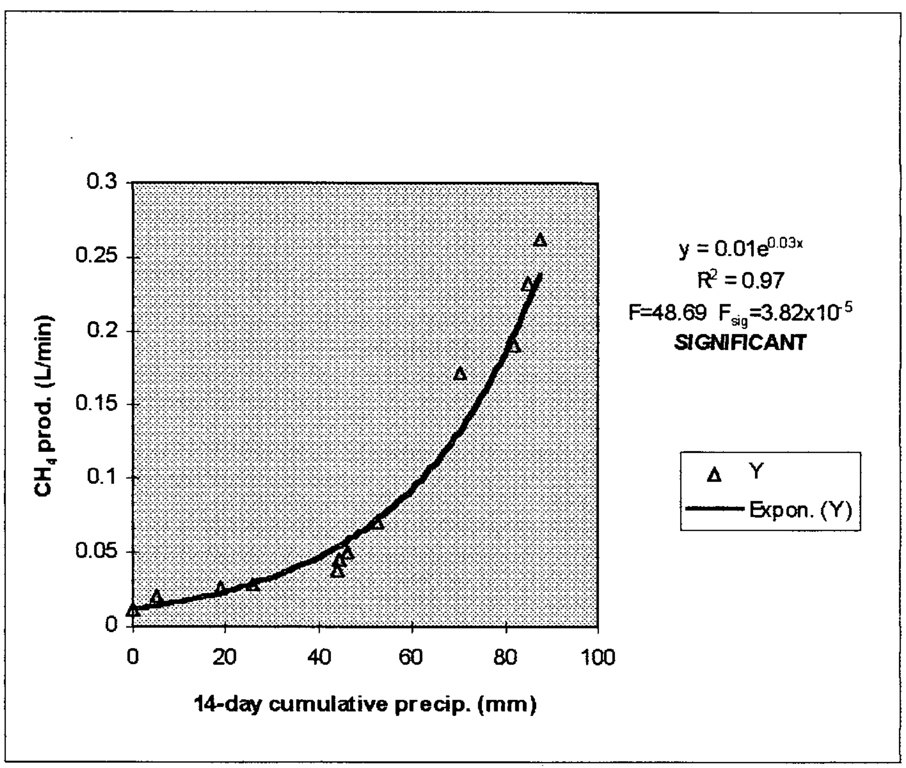

FIGURE C-1.4: CH_4 production in response to 14-day cumulative precipitation - PORT F29

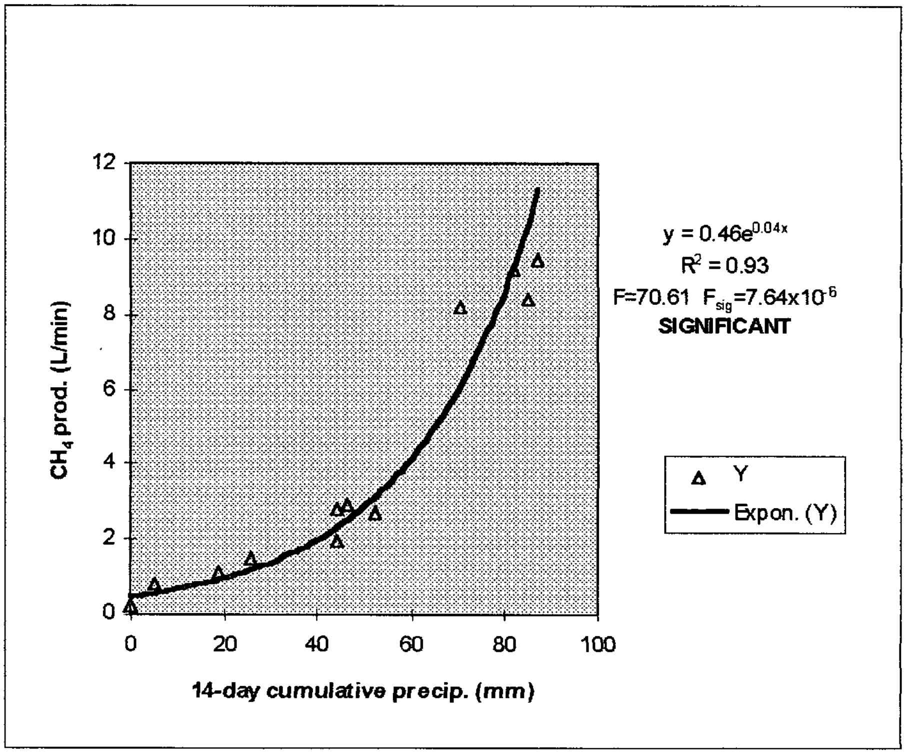

FIGURE C-1.5 CH_4 production in response to 14-day cumulative precipitation - PORT G5

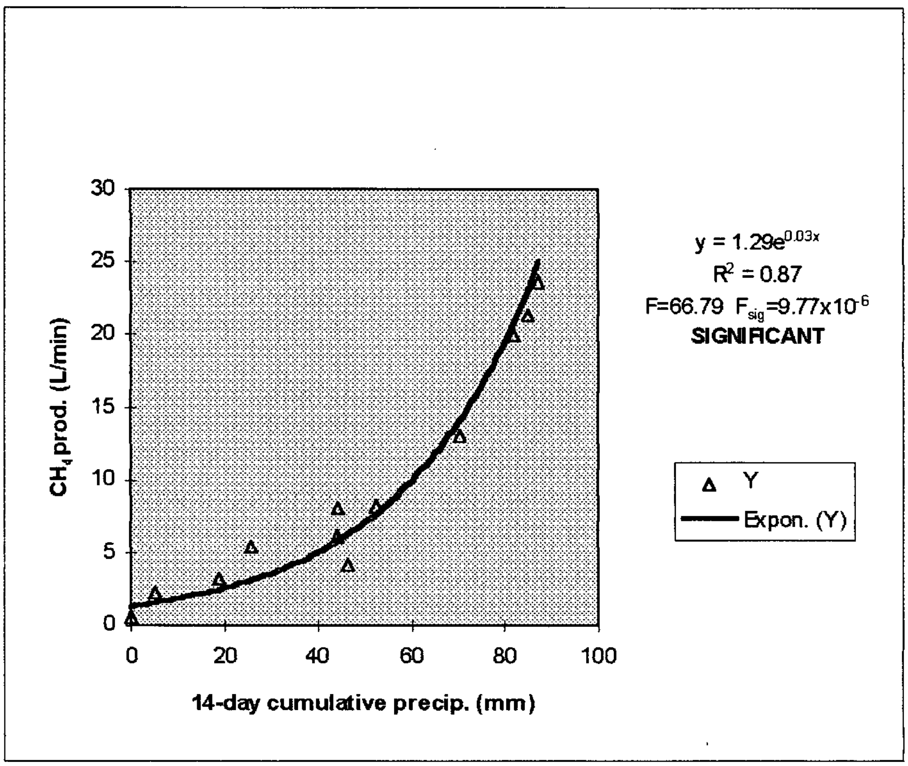

FIGURE C-1.6: CH_4 production in response to 14-day cumulative precipitation - PORT G9

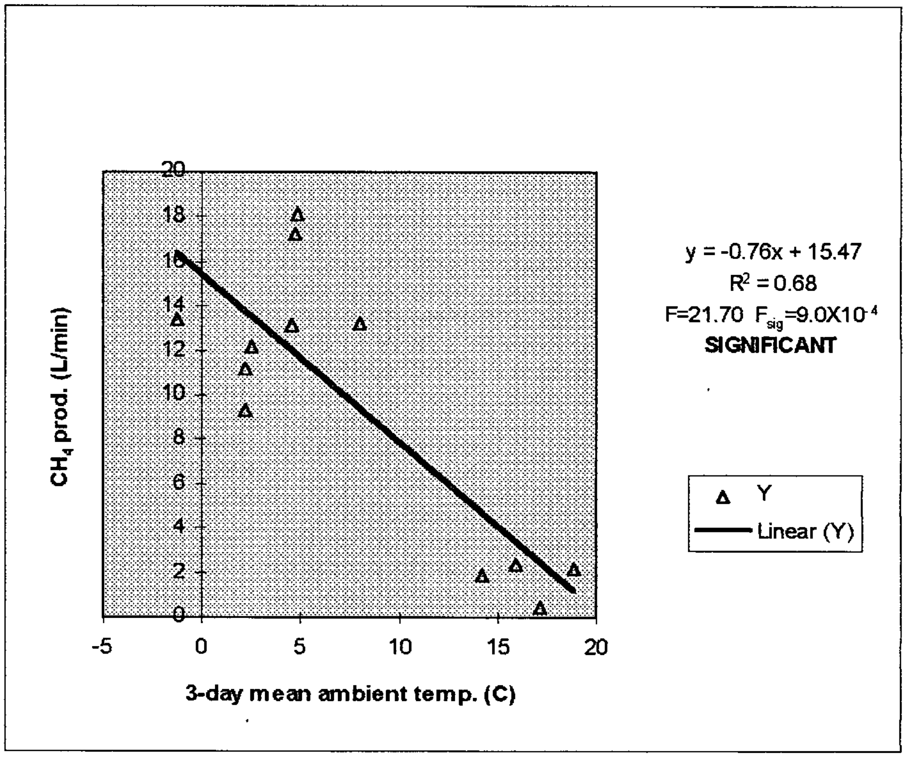

FIGURE C-2.1: CH_4 production in response to 3-day mean ambient temperature - PORT C14

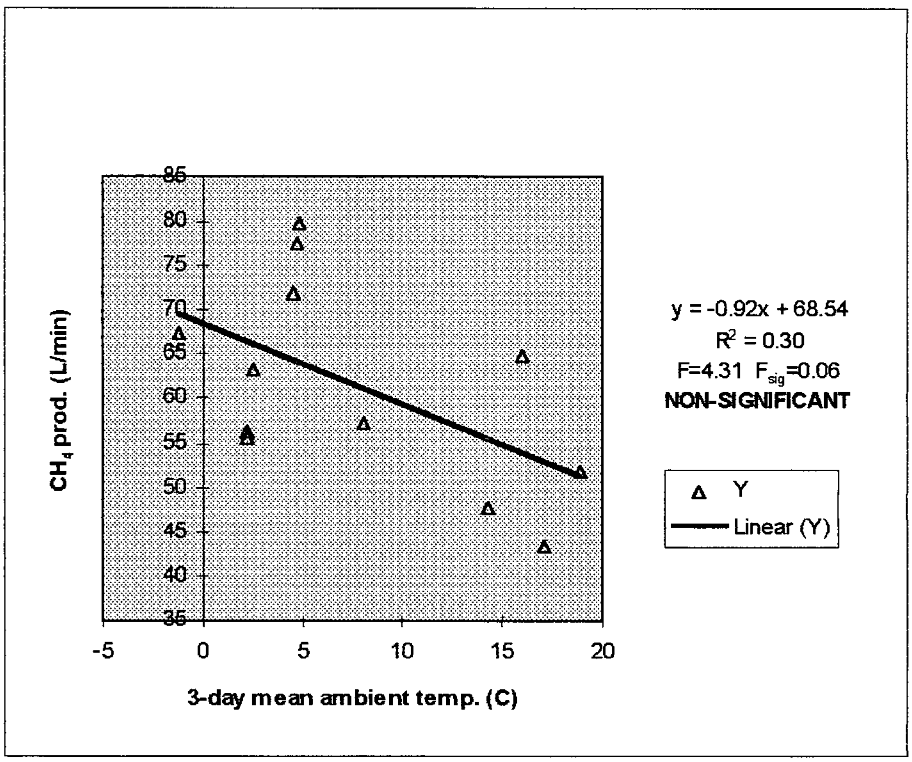

FIGURE C-2.2: CH_4 production in response to 3-day mean ambient temperature - PORT D23

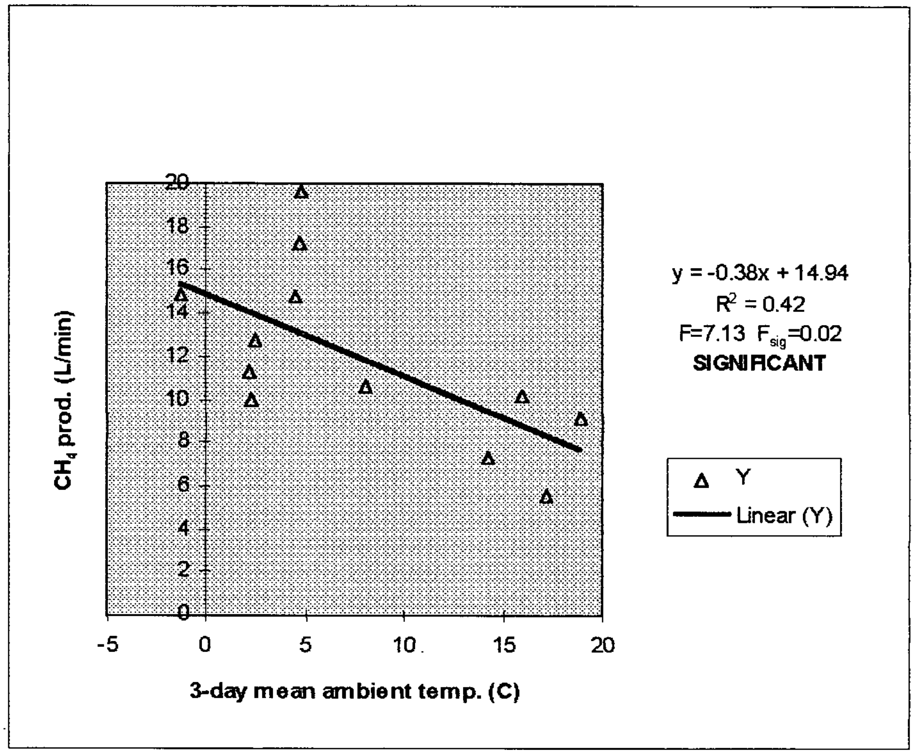

FIGURE C-2.3: CH_4 production in response to 3-day mean ambient temperature - PORT F6

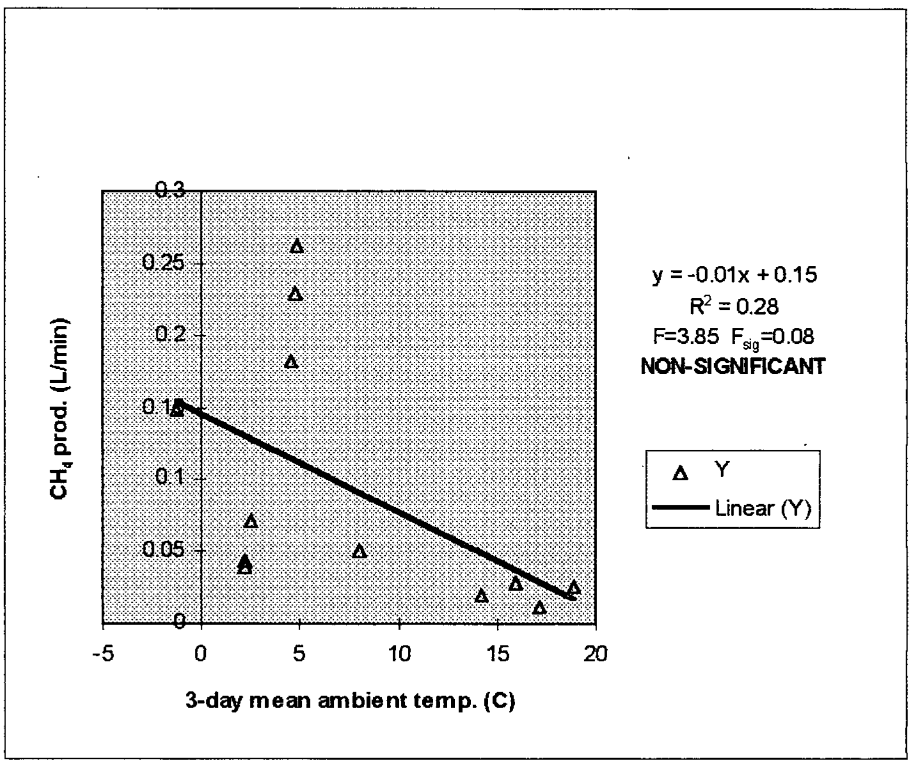

FIGURE C-2.4: CH_4 production in response to 3-day mean ambient temperature - PORT F29

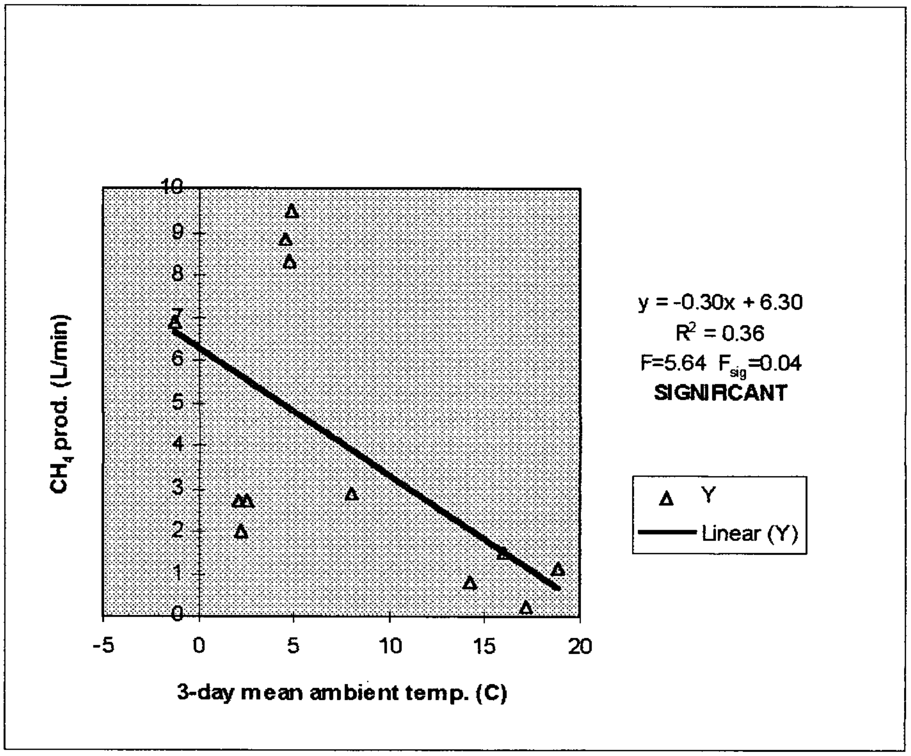

FIGURE C-2.5: CH_4 production in response to 3-day mean ambient temperature - PORT G5

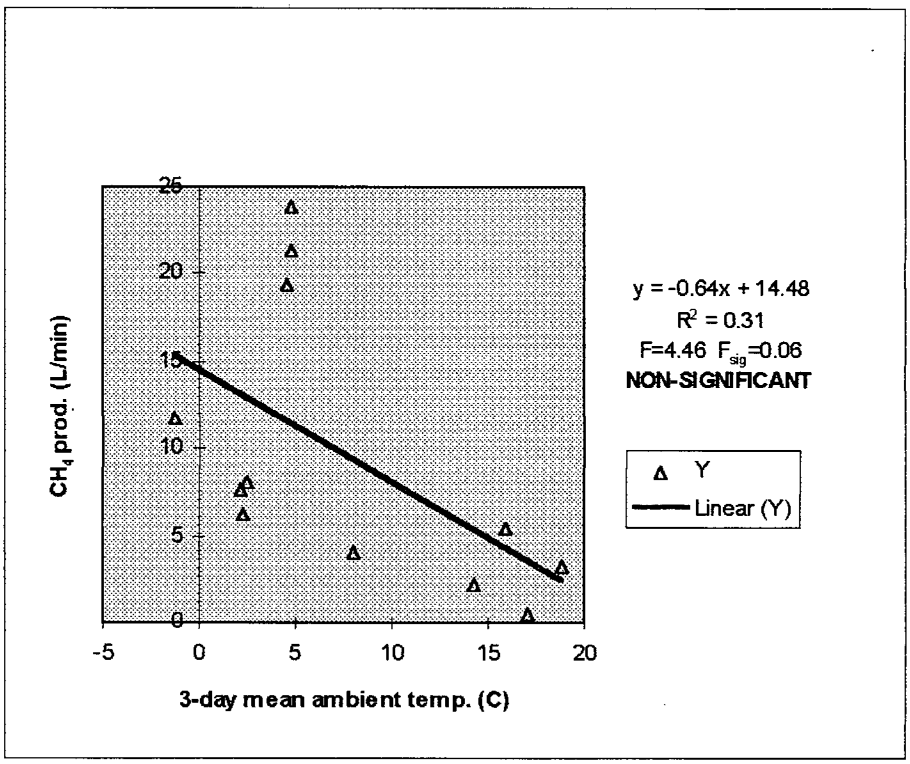

FIGURE C-2.6: CH_4 production in response to 3-day mean ambient temperature - PORT G9

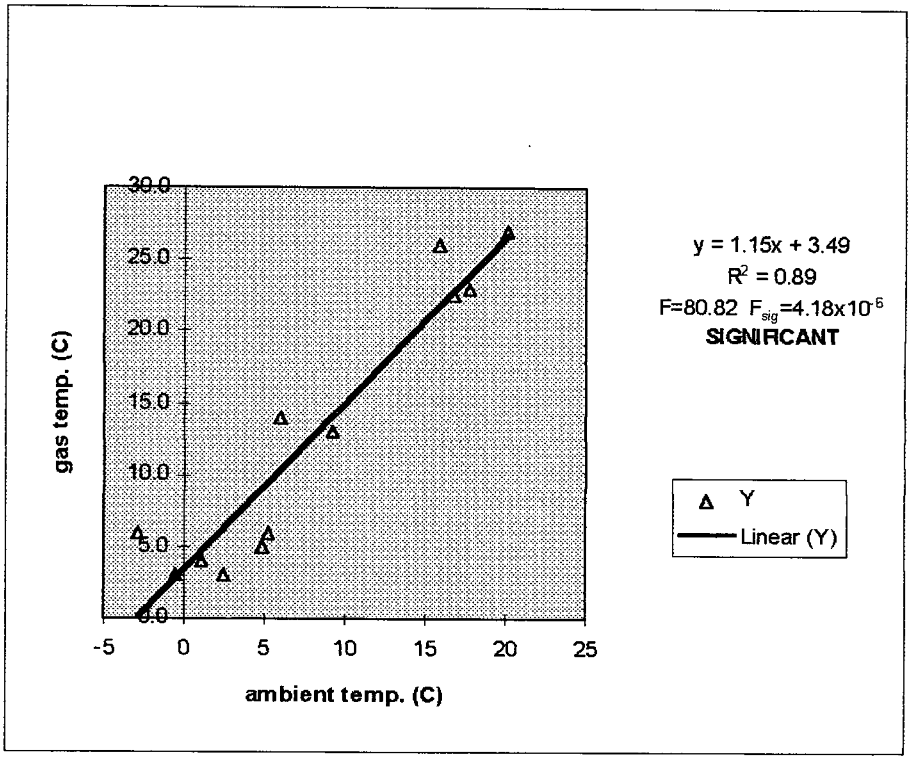

FIGURE C-3.1: Landfill gas temperature in response to ambient temperature on sampling day - PORT C14

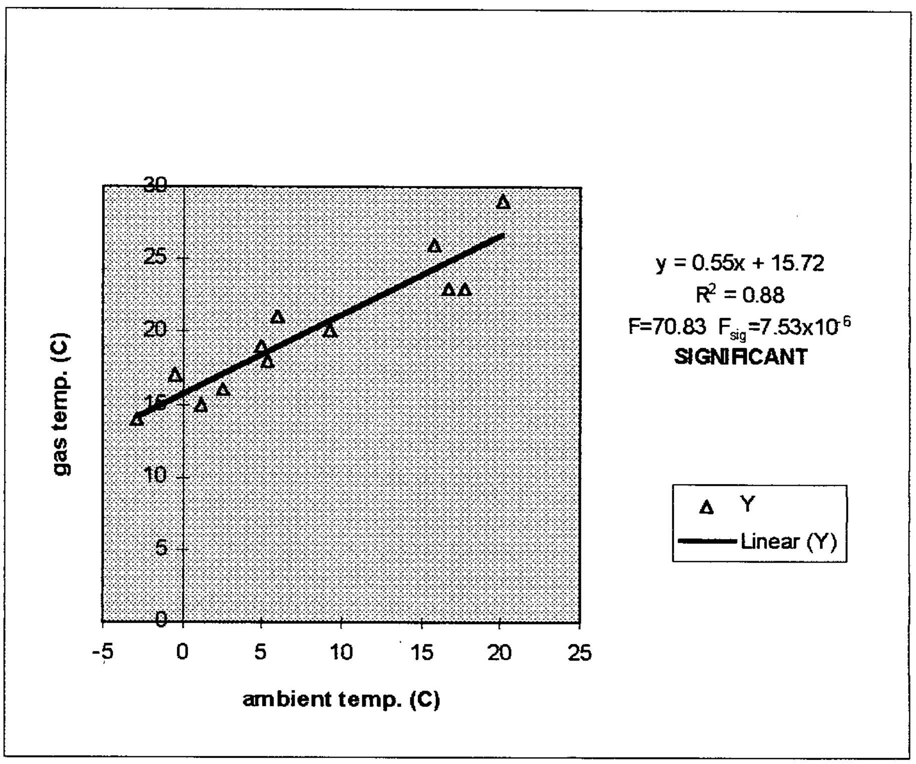

FIGURE C-3.2: Landfill gas temperature in response to ambient temperature on sampling day - PORT D23

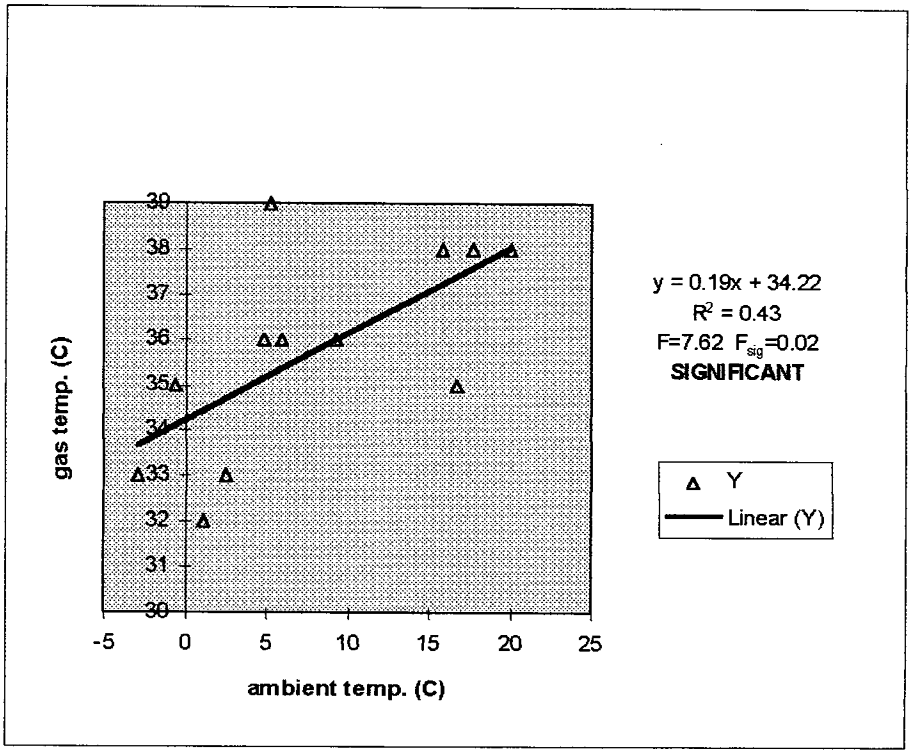

FIGURE C-3.3: Landfill gas temperature in response to ambient temperature on sampling day - PORT E20

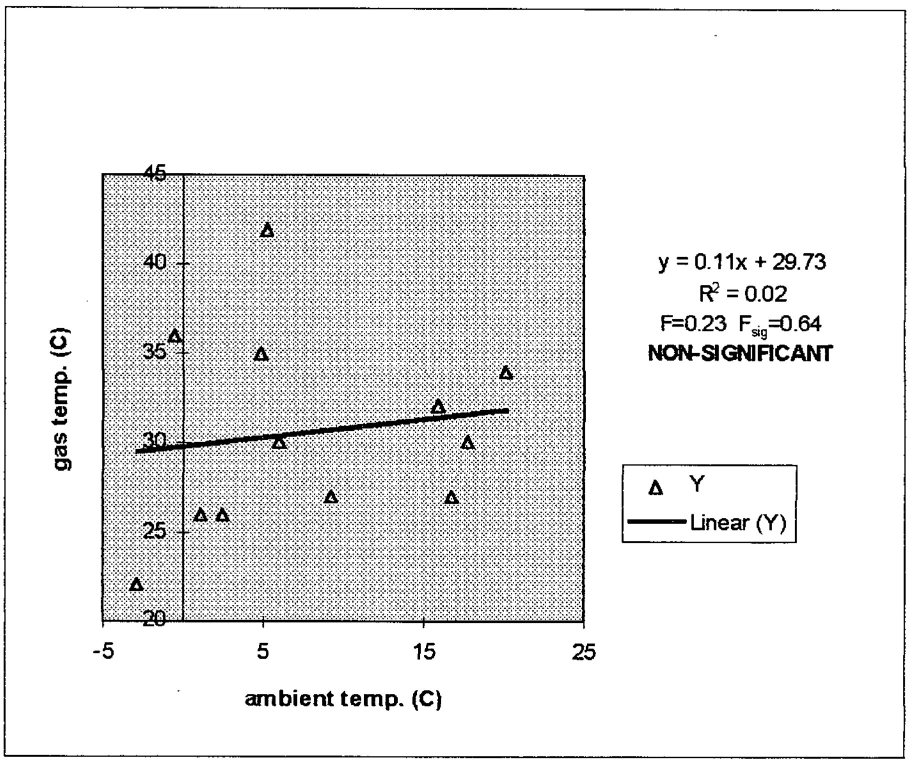

FIGURE C-3.4: Landfill gas temperature in response to ambient temperature on sampling day - PORT E7

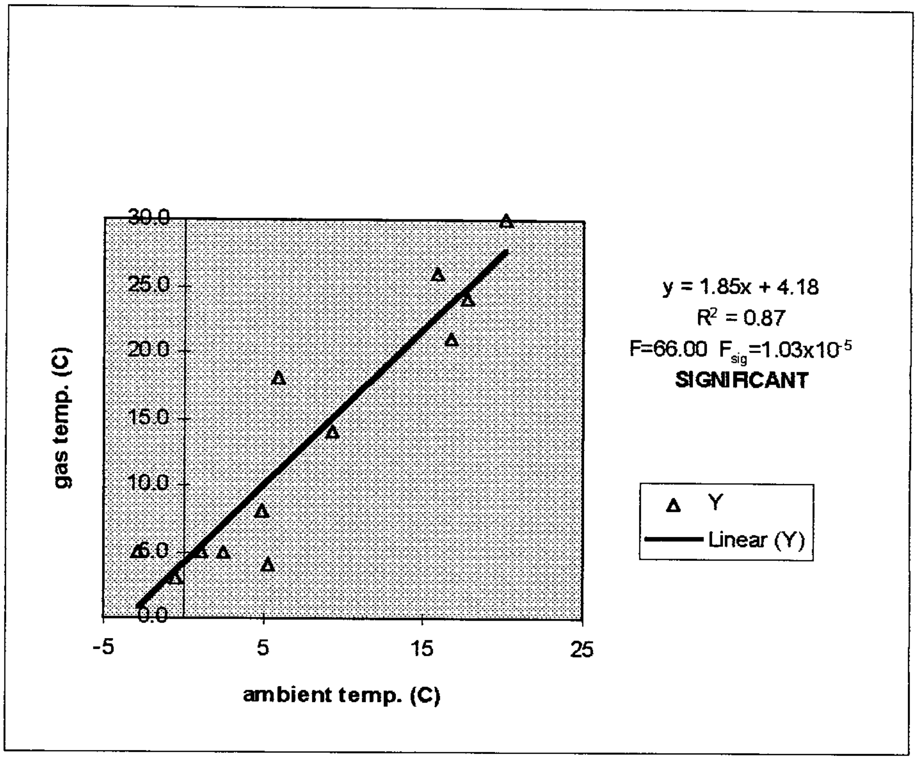

FIGURE C-3.5: Landfill gas temperature in response to ambient temperature on sampling day - PORT G5

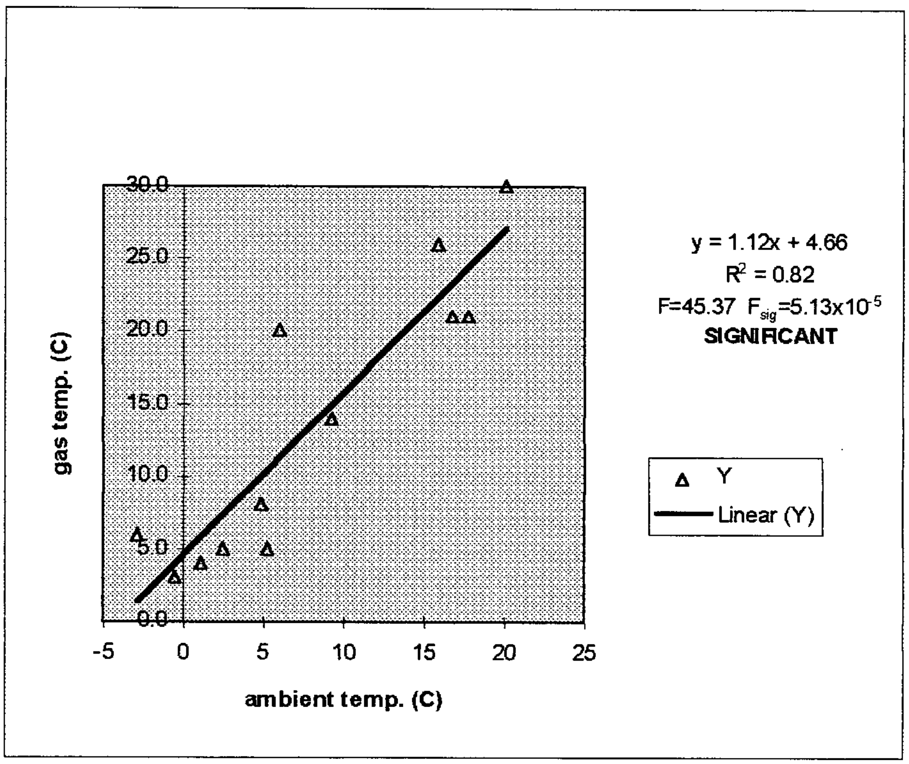

FIGURE C-3.6: Landfill gas temperature in response to ambient temperature on sampling day - PORT G9

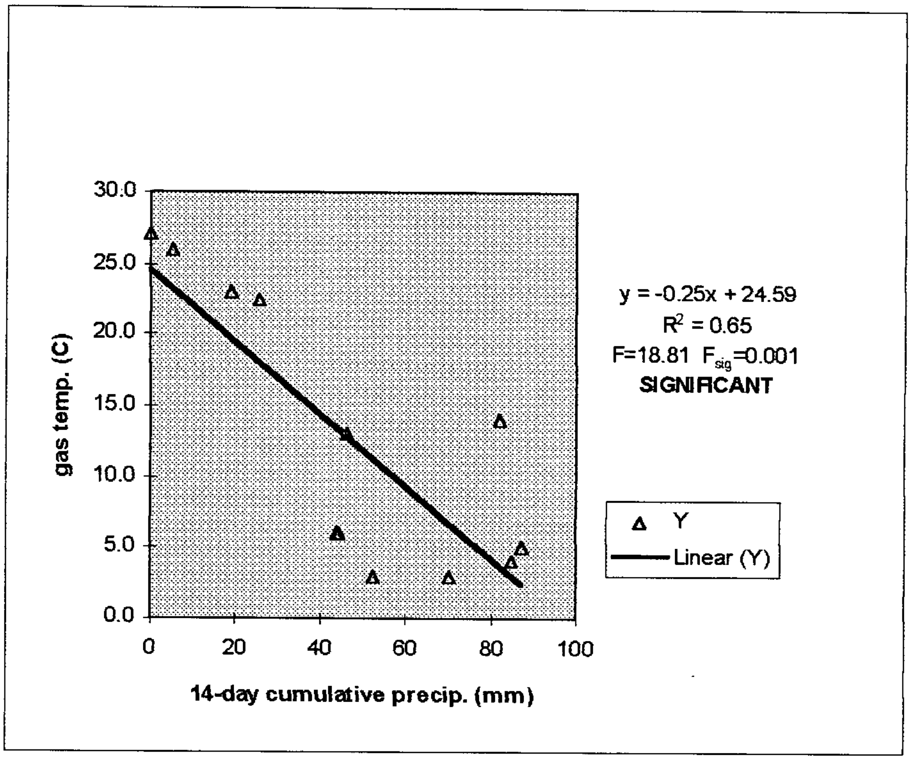

FIGURE C-4.1: Landfill gas temperature in response to 14-day cumulative precipitation- PORT C14

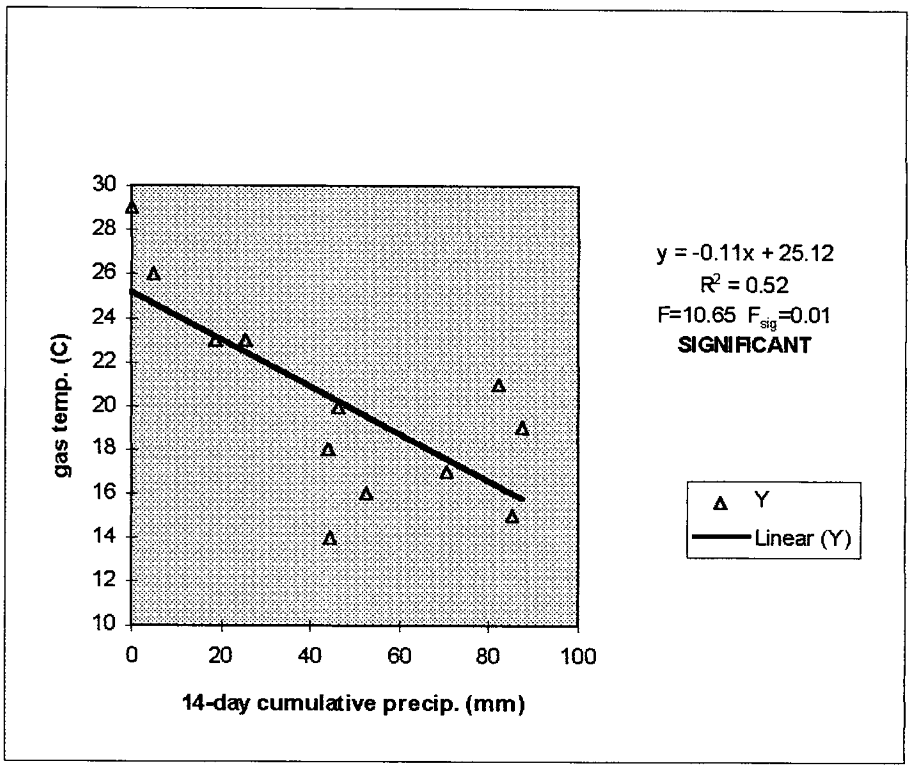

FIGURE C-4.2: Landfill gas temperature in response to 14-day cumulative precipitation- PORT D23

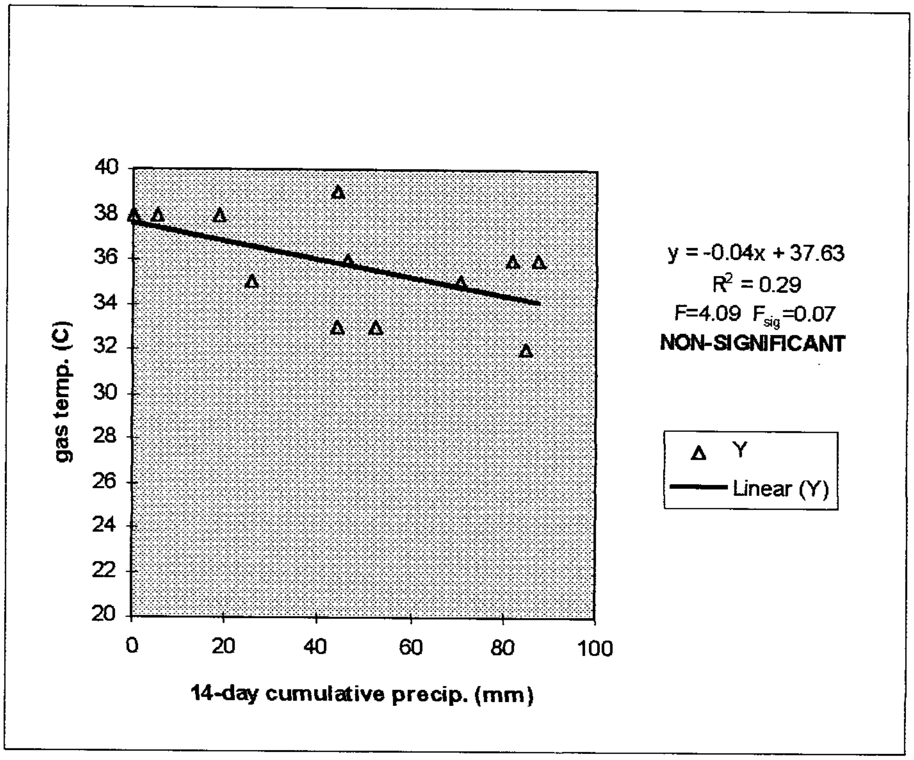

FIGURE C-4.3: Landfill gas temperature in response to 14-day cumulative precipitation- PORT E20

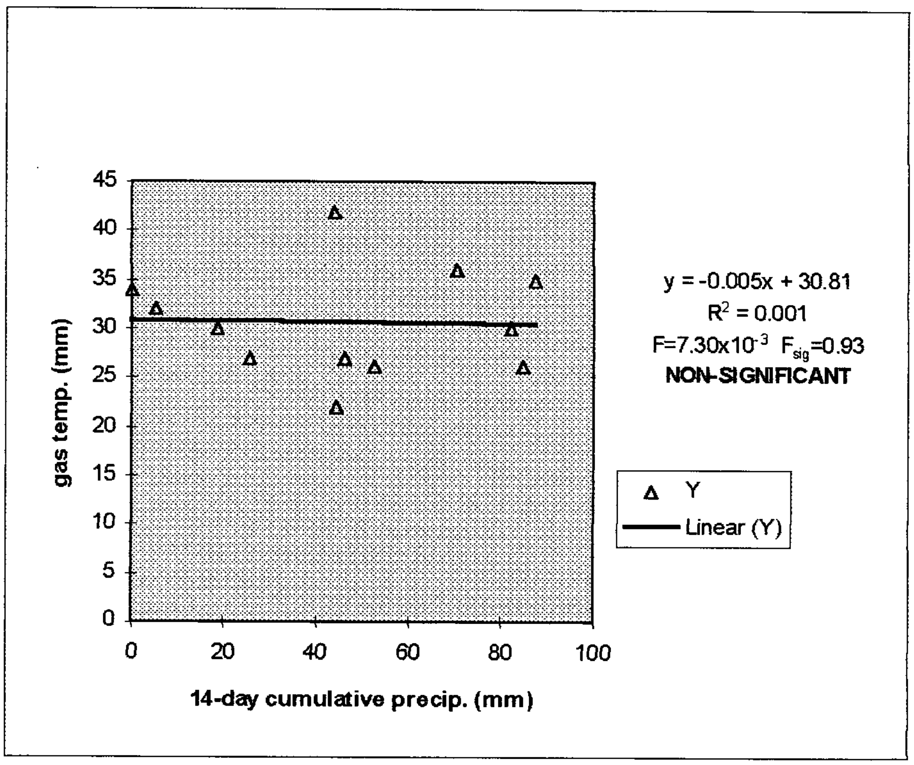

FIGURE C-4.4: Landfill gas temperature in response to 14-day cumulative precipitation- PORT E7

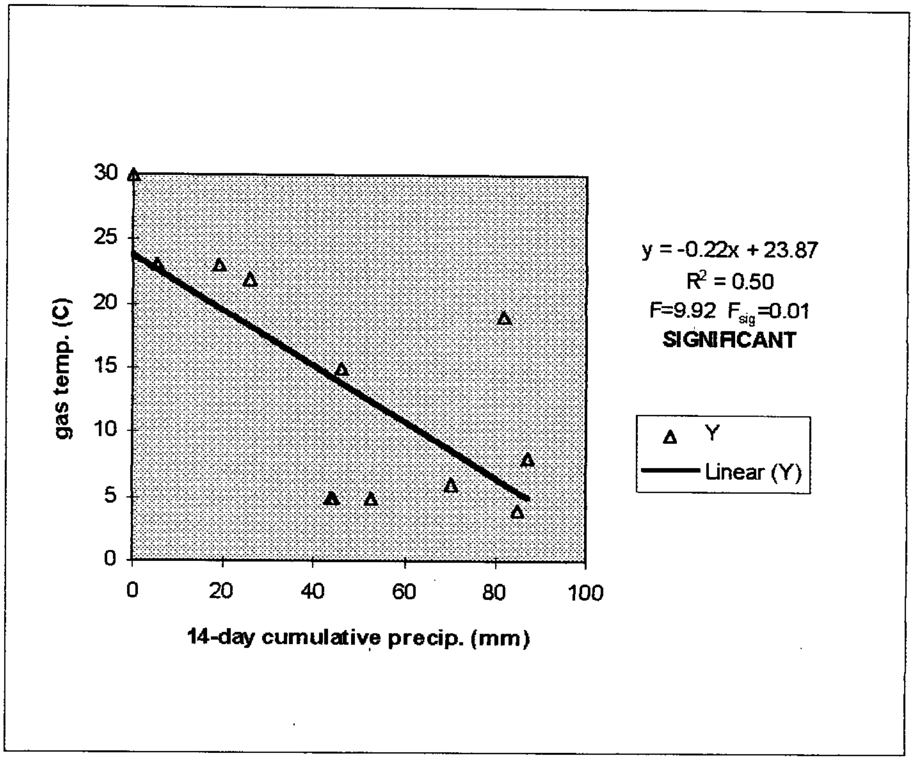

FIGURE C-4.5: Landfill gas temperature in response to 14-day cumulative precipitation- PORT F6

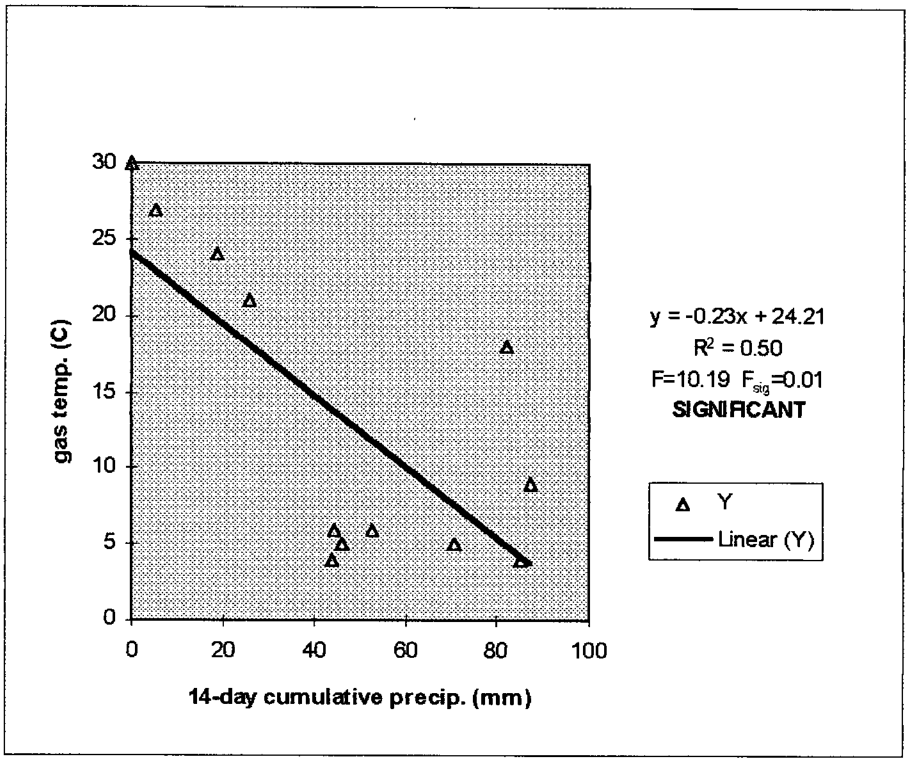

FIGURE C-4.6: Landfill gas temperature in response to 14-day cumulative precipitation- PORT F29

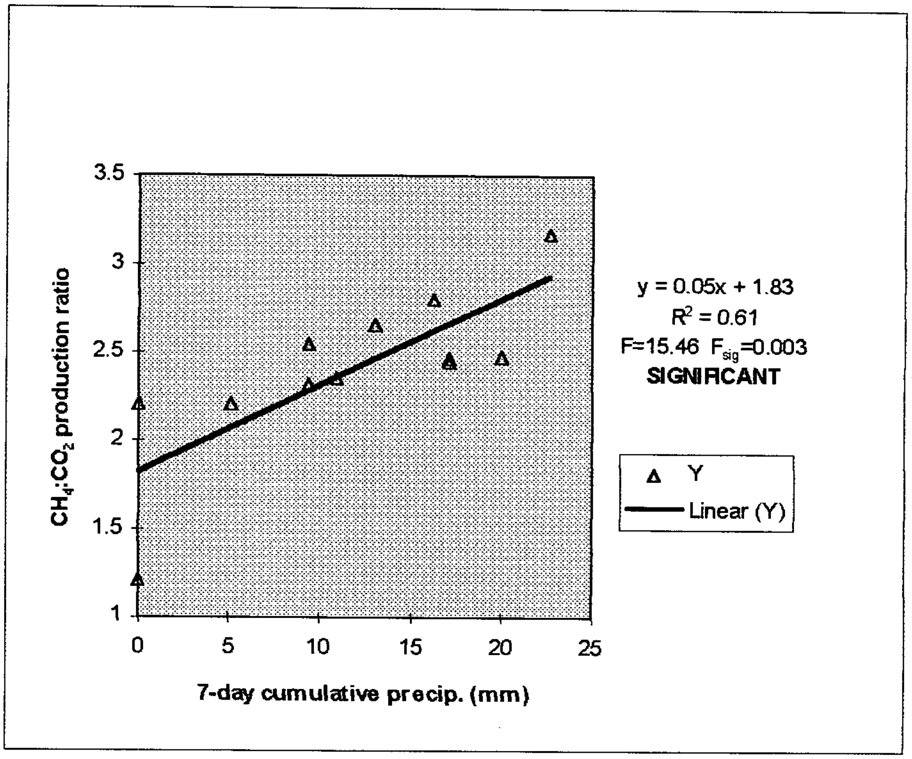

FIGURE C-5.1: CH_4:CO_2 production ratios in response to 7-day cumulative precipitation - PORT C14

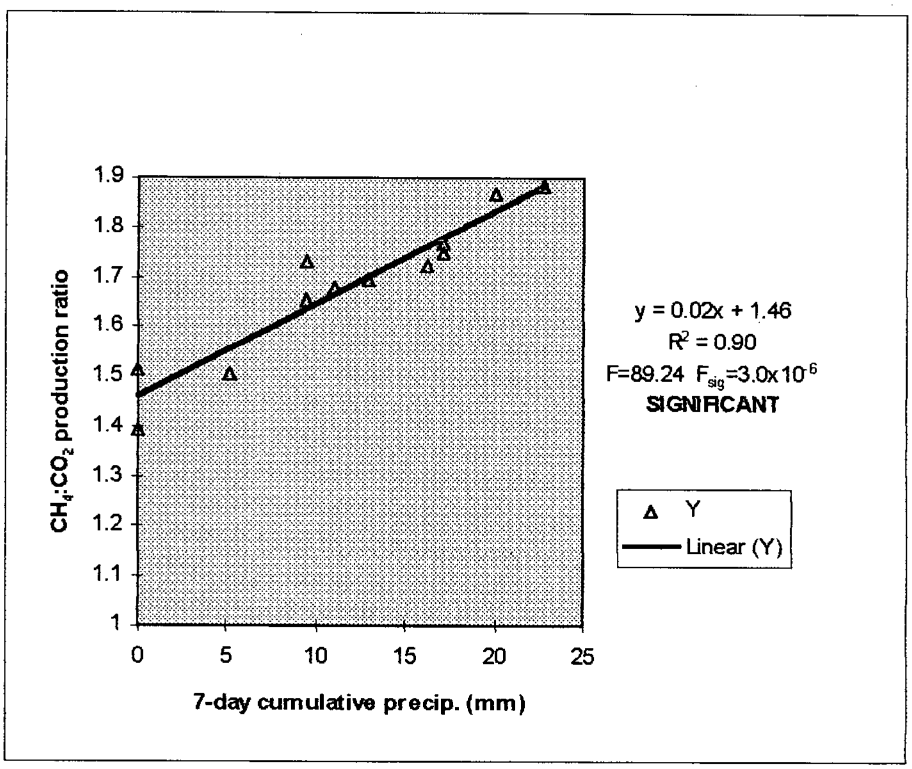

FIGURE C-5.2: CH_4:CO_2 production ratios in response to 7-day cumulative precipitation - PORT D23

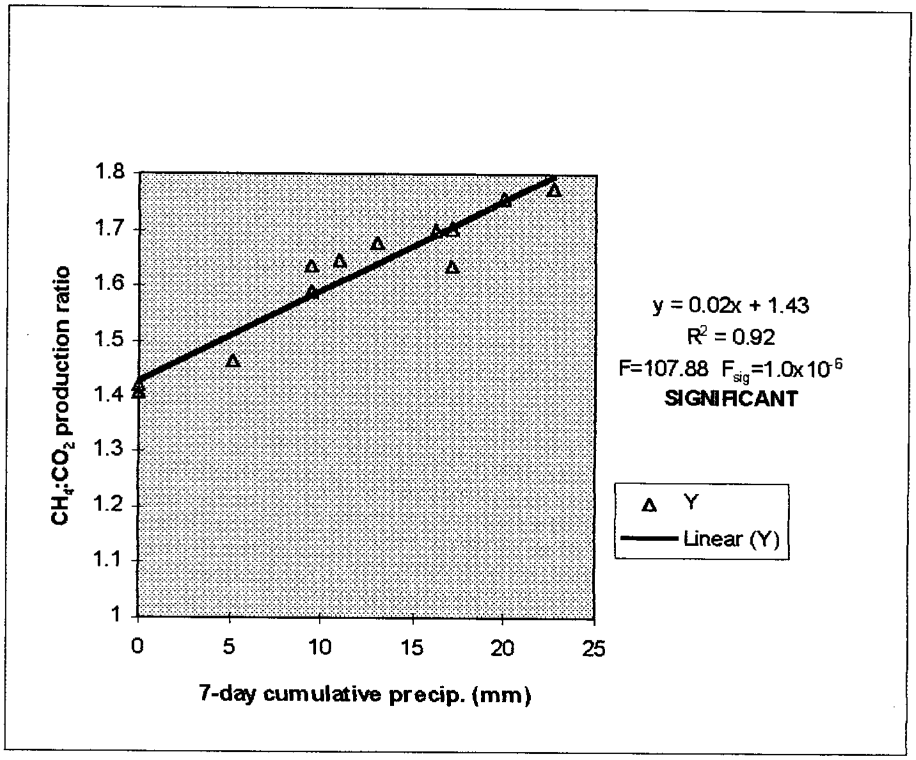

FIGURE C-5.3: CH_4:CO_2 production ratios in response to 7-day cumulative precipitation - PORT F6

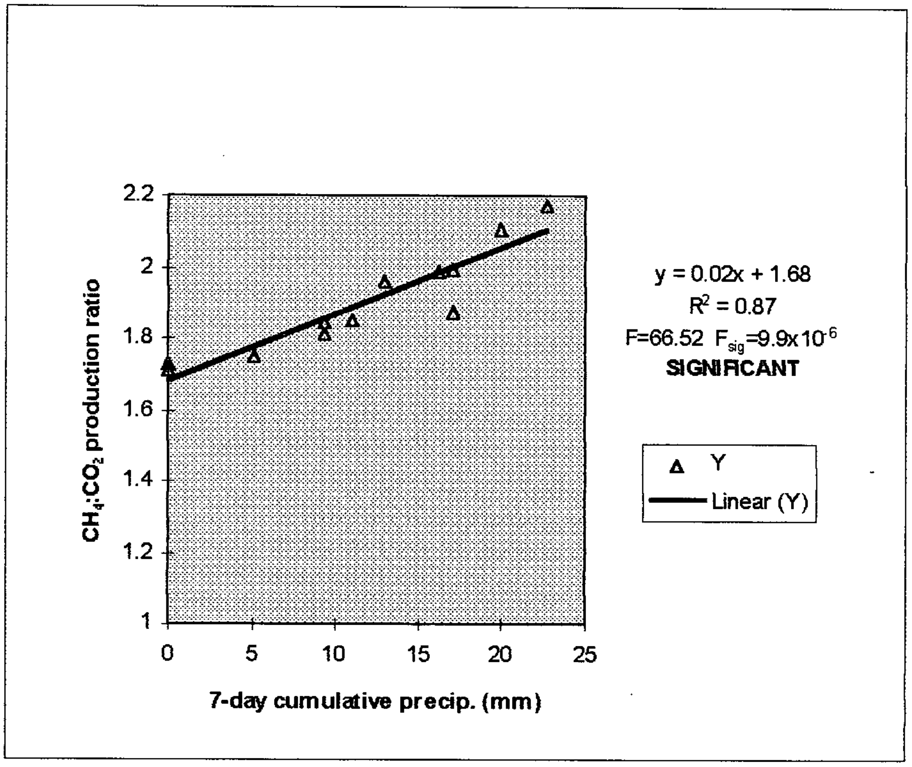

FIGURE C-5.4: CH_4:CO_2 production ratios in response to 7-day cumulative precipitation - PORT F29

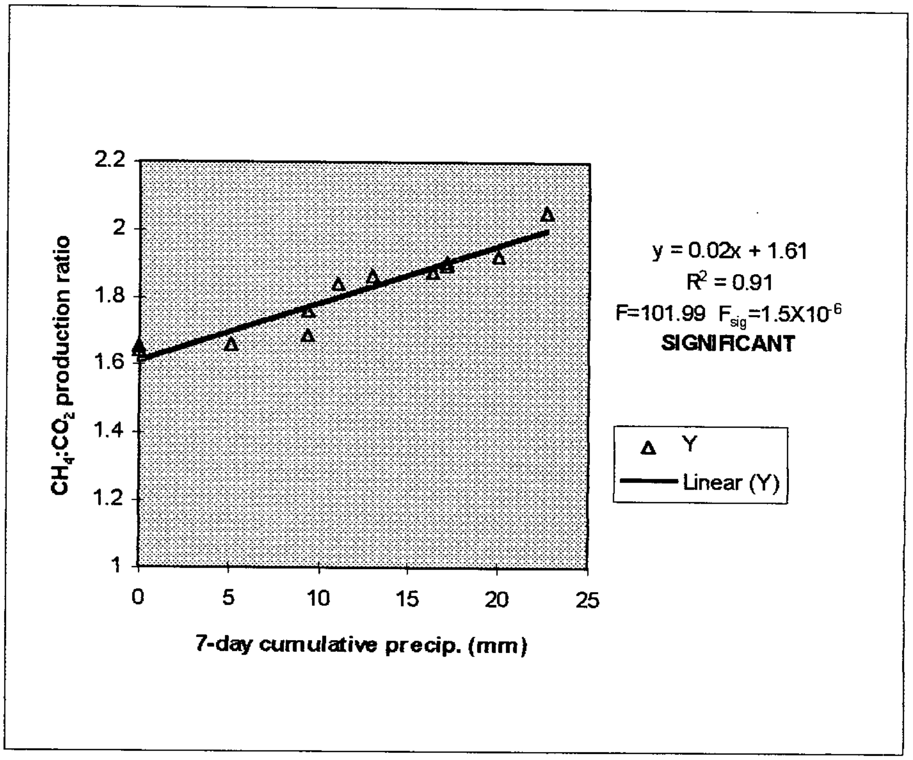

FIGURE C-5.5: $CH_4:CO_2$ production ratios in response to 7-day cumulative precipitation - PORT G5

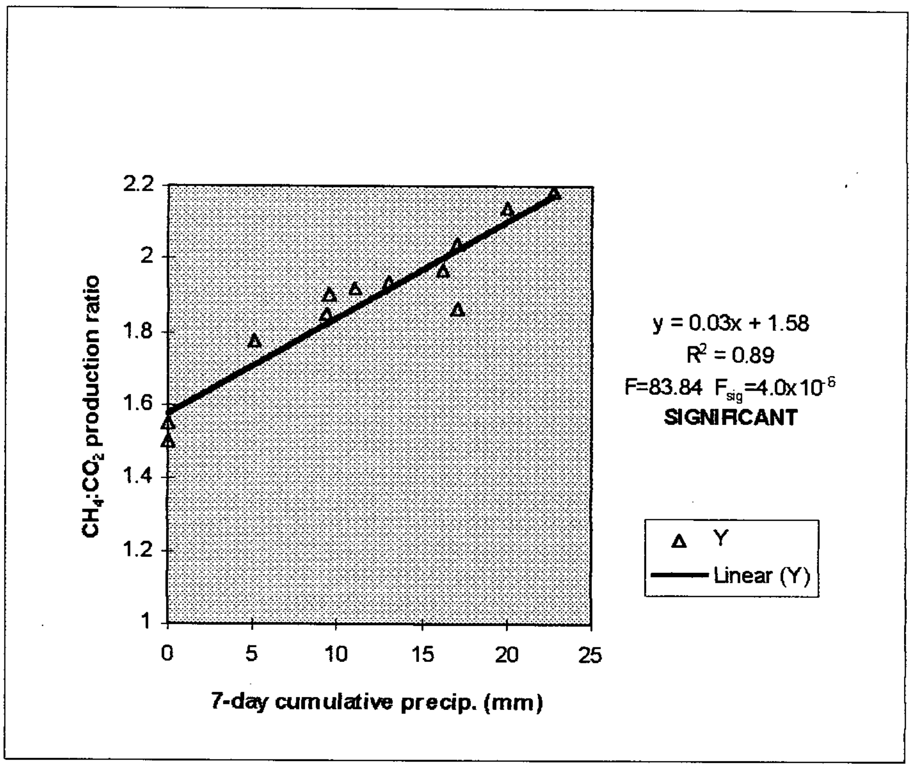

FIGURE C-5.6: $CH_4:CO_2$ production ratios in response to 7-day cumulative precipitation - PORT G9

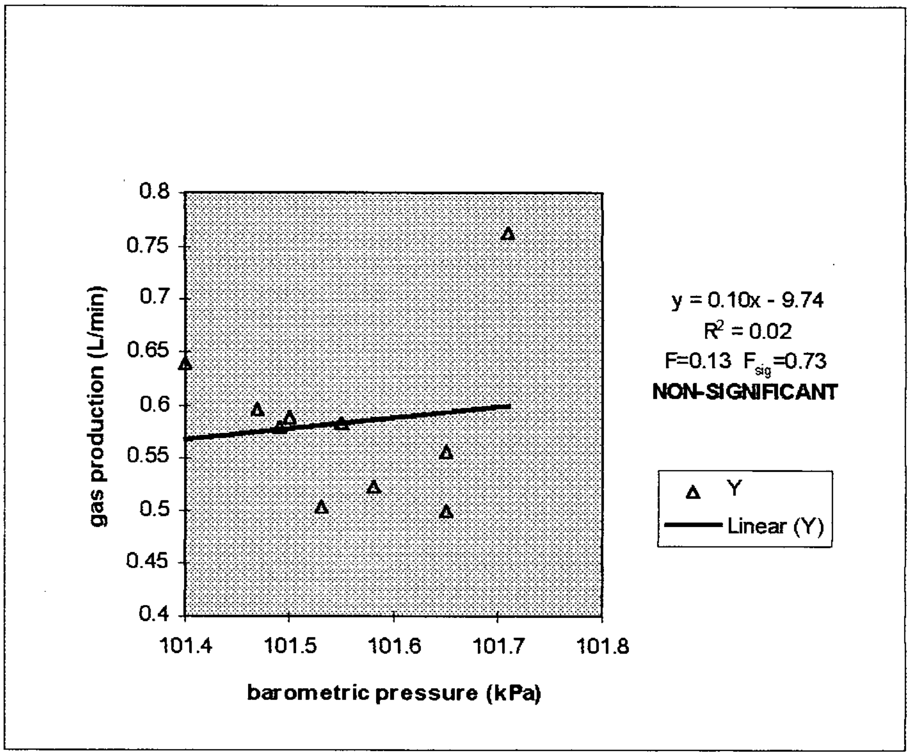

FIGURE C-6.1: The effects of increasing barometric pressure on landfill gas production - PORT C14

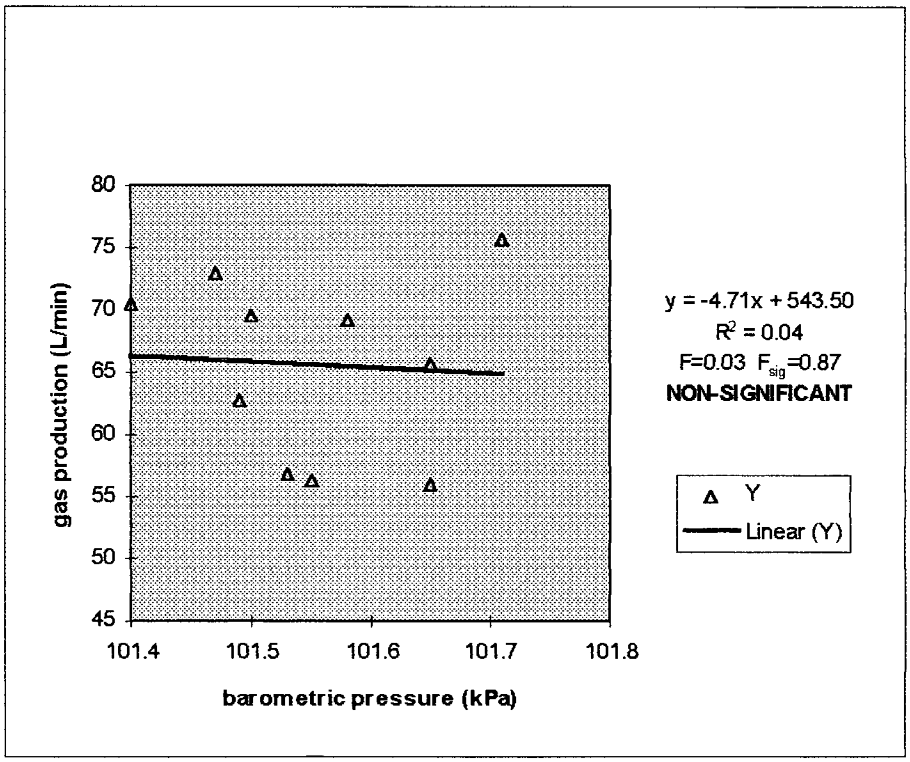

FIGURE C-6.2: The effects of increasing barometric pressure on landfill gas production - PORT D23

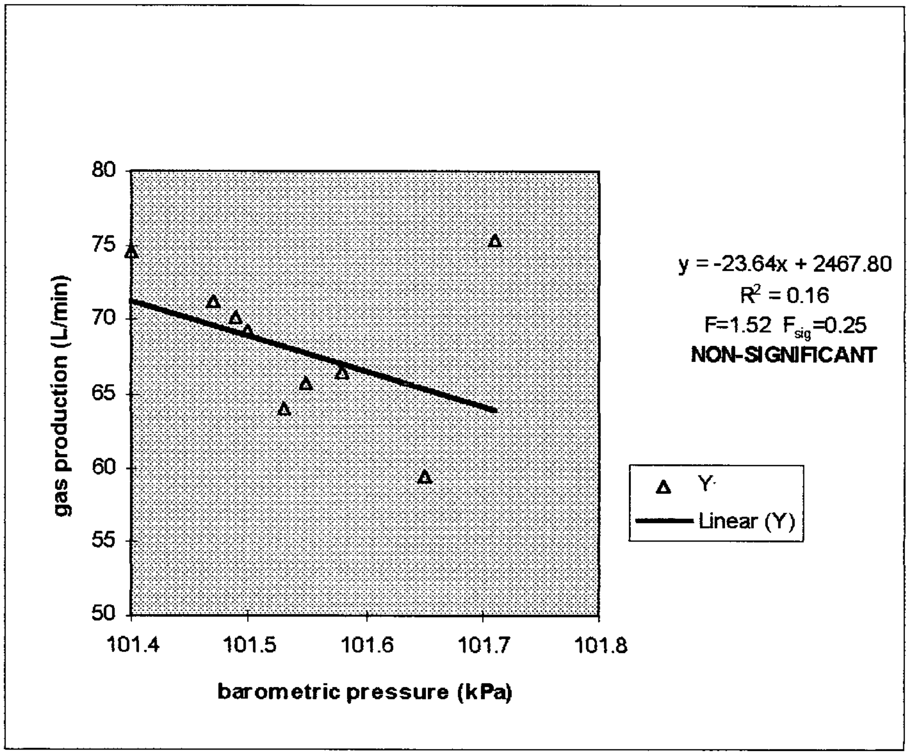

FIGURE C-6.3: The effects of increasing barometric pressure on landfill gas production - PORT E20

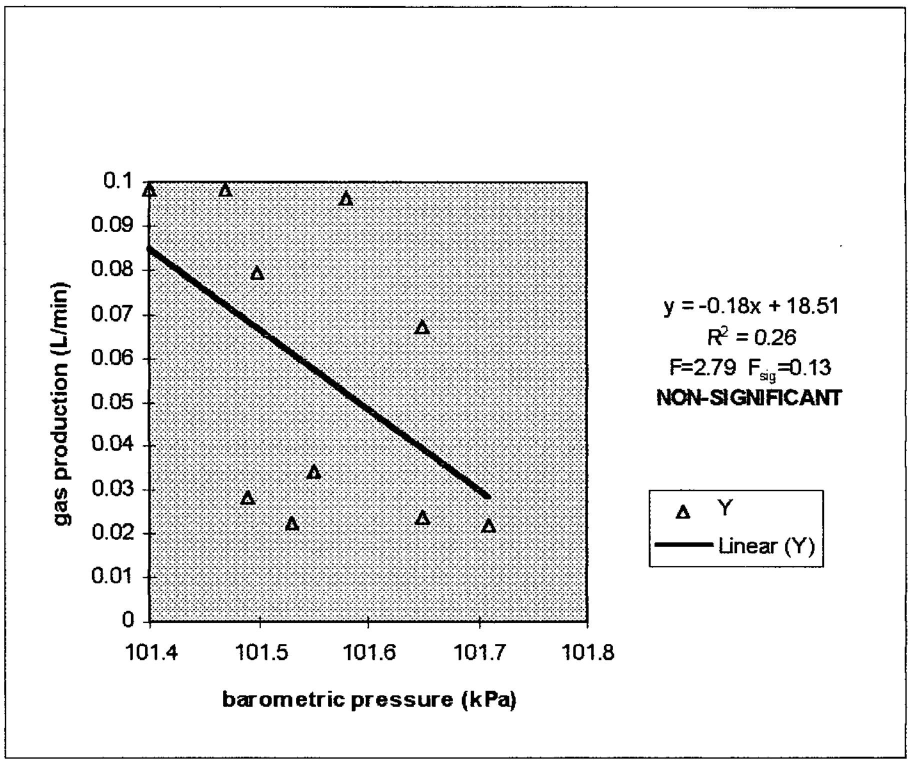

FIGURE C-6.4: The effects of increasing barometric pressure on landfill gas production - PORT F29

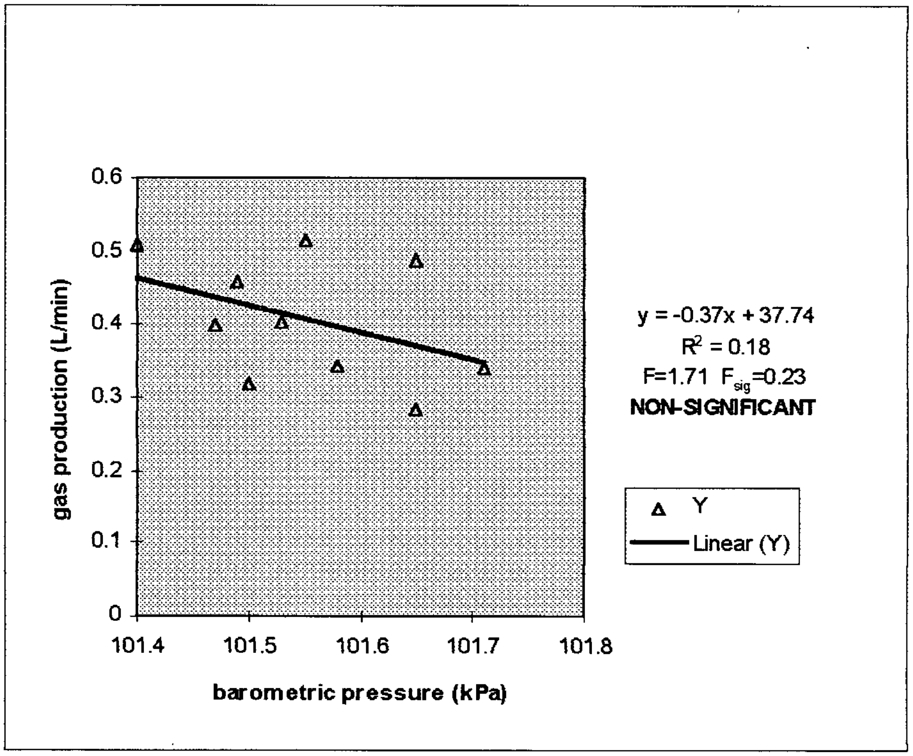

FIGURE C-6.5: The effects of increasing barometric pressure on landfill gas production - PORT G5

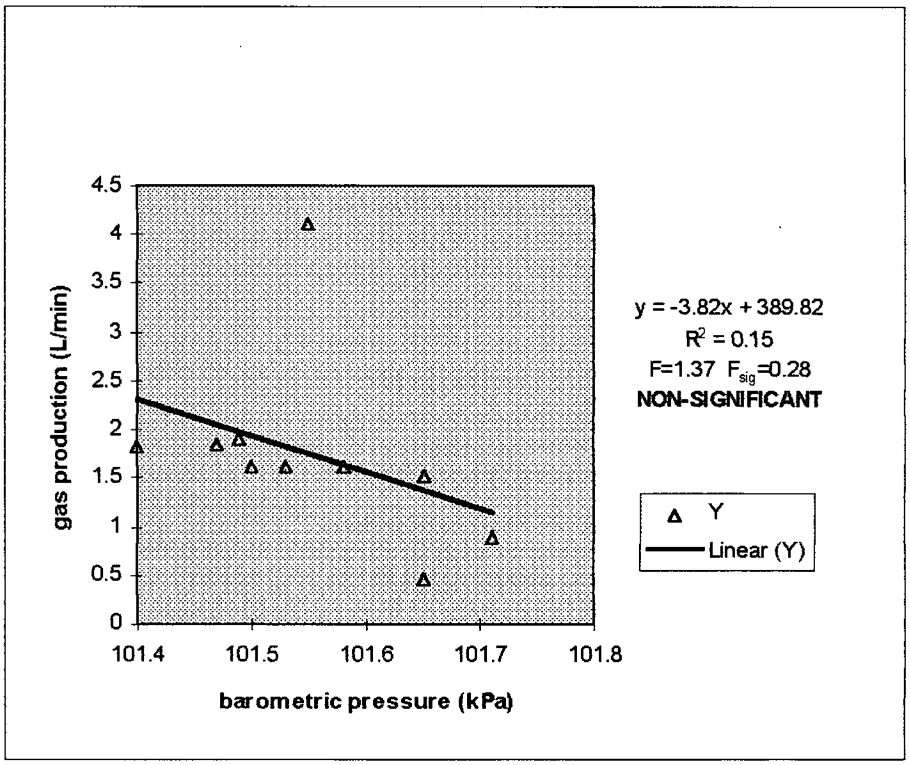

FIGURE C-6.6: The effects of increasing barometric pressure on landfill gas production - PORT G9

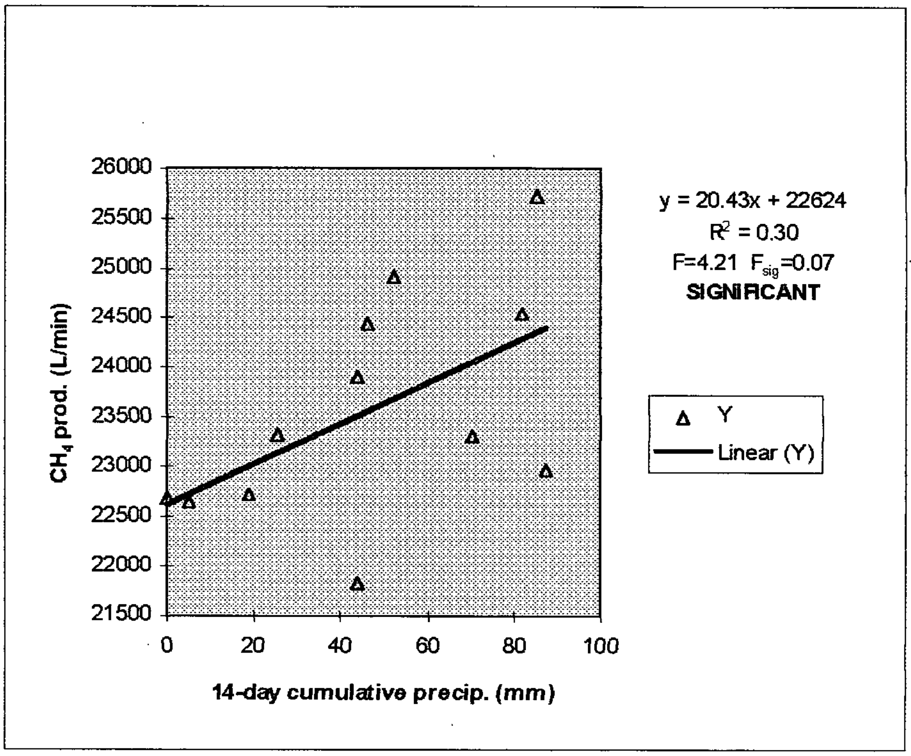

FIGURE C-7.1: Total CH_4 production in response to 14-day cumulative precipitation - D-LINE

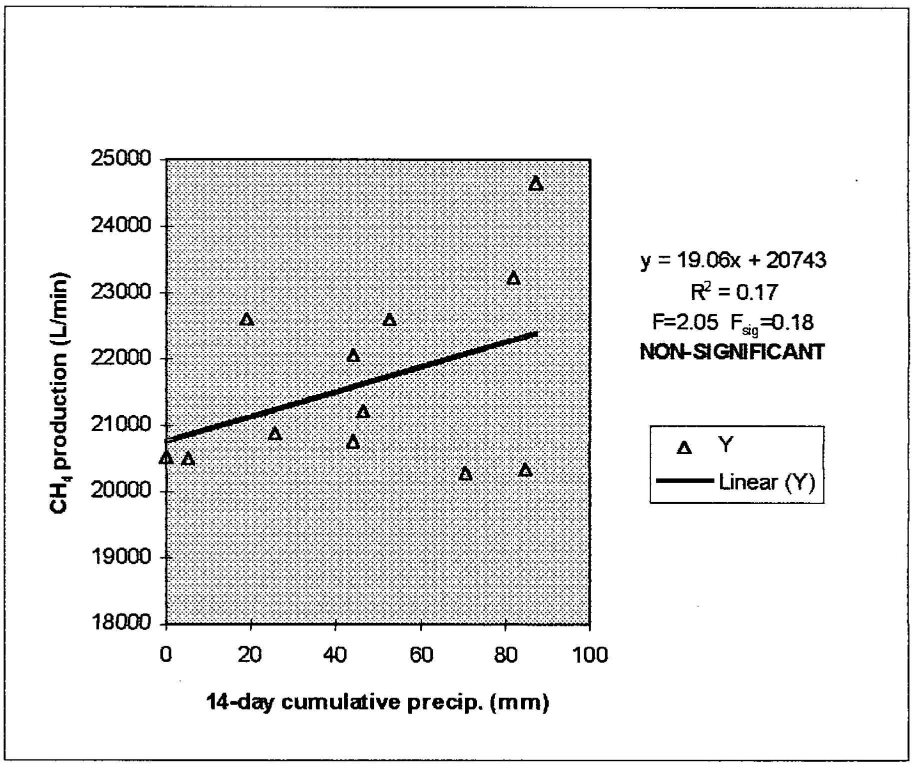

FIGURE C-7.2: Total CH_4 production in response to 14-day cumulative precipitation - F-LINE

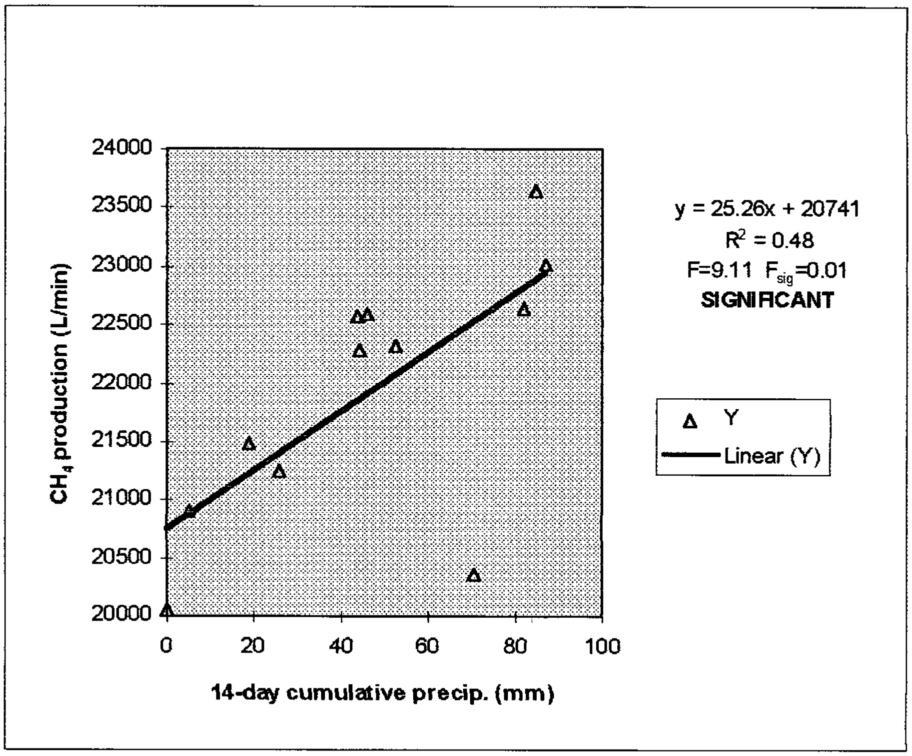

FIGURE C-7.3: Total CH_4 production in response to 14-day cumulative precipitation - G-LINE

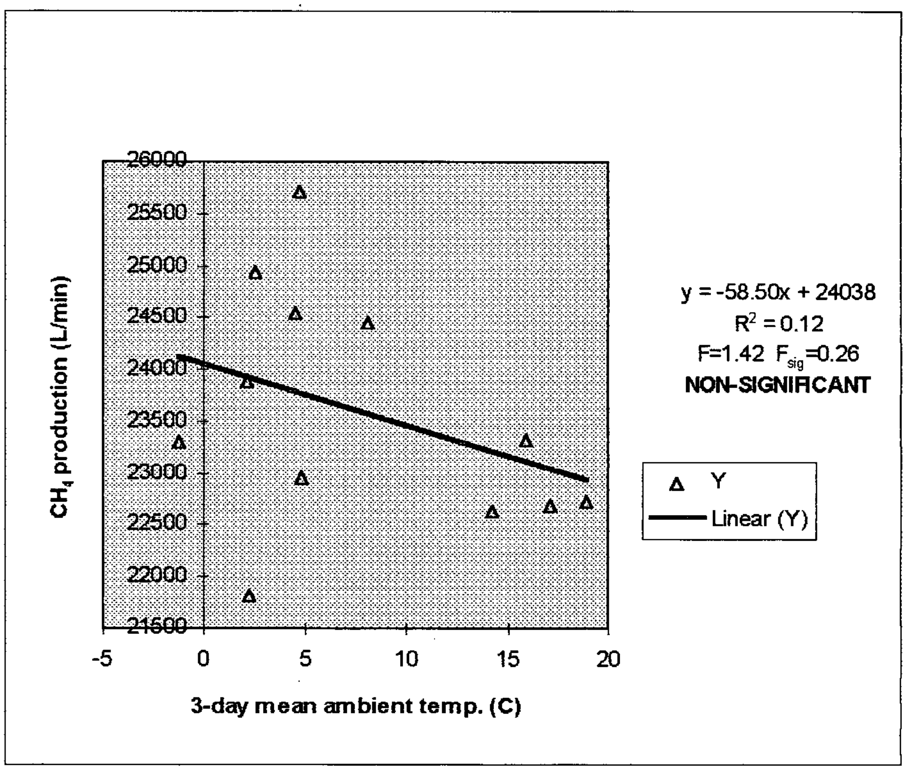

FIGURE C-8.1: Total CH_4 production in response to 3-day mean ambient temperature - D-LINE

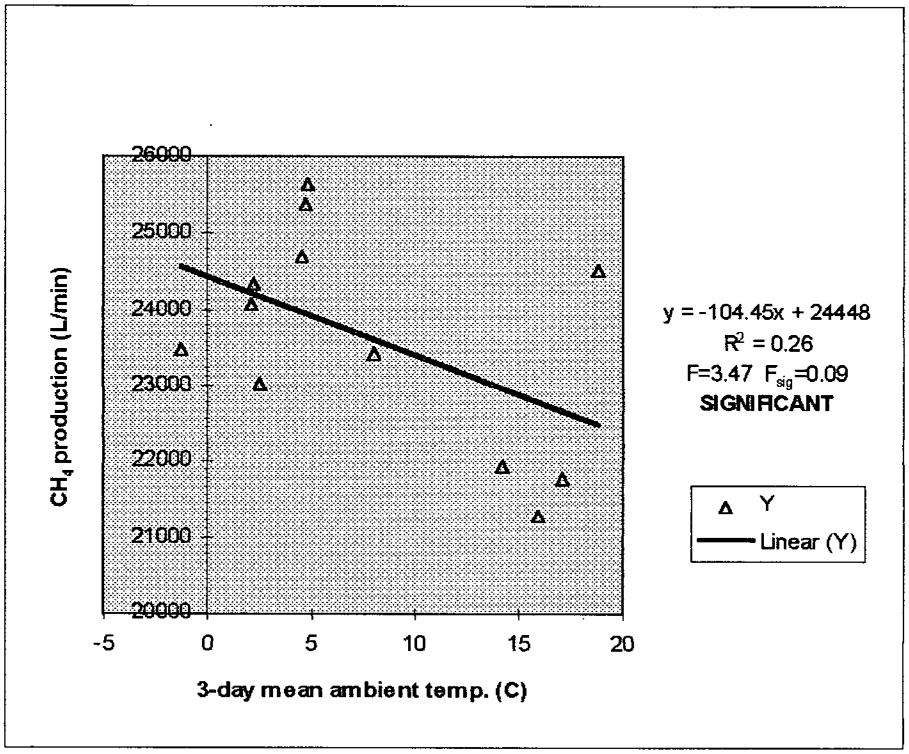

FIGURE C-8.2: Total CH_4 production in response to 3-day mean ambient temperature - E-LINE

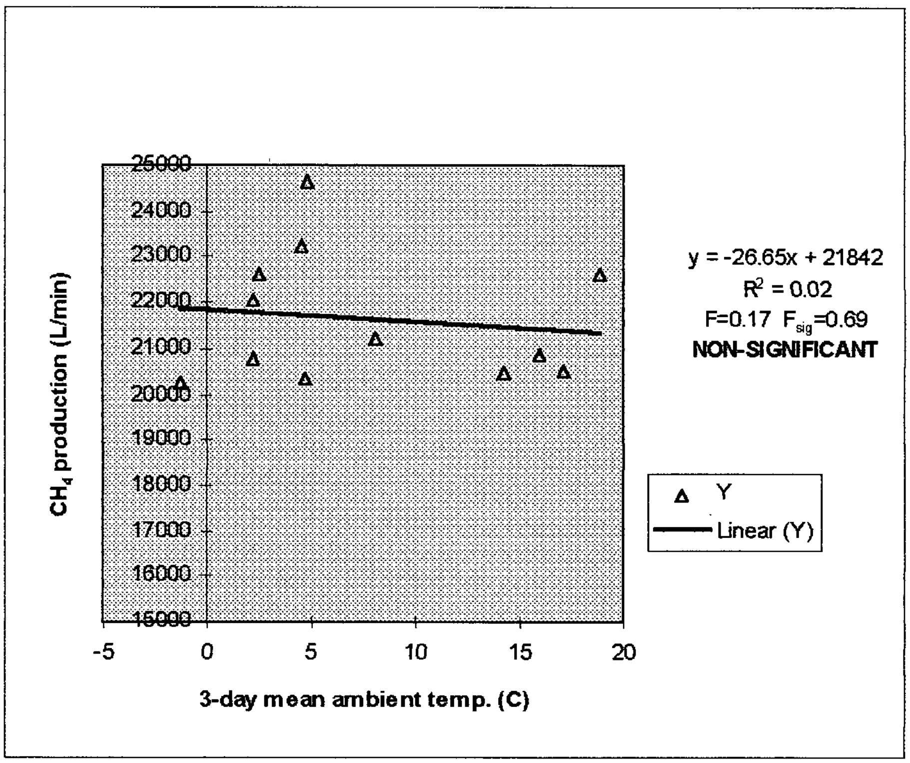

FIGURE C-8.3: Total CH_4 production in response to 3-day mean ambient temperature - F-LINE

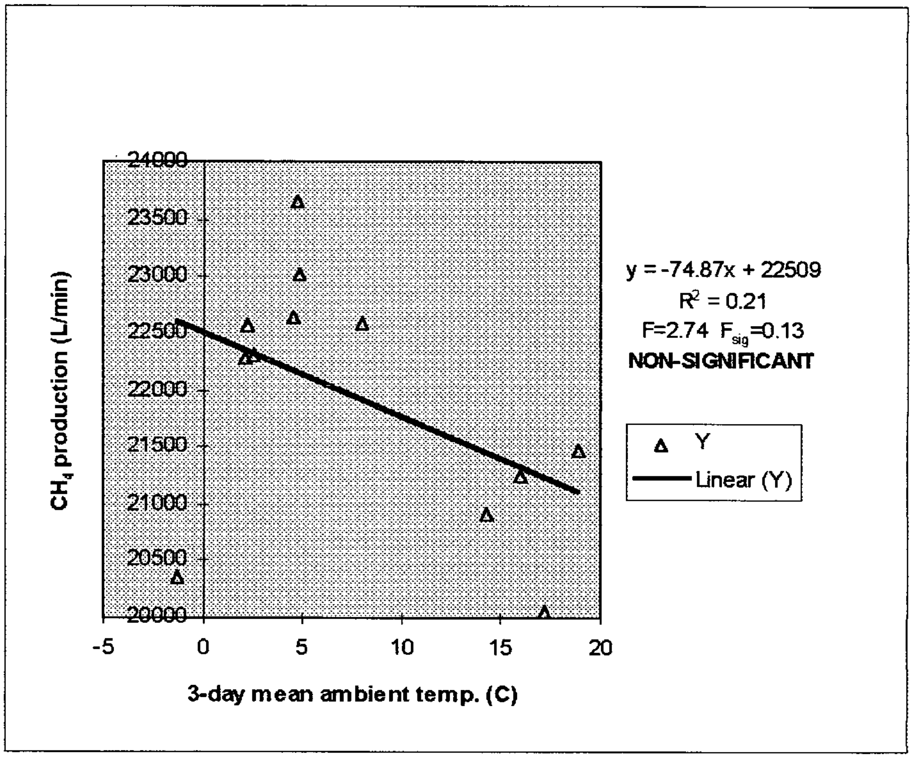

FIGURE C-8.4: Total CH_4 production in response to 3-day mean ambient temperature - G-LINE