AMMONIA GAS DYNAMICS IN FOUR

VANCOUVER AREA LANDFILLS

By

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ABSTRACT

A nine month field and laboratory study was undertaken to measure, predict and model the variation of detected ammonia concentrations in landfill gas. An additional side study attempted to characterize organic trace contaminants found in landfill gas.

The field project consisted of biweekly sampling of gas extraction wells from four Vancouver-area landfills for the analysis of NH_3-N in the gas and leachate. Methane and other common landfill gases were also analyzed. The wet chemical boric-acid sampling technique used in this study was estimated to have a ammonia gas recovery efficiency of 50 %. Other than a low recovery efficiency, problems encountered with this sampling technique was the high humidity and negative interferences inherent in the landfill gas. Laboratory analysis of the collected NH_3-N gas samples was by the automated phenate method, which could detect NH3-N gas concentrations greater than 10 ppb.

The NH_3-N concentrations in gas were found to exceed 600 ppb, but were more commonly in the 50 to 200 ppb range. In the statistical and graphical analysis, gas temperature and precipitation were found to correlate the most to the variation in ammonia gas concentration, while leachate ionic strength correlated strongest with most CH_4 % analysis. Prediction of both NH_3-N gas and CH_4 % by regression analysis was found to be suspect due to low R^2 values and non-normality of some data.

Four different Henry's Law constants of ammonia gas were

evaluated to help predict the concentration of NH_3-N in the gas phase. The combination of already measured NH_3-N leachate concentrations and Henry's Law constants yielded results that over and underpredicted measured NH_3-N gas data by 2000 fold or more. This leads the author to believe Henry's Law may not be applicable in a landfill environment due to non-equilibrium conditions coupling with various other reaction mechanisms.

Comparison of landfill ammonia gas flux rates with total ammonia leachate flux rates in two of the four landfills yielded an insignificant gas flux rate of less than 0.03 % of the total leachate NH_3-N fluxes. The NH_3-N gas flux results were calculated from a spreadsheet emission model employing both convection and diffusion flow through the landfill cover. A comparison of the emission model results for the 20 ha Richmond landfill study area (3.862 kg/yr) compared favorably to the mass flux results determined from a simple gas generation mass balance model.

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CHAPTER 1

1.   INTRODUCTION

1.1.   BACKGROUND

Most landfill gas research has concentrated on studying the dynamics and movement of methane gas. Studies of this nature have mostly focused at a lysimeter-scale. Recently, a portion of this research has shifted into the field sampling actual landfill gas, mainly for the purpose of quantifying and characterizing the trace gas components; primarily the organic contaminant fraction. This study does characterize volatile organic contaminants in samples, but concentrates mainly on the analysis of an inorganic component, namely ammonia gas.

Very few investigations have documented a release of ammonia gas from landfills. Authors such as Tanasci (1982) and Farquhar and Rovers (1973) mention ammonia as a trace component in landfill gas, but present no quantitative measurement to substantiate their claim. Ham (1979) reported a concentration of 0.71 ppb of NH_3-N in the landfill gas condensate, but does not mention the analytical technique used to determine this concentration. The most promising study was by Winter (1979) who reported concentrations of 0 to 350 ppb in landfill gas. Unfortunately, Winter's report does not mention the analytical technique used.

Al-Omar et al. (1985) reported that atmospheric mean and maximum NH_3-N levels of 13 ppb to 174 ppb were measured around an open dump site in Baghdad, Iraq. Ham (1979) mentions that the

BKK co-disposal site in West Covina, CA has considered construction of an ammonia synthesis plant in-line with their planned landfill gas collection system.

While there have been numerous studies done on estimating the mass flux of NH_3-N from landfill leachate (Cameron, 1979, Atwater, 1980 and Jasper and Atwater, 1985), to this author's knowledge, there have been no previous attempts to estimate the mass flux of ammonia lost through the gas phase. This loss could conceivably be significant if the proper chemical conditions favoring ammonia volatilization (ie, high pH, high temp, high NH_3-N in leachate) were appparent in the landfill. In a recent paper (Baccini et al., 1987), Swiss researchers have estimated element mass fluxes from both the landfill leachate and gas in an attempt to correlate these element fluxes to relative landfill age. While Baccini et al. presents an estimation for leachate nitrogen flux, he fails to estimate the nitrogen flux lost through the gas phase via ammonia volatilization.

1.2. OBJECTIVES OF STUDY

This study was undertaken to improve the data base concerning trace components in landfill gas and to determine whether the ammonia gas flux constitutes a substantial percentage of nitrogen flux through a landfill. Including the above, the objectives of this study are listed below:

A. To develop a simple, fast and reliable analytical technique to measure the concentration of NH_3-N in landfill gas.

B. Investigate the factors that could affect the temporal

variation of NH_3-N and methane concentrations in landfill gas.

C. Develop a statistical model to help predict NH_3-N concentration and methane percent from collected data.

D. Determine whether one can apply documented values of Henrys Law constants to predict NH_3-N gas concentrations given a known NH_3-N concentration in the leachate.

E. Determine if NH_3-N mass flux in the landfill gas is a substantial flux component when compared to known mass fluxes of NH3-N in leachate.

F. Determine qualitatively the types of organic contaminants that exist in the landfill gas.

1.3. SCOPE OF INVESTIGATION

To satisfy the above objectives, a nine month field and laboratory project was undertaken beginning in July, 1987 and finishing in early April of 1988. The length of the study period was governed by one; the attempt to monitor the landfill environment during a full seasonal change and two; to gather enough data to get 15 sample periods from each landfill. The number of sample periods was considered optimal for doing the statistical and modelling study discussed later in the thesis.

The field study consisted of sampling gas extraction wells for leachate and gas at four Vancouver-area landfills. The samples were taken bi-weekly from each landfill. Other data taken during field sampling included: water levels, static gas flow, air, gas and leachate temperature, pH of the leachate, and barometric pressure. The trace organic contaminant fraction of

the landfill gas was sampled by Tenax GC traps during three sample dates. The four landfills studied were Matsqui, Stride Avenue, Richmond and Premier Street. The reasons these four landfills were selected are stated below:

A. Landfills were completed and accessible by automobile.

B. Landfills had accessible gas collection wells for leachate and gas sampling.

C. Collection wells had individual shut-off valves to isolate from any on-going system vacuum while sampling.

D. Landfills had a variety of cover material.

E. Landfills had a varied age and construction history.

The laboratory study consisted of analyzing the gas and leachate values for CH_4, CO_2, N_2, O_2 percentages, NH_3-N in the gas, NH_3-N and specific conductivity in the leachate. Also, analysis of the non-metal constituents from each leachate-containing sample well was done twice during the study. The leachate was analyzed for alkalinity, COD, total and organic carbon, total volatile acids, and total and volatile solids. The ammonia gas samples were analyzed by the automated phenate method. After sampling, the trapped landfill gas organic contaminants were analyzed by a GC/MS.

The collected data was analyzed in three different steps beginning with the graphical and statistical analysis. In the statistical analysis, collected data was checked for normal distribution and further analyzed by product-moment correlation, and bivariate and multiple regression. This was done in an

attempt to explain or predict the temporal and spatial variation of NH_3-N and CH_4 in landfill gas. The second step attempted to compare four different ammonia gas Henry's Law constants for their potential to be used as a predictive tool for NH_3-N gas when the NH_3-N leachate concentration is known. The last step was to estimate landfill NH3-N mass fluxes from the gaseous phase through a simple emission model and compare these estimations with documented estimations of NH_3-N mass fluxes in landfill leachate. This analysis was attempted to observe if any substantial proportion of NH_3-N was being lost in the gas phase relative to the mass lost in the leachate.

1.4. SCOPE OF CONTENTS

1.4.1. LITERATURE REVIEW

A large literature review was undertaken in this thesis because of the breadth of topics that had to be addressed concerning landfill gas and ammonia movement in landfills.

The literature review first describes some basic characteristics in landfill leachate and gas. The review then proceeds into a detailed discussion of the biological and physical factors affecting decomposition and resultant landfill gas production. Technological aspects of gas recovery systems are then briefly presented.

The final portion of the literature review focuses primarily on discussing the properties, sources, sinks and mass transfer of ammonia within the landfill environment.

1.4.2. SITE DESCRIPTION AND HISTORY

Presented in this chapter are descriptions of the landfill location, and the physical and historical aspects of each one. A section is devoted to describing each of the landfill's gas extraction system and why certain wells were chosen to sample.

1.4.3. METHODOLOGY

In detail, the field, laboratory and statistical methods used in the study are discussed in this chapter.

1.4.4. DISCUSSION OF RESULTS

Beginning this chapter, is a discussion of the data from the analysis of the NH_3-N gas analytical technique. Included are the results from determining interferences, detection limit, recovery efficiency and lastly, an evaluation of the practicality of this technique.

Following the analytical discussion is a graphical and statistical presentation of all data with the emphasis on how various parameters control NH_3-N and CH_4 gas concentrations in landfills. Immediately following the above is a brief section presenting the results of the organic trace study on the sampled landfill gas.

Following the trace organic results, are discussions about the last two study objectives; comparison of Henry's Constants and estimation of NH_3-N gas fluxes.

1.4.5. CONCLUSIONS AND RECOMMENDATIONS

1.4.6. REFERENCES

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CHAPTER 2

2. BACKGROUND AND LITERATURE REVIEW

2.1. LANDFILL CHARACTERISTICS

2.1.1. LEACHATE PRODUCTION

The majority of landfill leachate is generated after the moisture holding capacity (field capacity) of the refuse is exceeded. This usually happens during precipitation infiltration. Field capacity of refuse has been studied in lysimeters and has units of either % moisture content (Metry, 1980 found 40 %) or amount of precipitation one has to apply at the surface to reach field capacity in a given depth of refuse material. Qasim and Burchinal (1970) found that about 13.5 cm of water could be placed per meter depth of refuse above the refuse's existing moisture content. Landfill leachate is also produced from groundwater intrusion, water from microbial decomposition and application of liquid waste materials like chemical, sewage or septic sludges.

Factors that affect landfill leachate production include following: precipitation, mean annual temperature, evapotranspiration, runoff, landfill cap material (e.g. porosity, permeability, field capacity), refuse density, initial moisture content in refuse, and depth of landfill (Leckie, 1979).

2.1.2. LANDFILL GAS PRODUCTION

2.1.2.1. DECOMPOSITION OF REFUSE

Once solid wastes are placed in landfills, aerobic biological activity immediately begins to degrade the organic

waste fraction. This aerobic phase results in accelerated waste consolidation, high internal temperatures and produces large volumes of carbon dioxide gas and degraded residual organics (Ham et. al. 1979). This CO_2 gas "bloom" was first referred by Engineering-Science (1961) and can reach up to 90 % volume in this initial phase.

This aerobic phase lasts for a short period of time as an oxygen deficit builds up creating semi-anaerobic conditions; conditions which facultative anaerobes can then begin to metabolize and grow.

The dominant anaerobic phase begins shortly thereafter when a fauna of obligate anaerobes reach large numbers within the refuse. This longstanding anaerobic phase is characterized by Lawrence and McCarty (1964) as involving three phases of biological activity from two physiologically different bacterial populations (Toerien and Huttingh, 1969). The three stages are hydrolysis, acid formation, and methane formation.

The first bacterial population is referred to as the non-methanogenic organisms and are responsible for the first two stages of hydrolysis and acid formation. These anaerobes hydrolyze and metabolize the organic refuse substrate of carbohydrates, fats, proteins and cellulose by their own enzymes into end-products of mainly saturated fatty acids with lesser amounts of carbon dioxide, ammonia, alcohols and ketones (Toerien and Huttingh, 1969). Songonuga (1969) identified the main endproduct acids to be acetic, propionic, butyric, valeric and

caproic when sampling refuse after 2 years of emplacement. The dissociated forms of these acids could account for approximately 75 % of the anions found in a given leachate (Songonuga, 1969). Bacillus and more likely Clostridia sp. appear to be the dominant non-methanogen fauna (Thompson, 1969).

As these hydrolyzers continue to solubilize salts and organic material, the alkalinity increases enough to where methanogens can slowly assert themselves. The bacteria active in this stage are generally considered to be from the genus Methanobacterium, which require strict anaerobic conditions and a redox potential (Eh) of less than -200 mV (Farquahar and Rovers, 1973). These methanogens obtain energy for growth from two reactions. The first is methane formed by an eight-electron reduction of CO_2 by H_2 gas, which produces ample energy for growth as indicated by a negative standard free energy change of -136 kJ/mol (Large, 1982). The second reaction involves the cleavage of acetic acid (CH_3COOH) into CH_4 and CO_2 by acetate decarboxylation (Farquhar and Rovers, 1973). The two reactions are shown below:

$$CO2\ Reduction \quad CO_2 + 4H_2 \longrightarrow CH_4 + 2H_2O$$

$$Acetate\ Decarboxylation \quad 2CH_3COOH \longrightarrow 2CH_4 + 2CO_2$$
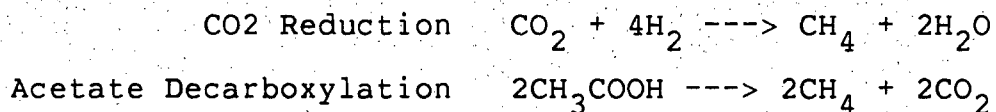
From studying results on anaerobic digestion of sewage sludge, Zehnder (1978) concludes that about 70 % of the methane produced originates from acetate decarboxylation while the other 30 % is derived from CO_2 reduction (from Schumacher, 1983).

2.1.2.2. TEMPORAL STAGES IN GAS PRODUCTION

Farquhar and Rovers (1973) designed a graphical presentation of their four stages in gas production. This is shown in Figure 2.1 where gas composition is a function of time after refuse emplacement. This conceptual gas production model assumes that an anaerobic environment could be achieved and maintained after refuse emplacement. The four phases identified were: I Aerobic; II Anaerobic Non-Methanogenic; III Anaerobic Methanogenic Unsteady; IV Anaerobic Methanogenic Steady.

FIGURE 2.1 - Landfill Gas Percentages as a Function of Time

(Figure modified from Farquahar and Rovers, 1973)
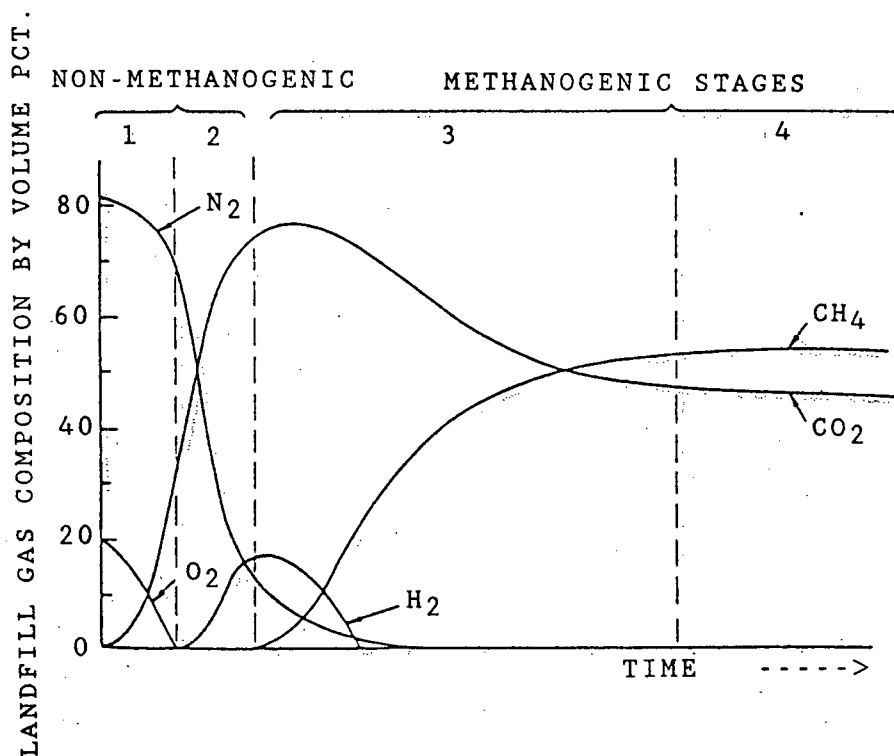
Completion time for phases I,II and III varies from as little as 180 days (Ramaswamy, 1970) to 500 days (Beluche, 1968).

In the steady state phase IV, landfill gas concentrations are generally around 55 % CH_4, 40 % CO_2, with the rest being N_2, O_2, H_2, Argon, Ammonia and other trace gases made up mostly of hydrocarbons.

2.1.3. FACTORS AFFECTING DECOMPOSITION AND GAS PRODUCTION

2.1.3.1. REFUSE COMPOSITION

Composition of refuse will affect the landfill decomposition rate, relative percentages of CH_4 and CO_2, and methane production rates. There are large variations in refuse composition as a function of geography and lifestyle. Table 2.1 presents some common refuse compositions from mostly around North America. The most readily degradable portion of refuse are the sum of putrescibles (Food + Garden Wastes), paper, cloth, and fines which in Table 2.1, generally account for 70 - 75 % wet weight of the refuse fraction.

TABLE 2.1 - Spatial Differences in Refuse Compositions

ITEM	Haifa Israel Raveh (1979)	Sonoma Calif. Leckie (1979)	Pennsyl- vania Remson (1968)	Waterloo Ontario Rovers (1973)	Northham. England Rees (1980)	U.S. Average Smith (1975)	Davis Calif. Tchobanag (1977)	West Laf. Indiana Bell (1963)	Vanc. B.C. Bird & H. (1978)	Cincinat. Ohio Pfeffer (1974)
PUTRESCIBLES	54.7	21.1	15.0	34.9	24.8	28.8	23.8	24.0	25.0	25.0
PLASTICS	4.4	4.6	3.8	3.2	4.8	6.5	2.6	2.1	2.2	2.0
PAPER AND CLOTH	30.6	42.3	59.4	41.4	38.7	39.4	50.5	42.9	38.9	49.0
WOOD	3.2	1.0	4.2	1.1	--	3.7	3.5	2.4	14.9	2.0
METALS	3.1	9.0	7.5	7.1	6.9	10.1	11.0	8.0	8.2	8.0
GLASS	3.0	10.9	8.5	12.1	8.2	10.0	7.5	6.0	7.2	6.0
FINES	--	8.3	1.7	0.2	12.3	--	--	1.0	--	6.0
INORGANIC	--	2.8	0.9	--	--	1.5	1.1	3.1	--	2.0
UNCLASSIFIED	--	--	--	--	4.3	--	--	0.5	3.6	--

Note: PUTRESCIBLES include food and garden waste

* Inert was considered UNCLASSIFIED waste items

In the future, as more plastics are produced, there will be a lesser proportion of readily degradable refuse available to the bacteria. Theoretical production of CH_4 and CO_2 gas can be estimated from an elemental analysis performed on the refuse. This is done by either calculating the volume production of gas per mass of component (e.g. carbohydrates, fats, proteins, etc.) (See Emcon Assoc., 1980), or by estimating a volume or molar percentage of gas from a given empirical formula. Some empirical formulas found or calculated from the literature are presented in Table 2.2. Inspection of this table shows a fairly constant ratio between H and C, which is in contrast to the ratio of these two elements and nitrogen. This wide range of stochiometric ratios is a resultant of the wide variation in the refuse composition reported by these authors. This difference could have a profound effect on how much ammonia will exist in the landfill leachate and gas phase.

TABLE 2.2 - Refuse Empirical Formulas Obtained From the Literature.

===

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) after Bell (1963)	$C_{84} H_{120} O_{53} N_1$
Emcon Assoc. (1980)	$C_{99} H_{149} O_{59} N_1$

===

Estimating the volume percentages of gas can be done by subjecting an empirical waste formula ($C_n H_a O_b N_c$) to complete

anaerobic degradation of end-products of CH_4, CO_2, cell material, ammonia and bicarbonate alkalinity (Emcon Assoc., 1980). This reaction is shown below:

$$C_nH_aO_bN_c + (2n + c - b - 9sd/20 - de/4)H_2O =$$

$$(de/8)CH_4 + (n - c - sd/5 - de/8)CO_2 + (sd/20)C_5H_7O_2N$$

$$+ (c - sd/20)NH_4+ + (c - sd/20)HCO_3-$$
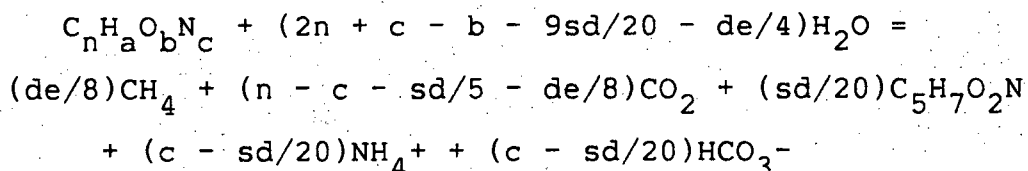
Where d = 4n + a - 2b - 3c
s = the fraction of COD synthesized or
   coverted to cells (= 0.04)
e = the fraction of COD synthesized or
   converted to CH_4 (1 - s)

2.1.3.2. NUTRIENT AVAILABILITY

Somewhat related to refuse composition is the availability of nutrients for biological uptake. Nutrients important for landfill microbe growth include: ammonia nitrogen, soluble phosphate, organic nitrogen, potassium, sulfate and various trace elements. Ramaswamy (1969), concluded in his investigation that the maximum gas production occurred in refuse where N, P and K were 1.86, 0.31, 0.23 percent respectively. The N value is close to the value of 1.70 % reported by Alexander (1931) for maximum decomposition of organic material in soils.

A common measure used to explain nutrient availability, is the C:N ratio of the refuse. Using data from anaerobic digestors, Sanders and Bloodgood (1965) found C:N ratios for optimal methane production of around 16:1. However, from data presented in landfill studies, this C:N ratio for optimal methane production is much higher. One reason landfill bacteria might tolerate this higher ratio could stem from genetic adaptation.

Dobson (1964), found variations of C:N from 34:1 to 104:1 in samples from the Fairmont, West Virginia landfill (Thompson, 1969).

Clement (1981) concludes that a commonly found ratio of COD:N:P of 100:0.44:0.08 for optimal gas production is not satisfied in landfills for soluble P and concludes that lower rates of degradation will probably occur. In contast, Rees (1980) demonstrates through a mass-balance approach that N and P are present in access and do not limit the growth of landfill microbes, even with C:N ratios in excess of 50:1. Rees (1980) concludes that if an N or P limitation exists, there would be near zero concentrations of ammonia and P in landfill leachate, which is not common in most landfill leachates.

Even though sulfate has been demonstrated to be an essential element, if present in excess amounts, it can have an inhibitory effect on methane production. This is due to; one, sulfate reducers outcompeting methanogens for H_2 gas; two, production of sulfides which can cause toxicity to methanogens (Jones, 1983 and Rees, 1980). While they can be toxic to methanogens, sulfides can also have a positive effect by precipitating out certain toxic metals. High salt concentrations have been reported to inhibit methane production, such as the addition of 2000 mg/L of calcium ions (Crawford and Smith, 1985). Failure of anaerobic digestors have been shown to occur with very high amounts 2000 mg/L of ammonia-nitrogen (McCarty, 1966).

The role that hazardous wastes plays as possible inhibitory

or nutrient sources is unclear in co-disposal landfills and is an area that needs to be studied.

Ways to increase landfill nutrient availability include addition of sewage or septic sludge, anaerobic digester supernatant, animal and agricultural wastes, and lastly, leachate recirculation (Schumacher, 1983).

2.1.3.3. REFUSE EMPLACEMENT

Method of cell construction during landfilling could have a major impact on gas and leachate production. The amount of precompaction from landfill equipment (i.e. bulldozers, compactors) will have a drastic effect of emplaced refuse density. Usually, landfill operators attempt to achieve a emplacement density of 590 kg/m^3 (1000 lbs/yd^3) (Tchobanaglous, 1977). The greater the density by preconsolidation, the greater the total mass per unit volume will be, which should enhance total gas yields (Schumacher, 1983). However, this increased density could hamper moisture and nutrient transport to active biological areas. This has an effect of producing gas at lower rates over larger periods (Crawford and Smith, 1985).

2.1.3.4. REFUSE PARTICLE SIZE

A reduction in particle size will expose a greater surface area for microbial degradation. The shredding of refuse creates a pseudo-homogeneous mass of refuse that alters its density as well. Shredding will also increase microbial activity, and mass transfer of nutrients. DeWalle and Chian (1979) showed that decreasing the mean diameter of solid waste from 250 mm to 25 mm

increased the gas production rate (mainly CO_2) from 0.73

m^3/tonnes-yr to 4.75 m^3/tonnes-yr (Rees, 1980). Grinding can

also introduce a lot of trapped air into the system. The

decrease in diameter also increases the strength of leachate by

first, increasing the amount of leached organic carbon during

the first year and secondly, extending this amount of leaching

for a longer period of time (Raveh and Avnimelech, 1979).

2.1.3.5. HYDROGEOLOGY OF LANDFILL AREA

The effects of an encroaching water table within landfills

can inhibit gas production by washing out viable methanogens or

diluting the soluble substrate available to methanogens.

Encroaching water tables have also been observed to have a

stimulatory effect on unsaturated zone gas production because of

added moisture (Hughes, et. al., 1971).

2.1.3.6. LANDFILL AGE

It is generally thought that once the landfill reaches a

certain age, decomposition of easily degradable substrate

disappears, leaving only slightly degradable humic and fulvic

acids, soluble salts and refractory compounds. This

"inactivation age" signals a large drop in methane production.

The "inactivation age" depends on refuse depth, climate, and

refuse composition.

2.1.3.7. GAS RECOVERY SYSTEM

If a landfill is equipped with gas extraction wells

(discussed in more detail later), the potential for lower CH_4

production is certain when O_2 is introduced into the landfill

through air intrusion. Also, O_2 can stimulate aerobic activity in the upper lifts, causing accelerated decomposition and differential landfill settlement. A proper landfill cover coupled with an efficient well collection system should decrease the probability of air intrusion.

2.1.3.8. OXIDATION-REDUCTION POTENTIAL

Both Clement (1981) and Farquhar and Rovers (1973) mention that for efficient methane generation the ORP (Eh) must be less than -200 mV. Chian et. al. (1985) mentions that the highest concentration of methane gas in their lysimeters occurred when the ORP dropped below -200 mV. Zehnder (1978) states an even lower ORP value of -330 mV for initiation of methanogen growth.

Not many studies have attempted to measure the effects of changing ORP in landfills. This is mainly due to equipment failure or large analytical uncertainties within the collected data. Farquhar and Rovers (1973) experienced equipment difficulties which resulted in no ORP measurements made at their Ontario landfill study site. Also, Zehnder (1978) mentions that it is almost impossible to concur an effective redox potential in a complex solution like digestor sludge (or landfill leachate), because several different uncoupled redox levels frequently occur in the same environment.

Lastly, studies show that an increase in Eh decreases methane production. This increase in ORP could be due to encroachment from an oxidizing groundwater source or more likely, from infiltrating rain water.

2.1.3.9. MOISTURE CONTENT

When raw refuse is placed in the landfill, it has an inherent moisture content that will aid in the initial decomposition process. This moisture content is around 25 % (wet wt.) and will be greater with larger waste fractions of putrescibles (Emcon Assoc., 1980). Mandeville (1979) adds that without a minimum moisture content of 25 % wet wt., the anaerobic phase is virtually non-existent or occurs at very slow rates (Clement, 1981). Concurring with this was the study of Merz and Stone (1969), who found that refuse placed at a moisture content ranging from 30 to 40 % wet wt. developed an initial CO_2 bloom after which gas production ceased until additional moisture was added.

Dobson (1964) reported that the maximum decompostion rate in refuse took place at approximately 56 % moisture (wet wt.) (Thompson, 1969). Both Ramaswamy (1970) and Songonunga (1970) got higher values of 60 to 80 % moisture content for maximum decomposition. These values agree with Alexander (1961), who reported that the maximum rate of decomposition of organic matter in soils lies in the range of 40 to 80 %.

Many researchers claim moisture content is the most important parameter for optimizing gas production. However, this is not always the case when excessive infiltration occurs. Rovers and Farquhar (1972) noticed CH_4 concentration decrease from 19 to 4 % when large volumes of water infiltrated their field test cells after snowmelt. They observed increases in COD,

BOD and TDS while observing decreases in refuse temp., alkalinity and pH. Excessive infiltration can also wash out viable bacterial cells, increase the ORP (Eh), and solubilize inhibitory metals and salts.

Techniques to increase moisture input into landfills include the following: recirculation of leachate, addition of waste liquids (sewage sludge, chemical sludge), increasing the permeability of the cover, or construction on the landfill surface of runoff catch basins. Ways to decrease moisture input, include constructing a low permeability cover, or design of a landfill that maximizes runoff.

2.1.3.10. TEMPERATURE

Most laboratory studies have shown that the optimal temperature for anaerobic decomposition and methane production is around $30 - 37^{\circ}C$ (Dobson, 1964, Ramaswamy, 1970 , Kotze et. al. 1969). At the Aveley, U.K. landfill, temperatures of $43^{\circ}C$ appear to be very favorable for gas production (Rees, 1980). During summer conditions this temperature first appears at 3 m below the surface and extends through the water at 7.5 m deep (Jones et. al., 1983). Hartz (1982) found a similar temperature of $41^{\circ}C$ for optimal CH_4 production in laboratory heated samples of refuse.

Most landfills do not approach the 30 to $35^{\circ}C$ temperature on an annual basis. Robinson and Lucas (1985) noticed a variation in temp. from 18 to $35^{\circ}C$ in buried refuse 20 meters deep. Farquahar and Rovers (1973) found the average annual temperature at a refuse depth of 1.25 m to be $12^{\circ}C$ with

seasonal fluctuations from 2 to 21°C. An excellent example of how refuse depth and air temperature affect refuse temperature is found in the study of shallow test cells constructed in Sonoma County, CA (Leckie, Pacey and Halvadakis, 1979). This temperature profile indicates a high initial temperature (aerobic decomp.) followed by lower seasonal variations in temperature that mirror the variation in ambient air temperature. A comparison of temperature changes with percent methane was unfortunately not done in this study.

McBean and Farquhar (1979) did compare variations in percent CH_4 with variations of both temp. and precipitation through linear regression. However, their attempt to correlate these parameters were inconclusive. One possible reason behind the non-correlation of % CH_4 and landfill temp. could stem from their (the methanogens) immediate adaptation to lower seasonal temperatures.

One disadvantage for cold-climate landfills (such as Ontario landfills) is the impedence of necessary moisture flow caused by seasonal freezing of the landfill surface. This moisture flow is needed for maximum gas production in landfills that have not reached field capacity.

2.1.3.11 <u>ALKALINITY AND pH</u>

Optimal pH values found in anaerobic digestion range from around 6.4 to 7.4 with digestor performance collapsing at pH below 6.0 (Kotze et. al., 1969). Rhyne and James (1978) conclude that methane production ceases in a landfill when the average pH

drops below 6.2 (Schumacher, 1983). However, because of microenvironments and bacterial adaptability, methane production can occur at pH's less than 6.0. After refuse emplacement, there generally is a gradual increase in pH to an optimal limit. Originally, the pH could be as low as 5.0 due to production of fatty acids and CO_2. As more substrate is mineralized and CO_2 is coverted to HCO_3^-, the buffering capacity to resist changes in pH is established. As the alkalinity increases, so does the pH to a point where methanogens can produce CH_4. The influx of methanogenic activity will consume more organic acids while raising the pH even further. This relationship between methane formers and volatile fatty acid production reaches a pseudo-steady state in mature landfills (Stage IV).

For optimum methane gas production the bicarbonate alkalinity should be greater than 2000 mg/L as $CaCO_3$ (Kotze et. al., 1969).

Zehnder (1978) believes that the carbonate buffering system is the only important system controlling pH for methane production. However, a few other researchers believe otherwise (DeWalle, 1980 and Pfeffer, 1974).

DeWalle concludes that ammonia can act as a pH buffer, especially in landfills where low values of TIC (Total Inorganic Carbon) (less than 50 mg/L) can exist. Ammonia counteracts this drop in pH by consumption of H^+ in the below reaction:

$$H^+ + Ac^- + NH_3 = NH_4^+ + Ac-$$
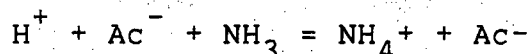
Pfeffer believes that high concentrations of certain organic

acids and acid salts can contribute to the total system
alkalinity. Pfeffer explains this by using McCarty's (1964)
equation for total alkalinity in digestors. This equation is
shown below:

$$TA = BA + (0.85) * 0.833(TVA)$$

Where TA = Total Alk. (mg/L as $CaCO_3$)
        BA = Total Bicarbonate Alk. (mg/L as $CaCO_3$)
        TVA = Total Volatile Acids (mg/L as Acetic Acid)
        0.833 is a conversion factor to mg/L as $CaCO_3$
        0.85 accounts for fact that only 85 % of volatile acid
            alkalinity is measured by titration to pH 4.

   Note: This equation assumes no other buffering systems
         exist.

In summary, pH values found in sanitary landfills may be
influenced by industrial waste discharges, alkalinity, rain water
infiltration, or the relative production of organic acids and
methane (Boyle, 1976).

Some of the eleven factors controlling gas production and
their interrelationships are summarized in Figure 2.3.

FIGURE 2.3 - Summary of Factors Affecting Gas Production

(Figure modified from Farquhar and Rovers, 1973)
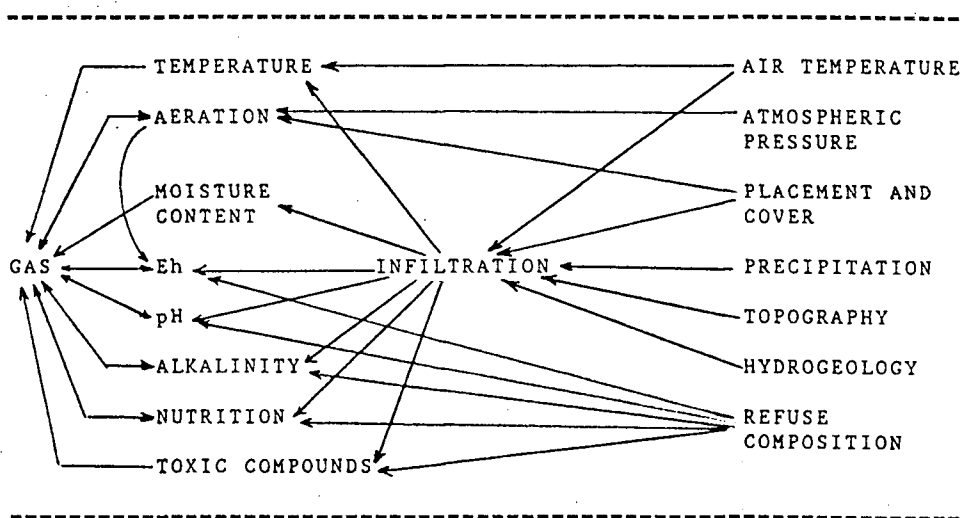
2.2. REVIEW OF FIELD STUDIES

In contrast to numerous lab or lysimeter-scale studies, on leachate and gas production, there have been much fewer studies attempted in a full-scale landfills. Some of these field projects are worth mentioning since they involve similar field techniques to this study. The projects are listed below in chronological order.

To this author's knowledge, the earliest such study was undertaken by the New York City Department of Sanitation around the mid-1930's. Their main goal was to determine how fast refuse decomposed, and what were the microorganisms that mediate that process. They originally performed a compositional study on fresh refuse, then later sampled decomposed refuse for microorganisms, organic nitrogen, pH, percent moisture and temperature over a 48 month period. Gas samples were also taken. (See Carpenter, 1940 and Eliassen, 1942).

In the early to mid-1960's an in-situ investigation of movements of gas from decomposing refuse was undertaken in Los Angeles, CA. This project was headed by Engineering-Science, Inc. and concentrated mostly on the Azusa Landfill. The project finished in 1967. The study concentrated mainly on estimating upward and downward fluxes of CO_2 and CH_4 gases in the test fill. Gas barrier materials were tested in the lab for the purpose of attenuating the downward flux of CO_2 into the groundwater system. Later studies were done on test fills at the Palos Verdes and Calabasas landfills, again located in L.A. County (See

Engineering Science, Inc., 1967).

In 1970, Waterloo University undertook a study to identify the parameters that affect the production of landfill gas and leachate. Three cells of 1.2 m in diameter and 2.3 m deep were placed in the ground at a local Ontario landfill. Gas production was found to be slow during periods of no infiltration and impeded during spring snowmelt periods. As expected, leachate generation was greatest during this spring thaw period. (See Farquahar and Rovers, 1973 and Rovers and Farquhar, 1973).

In 1972, a similar study to the above was initiated in a Sonoma County, CA. landfill. Different moisture applications and cell construction were used in the five separate large-scale test cells. One of five cells had leachate recycle while another had application of septic tank pumpings. Variables monitored over a three year period include average consolidation, thermal responses, and leachate and gas production variability (See Leckie et al., 1979).

Around 1977, a group of English researchers began a thorough study of the Aveley (Essex) landfill in the U.K.. This project was attempting to determine what parameters affect landfill microbial activity (Rees, 1980). They developed a technique of estimating relative microbial activity by enzyme activity measurements taken within the landfill. Their results indicate a correlation of higher methane gas production in areas of greater enzyme activities at depth (Jones et al., 1983 and Grainger et al., 1984).

Technical University of Braunschweig, W. Germany initiated a program in early 1980 to study the effects that landfill operation has on gas and leachate production at the Lingren Sanitary landfill (See Stegmann and Spendlin, 1985).

Another English research group headed by Robinson (1985) began a study in 1982 at the Stangate East landfill in Kent, England. The main goal of this on-going study is to monitor (in-situ) the attenuation of landfill leachate in the unsaturated zone. Before and during refuse placement, over 100 instruments have been installed to measure thermal responses, gas concentration, and leachate concentration and salinity. To the author's knowledge, this is the most extensive in-situ landfill study ever undertaken.

The last landfill study worth mentioning deals with the BKK co-disposal landfill in West Covina, CA.. This landfill not only received MSW but also 2 billion U.S. gallons of liquid hazardous waste. Numerous earlier studies have concentrated on determining landfill surface emissions of hazardous volatiles (California Dept. of Health Services, 1983 and Baker and McKay, 1985), but a recent study (Stephens et al., 1986) looked at the partitioning of four hazardous volatiles between the leachate and gas stream.

2.3. OFFSITE GAS MIGRATION

Landfill gas can migrate from landfills by two mechanisms: convection due to pressure gradient, and diffusion due to a concentration gradient (Mohsen, 1980). The diffusive flow component consists of Knudsen flow, molecular flow and surface

flow (EPS, 1977). Because of landfill gas production, positive internal pressure heads of 2.5 to 5.0 cm of water can create a pressure gradient which causes the gas to flow convectively from higher to lower pressure (Crawford and Smith, 1985). Vertical migration of gas through the landfill cover is mainly controlled by diffusion. Factors affecting diffusion through landfill covers are summarized in Table 2.4.

Attempts to model the emissions of landfill gas through covered landfills (Findikakis and Leckie, 1979; Farmer, 1980; Shen, 1981; Thibodeaux et al., 1981) due to diffusion and convection are discussed in more detail later in this thesis.

TABLE 2.4 - Factors Affecting Diffusion Through a Landfill Cover

(Table modified from Baker and MacKay, 1985)

===
| FACTOR | EFFECT |
===

Soil porosity — High porosity allows more diffusion and emission. Porosity is the controlling parameter in the emission of vapors.

Atmospheric pressure fluctuations — Pumping action from pressure fluctuations enhance the measured diffusion rate of benzene through a soil layer by 13 %.

Temperature gradient between landfill bottom bottom and surface — Large gradients between a warm landfill interior and a cool surface enhance thermally-induced diffusion.

Temperature of cover — Warm gas can form condensate leaving the vapor absorbed in the cover, decreasing the effective diffusion rate.

Wind speed — Increased wind at the surface enhances the "wick effect," speeding diffusion.

Anaerobic Decomposition — This elevates internal landfill temperature and produces gases, primarily methane, which accelerate diffusion.

Chemical reactions — Exothermic reactions can increase thermal diffusion.

Thickness of soil landfill cover — Increased thickness increases diffusion time.

Infiltration of surface water and resultant soil moisture content. — Methane gas production is enhanced moisture input hence, accelerating diffusion. Rapid infiltration fills soil pores, slowing diffusion.

===

2.4. <u>GAS COLLECTION SYSTEMS</u>

Generally, gas collection systems are used for control of odors, offsite migration of landfill gas, and more importantly, for further utilization of landfill gas. They are important for this study because the collection wells are sampled for gas and leachate. Gandolla et al. (1982) divides a landfill gas recovery and utilization system into six possible steps. These steps are: collection, pretreatment, storage, combustion, energy storage and energy consumption. This author will mention only the first two in detail.

2.4.1. <u>COLLECTION</u>

The collection step is usually taken care of by collection wells but there are some alternative collection methods worth mentioning.

One method is through ground probes that are driven into the landfill and placed on a subsequent vacuum. At the Croglio landfill in Switzerland, steel-tipped, 5 cm diameter probes were driven 5 to 10 meters into the refuse and 40 to 60 m/day of methane was extracted in 2 months time from 10 probes in a 1000 sq. meter area (Gandolla et al., 1982). This recovery system is greatly affected by air intrusion and clogging, but has the advantages of a low installation cost and immmediate installment after landfill completion (Gandolla et al., 1982).

Another gas collection method is through coarse permeable corridors of gravel (3.5 to 7.5 cm minus) that can be used in configurations of blankets, trenches, slanted drains and mounds

(Schumacher, 1983). In every case, a perforated pipe system must be used to transport the gas. Most of these systems must be constructed during the filling phase of the landfill and have water drains to decrease the potential for seepage build-up. This system is relatively inexpensive but has problems with air intrusion and seepage build-up.

The preferred and most common collection system is by cased extraction wells. To optimize gas recovery, extraction well depth should equal 3/4 of the depth of waste (Shen, 1981). The wells can be drilled by a number of techniques such as a telescopic spindle, cable tool rig, down hole hammer, rotary drill, or with a hollow bore auger (Giuliani, 1980).

The most efficient and common method for drilling in refuse less than 25 meters in depth, is the truck mounted continuous flight hollow bore auger. Drilling problems encountered with hollow bore augers include: borehole cave-ins when drilling in poorly compacted refuse, and slow rates of penetration when drilling through houshold or construction debris (Emcon Assoc., 1980). A core barrel bit is often used for drilling in intervals containing any construction debris (Schumacher, 1983). Borehole diameters range from 15 cm (6 in.) to 90 cm (36 in.). Some deeper landfills in California have installed 90 meter deep wells that require the use of a crane mounted auger rig instead of a truck mounted rig (Giuliani, 1980).

Once the boreholes have been completed, the well casing is installed in the borehole and backfilled with soil or gravel.

Well casing is typically constructed of PVC, even though fiberglass, polyethylene, and steel have also been used (Emcon Assoc., 1980). Typical well casing diameters range from 7.5 cm to 15 cm. Well casing is typically sized according to the expected gas flow rate and the pressure loss within the well casing (Schumacher, 1983). The casing is typically telescoped at one point to create a slip joint that can accomadate up to 120 cm of landfill subsidence before casing breakage will occur (E.H. Hanson, 1985). Collection intervals are determined by the length of perforation in the well. Perforations are usually made in the field with a drill or saw or casing can be purchased already perforated from the manufacturer. The primary requirements for perforations are: one, that they remain unclogged, two, that they do not require excessive pressure losses to draw the gas through them, and three, that they do not unduly weaken the well casing (Emcon Assoc., 1980). Above the gravel-filled collection interval, an impermeable concrete or bentonite plug is installed (60 to 90 cm thick) to prevent air intrusion into the collection interval. Above this impermeable plug, soil is backfilled up to the well head assembly.

The well head assembly consists of one, a well head cap equipped with special connections for gas sampling and pressure readings, two, a PVC tee to route the gas into the collection header, three, a butterfly or gate valve that controls gas flow into the header, and four, the collection header itself. The collection header is normally Sch. 40 PVC pipe that takes the

extracted gas to a compressor for further distribution. Header pipe is sized much like well casing with pressure loss estimated through a commonly employed pipe friction equation (Emcon Assoc., 1980).

An example of a typical extraction well with well head assembly and collection header is displayed in Figure 2.4

2.4.2. PRETREATMENT

Because vapor saturated landfill gas typically leaves the landfill at elevated temperatures relative to atmospheric temperatures, condensate will form in the well head and collection headers, eventually causing operational problems. The simplest technique to control condensate build-up is through condensate drains that empty the condensate back into the refuse and away from the collection system. A general rule is to install a condensate trap for every 60 m of collection header (Schumacher, 1983). These drains are connected onto collection headers by a simple Tee at the lowest points in the header pipe to maximize drainage. Other ways to eliminate condensate from the gas stream include scrubbers, dehydrators, or lowering the dewpoint of the gas below the ambient collection line temperature (Emcon Assoc., 1980).

In upgrading landfill gas to pipeline quality, one usually has to separate the CO_2 and other impurities from the methane. A common absorbing solvent used for landfill gas is triethylamine, which the CO_2 can be later recovered by heating up the solvent (Gandolla et al., 1982). Other solvent treatment systems

CONTROL VALVE & BOX

COLLECTION HEADER

LOOSE INERT FILL STYRENE, SAWDUST OR PAPER

BENTONITE SEAL

SOLID PIPE

PEA GRAVEL

SLOTTED PIPE

TYPICAL BELOW GROUND
GAS COLLECTION ASSEMBLY
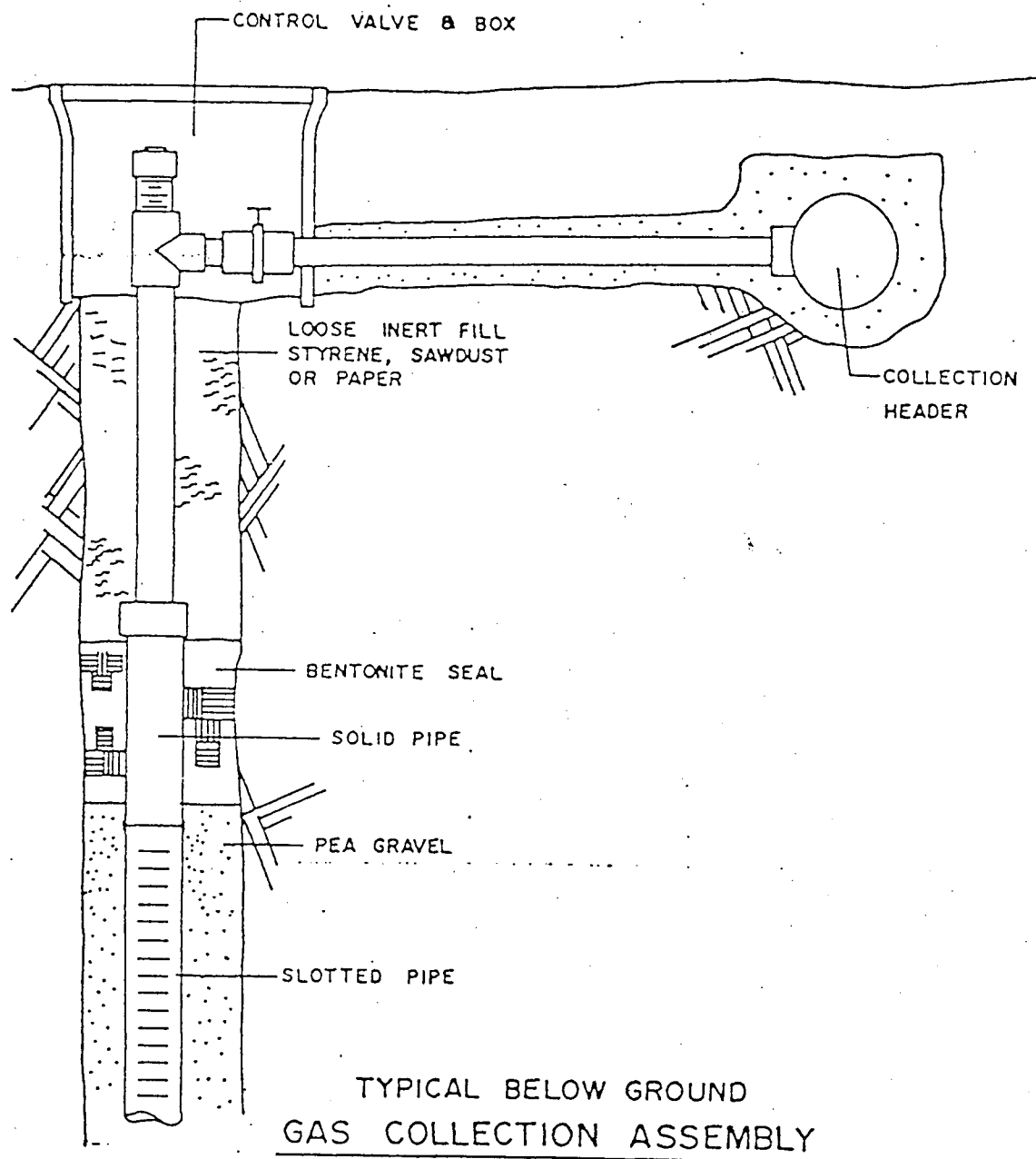
FIGURE 2.3 - Example of a Typical Extraction Well

(Reprinted with permission of
E.H. Hanson and Associates, 1986.)

recently in use include: diglycolamine, hot potassium carbonate, propylene carbonate, selexol, and fluor solvent (Emcon Assoc., 1980). Trace gases can also be removed by dry absorption systems such as the molecular sieve system at Palos Verdes landfill (see Bowerman, 1977), and activated carbon. All these systems are expensive and require very large landfills to be cost-effective.

2.4.3. GAS EXTRACTION PARAMETERS

The design and modelling of gas extraction systems require some parameters to be determined or estimated. Some of these are: extraction well spacing, gas extraction and production rates, refuse and cover permeability, and landfill gas velocity.

2.4.3.1. EXTRACTION WELL SPACING

Well spacing is a function of the radius of influence (RI), which is determined in the field during an extraction test. This test consists of installation of a piezometer or pressure probe network around the extraction well, which later are monitored for gauge pressure changes during pumping or recovery of the extraction well. These measured pressure responses are then used to determine the proper radius of influence of that extraction well. The basic assumption is that no gas is drawn to the extraction well from a distance greater than that wells RI.

Clement (1981) ran into difficulty determining an RI in his study because of faulty gauge pressure responses, improper pressure probe networking, and heterogenieties within the landfill study area.

The extraction tests to determine RI usually last from several hours to several days for each extraction rate. Typically, 2 to 4 extraction rates are used for each well and 2 to 4 wells are tested per landfill (Emcon Assoc., 1980).

After determining RI, the proper well spacing begins with spacing from the landfill perimeter inward with overlap of RI occurring to help control landfill gas migration (Schumacher, 1983). Once the outer well spacing is confirmed, inner wells are spaced ideally (given no constraints) at the vertices of equilateral triangles.

2.4.3.2. GAS EXTRACTION AND PRODUCTION RATES

To determine the optimal flow rates for a given well, one can use the following equation:

$$Q_w = (K * \pi * RI^2 * t * D * Gr) / C \qquad (i)$$

Where Q_w = optimal well flow rate (L/sec)
  K = Conversion Factor (1.157E-08 L/day/ml/sec)
  RI = Radius of influence (m)
  t = Refuse thickness (m)
  D = in-place refuse density (kg/m^3)
  Gr = methane production rate (mL/kg-day)
  C = Fractional methane concentration

The most difficult parameter to obtain in equation (i) is the methane gas production rate (Gr), that is dependent on a number of variables already in that equation. Generally, Gr is determined during the gas extraction tests that determine RI. In this determination, the well flow rate is varied until attainment of the maximum extraction rate which minimizes air intrusion occurs. This extraction rate is assumed to be equal to the rate at which methane is produced within the volume of refuse

defined by the wells RI. With this in mind, Gr can be determined by a modification to eqn. (i) below:

$$Gr = Qw \; / \; (\pi * RI^2 * t * D) \qquad (ii)$$

Where Qw = Optimal well flow rate (L/sec)

This equation assumes steady state conditions and a 100 % gas recovery efficiency, which is never true since gas production rates vary over an age of a landfill, and not all gas produced will be recovered. In fact, based on early experience in landfill gas recovery, Pacey (1976) estimated that only 10 to 50 percent of the theoretical gas produced will be extracted (Boyle, 1976). One way to increase recovery efficiency would be to increase the density of extraction wells.

In summary, gas production rates calculated by eqn (ii) from field tests in existing landfills range from 6.8 to 45.0 mL CH_4/kg of refuse per day (Emcon Assoc., 1980; Clement, 1981; and Schumacher, 1983). Determination of both the gas extraction and production rates are full of uncertainty and error. Emcon Assoc. (1980) suggests one way to make a more accurate determination of gas production rate would be through a more thorough theoretical mass balance (see Emcon Assoc., 1980). On the other hand, this author believes stochastic techniques available from the groundwater literature may be a better way to handle the uncertainty in landfill gas production rates.

2.4.3.3. <u>REFUSE PERMEABILITY</u>

The standard coefficient of permeability (K) depends on both the characteristics of the gas and porous media (refuse, cover or

surrounding soils). This coefficient can be expressed as:

$$K = (\gamma/\mu)*Ks \qquad (iii)$$

Where γ = specific wt. of the gas (kg/m^3)
μ = specific viscosity "" "" (N-sec/m^2)
Ks = intrinsic permeability of
refuse and/or cap material (Darcys)

Intrinsic permeability depends on upon the following

properties of the porous media: porosity, range and distribution

of grain sizes, and shapes, orientation and packing of the

grains.

The coefficient of permeability (K) determined by equation

(iii) in the Palos Verdes and Sheldon Arleta landfills range from

1.04 to 1.55 m/day. Clement (1981) employed field extraction

data to estimate the K at an Ontario landfill by the Cooper-Jacob

approximate method for confined unsteady flow. This method is

often used for determining K in groundwater investigations. His

six K values range from 0.88 to 4.82 m/day, which are within the

tolerance of the values obtained from from eqn. (iii).

2.4.3.4. GAS VELOCITY

Determining the gas velocity at which it enters the

extraction well is very important for determining whether flow is

laminar or turbulent, which in turn determines if darcian flow

can be assumed or not. If non-darcian flow exists, well

efficiency would unequivocally decrease.

Gas velocity into an extraction well is determined by the

equation (iv) that assumes the gas flows normal to an imaginary

cylindrical surface surrounding the well casing:

$$Vr = Qw/Area = Qw/(2\pi*r*h) \qquad (iv)$$

Where Vr = internal gas velocity (m/sec)
    Qw = well flow rate (m³/sec)
     r = radius of imag. cylinder (m)
     h = distance of collection interval (m)

Once Vr is determined from (iv), the flow description can then be found by using the dimensionless parameter, the Reynolds Number (Re). Re is found below:

$$Re = (\ell * Vr * D)/ \qquad\qquad (v)$$

Where ℓ = Density of gas mixture (kg/m³)
         D = Characteristic dimension of the system
             (Usually the mean grain diameter
             of the porous media)

If Re is less than 1.0 then flow is generally perceived to be laminar, and Darcy's flow equation applies. As a general rule, this seems to occur in landfills where flow rates are low enough to keep laminar flow. However, Emcon Assoc. (1980) cautions that if landfill grain sizes reach large sizes proportional to large gravel, turbulent flow may prevail, decreasing recovery efficiency in extraction wells.

2.5. AMMONIA GAS FROM LANDFILLS

2.5.1. PHYSICAL PROPERTIES OF AMMONIA GAS

Ammonia is a colorless gas under standard conditions, whose pungent odor is easily discernible above 50 ppm (NRC, 1979). The ammonia molecule has a pyramidal structure, with the nitrogen atom at the apex and hydrogen atoms at the base. The bond angles between the H-N-H have been observed to be $106°47'$ (NRC, 1979). Other physical properties of ammonia are listed in Table 2.4.

TABLE 2.4 - Physical Properties of Ammonia Gas

===
PROPERTY   VALUE   SOURCE
===
molecular weight   17.03 gm/gm-mole   API, 1981
melting point   -77.70 C degrees   API, 1981
boiling point   -33.35 C degrees   API, 1981
critical temp.   132.45 C degrees   NRC, 1979
critical press.   112.30 atmospheres   NRC, 1979
density (gas)   0.7714 kg/m^3 API, 1981
heat of vapor.   5,581 cal/mole   NRC, 1979
specific heat   8.523 cal/mole-degree   NRC, 1979
solubility *   89.9 gm NH3/100 gm H2O (0°C, 1 atm)
                68.4 gm NH3/100 gm H2O (10°C, 1 atm)
                51.8 gm NH3/100 gm H2O (20°C, 1 atm)
                40.8 gm NH3/100 gm H2O (30°C, 1 atm)
                33.8 gm NH3/100 gm H2O (40°C, 1 atm)

        * All solubility data is from Freney (1981)
===

2.5.2. SOURCES AND AMBIENT ATMOSPHERIC LEVELS OF NH3

2.5.2.1. NATURAL SOURCES

The NRC (1979) believes that over 99.5 % of atmospheric ammonia is produced by natural biological processes due to decomposition of organic waste material. This percentage contrasts with a Canadian study done by Geadah (1985) that estimates natural decomposition emissions account for 71.2 % of the total atmospheric emission of ammonia. Geadah (1985) lists the natural sources of ammonia emission to be: biological litter decomposition, animal waste, vegetation emissions, forest fires, and human breath. Ammonia released from soils due to decomposition can be estimated by Dawson's model (Geadah, 1985). Ammonia released from animal waste is mainly due to urea hydrolysis from the enzyme urease. Estimated production of ammonia by carnivores and herbivores is 186.3 and 16.42 gm of NH$_3$

per kg of animal weight per year (Geadah, 1985). This estimation assumes that 10 % of the generated urea produces volatilized ammonia. Because of this substantial amount, ambient NH_3 gas levels around dairy farms have been measured as high as 450 ppb (usual ambient level around 5 ppb) (NRC, 1979). Forest fires have been estimated to produce 0.15 kg of NH_3/tonne of dry wood during combustion (Geadah, 1985). Human breath has been found to emit 11.2 mg NH_3/day for non-smokers and 16.8 mg NH_3/day for smokers.

Geadah (1985) concludes in her 1980 study that microbial activity emits a 10-fold greater mass of NH_3 in tonnes/annum than the three other natural sources combined.

2.5.2.2. ANTHROPOGENIC SOURCES

Major anthropogenic sources of NH_3 include the following list by NRC (1979):

1. Combustion processes in urban areas, such as domestic heating, internal combustion engines, and municipal waste incineration.

2. Industrial sources, such as fertilizer plants, refineries, organic chemical process plants, and strip mining.

3. Miscellaneous sources, such as cattle feedlots, food processing plants, use of NH_3 in industrial and household cleaning, fertilizer application, and sewage treatment plants.

2.5.2.3 AMBIENT ATMOSPHERIC LEVELS

Ambient atmospheric concentrations of non-particulate ammonia in rural unpolluted areas has been measured by a number of researchers (Junge, 1963, NRC, 1979, Harward et. al., 1982, and Kelly et. al., 1984). Their reported mean NH_3-N values

range from 2.2 to 10.0 ppb. Non-particulate ammonia levels

measured in urban areas are much higher (max. 400 ppb) in most

cases, with marked maximums in the winter, owing to the increased

contribution from combustion sources.

2.5.2.4. ANALYTICAL TECHNIQUES

Some of the analytical techniques employed to measure these

low atmospheric levels of NH_3-N are listed below:

1. Bubbler techniques using acid solutions to absorb the
   NH_3, which is then analyzed by colorimetric-titrimetric
   methods. This method was used in this study on
   landfill gas.

2. Ring oven techniques using impregnated filter substrate
   for direct absorption of ammonia gas.

3. Photoacoustic detection of desorbed ammonia from a
   teflon bead sampler (see Harward, 1982).

4. Real time measurement using a calibrated fluorescence
   derivatization technique. Detection limit is about 0.3
   ppb (see Kelly et. al., 1984)

5. Recent developments in more sensitive, reliable and
   more expensive techniques such as Fourier-transform
   long-path infrared spectroscopy, second derivative
   spectroscopy, and the combination of gas
   chromatography and chemiluminescence (see NRC, 1979).

2.5.3. AMMONIA GENERATION IN LANDFILLS

2.5.3.1. SOURCES

The overwhelming majority of ammonia inherent to landfills

is produced from decomposition of proteins indigenous to the

bulk refuse. Other sources of NH_3 could be due to landfilling of

fertilizer products, ammonium salts, animal wastes, sewage or

chemical sludge, or from atmospheric input. Nucleic acid (RNA

and DNA) decomposition is another minor source of ammonia in

landfills.

Total nitrogen has been reported in bulk analysis of refuse to range from a low of 0.33 % weight (Bell, 1963) to a high of 3.0 % in Raveh and Avnimelech (1979). Most researchers (Thompson, 1969, Pfeffer, 1974, Tchobanagolous, 1977, and Rees, 1980) report values from 0.5 % to 1.25 % total nitrogen with 1.7 % required for maximum decompositon of organic matter (Alexander, 1961). Landfills that are deficient in nitrogen can benefit by the addition of sewage sludge, as percent nitrogen in these sludges has been reported to be on the average about 3.1 % (Hobson et. al., 1974).

2.5.3.2. PRODUCTION OF AMMONIA

The generation of ammonia from proteins is a biologically mediated procedure involving multiple steps of biological activity. These steps can basically be superimposed on the stages of methane production discussed in 2.1.2.2.. A simplified reaction for ammonia generation would be as follows:

$$Protein \xrightarrow[H_2O]{enzymes} Amino\ Acids \xrightarrow[H_2O]{} Fatty\ Acids + NH_3 + CO_2$$
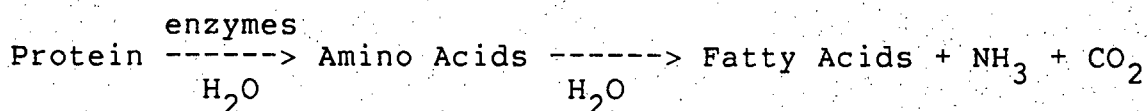
In the first reaction, protein is attacked by extracellular enzymes known as proteases that hydrolyze the peptide bonds between amino acids. This hydrolysis reaction releases free amino and carboxyl groups that can be further degraded by reaction 2. The major group of organisms responsible for reaction 1 are the proteolytic bacteria. Clostridium species were found to be the most prevalent proteolytic bacteria in anaerobic digestor studies performed by Siebert and Toerian

(1969).

Separation of the amino acids into carbon and nitrogen sources in reaction 2 is done a number of ways. Four common mechanisms are shown below using the amino acid Glycine ($CHNH_2COOH$) as example:

1. Hydrolytic deamination

    Glycine ---> $RCH=CHCOOH + NH_3$
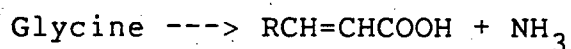
2. Reductive deamination

    Glycine + H_2 ---> Acetate- + NH_4+
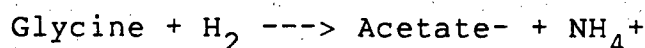
3. Decarboxylation (leading to subs. alcohol fermentation)

    Glycine ---> Amine + CO_2 ---> Alcohol + NH_3
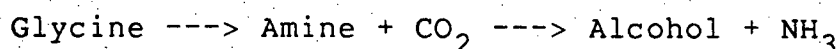
4. Strickland Reaction (coupled deamination)

2 Glycine + Alanine + 3 H_2O ---> 3 Acetate- + 3 NH_4+ + HCO_3- + H+
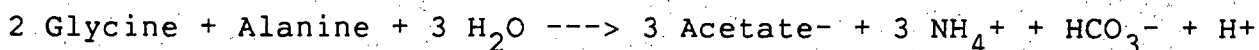
Some amino acids are resistent while others are highly susceptible to decomposition to ammonia. For example, ammonia is formed readily from arginine and tryptophane, while lysine, threonine and methionine have a more extended persistence in soil tests (Alexander, 1961). Again, Clostridia sp. appear to be the most dominant microorganism in reaction 2. Anaerobic cocci were also found as a contributor to reaction 2 in Songonunga's (1970) work.

The Strickland Reaction appears to be the controlling mechanism for ammonia formation. At least 15 species of Clostridia can obtain energy from the Strickland Reaction (Thompson, 1967). Other than regulating the formation of ammonia in landfills, the Strickland Reaction is a major contributor to

volatile fatty acid production in leachate, and has been
theorized to be a major competitor for H_2 needed for methane
production (Nagase and Matsuo, 1982). The reaction also releases
H^+ ions, dropping the pH, which is not favorable for mechanism
(1), hydrolytic deamination (Songonunga, 1970). Instead,
decarboxylation (2) becomes more prevalent at low pH's hence,
releasing more alcohols into solution.

2.5.3.3. AMMONIA SINKS

The major sink of newly generated ammonia appears to be due
to growth assimilation from the bacteria that produce it in the
first place. The majority of bacteria need NH_4^+ and not organic
nitrogen (amino acids, amines, etc.) for assimilation into their
protoplasm. In fact, ammonia has been proven to be the only
nitrogen compound needed for growth in methanogens (Hobson et
al., 1974).

Other than NH_4^+ assimilated by cell synthesis, there are
other less common sinks of free ammonia. They are listed in
point form below:

1. Cation exchange of NH_4^+ onto refuse or soil colloids.

2. Ammonia fixation or "ammonylsis" by organic compounds
   such as halogenated aromatics (NRC, 1979) or carboxyl
   and other acidic organic groups that combine with NH3
   to form soluble salts (Freeney et. al., 1981)

3. Nitrification could occur if free oxygen is around to
   be an electron acceptor.

4. Volatilization of NH_3 through landfill.

2.5.3.4. LANDFILL AMMONIA BALANCE

When decomposition and growth become psuedo-steady state,
the ammonia balance within an completely anaerobic landfill

environment can be presented as follows (modified from Waksman, 1931):

N decomp. - (N growth + N org. nitrogen + N sinks) = N as NH_3-N

This balance indicates that as protein decomposition rates exceed growth requirements for NH_4^+, ammonia will begin to accumulate as a waste product. This accumulation will either be leached, fixed, exchanged or volatilized from the system.

A mathematical treatment of these processes has been done by Smith (1982) regarding soil microbes. He uses Michaelis-Menton substrate kinetics to calculate a net soil solution NH_3-N by subtracting the ammonia production rate (mostly from deamination) from the various NH_3-N uptake rates. Refer to page 135 in Smith (1982) for further detail.

2.5.4. FACTORS AFFECTING AMMONIA MOVEMENT IN LANDFILLS

2.5.4.1. MASS TRANSFER IN UNSATURATED ZONE

In the unsaturated zone of the landfill, there are four phases in which ammonia can occur. The two solid phases are the bulk refuse and the biofilm surrounding the refuse. Surrounding this biofilm is a liquid layer followed by the gas filled fraction of the refuse pores. A cross-section of these four phases is presented in Figure 2.4.

The rate-limiting step in NH_3 transfer to the gas phase appears to occur in the biofilm where the microbial processes inherent in the biofilm regulate further NH_3 transport. If there is a net accumulation of NH_4^+, then NH_4^+ will move through the biofilm as a function of it's diffusion coefficient. From
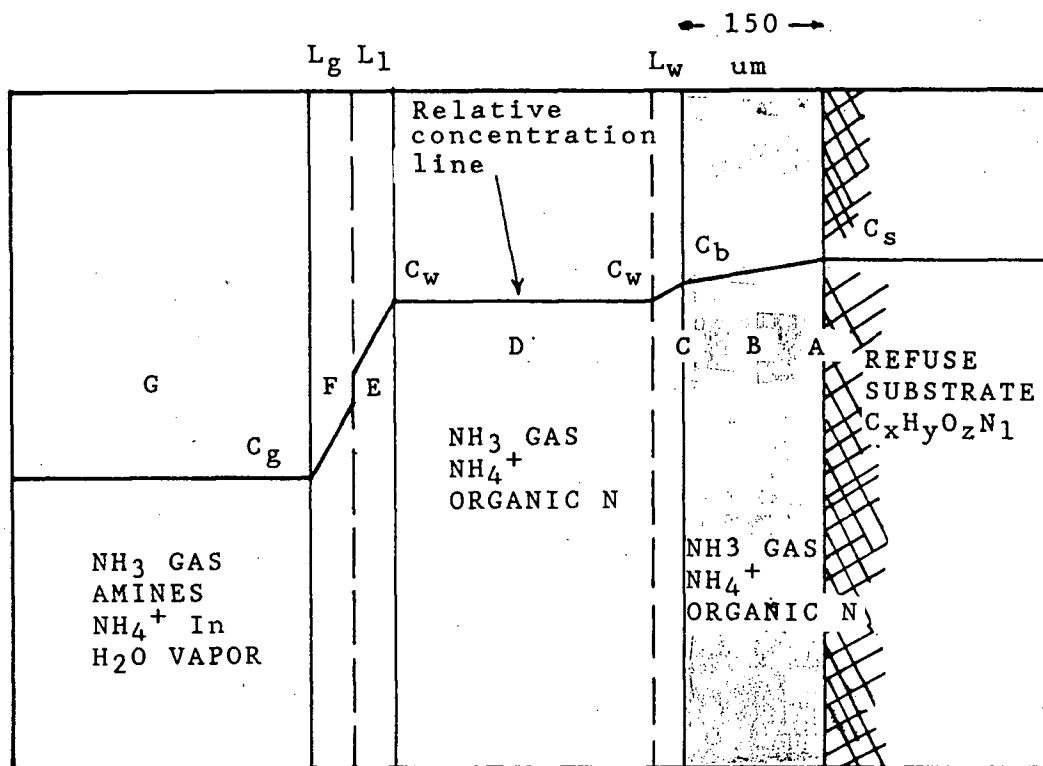
A. Biofilm-refuse interface

B. Biofilm - NH_4^+ movement through biofilm depends on
        diffusion and biofilm uptake rate.

C. Liquid Film

D. Bulk Liquid - Assume liquid is completely mixed and
                contains biofilm slough, soluble substrate
                and bacteria floc. Assume steady state
                gain or loss of NH3-N in this zone.

E. Liquid Film

F. Gas Film

G. Bulk Gas - Contains H_2O vapor, and landfill gas
                components. Assume partculate mass is
                negligible.

FIGURE 2.4 - Microscopic Cross-section through landfill showing
            mass transfer of NH3-N into bulk gas, assuming a
            biofilm model.

studies done on mixed and pure biofilm cultures, the diffusion coefficient ranges from 1.03E-05 to 1.50E-05 cm^2/s (Williamson and McCarty, 1976, and Onuma and Omura, 1982). This diffusion coefficient has been seen to vary with varying ratios of C:N in the biofilm (Onuma and Omura, 1982). Other than microbial assimilation of NH_3-N, ion exchange can be an effective sink of NH_3-N in biofilms. Most of the NH_3-N will be in the ammonium ionized form due to fairly low pH's caused by fatty acid production (Strickland Reaction), especially where inadequate alkalinity exists. Sloughing of the biofilm releasing NH_3-N could occur due to normal sloughing mechanisms, or due to CO_2-CH_4 gas bubble formation shearing the biofilm.

Mass transfer from the biofilm to the bulk liquid is mostly a function of the diffusional resistance encountered by the liquid thin film (part c in Figure 2.4). The liquid thin film thickness is a function of the Reynolds Number (Re) of the fluid, with thickness approaching zero with increasing values (meaning greater fluid turbulence) of Re. The flux or mass of NH_3-N transported per unit area per unit time is given by (Grady, 1983):

$$J = Dw/Lw*(Cb - Cw) \qquad (vii)$$

Where Dw = liquid film diffusion coeff. (cm^2/sec)
    (est. at 1.7E-07 from Reddy and Patrick, 1983)

    Lw = liquid film thickness (cm)
    Cb = concentration of NH_3-N in biofilm (mg/L)
    Cw = concentration of NH_3-N in bulk liquid (mg/L)

Once the NH_3-N is in the bulk liquid, NH_3 transfer into the bulk gas depends on it's solubility, Henry's Law constant (Hx)

and mass transfer coefficient (K) of NH_3. Solubility plays a key part in how much of the total NH_3-N in solution is actually unionized NH_3. This fraction is then available for transport into the bulk gas. The governing equilibria of NH_3 formation is shown in the hydrolysis reaction below:

$$NH_3 + H_3O+ <====> NH_4+ + OH-$$
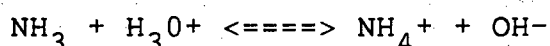
This reaction indicates that as pH increases, so will the unionized fraction of NH_3-N increase, leaving a greater fraction for transfer into the bulk gas. Other than pH, the unionized fraction of NH_3-N is affected by changes in temperature, pressure, ionic strength and salinity. Numerous authors such as Trussel (1972), Skarheim (1973), Thurston et. al. (1974), Whitfield (1974) and Bower and Bidwell (1978) have calculated the variation of unionized fraction of NH_3-N due to variations in these parameters.

Mass transfer of the soluble NH_3 across the water/gas interface (D-G on Figure 2.4) is regulated by the diffusional resistence encountered in both the liquid and gas thin films. The two film diffusion model was developed by Lewis and Whitman in 1924. The model assumes that the solute (NH_3) is uniformly mixed in the bulk air and gas phases and encounters molecular diffusion only in the thin films (E and F in Figure 2.4). Steady state conditions are assumed as well, so that the mass fluxes through each film is equal (Rathbun and Tai, 1982). With this in mind, the overall resistance to mass transfer is the sum of the resistances in the liquid and gas film.

$$Rt = Rl + Rg \qquad (viii)$$

Where $Rl = 1/kl$ where $kl = Dl/Ll$

$Rg = 1/Hxkg$ where $kg = Dg/Lg$

So $Rt = 1/Kt$ Where Kt is in meters/day

Therefore, the overall mass transfer coefficient is:

$$1/Kt = 1/kl + 1/Hxkg \qquad (ix)$$

Usually this mass transfer coefficient is determined through laboratory measurements (Rathbun and Tai, 1982, Murphy et. al., 1987, or MacKay and Shiu, 1981).

Again, the film thicknesses depend on the Re of the surrounding fluid, which can become quite important in landfill environments where turbulent methane convection flow can create thin gas films.

The value of Henry's Law constant (Hx) will determine in most cases whether the resistance to mass transfer is in the liquid, gas or both thin films. Solutes with high Henry's Law constants (>>1.0 atm/mole fraction), have resistance mostly in the liquid film, while small Hx's (<<1.0 atm/mole fract.) will have mostly gas film resistance (Thibodeaux, 1979). For Hx's of around 0.5 to 1.5 atm/mole fract., resistances may occur from both thin films. This is especially true for a highly soluble volatile compound like ammonia. Some Hx's for common landfill gas constituents are listed below (from Thibodeaux, 1979):

COMPOUND	Hx (atm/mole frac.)	RESISTANCE
N_2	86,500.0	
CO	57,000.0	
H_2S	54,500.0	Liquid Phase
O_2	43,800.0	
CH_4	41,000.0	
CO_2	1,640.0	
NH_3	0.843	Both Phases
Propionic Acid	0.0130	Gas Phase

Once the Kt is determined, the flux (Jg) into the bulk gas phase can be estimated from equation (x) below. To use this equation, one must know or acquire concentrations of the bulk gas and liquid phase, and also convert Hx from atm/mole frac. to atm-m^3/mole.

$$Jg = Kt(Cw - RTCg/Hx) \qquad (x)$$

Where R = is gas constant (in atm-m^3/mole-K degrees)
     T = Temperature in K
    Cg = Bulk concentration in gas phase (mg/L)
    Cw = Bulk concentration in liquid phase (mg/L)

A typical Hx for NH_3 at $25^{\circ}C$ calculated from Stumm and Morgan (1981) is 1.73E-05 atm-m^3/mole. Different expressions for Hx will be discussed in further detail later in this thesis.

2.5.4.2. MASS TRANSFER IN SATURATED ZONE

In most cases when landfills have a permeability greater than the surrounding soils, mounding of the local water table may occur within the landfill, creating a landfill saturated zone. Other than mounding, heterogenieties within the landfill refuse may cause perched zones of leachate to develop. This scenario creates a macroscopic planar feature where mass transfer of

ammonia can occur at the saturated-unsaturated interface regulated by the same two-film theory already discussed. A macroscopic conceptual model of this mass transfer is presented in Figure 2.5. Some important equilibria reactions that can affect the amount of ammonia available for transfer into the gas phase are also presented in Figure 2.5. These reactions will be discussed in more detail later.

2.5.4.3. FURTHER MOVEMENT IN LANDFILL

Once NH3 is in the bulk gas, further movement in the landfill would be from diffusion or convection flow. Retardation or removal of NH_3 from the bulk gas would be from sorption onto landfill or cover material, or redissolving into the saturated landfill gas vapor.
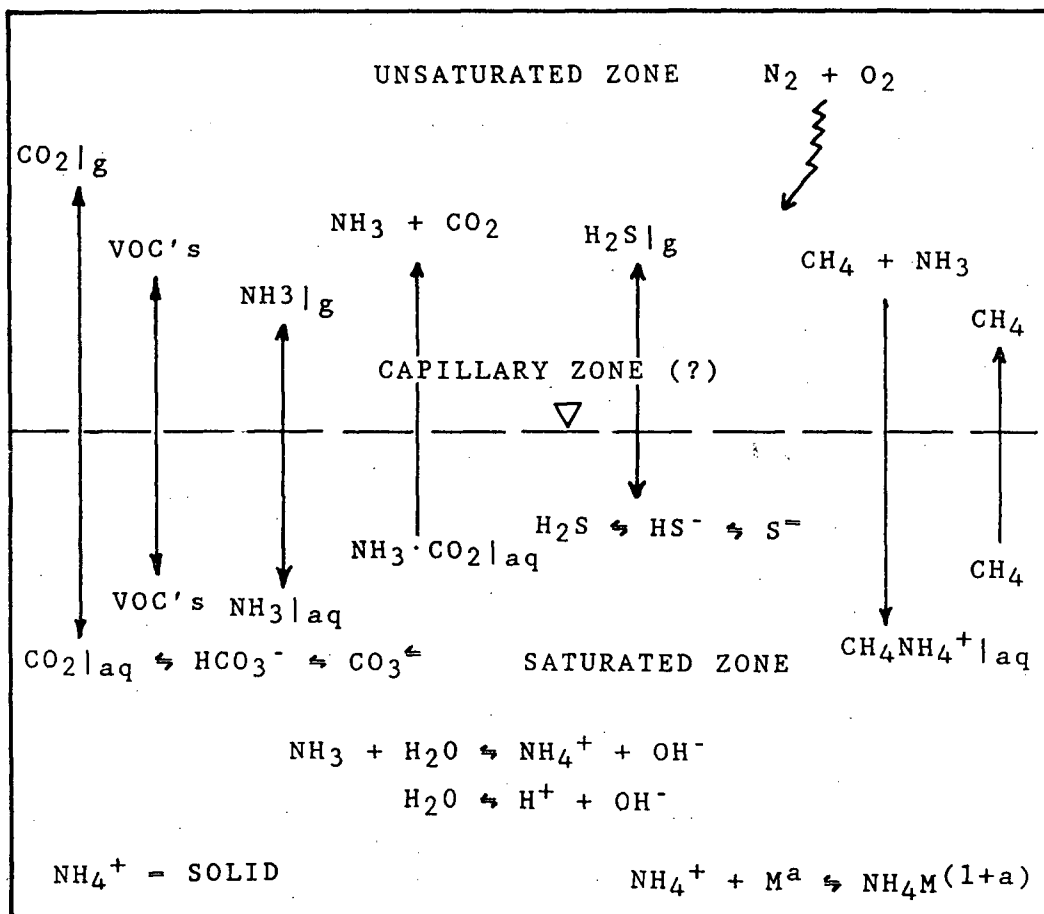
FIGURE 2.5 - Cross-Section of Saturated-Unsaturated Zone Showing
mass-transfer and major chemical reactions affecting
mass transfer of landfill gas.

CHAPTER 3

3.   SITE DESCRIPTION AND HISTORY

3.1 MATSQUI - CLEARBROOK LANDFILL

   3.1.1. LOCATION

   Matsqui - Clearbrook landfill is a 10 ha site located
approximately 3 km north of downtown Clearbrook just off
Tretheway Street (Figures 3.1. & 3.2).   The approximate
elevation of the site is 45 m above mean sea level.

   3.1.2. PHYSICAL DESCRIPTION

   The regional hydrogeology around Clearbrook is dominated by
a glaciofluvial till interbedded within fluvial sands and
gravels.   These deposits were termed "Sumas Drift" by Halstead
(1986).   These deposits can be found in a neighboring gravel pit
operation (See Figure 3.3) where a cut bank 15 meters high shows
interbedded sands and gravels.   Some of the coarse bedding even
exhibits imbrication, a common indication these gravels are of
fluvial (channel deposition) origin.   Local groundwater levels
appear to be about 12-13 m below the land surface in the winter
by direct inspection of gravel pit ponds.   The average annual
precipitation on the site is approximately 1400 mm taken from the
local weather station in nearby Abbotsford.

   3.1.3.   HISTORY AND CHARACTERISTICS OF FILL

   This trench-fill operation began in 1974 with landfilling
moving from a west to east direction at the site.   Intermediate
or daily cover was a thin layer of the trenched sands and
gravels.   The last cell opened in 1983 and ended in early 1984

(Willie Riemer, pers. comm., 1987).

The fill averages about 12 m in thickness and consisted mostly of MSW with unusually large amounts of dead animals that were landfilled in cells or individual pits. The dead animals were primarily from the local poultry industry. Other types of material landfilled include: large volumes of gypsum board, which causes greater sulfide formation and regular dumpings of sewage sludge (Willie Riemer, pers. comm., 1987).

The final cover was constructed of highly compacted local trenched sands and gravels (same as intermediate cover) with approximate thickness of about 0.70 m. On top of the final cover a layer of crushed gravel has been installed, so that the landfill can be used as a parking lot for local activities at the neighboring multi-purpose building (See Figure 3.3). Total porosity of the cover is estimated to be about 35%.

Offsite migration of leachate has not been documented; however, steps have been taken to regulate the drainage flow a few 100 meters northwest of the site. Gravel pit ponding shows no physical evidence (color or smell) of leachate contamination; hence, the author believes the groundwater gradient is in a north-northwest direction. Low volume, high strength seepage was noticed for the first time in early April, 1988 in the gravel pit cut bank adjacent to the fill area. This discharge seemed to follow consistently heavy rains the week before.

3.1.4. GAS EXTRACTION SYSTEM

Problems with offsite methane migration were detected in
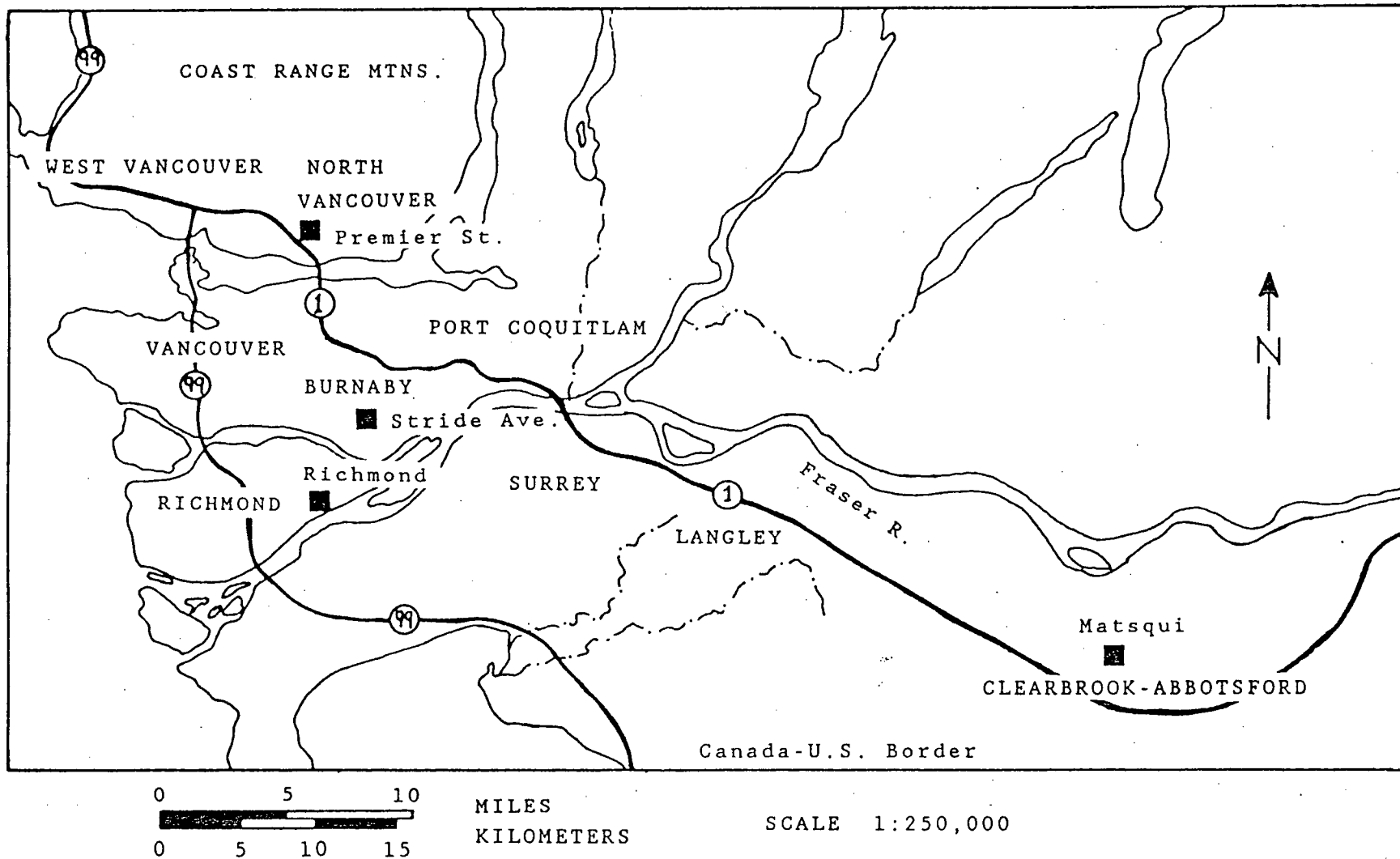
FIGURE 3.1 - SITE LOCATION MAP Showing Major Waterways,
Roads and Metropolitan Areas
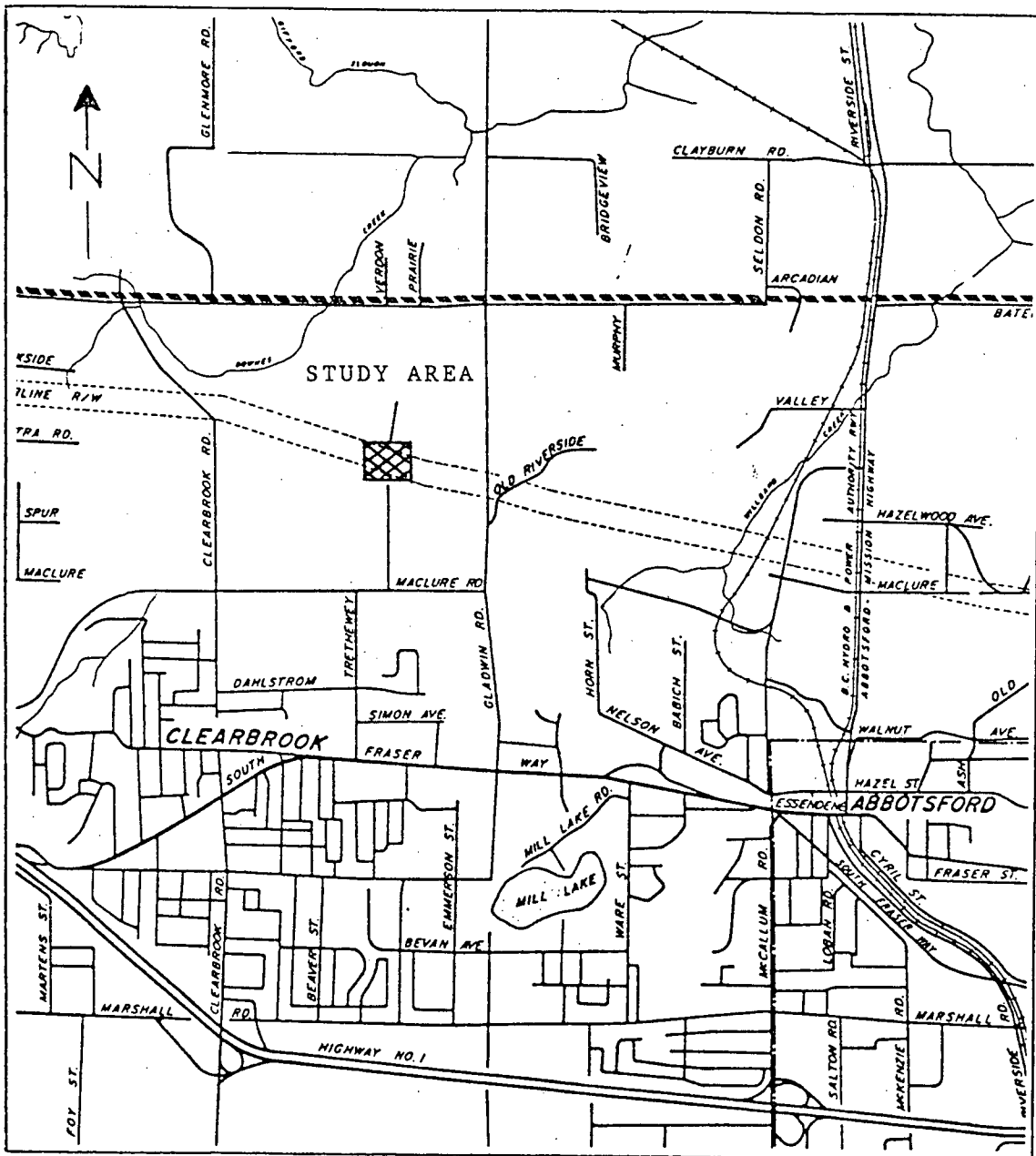
FIGURE 3.2 - LOCATION MAP Clearbrook-Matsqui Landfill
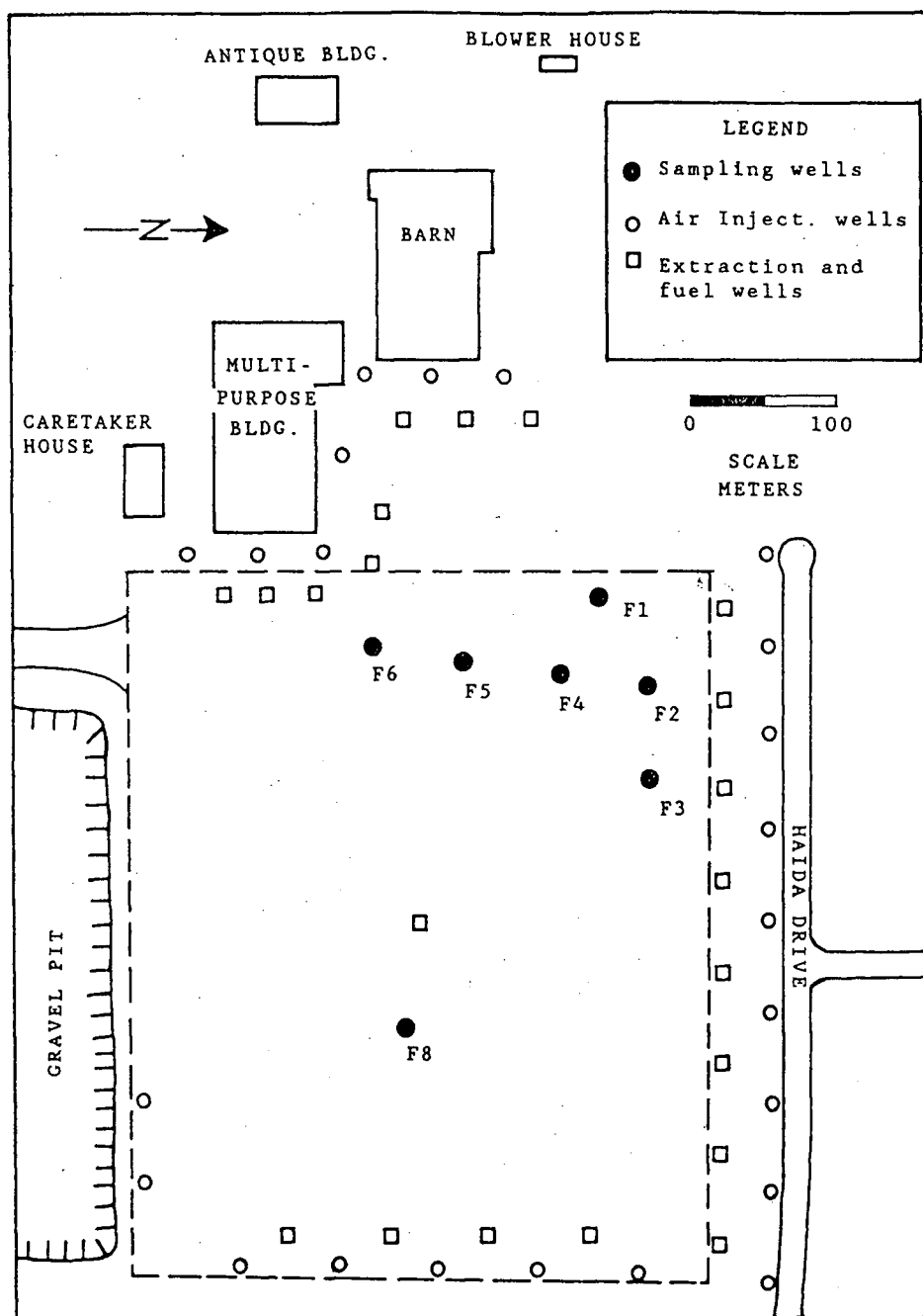
FIGURE 3.3 - SITE MAP of Clearbrook-Matsqui Landfill

(Adapted from E.H. Hanson & Assoc., Jan. 1985)

1983 before the last fill was completed. In November, 1983, E.H.

Hanson & Assoc. began a design of a gas collection and

utilization system. The structures that were in greatest danger

of methane explosions were the multi-purpose building and storm

sewer on Haida Drive (See Figure 3.3). Methane concentrations of

greater than 50% and 20% were detected below the foundation slab

and washroom drains respectively in the multi-purpose building

(E.H. Hanson & Assoc., 1985). A gas trap was installed in the

storm sewer, while an air injection gas extraction system

eliminated any methane under the multi-purpose building in less

than 24 hours after system start-up (E.H. Hanson & Assoc., 1985).

In May, 1984, construction of the gas extraction utilization

system was completed. The system originally consisted of 16 air

injection and 16 withdrawal wells on the north and west perimeter

of the landfill with 6 fuel wells located within the western

portion of the refuse layer. Because of off-site migration east

of the landfill, more injection-withdrawal wells (7 and 4

respectively) were installed in early 1985. Also, two more fuel

wells (F7, F8) were drilled at this time in the more easterly

portion of the landfill. The fuel wells (ones used for this

study) are 7.5 cm in diameter, average 9-10 meters in depth and

are perforated the entire length starting from 1.5 meters below

the landfill surface.

The extracted gas is collected and is first sent to the

compressor and second to the storage pressure tank. The

compressed gas (untreated) is piped to 8 furnaces and a hot

water tank located within the multi-purpose building. The
furnaces were retrofitted to accept the untreated landfill gas,
which has only about a 500 BTU/CF heating value (E.H. Hanson &
Assoc., 1985).

The six fuel wells were used for leachate and gas sampling
because of their easy access and location within the landfill.
Only two wells, F2 and F5 Matsqui contained leachate throughout
the study period. Wells F1 and F3 began to show leachate in
December of 1987 after heavy rains. Because of sampling
problems, F6 was discontinued in mid-November and replaced by
Well F8. The locations of all sampling wells are located on
Figure 3.3.

3.2. STRIDE AVENUE LANDFILL

3.2.1. LOCATION

Stride Avenue is located just upslope of S.E. Marine Drive
on Burnaby's south slope at approximately 100 meters above mean
sea level (See Figure 3.1, 3.4). This 8.08 ha landfill site is
some 1200 meters north of the north arm of the Fraser River
(Atwater, 1980).

3.2.2. PHYSICAL DESCRIPTION

The main site was originally a gully that has since been
filled (See original surface elevation contours on Figure 3.4).
The site is generally underlain by post glacial sands with some
gravel. Along the gully floor there is evidence of interbedded
silt in the sandy gravel (Atwater, 1980).

Surface water runoff from the site is flumed alongside the

fill and is discharged into the gully at the toe of the fill.
This creek eventually discharges into the Fraser River at Byrne
Road. There have been elevated concentrations in the creek of
certain inorganic constituents from leachate seepage into the
creek. Atwater (1980) voiced a concern about high manganese
concentrations measured downstream of the landfill in 1979 that
exceeded the recommended concentration of 0.2 mg/L in irrigation
water by almost 10 fold.

Adjacent to the fill, groundwater was encountered at a depth
of 15 m (Atwater, 1980). This author detected red-coloured
seepage from the thicker portion of the landfill north of well
F7 (See Figure 3.5) after heavy rains in early April, 1988.

Average annual precipitation at this site is estimated to be
about 1270 mm (Atwater, 1980).

3.2.3. HISTORY AND CHARACTERISTICS OF FILL

Stride Avenue opened around 1910 for refuse disposal and
closed in 1969. Since 1986, the western portion of the fill has
been reopened for disposal of garden wastes and slash for Burnaby
residents.

The original filling operation proceeded in a southernly
direction from the north east end of the site (See Figure 3.5).
The operation consisted of gully fill with some filling of 6-9 m
deep sand excavations on the western flank (Atwater, 1980). The
fill depth is believed to average 12-14 m but can be up to 27 m
deep(Atwater, 1980). E.H. Hanson & Assoc. (1985) used
historical data with drill hole logs to construct an isopac map
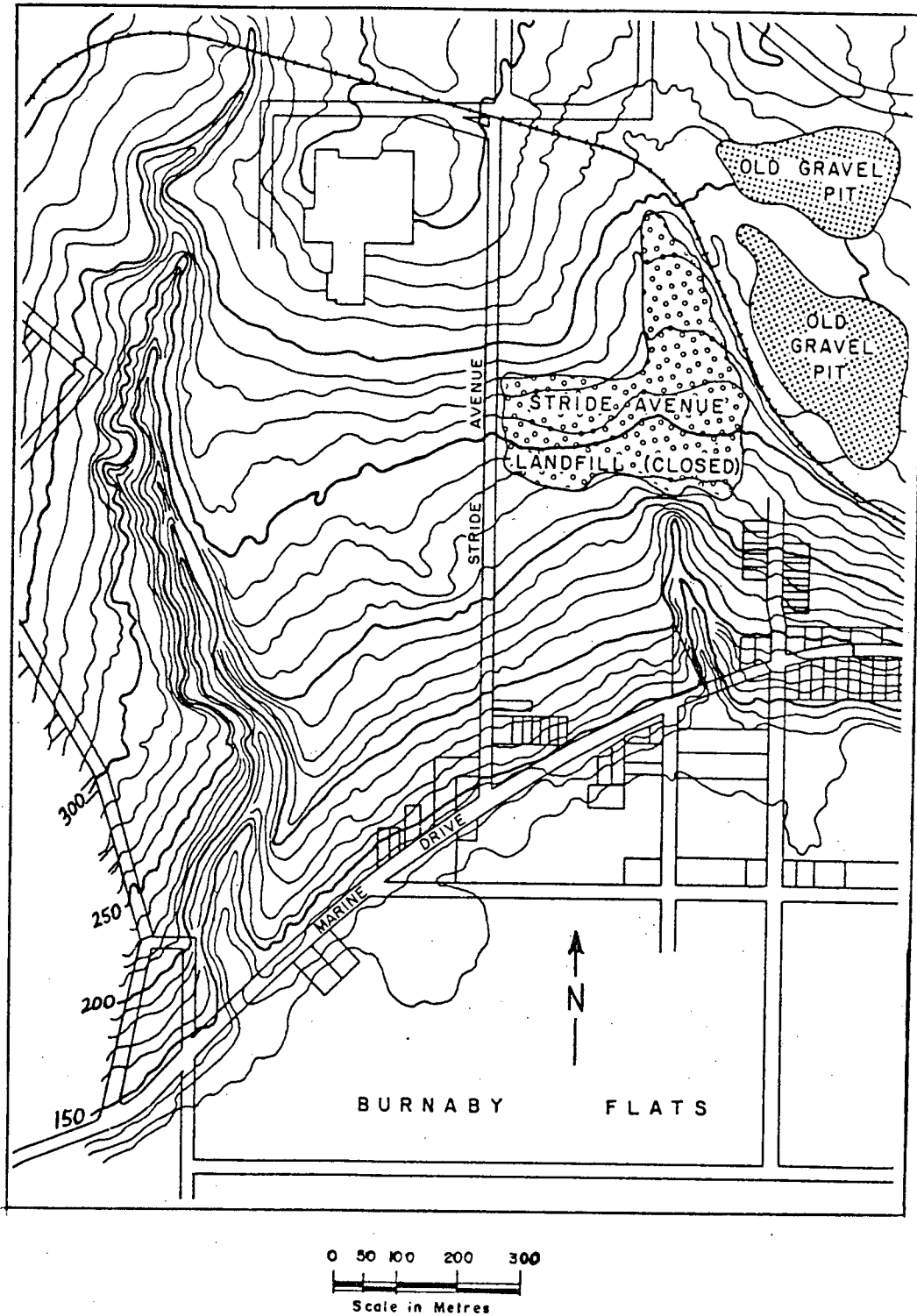
FIGURE 3.4 - LOCATION MAP Stride Avenue Landfill

(Map adapted from Atwater, 1980)
Note: Elevation contours are in feet

showing the relative thickness of the landfill. Inspection of this map indicates the deepest portion of the fill to be just north of wells F6 and F7 (See Figure 3.5).

The fill is mostly MSW, with lesser amounts of municipal cleaning debris (road cleaning, etc.)., while demolition and construction material was generally directed elsewhere (Atwater, 1980). Fill volume and total mass were estimated by Atwater (1980) to be 987,000 m^3 and 5.3 X 10^8 kg (527,000 tonnes) respectively.

Cover thickness is estimated from drill records by E.H. Hanson & Assoc. to average about 2 meters in thickness. Near-surface samples taken of the cover material indicate a clay-wood chip mixture with good consolidation. Total porosity of the cover is estimated to be about 30% by this author.

3.2.4. GAS EXTRACTION SYSTEM

E.H. Hanson & Assoc. began investigating possible offsite methane migration at Stride Avenue in 1981. They implemented a monitoring program complete with a gas well collection system that was completed in late 1984. In 1986 new development proposals to re-zone the land surrounding Stride Avenue landfill called for more observation wells to be drilled north of the landfill (See Figure 3.5).

One incident of methane explosion did occur at the landfill in 1985 during construction of a new storm sewer. However, there is no documentation of methane migration threatening any offsite structures to date.
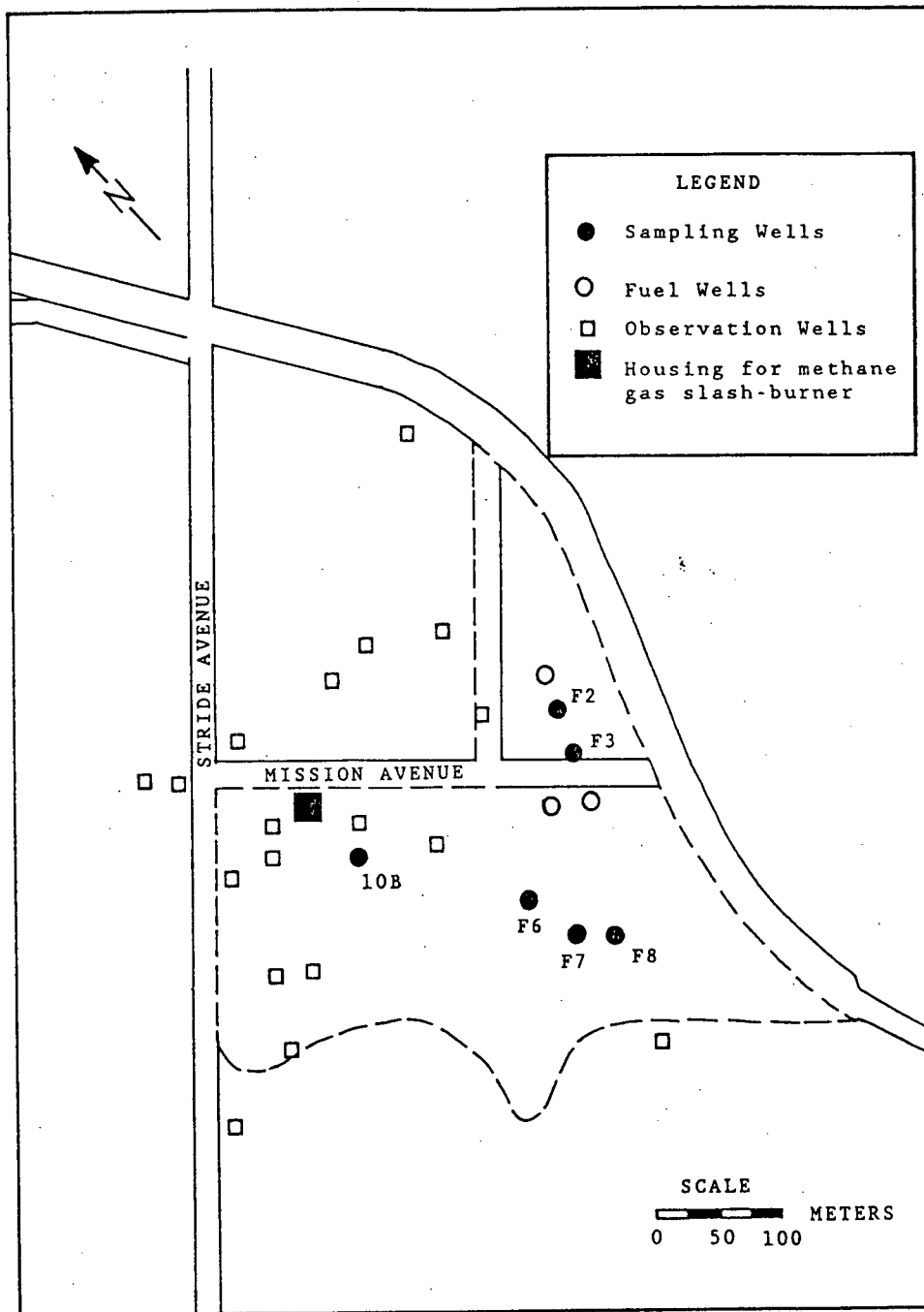
FIGURE 3.5 - SITE MAP of Stride Ave. Landfill

(Adapted from E.H. Hanson & Assoc. Jan., 1987)

Overall, the system at Stride Avenue has at least 20 monitoring wells and 8 extraction wells. The extraction-fuel wells range from 8 to 20 m in depth and are 7.5 cm in diameter.

At certain times of the year, gas from these fuel wells (F1 to F8) is collected and sent to the burner housing located on the western portion of the fill (See Figure 3.5). This burner uses the methane as a fuel for burning recently deposited garden waste and slash. Also, when on vacuum, these fuel wells help to contain any offsite methane migration.

Sample wells used were F2, F3, F6, F7, F8 and B10. Location of these wells are presented in Figure 3.5. The wells were chosen because all wells except F8 contained leachate. After heavy rains, F8 began showing leachate in mid-December 1987. Well B10 was originally chosen because of it's direct proximity to the active fill area. However, this well was buried by deposited garden slash in mid-October and never sampled again. All other wells in the active fill area were inaccessible for sampling the leachate.

3.3.   RICHMOND LANDFILL

3.3.1.   LOCATION

Richmond Landfill is located in the Municipality of Richmond just north of the main arm of the Fraser River and just south of Westminster Highway (Figures 3.1). The landfill property consists of about 270 ha, which, about 20 ha consists of the study site. This study site is located just off No 8 Road at the north end of the landfill property (See Figure 3.6). The

elevation of the landfill site is just a few meters above sea level.

3.3.2 PHYSICAL DESCRIPTION

The site rests on a peat bog of thickness up to 5 m which is underlain by 0.9 to 7.3 m of silt and clay. This silt and clay is underlain by up to a 30 m thick unit of deltaic sands (Atwater, 1980).

Regional water table levels are close to the ground surface at this site. Within the landfill, refuse loading on the peats has caused a concave depression to form in the peats where water table elevation has become higher than the water levels of the neighboring Fraser River. Piezometers in the sand and refuse layers show a profound head response to tidal fluctuations, whereas response in the peat unit is ever increasing due to the load of the refuse (Atwater, 1980).

Average annual precipitation of the site is just over 1000 mm/year.

Cut off ditches were installed to collect leachate on the perimeters of the landfill in the mid-1970's. These ditches divert leachate either to the northwest storage lagoons or are discharged into the Fraser River at the Nelson Road pump station. For a more thorough discussion on leachate from Richmond landfill, refer to Atwater (1980).

3.3.3. HISTORY AND CHARACTERISTICS OF FILL

The landfill operation began in 1971 and ended in December, 1986 (E.H. Hanson & Assoc., 1988). The last fill to be completed
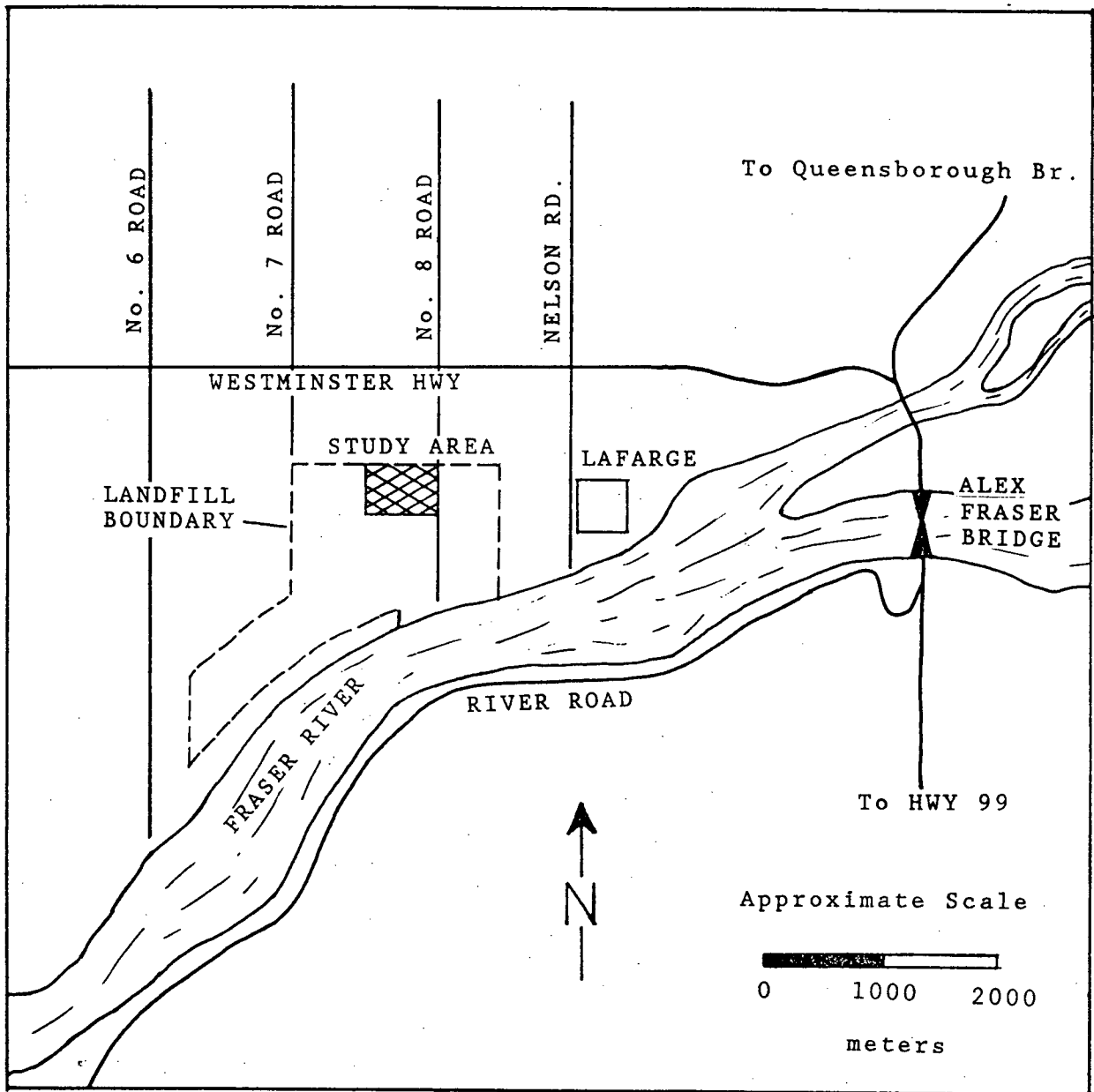
FIGURE 3.6 - LOCATION MAP Richmond Landfill

(Adapted from Atwater, 1980)
(No scale given)

was in the study area site. Richmond Landfill, Ltd. operated the fill operations under an agent's agreement with the Fraser River Harbour Commission (FRHC), which owns the landfill property.

The filling operation consisted of a 1.2 to 2.1 m lift of mattress fill followed by a second lift of 2.4 to 4.3 m of refuse. An additional two lifts were placed in the 20 ha study site. Estimated fill densities for the 20 ha study site have not been documented. Older fill densities, before regular cell construction techniques were practiced, was estimated at 415 kg/m^3 (Atwater, 1980).

Daily and final cover was dredged Fraser River sand. The final cover on the study site is estimated to average 1.5 m in thickness (G. Huckulak, pers, comm., 1988) This sand and gravel cover is unconsolidated, highly permeable, with total porosities estimated by this author of over 50%. The high porosity of the cover has allowed large volumes of rain water to infiltrate the landfill, mounding water up to 2 m below the landfill surface.

The fill was characterized by over 4.4 X 10^8 kg (435,000 tonnes) of MSW deposited annually, with large amounts of liquid waste discharged onsite up to 1978 when this was stopped. Large volumes of construction and demolition debris were also deposited on the landfill property. The 20 ha study site consists solely of MSW fill.

3.3.4. GAS EXTRACTION SYSTEM

About 2 years prior to closure of the active fill area, E.H. Hanson & Assoc. approached FRHC for acquisition of landfill gas

rights while consulting the commission on landfill gas control measures. Gas control measures were considered in an attempt to reduce or eliminate the risk of gas migration into the planned future industrial park that was to serve new port facilities along the Fraser River.

After an extensive rod-probe testing program of over 270 ha of the potential developable area, E.H. Hanson prepared recommendations to the FRHC control of landfill gas. Their recommendations included containing, extracting and burning the gas. At this point, FRHC gave gas rights to E.H. Hanson & Assoc. in return for a royalty payment. They were able to find a customer for the gas in La Farge Cement (See Figure 3.6), which uses the gas in their cement kilns as a supplementary fuel (supplies 13% of their energy requirements). This high kiln temperature coupled with a long retention time ensures complete combustion of all gas components (E.H. Hanson & Assoc., 1988).

Costs for this system were shared from Energy, Mines and Resources, Canada (contributed to 18% of capital cost) and Bio Gas Industries of Vancouver, which is a group of private investors. At the time, payback for investors was estimated at 3 years. Original capital costs were valued at over $500,000. This project is the only one in the world supplying landfill gas as fuel to cement kilns (E.H. Hanson & Assoc., 1988).

Installment of the gas collection system began in June 1986 with the installation of 36 wells on the eastern portion of the landfill study area (See Figure 3.7). This part of the system

became operational on November 4th, 1986. In early December of 1986, after disposal operations ceased, an additional 28 wells were drilled and put on line by late December. In late 1987, the gas production from this 64 well collection system was around 20.5 m^3/min (725 CFM) while averaging 56.5% methane (E.H. Hanson & Assoc, 1988).

Extraction wells are 7.5 cm in diameter and reach an average depth of 7.5 m into the landfill. Perforations begin 1.5 m below the top of the casing and extend for the remaining 6 m. The borehole is about 20 cm in diameter, with gravel filling the annular space between the borehole and casing. In contrast to the other three landills studied, well head assemblies in Richmond Landfill are located above ground.

The collection system consists of rows of 10 cm diameter PVC piping where a 20 cm diameter header connects to each row of this piping. Each row is valved. Condensate drains are spaced throughout this collection system.

The gas from the headers is then routed into a 25 cm diameter 1.6 km long transfer pipe that transports the gas to a blower which imparts about 70 cm (28 in) of vacuum to this transfer line (E.H. Hanson & Assoc., 1988). On the outlet end of the blower is a 150 cm diameter pressure line with about 12.5 psi of pressure that transports the gas another 1.6 km to the cement kiln. The pressure of the line when reaching the kiln is about 5 psi. Blow out valves to rid condensate from this line are located throughout the distribution system. No pretreatment of
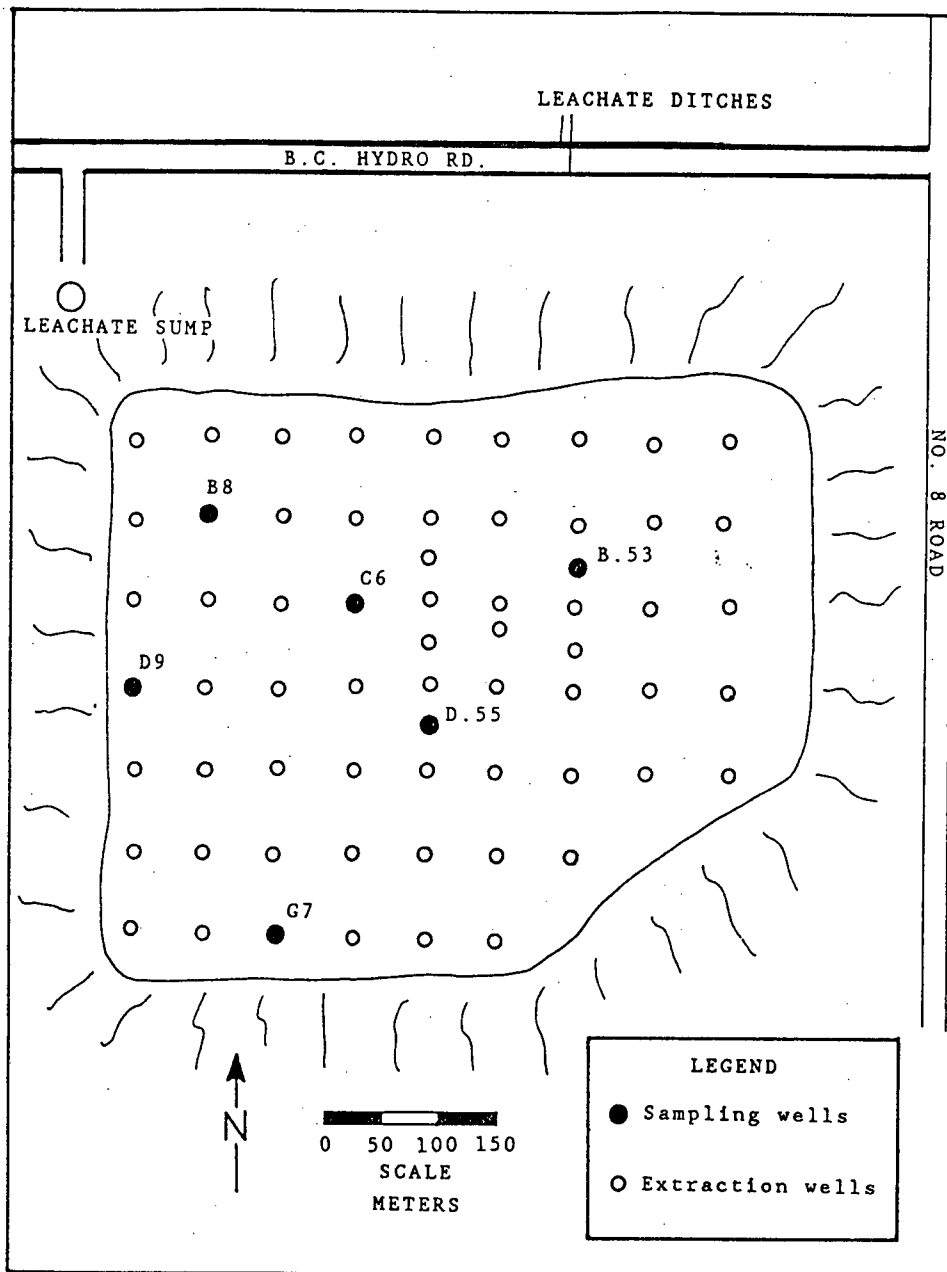
FIGURE 3.7 - SITE MAP Richmond Landfill

(Adapted from E.H. Hanson & Assoc. July, 1986)

gas is employed at this site. For a more detailed plan of this system refer to E.H. Hanson & Assoc., 1988.

Sample wells used in this landfill site were B8, D9, C6, G7, D.55 and B.53. Location of these wells is presented in Figure 3.7. These wells were chosen for sampling because of their easy accessibility, and varied water levels. Also, sample wells were spaced around the landfill for a better representation of spatial differences found in this very heterogeneous fill.

3.4 PREMIER STREET LANDFILL

3.4.1. LOCATION

Premier Street Landfill is located in the District of North Vancouver on the east flank of Lynn Creek, approximately 2 km north of Second Narrows Bridge (See Figure 3.8). The overall site is approximately 20 ha in size at a base elevation of about 25 m.

3.4.2. PHYSICAL DESCRIPTION

The landfill lies on fluvial sands and gravels, which make up a 2-9 m terrace just above Lynn Creek. This unit is very coarse and permeable. Underlying this unit is a dense grey silty sand and gravel till. Previous investigations have detected upward groundwater seepage from the till into the more permeable fluvial sands and gravels (Golder Assoc., 1983).

This hydrogeologic environment is suitable for large volume discharges of groundwater into Lynn Creek. A water balance calculation done by Golder Assoc. (1983) estimated a groundwater discharge of 55,188 m^3/yr into Lynn Creek from the newer landfill

site. They mention, however, many of the inputs to the water
balance are poorly defined. Much of this groundwater is
contaminated by landfill leachate, which has been mostly
contained by a dyke and slurry bentonite cutoff trench located
in one area between the landfill boundary and Lynn Creek and
another area seperating the younger from older fills. A
perforated leachate collection pipe runs parallel to this trench
and dyke adjacent to Lynn Creek to contain and direct the
leachate to a central collection point for further pumping to the
municipal sewer system.

Average annual precipitation at this site is the greatest of
the four sites and is estimated by Golder Assoc. (1983) to be
about 1880 mm/yr.

3.4.3. HISTORY AND CHARACTERISTICS OF FILL

The District of North Vancouver began fill operations in
1959 and ceased operations in the active fill area in the Spring
of 1988 (See Figure 3.8). The study site is located in the older
fill, which completed operations in 1981 (Peddie, 1986). The
study site consists of an area fill up to 25 m deep.

It is understood that construction of the older landfill was
preceeded by constructing a 6 m high dike of loose silty sand
and gravel along the east bank of Lynn Creek. In addition,
construction of a mattress layer of impermeable mineral fill
preceeded normal fill operations (Golder Assoc., 1983). This
older fill area is now used for recreational ball fields and
tennis courts. It is generally understood all types of material,

SCALE

| 0 | 1000 | 2000 | 3000 | 4000 | 5000 | FEET |

| 0 | 500 | 1000 | 1500 | METERS |
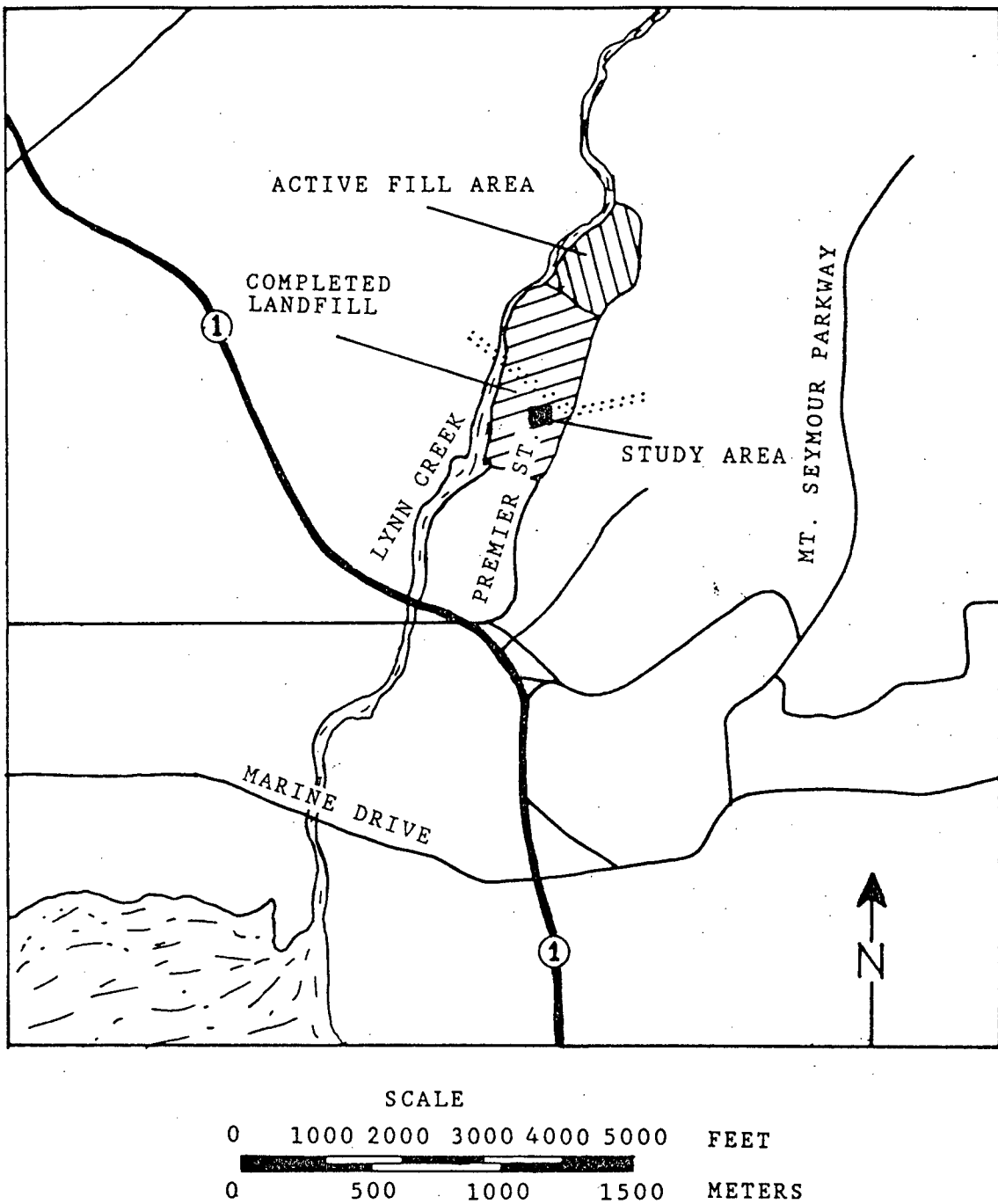
FIGURE 3.8 - LOCATION MAP Premier Street Landfill

(Adapted from Golder Assoc., 1983)

including liquid waste, were accepted for disposal at Premier
Street throughout the 1960's.

The landfill cover around the study site was found to be
compacted altered clay and shale debris with an estimated total
porosity of 25%.

3.4.4. GAS COLLECTION SYSTEM

In 1985, an extraction and flaring system was installed to
control or reduce odorous emissions from Premier Street Landfill.
The flare stack is located just west of the weigh scale and was
in March, 1986 receiving approximately 8.5 m^3/min (300 CFM) of
extracted landfill gas (E.H. Hanson & Assoc., 1986).

Presently on site there are 21 extraction wells of 7.5 cm
in diameter that average 20 m deep. Additional gas collection is
through a perforated pipe system buried in the most recently
completed fill area (See Figure 3.9). This collection network
has been found to be very inefficient (E.H. Hanson & Assoc.,
1986). Plans for the future include well installation into the
now active portion of the fill for further control of odors.

My reasons for using only two wells (P1 and P2) for sampling
at this site was due to their accessibility for downhole leachate
collection. All other wells on site had a seperate below ground
control valve assembly with an inaccessible buried well head
that was impossible to collect leachate from.
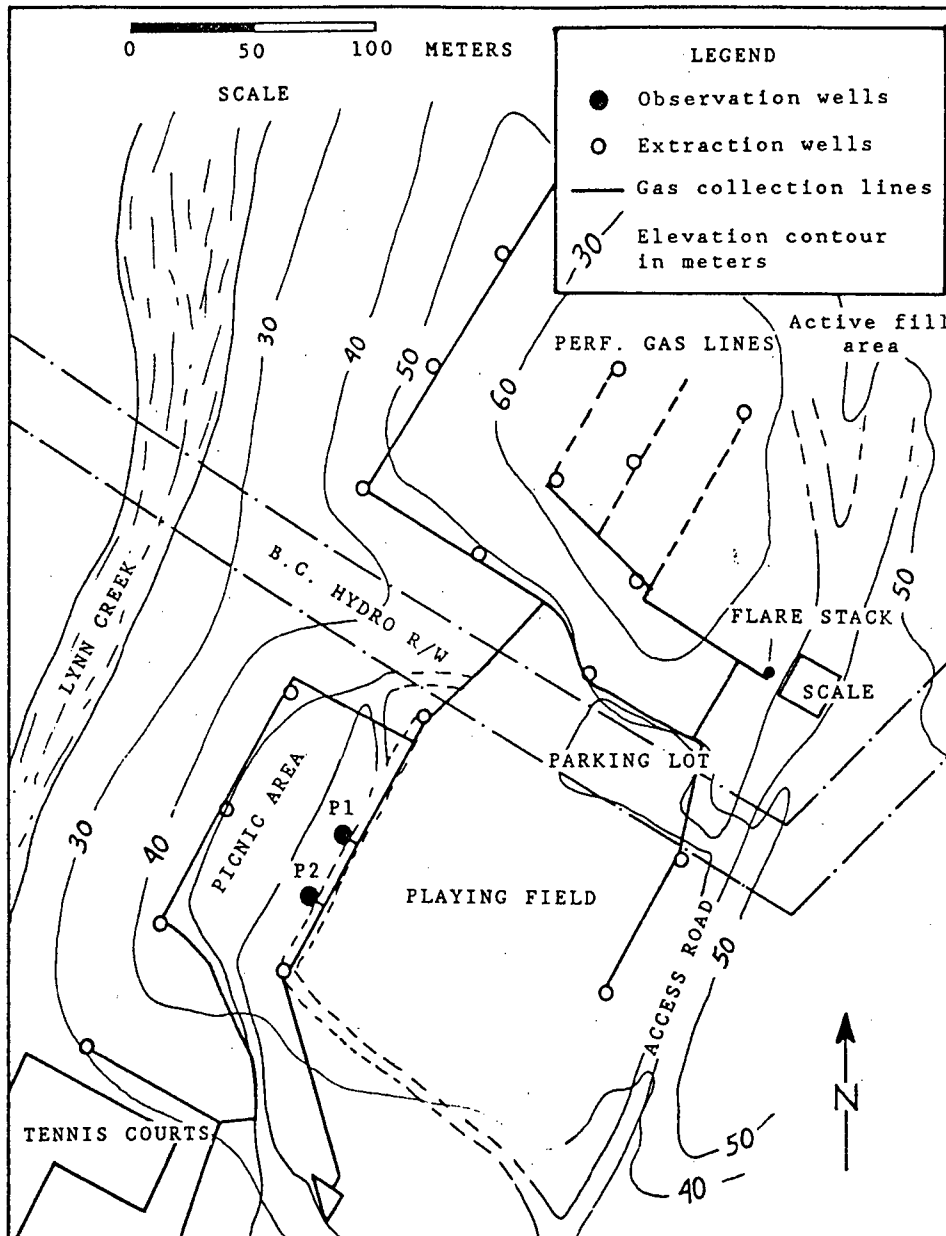
FIGURE 3.9 - SITE MAP Premier Street Landfill

(Adapted from E.H. Hanson & Assoc. March, 1986)
(Elevation contours sketched from Golder Assoc., 1983)

CHAPTER 4

4. METHODOLOGY

4.1. FIELD METHODS

4.1.1. INSTRUMENTATION AND TECHNIQUE

Parameters that were measured on site include leachate pH, water level, ambient air, gas and leachate temperature, barometric pressure, and lastly, static gas flow. Samples collected for lab analysis include leachate samples, gas samples for gas partitioner analysis, and NH_3-N gas samples for autoanalyzer analysis.

The following instruments were used in the field:

A. Leachate Collection

Leachate was collected from 7.5 cm diameter gas extraction wells with two different diameter PVC bailers. The bailers were both about 1 meter in length and varied in diameter from 2.2 cm (ID) to 3.75 cm (ID). Leachate entered the bottom of the bailer through a 4 mm diameter plastic check valve. These check valves were loosly fitted and easily removed for cleaning when the valve got clogged, which it did frequently. The smaller diameter bailer was used at Richmond and Premier St. Landfills because the larger bailer got hung up in these landfill well casings.

Leachate was collected in 500 mL plastic bottles after discarding two bailer volumes of leachate. After lab analysis of the samples, both the bailer and bottles were acid washed.

Water levels in the wells were measured by the calibrated nylon rope that lowers the bailer into the well. Originally, a

steel surveying tape was employed, but was found to be rusting, so it was discontinued. As the bailer encounters leachate, a tugging motion from leachate surface tension is easily felt on the rope. At this time, the spot where the rope and wellhead top match is marked and measured by a carpenter's tape to a known length on the rope. A tare of 1.64 m is added to to this length to account for the length of the bailer and rope from the defined zero mark on the rope.

B.   Static Gas Flow

For well flows of approximately 8.0 L/min and over, a Rockwell International RC-230 residential gas flow meter was used. For static flows generally less than this, the pressure flow was not great enough to turn the crank bracket in the meter, so alternative meters were tried. Both bubble flow and dial flow meters were tried, but had problems because tubing adapters were installed to match the flow meter's 1 cm diameter outlet with the well head 2.5 cm (ID) diameter sample tubing. In turn, this flow constriction decreased flow rates to give erroneous results. I solved the problem by going to small, one-liter plastic Safeway coffee bags that were easily calibrated to 0.5 and 1.0 liter volumes. To calculate flow rate, a stop watch was used to measure the time it took to fill up the liter bag. This technique is error prone, probably 15 to 20 % error, but was the only feasible technique available at the time.

The RC-230 residential flow meter has a rated flow capacity of 230 SCFH (110 L/min) and a total percent error of less than

1%. Greater error may exist in some measurements where well flow was measured above 110 L/min (ie, D9 and C6 Richmond).

C. Barometric Pressure

Barometric pressure was measured by a "Baromaster" barometer that was calibrated every two weeks from the Vancouver Intl. Airport Environment Canada weather station on the way to sampling Richmond landfill. Accuracy of this instrument was not documented in the user manual.

D. Temperatures

Ambient air, landfill gas and leachate temperatures were measured by a normal mercury-filled glass thermometer. This thermometer was encased in an unbreakable stainless steel sheath and lowered on string within the well to approximately 1 to 2 m above the water level to record well gas temperature. Problems with this method include well casing condensate contacting the thermometer. Leachate temperature was measured once the leachate was in the sample bottle.

E. pH

Leachate pH was determined less than 5 minutes after collection to guard against erroneous readings due to carbonate equilibria shifts. These equilibria shifts commonly occur from pressure and temperature changes of the leachate when the sample is brough up and out of the well. The field pH meter used was a Horizon #5996-30 battery-operated LCD-digital display meter. The power source is a Ni-Cadmium rechargeable battery. The pH electrode used was a 91-06 Orion epoxy body gel-filled

combination general purpose electrode. Calibration of the meter

with pH 7.0 buffer standard was practiced first thing every

morning at site and was checked periodically for calibration

decay. Decay was never found to be a problem as long as the

meter was set in stand-by mode between readings. This pH meter

also was equipped with manual temperature correction.

Documented accuracy of the pH meter is reported at $\pm$ 0.01

pH units with a resolution of $\pm$ 0.01 pH units. Results of an

accuracy comparison made in this study are summarized in Appendix

A.7 and detailed in Appendix A.6.

4.1.2. NH3-N GAS SAMPLING TECHNIQUE

NH3-N from landfill gas was sampled using a gas bubbler

containing a trapping solution of 20,000 ppm of boric acid. This

acid bubbler technique is common for sampling atmospheric ammonia

(see NRC, 1979), while using H_2SO_4 instead of H_3BO_3. The

technique is feasible for sampling low NH3-N concentrations

because large volumes of gas can be passed through the solution

concentrating the solution enough to be detected by normal

analytical techniques.

A schematic of this simple sampling technique is shown in

Figure 4.1. In summary, landfill gas is pumped from the

extraction well at around 6 L/min into the gas bubbler (#8 on

Fig. 4.1) where ammonia is protonated to NH_4^+, which then stays

in solution by reaction (i):

$$NH_3 + H^+ + H_2BO_3^- \dashrightarrow NH_4^+ + H_2BO_3^- \quad (i)$$
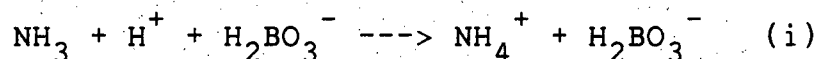
Boric acid is used as the trapping solution because it is

easy to handle in the field (a very weak acid), simple and inexpensive to prepare, and lastly, it showed the same NH3-N retention capacity as 0.1N H2SO4 and oxalic acid in limited tests run.

The gas bubbler is a glass Fisher-Milligan "gas washer" that is sealed at the screw-off cap by a rubber cap gasket. Connected on the cap is a glass flow tube where pumped gas flows through a 1.5 mm diameter flow constriction for maximum dispersion and out into the boric acid solution. Within the glass bubbler, is a spiral network of channeled glass which maximizes contact time of the bubble and solution. A solution volume of around 70 mL was found to be optimal since greater volumes seemed to leak from the cap gasket.

The sampling pump used is a Cole Parmer diaphragm-operated "Air Cadet" pump specially designed for pressure suction and gas circulated applications. This single-speed pump requires 12 volt battery power and can handle max. pressure loads of 15 psig. Maximum vacuum and gas flow are rated at 18 in. Hg and 18.8 L/min. The 12 volt pump motor has a capacity of 1/30 hp at 1650 RPM. Throughout the study period, the pump operated at around 6 L/min flow with occasional flow decrease from particulate matter clogging the valve seats.

The RD-230 gas flow meter was used to record the cumulative volume in liters, of gas that passed through the bubbler. To get ample NH_3-N mass for analysis, sampling was carried out for 30 minutes which results in just under 200 liters of total gas

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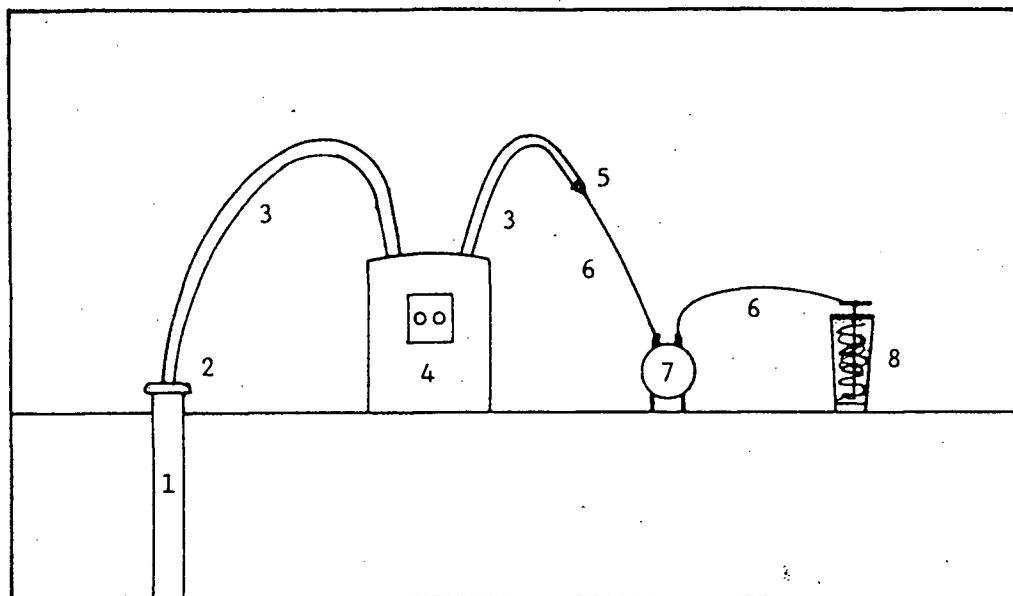
1. Gas extraction well

2. Special PVC well cap

3. 1" (2.5 cm) diameter tygon tubing

4. RD-240 Gas flow meter

5. Tubing reducers from 1" down to 3/8" (1.0 cm)

6. 3/8" tygon tubing

7. "Air Cadet" 12 volt pump

8. Gas bubbler

FIGURE 4.1 - Schematic for NH3-N gas sampling

volume being passed through the boric acid sample.

In order to decrease the potential for air and/or rainfall contamination, funnels were used to pour bubbler solution and sample into their respective containers. Evaporation of sample and ammonia contamination from human breath were considered negligible. After sampling, the gas bubbler was rinsed 2 times with ammonia-free distilled water. After every sampling run, the bubbler was throughly soaked in HCl cleaning acid.

Problems encountered during sampling included dirt and sand intrusion into samples and condensate build-up on sampling tubes. Condensate was especially apparent at Richmond landfill where the landfill gas is saturated with water vapor. A major concern with this condensate build-up was the potential sorption of NH_3-N onto the moistened sample tubes. On a number of occasions, this condensate was sampled at the end of the day by flushing the tube with 100 mL of distilled water.

Two ways were attempted to decrease condensate build-up on the tubes. One was to shorten the sample tube length, which did not help any, and two, was to insert a cotton plug at the front end of the tube. The cotton plug was found to be too porous in decreasing condensate build-up. I also rinsed the cotton plug after use and analyzed it on the autoanalyzer only to find no trace of NH3-N. The same problems occurred when using a Whatman No. 41 filter instead of the cotton plug.

One way I did not try is wrapping the sample train with thermal heating tape to keep the temperature above the dew point

of the gas while sampling.

Other than using the Whatman 41 filter for ridding the condensate build up, I did not at any other time prefilter the landfill gas before the sampling bubbler. Prefiltering is done to rid the gas of any interferring NH_4^+ that may be bound within the particulate aerosol. However, in high humidity environments like landfill gas, the filter medium can become a substantial removal mechanism of ammonia gas. Much of this sorbed ammonia could be protonated to NH_4^+ in the presence of acid-containing aerosols. This may be true in landfill gas where chlorinated hydrocarbons can react with water to form HCl on the filter medium. Work would need to be done to substantiate this claim.

In reality then, the ammonia gas analysis is actually measuring total ammonia ($NH_4^+ + NH_3$). The contribution of NH_4^+ in my analysis is questionable. Koike et al. (1973) found that by not prefiltering atmospheric gas streams for ammonia analysis results in a positive error of around 30 % results when not prefiltering the atmospheric gas stream during ammonia sampling (in NRC, 1979). In landfill gas this contribution could be less because a saturated landfill environment is probably a much more efficient sink for aerosol nuclei than in the atmosphere.

4.1.3. VOLATILE ORGANIC SAMPLING

The main goal of this phase of the sampling program was to qualitatively characterize or fingerprint the types of non-polar organics present within the landfill gas. The sampling technique was kept very simple and was limited to trapping only non-polar

organic contaminants. The sample train consisted of one Tenax GC adsorption trap. The simplicity of the sample train contrasts greatly to the elaborate sampling setups suggested by Krost et al. (1982), Bruckmann and Muller (1982), Brookes and Young (1983) and Young and Parker (1984).

The Tenax GC 60/80 traps were constructed from 1/4 inch (OD) brass in 3.5 in. lengths. Tenax GC material is packed within the trap and brass fittings are connected to each end of the trap. Prior to sampling, the Tenax traps were conditioned overnight at 300 oC. Once sampling was completed, the traps were capped by brass fittings and returned to the lab for GC-MS analysis (discussed later in this section).

Landfill gas organic contaminants were first sampled in late January, 1988 at Premier St. landfill. In addition to this sample, the next two samples from F5 Matsqui and C6 Richmond were trapped solely using well flow. At all three wells, well flow had to be reduced to approximately 40 mL/min to decrease the probability of any organic breakthrough out the end of the trap. Sampling proceeded for 20 minutes to pass a cumulative volume of 800 mLs through the trap.

After the samples were analyzed, potential contamination from the sample tubing was noticed, so the sampling technique was modified. To correct this problem, two SKC model 222-3 varaible flow personal sampler pumps from the UBC Health and Epidemiology Dept. were located. These pumps alleviated the problem of tubing contamination since the Tenax traps could be placed directly in

the well with suction being applied via the pump. Sample time

was increased to 40 min at a rate of 48 mL/min to get a much

greater volume of gas through the traps. This improved sampling

technique resulted in a much greater detection of organic

contaminants as will be shown later. In Well C6, condensate

build-up on the traps was found to be a problem during sampling.

4.2. LABORATORY METHODS

4.2.1. INSTRUMENTATION AND TECHNIQUE

4.2.1.1. LEACHATE CONSTITUENTS

The analytical methods used in this study of non-metal

leachate constituents are described in detail in Standard

Methods, 16 Edition, except where noted.

A. Alkalinity

The titration was performed to the pH 4.5 end point using a

Beckman 44 pH meter as per the 16th ed. of Standard Methods.

B. Chemical Oxygen Demand (COD)

COD measurement was done by employing the closed refux,

titrimetric technique as adapted for UBC as a lab standard from

the 13th ed. of Standard Methods.

C. Total and Organic Carbon

Both carbon forms were measured using a dual channel Beckman

915A Total Carbon Analyzer (TOCA) with a model 865 Beckman infra-

red detector. The chart recorder was a Kipp and Zonen BD41.

Accuracy of this method is documented at 1 % of full scale.

D.   Total Volatile Acids (TVA)

The distillation method in <u>Standard Methods</u>, 16th ed. was employed.   This method is limited to detection of organic acids containing up to six carbon atoms.

E.   Total and Volatile Solids

Same method used in <u>Standard Methods</u>, 16th edition. Leachate samples of 20 mLs were used.

4.2.1.2.   <u>SPECIFIC CONDUCTIVITY</u>

Specific conductivity of the leachate were measured in the laboratory because no field meters were available at the time. The lab conductivity meter was a Radiometer CDM3 with a model CDC 304 platinum electrode.   Measuring accuracy is $\pm$ 0.6 % of the standard deviation, except in measurements less than 500 umho/cm, where the accuracy decreases to $\pm$ 1.5 % of the standard deviation.   The platinum electrode has a cell constant of 1.00 cm^{-1} $\pm$ 10 %.   The meter has a cell constant correction dial which is used before sample analysis for calibration with 0.01 N KCl solution.

4.2.1.3.   <u>NH3-N DISTILLATION-TITRATION ANALYSIS</u>

Leachate samples were analyzed with the technique as reported in the 16th edition, <u>Standard Methods</u>.

Accuracy of this method has been reported to have a std. deviation of as great as 21.6 % for the lowest concentration measured of 1.5 mg/L.   Errors in this method could result from volume measurement errors and inconsistent acid normality of the 0.02 N H_2SO_4.

4.2.1.4. GAS CHROMATOGRAPHY/MASS SPECTOMETRY ANALYSIS

Qualitative analysis of the trapped volatile organics were done on a Hewlett-Packard GC/MS model 5985B equipped with a HP 7576 Purge and Trap device. The trapped organics were subjected to thermal desorption which involves the process of flash heating the Tenax GC trap with a flow of helium carrier gas. This releases the landfill gas organics that are subsequently carried by helium gas into a GC column where chromatographic separation takes place. This separation produces peaks of compounds when eluted from the column. These peaks are detected by a electron impact detector (EID). The compounds are further subjected to a quadrapole mass spectrometer which analyzes the generated mass spectra. The identification of these seperate organic compounds were achieved by library matching of the EPA/NIH Mass Spectra Library Data Base, and comparisons with published mass spectra.

The physical conditions used for these GC/MS analysis are presented below:

Desorb Temperature and Time : 180°C for 6 min

Column Type and Dimensions : Durawax Megabore Capillary column
50 % phenyl methyl silicone,
0.53 mm (ID) x 15 m

Temperature Program : 30(4 min hold) - 265°C @ 5°C/min

Interface Temperature : 250°C

Ion Source Temperature : 200°C

Scanning Parameters : 40-450 atomic mass units @ 1.5 A/D

Problems encountered with this trap analysis include some contamination of both tubing and trap bleed (styrenes and methyl

styrenes found), and poor chromatography, maybe due to CO_2 and water vapor interference.

4.2.1.5. METHANE GAS ANALYSIS

A Fisher Model 29 Gas Partitioner was used to separate common landfill gas components methane, carbon dioxide, nitrogen and oxygen into discernible peaks. These eluted peaks are detected by a thermal conductivity cell containing four tungsten filaments; two for reference and two for detection of the resultant change in thermal conductance when a gas compound passes by. The detector records these peaks on a Hewlett Packard 3380A Integrator, which with proper calibration, records these peaks as % volume of gas.

Originally, the gas is collected in the field by 50 mL glass vials that have a rubber septum withdrawl point and plastic stopcock inlet-outlet valves. When returned to the lab, a 1 mL syringe withdraws gas from the vial and injects it directly into the Gas Partitioner.

The two columns used to separate gas components are column 1: 6 ft x 1/4 in aluminum packed with 30 % DEHS on 60/80-mesh chromosorb; column 2: 6 1/2 ft x 3/16 in aluminum packed with 40/60-mesh Molecular Sieve 13x. CO_2 is separated through column 1, while other gases are separated through column 2. Carrier helium gas flows at 40 mL/min. The thermal conductivity detector temperature is around 70 $^{\circ}C$.

Reproducibility of this method is documented at $\pm$ 1 %. Results summarizing the accuracy of 10 injections of a standard

gas sample are listed in Appendix A.7. Raw data for this test is presented in Appendix A.1. In terms of potential error, my main concern resulted from leakage from sample vials during the time after sampling and before Gas Partioner injection. This concern warranted a investigation into this where all six sample vials were tested for leakage over a 2 day period. The gas source was the laboratory natural gas line that had over 80 % methane by volume. There was subsequent leakage in the vials as indicated in Appendix A.7. Detailed data for this test can be found in Appendix A.2.

Other errors in this analysis could stem from the leaky injection septum already mentioned or from inconsistent injection volumes. To ensure no lab air intrusion, the injection septum was replaced after every 25 to 30 injections.

4.2.2. AMMONIA GAS ANALYSIS

This section is concerned with describing the laboratory analysis of ammonia gas samples collected in the field. After returning the 70 mL boric acid samples to the lab, they were refridgerated at $4^{o}C$ or immediately analyzed. No acid preservation of the samples was needed since the boric acid samples were already at pH 4.0. Headspace loss of NH_3 was considered negligible during transport and storage of samples. Samples were analyzed on the Technicon Autoanalyzer II within 3 weeks after sampling. No sample decay during this period was assumed to occur since boric acid NH_3-N standards were found to stay stable for well over a month.

The boric acid NH_3-N standards had NH_3-N concentrations of

0.0, 0.05, 0.1, 0.2, 0.5, 1.0 mg/L and were loaded ahead and

behind the samples on the Technicon autosampler rack. All

standards and samples were analyzed in triplicate.

This autoanalyzer uses the automated phenate method to

analyze total ammonia (NH_3-N). As already mentioned, samples can

be analyzed at a rate of 60/hr when loaded with a 6:1 cam. The

technique is simply a reaction of ammonia with a sodium phenate

and hypochlorite solution in alkaline conditions. This forms a

quinochloramine compound that exhibits a distinct blue color

called indophenol blue. The blue color formed is intensified

further with the addition of the reagent sodium nitroprusside

($Na_2Fe(CN)_5NO \cdot 2H_2O$). This indophenol reaction is catalyzed by

heating of the solution at $50^{\circ}C$. The indophenol reaction is

shown below in Figure 4.3.:

FIGURE 4.3 - Indophenol Blue Reaction

(Taken from NRC, 1979)

$$NH_3 + HOCl = NH_2Cl + H_2O$$

indophenol
blue
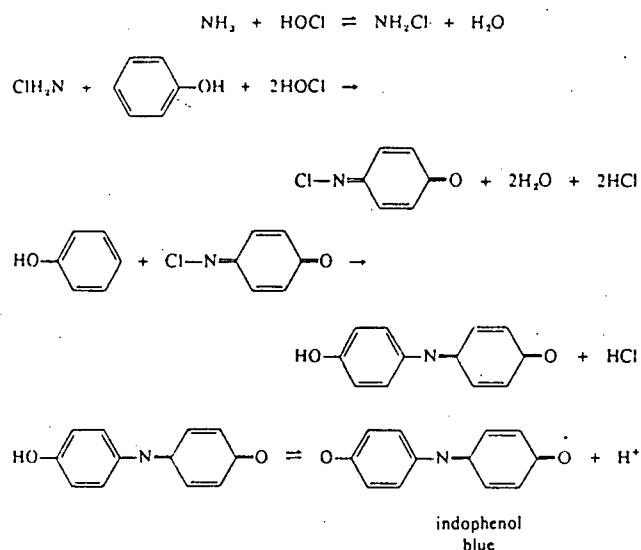
The resultant color intensity at 630 nm is analyzed in a 50 mm tubular flow cell by a colorimeter. This signal is then translated onto a Kipp and Zonen BD41 chart recorder. A flow chart of the complete Technicon Autoanalyzer II is shown in Figure 4.4.

FIGURE 4.4 - Technicon Autoanalyzer Flow Chart

(From Standard Methods, 16th Ed., 1985)
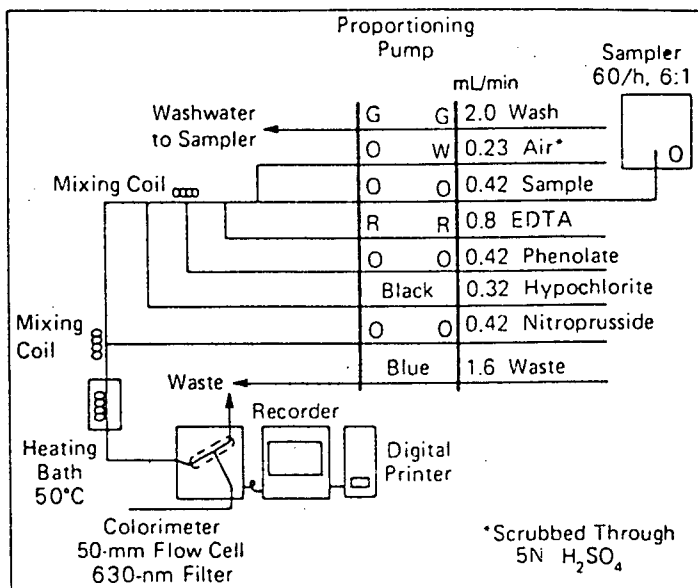
The peaks from the samples are translated onto a standard calibration curve to get NH_3-N in the sample (mg/L). This ammonia concentration is then multiplied by the sample volume (around 70 mL) to get the mass of NH_3-N in the sample. This mass is then divided into the total landfill gas volume that passed through the bubbler and multiplied by 10^6 to convert the concentration into ug/m^3. This concentration is then converted later into ppb as shown in Appendix B.4.

The advantages to using this automated phenate technique for ammonia gas are as follows:

   a. The automated indophenol-blue method is a proven
       analytical technique for trace levels of NH3-N greater
       than 0.02 mg/L.

   b. Can analyze a large amount of samples in a small period
       of time (60 samples/hr).

   c. Not a labor-intensive technique, except for preparation
       of standards and reagents.

   d. Flexibility of analytical technique to have the freedom
       to modify the analytical set-up for special needs, such
       as replacing certain reagents with other ones less
       affected by potential interferences. This technique
       will be discussed in detail later.

4.3. PRECIPITATION STATIONS

Precipitation data for each landfill site was collected from the closest certified weather station operated by Environment Canada. The three stations used and their respective landfill(s) are listed below:

```
Vancouver International Airport
     - Lat. Long.: 49.11 - 123.10
     - Elevation:   2.0 m
```

                    - Landfills: Stride Ave. and Richmond

Vancouver Harbour
        - Lat. Long.: 49.18 - 123.10
        - Elevation: Sea Level
        - Landfill: Premier St.

Abbotsford Station
        - Lat. Long.: 49.02 - 122.22
        - Elevation: 58.0 m
        - Landfill: Matsqui

4.4. BASIC DATA PARAMETERS MONITORED

The data collected for all parameters in each well is listed on tables in Appendix D. Associated statistics for each parameter is listed below the basic data for each well. Statistics calculated for each parameter were max, min, mean, standard deviation and % coefficient of variation (C.V.). The statistics help in understanding the variance of each parameter collected.

4.5. NON-BASIC DATA PARAMETERS

There are a number of parameters that were calculated from the basic data measurements or collected elsewhere. These parameters include: N_2/O_2 gas ratio, CH_4 flux, CO_2 flux, gas density, leachate ionic strength and activity coefficient, and lastly, site precipitation. These parameters are located in Appendix E presented in tables just like the basic data. Statistics on these parameters was not attempted since most of them are a function of the basic data. Examples of how each of these parameters were estimated or calculated is presented in Appendix B.

4.6. STATISTICAL ANALYSIS DONE ON PARAMETERS

In addition to the statistics done on the basic data, there were a number of other analysis done on the data to one, help describe causal relationships between parameters and two, try to predict both NH_3-N gas and CH_4 % through the regression of fitted parameters. These statistics include: linear bivariate regression, non-parametric K-S normality tests, Pearson product-moment correlation and lastly, multiple regression. Except for the bivariate linear regression, all other statistics were run on the UBC MTS mainframe program SPSS:X.

4.6.1. LINEAR BIVARIATE REGRESSION

Regression was done on six parameters versus NH_3-N gas in a first attempt to determine any relationships between parameters and NH_3-N in gas. These regressions were run on a LOTUS 1-2-3 spreadsheet and were specific to each well. Parameters that were analyzed include: gas temp., pH, ionic strength, NH_3-N in leachate, CH_4 flux and CO_2 flux.

4.6.2. PEARSON PRODUCT MOMENT CORRELATION

Correlation matrices were calculated for each well involving 13 variables to help in infering relationships between pairs of these variables. Pearson Product Moment Correlation calculates a correlation coefficient and its associated level of significance. All correlations whose p value was greater than 0.025 were rejected as being insignificant. Results of these correlations are summarized in Appendix F.3.

The product moment correlation coefficient (r) is used to

explain the fraction of variance of one variable by another variable. A high correlation coefficient ≤ 1.0000 infers a greater commonality between variables than a lower one. A high negative correlation coefficient ≥ -1.0000 expresses a large negative effect one variable has over another (ie, an increase in one variable results in a decrease of another).

4.6.3. KOLMOGOROV-SMIRNOV GOODNESS OF FIT TEST

This method is a non-parametric test to determine whether or not each variable is normally distributed. Tests were run on separate and then combined wells to check for normality. This test was especially important for multiple regression, which requires normally distributed data for accurate results. All variables in separate well tests were found to be normal with non-normality occurring during combined well tests for some variables. Non-normal variables were discarded from further analysis in multiple regression. In the K-S test, all variables below the p value of 0.05 were considered non-normal. Results of these tests are listed in Appendix F.2.

4.6.4. MULTIPLE REGRESSION ANALYSIS

In an attempt to predict NH_3-N gas and CH_4 % from available data, multiple regression was used. The form of the multiple regression equation used is below:

$$Y = A + B_1X_1 + B_2X_2 + B_3X_3 + \ldots B_nX_n$$

Where Y is the dependent variable
    A is the Y-intercept (or constant)
    B_n is the partial regression coefficient
    X_n is the independent variable

In this equation it is shown that the larger the partial

regression coefficient, the more influence its corresponding independent variable has on estimating or predicting the dependent variable.

Stepwise regression was used in this analysis. The first step in this form of regression is for the independent variables to pass a tolerance test before entering the equation. The tolerance test is the proportion of the variable's variance not accounted for by other independent variables in the equation. The default tolerance of 0.010 was used.

After passing the tolerance test, the independent variable with the lowest probability of F value is entered into the equation. If a variable has an F that exceeds Pout (set at 0.010), it is removed from the equation and another variable not in the equation is tested. This iterative method proceeds until no variables not in the equation are eligible for entry (SPSS:X Users Manual, 1983).

In addition to regression equation statistics, statistical analysis was done on the residual error of the equation. The residual analysis was helpful in determining the viability of the resultant regression equation. This was done by inspection of the normal probability and residual scatterplots. If any excessive non-linearity was found, the equation was considered suspect.

CHAPTER 5

5. RESULTS AND DISCUSSION

5.1. AMMONIA GAS ANALYTICAL TECHNIQUE

    5.1.1. PROBLEMS ENCOUNTERED ON AUTOANALYZER

Other than the problems already discussed concerning the field sampling technique, there were a number of problems that arose during the laboratory analysis of NH_3-N gas. These concerns or problems are listed below:

A. Sensitivity - Because of low standard concentrations of down to 0.05 mg/L, the gain on the instrument was increased from the normal 200 to 500. This had the effect of increasing the sensitivity, but also increased signal noise.

B. Baseline wandering - Blanks were added to the sample train every 5 or 6 samples to locate baseline drift.

C. To hopefully intensify the indophenol blue even further, 0.5 % potassium ferrocyanate was added in place of Na-nitroprusside. The results however, only increased signal noise.

D. Because my gain settings and standards were different from other lab projects using the autoanalyzer, my samples were run at the end of the day. This late day analysis seemed to cause problems from possible aged reagents and a "tired" signal response. However, tests comparing day-old and freshly made up phenate showed no change in signal response. Flushing of the autonalyzer with distilled water before my sample analysis was always done.

E.   Suppressed Signal Response - Concern for a suppressed signal response from the boric acid standards and samples was layed to rest when standards of boric acid-NH_3-N and distilled water-NH_3-N were run side by side. Accompanying the boric acid was two other acids used commonly in ammonia absorption, 0.1N H_2SO_4 and oxalic acid. The comparison of signal responses are shown in Figure 5.1. Direct inspection of the four standards indicate about an equal signal response when subtracted from their blank response. A table of % signal response is shown below:

TABLE 5.1 - Results of Signal Response Comparison

==

Standard (mg/L)	Water	Boric	H_2SO_4	Oxalic
1.0	36.7	38.5	39.0	38.3
0.5	17.7	21.5	21.0	20.2
0.2	12.8	8.5	8.2	8.1
0.1	4.6	4.5	2.7	4.0

==

F.   Temperature and pH effects - These effects were not investigated, but studies from other investigators is worth mentioning. The pH for optimal color was found to be from 11.3 to 11.7 (Scheimer, 1976). Because of the presence of a weak acid, it is highly doubtful that this pH was ever reached in the automated analysis. However, no decrease in signal response is found when compared to the distilled water, so pH effects may not make a difference. Stewart (1985) on the other hand, looked at temperature responses and found that the initial temperature at
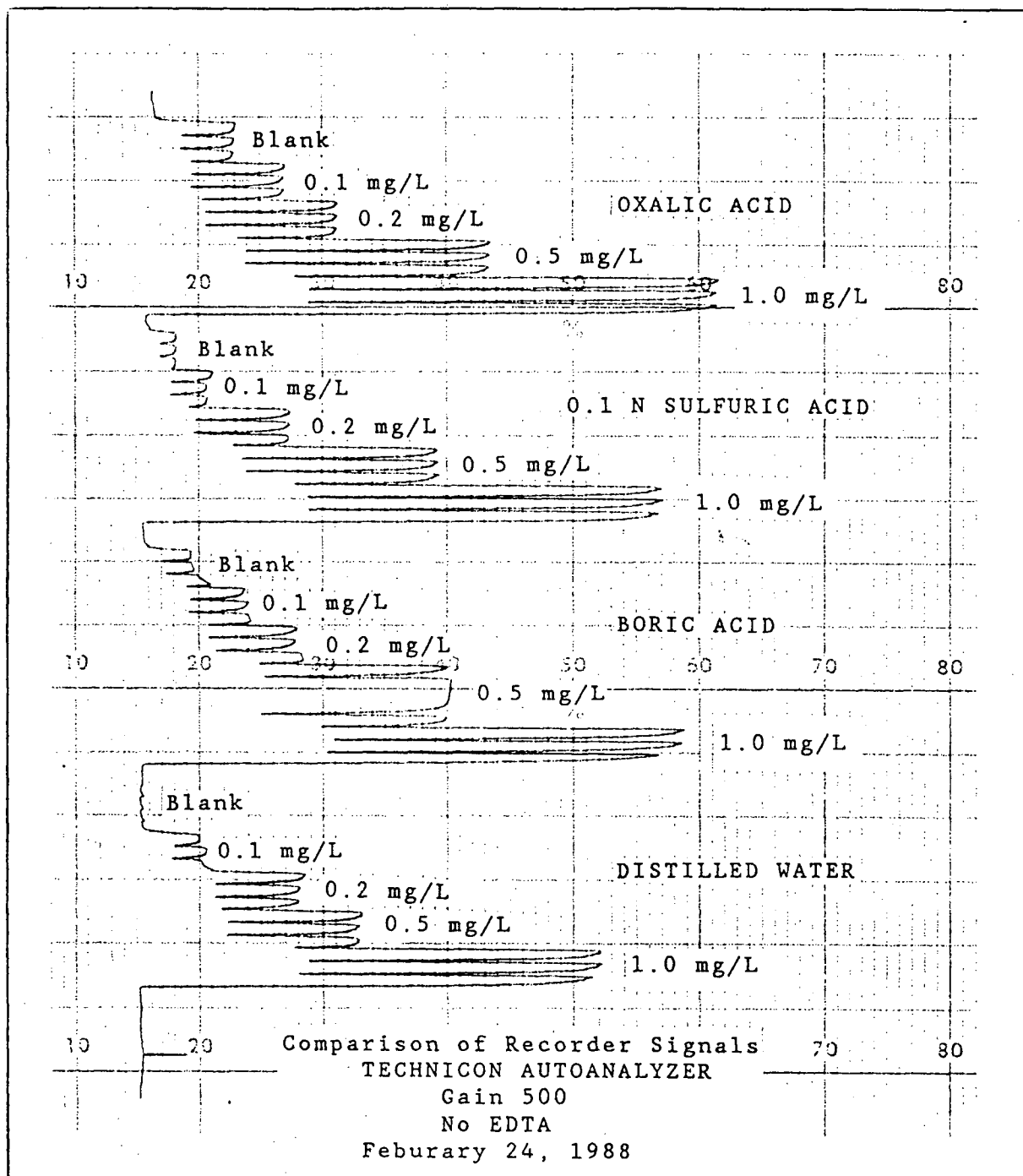
FIGURE 5.1 - Comparison of Signal Responses From Standards of
Four Solutions

reagent mixing was found to determine the final color absorbance of the solution and any further increase in temp. ($50^{\circ}C$) only catalyzes the time to reach maximum absorbance. This is interesting, because mixing of chilled samples and room temperature standards could result in variability of signal response.

5.1.2. INTERFERENCES

After preliminary analysis of data showed NH_3-N values lower than expected, an investigation was initiated to determine if there is any negative interferences in the analytical technique. Potential negative interferences are listed below in point form:

1. Landfill gas compounds could cause a decrease in absorbance of NH_3-N into the boric acid solution by acting as a carrier or complexer of the ammonia gas. This effect could result in an recovery efficiency lower than estimated. The main cause to this is aqueous carbon dioxide, which can covalently bond with NH_3 to form carbamic acid $NH_3 \cdot CO_2$. This carbamic acid has been mentioned to be quite volatile (Hales and Drewes, 1982) and could carry substantial amounts of NH_3 from solution and out of the bubbler. This is especially true where CO_2 can exceed 45 % by volume in landfill gas. More work would have to be done to substantiate this claim.

2. Another possible negative interference could result from soluble gas components affecting indophenol blue color development in the autoanalyzer. Detailed investigations have been done on this problem by Bolleter (1961), Scheiner (1976) and

Ngo et al. (1981) for other chemical applications on the autoanalyzer.

Soluble and volatile compounds that are usually in landfill gas that could depress the color formation include the following: compounds with an amino functional group such as amines, hydrogen sulfide and thiol group compounds and lastly, carbon dioxide. Amines are a common decomposition product of protenaceous matter and could be adsorbed into boric acid at sub-ppm concentrations. A more likely suspect however, for causing odor suppression are the soluble sulfur group compounds. Especially apparent is H_2S, which has been detected at up to 1000 ppm in Richmond landfill gas. Both thiol compounds and H_2S are strong reducers that Ngo et al. (1982) suggests could deplete the concentration of the strong oxidizer hypochlorite, which is required for the formation of indophenol blue. Koroleff (1970) concludes from his study on sludge analysis that total sufides can be present in up to 2 mg/L in a sample without causing interference.

If total sulfides are in ppm concentrations in landfill gas, what fraction of this is going to be converted to sulfates by oxidation from sample handling and more likely, from oxygen found within the landfill gas? Unfortunately, this study did not attempt to determine sulfate concentrations in samples before and after sampling to see if there is any substantial difference.

In an attempt to rid the sample from thiol reducers and H_2S, two tests were attempted on Richmond Landfill samples. First, pre-distillation was performed on samples that were trapped by

boric acid. The results of this test showed no increase in signal response over the undistilled samples. The second test involved adding H_2O_2 directly to samples before autoanalysis to oxidize any reducing compounds. This test was unsucessful, because it caused increased color interference in the sample after reagents were added.

A last-ditch effort to determine if negative interferences were apparent in samples was the running of standard addition tests. The samples run were from F1 and F3 Matsqui, and D9 and D.55 Richmond.

The resultant concentrations and their differences are shown below in Table 5.2.

TABLE 5.2 - Results of Standard Addition Tests

Well	Measured (mg/L)	Std. Addition	% Diff.
D9 Richmond	0.500	0.500	0.0
D.55 Richmond	0.200	0.250	+ 25.0
F1 Matsqui	0.095	0.125	+ 31.0
F3 Matsqui	0.113	0.125	+ 11.0

Inspection of the results do indicate a depressed concentration in some of the samples, which would be common if there were negative interferences. However, these results should be treated with caution since more standard addition work needs to be done. This difference in concentration could also be due to sample variance.

5.1.3. DETECTION LIMIT

The detection limit of this technique was found to be 0.03 mg/L. This compares favorably to Dawson (1978) and NRC (1979), who mention detection limits of 0.02 and 0.01 mg/L. A sample concentration of 0.03 mg/L is about 12 ug/m^3 (9 ppb) of NH3-N when the total gas volume is around 175 liters. So in summary, this method detects NH$_3$-N concentrations generally greater than 10 ug/m^3.

5.1.4. PRECISION

Tests on 0.2 and 0.5 mg/L standards indicate a relative standard deviation of 2.0 and 1.5 % respectively for 11 samples each. This compares favorably with values of 0.5, 1.0 and 2.0 % mentioned in Standard Methods, 16th Edition, Scheiner (1976) and O'Brien and Fiore (1962) respectively.

Reproducibility was not as great in the limited number of samples tested. Relative errors ranged from 4.5 to 8.5 % in these samples.

Accuracy of the technique was not attempted, since all samples were at too low a concentration for comparison with the distillation-titration technique. Comparison with an ion-specific electrode was also ruled out because of questions of accuracy concerning the electrode. One comparison has been made by Scheiner (1976) of the indophenol method and distillation. Results from this paper indicate a relative error of 5.2 % at 2 mg/L, which was the lowest concentration tested.

5.1.5. RECOVERY EFFICIENCY

Originally when this study began, I assumed that the bubbler technique would collect NH_3-N in quantitative form (100 % collection efficiency). However, after analyzing the data, tests were run to calculate a recovery ratio that could be applied to the measured NH_3-N to get a more accurate corrected concentration.

Determining a recovery ratio became a more difficult task than previously expected. The first attempt involved injection of small volumes of "pure" ammonia gas into a large garbage bag that was filled with air up to 180 liters. The ammonia "standard" was then pumped through the bubbler simulating field conditions. These injections varied from about 25 to 100 uL of ammonia, which is equivalent to 43 to 172 ppm of ammonia. High ammonia amounts were used to see if this technique could be applied in determining recovery efficiency. However, the results were disappointing, with very little if any ammonia detected by the autoanalyzer. The problem with this technique seemed to result from how the ammonia gas is sampled from the lecture cylinder that contained pure ammonia. Because of no direct sample path into the lecture cylinder, the gas had to first be stored into a sample vial equipped with a rubber sample port, then withdrawn from the sample vial by the syringe. This was then directly injected into the filling garbage bag. The errors seem to result in not enough flushing of the sample vial to get pure ammonia gas, or could be due to diffusion of ammonia from

the garbage bag into the lab air before going through the bubbler to be absorbed.

The next attempt with prolonged flushing of gas through the sample vial did not improve the results. Two samples of 100 uL injection did indicate an uncertain recovery efficiency of around 10 % at flows of 11.5 L/min.

The last attempt to determine a recovery efficiency was to go in a different direction than before. The technique used at this time was to sample the filtered air from the laboratory air lines, since blanks were found to contain enough ammonia (100 ug/m^3) for analytical detection. The apparatus used in this test had three bubblers in series with the gas passing through each one. Each bubbler had the usual volume of 70 mLs of boric acid, and air flow was varied from 2.1 to 11.5 L/min. This type of apparatus was first used by Okita and Kanamori (1971) testing the collection efficiency of glass impingers in a 0.1 N H_2SO_4 solution at a flow rate of 1.5 L/min. Their ammonia standard was reported to be 30 ppb. Their recovery efficiency for the first impinger averaged about 50 %.

My results are summarized below in Table 5.3 for the three flow rates. The raw data is listed in Appendix A.3. Recovery efficiency for the normal 6.0 L/min flow is estimated at around 50 %. This "safe" efficiency was estimated by assuming a very modest 30 % recovery efficiency in the third bubbler and taking into account, one, the standard deviation of these results, two, the decreased recoveries in field conditions and three, many of

the NH_3-N gas values are much less than the ambient air NH_3-N concentrations used in this experiment.

TABLE 5.3 - Results of Recovery Efficiency Tests

Flow (L/min)	Mean Concentration in each bubbler (ug/M^3)			Escape From 3rd (ug/M^3)	Recov. Eff.	"Safe" Eff.
	1	2	3			
6.0	107.0	28.4	22.9	16.0	61.4 %	50 %
10.5	89.8	38.5	24.2	16.9	53.0 %	45 %
2.1	140.3	36.0	58.1	40.7	51.0 %	45 %

Interestingly enough, the other two flow rates show a lesser recovery efficiency than the 6.0 L/min. My assumptions were that recovery efficiency should be greater in lower flows, but this is not the case. This was also shown to be the case by Okita and Kanamori (1971) using 0.02 N sulfuric acid and 1.5 L/min flow. In contrast, Morgan, Golden and Tabor (1967) indicate almost 100 % recovery efficiency from a bubbler solution containing 0.05 N sulfuric acid and 0.5 L/min flow. The high flow rate of 10.5 L/min gives approximately the same recovery efficiency as the low flow rate. The results indicate an efficiency of no greater than 50 % and more like 45 %. These results concur with the high flow efficiencies measured by Kawamura and Sakurai (1966), who calculated efficiency values of 0, 20 and 51 % for 0.02 sulfuric acid solution and 15 L/min flow (in Okita and Kanamori, 1971).

In spite of the analytical uncertainty, this 50 % recovery

efficiency seems to be representative of the kind of recovery
this sample technique gets in actual field conditions.

5.2. TEMPORAL AND SPATIAL VARIATION OF DATA

5.2.1. VARIATION IN COLLECTED DATA

As mentioned in Chapter 4, the results for all the basic
data parameters are listed in Appendix D. Inspection of the
statistical results on each parameter (ie, min., max., % C.V.)
indicate some interesting trends. For instance, inspection of
the C.V. indicates in most instances, the variability was
greatest in NH_3-N gas and static gas flow, while pH, barometric
pressure and leachate temp. exhibit the lowest sample variance.

5.2.2. NON-METAL LEACHATE CONSTITUENTS

Analysis of non-metal leachate constituents from gas
extraction wells was done twice during the study in an attempt to
show temporal changes and relative differences in leachate
strength between each landfill. The results comparing the
September and January samples are presented concurrently in
Tables 5.4 to 5.7.

In general, leachate strength was highest in the younger
landfills and lowest in the older fill, Stride Ave.. Chemical
oxygen demand (COD) is one constituent that indicates this
relationship. In Matsqui and Richmond landfills, various wells
indicate a fairly high COD (average over 1000 mg/L) whereas
Stride Ave. averages less than 150 mg/L. This reflects Stride
Avenue's much older fill age where most of the soluble organic
material is probably stable humic and fulvic acids. In contrast

to COD's, most of the results indicate TVA values in Stride Ave. to be comparable to the much younger leachate of Richmond landfill. TVA is considered the most readily biodegradable substrate for methanogen utilization and is usually more abundant in young landfills. This anomalous similarity in TVA values may be a result of the much higher methane production rates exhibited by Richmond landfill, where any available TVA in the leachate is consumed. Overall, the highest TVA amounts were from Matsqui, which was expected since the strongest leachate odors usually emanated from those samples.

Matsqui landfill also exhibits very high NH_3-N leachate concentrations in two of the wells (F1 and F5) and could be indicative of the high protein in animal waste that was dumped at this landfill. All three younger landfills exhibit high proportions of TOC, which may be a resultant of the organic liquid waste and sludges reported to be dumped in these landfills over their lifetime.

An interesting point to all of this analysis is that one would assume after noticing the relative low values of TOC and COD from Stride Ave that this landfill would exhibit low CH_4 percentages. However, this is not always the case if one notices CH_4 % values in Appendix D for wells F2, F3, F7, F8 where CH4 % generally exceeds 40 %. This might be a resultant of the relative high TVA values already discussed or because during the study period this extraction well system was never operational.

In most instances, temporal variation between samples taken

- Matsqui Landfill -

Well No.	DATE	pH	Specific Conduct.	Alk.	NH3-N (mg/L)	COD (mg/L O2)	TC	TOC	TVA	Total Solids	Volatile Solids	% Vol. Residue
F1	Feb. 88	6.34	21,200	7500	2669.3	35,100	16,300	16,225	21,736	30,350	18,290	60.3
F2	Sept. 87	7.40	3640	1254	252.0	1716	480	295	--	--	--	--
F2	Feb. 88	6.29	1083	340	70.6	2344	1135	1035	208	3555	1465	41.2
F3	Feb. 88	6.60	1660	375	142.8	712	805	660	201	3710	1060	28.6
F5	Sept. 87	6.82	21,913	6650	1891.6	30,400	10,900	10,637	15,390	28,635	18,575	64.9
F5	Feb. 88	6.17	4405	1120	300.6	5634	2240	2065	2784	4530	2440	53.9
F8	Feb. 88	5.79	439	153	1.4	--	--	--	12	500	100	20.0

- Stride Ave. Landfill -

Well No.	DATE	pH	Specific Conduct.	Alk.	NH3-N (mg/L)	COD (mg/L O2)	TC	TOC	TVA	Total Solids	Volatile Solids	% Vol. Residue
F2	Sept. 87	6.46	1182	577	1.8	200	178	N.D.	40	781	165	21.1
F2	Feb. 88	6.26	1270	594	4.1	60	240	30	112	1410	685	48.6
F3	Sept. 87	6.38	999	472	2.9	64	83	N.D.	60	785	225	28.7
F3	Feb. 88	6.14	977	459	7.1	112	217	71	86	985	380	38.6
F6	Feb. 88	5.88	839	333	15.4	124	147	26	255	1070	690	64.5
F7	Sept. 87	6.25	1089	495	15.4	128	105	39	70	1256	309	24.5
F7	Feb. 88	6.31	1081	504	9.5	248	189	167	251	1490	390	26.2
F8	Feb. 88	5.86	763	351	2.8	92	120	21	237	860	250	29.1
10B	Sept. 87	6.04	1377	609	1.2	160	120	N.D.	89	1178	387	32.8

Specific Conductance in umho/cm
Alkalinity in mg/L as CaCO3
TC = Total Carbon (mg/L as C)
TOC = Total Organic Carbon (mg/L as C)
TVA = Total Volatile Acids (mg/L as Acetic Acid)

TABLES 5.4 & 5.5 - NON-METAL LEACHATE CONSTITUENTS IN MATSQUI AND STRIDE AVE. LANDFILLS

- Richmond Landfill -

Well No.	DATE	pH	Specific Conduct.	Alk.	NH3-N (mg/L)	COD (mg/L O2)	TC	TOC	TVA	Total Solids	Volatile Solids	% Vol. Residue
B8	Sept. 87	6.40	3301	1215	122.1	1137	335	146	452	2429	1190	49.0
B8	Feb. 88	6.16	1755	1719	58.2	237	350	20	128	1105	490	44.4
D9	Sept. 87	6.80	8347	2320	378.0	1217	1230	495	348	4766	1410	29.6
D9	Feb. 88	6.81	7493	390	425.6	1473	1340	470	360	4300	1365	31.8
C6	Sept. 87	6.42	2732	920	23.5	1321	290	105	452	2142	1473	68.8
C6	Feb. 88	6.17	2177	555	16.8	1175	670	320	592	1980	800	40.4
G7	Sept. 87	6.48	3426	1340	73.9	342	305	109	191	2291	843	36.8
G7	Feb. 88	6.11	1835	525	25.8	157	360	N.D.	80	1280	270	31.1
D.55	Sept. 87	6.74	4243	1760	113.1	653	330	70	209	3030	1015	33.5
D.55	Feb. 88	6.40	3465	1260	101.9	410	730	45	108	2345	830	35.4
B.53	Sept. 87	6.58	3432	1420	121.0	453	315	108	139	2252	652	29.0
B.53	Feb. 88	6.22	1394	360	22.4	76	205	10	35	770	395	51.3

- Premier Street Landfill -

Well No.	DATE	pH	Specific Conduct.	Alk.	NH3-N (mg/L)	COD (mg/L O2)	TC	TOC	TVA	Total Solids	Volatile Solids	% Vol. Residue
P1	Sept. 87	6.72	6683	1840	213.9	690	815	350	166	3965	885	22.3
P1	Feb. 88	6.67	5915	1320	254.2	487	720	130	100	3860	805	20.9
P2	Sept. 87	6.74	6411	1820	221.8	444	768	108	145	3432	909	26.5
P2	Feb. 88	6.75	5459	1200	231.8	447	670	95	120	3065	610	19.9

Specific Conductance in umho/cm
Alkalinity in mg/L as CaCO3
TC = Total Carbon (mg/L as C)
TOC = Total Organic Carbon (mg/L as C)
TVA = Total Volatile Acids (mg/L as Acetic Acid)

TABLES 5.6 & 5.7 - NON-METAL LEACHATE CONSTITUENTS IN RICHMOND AND PREMIER ST. LANDFILLS

in September and then in January is fairly low. The wells that show large decreases in concentrations are mostly due to large volume dilution from excessive rainfall infiltration. This is especially apparent in Richmond landfill wells and F5 Matsqui where fresh water has entered the well above the leachate due to a crack in the casing caused by landfill subsidence. In Richmond, high volumes of rainfall have diluted leachate because of the landfill's porous sand cover coupled with an already high water table. Some wells such as F2 Matsqui, F2 and F7 Stride indicate increased leachate strength, which is most likely due to precipitation infiltration flushing out organics from the unsaturated zone which are then deposited into the leachate.

5.2.3. PRECIPITATION

Comparison of weekly precipitation from the three weather stations is shown below in Figure 5.2. The weekly precipitation data is presented in Appendix C. In general, the wettest weather station of the three is Vancouver Harbour, which receives over 1600 mm precipitation per year. The dryest station is Vancouver International that averages just over 1100 mm/year.

Inspection of Figure 5.2 indicates an unseasonably dry and mild autumn and mid-winter period where minimal amounts of precipitation occurred. These periodic dry periods helped in keeping cumulative precipitation over 20 % below normal throughout the study period.

FIGURE 5.2 - Comparison of Weekly Precipitation From Three
Weather Stations

Note : Vancouver Harbor Station was discontinued at end of March
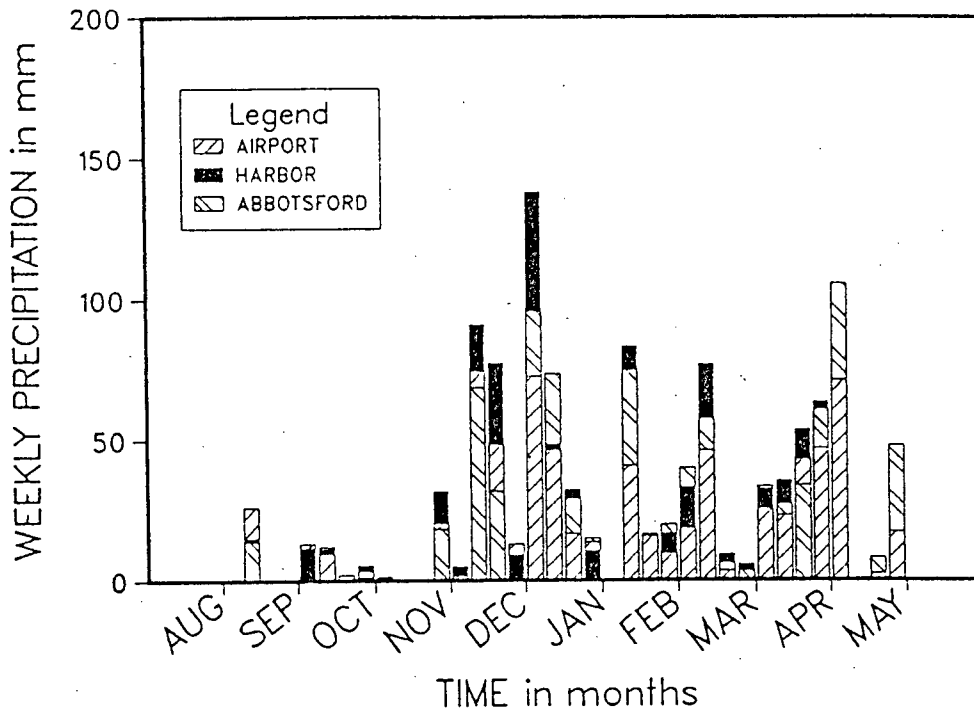
The results discussed previously and ones presented later
indicate that excessive infiltration of this precipitation may
cause the greatest changes in leachate strength and gas
production. Although an increase in moisture content has been
found by many authors (see Chapter 2 - Lit. Review) to help gas
production, this study found the opposite when excessive
precipitation fell on the study areas. This was especially
evident after large precipitation episodes. To strengthen this
observation, correlation analysis'usually indicate a strong
negative relationship between precipitation and various other
parameters (See Appendix F.3). The main reason for this negative

correlation is probably either from volume dilution of leachate or the precipitation shock loading the unsaturated zone microbial population. This has the effect of decreasing gas production. One sample well, P2 Premier St. responded quite abruptly with increased precipitation infiltration. Results presented in Figure 5.3 indicate CH_4 % dropped very rapidly from over 50 % to 5 % (See Figure 5.4) in less than a month after a major precipitation influx in mid-November. The percent methane never recovered throughout the rest of the study period. The contribution of precipitation in decreasing the gas percentage at P2 Premier is not clear, since the well is on vacuum during the winter months. This vacuum may cause the gas sample to be diluted with atmospheric air from air intrusion. So these samples may be unrepresentative of the unsampled CH_4 concentration deeper in the well. Other wells plotted in Fig's 5.3, 5.5 and 5.6 do not indicate accelerated drops in CH_4 % but do exhibit a general decrease throughout the study period.

In addition to a methane production drop, CO_2 % changes were analyzed to see if increased precipitation would result in decreasing CO_2 % relative to methane percent. The added precip. was generally believed to resolubilize a fraction of the CO_2, taking it out of the gas phase. Results however, indicate no profound relationship between CO_2 % and precip., except in F7 Stride (See Fig. 5.6) where some drop in CO_2 % in Feburary-March may be due to this or to a microbially mediated phenomenon.

FIG. 5.3 -

TEMPORAL VARIATION OF WEEKLY PRECIP. vs. GAS %
G7 RICHMOND
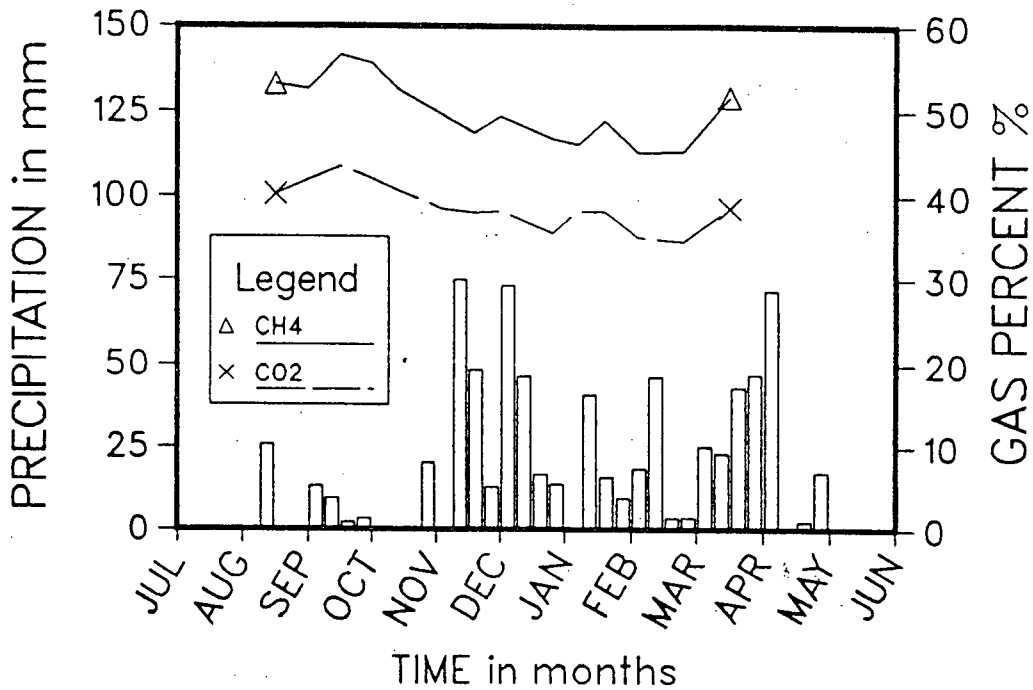
P2 PREMIER St.
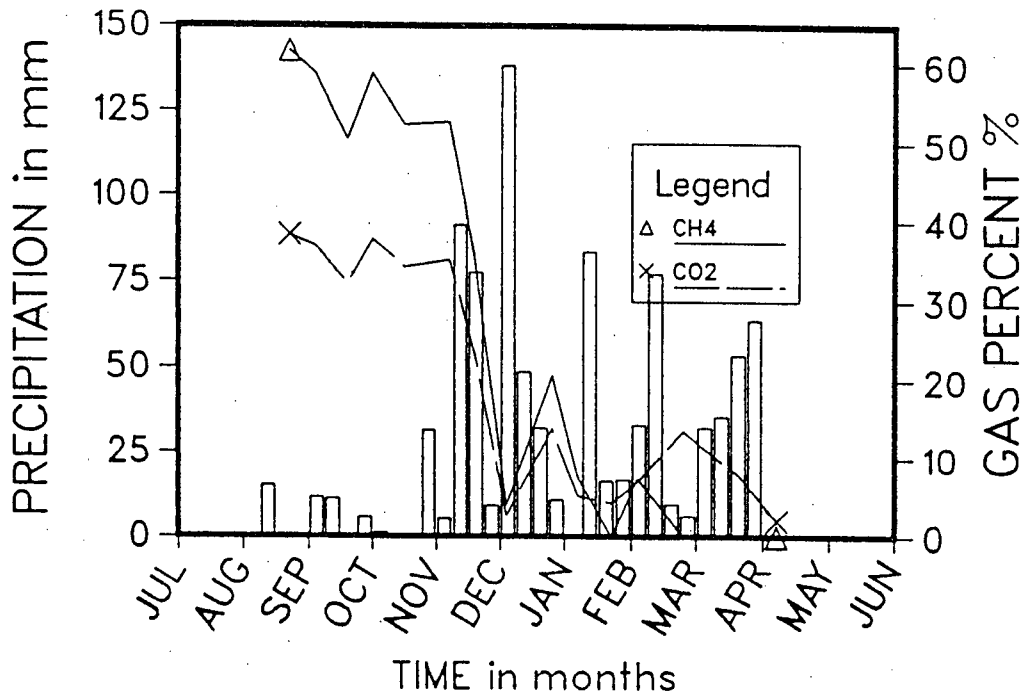
FIG. 5.4 -

TEMPORAL VARIATION OF WEEKLY PRECIPITATION VS. NH3-N
GAS, P2 PREMIER STREET

FIG. 5.5 -

TEMPORAL VARIATION OF WEEKLY PRECIP. vs. GAS %
F3 MATSQUI

Legend
△ CH4
× CO2

TIME in months

F7 STRIDE

Legend
△ CH4
× CO2

TIME in months
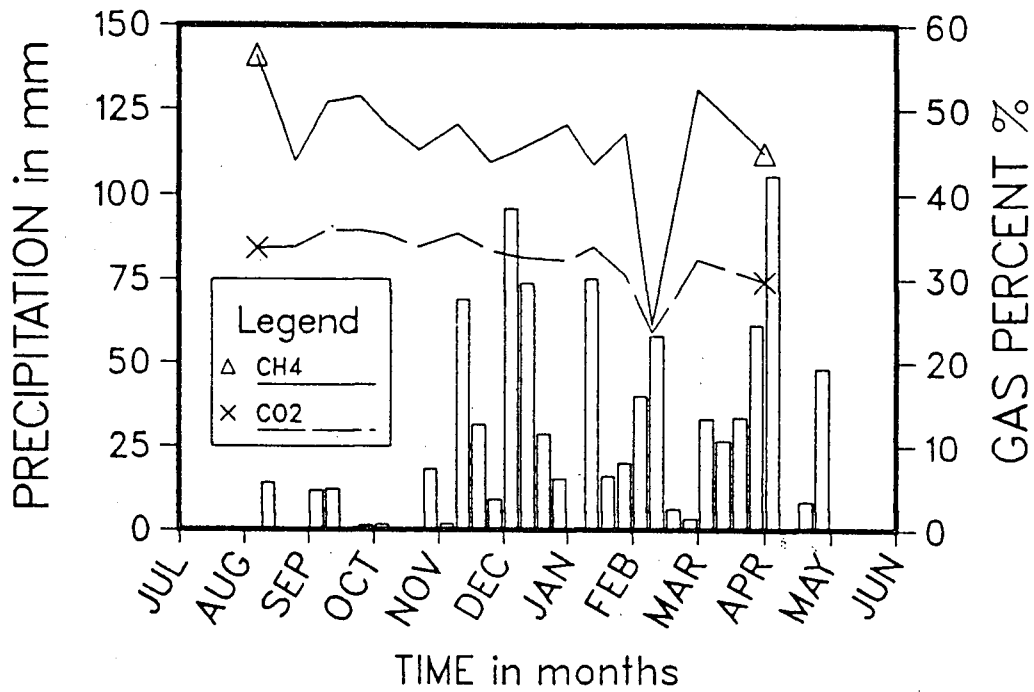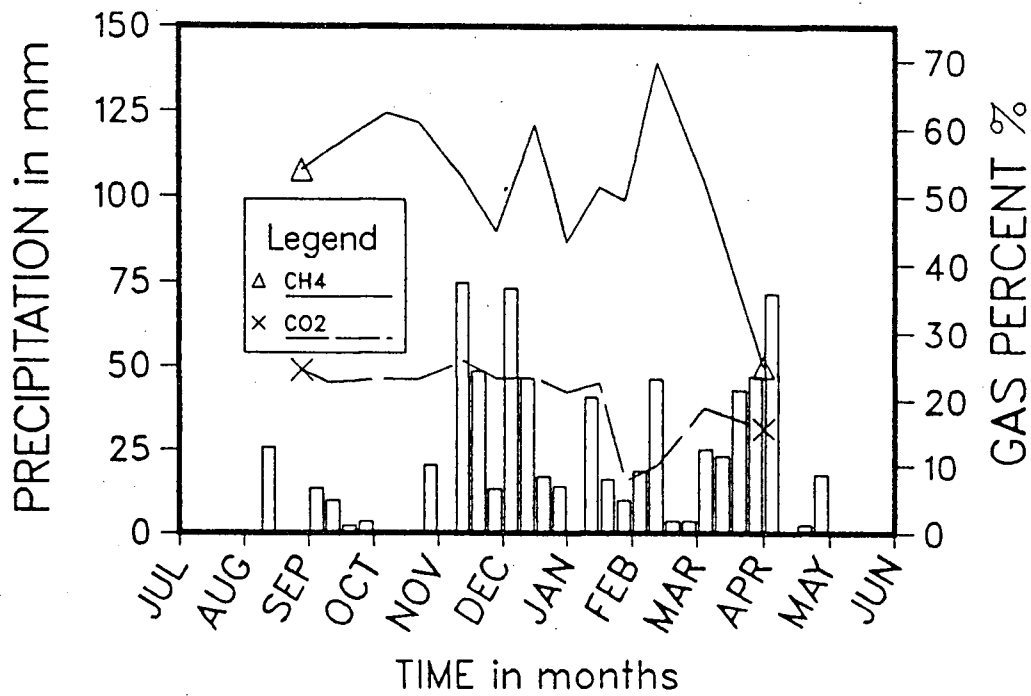
FIG. 5.6 -

TEMPORAL VARIATION OF WEEKLY PRECIPITATION VS. NH3-N
GAS, F7 STRIDE AVE.

5.2.4. TEMPERATURE

In all wells, there was a general decrease in gas and water
temperature with the colder winter months. Temperature profiles
for four wells are presented in Figs 5.7 through 5.10.. In
general, most gas temperature fluctuations reflect a fluctuation
in ambient air temperature in the more mild fall months preceeded
by more divergence in the winter months. This difference in
winter months between gas and air temperature may be regulated by
the insulating ability of the landfill. Also, precipitation
infiltration may help in depressing gas temperatures even more.
This may be the case in G7 Richmond (See Fig. 5.9) where the
temperature range goes from 29 to 8°C. The other three deeper
wells located in different landfills decrease to no lower than a
"threshold temperature" of about 12°C. This temperature could
again be due to the better insulating capacity and lesser precip.
influx at these landfills than in Richmond. In contrast to well
G7, some wells like D9 Richmond exhibit very little decrease in
leachate (Tw) and gas temperature (Tg) over the study period. D9
Richmond temperatures were consistently the highest measured and
ranged from a Tg of 32 - 16°C to a Tw of 28 - 23°C. The reason
D9 Richmond may be relatively unaffected by precipitation
infiltration and colder air temperatures like other Richmond
wells, could be due to a very efficient biological system that
creates large volumes of insulating heat. The differences
between temperature ranges in all the Richmond study wells give
an indication of how much spatial heterogenity can occur within

the same landfill.

Within all the wells studied, the temperature ranges for gas, leachate and ambient air were 32 - 7°C, 28 - 7°C and 26 minus 3°C respectively.

The decrease in air and gas temperature indicate an overall mixed pattern of methane percentage for most of the wells. In Richmond Landfill, the temperature drops did not seem to effect CH_4 %, while in Stride Ave (F2 and F3), there are sometimes large decreases due to temperature drops. However, the effect that temperature drop is not certain because of the coupling effect precipitation infiltration may have in controlling both temperature and CH_4 %.

One observation directly related to temperature was freezing of the landfill surface during the cold winter periods. This was especially apparent at Matsqui landfill where precipitation infiltration could be inhibited by the frozen surface, which in effect may have helped gas production while offsetting some detrimental effects caused by cold temperatures.

5.2.5. OXIDATION REDUCTION POTENTIAL

Another parameter related to precipitation infiltration and could be very important in controlling gas production is ORP. As already mentioned, methanogens require an Eh of -200 to -300 mV for proper growth and are very sensitive to changes in ORP. Infiltrating rainwater in most cases has a positive Eh that may cause a shock to methanogenic bacteria hence, lowering gas production rates. Unfortunately, this is one parameter that was

FIG. 5.7 -

TEMPORAL CHANGES IN GAS AND AMBIENT TEMP.
F2 MATSQUI

TIME in months

F7 STRIDE

TIME in months
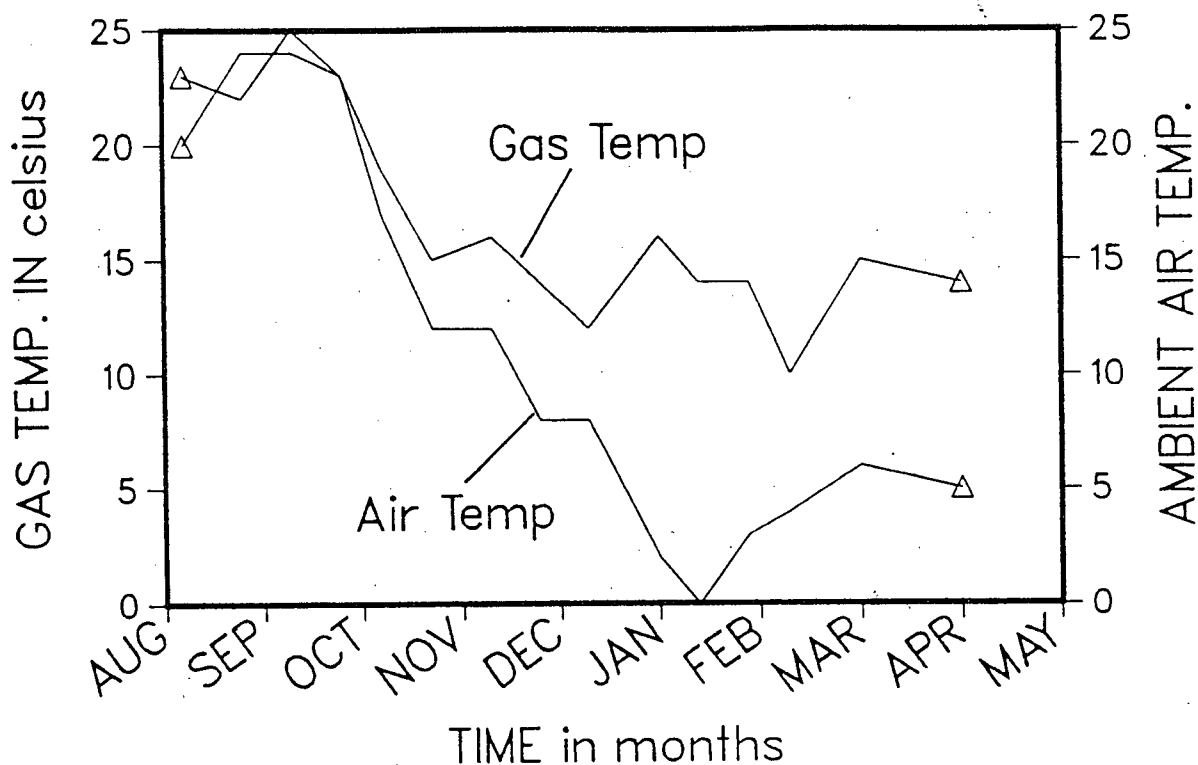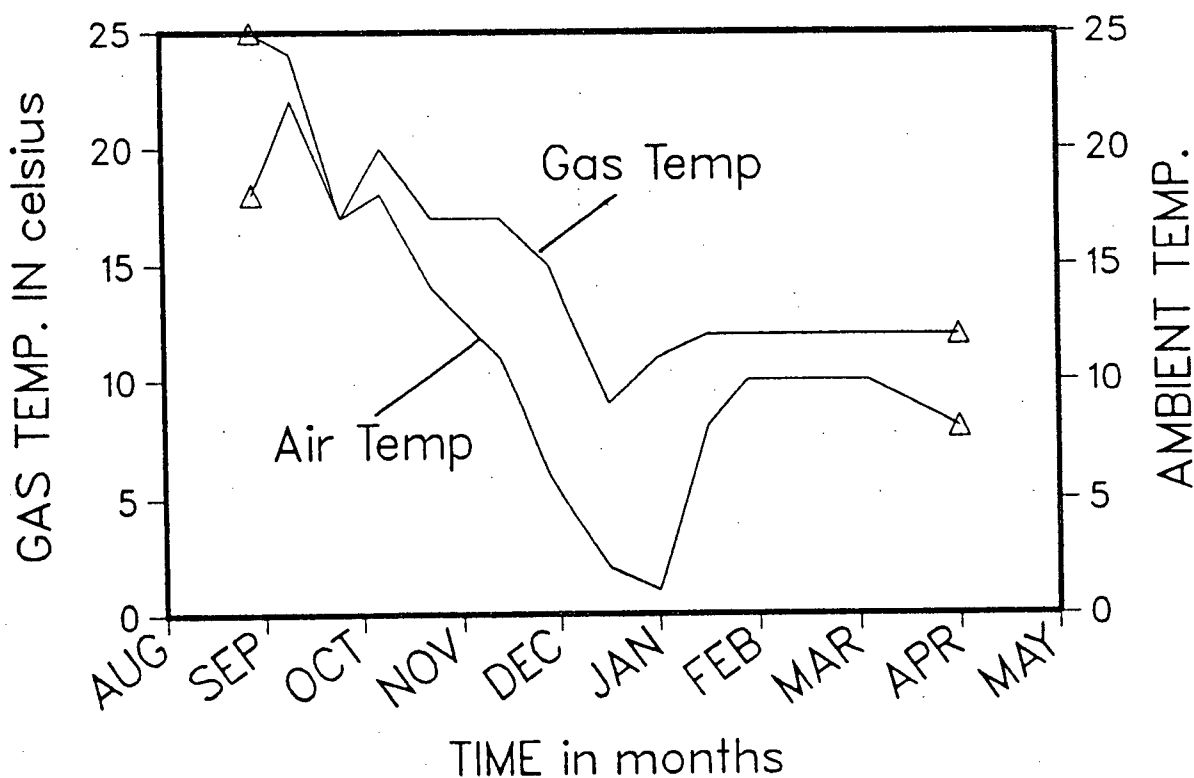
FIG. 5.8 -

TEMPORAL CHANGES IN GAS AND AMBIENT TEMP.
F7 STRIDE AVE.

FIG. 5.9 -

TEMPORAL VARIATIONS IN GAS vs. AMBIENT TEMP.
G7 RICHMOND
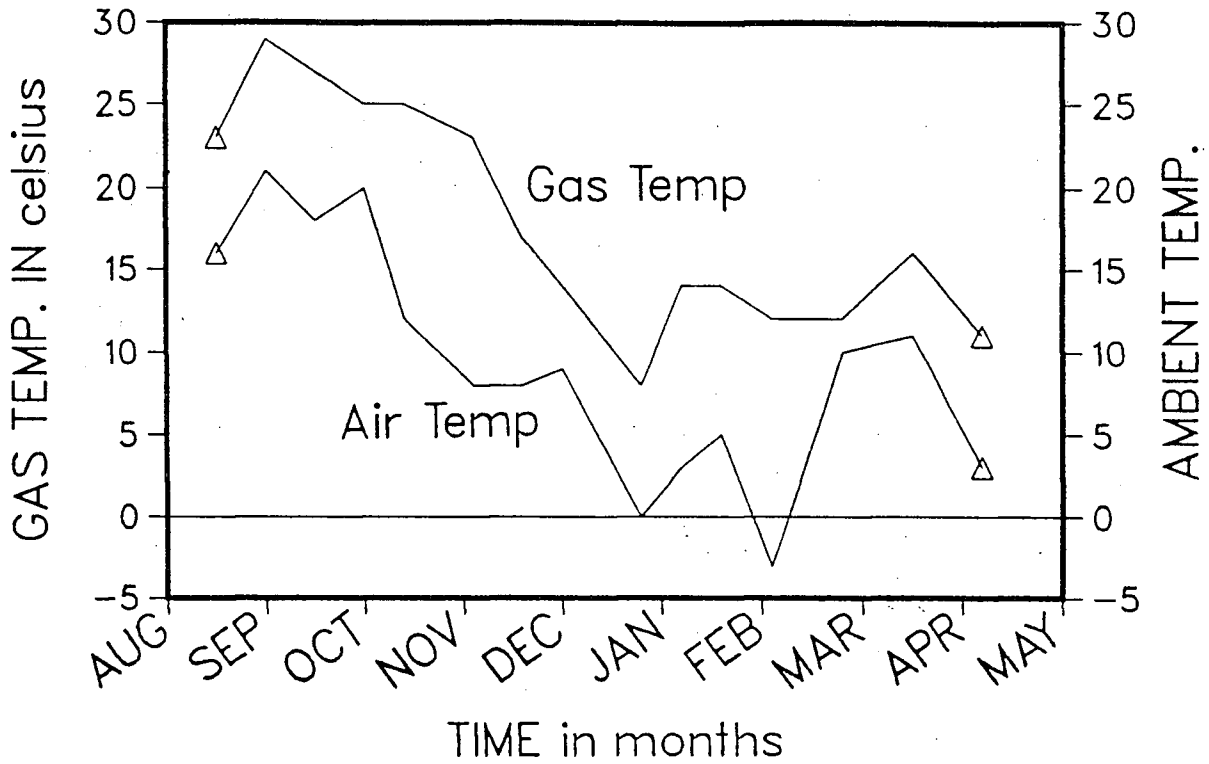
P1 PREMIER St.
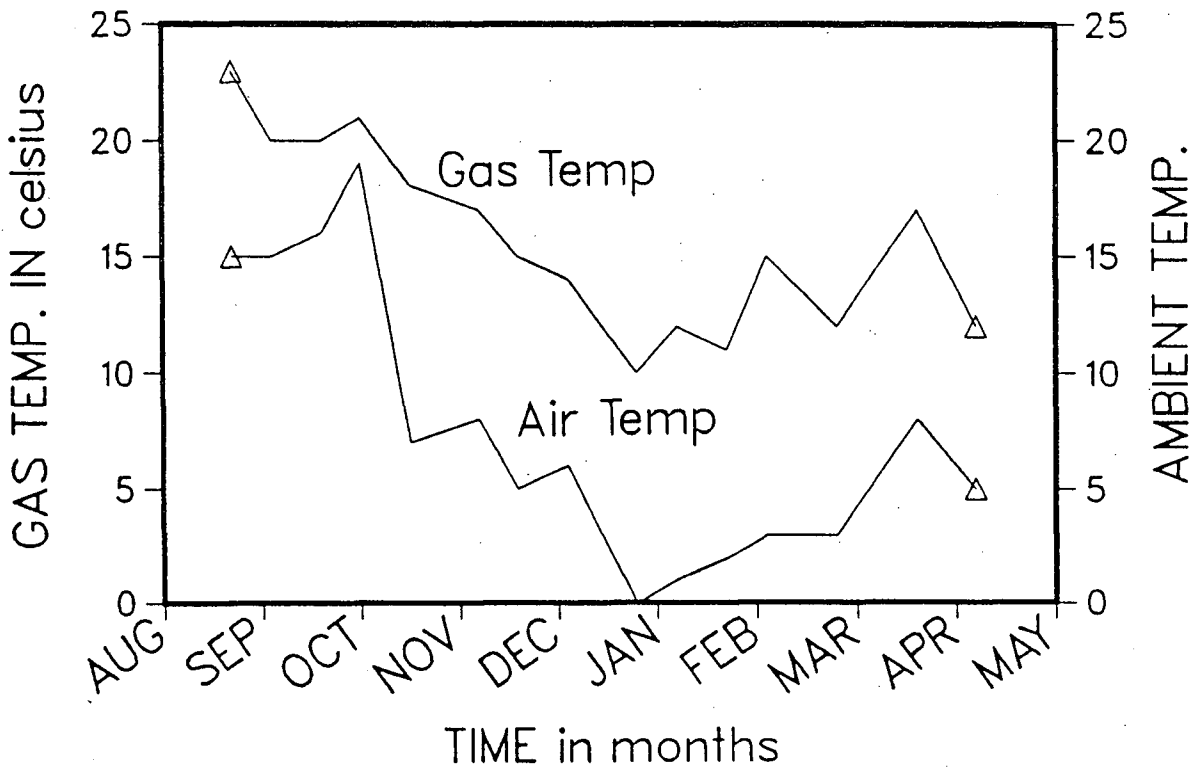
FIG. 5.10 -

TEMPORAL CHANGES IN GAS AND AMBIENT AIR TEMP.,
P1 PREMIER ST.

not monitored because a downhole insitu redox probe was not available at the time.

5.2.6. STATIC GAS FLOW

A few authors (Thibodeaux et al., 1982 and Shen, 1981) have observed during low barometric pressure periods, an increase in emission flux from covered landfills due to pressure pumping from high pressure built up inside the landfill. This phenomenon was monitored throughout my study period by comparing barometric pressure with static gas flow. My results indicate no relationship between the two parameters in not only the plots (See Figs 5.11 to 5.16) but also in the Pearson Correlation analysis. If there is a relationship, one would observe a significant negative correlation between gas flow and pressure.

Inspection of Figs 5.14, 5.15 and 5.16 indicate an unusual pattern in Matsqui wells where falling pressure may be causing lower flow, which is the direct opposite of what should be found. The reason for this anomaly may be due to landfill microbe metabolism being sensitive to changes in barometric pressure, or most likely, a decompression of the landfill during lower pressure regimes. The latter effect would cause lower internal landfill pressures which, translates into lower static gas flows.

The main reason why no low pressure pumping responses were observed in these four landfills could result from each landfill's cover characteristics. Landfills that have been observed to respond to barometric pressure fluctuations have a well constructed "tight" clay cap that helps to build up internal

FIG. 5.11 - GAS FLOW vs BAROMETRIC PRESSURE
B8 RICHMOND
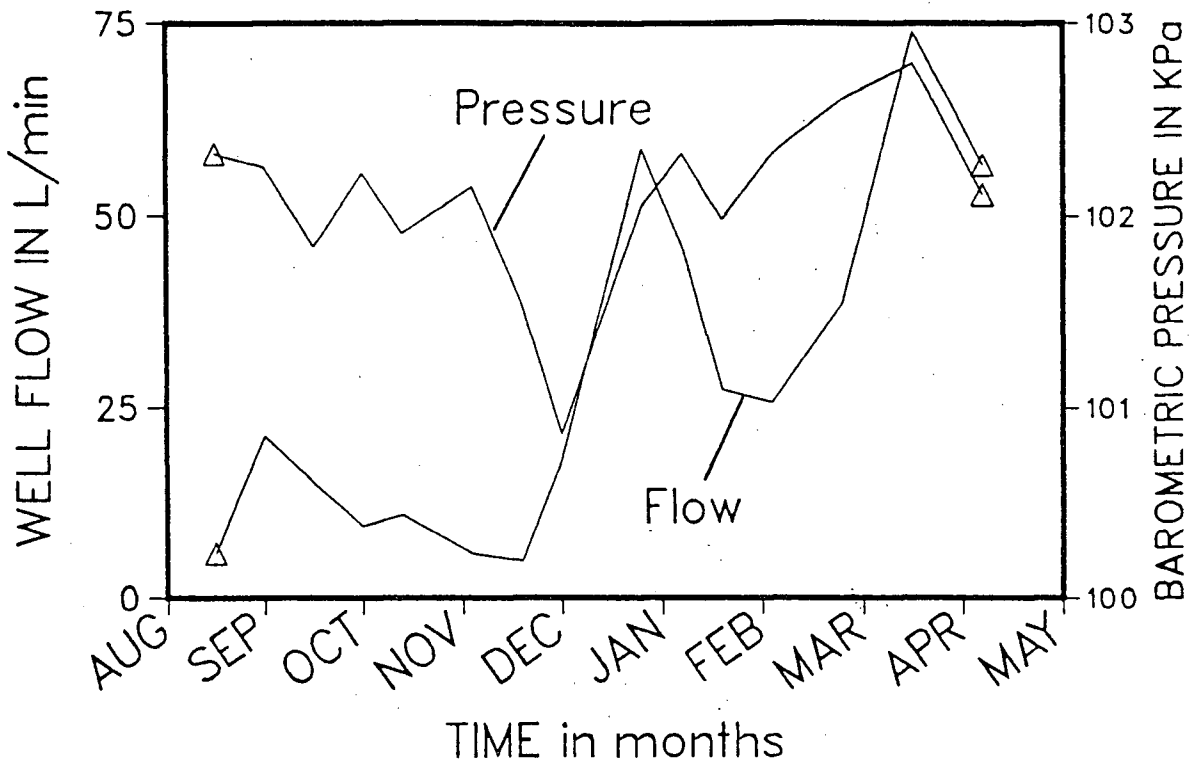
FIG. 5.12 - GAS FLOW vs BAROMETRIC PRESSURE
P2 PREMIER ST.
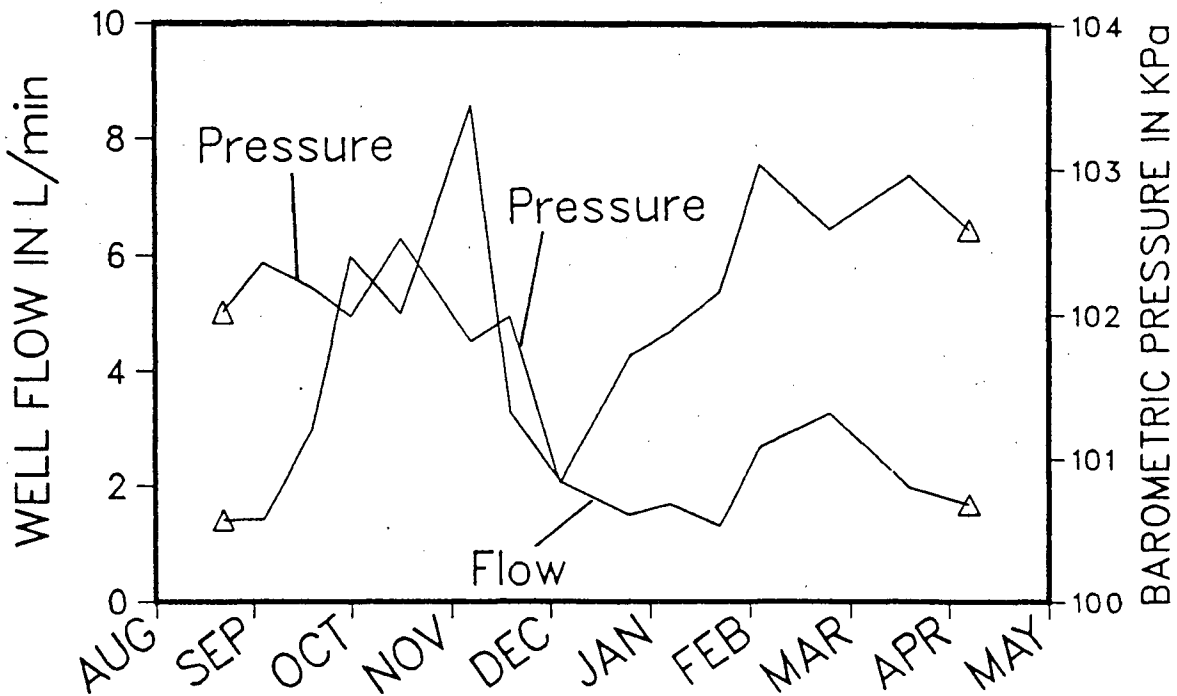
FIG. 5.13 - GAS FLOW vs BAROMETRIC PRESSURE F8 STRIDE
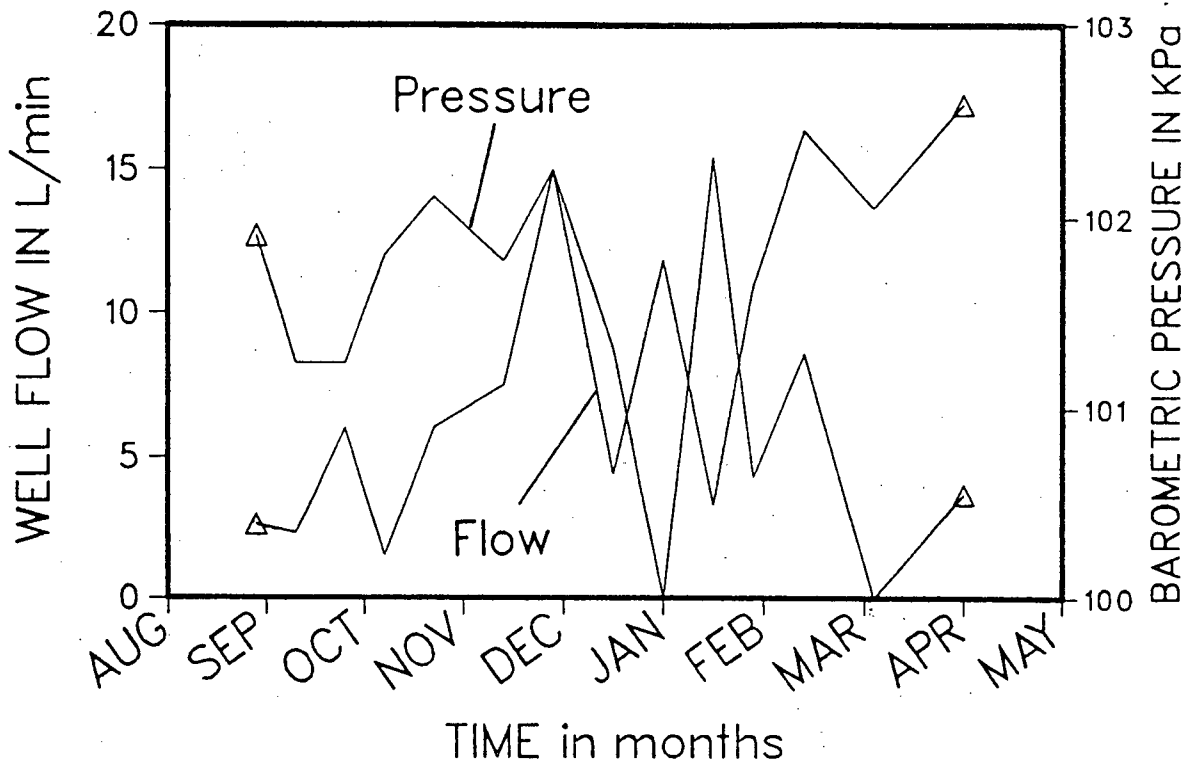
FIG. 5.14 - GAS FLOW VS. BAROMETRIC PRESSURE F2 MATSQUI
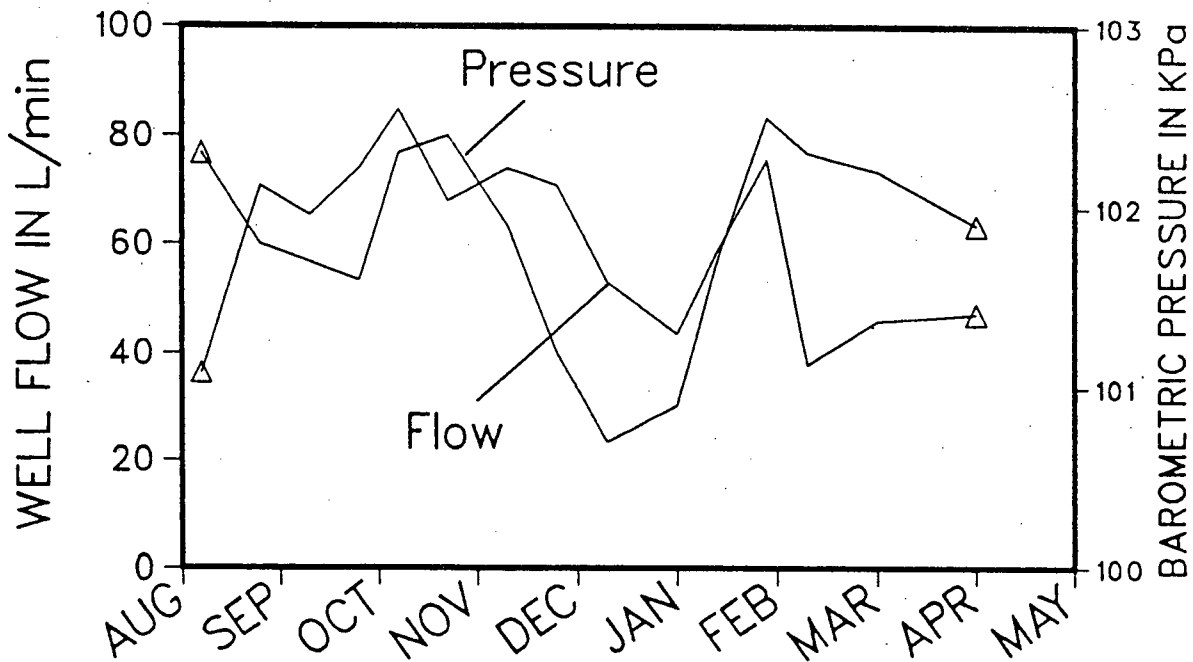
FIG. 5.15 - GAS FLOW vs BAROMETRIC PRESSURE
F3 MATSQUI

Flow

Pressure

WELL FLOW IN L/min

BAROMETRIC PRESSURE in KPa

AUG SEP OCT NOV DEC JAN FEB MAR APR MAY

TIME in months
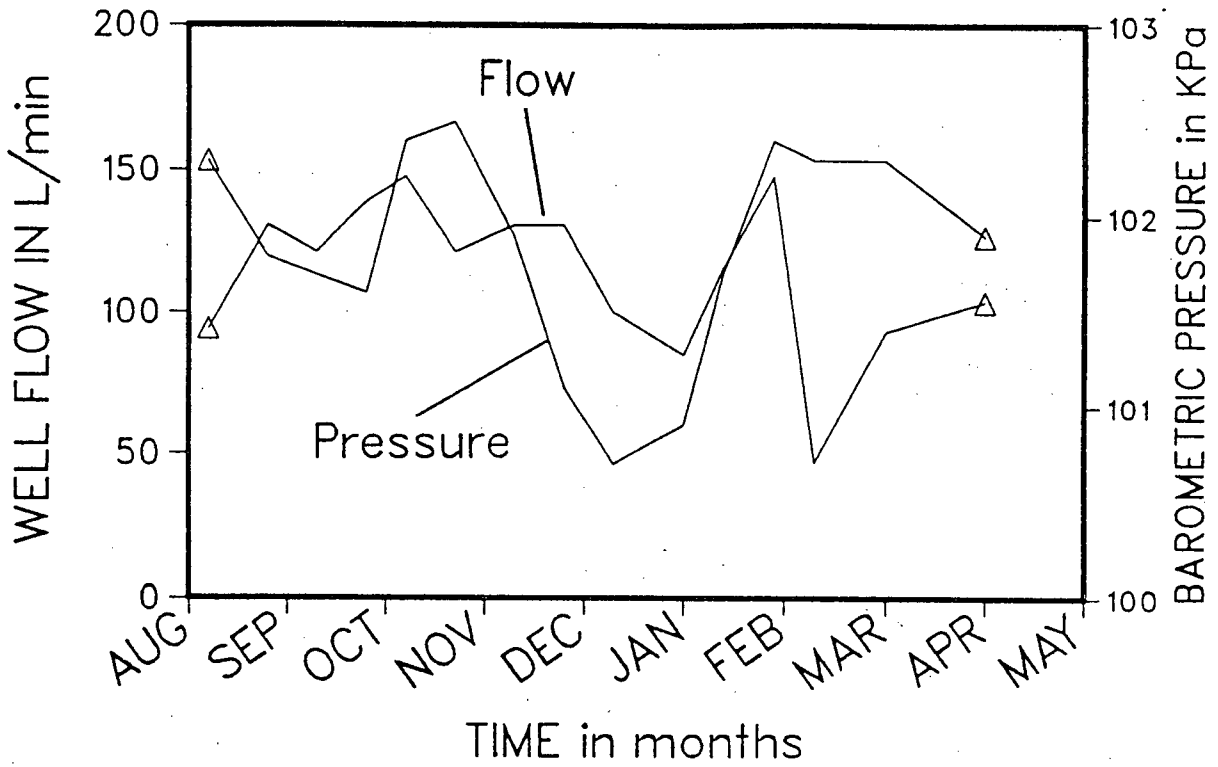
FIG. 5.16 - GAS FLOW vs. BAROMETRIC PRESSURE
F4 MATSQUI

Pressure

Flow

WELL FLOW IN L/min

BAROMETRIC PRESSURE IN KPa

AUG SEP OCT NOV DEC JAN FEB MAR APR MAY
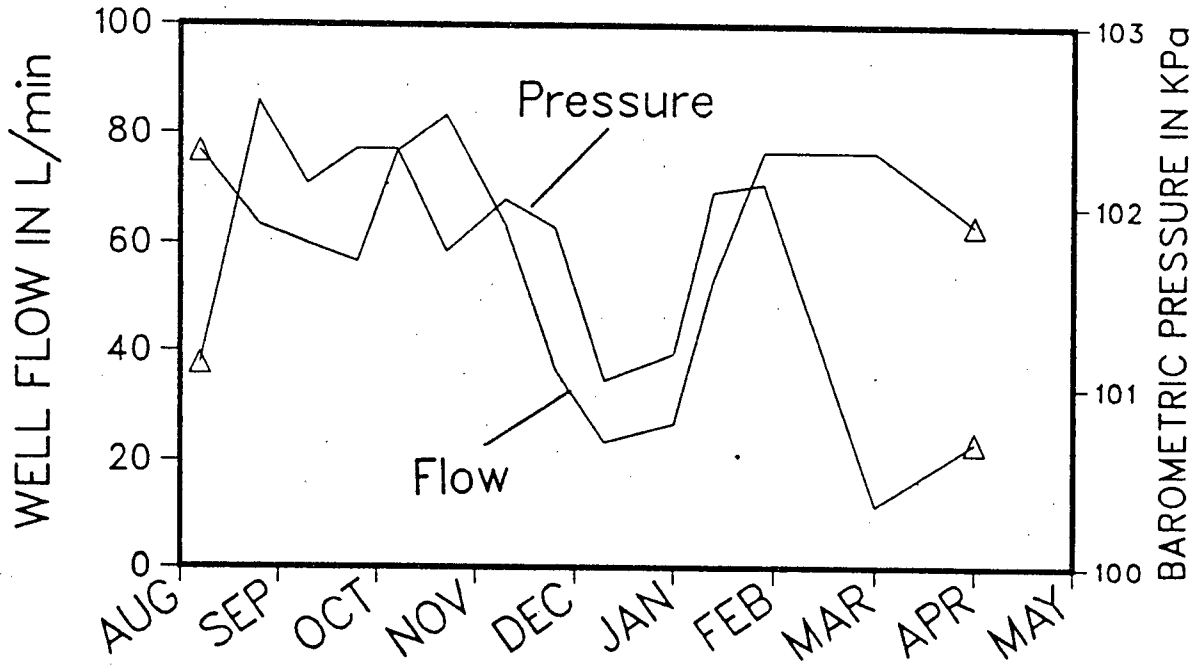
landfill pressures, whereas in these four landfills, the caps were constructed of heterogeneous material where internal landfill pressure may be relieved continuously through the cover.

Since barometric pressure fluctuation cannot explain the changes in static landfill gas flow, there must be other mechanisms behind this natural flow. I believe these mechanisms are:

1.   Microbial activity - probably the most important mechanism for static gas flow. Internal landfill pressure built up through microbial gas production causes convection flow towards the lower pressure landfill surface.

2.   Thermal flow - This could become important during the winter months when a warmer landfill interior and cooler landfill surface cause thermal convection currents to flow upward through the landfill.

3.   Diffusion flow - May become important where convection flow is minimal.

4.   Cell construction - The morphology of the cell and how it is constructed can influence gas pressure build-up and how this pressure is released.

The fraction of the static flow caused by thermal convection is probably small, but may have contributed substantially to the increase of well flows of D9 and C6 in Richmond (see Appendix 4) during the last months of the study. The effects of cell construction are probably contributing greatly to the spatial variability of gas flows in each landfill.

Measurements of static gas flows in this study ranged from no detection to over 290 L/min. In most instances, certain wells in Matsqui (F1, F2, F3, F4) and Richmond (D9 and C6) always registered the highest static flows, while Stride Ave and

Premier St. wells usually registered lower flows. An
interesting observation to note was in two sample periods (Dec.
31st. and Mar. 3rd), flows were undetected in all sample wells
at Stride Ave. Why this happened is not known, since both
periods were not preceeded by heavy rains or subjected to
unsually high barometric pressure.

In most instances, correlation analysis found no
relationship between increased microbial activity (in this case,
increased CH_4 %) and static gas flow. R's of the significant
correlations were all less than 0.5000. The well with continual
high flows, C6 Richmond, did show a response of greater CH_4 %
with increased gas flow.

To study how static gas flow may change during the day, flow
measurements were done at F1 Matsqui on an hourly basis during
four sample periods. The results of these measurements are
presented in Figure 5.17. Inspection of Figure 5.17 indicates a
increase of gas flow from 10 A.M. to 3 P.M. with two of the
results indicating a steadying decrease in flow after this time.
Sampling periods were done on days of slightly increasing or
steadying barometric pressure, so pressure pumping cannot be a
factor in these results.

These results may indicate the potential for diurnal
fluctuations in static gas flow. Because Thibodeaux et al.
(1981) did detect a diurnal fluctuation in internal landfill
pressures, the above hypothesis may be true, but needs more
field work to substantiate this claim.

5.2.7. N_2/O_2 GAS RATIO

The analysis of gas percentage results uncovered something unusual concerning N_2/O_2 gas ratios from some sample wells. In most instances, the N_2/O_2 ratio is around 4.0, which is common for normal air intrusion, however, some wells in Matsqui and Stride Ave exhibit ratios that sometimes exceed 20.0. For four of these wells (F1, F3 Mats and F2, F7 Str) the temporal variation of this ratio is presented in Figs 5.18 & 5.19. Inspection of these figures indicate a large variability of the ratio throughout time. One thing to note is the 0.0 ratio of F7 Str in late October. This is because air was not detected in the sample by the gas partitioner. N_2/O_2 ratios for all the sample wells are listed in Appendix E.

The higher proportion of N_2 from the gas in these wells could be caused by three processes listed below:

1. There could be an increase of N_2 due to denitrification.

2. Consumption of oxygen by inorganic redox processes operating within the landfill could occur.

3. Oxygen could also be consumed by aerobic microorganisms in the landfill.

For #1 to be substantial, there would have to be sufficient source of nitrate, which denitrifiers use as the terminal electron acceptor for N_2 production. The oxidation of ammonia to nitrate is unlikely to occur in an anaerobic landfill environment since the nitrifiers are strict aerobes.

FIG. 5.17 - WELL FLOW vs. HOURLY TIME
F1 MATSQUI

Legend
△ OCT6
× OCT20
□ JAN12
⊠ JAN26
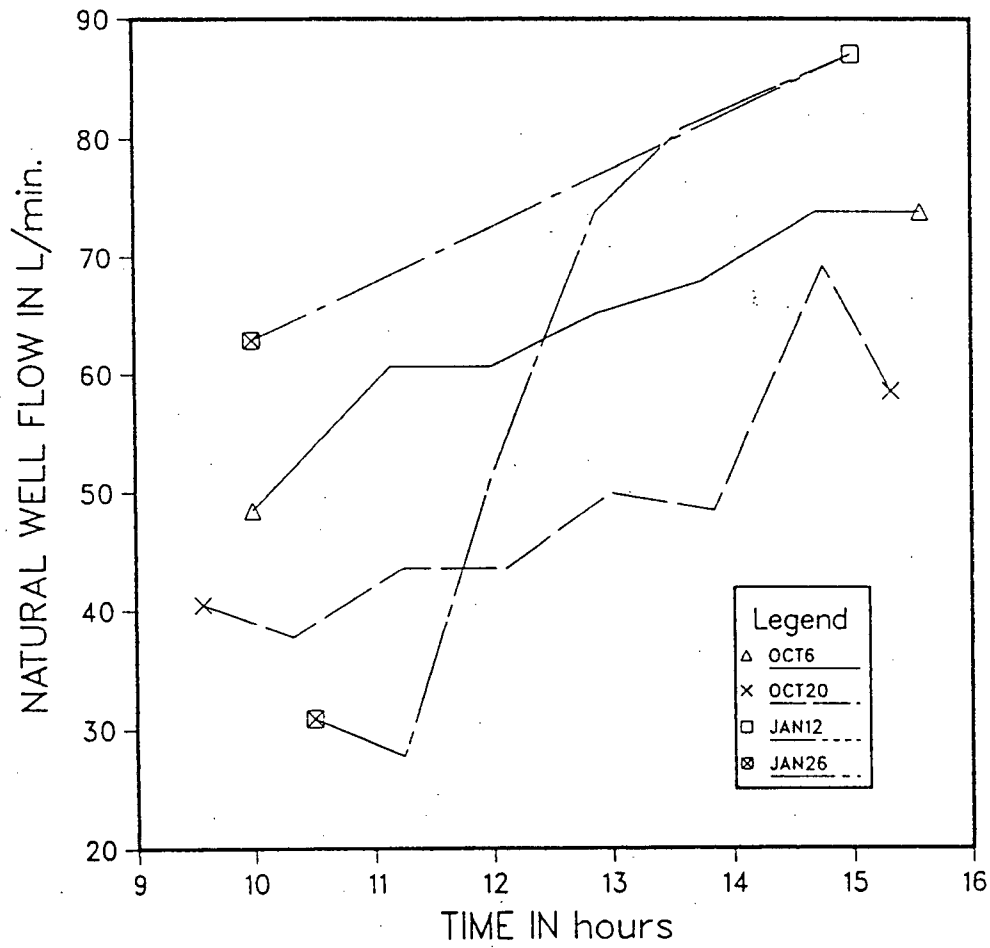
FIG. 5.18 -

LANDFILL GAS N2/O2 RATIO vs TIME
MATSQUI F1 and F2

TIME in months

STRIDE F2 and F7

TIME in months
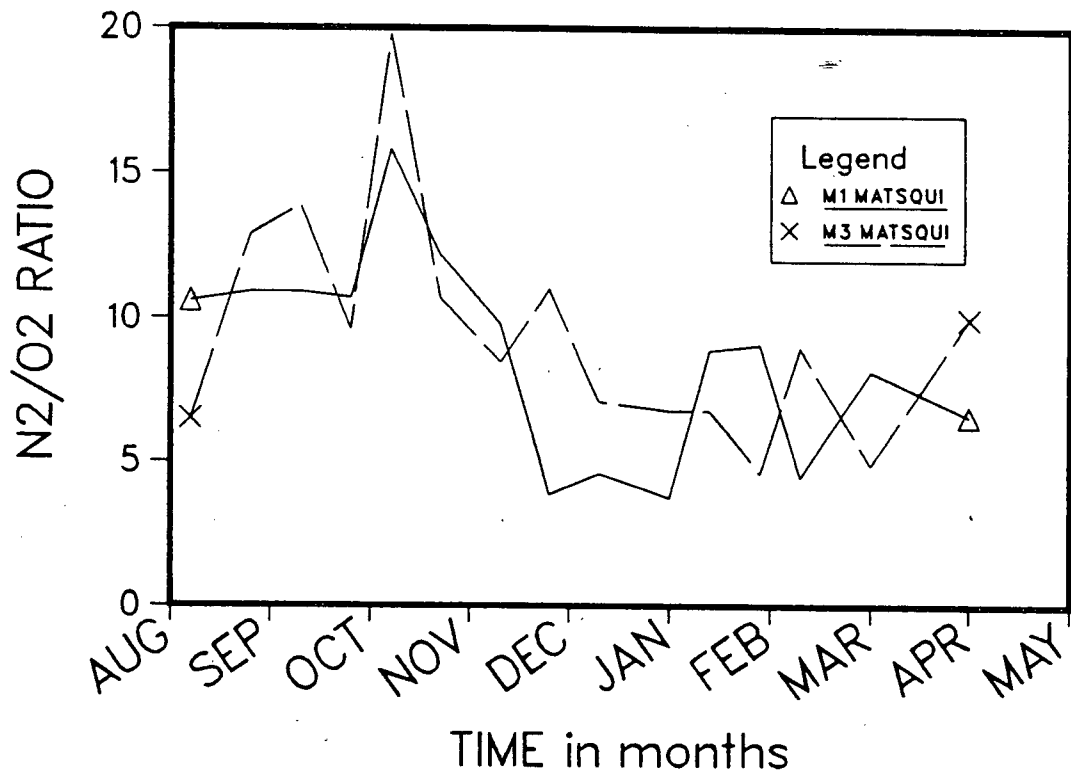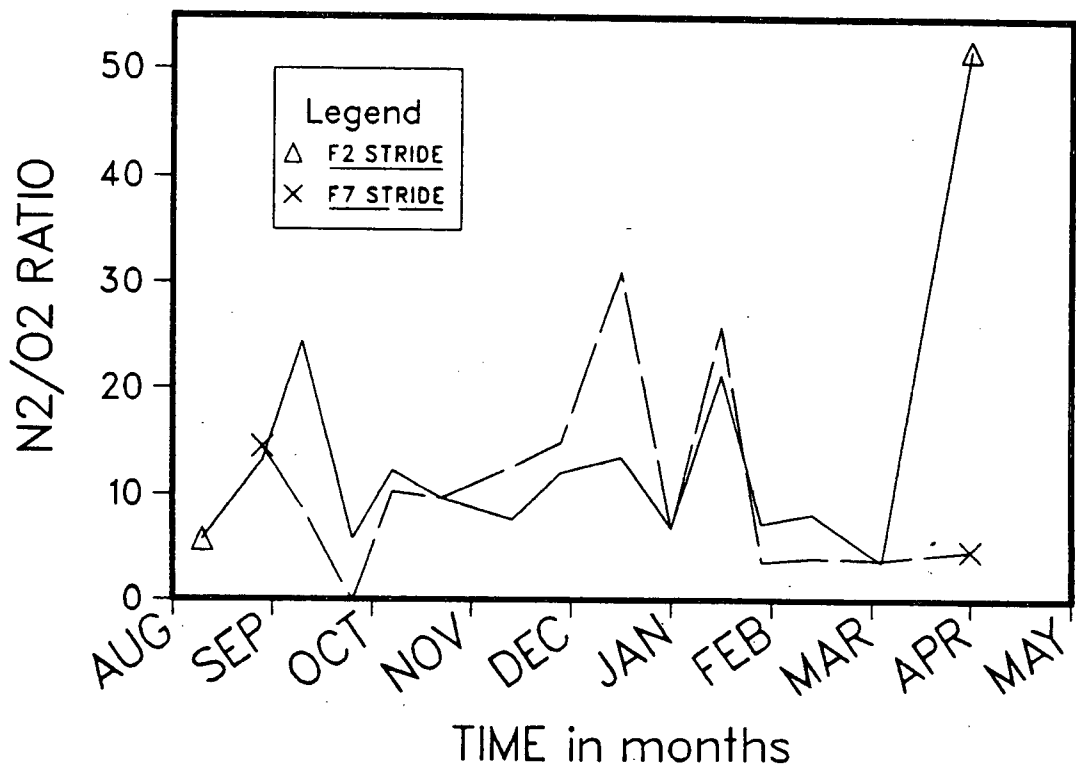
FIG. 5.19 -

LANDFILL GAS N2/O2 RATIO VS. TIME
STRIDE AVE. F2 AND F7

Mechanism #2 may occur in substantial amounts where reducing agents such as metals and sulfide compounds could consume oxygen through redox processes, hence causing a greater build-up of N_2 relative to O_2.

Mechanism #3 is probably the most dominant sink of gaseous O_2 from landfill gas. The consumption of O_2 by aerobic bacteria in landfills is generally considered to be a short term process during the early stages of a completed landfill. However, there is a certain group of aerobic bacteria called Methanotrophs that can utilize the O_2 as a terminal electron acceptor while utilizing methane gas as a growth substrate. CO_2 is then produced as a gaseous byproduct. The following equation from Large (1982) summarizes this oxidation of methane to CO_2 by methanotrophs:

$$CH_4 \dashrightarrow CH_3OH \dashrightarrow H^{\cdot}CHO \dashrightarrow H^{\cdot}COOH \dashrightarrow CO_2$$
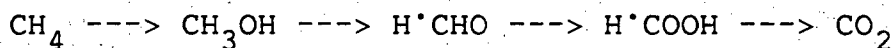
In theory, these bacteria could survive nicely in the upper landfill environment where ample amounts of air intrusion can occur due to oxygen diffusion through the cover, or via landfill gas pumping. For a more detailed discussion on methanotroph ecology and their related growth activity refer to Wolfe and Higgins (1979) and Leak and Dalton (1986).

In addition to consuming O_2 and CH_4 for growth, methanotrophs can also act as nitrifiers, oxidizing ammonia-nitrogen to nitrate much like nitrosomonas and nitrobacter do under normal oxidizing conditions. So mechanism #3 can produce the source of nitrates required for #1 to function. This

symbiotic relationship produces even more N_2 to increase the N_2/O_2 ratio even further. Unfortunately, the leachate was not analyzed for nitrate.

Therefore, given the right environmental conditions, this methane degrading group of bacteria may be causing the anomalous N_2/O_2 gas ratio observed in two of four landfills studied.

5.3. VARIABLES THAT AFFECT METHANE GAS PCT.

In addition to precipitation, temperature and ORP affecting CH_4 %, other parameters such as CO_2 flux, ionic strength and gas flow can also be considered a factor in CH_4 % fluctuation. Interestingly enough, pH was not found to be a factor in CH_4 %.

Pearson correlations done on the parameters listed above indicate the strongest relationship occurring between ionic strength and CH_4 %. R's for ionic strength vs. CH_4 % in gas ranged from 0.35 to 0.70 for separate and combined well analysis.

The resulting stepwise multiple regression analysis equations attempting to predict CH_4 % are listed below for each landfill except Stride Ave., where no correlation between any of the variables and CH_4 % was found.

<div align="center">MATSQUI LANDFILL</div>

CH_4 % = 29.31 + 28.57 (Ionic Strength) − 1.22 (Gas Flow) + ...
... + 8.00 (CO_2 Flux)

$$R^2 = 0.5725 \quad Sig\ F < 0.000 \quad N = 49$$

<div align="center">RICHMOND LANDFILL</div>

CH_4 % = 31.66 + 0.725 (Tg) + 0.189 (CO_2 Flux)

$$R^2 = 0.2319 \quad Sig\ F < 0.000 \quad N = 86$$

<div align="center">PREMIER ST. LANDFILL</div>

$$CH_4 \% = -27.93 + 1.334 \ (Tg) - 9.13 \ (Gas \ Flow) + 67.19 \ (CO_2 \ Flux)$$
$$... + 358.47 \ (Ionic \ Strength)$$

$$R^2 = 0.8288 \quad Sig \ F < 0.000 \quad N = 30$$

The results of these equations indicate the best correlation of variables to CH_4 % are from Premier St. data, which was expected since the variability in variables is not as extreme as Richmond or Matsqui Landfill. Because of the low R^2's and non-normal distribution of ionic strength in Matsqui, all three equations are considered suspect for predicting CH_4 % in a given sample well. This was also the case when McBean and Farquhar (1980) tried regressing 5 day cumulative precip. and ambient air temp. on their methane percent data. Their results indicate R^2's of less than 0.5.

Regressions on separate sample wells were not attempted because of time constraints and the sample population (N = 15) was considered too small for multiple regression.

Each parameter that appeared in the three equations is briefly mentioned below explaining why they may influence CH_4 %:

1. Gas Temperature (Tg) - The increase in Tg was shown to a have a concomitant response with an increase in CH_4 %. Increase in both parameters is probably the result of a combination of increased microbial activity caused by an increase in ambient air temperature (Ta). Decrease of Tg is mainly due to a combination of Ta and cooler precipitation that has infiltrated.

2. Static Gas Flow - An increase in both gas flow and CH_4 % is again probably a function of increased microbial activity.

However, there might also be a situation where increased gas flow decreases CH_4 % because of mass dilution.

3. CO_2 Flux - This parameter is a function of static gas flow and CO_2 %, which can either cause an increase or decrease in CH_4 %.

4. Ionic Strength (I) - This parameter is calculated from leachate specific conductivity as shown in Appendix B.5. This was the only leachate-specific variable that stayed in the regression equation. Since this variable reflects the concentration of dissolved ions in solution, an increase in dissolved ions had the effect of increasing CH_4 %. This increase is most likely a result of higher strength leachate being flushed into the methane producing region or less dilution of leachate from decreased rainfall infiltration.

In addition to the parameters mentioned above, landfill age was considered to be a factor in CH_4 %. Because of it's advanced age, Stride Ave. was originally considered to have a very low methane pct. which was not the case when an assessment of the results of four of the Stride Ave. wells was made (Appendix D). Probably the main reason why Stride Ave consistently exhibited some of the highest CH_4 percentages in the study may stem from the fact that during the study period, the well extraction system was never operational, so steady state CH_4 production occurred with no external perturbances. However, this is not always the case when the extraction system is operating. CH_4 percentage has been observed to drop rapidly in some wells (Len Hanson, pers.

comm., 1987) after pumping. This decrease in CH_4 % is probably a result of not only air intrusion, but also gas production rates that lag far behind the extraction flow rate. So even though Stride Ave may have relatively high methane percentages, its mass production rates of methane are much lower than the younger Matsqui and Richmond landfills which still produce high CH_4 % even during continous pumping.

In the landfills where gas extraction was operational, attempts to correlate CH_4 % variation with operational fluctuations were successful in only two sample wells, P2 Premier and F5 Matsqui. Well P2 Premier was on constant vacuum throughout the study period while F5 Matsqui had intermittent vacuum applied to it during winter demand periods. Results show the large drop in CH_4 % in P2 may be caused by a combination of precipitation infiltration and decrease in gas temperature. Recovery of the methane pct. may be hampered by the constant vacuum applied to the system, since the rate of air intrusion probably exceeds a decreased rate of methane production. This high rate of air intrusion probably causes a volume dilution of methane. The intermittent drops of CH_4 % in F5 Matsqui may be a function of intermittent well pumpage accompanying the effects of precipitation infiltration and gas temperature decrease.

5.4. VARIABLES THAT AFFECT AMMONIA GAS CONCENTRATION

5.4.1. INTRODUCTION

NH_3-N gas concentration ranged from non-detectable (< 10ppb)

to over 600 ppb during the 8 month study. Results in NH_3-N gas distribution from the four landfills were surprising since lower than expected concentrations occurred in Richmond while much higher than expected levels were detected in Stride Ave. This was unusual since Richmond had quite average to high NH_3-N concentrations in the leachate, while Stride Ave. exhibited very low NH_3-N concentrations. The reasons for this are not quite apparent, but will be theorized in a later section.

Throughout the study, most landfill gas NH_3-N levels moved in a general decreasing trend, dropping to their lowest levels in the winter months.

When this study began, this author felt there were maybe four parameters that affected the temporal variation of NH_3-N gas concentrations. These were pH and NH_3-N in leachate, methane flux and precipitation infiltration. The pH of the solution was believed to control the fraction of NH_3 available for transfer into the gas phase. Higher NH_3-N in the leachate was believed to reflect a higher NH_3-N in the gas as regulated by Henry's Law. Methane flux was considered important because of the possibility that methane flow could be acting as a stripping mechanism within the landfill causing accelerated NH_3-N transfer into the gas phase. Hence, higher methane fluxes were considered to result in higher NH_3-N gas concentrations. Lastly, precipitation infiltration was generally considered to speed up microbial metabolic rates releasing more NH_3-N into the gas phase.

Post analysis on these control parameters indicate that none

of the original assumptions were true on any consistent basis.

Temporal variability of these parameters vs. NH_3-N for 9 of the

study wells are presented in Figs 5.20 through 5.63 and discussed

in more detail later. In addition to these four parameters, gas

temp. was plotted, since it was found to be the parameter after

post-sampling analysis to explain the variability of NH_3-N gas.

The wells plotted were B8, D9, C6, D.55 Richmond, F2, F5 Matsqui,

F2, F7 Stride Ave. and P2 Premier St.. These wells were chosen

for plotting because all 9 wells possesed complete sets (15) of

leachate and gas data.

5.4.2. PRECIPITATION

Direct inspection of Fig's 5.20 through 5.27 show the

temporal variation of NH_3-N gas and weekly precipitation in 8 of

the wells. Weekly precipitation is shown in the bar chart with

the NH_3-N gas shown on the connected line plot. In nearly all

the wells, there is a large fluctuation of NH_3-N gas

concentration, variation which in most instances is around 100 %

of the standard deviation (see Appendix D). Generally, in most

instances, the trend is NH_3-N concentrations to drop off rapidly

during the first high precipitation period in November.

Pearson correlation analysis indicate some slight negative

correlation between precipitation and NH_3-N gas in combined well

analysis of all four landfills. The r values range from -0.3745

to -0.5391. For this and any other statistical analysis, the

precipitation variable was taken as the cumulative 2 week

precipitation preceeding the given sample period. This was

FIG. 5.20 -
TEMPORAL VARIATION OF WEEKLY PRECIP. vs. NH3-N IN GAS
B8 RICHMOND

PRECIPITATION in mm

NH3-N IN LANDFILL GAS ppb

TIME in months

FIG. 5.21 -
TEMPORAL VARIATION OF WEEKLY PRECIP. vs. NH3-N IN GAS
C6 RICHMOND

PRECIPITATION in mm

NH3-N IN LANDFILL GAS ppb

TIME in months
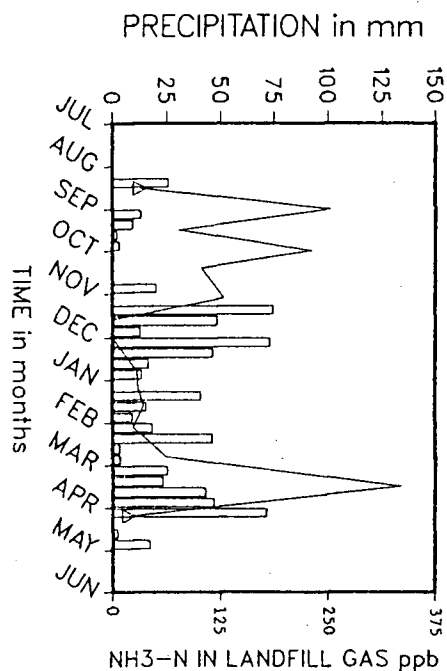
FIG. 5.22 -
TEMPORAL VARIATION OF WEEKLY PRECIP. vs. NH3-N IN GAS
D9 RICHMOND

PRECIPITATION in mm

NH3-N IN LANDFILL GAS ppb

TIME in months
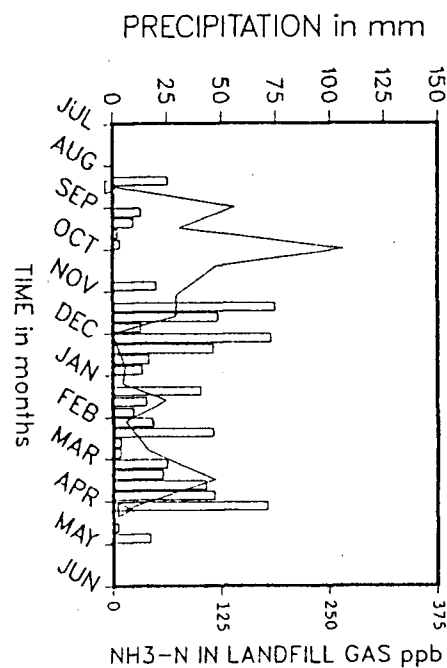
FIG. 5.23 -
TEMPORAL VARIATION OF WEEKLY PRECIP. vs. NH3-N IN GAS
D.55 RICHMOND

PRECIPITATION in mm

NH3-N IN LANDFILL GAS ppb

TIME in months
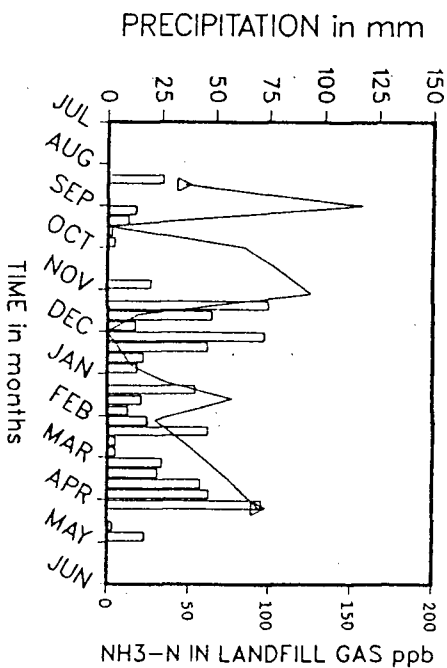
FIG. 5.24 -
TEMPORAL VARIATION OF WEEKLY PRECIP. vs. NH3-N IN GAS
F2 MATSQUI

FIG. 5.25 -
TEMPORAL VARIATION OF WEEKLY PRECIP. vs. NH3-N IN GAS
F5 MATSQUI
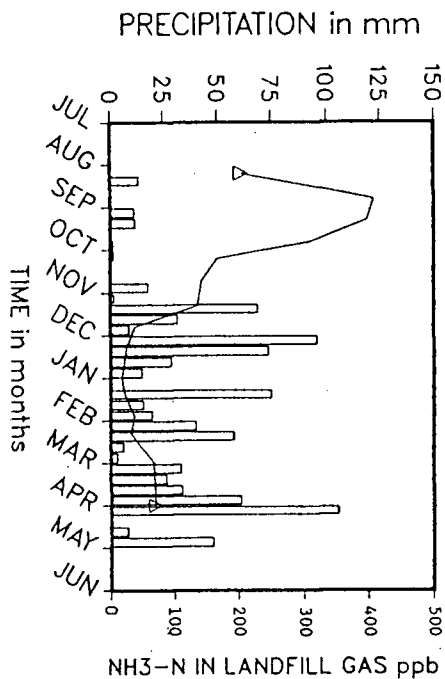
FIG. 5.26 -
TEMPORAL VARIATION OF WEEKLY PRECIP. vs. NH3-N IN GAS
F2 STRIDE
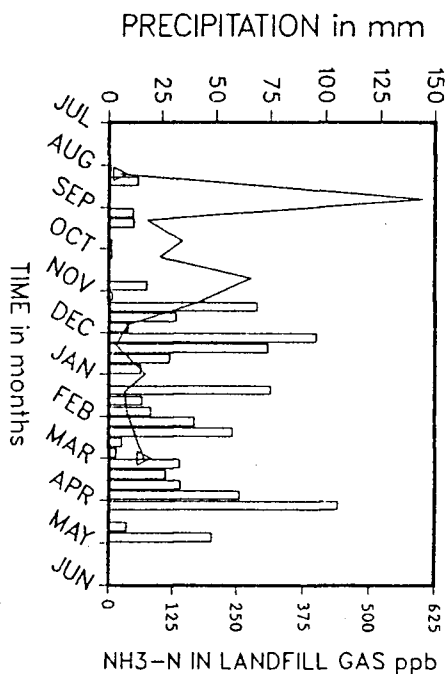
FIG. 5.27 -
TEMPORAL VARIATION OF WEEKLY PRECIP. vs. NH3-N IN GAS
F7 STRIDE

136
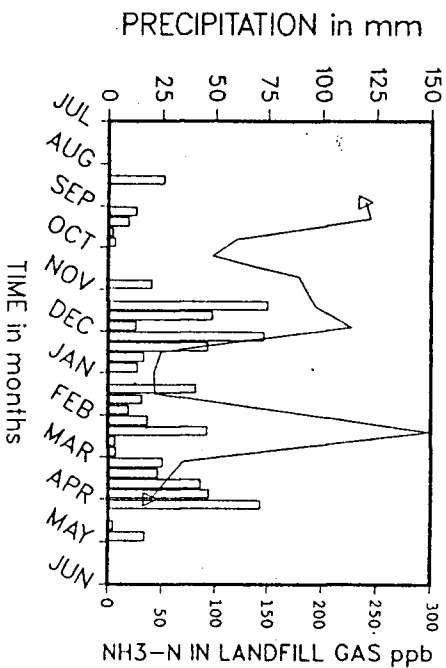
FIG. 5.28 -
TEMPORAL VARIATION OF NH3-N LEACHATE vs. NH3-N GAS
B8 RICHMOND
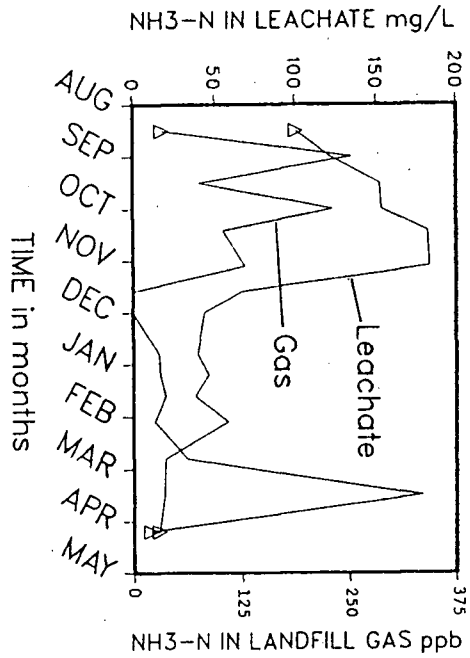
FIG. 5.29 -
TEMPORAL VARIATION OF pH vs. NH3-N IN GAS
B8 RICHMOND
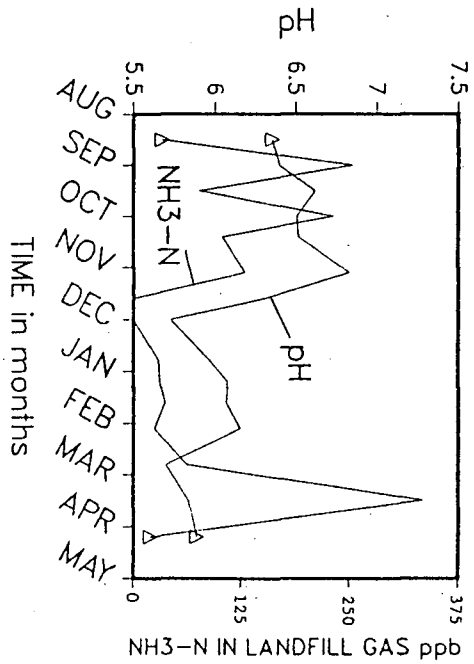
FIG. 5.30 -
TEMPORAL VARIATION OF CH4 FLUX vs. NH3-N IN GAS
B8 RICHMOND
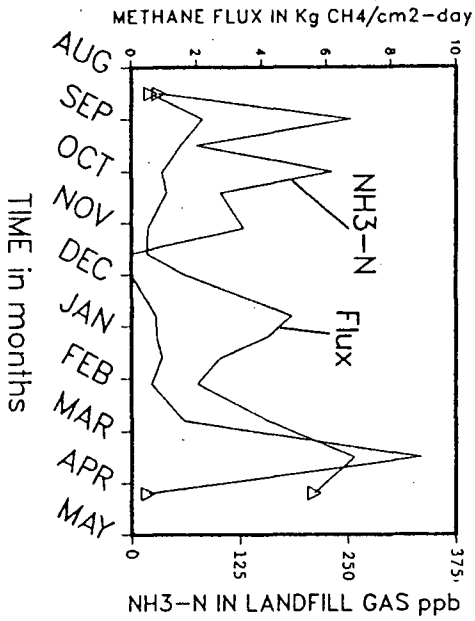
FIG. 5.31 -
TEMPORAL VARIATION OF GAS TEMP vs. NH3-N IN GAS
B8 RICHMOND

137
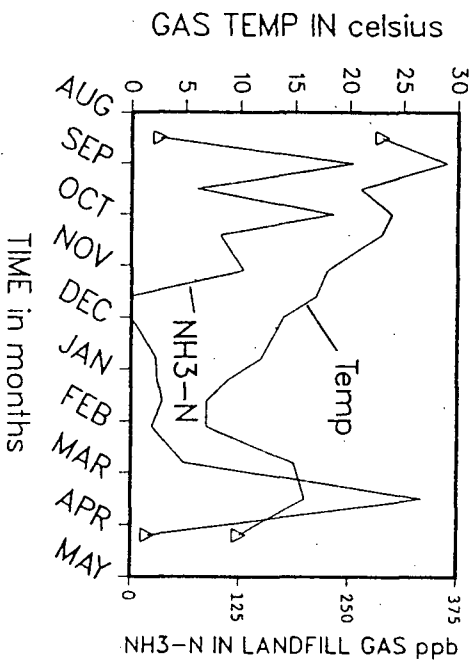
FIG. 5.32 -
TEMPORAL VARIATION OF NH3-N LEACHATE vs. NH3-N GAS
D9 RICHMOND
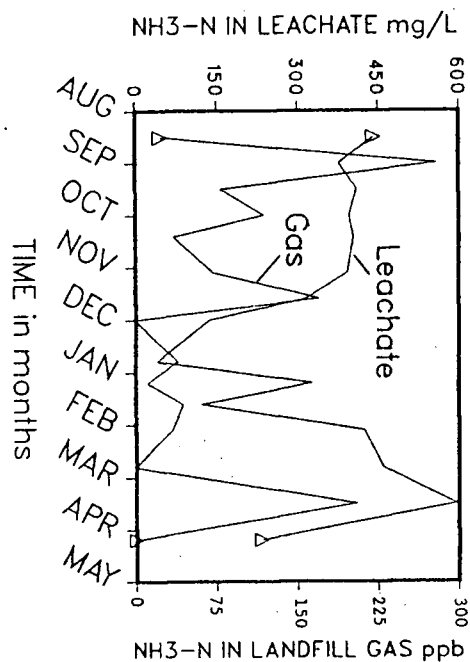
FIG. 5.33 -
TEMPORAL VARIATION OF pH vs. NH3-N IN GAS
D9 RICHMOND
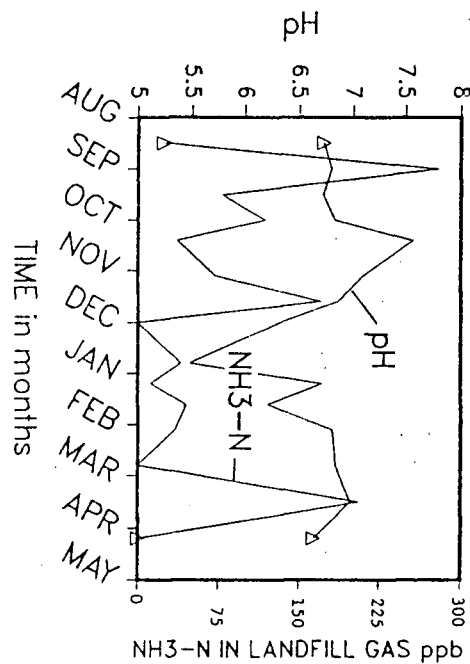
FIG. 5.34 -
TEMPORAL VARIATION OF CH4 FLUX vs. NH3-N IN GAS
D9 RICHMOND
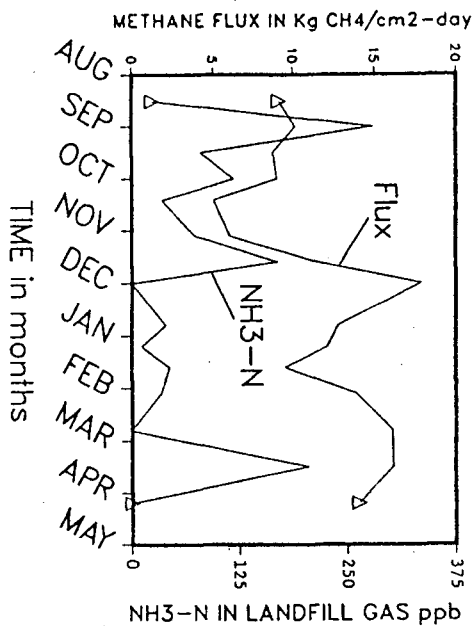
FIG. 5.35 -
TEMPORAL VARIATION OF GAS TEMP. vs. NH3-N IN GAS
D9 RICHMOND
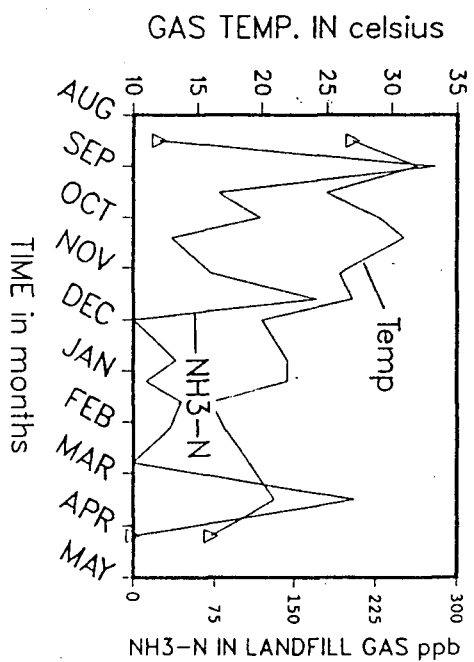
FIG. 5.36 -
TEMPORAL VARIATION OF NH3-N LEACHATE vs. NH3-N GAS
C6 RICHMOND
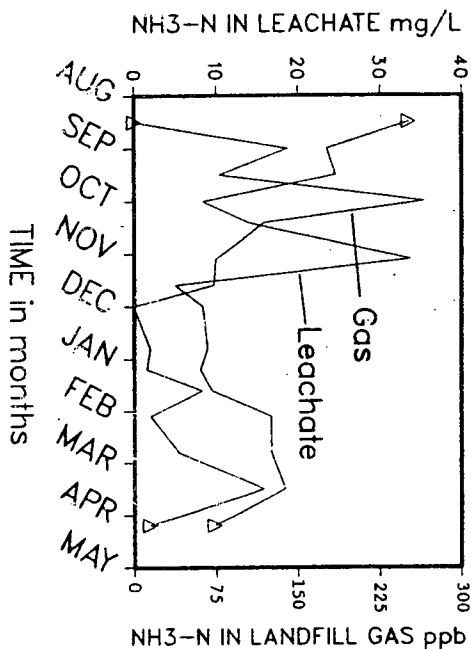
FIG. 5.37 -
TEMPORAL VARIATION OF pH vs. NH3-N IN GAS
C6 RICHMOND
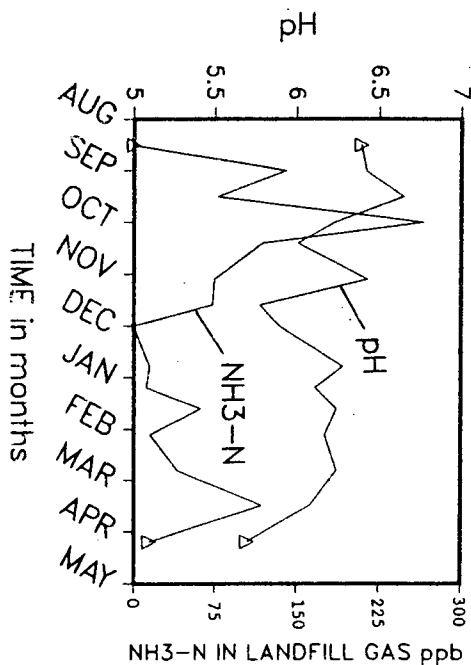
FIG. 5.38 -
TEMPORAL VARIATION OF CH4 FLUX vs. NH3-N IN GAS
C6 RICHMOND
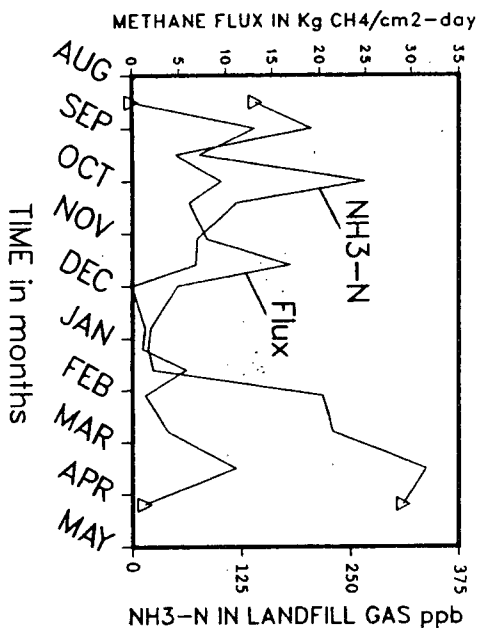
FIG. 5.39 -
TEMPORAL VARIATION OF GAS TEMP. vs. NH3-N IN GAS
C6 RICHMOND
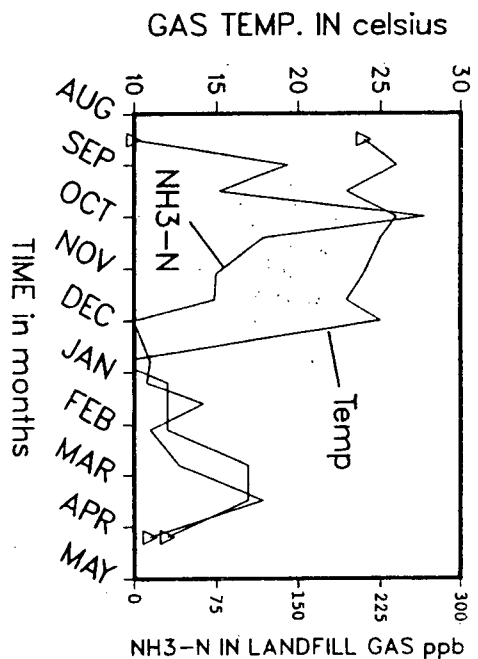
FIG. 5.40 -
TEMPORAL VARIATION OF NH3-N LEACHATE vs. NH3-N GAS
D.55 RICHMOND
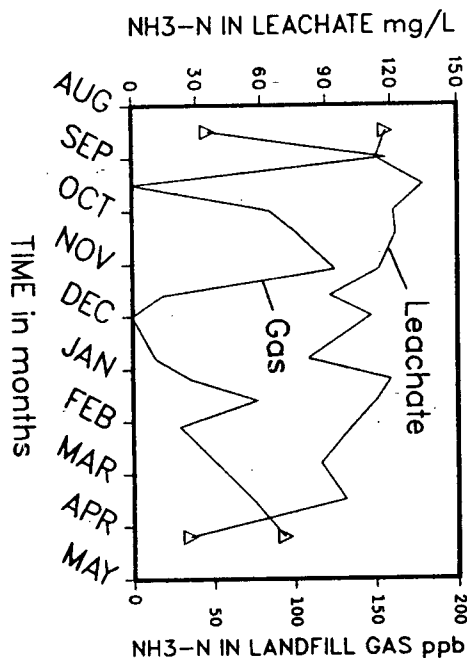
FIG. 5.41 -
TEMPORAL VARIATION OF pH vs. NH3-N IN GAS
D.55 RICHMOND
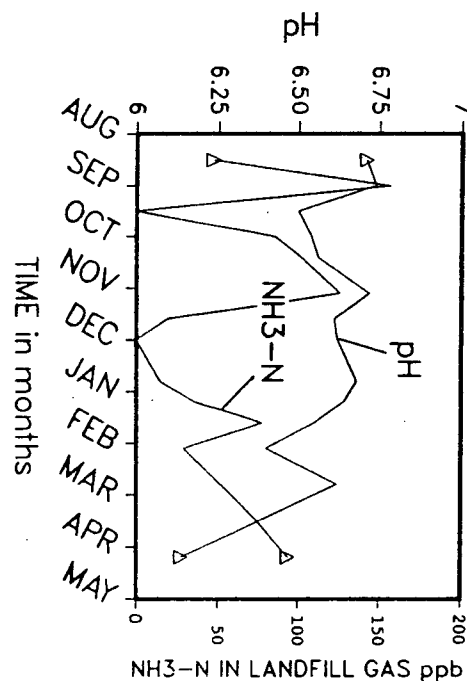
FIG. 5.42 -
TEMPORAL VARIATION OF CH4 FLUX vs. NH3-N IN GAS
D.55 RICHMOND
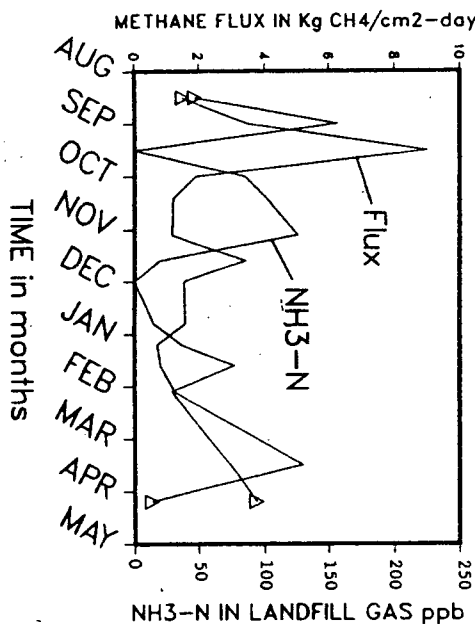
FIG. 5.43 -
TEMPORAL VARIATION OF GAS TEMP. vs. NH3-N IN GAS
D.55 RICHMOND

FIG. 5.44 -
TEMPORAL VARIATION OF NH3-N LEACHATE vs. NH3-N GAS
F2 MATSQUI

FIG. 5.46 -
TEMPORAL VARIATION OF CH4 FLUX vs. NH3-N IN GAS
F2 MATSQUI

FIG. 5.45 -
TEMPORAL VARIATION OF pH vs. NH3-N IN GAS
F2 MATSQUI

FIG. 5.47 -
TEMPORAL VARIATION OF GAS TEMP. vs. NH3-N IN GAS
F2 MATSQUI
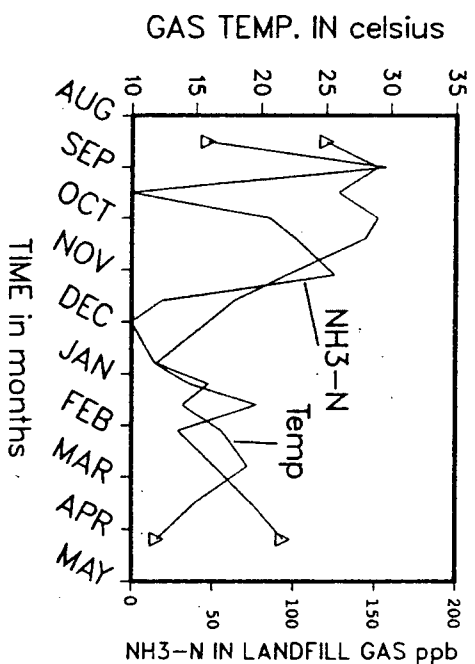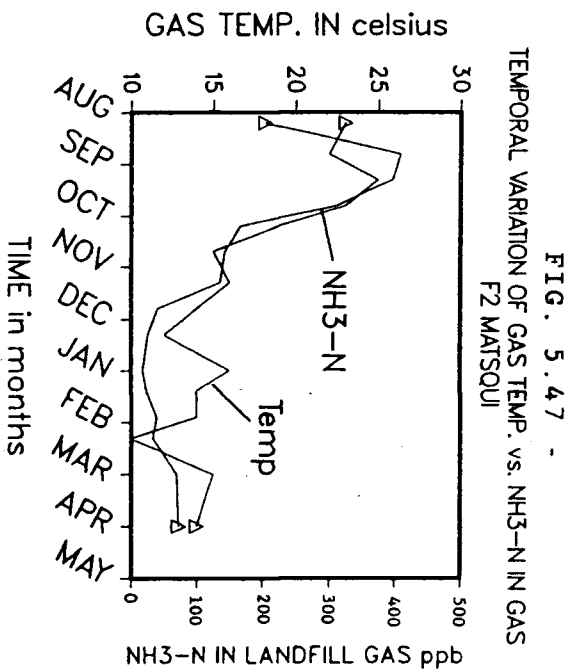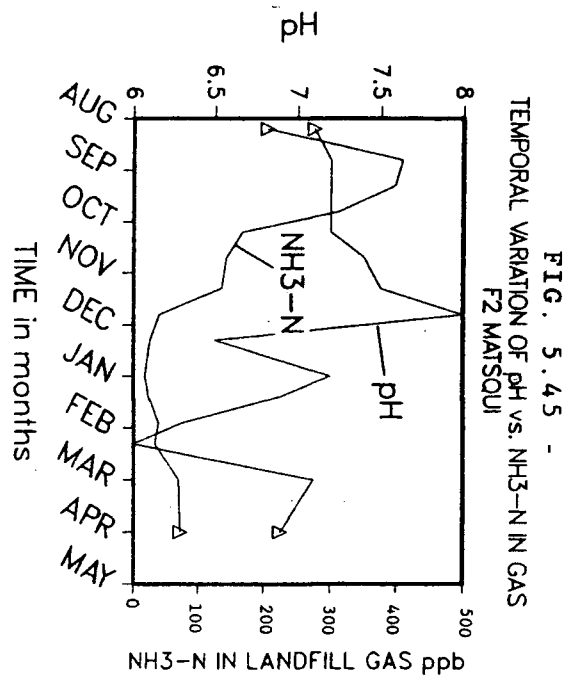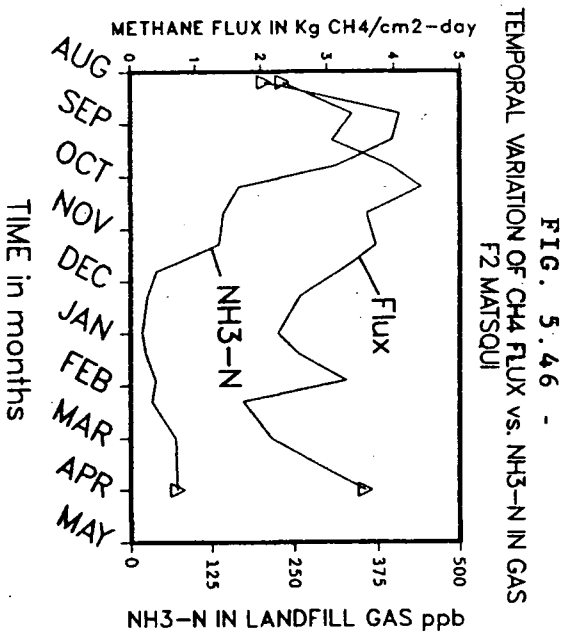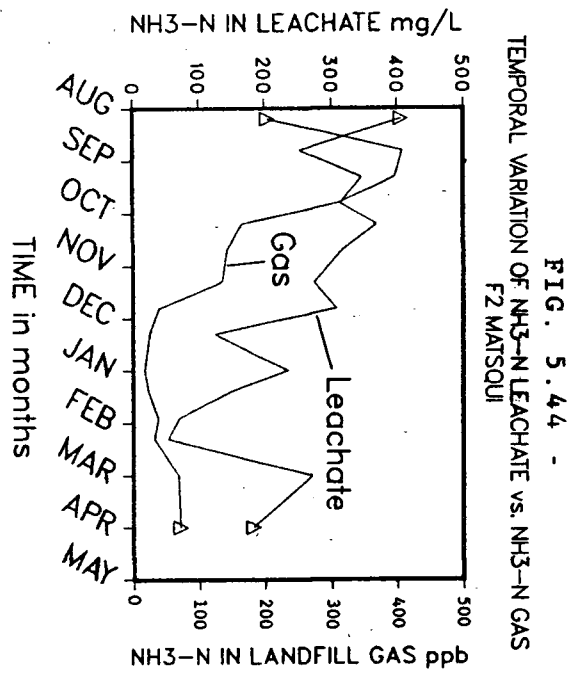
FIG. 5.48 -
TEMPORAL VARIATION OF NH3-N LEACHATE vs. NH3-N GAS
F5 MATSQUI

FIG. 5.50 -
TEMPORAL VARIATION OF CH4 FLUX vs. NH3-N IN GAS
F5 MATSQUI
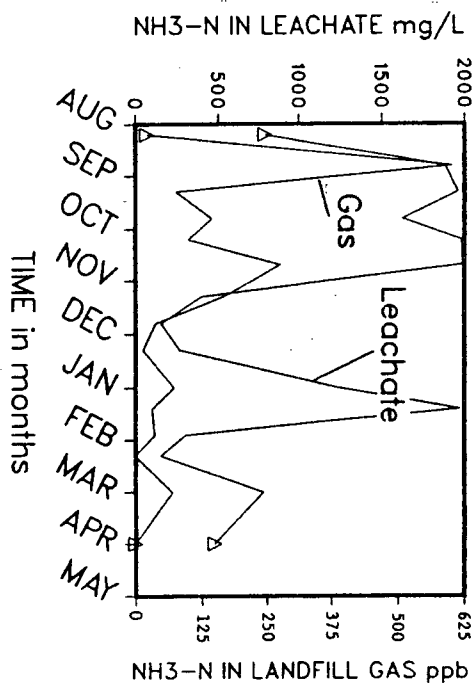
FIG. 5.49 -
TEMPORAL VARIATION OF pH vs. NH3-N IN GAS
F5 MATSQUI
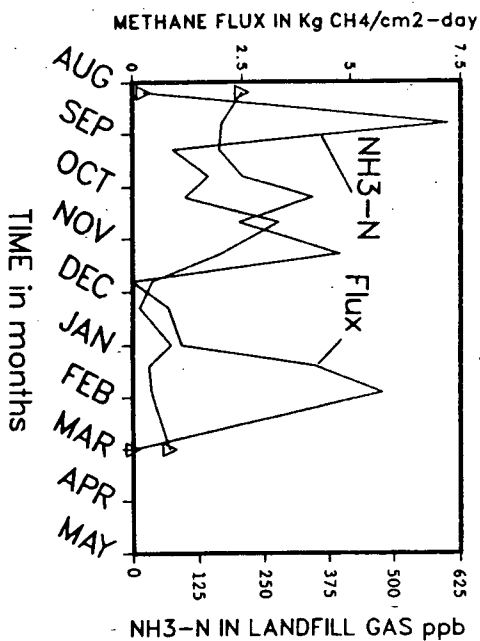
FIG. 5.51 -
TEMPORAL VARIATION OF GAS TEMP. vs. NH3-N IN GAS
F5 MATSQUI
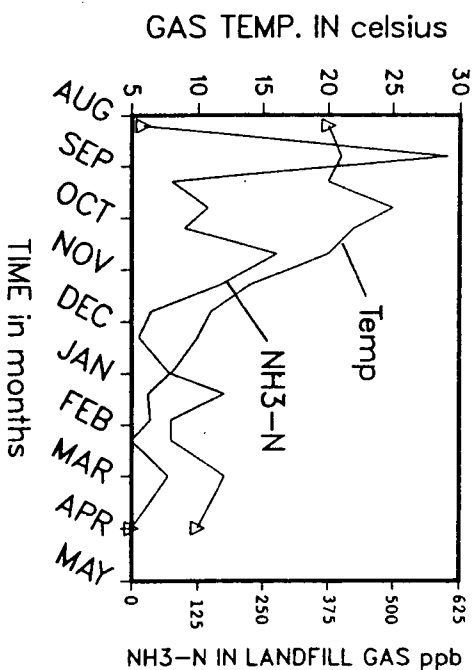
FIG. 5.52 -
TEMPORAL VARIATION OF NH3-N LEACHATE vs. NH3-N GAS
F2 STRIDE
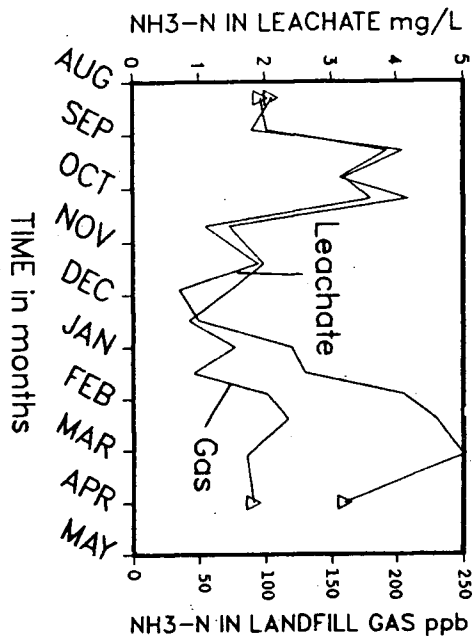
FIG. 5.53 -
TEMPORAL VARIATION OF pH vs. NH3-N IN GAS
F2 STRIDE
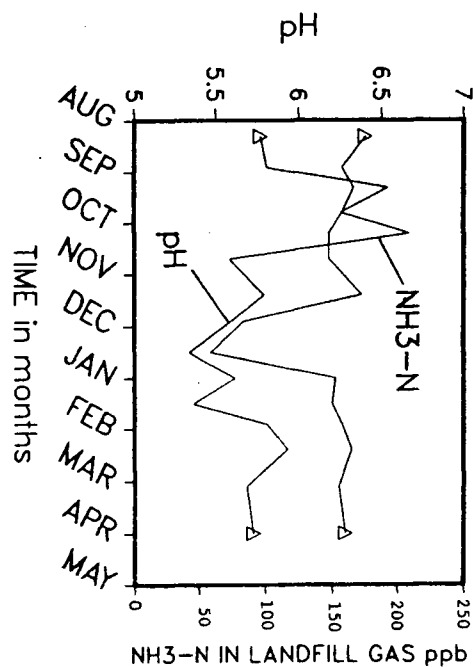
FIG. 5.54 -
TEMPORAL VARIATION OF CH4 FLUX vs. NH3-N IN GAS
F2 STRIDE
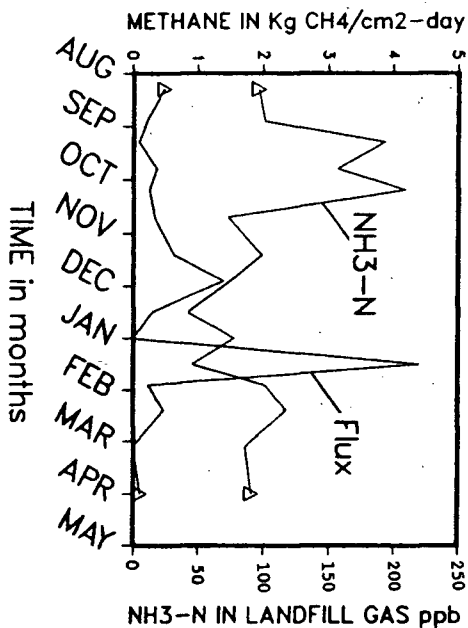
FIG. 5.55 -
TEMPORAL VARIATION OF GAS TEMP. vs. NH3-N IN GAS
F2 STRIDE
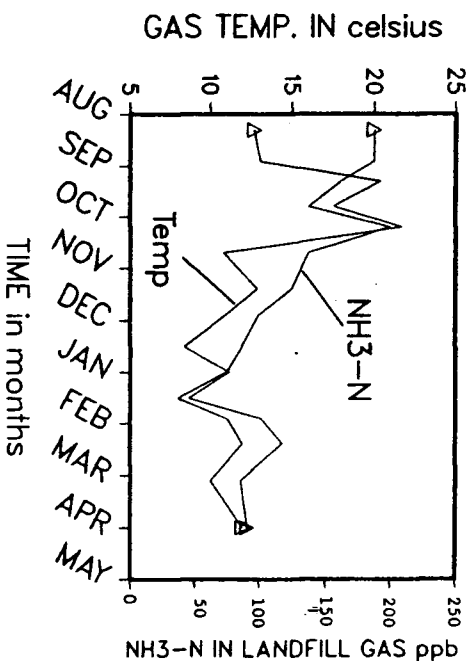
FIG. 5.56 -
TEMPORAL VARIATION OF NH3-N LEACHATE vs. NH3-N GAS
F7 STRIDE

NH3-N IN LEACHATE mg/L

Leachate

Gas

TIME in months

NH3-N IN LANDFILL GAS ppb
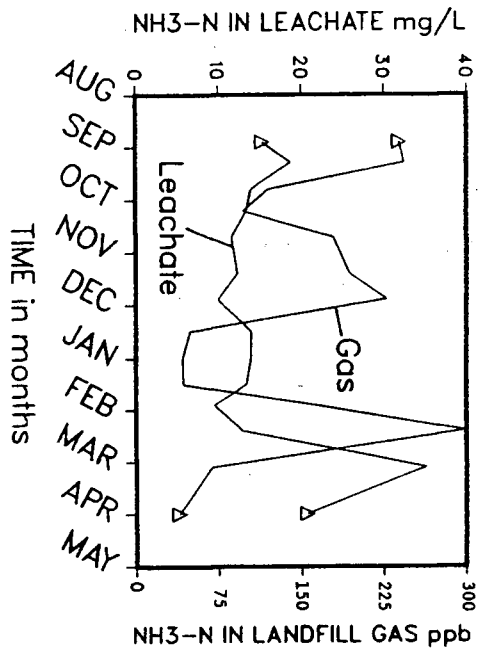
FIG. 5.57 -
TEMPORAL VARIATION OF pH vs. NH3-N IN GAS
F7 STRIDE

pH

pH

NH3-N

TIME in months

NH3-N IN LANDFILL GAS ppb
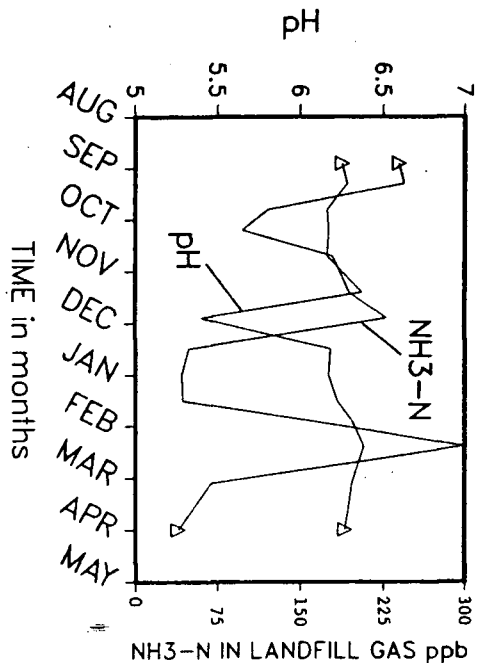
FIG. 5.58 -
TEMPORAL VARIATION OF CH4 FLUX vs. NH3-N IN GAS
F7 STRIDE

METHANE FLUX IN Kg CH4/cm2-day

Flux

NH3-N

TIME in months

NH3-N IN LANDFILL GAS ppb
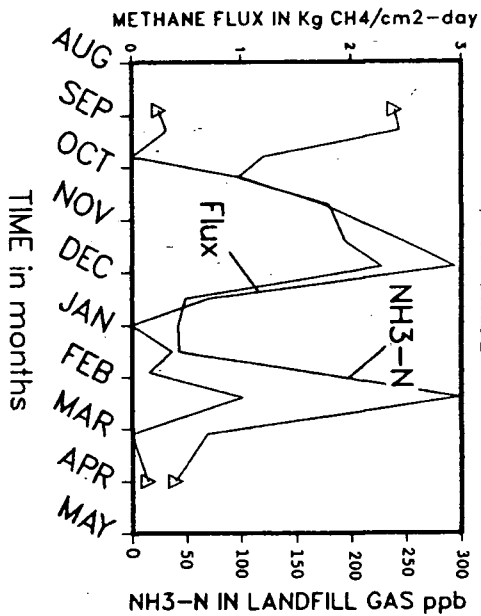
FIG. 5.59 -
TEMPORAL VARIATION OF GAS TEMP. vs. NH3-N IN GAS
F7 STRIDE

GAS TEMP. IN celsius

Temp

NH3-N

TIME in months

NH3-N IN LANDFILL GAS ppb

FIG. 5.60 -
TEMPORAL VARIATION IN NH3-N LEACHATE vs. NH3-N GAS
P2 PREMIER St

NH3-N IN LEACHATE mg/L

Leachate

Gas

TIME in months

NH3-N IN LANDFILL GAS ppb

FIG. 5.61 -
TEMPORAL VARIATION OF pH vs. NH3-N IN GAS
P2 PREMIER St.

pH

pH

NH3-N

TIME in months

NH3-N IN LANDFILL GAS ppb

METHANE FLUX IN Kg CH4/cm2-day

Flux

NH3-N

FIG. 5.62 -
TEMPORAL VARIATION OF CH4 FLUX vs. NH3-N IN GAS
P2 PREMIER

TIME in months

NH3-N IN LANDFILL GAS ppb

GAS TEMP. IN celsius

Temp

NH3-N

NH3-N

FIG. 5.63 -
TEMPORAL VARIATION OF GAS TEMP. vs. NH3-N IN GAS
P2 PREMIER St.

TIME in months

NH3-N IN LANDFILL GAS ppb

assumed to be a reliable estimate of the effective precipitation inflow into the system between sample periods. This scenario was decided upon because calculating an effective precipitation influx through a water balance was cumbersome and also required more site-specific variables than had been collected for this study. Probably the most accurate way to do a statistical analysis on this time-dependent precipitation variable and NH_3-N would be through a Box-Jenkins time series analysis, which was not attempted because of time constraints.

There a number of reasons why precipitation influx may be decreasing NH_3-N gas concentrations. They are listed in point form below:

1. The effective dilution of the leachate and unsaturated zone may decrease the amount of ammonia mass available for mass transfer into the gas phase.

2. The "wetting front" of the lower pH infiltrating rainfall acts as an effective sink for NH_3-N gas by resolubilizing the NH3-N and protonating this to NH_4^+ hence, removing it from the gas phase.

3. Precipitation could be "choking" or shock loading the microbial fauna that produce NH_3-N as a waste product, resulting in less NH_3-N available to transfer.

Out of these three reasons, probably the coupling of #1 and #2 is the dominant mechanism in affecting NH_3-N gas concentrations.

5.4.3. NH3-N IN LEACHATE

In most cases, leachate NH_3-N concentration is decreasing throughout the study period much like the NH_3-N gas does. There are exceptions such as C6 Richmond (Fig 5.36) which displays a semi-inverse relationship and F5 Matsqui, whose leachate values may vary from 2000 mg/L down to 150 mg/L but the NH_3-N in the gas does not reflect this change. The reason for this variability concentrations in F5 Matsqui is again related to a cracked casing where large volumes of rainwater dilute the leachate at certain times followed by recovery to full strength (Fig. 5.48). Even though some of the plots indicate a possible interrelationship between NH_3-N in leachate and gas, only Richmond Landfill indicates any significant correlation between variables. The r was found to be a fairly low 0.4258. One Stride Ave well, F2 (Fig. 5.52) shows a profound masking of the two parameters but only correlates to an r of 0.5605 and is not regarded as significant since it exceeds the p of 0.025.

One reason why NH_3-N in leachate may not describe more of the variation in NH_3-N gas, could stem from the fact that most of the mass transfer of NH_3-N into the gas phase probably occurs in the unsaturated zone (esp. in the deeper wells) where entirely different variations and concentrations of NH_3-N and pH may occur. Therefore, sampling the leachate may not entirely describe the whole ammonia system, especially in wells (other than Richmond) where unsaturated zones greater than 8 meters exist.

5.4.4. LEACHATE pH

In most instances, the pH follows the same patterns as the NH_3-N during the study period. This is probably due to precipitation infiltration decreasing gas production, which causes an accumulation in organic acids to suppress the pH. This rainwater may also help to dilute the buffering alkalinity to cause the system to be more susceptible to pH drop from these organic acids.

The results of the Pearson correlation indicate that there are no significant statistical relationships between pH and NH_3-N gas concentrations in any of the landfills. There may be a relationship due to a combination of pH and leachate NH_3-N controlling the formation of NH_3-N gas as regulated by the ammonia equilibrium expression already discussed.

5.4.5. METHANE FLUX

The effect of air stripping by methane flux caused by gas production was noticed in a few wells such as B8, D9, C6 Rich and F7 Stride (Fig's 5.30, 5.34, 5.38 and 5.58 respectively). These plots indicate some elevated concentrations of NH3-N gas with increased CH_4 flux.

Even though these plots indicate some interrelationship, the Pearson correlation coefficients indicate that none of the four wells show a significant correlation (r). The only two wells found to have significant r's were two non-leachate wells, F1 and F4 Matsqui, which exhibit r's of 0.6439 and 0.6144.

Potential reasons why CH_4 flux does not explain any

variability in NH_3-N gas are listed in point form below:

1.   The increased flux in kg CH_4/cm^2-day may actually create a large volume dilution of gaseous components so values are in turn, lower than expected. This could be the case at Stride Ave where low methane fluxes are associated with higher than expected NH_3-N gas concentrations.

2.   The internal velocities of the methane flow around the refuse grains is not a substantial enough force to accelerate the normal mass transfer rates of ammonia into the gas phase.

3.   The variation in methane fluxes are due to analytical variation in many wells.

5.4.6. GAS TEMPERATURE

When this study originally began, gas temperature (Tg) was not considered a variable that could affect concentrations of NH_3-N in gas. However, after the statistical and graphical analysis, it has become the parameter that best describes the variation of NH_3-N in gas.

All of the plots exhibit a fairly consistent interrelationship between falling gas temperature and decreasing NH_3-N gas concentration. The statistical analysis also indicates a strong correlation between the two variables. In the linear regression analysis, R^2's generated from the least squares method were always greater for Tg than the other parameters analyzed (pH, NH_3-N leachate, ionic strength, CH_4 and CO_2 flux). The average R^2 from each landfill ranged from a low of 0.2504 at Premier St. to a high of 0.5247 at Matsqui landfill. Results

from the Pearson correlation indicate that 8 out of 18 wells analyzed exhibit a significant correlation between variables. All four combined well analysis also exhibit significant correlations ranging from a low of 0.4716 in Richmond to a high of 0.6668 in Stride Ave..

Stepwise multiple regression also indicates Tg is somewhat interrelated to NH_3-N gas as it was the only independent variable that fit into the equation predicting NH_3-N gas. The one exception to this rule was Premier St. where leachate temp (Tw) replaced Tg as the lone independent variable. The results of these stepwise regressions are listed below:

MATSQUI LANDFILL

NH_3-N GAS (ppb) = -267.61 + 33.2 (Tg)

R^2 = 0.4551   Sig F<0.000   N = 49

STRIDE AVE. LANDFILL

NH_3-N GAS (ppb) = -70.06 + 22.15 (Tg)

R_2 = 0.3366   Sig F<0.000   N = 44

RICHMOND LANDFILL

NH_3-N GAS (ppb) = -68.42 + 10.84 (Tg)

R^2 = 0.2224   Sig F<0.000   N = 86

PREMIER ST LANDFILL

NH_3-N GAS (ppb) = -908.77 + 48.10 (Tw)

R^2 = 0.3171   Sig F=0.001   N = 30

Inspection of the above results indicate some very low R^2's which makes it very difficult to have any confidence in predicting NH_3-N gas concentrations from these equations. In

addition to finding minimal statistical relationship between variables, a non-normal distribution was discovered in both Matsqui and Richmond NH_3-N data. Since these multiple regression equations were reduced to a bivariate regression equation, the results for each well can be expressed graphically. These plots are located in Figures 5.64 through 5.67. These plots exhibit a large point scatter around the best fit line. This point scatter is indicative of very low R^2's like the ones calculated in this analysis.

The somewhat linear relationship between Tg and NH_3-N gas could be due to three reasons which are listed below:

1. The higher landfill gas temperature could increase microbial metabolism rates, or vice-versa. This may cause a release of more NH_3-N for mass transfer into the gas phase.

2. The greater the landfill gas or leachate temperature, the greater the Henry's Law constant is because of a decrease in solubility. This effect causes a greater mass of NH_3-N to be transfered into the gas phase elevating NH_3-N gas concentrations.

3. The lower landfill temperatures are a resultant of precipitation infiltration which, already discussed could be a sink for NH_3-N gas. So in this scenario, Tg or Tw are indirect causes for NH_3-N gas variation.

The most important factor causing NH_3-N gas variation by Tg or Tw is probably mechanism #2, where mass transfer is enhanced by higher temperatures. For #1 to be valid, there would tend to be a general increase in NH_3-N in the leachate, which was not

FIG. 5.64 -

REGRESSION PLOT OF GAS TEMP VS. NH3—N IN GAS
MATSQUI LANDFILL

NH3-N GAS = -267.61 + 33.2 (Tg)

$R^2 = 0.4551$
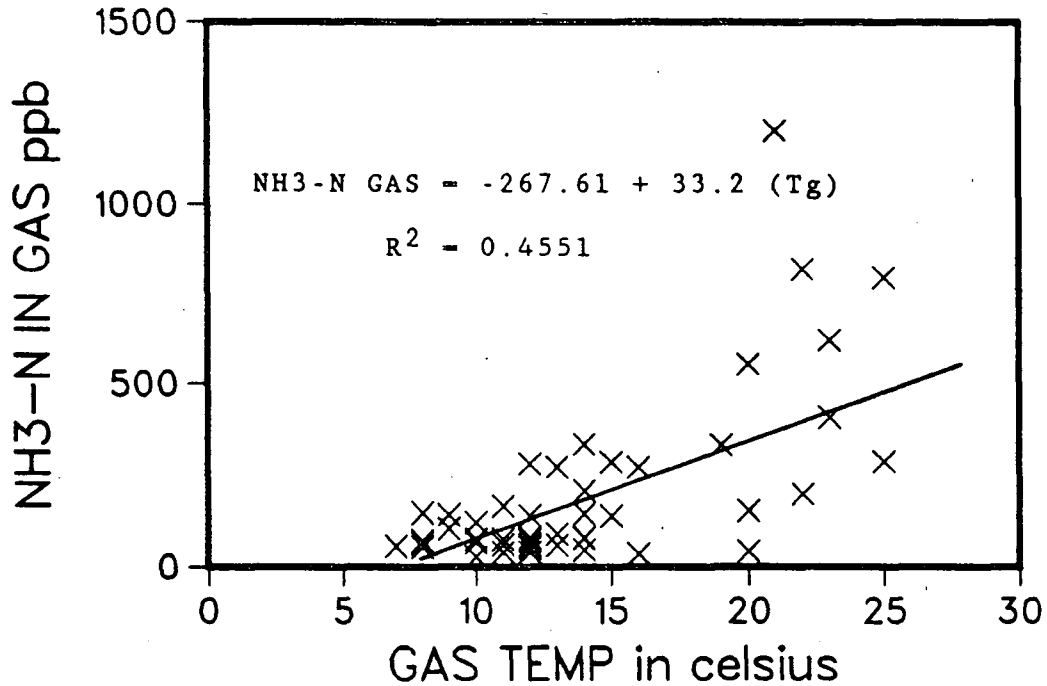
FIG. 5.65 -

REGRESSION PLOT OF GAS TEMP vs. NH3—N IN GAS
STRIDE AVE LANDFILL

NH3-N GAS = -70.06 + 22.15 (Tg)

$R^2 = 0.3366$
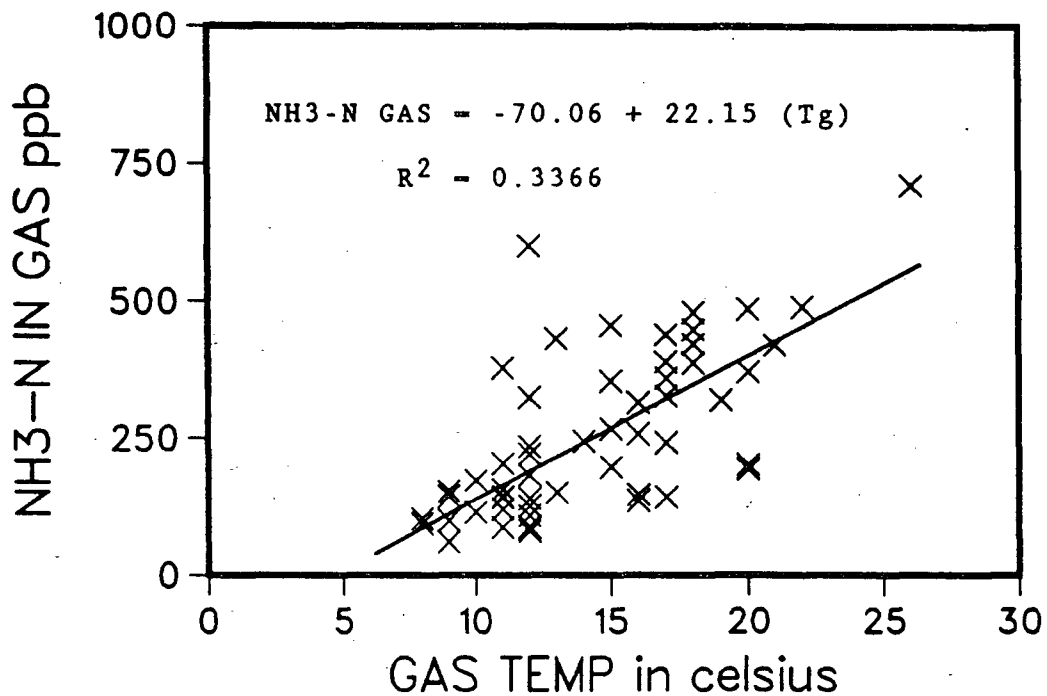
FIG. 5.66 -

REGRESSION PLOT OF GAS TEMP vs. NH3–N IN GAS
RICHMOND LANDFILL

NH3-N GAS = -68.42 + 10.84 (Tg)

R^2 = 0.2224
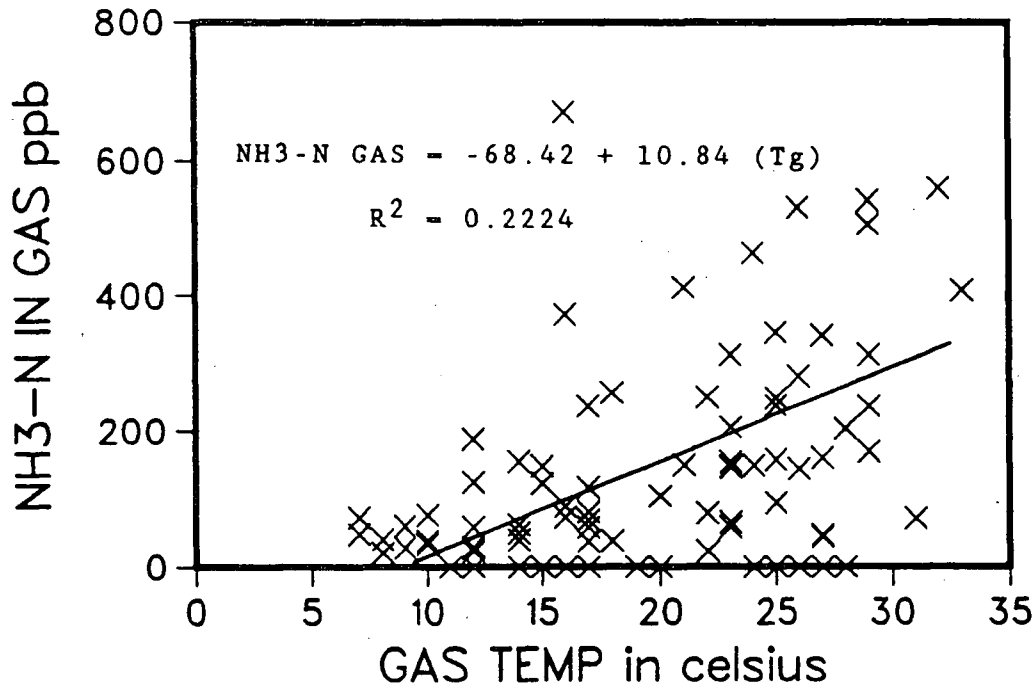
REGRESSION PLOT OF LEACHATE TEMP vs. NH3–N IN GAS
PREMIER ST. LAND

NH3-N GAS = -908.77 + 48.10 (Tw)

R2 = 0.3171
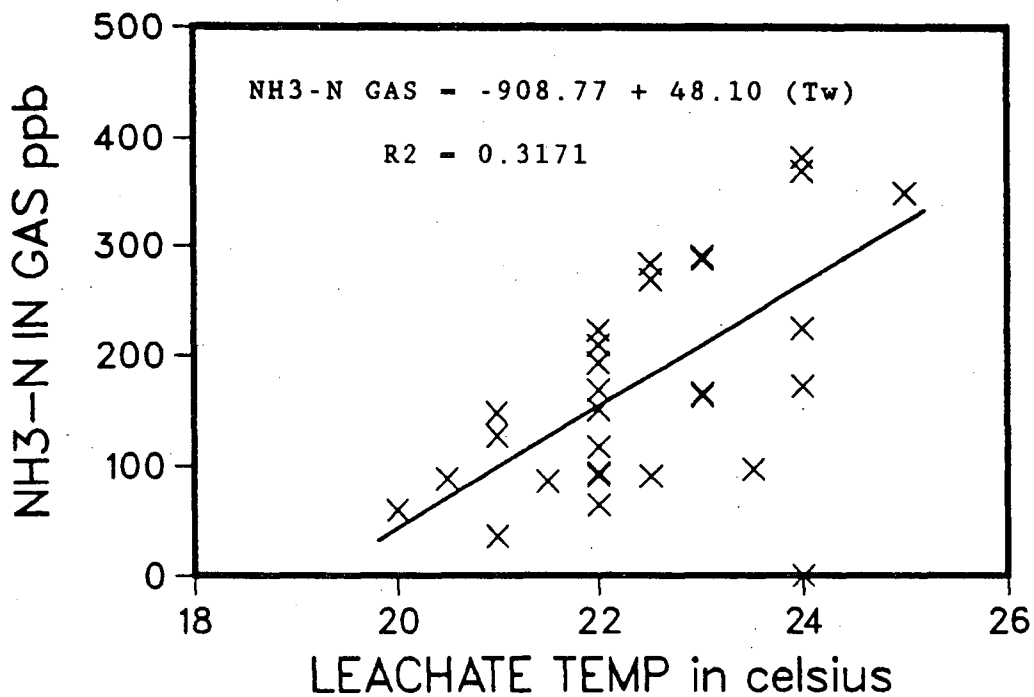
found. However, this could happen in the unsaturated zone which would not be noticed in my results. The indirect relationship of #3 may be important, but because precipitation was rejected from the regression equation, the impact of precipitation on NH_3-N gas is uncertain.

5.4.7. OTHER PARAMETERS

Two other parameters monitored to see if they contributed to the temporal variability of NH_3-N gas were, static gas flow and ionic strength of the leachate.

An increase in gas flow was originally believed much like CH_4 flux, to cause an increase in NH_3-N in the gas phase from accelerated mass transfer or consequently, cause a decrease due to mass dilution. Results however, indicate static flow showed minimal correlation with NH_3-N gas.

An increase in the ionic strength of leachate was generally believed to decrease the solubility of NH_3-N in the leachate thereby causing an increase of NH_3-N into the gas phase. In analysis of the data, only one well (F2 Matsqui) exhibited any interrelationship between the variable pair with a significant r of 0.6026. Deficiency in correlation with ionic strength and NH_3-N gas may be a result of estimating ionic strength from conductivity measurements (Appendix B.5) instead of calculating ionic strength from a complete leachate ionic analysis.

5.5. LANDFILL GAS ORGANIC CONTAMINANTS

Qualitative data collected from Tenax GC trap analysis on gases from three of the four landfills is listed in tables 5.8

through 5.11. The tables are ordered in a specific sequence
determined by the type of compound. The divisions of the table
are described below:

1. CH_4, CO_2, N_2, O_2 percentages

2. Halogenated Hydrocarbons

3. Benzene and Toluene Compounds

4. Alcohols

5. Saturated and unsaturated hydrocarbons

6. Miscellaneous compounds

No organic analysis was done on Stride Ave. gas because of
time constraints and the general assumption that not many
organics would be detected in this older landfill.

Compounds that were not detected but generally considered to
be in sufficient concentration (sub ppm) were vinyl chloride and
thiol group compounds. Vinyl chloride is carcinogenic while
thiol group compounds constitute a major fraction of landfill gas
odor (Young and Parker, 1984). Vinyl chloride was expected to be
found since it is a waste product of the PVC industry and also a
daughter product of the microbially mediated anaerobic
degradation of certain halogenated hydrocarbons (ie,
tetrachloroethylene) common to these landfills (Refer to Vogel,
Criddle and McCarty, 1987). Vinyl chloride has been found to be
quite abundant in landfill gas at concentrations up to 12,800 ppm
in a study by Stephens et al. (1986). Thiol group compounds were
important to detect not only for their odor properties but also
as a potential interference source in the NH_3-N gas analytical

WELL P1 PREMIER ST., January 20, 1988

==

Methane   Tr
Carbon Dioxide   9.9%
Nitrogen   70.7%
Oxygen   19.4%

Tetrachloroethylene

Benzene and isomers (3)
Ethyl Benzene
Toluene

Hexane and isomer
Cyclohexane isomers (4)
Heptane isomer
Cycloheptane
Bicycloheptane isomer
3-methyl pentane
Methyl-cyclopentane isomers (2)
C10-C12 hydrocarbons
Pentene isomer
Xylenes *

Furan isomer
Cyclohexanone isomer
Benzaldehyde

==

* Appearance of this could be due to trap bleed

TABLE 5.8 - Landfill gas VOC's detected by GC-MS and Tenax Trap

WELL F5 MATSQUI LANDFILL, April 13, 1988

==

Methane   --
Carbon Dioxide   --
Nitrogen   --
Oxygen   --

1,2-dichloroethene
Tetrachloroethylene
Difluorodimethyl Silane

Benzene and isomers(8)
Toluene

Phenol

Nonane
Cyclohexane isomers (2)
Xylene and isomer *

Benzaldehyde and isomer
1-phenyl Ethanone

==

* Appearance of this could be due to trap bleed

TABLE 5.9 - Landfill Gas VOC's detected by GC-MS and Tenax Trap

WELL F3 MATSQUI LANDFILL, April 22, 1988

===

Methane	50.1 %
Carbon Dioxide	32.5 %
Nitrogen	17.4 %
Oxygen	Tr

1,2-dichloroethane
Trichlorofluoromethane
1,1-dichloroethene
1,2-dichloroethene
Trichloroethylene
Tetrachlorethylene
Dichlorobenzene
Trichlorobenzene

Benzene and isomers (10)
Trimethyl Benzene
Tetramethyl Benzene isomers (3)
Toluene

Phenol
Phenol isomers
Dimethyl Cyclooctanemethanol isomer

Hexane
Heptane
Cyclohexane isomers (3)
Tetradecane
Octane isomer
Nonane and isomers (2)
Decane and isomer
Bicyclo-heptane isomers (2)
Cycloundecane isomer
Dodecane
1,3,5-cycloheptatriene
4-ethyl-2-octene
Xylenes *
Indene isomers (4)

1,1 Diethyl Ether
1,1'-Biphenyl
Naphthalene and isomers (5)
Phenyl-Oxazole isomer
Benzofuran isomer

===
    * Appearance of this could be due to trap bleed

TABLE 5.10 - Landfill gas VOC's detected by GC-MS and Tenax Trap

WELL C6 RICHMOND LANDFILL, April 22 and April 13, 1988

```
=====================================================================
Methane            56.5 %     Methane            54.3 %
Carbon Dioxide     43.5 %     Carbon Dioxide     41.8 %
Nitrogen            0.0 %     Nitrogen            3.1 %
Oxygen              0.0 %     Oxygen              0.7 %

Trichlorofluoromethane       Trichlorofluoromethane
Methylene chloride           dichloromethane
1,2-dichloroethene           1,2-dichloroethene
Trichloroethylene            Trichloroethylene
Tetrachloroethylene          Tetrachloroethylene
1,2-dichlorobenzene
Trichlorobenzene
Fluorene

Benzene and isomers (5)      Benzene and isomers (6)
Trimethyl benzene isomer     Ethyl Benzene
Tetramethyl benzene isomers (3)
propyl benzene
Toluene
p-isobutyl Toluene

Phenol isomers (2)           Phenol
Bicyclo-octanol isomer       Benzenemethanol-ethenyl

Hexane                       Cyclobutane isomers
Heptane and isomer           Pentyl Cyclopropane
Nonane and isomer            Cyclopentane isomer
Tricycloheptane isomer
Decane and Tridecane isomers
Xylenes *                    Xylenes *
Bicyclohexene isomer
3,9-Dodecadiene
Indene isomers (3)           Methyl Indene and isomer
Trimethyl dihydro Indene

Ethyl and Methyl Ester Butanoic Acid
Naphthalene and isomers (6)
Disulfide isomers (2)        Benzaldehyde
Trans-Cyclohexanone isomer   1-phenyl-Ethanone
Benzofuran isomer            2,2'-bifuran
1,1'-Biphenyl
Methyl Benzofuran
Dibenzofuran
Acenaphthylene isomer
=====================================================================
```

* Appearance of this could be due to trap bleed

TABLE 5.11 - Landfill Gas VOC's detected by GC-MS and Tenax Trap

technique already discussed.

The reason(s) vinyl chloride was not detected is probably due to analytical limitations during thermal desorption of the trapped organics. On the other hand, thiol group compounds are more polar and less likely to be trapped on Tenax GC material. Other trapping material such as Porapak Q as suggested by Brookes and Young (1983), or analysis of the condensate may be more effective in detecting thiols.

Inspection of Tables 5.8 through 5.11 indicate that up to 8 chlorinated hydrocarbons were detected. Probably the most abundant class of organics found were the substituted benzenes and related isomers. Also noticable in Table 5.11 is the greater detection of compounds in C6 Richmond after the sampling technique was refined.

5.6. PREDICTION OF NH3-N GAS THROUGH HENRY'S LAW

5.6.1. INTRODUCTION

The law that governs the partitioning of a volatile compound between the gas and aqueous phases is commonly referred to as Henry's Law. The constant to Henry's Law (Hx) comes in many units, but is usually reported as the partial pressure (Pa) of the volatile compound divided by it's mole fraction (Xa) in the aqueous phase as shown in equation (i):

$$Hx = Pa/Xa \qquad (i)$$

Henry's Law constants are measured in the lab by three common techniques listed below (From MacKay and Shiu, 1981):

1. The use of vapor pressure and solubility data.

2. Direct measurement of air and aqueous concentrations.

3. Measurements of relative changes in concentration within one phase, while affecting a near-equilibrium exchange with the other phase.

A novel fourth approach, called "Equilibrium Partitioning in Closed Systems" (EPICS), has been sited by many to be a more accurate technique for measuring Hx's, especially for volatile organics. This technique is discussed in more detail by Gossett (1987).

The main assumption for Henry's Law to be valid is that the aqueous and gaseous phases must be in equilibrium. The gas phase should behave ideally while the aqueous phase can behave non-ideally as long as the solution (ie., leachate) is dilute (< 0.05 mole fraction). In this data, all mole fractions are less than 10^{-6}, so Henry's law is valid.

In the following section, four entirely different Hx's will be evaluated for their potential to predict NH_3-N in the gas phase given the NH_3-N concentration in the leachate.

After evaluating the spreadsheet results, a section in this thesis will be devoted to discussing the potential reasons for deviation observed between the ratio of predicted versus measured NH3-N gas concentrations.

5.6.2. COMPARISON OF DIFFERENT HENRY'S LAW CONSTANTS

5.6.2.1. CORRECTED VAPOR PRESSURE METHOD

This method is employed by MacKay and Shiu (1981) and others for calculating Henry's Constants from available solubility and

vapor pressure data. Equation (ii) is presented below:

$$H_1 = Pc/S \qquad (ii)$$

Where Pc = corrected vapor pressure (atm)

S = Solubility of Ammonia in
distilled water (moles/L)

The corrected vapor pressure is considered more accurate than the reference vapor pressure because the system is non-ideal and dilute. Corrected vapor pressure is a function of the temperature and solubility and is calculated in Appendix B.10. Regression equations are used to calculate both the solubility and reference vapor pressure as a function of temperature. These equations are also listed in Appendix B.10.

Possible errors introduced into calculating this constant include the following:

1. Variation in the reference vapor pressure calculation. Unfortunately, no coefficient of variation was documented.

2. The small variation in the regression equation to estimate solubility. The coefficient of variation (% C.V.) is less than 1.0 % with the r^2 being a respectible 0.999806.

3. Solubility data is taken from pure water measurements, so errors are uncertain when considering a leachate. Solubility of NH_3 has been shown to decrease with increasing ionic strength, so this method may overpredict solubility in non-pure systems.

Inspection of the results in Tables 5.12 through 5.19, indicate that pt. #4 is most likely the major cause behind the higher than usual ratios between predicted and measured NH_3-N in gas. The overprediction of NH_3-N in gas is most likely due to an

DATE	NH3-N GAS (ppb)	H1 (moles/ L-atm)	NH3 BY H1 (ppb)	RATIO H1/MEAS	H2 (atm/X)	NH3 BY H2 (ppb)	RATIO H2/MEAS	H3 (moles/ L-atm)	NH3 by H3 (ppb)	RATIO H3/MEAS	H4 by FORMULA AS f(T)	NH3 by H4 (ppb)	RATIO H4/MEAS
						F1 MATSQUI							
01/12/88	44.8	27.1	1823.3	40.6832	0.57	507.5	11.3232	143.7	344.4	7.6840	3.84E+03	158.7	3.5422
01/26/88	39.4	19.3	2561.8	65.0311	0.69	843.2	21.4049	116.6	424.7	10.7803	3.23E+03	188.7	4.7913
02/09/88	30.2	20.8	1842.9	60.9780	0.67	644.6	21.3278	119.6	320.6	10.6080	3.30E+03	150.9	4.9931
03/01/88	140.4	15.5	2366.8	16.8561	0.78	676.0	4.8145	100.0	365.9	2.6059	2.85E+03	177.6	1.2650
03/29/88	37.1	20.6	1186.1	31.9394	0.69	399.6	10.7587	116.6	210.1	5.6578	3.23E+03	102.8	2.7678
						F2 MATSQUI							
08/05/87	204.7	9.0	9218.9	45.0424	0.87	1465.9	7.1620	86.0	968.4	4.7312	2.52E+03	416.1	2.0332
08/25/87	408.4	9.3	7053.3	17.2725	0.87	1144.3	2.8021	86.0	763.4	1.8695	2.52E+03	322.0	0.7885
09/08/87	397.4	8.3	10815.4	27.2178	0.90	1602.6	4.0330	81.9	1092.5	2.7494	2.42E+03	458.9	1.1547
09/22/87	311.4	9.3	9773.9	31.3837	0.87	1560.6	5.0110	86.0	1057.9	3.3968	2.52E+03	448.8	1.4410
10/06/87	166.5	9.6	11834.8	71.0840	0.90	2049.0	12.3069	81.9	1390.5	8.3521	2.42E+03	584.2	3.5090
10/20/87	143.1	11.6	10136.7	70.8429	0.87	2025.2	14.1539	86.0	1363.4	9.5282	2.52E+03	575.3	4.0208
11/10/87	135.7	11.9	12268.7	90.4243	0.84	2429.3	17.9050	90.4	1616.8	11.9166	2.63E+03	688.0	5.0707
11/24/87	40.0	12.7	33393.5	834.3575	0.84	6907.2	172.5808	90.4	4691.7	117.2254	2.63E+03	1958.7	48.9402
12/08/87	25.8	19.3	220.0	8.5443	0.69	56.9	2.2108	116.6	36.5	1.4164	3.23E+03	16.5	0.6395
12/29/87	18.2	17.0	2453.9	134.8581	0.69	562.0	30.8862	116.6	357.5	19.6465	3.23E+03	160.5	8.8190
01/12/88	23.7	23.7	477.8	20.1736	0.60	128.5	5.4267	136.3	83.0	3.5052	3.68E+03	38.8	1.6370
01/26/88	38.7	15.5	117.9	3.0430	0.75	25.2	0.6509	105.2	17.4	0.4495	2.97E+03	7.8	0.2002
02/09/88	33.2	16.0	46.8	1.4124	0.79	10.9	0.3298	97.5	7.7	0.2313	2.80E+03	3.3	0.1008
03/01/88	69.3	15.0	2509.9	36.2206	0.75	555.9	8.0223	105.2	359.0	5.1810	2.97E+03	164.6	2.3758
03/29/88	72.1	15.5	1314.1	18.2185	0.75	284.3	3.9417	105.2	194.1	2.6911	2.97E+03	92.7	1.2854
						F3 MATSQUI							
12/08/87	19.8	21.0	1600.1	81.0053	0.66	443.0	22.4275	122.8	273.8	13.8607	3.37E+03	129.7	6.5668
12/29/87	35.9	21.0	939.2	26.1848	0.66	258.0	7.1935	122.8	160.7	4.4805	3.37E+03	77.2	2.1533
01/12/88	26.7	21.0	545.8	20.4326	0.66	145.0	5.4266	122.8	93.4	3.4962	3.37E+03	43.6	1.6332
01/26/88	29.6	15.0	531.0	17.9519	0.78	116.9	3.9515	100.0	79.4	2.6859	2.85E+03	36.9	1.2469
02/09/88	52.0	17.1	158.8	3.0532	0.78	40.0	0.7685	100.0	27.1	0.5216	2.85E+03	12.1	0.2333
03/01/88	135.9	12.3	92.4	0.6801	0.87	18.5	0.1358	86.0	13.3	0.0976	2.52E+03	6.4	0.0472
03/29/88	44.7	16.1	151.3	3.3834	0.75	33.7	0.7540	105.2	23.1	0.5163	2.97E+03	11.4	0.2547

TABLE 5.12 - Results of Henry's Law Comparison
F1, F2, F3 Matsqui

H_1 = Henry's Law Constant - Corrected Vapor Pressure Method

H_2 = Henry's Law Constant - Mole Fraction Method

H_3 = Henry's Law Constant - Gibbs Free Energy Method

H_4 = Henry's Law Constant - Solubility-Equilibrium Method

DATE	NH3-N GAS (ppb)	H1 (moles/ L-atm)	NH3 BY H1 (ppb)	RATIO H1/MEAS	H2 (atm/X)	NH3 BY H2 (ppb)	RATIO H2/MEAS	H3 (moles/ L-atm)	NH3 by H3 (ppb)	RATIO H3/MEAS	H4 by FORMULA AS f(T)	NH3 by H4 (ppb)	RATIO H4/MEAS
						FS MATSQUI							
08/05/87	22.0	9.9	4575.0	207.7523	0.87	901.5	40.9395	86.0	526.2	23.8932	2.52E+03	227.0	10.3100
08/25/87	601.6	9.1	19743.9	32.8197	0.90	3980.2	6.6162	81.9	2182.0	3.6271	2.42E+03	938.8	1.5605
09/08/87	75.9	9.9	19145.1	252.2225	0.87	3986.3	52.5164	86.0	2201.8	29.0076	2.52E+03	956.8	12.6057
09/22/85	143.9	8.5	14740.2	102.4617	0.87	2624.8	18.2455	86.0	1459.4	10.1446	2.52E+03	634.5	4.4107
10/06/87	99.1	8.8	23934.9	241.4131	0.90	4597.0	46.3668	81.9	2566.4	25.8856	2.42E+03	1109.8	11.1942
10/20/87	276.9	9.9	16482.6	59.5349	0.87	3442.5	12.4342	86.0	1895.6	6.8470	2.52E+03	867.1	3.1320
11/10/87	167.6	13.5	2553.1	15.2349	0.81	591.0	3.5263	95.1	363.7	2.1704	2.74E+03	162.8	0.9717
11/24/87	37.3	16.0	33.1	0.8876	0.78	8.1	0.2183	100.0	5.3	0.1418	2.85E+03	2.4	0.0647
12/08/87	13.7	16.5	62.7	4.5932	0.78	16.1	1.1779	100.0	10.4	0.7588	2.85E+03	4.7	0.3437
12/29/87	72.9	17.7	4335.8	59.4643	0.78	1404.1	19.2569	100.0	766.3	10.5098	2.85E+03	352.8	4.8391
01/12/88	30.8	16.0	9305.9	302.4283	0.76	2769.4	90.0030	102.6	1452.2	47.1960	2.91E+03	675.5	21.9541
01/26/88	36.0	17.1	348.0	9.6723	0.79	96.8	2.6918	97.5	61.0	1.6948	2.80E+03	28.2	0.7840
02/09/88	--	20.4	250.9	--	0.72	72.6	--	110.7	46.3	--	3.10E+03	--	--
03/01/88	69.1	14.5	2680.3	38.7702	0.81	697.3	10.0869	95.1	407.6	5.8952	2.74E+03	169.2	2.4472
03/29/88	--	16.5	845.4	--	0.78	230.9	--	100.0	139.7	--	2.85E+03	--	--
						F8 MATSQUI							
11/10/87	102.9	12.0	0.4	0.0036	0.87	0.1	0.0007	86.0	0.1	0.0005	2.52E+03	0.0	0.0002
11/24/87	40.0	14.5	0.1	0.0014	0.81	0.0	0.0003	95.1	0.0	0.0002	2.74E+03	0.0	0.0001
12/08/87	19.9	17.8	0.0	0.0020	0.73	0.0	0.0004	107.9	0.0	0.0003	3.04E+03	0.0	0.0002
12/29/87	32.4	19.7	1.0	0.0294	0.73	0.2	0.0075	107.9	0.2	0.0054	3.04E+03	0.1	0.0025
01/12/88	28.3	27.2	0.2	0.0067	0.63	0.1	0.0020	129.3	0.0	0.0014	3.52E+03	0.0	0.0007
01/26/88	59.8	22.4	0.4	0.0071	0.66	0.1	0.0018	122.8	0.1	0.0013	3.37E+03	0.0	0.0006
02/09/88	27.3	32.1	0.3	0.0092	0.57	0.1	0.0031	143.7	0.1	0.0021	3.84E+03	0.0	0.0010
03/01/88	82.4	20.0	--	0.0000	0.69	--	--	116.6	--	--	3.23E+03	--	--
03/29/88	70.3	25.4	--	0.0000	0.63	--	--	129.3	--	--	3.52E+03	--	--

TABLE 5.13 - Results of Henry's Law Comparison
F5, F8 Matsqui

DATE	NH3-R GAS (ppb)	H1 (moles/ L-atm)	NH3 BY H1 (ppb)	RATIO H1/MEAS	H2 (atm/X)	NH3 BY H2 (ppb)	RATIO H2/MEAS	H3 (moles/ L-atm)	NH3 by H3 (ppb)	RATIO H3/MEAS	H4 by FORMULA AS f(T)	NH3 by H4 (ppb)	RATIO H4/MEAS
						F2 STRIDE							
08/27/87	101.3	12.0	3.9	0.0385	0.78	0.7	0.0067	100.0	0.5	0.0046	2.85E+03	0.2	0.0025
09/10/87	192.5	12.8	9.8	0.0511	0.78	1.8	0.0094	100.0	1.3	0.0065	2.85E+03	0.7	0.0035
09/24/87	156.8	12.7	7.2	0.0456	0.81	1.3	0.0086	95.1	1.0	0.0061	2.74E+03	0.5	0.0031
10/07/87	209.4	11.6	6.7	0.0320	0.78	1.1	0.0054	100.0	0.8	0.0037	2.85E+03	0.4	0.0018
10/22/87	72.8	15.7	1.3	0.0179	0.72	0.3	0.0037	110.7	0.2	0.0025	3.10E+03	0.1	0.0014
11/12/87	98.9	16.2	3.5	0.0350	0.72	0.7	0.0075	110.7	0.5	0.0051	3.10E+03	0.3	0.0028
11/26/87	74.7	18.0	0.2	0.0029	0.70	0.1	0.0007	113.6	0.0	0.0005	3.17E+03	0.0	0.0003
12/15/87	42.6	18.6	0.2	0.0045	0.70	0.0	0.0011	113.6	0.0	0.0007	3.17E+03	0.0	0.0004
12/31/87	77.5	19.2	2.5	0.0317	0.70	0.6	0.0079	113.6	0.4	0.0054	3.17E+03	0.2	0.0028
01/14/88	46.0	21.2	2.3	0.0502	0.70	0.6	0.0137	113.6	0.4	0.0094	3.17E+03	0.2	0.0051
01/28/88	101.6	17.8	5.3	0.0524	0.73	1.3	0.0127	107.9	0.9	0.0086	3.04E+03	0.4	0.0040
02/11/88	117.3	17.9	6.5	0.0558	0.72	1.6	0.0133	110.7	1.1	0.0090	3.10E+03	0.5	0.0046
03/03/88	86.1	18.4	6.0	0.0699	0.73	1.5	0.0174	107.9	1.0	0.0119	3.04E+03	0.5	0.0057
03/31/88	91.0	17.9	4.2	0.0457	0.72	1.0	0.0109	110.7	0.7	0.0074	3.10E+03	0.3	0.0037
						F3 STRIDE							
08/27/87	210.6	14.7	3.7	0.0175	0.72	0.7	0.0034	110.7	0.5	0.0023	3.10E+03	0.3	0.0013
09/10/87	242.6	13.9	8.6	0.0354	0.72	1.6	0.0065	110.7	1.1	0.0044	3.10E+03	0.6	0.0024
09/24/87	162.6	14.1	9.3	0.0573	0.75	1.8	0.0110	105.2	1.3	0.0077	2.97E+03	0.6	0.0039
10/07/87	70.6	15.2	7.0	0.0994	0.72	1.4	0.0199	110.7	1.0	0.0137	3.10E+03	0.5	0.0069
10/22/87	128.7	16.3	6.2	0.0478	0.70	1.3	0.0100	113.6	0.9	0.0069	3.17E+03	0.5	0.0038
11/12/87	133.3	16.2	9.7	0.0728	0.72	2.0	0.0153	110.7	1.4	0.0107	3.10E+03	0.8	0.0058
11/26/87	110.5	18.6	6.3	0.0567	0.70	1.6	0.0142	113.6	1.0	0.0093	3.17E+03	0.6	0.0051
12/15/87	59.5	18.5	4.2	0.0705	0.72	1.0	0.0172	110.7	0.7	0.0118	3.10E+03	0.4	0.0061
12/31/87	75.8	19.0	4.8	0.0636	0.73	1.2	0.0161	107.9	0.9	0.0112	3.04E+03	0.5	0.0060
01/14/88	56.4	19.1	1.3	0.0228	0.72	0.3	0.0055	110.7	0.2	0.0039	3.10E+03	0.1	0.0021
01/28/88	215.4	16.6	7.6	0.0352	0.73	1.7	0.0079	107.9	1.2	0.0054	3.04E+03	0.6	0.0027
02/11/88	62.2	17.2	6.3	0.1006	0.73	1.4	0.0230	107.9	1.0	0.0160	3.04E+03	0.5	0.0082
03/03/88	53.8	17.9	7.8	0.1442	0.72	1.8	0.0329	110.7	1.3	0.0233	3.10E+03	0.6	0.0116
03/31/88	77.9	17.1	11.8	0.1514	0.75	2.8	0.0355	105.2	1.9	0.0247	2.97E+03	1.0	0.0123
						F6 STRIDE							
10/22/87	113.6	12.4	30.7	0.2705	0.76	5.6	0.0494	102.6	3.7	0.0327	2.91E+03	1.7	0.0152
11/12/87	245.4	14.5	18.4	0.0750	0.78	3.8	0.0154	100.0	2.7	0.0109	2.85E+03	1.3	0.0051
11/26/87	202.2	18.4	3.0	0.0147	0.73	0.7	0.0036	107.9	0.5	0.0025	3.04E+03	0.2	0.0012
12/15/87	82.3	20.4	2.7	0.0330	0.73	0.7	0.0090	107.9	0.5	0.0062	3.04E+03	0.2	0.0029
12/31/87	60.2	24.0	5.2	0.0866	0.66	1.5	0.0247	122.8	1.0	0.0169	3.37E+03	0.5	0.0082
01/14/88	35.5	24.0	3.4	0.0958	0.66	1.0	0.0273	122.8	0.7	0.0187	3.37E+03	0.3	0.0078
01/28/88	257.4	19.8	7.1	0.0275	0.70	1.8	0.0070	113.6	1.2	0.0048	3.17E+03	0.6	0.0023
02/11/88	N.D.	22.1	6.3	--	0.69	1.8	--	116.6	1.2	--	3.23E+03	--	--
03/03/88	65.1	19.8	6.8	0.1037	0.70	1.7	0.0262	113.6	1.2	0.0181	3.17E+03	0.6	0.0086

TABLE 5.14 - Results of Henry's Law Comparison
F2, F3, F6 Stride Ave.

DATE	NH3-N GAS (ppb)	H1 (moles/ L-atm)	NH3 BY H1 (ppb)	RATIO H1/MEAS	H2 (atm/X)	NH3 BY H2 (ppb)	RATIO H2/MEAS	H3 (moles/ L-atm)	NH3 by H3 (ppb)	RATIO H3/MEAS	H4 by FORMULA AS f(T)	NH3 by H4 (ppb)	RATIO H4/MEAS
						F7 STRIDE							
08/27/87	239.8	12.8	30.8	0.1286	0.78	5.6	0.0235	100.0	3.9	0.0164	2.85E+03	2.0	0.0082
09/10/87	244.4	10.6	52.7	0.2156	0.81	8.3	0.0338	95.1	5.9	0.0239	2.74E+03	2.9	0.0120
09/24/87	120.7	13.6	21.6	0.1793	0.78	4.2	0.0345	100.0	2.9	0.0244	2.85E+03	1.5	0.0125
10/07/87	97.3	13.9	17.7	0.1822	0.72	3.2	0.0332	110.7	2.2	0.0228	3.10E+03	1.2	0.0121
10/22/87	179.0	13.2	18.4	0.1029	0.78	3.4	0.0193	100.0	2.4	0.0135	2.85E+03	1.3	0.0070
11/12/87	193.8	13.6	29.7	0.1531	0.76	5.6	0.0289	102.6	3.9	0.0203	2.91E+03	1.9	0.0100
11/26/87	228.2	15.0	2.3	0.0100	0.75	0.0	0.0002	105.2	0.3	0.0014	2.97E+03	0.2	0.0007
12/15/87	49.2	16.0	20.3	0.4117	0.81	4.9	0.0992	95.1	3.4	0.0692	2.74E+03	1.7	0.0355
12/31/87	42.9	16.0	18.5	0.4307	0.78	4.3	0.0994	100.0	2.9	0.0688	2.85E+03	1.4	0.0335
01/14/88	43.7	14.5	23.7	0.5436	0.81	5.1	0.1174	95.1	3.6	0.0827	2.74E+03	1.8	0.0410
01/28/88	161.4	15.5	18.0	0.1117	0.78	4.0	0.0247	100.0	2.8	0.0173	2.85E+03	1.5	0.0095
02/11/88	299.4	15.5	28.4	0.0950	0.78	6.4	0.0213	100.0	4.4	0.0147	2.85E+03	2.6	0.0088
03/03/88	69.2	14.9	71.4	1.0331	0.79	15.7	0.2270	97.5	11.0	0.1583	2.80E+03	5.9	0.0847
03/31/88	39.6	14.9	38.4	0.9708	0.79	8.4	0.2122	97.5	5.9	0.1488	2.80E+03	2.8	0.0711
						F8 STRIDE							
12/15/87	30.1	19.7	0.6	0.0191	0.72	0.1	0.0049	110.7	0.1	0.0034	3.10E+03	0.0	0.0015
12/31/87	75.7	19.7	3.0	0.0390	0.72	0.8	0.0099	110.7	0.5	0.0070	3.10E+03	0.3	0.0038
01/14/88	50.9	20.4	3.9	0.0758	0.72	1.0	0.0200	110.7	0.7	0.0140	3.10E+03	0.4	0.0074
01/28/88	188.3	18.5	1.4	0.0073	0.72	0.3	0.0018	110.7	0.2	0.0012	3.10E+03	0.1	0.0006
02/11/88	71.2	24.0	0.5	0.0071	0.66	0.1	0.0020	122.8	0.1	0.0014	3.37E+03	0.1	0.0008
03/03/88	69.8	18.5	0.8	0.0120	0.72	0.2	0.0028	110.7	0.1	0.0020	3.10E+03	--	--
03/31/88	71.3	21.7	1.1	0.0147	0.66	0.3	0.0038	122.8	0.2	0.0026	3.37E+03	0.1	0.0013
						10B STRIDE							
08/27/87	278.8	12.0	1.3	0.0046	0.78	0.2	0.0008	100.0	0.2	0.0006	2.85E+03	0.1	0.0002
09/10/87	283.1	11.1	3.2	0.0112	0.75	0.5	0.0017	105.2	0.3	0.0012	2.97E+03	0.1	0.0005
09/24/87	98.0	13.3	1.4	0.0141	0.75	0.3	0.0026	105.2	0.2	0.0018	2.97E+03	0.1	0.0008
10/07/87	112.0	11.4	2.0	0.0176	0.75	0.3	0.0028	105.2	0.2	0.0019	2.97E+03	0.1	0.0008

TABLE 5.15 - Results of Henry's Law Comparison
F7, F8, 10B Stride Ave.

DATE	NH3-N GAS (ppb)	H1 (moles/ (L-atm)	NH3 BY H1 (ppb)	RATIO H1/MEAS	H2 (atm/I)	NH3 BY H2 (ppb)	RATIO H2/MEAS	H3 (moles/ (L-atm)	NH3 by H3 (ppb)	RATIO H3/MEAS	H4 by FORMULA AS f(T)	NH3 by H4 (ppb)	RATIO H4/MEAS
						B8 RICHMOND							
09/01/87	253.4	6.4	991.4	3.9126	0.96	121.5	0.4797	74.3	85.5	0.3375	2.24E+03	36.0	0.1421
09/15/87	75.5	8.6	1407.9	18.6564	0.93	226.3	2.9993	78.0	154.4	2.0465	2.33E+03	65.6	0.8691
09/29/87	231.8	7.4	1366.4	5.8960	0.96	196.6	0.8485	74.3	136.2	0.5878	2.24E+03	57.4	0.2478
10/13/87	102.8	8.1	1394.4	13.5610	0.93	215.6	2.0970	78.0	144.0	1.4007	2.33E+03	61.0	0.5937
11/03/87	128.9	8.9	2818.3	21.8575	0.96	491.3	3.8105	74.3	337.1	2.6144	2.24E+03	141.1	1.0946
11/17/87	N.D.	10.0	266.8	--	0.91	47.5	--	79.9	33.2	--	2.38E+03	14.2	--
12/01/87	N.D.	12.3	31.6	--	0.85	6.4	--	88.2	4.4	--	2.58E+03	1.9	--
12/24/87	29.1	14.9	35.5	1.2168	0.79	8.0	0.2735	97.5	5.4	0.1865	2.80E+03	2.4	0.0828
01/06/88	30.2	16.0	52.6	1.7438	0.81	12.8	0.4236	95.1	8.8	0.2930	2.74E+03	3.9	0.1294
01/19/88	36.5	16.5	38.1	1.0431	0.78	9.1	0.2504	100.0	6.3	0.1723	2.85E+03	2.8	0.0769
02/02/88	24.1	23.8	37.5	1.5550	0.67	11.4	0.4739	119.6	7.5	0.3096	3.30E+03	3.4	0.1422
02/24/88	61.9	15.0	8.7	0.1405	0.75	1.7	0.0282	105.2	1.2	0.0201	2.97E+03	0.6	0.0090
03/15/88	334.9	13.6	13.7	0.0409	0.78	2.6	0.0079	100.0	1.9	0.0056	2.85E+03	0.9	0.0026
04/05/88	19.6	19.8	7.2	0.3643	0.70	1.8	0.0934	113.6	1.2	0.0636	3.17E+03	0.6	0.0308
						D9 RICHMOND							
09/01/87	280.3	4.2	17593.4	62.7740	1.17	1894.3	6.7590	53.3	1390.6	4.9616	1.71E+03	546.9	1.9512
09/15/87	79.0	5.4	11599.5	146.7584	1.14	1560.0	19.7370	55.8	1115.8	14.1171	1.77E+03	443.1	5.6067
09/29/87	118.5	4.6	18289.3	154.3355	1.17	2134.4	18.0115	53.3	1571.9	13.2649	1.71E+03	621.8	5.2470
10/13/87	35.9	4.5	97381.0	2716.08	1.14	10688.8	298.1247	55.8	7892.4	220.1303	1.77E+03	3072.7	85.7010
11/03/87	72.6	5.2	28361.6	390.7305	1.14	3573.6	49.2328	55.8	2649.7	36.5045	1.77E+03	1046.3	14.4140
11/17/87	170.7	4.6	17157.6	100.5137	1.20	2011.3	11.7828	50.9	1566.7	9.1780	1.64E+03	609.9	3.5731
12/01/87	N.D.	4.7	2190.6	--	1.18	245.0	--	52.1	199.7	--	1.68E+03	78.1	--
12/24/88	39.8	6.2	68.7	1.7289	1.14	9.1	0.2278	55.8	7.7	0.1932	1.77E+03	3.1	0.0777
01/06/88	11.7	5.9	8816.7	750.6831	1.14	1241.6	105.7148	55.8	927.1	78.9386	1.77E+03	373.2	31.7747
01/19/88	44.7	8.1	644.9	14.4320	1.05	107.7	2.4091	64.3	81.5	1.8229	1.99E+03	33.8	0.7569
02/02/88	34.4	7.5	9324.1	270.8809	1.08	1631.5	47.3978	61.3	1140.7	33.1395	1.91E+03	468.2	13.6033
02/24/88	N.D.	6.9	12082.9	--	1.09	1980.9	--	59.9	1389.2	--	1.88E+03	565.5	--
03/15/88	205.7	6.3	23771.1	115.5444	1.11	3724.0	18.1012	58.5	2572.0	12.5016	1.84E+03	1114.5	5.4171
04/05/88	N.D.	9.5	2129.4	--	0.96	401.7	--	74.3	271.2	--	2.24E+03	121.5	--

TABLE 5.16 - Results of Henry's Law Comparison
B8, D9 Richmond

DATE	NH3-N GAS (ppb)	H1 (moles/ L-atm)	NH3 BY H1 (ppb)	RATIO H1/MEAS	H2 (atm/X)	NH3 BY H2 (ppb)	RATIO H2/MEAS	H3 (moles/ L-atm)	NH3 by H3 (ppb)	RATIO H3/MEAS	H4 by FORMULA AS f(T)	NH3 by H4 (ppb)	RATIO H4/MEAS
						C6 RICHMOND							
09/01/87	141.1	5.7	304.0	2.1549	1.08	36.8	0.2607	61.3	28.3	0.2008	1.91E+03	11.4	0.0811
09/15/87	77.6	6.5	437.9	5.6428	1.05	59.1	0.7618	64.3	44.6	0.5746	1.99E+03	18.1	0.2333
09/29/87	266.2	6.0	62.3	0.2342	1.05	7.7	0.0289	64.3	5.8	0.0218	1.99E+03	2.4	0.0089
10/13/87	119.2	5.6	76.4	0.6404	1.11	9.4	0.0789	58.5	7.3	0.0615	1.84E+03	2.9	0.0247
11/03/87	74.8	6.1	423.1	5.6584	1.08	54.3	0.7259	61.3	41.8	0.5592	1.91E+03	16.7	0.2234
11/17/87	73.4	6.2	14.1	0.1924	1.08	1.8	0.0245	61.3	1.4	0.0196	1.91E+03	0.6	0.0080
12/01/87	N.D.	10.6	12.2	--	0.91	2.3	--	79.9	1.6	--	2.38E+03	0.7	--
12/24/87	14.4	16.5	15.0	1.0441	0.79	3.7	0.2599	97.5	2.5	0.1769	2.80E+03	1.1	0.0786
01/06/88	11.5	15.5	9.5	0.8252	0.78	2.1	0.1869	100.0	1.5	0.1276	2.85E+03	0.7	0.0575
01/19/88	62.6	13.6	19.8	0.3162	0.84	4.3	0.0680	90.4	3.0	0.0474	2.63E+03	1.3	0.0210
02/02/88	14.9	14.5	25.4	1.7072	0.81	5.7	0.3851	95.1	3.9	0.2596	2.74E+03	1.7	0.1153
02/24/88	40.6	12.3	35.5	0.8743	0.81	6.7	0.1658	95.1	4.6	0.1132	2.74E+03	2.0	0.0503
03/15/88	118.9	8.7	59.0	0.4962	0.99	9.8	0.0823	70.8	7.3	0.0610	2.15E+03	--	--
04/05/88	14.2	13.6	5.8	0.4073	0.84	1.3	0.0894	90.4	0.9	0.0611	2.63E+03	0.4	0.0288
						G7 RICHMOND							
09/01/87	271.2	5.8	922.1	3.4006	1.02	108.6	0.4006	67.4	79.0	0.2913	2.07E+03	32.6	0.1200
09/15/87	80.5	6.4	1131.0	14.0527	0.99	145.5	1.8081	70.8	102.9	1.2782	2.15E+03	43.1	0.5351
09/29/87	173.1	6.5	1524.3	8.8054	1.02	203.2	1.1736	67.4	146.5	0.8465	2.07E+03	61.0	0.3524
10/13/87	124.8	6.2	1489.0	11.9264	1.05	195.8	1.5681	64.3	142.9	1.1448	1.99E+03	58.7	0.4699
11/03/87	74.4	6.9	2488.8	33.4312	1.02	354.4	4.7607	67.4	253.8	3.4096	2.07E+03	105.4	1.4153
11/17/87	18.8	7.9	1781.0	94.7868	1.05	299.5	15.9388	64.3	218.0	11.6000	1.99E+03	89.3	4.7538
12/01/87	N.D.	10.4	136.7	--	0.94	26.1	--	76.1	18.6	--	2.28E+03	7.9	--
12/24/87	10.6	16.5	18.2	1.7217	0.81	4.5	0.4300	95.1	3.2	0.2993	2.74E+03	1.4	0.1335
01/06/88	25.2	9.6	97.4	3.8659	0.99	17.3	0.6851	70.8	13.2	0.5228	2.15E+03	5.5	0.2170
01/19/88	20.0	10.1	64.6	3.2263	0.96	11.6	0.5804	74.3	8.8	0.4381	2.24E+03	3.7	0.1850
02/02/88	N.D.	12.0	51.8	--	0.90	10.7	--	81.9	7.6	--	2.42E+03	3.3	--
02/24/88	--	10.8	53.3	--	0.96	10.2	--	74.3	7.7	--	2.24E+03	3.3	--
03/15/88	186.3	9.5	67.0	0.3594	0.96	11.4	0.0613	74.3	8.5	0.0458	2.24E+03	3.9	0.0208
04/05/88	N.D.	16.5	2.4	--	0.76	0.5	--	102.6	0.4	--	2.91E+03	--	--

TABLE 5.17 - Results of Henry's Law Comparison
C6, G7 Richmond

DATE	NH3-N GAS (ppb)	H1 (moles/ L-atm)	NH3 BY H1 (ppb)	RATIO H1/MEAS	H2 (atm/X)	NH3 BY H2 (ppb)	RATIO H2/MEAS	H3 (moles/ L-atm)	NH3 by H3 (ppb)	RATIO H3/MEAS	H4 by FORMULA AS f(T)	NH3 by H4 (ppb)	RATIO H4/MEAS
D.55 RICHMOND													
09/01/87	156.8	5.2	3201.8	20.4204	1.08	369.2	2.3547	61.3	273.8	1.7463	1.91E+03	112.1	0.7149
09/15/87	N.D.	5.7	2001.8	--	1.08	252.8	--	61.3	186.6	--	1.91E+03	76.4	--
09/29/87	85.3	5.0	2427.5	28.4721	1.11	275.3	3.2285	58.5	207.7	2.4366	1.84E+03	84.3	0.9892
10/13/87	101.8	5.2	2477.5	24.3264	1.11	290.8	2.8555	58.5	218.1	2.1418	1.84E+03	88.2	0.8660
11/03/87	125.5	6.1	2843.3	22.6495	1.11	392.8	3.1290	58.5	298.5	2.3777	1.84E+03	119.4	0.9515
11/17/87	19.3	6.9	1563.3	80.8784	1.11	245.3	12.6891	58.5	185.5	9.5967	1.84E+03	75.0	3.8809
12/01/87	N.D.	9.5	996.4	--	0.96	183.1	--	74.3	126.9	--	2.24E+03	53.6	--
12/24/87	14.7	10.2	851.2	57.9230	0.99	171.9	11.6991	70.8	122.9	8.3604	2.15E+03	52.0	3.5409
01/06/88	36.6	8.3	1541.5	42.1301	1.03	267.6	7.3134	65.8	194.8	5.3245	2.03E+03	77.4	2.1160
01/19/88	77.4	9.6	923.8	11.9421	0.99	176.3	2.2791	70.8	124.9	1.6149	2.15E+03	52.0	0.6720
02/02/88	29.2	9.7	500.4	17.1148	0.93	91.3	3.1230	78.0	62.1	2.1244	2.33E+03	26.8	0.9169
02/24/88	--	8.2	999.9	--	0.99	160.0	--	70.8	115.5	--	2.15E+03	46.6	--
03/15/88	74.1	10.3	440.8	5.9477	0.93	84.4	1.1384	78.0	58.3	0.7866	2.33E+03	26.9	0.3635
04/05/88	93.8	14.0	41.3	0.4400	0.82	8.9	0.0943	92.7	6.2	0.0664	2.68E+03	3.0	0.0315
B.53 RICHMOND													
09/01/87	203.7	4.7	2701.7	13.2611	1.08	273.5	1.3425	61.3	206.7	1.0146	1.91E+03	83.6	0.4105
09/15/87	N.D.	5.3	2922.7	--	1.11	346.8	--	58.5	264.8	--	1.84E+03	106.2	--
09/29/87	N.D.	5.2	1991.4	--	1.11	227.1	--	58.5	175.3	--	1.84E+03	70.7	--
10/13/87	171.1	5.6	977.1	5.7103	1.08	117.1	0.6842	61.3	88.5	0.5170	1.91E+03	35.8	0.2090
11/03/87	29.6	5.7	1272.9	43.0637	1.14	161.4	5.4598	55.8	129.9	4.3947	1.77E+03	51.9	1.7565
11/17/87	52.4	6.5	1405.2	26.8419	1.11	200.9	3.8372	58.5	156.7	2.9941	1.84E+03	63.3	1.2096
12/01/87	N.D.	8.4	393.9	--	1.05	67.3	--	64.3	51.4	--	1.99E+03	21.1	--
12/24/87	20.4	13.8	129.6	6.3586	0.90	30.6	1.5033	81.9	21.8	1.0676	2.42E+03	9.7	0.4739
01/06/88	38.2	12.9	153.2	4.0150	0.90	33.6	0.8807	81.9	24.0	0.6301	2.42E+03	10.7	0.2799
01/19/88	31.5	14.5	99.7	3.1678	0.78	21.2	0.6732	100.0	14.4	0.4588	2.85E+03	6.6	0.2092
02/02/88	17.0	14.5	42.2	2.4780	0.84	9.6	0.5626	90.4	6.8	0.3971	2.63E+03	3.0	0.1785
02/24/88	--	11.6	37.3	--	0.88	6.8	--	83.9	5.2	--	2.47E+03	2.3	--
03/15/88	58.6	10.9	17.4	0.2963	0.87	3.0	0.0505	86.0	2.2	0.0374	2.52E+03	1.0	0.0164
04/05/88	--	17.1	5.1	--	0.79	1.2	--	97.5	0.9	--	2.80E+03	--	--

TABLE 5.18 - Results of Henry's Law Comparison D.55, B.53 Richmond

DATE	NH3-N GAS (ppb)	H1 (moles/ L-atm)	NH3 BY H1 (ppb)	RATIO H1/MEAS	H2 (atm/I)	NH3 BY H2 (ppb)	RATIO H2/MEAS	H3 (moles/ L-atm)	NH3 by H3 (ppb)	RATIO H3/MEAS	H4 by FORMULA AS f(T)	NH3 by H4 (ppb)	RATIO H4/MEAS
					P1 PREMIER								
08/20/87	96.4	6.9	3644.9	37.7923	1.02	545.9	5.6598	67.4	371.7	3.8544	2.07E+03	159.1	1.6501
09/03/87	81.6	7.2	5397.4	66.1317	1.05	864.2	10.5890	64.3	601.8	7.3737	1.99E+03	252.8	3.0979
09/17/87	184.6	6.8	3193.2	17.2958	1.08	501.3	2.7156	61.3	355.9	1.9279	1.91E+03	148.6	0.8048
10/01/87	111.3	7.3	2547.0	22.8779	1.02	402.6	3.6164	67.4	275.9	2.4780	2.07E+03	116.6	1.0477
10/15/87	75.4	8.0	2425.3	32.1572	1.02	421.8	5.5926	67.4	288.1	3.8198	2.07E+03	122.4	1.6231
11/05/87	141.6	8.1	2560.8	18.0882	1.03	455.3	3.2162	65.8	313.6	2.2149	2.03E+03	132.4	0.9354
11/19/87	84.3	8.8	1646.5	19.5323	1.02	312.8	3.7109	67.4	215.0	2.5507	2.07E+03	91.7	1.0881
12/03/87	17.9	9.6	1970.3	110.1788	0.99	390.3	21.8239	70.8	266.5	14.8996	2.15E+03	114.9	6.4229
12/22/87	42.7	10.6	2502.7	58.5619	1.00	570.4	13.3479	69.1	385.4	9.0183	2.11E+03	164.3	3.8435
01/05/88	63.8	10.2	3096.2	48.5514	0.99	655.9	10.2836	70.8	447.0	7.0077	2.15E+03	192.3	3.0157
01/20/88	45.1	9.8	2893.9	64.1195	1.03	617.4	13.6792	65.8	430.1	9.5305	2.03E+03	174.4	3.8642
02/04/88	58.9	8.8	3054.8	51.8665	1.02	578.3	9.8189	67.4	398.9	6.7733	2.07E+03	172.2	2.9241
02/23/88	134.5	9.5	2246.6	16.7060	1.03	457.9	3.4053	65.8	323.1	2.4025	2.03E+03	138.1	1.0273
03/17/88	82.8	7.9	3152.4	38.0492	1.05	547.8	6.6124	64.3	385.8	4.6564	1.99E+03	166.9	2.0148
04/07/88	45.3	9.7	1446.2	31.9009	1.02	296.1	6.5325	67.4	208.2	4.5917	2.07E+03	89.3	1.9697
					P2 PREMIER								
08/20/87	145.0	7.2	4098.9	28.2589	1.05	655.5	4.5190	64.3	457.0	3.1509	1.99E+03	197.1	1.3591
09/03/87	86.0	6.6	6008.2	69.8636	1.08	912.4	10.6098	61.3	649.6	7.5535	1.91E+03	276.7	3.2177
09/17/87	174.5	6.0	4545.6	26.0485	1.11	636.9	3.6501	58.5	463.1	2.6538	1.84E+03	200.5	1.1492
10/01/87	N.D.	6.4	4571.2	--	1.08	672.1	--	61.3	479.5	--	1.91E+03	203.6	--
10/15/87	112.5	7.0	3545.2	31.5206	1.08	574.2	5.1052	61.3	407.5	3.6232	1.91E+03	172.4	1.5325
11/05/87	191.1	6.6	3900.3	20.4100	1.08	593.6	3.1062	61.3	421.7	2.2067	1.91E+03	177.5	0.9288
11/19/87	48.4	7.4	2283.4	47.1801	1.06	379.9	7.8485	62.8	270.8	5.5942	1.95E+03	114.9	2.3748
12/03/87	74.0	9.9	1511.7	20.4338	0.99	303.6	4.1038	70.8	211.2	2.8544	2.15E+03	91.8	1.2406
12/22/87	44.3	11.2	1999.5	45.1436	0.97	465.7	10.5134	72.5	309.0	6.9760	2.19E+03	134.8	3.0438
01/05/88	143.7	8.4	3433.7	23.8962	1.05	623.8	4.3411	64.3	447.7	3.1160	1.99E+03	190.9	1.3284
01/20/88	32.2	8.8	2622.4	81.5086	1.02	486.6	15.1250	67.4	342.5	10.6443	2.07E+03	144.0	4.4758
02/04/88	46.8	9.7	3064.3	65.5094	1.02	633.7	13.5485	67.4	441.1	9.4293	2.07E+03	189.8	4.0580
02/23/88	43.1	9.3	2081.5	48.3383	1.00	395.4	9.1836	69.1	281.0	6.5267	2.11E+03	112.3	2.6073
03/17/88	104.6	8.8	2905.6	27.7838	1.02	539.6	5.1598	67.4	379.4	3.6283	2.07E+03	--	--
04/07/88	29.7	10.8	703.9	23.7070	0.96	146.0	4.9174	74.3	102.0	3.4361	2.24E+03	--	--

TABLE 5.19 - Results of Henry's Law Comparison
P1, P2 Premier St.

underprediction in solubility.

In Matsqui Landfill, this method overpredicts NH_3-N gas by an average range of 30 to 60 fold, when F8 Matsqui is not considered. F8 Matsqui is a bit of an anomaly, since it had a very low ammonia (< 2.0 mg/L) leachate, but still exhibited high NH_3-N in the gas. This may be due to lateral migration of higher NH_3-N gases from higher ammonia areas of the landfill.

In Stride Ave, much like in F8 Matsqui, this method consistently underpredicts NH_3-N concentrations by over 10 fold. Again, these sampling wells exhibited low NH_3-N leachate values and higher than expected NH_3-N gas values. Even though this method still underpredicts Stride Ave. values, it approaches the closest agreement of the four methods for predicting Stride Ave. gas values.

Because of the extreme heterogeneous nature of Richmond landfill, this method grossly overpredicts and underpredicts NH_3-N gas concentrations of up to 2600 and 25 respectively. Some wells do show a relative agreement with H_1, notably B8, C6 and B.53 wells.

The ratio in Premier St. landfill, showed a consistent overprediction of NH_3-N gas concentrations by 20-fold or greater.

5.6.2.2. <u>MOLE FRACTION METHOD</u>

As mentioned previously, this method is used most commonly for expressing Henry's law by the below relationship:

$$H_2 = Pa/Xa \qquad (iii)$$

Where Pa = Partial pressure of gas
above the aqueous solution (atm)

Xa = Mole fraction of chemical a
in aqueous solution

Two sources of Henry's law data were averaged and regressed to obtain an equation used to predict H_2 at a given temperature. The resulting regression equation has a % C.V. of 3 % and r^2 of 0.996236. Presentation of the data and regression equation is located in Appendix B.11.

Potential inaccuracies and errors in this method may be due to the following:

1. The large variation (over 30 %) between the literature values coupled with the variation in regression parameters may contribute significantly to error.

2. Literature source constants were calculated from pure-water measurements.

3. Roundoff errors from spreadsheet calculations.

The ratios of predicted vs. measured for this technique are generally about 3 times less than H_1 ratios which means this method agrees better with higher NH_3-N leachate wells and lesser with low NH_3-N sampling wells.

5.6.2.3. GIBBS FREE ENERGY METHOD

This method was adapted from Stumm and Morgan (1981) who used standard entropy and enthalpy data to calculate the equilibrium constant between the aqueous and gas phase. This entropy and enthalpy data are taken from the thermodynamic literature and corrected for temperature dependency.

The basic exothermic equilibrium reaction between NH3|aq

and NH3|g can be estimated by first calculating the free energy change with the entropy (H) and enthalpy data (S) (equation (vi)) and subjecting this to equation (v) :

$$\Delta G_0^o = H - T\Delta S \qquad (iv)$$

$$\ln H_3 = -\Delta G^o / RT \qquad (v)$$

Where ΔG^o is the Gibbs Free Energy

An example of this method is listed in Appendix B.12.

Potential errors in this method can result from the following:

1. Stumm and Morgan qualify in their discussion on this method that the quality of thermodynamic data is "highly variable" and they "do not claim to have critically selected the best data available." All data chosen is valid at standard state temp. and pressure which may not be true in landfills where internal pressures do exceed 1 atm.

2. The thermodynamic data was again calculated using a distilled water solution.

The results in Tables 5.12 through 5.19 indicate H_3 predicts ratios that are 2-fold less than H_2 and 6-fold less than H_1.

5.6.2.4. SOLUBILITY-EQUILIBRIUM METHOD

The last method compared is used quite often in the dynamic modelling of atmospheric ammonia. The method used by this author was adapted from the study by Hales and Drewes (1979). This constant is dimensionless and relates the molarity of both the aqueous and gas phase in the below equation:

$$H_4 = [NH_3|aq]/[NH_3|g]$$

The constant is temperature dependent and was regressed by Hale and Drewes (1979) for 30 data pairs to obtain an expression for calculating H_4. This equation has a C.V. of 10 % and an r^2 was never documented. Hale and Drewes (1979) do mention that errors in this equation can become excessive when dealing with aqueous molarities that are less than 10^{-9}. Small concentrations of 0.1 N sulfuric acid were also added to the ammonia solution to determine how NH_3-N solubility changes with addition of strong acid (ie, simulating acid rain effects). The authors also subjected the system to normal atmospheric levels of CO_2 to measure the response CO_2 had on H_3. The regression equation and a sample calculation of this method is presented in Appendix B.13.

As expected the errors of this method are a result of:

1. High C.V. in the Henry's constant equation could result in large variations, especially in the very dilute solutions.

2. Measurements were done in pure distilled water, which as mentioned before, is not indicative of a leachate system. Also their measurements done with CO_2 indicate large changes in solubility resulting in much greater than predicted gas phase NH_3. This will be discussed in more detail later.

Inspection of the results in Tables 5.12 through 5.19 indicate that H_4 further underpredicts Stride Ave. data while agreeing more closely with some Richmond and Matsqui data. H_4 also agrees quite favorably with Premier St. data where ratios are generally less than 3.0. The ratios calculated by H_4 are

generally 2-fold less than H_3 ratios and 12-fold less than H_1 ratios.

5.6.2.5. SUMMARY OF RESULTS

A table summarizing the major trends of the data presented in tables 5.12 through 5.19 is presented below:

TABLE 5.20 - Summary Matrix of the Average Range of Ratios (Predicted/Measured) found in each landfill.

| LANDFILLS | HENRY'S CONSTANTS | | | |
	H_1	H_2	H_3	H_4
MATSQUI	30-60	10-20	5-10	2.5-5.0
STRIDE	0.05-0.5	0.02-2.0	0.01-0.1	0.005-0.05
RICHMOND	0.3-100	0.1-35	0.05-20	0.025-10
PREMIER ST.	15-60	5-20	2.5-10	1.3-5.0

H_1 = Corrected Vapor Pressure Method

H_2 = Mole Fraction Method

H_3 = Gibbs Free Energy Method

H_4 = Solubility-Equilibrium Method

(Note: Values in matrix are predicted/measured NH3-N gas ratios)

Inspection of Tables 5.12 through 5.20 bring up some interesting relationships between the different constants and landfills that are worth mentioning below:

1. That documented Henry's constants are not applicable to high ammonia (> 250 mg/L NH_3-N) with high pH's (>6.6) and low ammonia leachates (< 20 mg/L NH_3-N) that have low pH's (<6.2).

Many sample wells that fit under this label are ones that were subjected to high volume rain water dilution of their leachate. In contrast, Stride Ave. wells were not sufficiently diluted and still exhibited consistently low NH_3-N leachate pH throughout the 8 month study period. Closest agreement to a ratio of 1.0 in Stride Ave. data resulted from the H_1 method that still underpredicted the ratio 10-fold.

2. The calculated ratios could be subjected not only to errors already discussed in formulating the Henry's constants but also from the analytical variability in the pH and conductivity meters and ammonia distillation-titration technique, which determines the leachate NH_3-N concentration.

The results of this study agree favorably with another study recently done by Stephens et al. (1986) on volatile organics from the BKK landfill in West Covina, Calif.. The ratios they found of predicted/measured concentrations ranged from 0.002 in vinyl chloride to 2.5 for benzene. Stephens et al. (1986) concluded that the discrepancy of the predicted/measured values was due to one; disequilibrium between the aqueous and gas phases make Henry's Law non-valid, or two; the low ratio found in vinyl chloride measurements are due to a greater production of vinyl chloride (due to microbial degradation of TCE ?) at a greater rate than the volatilization rate. The second cause is questionable since the volatilization rate of vinyl chloride is extremely high.

In summary, this author would use extreme caution in

applying documented Henry's constants for prediction of gas or leachate values in a landfill environment. This author believes the data support this conclusion. The main reason why caution should be heeded results from the uncertainty of whether or not a landfill system is in equilibrium between the aqueous and gas phases, which is the fundamental assumption behind Henry's law.

If one would have to choose between the 4 different Henry's constants for prediction of gas concentration in a landfill environment, I would have to choose either H_2 the mole fraction method or H_4 the equilibrium-solubility method. The main reason behind this choice is that these constants do have a reported variation whereas the other two methods have uncertain variation. Also, both constants are the most frequently used. Other reasons why H_1 and H_3 may be suspect stem from H_1's gross overprediction of all higher NH_3-N leachate wells and H_3's assumption that the standard free energy change occurs in a gas that behaves ideally, which is somewhat suspect behavior in a varied landfill gas mixture.

5.6.3 REASONS FOR DISCREPANCY IN PREDICTED/MEASURED RATIO

In addition to the error-prone Henry's constants, there may be other more important factors that contribute to this diverging ratio of predicted vs. measured NH_3-N gas values. These potential factors are discussed in more detail below.

5.6.3.1. ANALYTICAL TECHNIQUE

The main concern dealing with uncertainty in the analytical technique centers around the possible error that low NH3-N gas

values may exhibit. These low values were often bordering close to the detection limit of the autonanalyzer. Also, the large variation in data for determination of the recovery efficiency is another major uncertainty.

Because the sampling technique did not pre-filter the gas, there could be appreciable amounts of NH_4^+-containing aerosols causing a positive interference in the determination of NH_3-N gas. Even though I would assume this contribution to be very low, inspection of the results in Stride Ave. lead me to believe this could be a substantial contributor to high measured values in Stride Ave..

Lower than expected NH_3-N gas values in Matsqui, Richmond and Premier St. may one; due to signal suppression in the autoanalyzer by interferences or two; effects of high CO_2 concentrations that may form a volatile complex with ammonia that is subseqently not adsorbed into the boric acid solution.

Another potential major source of error contributed by the analytical procedure is variation of pH results. Since the fraction of unionized fraction of ammonia is dependent on the hydrogen ion concentration, accuracy of the pH meter is a must. In calculations done by Thurston et al. (1974) it can be observed that a pH increase of 0.5 units will subsequently increase the fraction of unionized fraction of ammonia by over 3-fold. This 3-fold increase in the unionized ammonia fraction can be translated into a 3-fold increase in NH_3-N gas concentration if the system is at equilibrium.

5.6.3.2. LANDFILL UNSATURATED ZONE

The values of leachate pH, total ammonia and specific conductivity may not be indicative of the whole landfill since their values may differ considerably from those found in the unsaturated zone.

In most instances without rainfall dilution, the concentrations of leachate in the unsaturated refuse pores will exceed concentrations found in the unsaturated zone. This may be especially true in the dryer months of this study, where the highest NH3-N concentrations were measured.

In addition to greater mass concentrations found in the unsaturated zone, there is also a greater effective surface area available for mass transfer into the gas phase than the pseudo-planar area available for mass transfer from the saturated zone.

For instance, in a hypothetical landfill, 25 ha in area with a planar water table 10 m below the bottom of the landfill cover, there would be an effective area for mass transfer of 25,000 m^2 assuming the landfill had an air-filled porosity of 0.10. In contrast, the unsaturated zone would have an hypothetical effective area available for mass transfer of 250,000 m^2. This figure is roughly 10 times the area available for gas phase mass transfer in the saturated zone. Both of these values will become less during active rainfall periods since the air-filled porosity may decrease.

This simplified example indicates that the deeper the landfill water table, the greater contribution exists in the

unsaturated zone for NH_3-N gas generation.

5.6.3.3. VOLUME DILUTION EFFECT

Not much is known about the possible mass dilution of NH_3-N gas concentrations from efficient methane and carbon dioxide production.   This dilution could very well be a major reason for lower than predicted gas values from some wells in Matsqui and Richmond, since their CH_4 and CO_2 fluxes were found to be much greater than Stride Ave. fluxes.

An example of this mass or volume dilution phenomenon is to look at a slab of refuse 10 m X 10 m X 1 m that exists in a completely anaerobic landfill environment with a density of 700 kg/m^3. This slab is subjected to an average CH_4 generation rate of 25 mL CH_4/kg of refuse per day that translates into a CH_4 production rate in the slab of 1750 L CH_4/slab-day.

Mass transfer of ammonia outwards from the slab can be estimated by using the common diffusion equation below:

$$Flux\ NH_3\text{-}N = (D/L) * (C_1 - C_g)$$

Where D = the apparent diffusion coefficient taken as 0.025 cm^2/s from Gardner (1966).

L = the liquid-gas film thickness taken as 0.01 cm

C_1 = concentration in liquid (ug/cm^3)

C_g = concentration in gas phase (ug/cm^3)

If Cl is 1.0 ug/cm^3 (ie, 1 ppm) and Cg is small enough to neglect then:

$$Flux\ NH_3\text{-}N = 25,000\ ug/m^2\text{-}day\ or\ 0.25\ gm/slab\text{-}day$$

$$Flux\ NH_3\text{-}N = 0.33\ L\ NH_3/slab\text{-}day$$

So the results indicate a volume dilution of ammonia gas to

be over 5000 fold in this simplified case. This is quite substantial when one observes that dilution due to CO_2 gas production was not considered in this estimation.

Low gas production rates causing a lesser dilution could explain why the measured NH_3-N gas values are higher than expected in Stride Ave. Conversely, one would expect to see Premier St. landfill gas data behave much like Stride Ave. since both have low gas fluxes. However, when studying the ratios, Premier St. was observed to exhibit much greater than measured values in most instances. The reason may not be solely due to high relative pH or NH_3-N leachate values, but maybe also due to volumetric dilution from the gas extraction system pulling atmospheric air into the system. This could be especially apparent in the winter months as evidenced by CH_4 percentages in wells P1 and P2.

5.6.3.4. LANDFILL HETEROGENIETIES

Because leachate in a sample well is only a point source of data, it may not be representative of the surrounding leachate due to landfill heterogenities. This is especially true in Richmond and Matsqui landfills where large spatial differences in leachate ammonia values are apparent.

Another point of concern is the effects of lateral gas migration helping to give erroneous results of NH_3-N gas concentrations not indicative of its corresponding leachate. As already mentioned, this could be the case in F8 Matsqui.

5.6.3.5. NON-EQUILIBRIUM LANDFILL ENVIRONMENT

The landfill is a dynamic environment that responds to internal and external perturbances. However, it could be a question of whether or not the landfill can ever establish an equilibrium between the aqueous and gas phases since the gaseous and liquid environments are forever fluctuating. Some factors that can prevent the landfill from reaching an equilibrium state are noted below:

1. Large fluxes of biogas being generated that vary both temporally and spatially.

2. Internal landfill pressures that exceed standard
   1 atmospheric conditions.

3. Large and varied precipitation fluxes observed during the rainy season causing chemical and biological changes.

Other than these factors there are some ammonia specific factors that may cause non-equilibrium. These are listed below:

1. The production rate of ammonia is much greater than the volatilization or gas transfer rate, causing an accumulation of unionized ammonia in the leachate. If this is true, then equilibration of the system is probably diffusion rate limited since there exists an ample concentration gradient available for mass transfer.

2. Initial elevated concentrations of ammonia in the leachate have not volatilized to equilibrium. If true, the combination of pt. #1 with this mechanism would leave a much greater fraction of $NH_3|aq$ in the leachate than would normally be

predicted by Henry's Law.

5.6.3.6. MASS TRANSFER LIMITATIONS

There are other factors that limit the diffusion rate and subsequent equilibrium of the aqueous and gas phases such as the chemical nature of the leachate.

Leachate ionic strength has been found to decrease the effective liquid diffusion rate in experiments by Ratcliff and Holdcroft (1963) (in Reid and Sherwood, 1966). They found that the diffusion coefficient of CO_2 gas in solution decreases linerly with an increase in salt concentration. This phenomenon could also conceivably occur with NH_3 in solution since both gases are soluble non-electrolytes and behave somewhat alike in solution.

Another factor that could be substantial in attenuating the diffusion rate is the addition of thin oil films surrounding the liquid thin film that could conceivably cause a weak barrier to NH_3-N transfer into the gas phase. This would especially be apparent in leachate that consists of less dense insoluble organics that float above the leachate at the saturated-unsaturated interface causing a barrier to mass transfer. This effect has been modeled in surface impoundments by including a mass transfer coefficient for the oil film (see Ehrenfeld, 1986).

5.6.3.7. SOLUBILITY OF AMMONIA

Other than sampling and performing the analytical work, a large amount of time in this study was spent trying to explain this apparent discrepancy between the predicted/measured NH_3-N

concentrations. Most of the efforts focused on understanding the solubility dynamics of ammonia in non-pure solutions such as leachate.

The major factors that effect ammonia solubility include: ionic strength, pH, pressure, temperature and salinity of the solution. In the spreadsheet calculations for estimating the unionized fraction of NH_3-N in solution, effects from temperature, pH and ionic strength were corrected in the calculations. Salinity was not considered to be a large problem since ionic strength includes any effects of salinity (see Whitfield, 1974). Ionic strength was converted to activity coefficients (see Appendix B.4) to correct for a non ideal solution. Pressure was assumed to be 1 atm which is close to correct. The unionized fraction was then converted into the proper units for calculation of the predicted NH_3-N in gas.

How much of this unionized fraction (NH_3|aq) may be removed from solution by chemical reactions is a mystery. Since most unionized NH_3-N values are already at low concentrations (< 1.0 mg/L), accumulation of certain compounds capable of reacting with NH_3|aq may result in removal of a portion of NH_3-N|aq. In this scenario, it is assumed that the rate of removal exceeds the rate of formation due to equilibrium shifts. Possible chemical reactions that could occur in a landfill leachate to remove NH_3|aq include the following:

1. Complexation of NH_3 with other compounds that covalently share the unpaired electrons of the nitrogen atom of NH_3. This

reaction is commonly called an addition reaction (NRC, 1979).
The types of compound available for this reaction are some metals
such as copper and zinc where values of over 1.0 mg/L may occur.
The addition reaction of Cu with NH_3 is shown below:

$$Cu^{++} + 4NH_3 \longrightarrow Cu \cdot (NH_3)_4^{++}$$
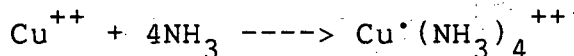
2. A substitution reaction of NH3 with organics to form an
amide group. This is commonly referred to as "ammonolysis" and
is similar to a hydrolysis reaction. Two reactions are shown
below that tie up 2 moles of NH_3 while releasing a protonated
ammonium ion:

   a. Reaction w/mercuric chloride (NRC, 1979)

   $$2NH_3 + HgCl_2 \longrightarrow Cl^- + NH_4^+ + ClHgNH_2$$
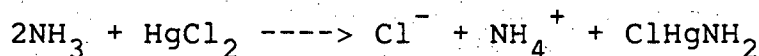
   b. Reaction w/acid chlorides (Brown W.H., 198)

   $$Acetyl\ chloride + 2NH_3 \longrightarrow Acetamide + NH_4^+ + Cl^-$$
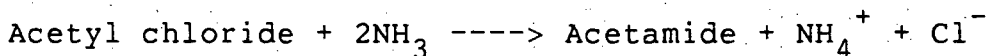
Both chemical reactions could become common in landfills
like Richmond, where leachate contains an abundance of
chlorinated organics and chlorine compounds.

3. Complexing of the methane molecule with the ammonia
molecule to form the soluble methyl ammonium ion ($CH_3NH_4^+$).
Even though methane is usually non-reactive with compounds at
standard state conditions, there could be enough random
occurrances where methane bonds with ammonia to provide a
substantial removal mechanism of $NH_3|aq$ available for transfer
into the gas phase.

4. In addition to methane complexing, there may be an
opposite reaction occurring between CO_2 and NH_3 that instead of

complexing ammonia in solution, may strip it out of solution. This reaction is the complexing of CO_2 and NH_3 to form a volatile compound called carbamic acid. This carbamic acid may be volatile enough to pass through the boric acid solution without being adsorbed causing analytical problems as well.

With this in mind, the effect of high CO_2 percentages may be a reason why large differences exist in ratios between predicted vs. measured NH_3-N in Richmond and Stride Ave landfills. In Richmond, CO_2 % can exceed 40 % while the measured values are much lower than predicted; in contrast, Stride Ave. has CO_2 % generally less than 20 % and a much higher ratio of measured versus predicted NH_3-N gas concentrations. So in Richmond landfill, there may be a substantial removal mechanism of $NH_3|aq$ by high CO_2 concentrations.

5.6.3.8. <u>LANDFILL SINKS</u>

In addition to chemical sinks located within the leachate, there are a number of other sinks that could help cause this discrepancy between predicted and measured NH_3-N concentrations. These are listed briefly below:

1. Adsorption of $NH_3|g$ onto landfill refuse material or soil within the landfill. The rate at which this can happen is a function of it's adsortion isotherm (Fruedlich isotherm). This adsortion of NH_3 is especially possible in more alkaline landfill environments.

2. Assuming the unsaturated zone is not a primary source of ammonia then $NH_3|g$ can be resolublized in the unsaturated zone

fluid to $NH_3|aq$ and reprotonated to NH_4^+. This NH_4^+ can be further utilized by microbial activity or more likely, exchanged onto colloids in solution or solid landfill substrate. As mentioned previously, excessive rainfall infiltration can create a wetting front that migrates downward in the landfill resolubilizing and reprotonating NH_3-N gas due to it's relatively lower pH.

3. Resolubilization into the acidic gas condensate that exists inside the well casing.

5.7 MASS FLUX EMISSION OF NH3-N GAS

5.7.1. INTRODUCTION

One of the original goals of this thesis was to get an idea of how much, if any, nitrogen in the form of NH_3-N was being emitted through the gas phase. In the following section, data is presented that estimates the mass flux of NH_3-N through two of the four study landfills. This estimation was calculated by a simplified model used until this time exculsively for modelling of organic flux emissions from covered landfills. The resulting mass fluxes are then later compared to estimated fluxes of NH_3-N in the leachate.

The model was originally conceived by Farmer et al. (1981) to study the emission rates of hexachlorobenzene by diffusion through the landfill cover soil. Thibodeaux (1981) modified this model to include the affects of convective transport through the landfill cover. He verified Farmer's hexachlorobenzene results with convection flow and also simulated the emission fluxes of

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four other organic chemicals, namely benzene, chloroform, vinyl

chloride and PCB (Aroclor 1248). Thibodeaux then modified his

own work in 1982 by simulating the emission fluxes of benzene by

including the barometric pressure pumping effect found in some

landfills. The simulation was carried out by using the IBM CSMP

(Continuous Systems Modelling Program) over various time steps.

The assumptions, limitations and detailed aspects of these

models are discussed in more detail later in the chapter.

Modelling ammonia gas fluxes in soils has mostly been done

in the agricultural sector concerning feedlot emissions and

fertilizer applications. Unfortunately, the majority of this

work is site specific and empirical.

5.7.2. MODEL INTRODUCTION

5.7.2.1. FARMER'S MODEL

In Farmers model, he assumed that the hexachlorobenzene

wastes were transported through the cover by diffusion only, and

that this diffusion obeyed Fick's First Law of Diffusion.

Because the porous media had an effect on the diffusion path

length, the reference diffusion coefficient (Do) was multiplied

by a porosity factor to the 4/3rd. This model is shown below:

$$J\ (M/(L^2-T)) = (De/L)*(Cs - C2) \qquad (vi)$$

$$\text{Where } De = Do*Pa^{1.33} \qquad (vii)$$

Where J is the gas flux usually in gm/m^2-day
    Do is the diffusion coefficient in air in m^2/day
    De is the effective diffusion coefficient in m^2/day
    Pa is Air-filled porosity
    Cs is saturated vapor concentration in gm/m^3
    C2 is vapor concentration at landfill surface in gm/m^3
    L is thickness of landfill cover in m

The effective diffusion equation (vii) was taken from Parton (1981) for describing diffusion of ammonia gas through soils.

5.7.2.2. THIBODEAUX'S MODEL

In a slight modification to Farmer's model, Thibodeaux added a product term to the diffusion equation that accounted for flow due to convection created from internal landfill gas generation. This equation is listed below. Specifics of how equation (ix) was derived are presented in Appendix B.14.

$$N = (De/L)*(Ca - C_2)* \frac{(Rexp(R))}{(exp(R)-1)} \qquad (ix)$$

Where N is gas flux from landfill surface usually in gm/m^2-day

Where Ca is concentration of compound a (gm/m^3)
       C_2 is concentration of a at the landfill surface

Where R = (L*v/De)   (x)

Where L is landfill cover thickness in m
       v is landfill cover gas velocity (ie, not Darcian velocity) in m/day.

The $\frac{(Rexp(R))}{(exp(R)-1)}$ is referred by this author as the G-factor, which is a multiplying factor describing the flux due to convection flow relative of the flux due to diffusion. This factor has been called the landfill gas enhancement factor by Baker and Mackay (1985). This factor increases with greater landfill gas production, and as found in this study and other literature, the factor can exceed 6.0 for a normal landfill environment.

In reality, equation (ix) is the same as Farmer's model equation (vi) except it is multiplied by the G-factor. So the

relative differences between Farmer's and Thibodeaux's model is that Farmer's model only solves for systems without gas generation where diffusion is the controlling transport process, while Thibodeaux's model is a combined diffusion-convection flux model.

5.7.2.3. ASSUMPTIONS FOR MODELS

A.   Assume gas phase is saturated with respect to the compound in question.

B.   Thibodeaux model assumes steady state diffusional and convective transport.

C.   Thibodeaux model assumes infinite source of generated gas exists at elevated pressures just under the base of the landfill cover.

D.   Thibodeaux model used assumes a constant landfill gas production rate and no build-up of internal landfill gas pressures.

E.   Assumes gas is behaving in a unidirectional flow with negligible reaction of the compound while being transported.

F.   All diffusion resistance is in the soil and none in the air boundary layer at the surface of the landfill cover.

G.   Thermal gradients are assumed to have no effect on the flux rate.

H.   No adsorption, degradation or chemical exchange is assumed to occur in the cover soil.

I.   Model is solved for a single-celled landfill with the proper boundary conditions.

5.7.2.4. LIMITATIONS TO MODEL

When dealing with an inorganic reactive molecular species like ammonia, there are some overlying limitations to applying a model that has only been tested on organic vapors. Some of these limitations are listed below:

A. Baker and Mackay (1985) mention in their evaluation of surface emission models, that the Thibodeaux model is unsolvable for organic chemicals with vapor pressures greater than 1 atm. In many respects the vapor pressure of ammonia exceeds 1 atm, but because of the non-ideal nature of the solution and gas, this vapor pressure is probably much less than 1 atm..

B. Model only accounts for one-dimensional vertical movement of gas and does not take into account lateral emissions of gas in area-fill type-landfills (ie, Richmond).

C. Model does not take into account any thermal contribution to convection flow and temperature dependence of the diffusion coefficient.

D. One must assume that the NH_3-N concentrations measured are reflectant of the concentration at the base of the landfill cover, this may not always be the case.

E. Assumes the gas component to be instaneously mixed and dispersed once at the landfill surface, so the concentration of C_2 is essentially zero. Because NH_3-N is ubiquitous in the atmosphere, I did not assume this to be zero, but instead assumed C_2 to be 20 ug/m^3, which is a common concentration found in the atmosphere around urban areas. There could be large

uncertainties in this assumption.

F.   Model does not take into account any diffusion transport
to the surface by liquid in the soil pores. Because the
diffusion coefficients are much less in water than gas, this was
assumed to be negligible. However, this could become an
important mode of transport when the cover is water logged during
high precipitation periods.

g.   Model does not take into account any build-up of
internal landfill gas pressure due to internal gas production.
The updated 1982 model by Thibodeaux does account for internal
pressure build-up and it's derivation is also listed in Appendix
B.14.

5.7.3.   MODEL RESULTS OF LANDFILL NH3-N GAS FLUXES

5.7.3.1.   INTRODUCTION

Input parameters common to both Farmer and Thibodeaux's
models are : total and air-filled porosity, reference diffusion
coefficient, landfill cover thickness and concentration of NH3-N
gas at base of landfill cover. Additional input parameters for
Thibodeaux's model include : refuse density, thickness of refuse
fill and gas generation rate. These three parameters are
combined with porosity to get an internal gas velocity which is
then subjected to a calculation to get R. Once R is found, then
the G-factor is easily calculated. Sample calculations for this
procedure is listed in Appendix B.15.   All calculations were
done using a LOTUS 1-2-3 spreadsheet.

Premier St. landfill was not included in the model runs

since the sample wells, P1 and P2 were located in an area whose surface was just a fraction of the landfill surface. Also, the cover characteristics at this landfill were very heterogeneous and never fully understood. Matsqui Landfill was not included in the model runs because no documented leachate flux data of this landfill was available.

The standard parameters used for calculating gas fluxes of ammonia were considered to be representative of that particular landfill, through previous documentation or from direct observation in this study. For example, if one looks at Table 5.21 which lists all the parameters chosen, one notices a large difference in internal gas generation rates between Stride Ave. and Richmond Landfill. This is mainly due to the assumption made already that Stride Ave has very low gas generation capacity mostly a result of it's advanced age. Richmond is much younger and exhibits gas values much closer to documented gas production rates in landfills of a comparable age.

The reference gas diffusion coefficient of NH_3 in a landfill gas mixture was chosen at 1.750 m^2/day for the three reasons mentioned below:

1. Binary gas coefficients for all major landfill gases are in the range of 1.25 to 2.00 m^2/day (Findikakis and Leckie, 1979).

2. A Do of 1.987 m^2/day was reported in Reid and Sherwood (1966) for the N_2-NH_3 binary system.

3. A Do of 1.598 m^2/day was mentioned in Parton (1981) as

being a representative diffusion coefficient of NH_3 in soils.

TABLE 5.21 - Standard Values Used For Modelling NH_3-N Gas
Emissions From Landfills.

Parameter	Stride Ave.	Richmond
Diffusion coefficient	1.750 m^2/day	1.750
Total Porosity	0.30	0.50
Air-filled porosity	0.20	0.40
Landfill cover Thickness	2.0 m	1.5
Internal Gas Velocity	0.01728 m/day	0.59962
Gas Production Rate (mL/kg-day)	5.0	40.0
Refuse Density	537.0 kg/m^3	600.0
Landfill Depth	14.0 m	10.0
Landfill Area	80,000 m^2	200,000

The source for the leachate flux data was Atwater (1980), which gives reliable estimations of ammonia mass flux through the aqueous leachate phase for both Stride Ave. and Richmond Landfills.

To calculate the mass flux per landfill per year, it was assumed the surface area at Stride Ave. to be 80,000 m^2, while assuming the study surface area of 200,000 m^2 in Richmond Landfill. To calculate an annual NH_3-N emission flux, the NH_3-N gas concentration values were averaged for each landfill to get

an average yearly NH_3-N gas concentration. The average

concentrations found were 198.3 ug/m^3 for Stride Ave. and 92.8

ug/m^3 for Richmond Landfill. These values were then inputed into

Thibodeaux's model to an average daily flux of NH_3-N gas. This

daily flux was multiplied by the landfill surface area and

multiplied by 365 days to get the average annual flux of NH_3-N

gas. Flux values for both landfills are listed below in Table

5.22. In these calculations it is assumed that Richmond Landfill

is a static system and gas extraction through the well system is

not taking place.

5.7.3.2. DISCUSSION OF RESULTS

The results indicate that in both landfills, the annual

NH_3-N fluxes are very small. In reality, this value could be

much less if the model would have accounted for adsorption and

consumption of NH_3-N through the landfill cap. The results also

indicate how much the flux is due to convection in Richmond

Landfill versus Stride Ave. This is mainly due to Stride Ave.

gas flows being diffusion dominated due to it's low gas

production rates and thick landfill cover. The thick landfill

cover helps to slow down diffusion because of a lengthened

diffusion path.

TABLE 5.22 - Comparing Annual NH_3-N Gas Mass Fluxes For
Both Landfills.

| Landfill | CONVECTION & DIFFUSION | | DIFFUSION-ONLY | |
	Daily Flux (ug/m2-day)	Annual (kg/yr)	Daily Flux (ug/m2-day)	Annual (kg/yr)
Stride Ave	19.9	0.582	18.3	0.536
Richmond	52.9	3.862	25.1	1.832

Results comparing fluxes from the documented estimations of
NH_3-N flux in the leachate are shown below in Table 5.23. All
results are reported in kg/yr. To calculate the proportion of
flux of NH_3-N in leachate from the Richmond study site, it was
assumed that the 20 ha site contributed to 1/5 of the total mass
of ammonia leached. The total mass leached per year was 82,125
kg NH_3-N/yr (Atwater, 1980), so the total mass flux from the
study site totaled 16,425 kg/yr.

TABLE 5.23 - Comparison between Gas and Leachate Annual
Fluxes of NH_3-N, Both Landfills.

	Gas Values (kg/yr)	Leachate Value (Atwater, 1980)	Percent of leachate mass flux
Richmond	3.862	16,425 kg/yr	0.024
Stride Ave.	0.582	1,975	0.029

The results indicate a very small fraction of NH_3-N being
lost through the gas phase. Less than 3/100 th of 1 percent of
the leachate ammonia fluxes for both Stride Ave. and Richmond

Landfills. As mentioned before, these values are probably the maximum flux obtainable, since the model does not account for any adsorption or consumption of ammonia before it reaches the surface of the landfill.

5.7.3.3. COMPARISON OF MODEL RESULTS WITH GAS GENERATION MASS BALANCE RESULTS

Since there are many limitations and assumptions to Thibodeaux's model, a comparison was made between the model results and a simple gas generation mass balance model. This comparison was done to check the validity of the Thibodeaux model results.

The gas generation mass balance model assumes that a covered landfill produces a certain finite mass of gas (ie, CH_4, CO_2, etc.) at a given rate throughout the landfilled refuse. All this gas produced is then emitted through the landfill cover. A gas generation rate can be inferred from the literature, or be estimated from extraction well pumping rates, which was previously discussed in Chapter 2. The assumptions for the mass balance model are listed below for the Richmond Landfill case:

1. Assume gas extraction is recovering all of the microbiologically generated gas.

2. Assume negligible air intrusion during extraction.

3. Assume the same average ammonia concentration (92.8 ug/m^3) in the generated gas as used in Thibodeaux model calculations.

4. Assume all generated gas is migrating vertically through

the landfill cover, and that none of the gas is being removed via the bottom of the landfill or by the leachate.

5. Assume a gas extraction pumping rate of 725 CFM (20.5 m^3/min) for the study area at Richmond Landfill (E.H. Hanson & Associates, 1988).

6. Assume no biological sink of the generated gas before leaving the surface of the landfill.

With these assumptions in mind, the results for NH_3-N mass emitted due solely to gas production at Richmond Landfill is listed in Table 5.24. Details of the calculation can be found in Appendix B.16.

In addition, a calculation is included to check the gas production rate used in the model run with the gas production rate calculated for the mass balance model. This mass balance production rate was calculated from the Richmond Landfill pumping extraction rate (ie, 20.5 m^3/min). The final comparison indicates that the gas production rate of 40 ml/kg-day used for Richmond Landfill was not in error, since the pumping gas production rate calculation is at least 24.6 ml/kg-day when assuming 100% pumped recovery of any generated gas.

Since pumping extraction rates were not available for Stride Ave., a gas production rate of the same 5 ml/kg-day for the model run was used in the mass balance calculation.

Results of comparing the flux for the Thibodeaux model and mass balance models are listed below in Table 5.24:

TABLE 5.24 - Comparison of Model Versus Mass Balance Flux
Calculations.

Landfill	Model Flux (kg/yr)	Mass Balance Flux (kg/yr)	Difference
Stride Ave.	0.582	0.192	3-fold
Richmond	3.862	1.000	3.8-fold

The results indicate at least a 3-fold difference exists
between the model and mass balance calculations. However, this
difference is probably less since the assumption of 100%
extraction of generated gas is impossible to achieve. In fact,
as stated in Chapter 2, Pacey estimates that only 10 to 50
percent of the theoretical gas produced will be extracted (Boyle,
1976). If this is the case, then the calculated flux using the
gas generation mass balance will increase proportionally with a
decrease in gas extraction efficiency. If this is true, then the
two model results may agree quite favorably.

5.7.3.4. SUMMARY OF RESULTS

The results of the first-order mass flux approximations
indicate that ammonia gas emissions are not a significant portion
(<0.03%) of the ammonia fluxes apparent in landfill leachate.
Therefore, these results indicate that when estimating an overall
ammonia or nitrogen balance on these landfills, one can neglect
the ammonia lost through the gas emission phase. Also, the
results indicate that ammonia is not a substantial contributor to
landfill gas contaminated air around covered landfills.

CHAPTER 6

6. CONCLUSIONS AND RECOMMENDATIONS

The analytical technique used for measuring ammonia from landfill gas was the wet-chemical automated phenate technique. Samples were collected in the field by pumping unfiltered landfill gas through a boric acid trap at a flow of around 6.0 L/min. Problems encountered with this technique include sample contamination of particulate matter during handling of samples, condensate build-up in sample tubing, and negative interferences from the landfill gas affecting both the accuracy of the sampling and analytical method.

Detection limit of the analytical technique was found to be about 0.03 mg/L of NH_3-N. This value translates into a detection limit of around 10 ug NH_3/m^3 of landfill gas under normal sampling conditions.

The sampling technique was proven to be deficient in approaching a quantitative recovery of NH3-N gas. Laboratory results suggest a recovery efficiency of about 50 % to be accurate in a landfill gas environment. This recovery efficiency was expected due to a combination of high pumping flows and already low concentrations of NH_3-N in the landfill gas.

Since this ammonia gas sampling and analysis technique exceeded all the criteria stated in the study objectives (ie, fast, inexpensive, simple to use), this author can conclude that this technique is a valid method for detection and measurement of ammonia in landfill gas. However, one should be cautious when

interpreting the data analyzed from this method since the accuracy may be hampered by the high humidity and soluble negative interferences apparent in landfill gas.

The greatest NH_3-N in leachate and gas was found in Matsqui landfill where gas values of up to 650 ppb and leachate values of over 2000 mg/L were detected. NH_3-N gas concentrations were consistently lowest in Richmond Landfill while leachate values ranged from 10 to 500 mg/L. Premier St. had fairly consistent leachate NH_3-N and pH values of around 200 mg/L and 6.60. While Stride Avenue exhibited the lowest strength leachate with NH_3-N less than 15 mg/L, it always exhibited higher than expected NH_3-N gas values. Overall, most NH_3-N gas concentrations were less than 150 ppb.

Gas flow and methane flux was found to be greatest in the younger landfills with Richmond exhibiting the greatest fluxes and gas flows of over 20 kg/cm2-day in some wells (C6 and D9). The high flows and fluxes are mostly a result of high gas production rates causing a build-up of internal landfill pressure build-up. Also, some flow may be due to thermal convection. Most CH_4 fluxes were found to be under 5.0 kg/cm^2-day, with Stride Ave. and Premier St. exhibiting fluxes usually under 1.0 kg/cm^2-day.

The variable found most often to cause a change in NH_3-N gas concentration was gas temperature (Tg). This was discovered not only in the multiple regression analysis, but also in the Pearson correlation analysis. The variable that may be causing

some of the observed cooling in gas temperature is infiltrating
precipitation. This infiltrating precipitation may also cause
the effect of decreasing NH_3-N gas concentrations in the
unsaturated zone from NH_3 absorption into the lower pH (< 6.0)
rainwater.

Other parameters such as CH_4 flux, pH and NH_3-N leachate
were found to explain a minimal variation in ammonia gas
concentrations. The results of the multiple regression analysis
on CH_4 % indicate the greatest relationship occurred between the
dependent variable CH_4, and ionic strength.

The major limitations found with using regression analysis
as a predictive tool for NH_3-N and CH_4 concentrations is one, the
non-normality present in some of the data, two, the resultant low
R2's and three, the large residual error found in the equations.
In conclusion, prediction of CH_4 % and NH_3-N gas by statistical
methods is very uncertain due mainly to the highly variable and
non-normal data collected in this study.

Decrease in barometric pressure was discovered not to
increase static gas flow rates by a low pressure pumping effect
observed in other documented landfills. In fact, some Matsqui
wells responded with lower flows during lower atmospheric
pressure.

One other observation worth noting was the detection of an
abnormal N_2/O_2 landfill gas ratio apparent in a few Matsqui and
Stride Ave. sampling wells. Ratios sometimes exceeded 20, which
means oxygen is being consumed by some process. This process is

possibly a combination of inorganic redox reactions and oxygen uptake from aerobic bacteria called Methanotrophs that consume CH_4 and O_2 to produce CO_2 gas.

Results of the the landfill gas organic contaminant analysis indicate that over 50 compounds were detected in Richmond and Matsqui wells after the sampling technique was improved. Most of these compounds were substituted benzene and saturated hydrocarbons. A maximum of eight chlorinated hydrocarbons were detected. Other compounds of interest that were detected include some furans, biphenyls, phenol and naphthalene compounds.

Results of the comparison between documented Henry's Law constants for predicting NH_3-N in gas show some large discrepancies of over 2000 fold between the predicted and measured gas concentrations. All methods grossly underpredict the NH_3-N in the gas fraction from Stride Ave. while overpredicting the gas concentration in wells that exhibit NH_3-N in leachate generally greater than 200 mg/L.

The reasons for this large discrepancy between predicted and measured ratio of NH_3-N gas may not be just due to invalid Henry's constants. Other reasons are summarized below:

1. The analytical technique is not accurate.

2. The NH_3-N leachate concentration is not necessarily reflective of the NH_3-N concentration inherent in the unsaturated zone where the major fraction of NH_3-N mass transfer to the gas phase may be occurring. Combined with this are landfill heterogenieties and lateral gas migration that possibly make the

gas sample non-indicative of the measured NH_3-N concentration in the leachate.

3. The aqueous and gas phases of ammonia are not in equilibrium in a landfill environment.

4. The NH_3-N is being volume diluted by high rates of gas production in some wells.

5. Discepancy is due to limitations of NH_3-N mass transfer into the gas phase.

6. Unpredicted solubility changes of ammonia resulting from the leachate chemistry.

7. Discrepancy could result from adsorption and resolubilization of NH_3-N in the unsaturated zone.

Probably a combination of pts. 1,2,3,4 and 6 cause the majority of discrepancy between predicted and measured NH_3-N gas.

Results comparing the NH_3-N gas fluxes with NH_3-N leachate fluxes show a negligible fraction of NH_3-N mass being lost through the emission of landfill gas. In a situation considered to result in maximum emissions, the ammonia gas fraction was found to be less than 0.03 % of the ammonia leachate mass flux in both Stride Ave. and Richmond Landfills. Mass flux results for NH3-N gas emission model also agreed favorably with the results calculated from a gas generation mass balance model.

In summary, this author believes there are some important implications that arise from this work on landfill gas. One, is the effect that climate has on production of methane in landfills. In colder, wetter climates such as Vancouver,

controlling the effects of climate would be paramount in designing a successful landfill gas utilization project. Secondly, is the issue of predicting gas concentrations from known leachate values by usage of a documented Henry's Law constant. This study's data imply that an accurate prediction using a documented Henry's constant may not be possible in a landfill. This has far reaching implications for persons trying to predict gas concentrations of certain volatile hazardous wastes from given leachate values. Lastly, the varied and disappointing results of the statistical analysis indicate that easily measured landfill parameters may not be useful in predicting the variation in concentration of gas components such as ammonia and methane.

Listed below are some potential future research projects this author feels should be undertaken to better improve this study's work.

1. Set up a field apparatus in an observation well that monitors the possible diurnal trend in landfill gas flow while monitoring changes in leachate pH and redox potential and methane gas percent. The main advantage to this system is the real time and continuous data offered showing small temporal trends that can be simulated on a computer later. Other than the high capital cost, a disadvantage to this system is the potential for vandalism.

2. In combination with the above, would be to set up instruments such as tensiometers and suction lysimeters to

monitor changes of moisture content and chemistry in the unsaturated zone. This would help in studying the effects that precipitation infiltration has on methane production in a full-scale landfill.

3. To determine if there is an active population of methanotrophs in the landfill environment an unsaturated zone sampling and soil extraction study should be attempted to isolate their metabolic enzyme Methane Monooxygenase.

4. Various potential laboratory projects worth mentioning are listed below:

- A study should focus on whether there is a biofilm culture surrounding refuse or is the bacteria population mostly in microcolonies. Determining this would have great consequences on trying to model the mass transfer of volatile compounds like ammonia.

- Study how the methanogens may be stimulated into greater gas production rates by an operating gas extraction system (ie Richmond Landfill). The study would consist of subjecting a sample of decomposing refuse under anaerobic conditions while applying the usual vacuum stresses applied during gas extraction.

- Determine what value of Henry's constant is applicable in a landfill environment by using ammonia as the study compound. This probably can be done in a closed anaerobic volatilization chamber.

- Perform more detailed research into the dynamics of

ammonia chemistry in leachate.

5.   To verify the modelled results of gaseous NH_3-N mass flux, I would recommend quantifying the emissions in the field by the use of volatilizing domes. This technique is discussed in more detail by Balfour et al. (1987). To improve the accuracy of the model runs, there should be a study to estimate the fraction of NH_3-N mass adsorbed or consumed in the landfill cover. Tests should also be performed on the landfill to verify the values chosen for standard parameters (ie, porosity, gas production rate etc...).   Lastly, the model should be upgraded to simulate pressure pumping effects while solving for n-layered and 2-d systems. This would best be done by finite difference or finite element modelling schemes.

CHAPTER 7

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```
===============================================
  SAMPLE    CH4 %    CO2 %    N2 %     O2 %
===============================================
       1  .  94.1      3.1      2.1      0.7
       2     94.5      3.1      1.8      0.6
       3     94.3      3.1      2.0      0.6
       4     93.6      3.0      2.6      0.8
       5     93.4      3.0      2.5      1.1
       6     92.3      3.0      3.4      1.3
       7     92.0      2.8      4.0      1.2
       8     91.4      3.0      4.1      1.5
       9     90.6      2.9      4.8      1.7
      10     89.4      2.9      5.6      2.0

MEAN = 92.6        STD. DEV. = 1.61

===============================================
```

APPENDIX A.1. - Results of Gas Partitioner Testing

```
=================================================================
  TIME     VIAL 1   VIAL 2   VIAL 3   VIAL 4   VIAL 5   VIAL 6
 (hours)
=================================================================

      0     71.2     72.9     54.2     78.1     87.7     81.2
            19.6     18.4     33.7     14.2      9.3     11.8

   2.25    88.04     76.7     82.7     83.6       85     84.4
              6      15.4     10.2       10      8.5      9.2

    4.5     75.4     60.1     77.1     82.3     81.8     68.3
            16.4     28.8     14.8     10.6       11     22.1

   6.75     76.1     76.3     75.7     73.1     63.5     79.5
            15.8     15.4     16.2     18.1     26.3     12.9

      9     73.7       67       72     70.7     66.4       75
            17.4     22.9     18.8       20     23.4     16.6

   21.5     68.6     63.2     67.5     68.6     60.5     64.2
            21.6     26.1     22.5     21.6   -  28.1     25.2

   28.5     64.9     60.4     64.6     63.8     54.6     57.6
            24.7     28.3     24.8     25.4     32.9     30.5

=================================================================
```

Appendix A2 - Results of Leakage Tests on Gas Sample Vials

APPENDIX A.3.- Recovery efficiency data for 6.0 L/min

RUN	BUBBLER NO.			ESCAPE	RECOVERY
	1	2	3		
1	82.1	47.6	26.2	18.3	47.1
2	98.2	22.0	22.0	15.4	62.3
3	102.8	22.0	21.7	15.2	63.6
4	144.8	21.8	21.8	15.3	71.0
MEAN	107.0	28.4	22.9	16.0	61.4
STD. DEV.	26.7	6.5	2.2	1.4	10.0
% C.V.	25.0	23.0	9.5	9.5	16.3

APPENDIX A.4.- Recovery Efficiency data for 2.1 L/min

1	92.9	38.1	37.5	26.3	47.7
2	183.9	38.0	82.8	58.0	50.7
3	144.0	32.0	54.0	37.8	53.8
MEAN	140.3	36.0	58.1	40.7	51.0
STD. DEV.	45.6	3.5	38.3	16.0	3.1
% C.V.	32.5	9.7	65.9	39.4	6.0

APPENDIX A.5.- Recovery efficiency data for 10.5 L/min

1	86.5	30.1	30.4	21.3	41.4
2	91.1	40.5	21.5	15.1	54.2
3	91.8	44.9	20.6	14.4	53.5
MEAN	89.8	38.5	24.2	16.9	53.0
STD. DEV.	2.9	7.6	5.4	3.8	1.5
% C.V.	3.2	19.7	22.4	22.4	2.8

APPENDIX A.6. - <u>RESULTS OF pH METER COMPARISON</u>

In an attempt to calculate the accuracy of the Horizon field pH meter a comparison was made between this and the lab reference Beckman 44 pH meter. The Beckman 44 has an LCD-digital display readout and is equipped with a calomel combined refillable electrode. Comparison of the two meters was made with various pH buffer solutions and distilled water. Results of the comparison are shown below:

Sample	Beckman	Horizon	% Error
Distl. water	5.39	5.28	-2.0
Distl. water + 0.2 ml aliquot of 6N NaOH	11.54	10.34	-10.4
Aliquot of disodium tetraborate $Na_2B_4O_7 \cdot 10H_2O$	9.17	8.94	-2.5
Aliquot of KH_2PO_4	4.67	4.43	-5.1
KH_2PO_4 + $Na_2B_4O_7 \cdot 10H_2O$	6.16	6.30	+2.3
Above mixture + aliquot of 0.02N NaOH	6.30	6.43	+2.0
Boric acid (20,000 ppm)	4.59	3.49	-24.0
Distl. water	5.63	5.02	-10.8
pH 7 buffer	6.99	6.76	-3.3
pH 4 buffer	4.00	3.89	-2.8

Inspection of these results show the greatest error to occur late in the comparison with the boric acid. In general however, the relative error of the Horizon pH meter is less than $\pm$ 5 % in the leachate pH range encountered in this study and usually underpredicts the pH. Errors are probably due to the Orion electrode not having enough time to equilibrate with the contacting ionic solution. To guard against electrode sensitivity decay, the Orion electrode was "rejuvenated" in saturated KCl solution almost every two weeks.

APPENDIX A.7. - <u>SUMMARY TABLE OF QUALITY ASSURANCE TESTS</u>

```
=================================================================
            METHOD                      ACCURACY RESULTS
=================================================================
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METHOD	ACCURACY RESULTS
Horizon Field pH meter (Compared to Beckman 44 Lab pH meter)	% Error of +2.3 to -24.0 % Usually less than ± 5 % of one pH unit (Detailed in Appendix A.6.)
Ammonia Distillation- Titration Method	20 mg/L NH3-N sample 4.2 % 200 mg/L sample 2.2 % (6 Samples each)
Fisher Gas Partitioner	% Error of ± 1.74 % (10 sample injections) (Detailed in Appendix A.1.)
Methane gas sample vials	% Leakage was 21.3 to 35.8 % over a 28 hr. period. Mean leakage value was 26.8 % (Detailed in Appendix A.2.)

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=================================================================
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Note: Accuracy tests of the NH3-N gas analytical method are
discussed in Chapter 5.

APPENDIX B. - SAMPLE CALCULATIONS OF SOME OF THE PARAMETERS

B.1. CALCULATION OF CH4 FLUX THROUGH SAMPLE WELLS

Known parameters are:

- CH4 % by volume
- Molecular weight of CH4 = 16.0 gm/mole
- Static gas flow in L/min
- Cross-sectional area through measurement tube
    r = 1.27 cm
    A = 5.07 cm^2
- Gas temp. in K
- Gas constant, R = 0.082057 L-atm/K-mol
- Assume gas is behaving ideally
- ideal gas law pV = nRT
- Where V = Flow * Time
- So Q (Flow) = V/t
- Assume p = 1 atm.
- So p/R = 12.195 K-mol/L

- To get CH_4 Flux in kg CH_4/cm^2-day then multiply by proper conversion factors to get from volume percent into mass.

Therefore, CH4 Flux is:

$$CH_4 \text{ Flux} = 55.6 * (Q/T^{\circ}K) * (CH_4 \text{ \%}/100)$$

Example Calculation is :

Suppose I have a well flow of 20 L/min., Gas Temp. of 290°K, CH_4 of 50 %, then will get:

$$CH_4 \text{ Flux} = 55.6 * (0.1034) * (0.50) = 2.8800 \text{ kg } CH_4/cm^2\text{-day}$$

B.2. CALCULATION OF CO2 FLUX

Is the same procedure as for CH_4 Flux except the molecular weight is increased to 44.0 gm/mole to change the equation below:

$$CO_2 \text{ Flux in kg } CO_2/cm2\text{-day} = 152.52 * (Q/T^{\circ}K) * (CO_2 \text{ \%}/100)$$

B.3. CALCULATION OF LANDFILL GAS DENSITY

Summation of the four main landfill gas constituents, CH_4, CO_2, N_2, O_2 were assumed to be indicative of the total landfill gas concentration. Density for each gas taken from the literature (listed below) was summed in the spreadsheet to get total gas density for each well in each sample period.

GAS	DENSITY	SOURCE
CH_4	0.714 kg/m^3	Emcon Assoc. (1980)
CO_2	1.950 kg/m^3	Emcon Assoc. (1980)
N_2	1.248 kg/m^3	CRC Handbook of Chem. and Physics (1979)
O_2	1.427 kg/m^3	Same as above

Total gas density was calculated as follows:

Gas density = $((CH_4\%/100)*0.714)$ + $((CO_2\%/100)*1.950)$ +
...... + $((N_2\%/100)*1.248)$ + $((O_2\%/100)*1.427)$

B.4. CALCULATION OF PPB IN GAS

Parts per billion of NH_3-N gas was calculated by dividing to NH_3-N gas concentration into the total gas density to get comparable mass units:

$$ug/kg = \frac{ug/m^3 \ NH3-N}{kg/m^3 \ Density} = ppb$$

Sample Calculation of NH3-N of 200 ug/m^3 and density = 1.30 kg/m^3

$$\frac{200 \ ug/m^3}{1.30 \ kg/m3} = 153.8 \ ppb$$

B.5. CALCULATION OF IONIC STRENGTH

From Snoeynk and Jenkins (1980) is a conversion factor for coverting specific conductance into ionic strength:

Spec. Conduct.$*1.6 \times 10^{-5}$ = Ionic Strength

B.6. CALCULATING ACTIVITY COEFFICIENTS

The Debye-Huckle approximation was used and the equation below is valid where ionic strength do not exceed 0.1, which is appropriate for my results since only two wells, F1 and F5 Matsqui exceeded the 0.1 I.

$$\log = \frac{- A*z^2*I^{0.5}}{1 + Ba*I^{0.5}}$$

Where A = 0.50   z = 1.0 for NH_4^+
       B = 0.326E+08   a = 3.0E-08 for NH_4^+ ions

Sample calculation: suppose leachate of 2000 umho/cm then the activity coefficient is :

$$\log \quad = -(0.50*1.0*0.032^{0.5})/1 + (0.978*0.032^{0.5})$$

$$= \text{antilog } (-0.076) = 0.84$$

B.7. CALCULATE FRACTION OF UNIONIZED AQUEOUS AMMONIA

Thurston et al (1974) regressed the data obtained from Pinching and Bates into workable equations estimating pKa and fraction of ammonia below:

$$pKa = 0.0901821 + 2729.92/T^{\circ}K$$

This equation is found to have about a 5 % C.V., which is exceptable. The fraction is then calculated below:

$$f = 1/(10^{pKa - pH} + 1)$$

This fraction can then be multiplied by the total ammonia measured to get the concentration, molarity and mole fraction

$$f*C(NH_3-N) = C(NH_3)$$

$$C(NH_3)/17.04 \text{ g/mole} = [NH_3|aq]/55.6 \text{ m/L} = X(NH_3)$$

B.8. ESTIMATION OF pKw

The ionization constant of water is a function of temperature from the below equilibrium expression:

$$Kw = [H^+]*[OH^-]$$

The data used to predict the pKw as a function of temperature was taken from Freney (1981):

Temp. in celsius	pKw
0	14.944
5	14.734
10	14.535
15	14.346
20	14.167
25	13.997
30	13.833
35	13.680
40	13.535

The resultant regression equation is :

$$pKw = 24.50198 - 0.03517(T^O K)$$

$$r^2 = 0.996584$$

- standard error is 2.2 % in this equation

B.9 CALCULATION OF AQUEOUS AMMONIA FROM EQUUILIBRIUM EXPRESSION

This method is an alternative to Thurston's calculation. It is based on the equilibrium expression of ammonia and water below:

$$NH_3 + H_2O <====> NH_4^+ + OH^-$$
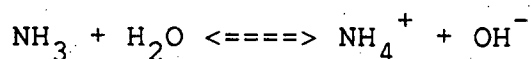
$$K_1 = ([NH_4^+]* *[OH^-])/[NH_3|aq]$$

$$Kw = [H^+]*[OH^-]$$

Where $pK_1 = pKw - pKa$

Where $[OH^-]$ is estimated from antilog(-(pKw-pH)

So $[NH_3|aq] = \dfrac{[NH_4+]* *[OH-]}{K_1}$

Example is a leachate of 200 mg/L total ammonia a   of 0.80, a pH of 6.5 and a leachate T of 15 degrees.

$$[NH_4^+] = 0.200 \text{ g/L}/17.04 \text{ gm/mole} = 0.012 \text{ m/L}$$

$$pKa = 9.569 \quad pKw = 14.373 \quad pK_1 = 4.80 \text{ or } K_1 = 1.58E-08$$

$$[OH^-] = antilog(-7.87) = 1.34E-08 \text{ m/L}$$

$$[NH_3|aq] = 8.11E-06 \text{ m/L}$$

B.10 ESTIMATION OF HENRY'S CONSTANT (H1) FROM THE VAPOR PRESSURE METHOD

a. Must first calculate the reference vapor pressure as a function of temperature (from NRC, 1979):

$$\log P_{ref} = 9.95028 - 0.003863(T) - 1473.12/T$$

Where T = K
P_{ref} = mm Hg

To get into atmospheres multiply mm Hg by 0.0013

b. Calculate solubility as a function of temperature from Freney (1981) data to get regression equation below:

$$\log S = 1.307360 + 934.63/T \text{ where } T = K$$

$$r^2 = 0.999806$$

Standard error is only 0.04 %

    c. Must calculate corrected vapor pressure (P_c) since a dilute solution doesn't obey Raoult's Law of an ideal solution, so a corrected vapor pressure as a function of it's solubility is employed (MacKay and Shiu, 1981).

$$P_c = P_{ref} * (1 - w)$$

Where w is the fraction of solubility of the weight of ammonia in a given weight of water.

Therefore: H_1 in atm-L/mole = Pc/S

    d. Example calculation for solution at 25 degrees celsius

$$H_1 = (9.32 \text{ atm} * (1 - (26.92/55.6)))/26.92 \text{ m/L}$$
$$H_1^1 = 0.1786 \text{ atm-L/mole}$$

B.11 ESTIMATION OF H2 FROM THE MOLE FRACTION METHOD

Two complete sources of data were used to estimate H2 as a function of temperature. The sources are listed below:

Temp	Tchobanaoglous (1985)	Perry (1963)	Thibodeaux (1979)
0	0.48	0.38	--
10	0.78	0.62	--
20	1.25	0.99	--
25	1.56	1.24	0.84
30	1.96	1.57	--
40	2.94	1.96	--
50	--	2.70	--

At 25 degrees, a statistical comparison of the three sources yields a highly variable mean of 1.104 with a standard deviation of 0.396 and a % C.V. of 36 %.

When averaging the two complete sets of data one gets the regression equation below:

$$H_2 = -7.83 + 0.03(T) \text{ where } T = K$$

$$r^2 = 0.996236$$

Standard Error is over 3 %
Example calculation at 25 degrees:

H_2 = 1.104 atm/X H_2 = 0.902 X/atm

0.906X*55.6 m/L = H_2*atm

50.37 m/L = H_2*atm

H_2 = 0.01986 atm-L/mole

B.12. ESTIMATE H3 FROM GIBBS FREE ENERGY METHOD

From enthalpy and entropy data in Stumm and Morgan (1981), one can calculate the equilibrium constant between the aqueous and gas phases of ammonia.

Species	H_f (Kcal/mol)	S (Kcal/K-mol)
NH_3|g	-11.04	46.01E-03
NH_3|aq	-19.32	26.30E-03

An example calculation at 25 degrees :

H = -19.32 - (-11.04) = -8.28 Kcal/mol
S = 26.30 - 46.01 = -19.7 cal/K-mol

T S = (298.16)*(-19.7) = -5.88 Kcal/mol

Therefore the standard free energy change is based on Gibbs Free Energy below:

ΔG^O = H - TΔS = -8.28 - (-5.88) = -2.40 Kcal/mol

So H_3 is calculated from equilibrium expression below:

$$-RTlnK = \Delta G^o$$

Where R = 1.987E-03 Kcal/K-mol

$$\log K = \frac{-\Delta G^o}{2.303*T*R}$$

$$\log K = 2.40/1.364 = 1.76 \quad K \text{ or } H = 57.3$$

$$K = [NH_3|aq]/P_{NH3} = 57.5 \text{ mol/atm-L}$$

$$H_3 = 1.73E-02 \text{ atm-L/mol}$$

B.13. CALCULATE H4 FROM THE SOLUBILITY EQUILIBRIUM METHOD

This method calculates a dimensionless constant as a ratio between the aqueous and gaseous molarities of ammonia. This can then be converted to the appropriate units.

$$H_4 = [NH_3|aq]/[NH_3|g]$$

In pure water studies by Hale and Drewes (1979), over 30 data pairs were regressed as a function of temperature and is shown below:

$$\log H_4 = -1.694 + 1477.7/T \quad \text{where } T = K$$

No r^2 was given and std. error was 9.7 %

Example of conversion to appropriate units at 25 degrees:

$$H_4 = 1842.0$$

$$[NH_3|g] = 1842 * [NH_3|aq] / H_4$$

$Xg = [NH_3|g]/22.4 \text{ m/L}$ and assume 1 atm pressure get:

$H_4 = 2.443E-5$ atm-L/mole, which is significantly less than the other henry's constants discussed so far.

B.14. DESCRIPTION AND DERIVATION OF THIBODEAUX'S MODEL FOR GAS EMISSIONS FROM COVERED LANDFILLS WITH INTERNAL LANDFILL PRESSURE BUILD-UP.

a. For a uniform composition of gas within a landfill cell, the equation of continuity can be expressed below:

$$n \cdot \frac{dC}{dt} = - \frac{C*v}{h} + r_g \qquad (i)$$

Where n = air-filled porosity
C = concentration in ug/m^3
t = time (days)
v = superficial outward velocity (m/day)
h = landfill cell depth (m)
r_g = rate of gas generation in cell (ug/m^3-day)

b. The equation that describes the one-dimensional flow of

gas through the cell or landfill cover is by Darcy's Law below:

$$v = \frac{K}{u*L} *(p - b) \qquad (ii)$$

Where v = m/day
  u = gas viscosity (cP)
  K = permeability of cover (m^2/day)
  L = thickness of cap (m)
  p = pressure within cap
  b = barometric pressure at landfill surface

So this equation describes covection flow caused by pressure induced flow.

c. Combining equations i, ii and a biological gas rate (rg), one can get an expression for the rate of change of internal landfill pressure. To get this expression, the gas density must be solved using the ideal gas law. The expression is below:

$$\frac{dP}{dt} = \frac{rg*\rho*p}{n} - \frac{Kp(p-b)}{n*h*L*u} \qquad (iii)$$

d. Equation (ii) can be combined with the below equation that describes steady state internal gas flow in one direction.

$$De*\frac{d^2C}{dZ} - v*\frac{dC}{dZ} = 0 \qquad (iv)$$

Where De is effective diffusion coefficient

If h and z = surface and base of landfill cover, then can solve the above equation by integrating at boundary conditions of Ca at z and C^2 at h to get:

$$C_2 = Ca - (Ca - C_2)*\frac{(1-exp(z*v/De))}{(1-exp(h*v/De))} \qquad (v)$$

The flux expression then is :

$$Na = v * \frac{Ca - C_2}{exp(h*v/Da) - 1} + v*Ca \qquad (vi)$$

This expression contains both a diffusive and convective flux term.

Equation (vi) is then converted into the more workable equation that by itself is used to estimate flux emission rates from landfills that are assumed to have

no internal pressure build-up. This is shown below:

$$Na = (De/L)*(Ca - C2)*\frac{(Rexp(R))}{(exp(R) - 1)} \qquad (vii)$$

Where L = Landfill cover thickness (m)
R = L*v/De

Na = Mass flux in M/L^2-T

B.15. SAMPLE CALCULATION OF THIBODEAUX'S MODEL, RICHMOND LANDFILL

a. Calculate Effective diffusion coefficient with diffusion coefficient in air (Do) = 1.750 m^2/day and air-filled porosity = 0.40

$$De = Do*(n_a^{1.33}) = 0.517 \ m^2/day$$

b. Calculate G-factor

R = L*v/De   where L = 1.5 m and v = 0.5996 m/day

R = 1.74

G-Factor = 2.11

c. Calculate NH_3-N flux from gas

$$N = (0.517 \ m^2/day/1.5M)*(92.8-20.0)*2.11$$

$$N = 52.9 \ ug \ NH_3-N/m^2-day$$

The results for without gas generation (ie, Farmer's model)

$$N = 25.1 \ ug \ NH_3-N/m^2-day$$

d. Calculate annual flux from the landfill

$$52.9 * 200,000 \ m^2 * 365 \ day/yr \ / \ 1 \ X \ 10^9 \ ug/kg$$

N = 3.862 kg/yr

B.16. SAMPLE CALCULATION OF GAS GENERATION MASS BALANCE MODEL AT RICHMOND LANDFILL

a. Assume gas pumping rate of 20.5 m^3/min and an ammonia gas concentration of 92.8 ug/m^3.

$$20.5 \ m^3/min * 92.8 \ ug/m^3 = 1902.5 \ ug/min$$

$$1902.5 \ ug/min * 1440 \ min/day * 1 \ X \ 10^{-9} \ kg/ug$$

$= 0.00273$ kg NH_3/day $= 1.00$ kg NH_3/year

b.   Check calculation of gas production rate used in Thibodeaux model run.

Get refuse mass $= 200,000$ m^2 * 10 m * 600 kg/m^3

$= 1.2 \times 10^9$ kg of refuse fill

20.5 m3/min $= 2.95 \times 10^{10}$ mL/day

Therefore gas production rate = flow/refuse mass

$= 24.6$ mL/kg-day which compares to assumed value of 40 mL/kg-day used in model runs.

```
=================================================================
          Vancouver Intl. Airport    Vancouver Harbor  Abbotsford
=================================================================

Aug. 87                 0.0              Tr              0.0
                       25.8             15.0             13.9
                        0.0              0.2             0.0
                         Tr              Tr              Tr

Sept. 87               13.2             11.4             11.6
                        9.6             11.1             12.0
                        2.2              0.0             0.0
                        3.4              5.6             1.4

Oct. 87                 0.2              1.2             1.6
                        0.0              0.0             0.0
                        0.0              Tr              Tr
                       20.2             31.4             18.2

Nov. 87                 0.6              5.2             1.8
                       74.8             91.1            69.0
                       48.4             77.5            31.5
                       13.0              9.0             9.0

Dec. 87                73.0            137.9            95.8
                       46.4             48.6            73.8
                       16.6             32.0            28.8
                       13.6             10.6            15.1

Jan. 88                 0.0              0.0             0.0
                       40.8             83.4            75.1
                       15.8             16.4            15.9
                        9.6             16.6            19.8

Feb. 88                18.3             32.8            40.0
                       46.2             77.1            57.9
                        3.6              9.4             6.2
                        3.6              6.0             3.4

Mar. 88                25.2             32.1            33.3
                       23.0             35.3            26.6
                       43.0             53.6            33.7
                       47.0             63.7            61.1

Apr. 88                71.6             n.d.           105.6
                         Tr             n.d.              Tr
                        2.4             n.d.             8.2
                       17.2             n.d.            48.0

=================================================================
```

NOTE: Precipitation in millimeters

APPENDIX C.1.- Weekly Precipitation Data For Weather Stations in Close
               Proximity to Landfill Study Sites.

      Note: Vancouver Harbour was Permanently Discontinued
            at the End of March, 1988.

APPENDIX D - TABLES OF BASIC DATA FROM EACH SAMPLE WELL

DATE	W.L. (meters)	TEMP LEACH	TEMP GAS	pH	NH3-N LEACH (mg/L)	SPEC. CONDUCT. (umho/cm)	NH3-N GAS (ppb)	% CH4	% CO2	% N2	% O2	GAS FLOW (L/min)	BARO. PRESS. (KPa)
						F1 MATSQUI							
08/05/87	--	--	--	--	--	--	108.6	45.9	39.1	13.8	1.3	28.2	--
08/25/87	--	--	--	--	--	--	678.2	48.4	36.2	14.2	1.3	65.9	101.78
09/08/87	--	--	25.0	--	--	--	500.2	46.4	37.0	15.2	1.4	56.6	101.64
09/22/87	--	--	21.0	--	--	--	408.4	41.9	34.8	21.4	2.0	62.9	101.64
10/06/87	--	--	19.0	--	--	--	256.4	38.5	33.0	26.9	1.7	48.5	102.28
10/20/87	--	--	18.0	--	--	--	104.4	38.6	32.4	26.8	2.2	40.4	102.35
11/10/87	--	--	16.0	--	--	--	184.2	38.0	32.7	26.5	2.7	48.5	101.84
11/24/87	--	--	14.0	--	--	--	73.4	38.9	31.5	23.5	6.0	54.8	101.24
12/08/87	--	--	13.0	--	--	--	51.4	40.0	30.5	24.2	5.3	19.8	100.73
12/29/87	--	--	13.0	--	--	--	35.0	50.2	36.5	10.5	2.8	13.3	101.07
01/12/88	9.69	7.0	13.0	6.49	2637.6	24040.0	44.8	30.2	33.4	32.8	3.7	30.9	101.78
01/26/88	9.69	11.0	12.0	6.34	2669.3	21200.0	39.4	32.9	34.7	29.2	3.2	62.9	102.49
02/09/88	9.67	10.5	11.0	6.27	2548.0	22550.0	30.2	45.0	32.5	18.4	4.1	25.0	102.32
03/01/88	9.75	14.0	12.0	6.25	1848.0	16290.0	140.4	47.6	33.0	17.3	2.1	15.2	102.25
03/29/88	9.70	11.0	10.0	6.19	1786.0	16023.0	37.2	37.8	28.6	29.2	4.4	7.4	102.05
Maximum	9.75	14.0	25.0	6.49	2669.3	24040.0	678.2	50.2	39.1	32.8	6.0	65.9	102.49
Minimum	9.69	7.0	10.0	6.19	1786.0	16023.0	30.2	30.2	28.6	10.5	1.3	7.4	100.73
Mean	9.70	10.7	15.2	6.31	2297.8	20020.6	179.6	41.4	33.7	22.0	2.9	38.7	101.82
Std. Dev.	0.03	2.2	1.0	0.10	395.1	3281.5	191.6	5.6	2.6	6.5	1.4	19.3	0.51
C.V.	0.28	20.8	6.7	1.63	17.2	16.4	106.6	13.5	7.8	29.6	48.4	49.8	0.50
						F2 MATSQU							
08/05/87	8.80	17.0	23.0	7.10	406.0	4000.0	204.6	34.3	31.0	31.5	3.2	36.2	--
08/25/87	8.99	17.0	22.0	7.20	252.0	3640.0	408.4	25.3	29.5	92.8	2.4	70.8	101.84
09/08/87	9.05	18.0	25.0	7.16	347.2	3400.0	397.4	25.2	28.3	44.0	2.5	65.4	101.71
09/22/87	9.09	17.0	23.0	7.24	313.6	3066.0	311.4	28.6	30.1	40.2	1.2	73.9	101.61
10/06/87	9.09	18.0	19.0	7.24	369.6	3614.0	166.4	27.4	29.6	41.9	1.1	85.0	102.28
10/20/87	9.03	17.0	15.0	7.35	316.4	3375.0	143.0	27.3	30.1	41.9	0.7	68.0	102.38
11/10/87	9.11	16.0	16.0	7.54	274.4	3371.0	135.6	26.2	28.8	42.8	2.2	73.9	101.88
11/24/87	9.09	16.0	14.0	7.95	308.3	3200.0	40.0	23.2	27.0	46.2	3.7	70.8	101.17
12/08/87	9.05	11.0	12.0	6.50	124.7	2400.0	25.8	25.0	27.1	44.4	3.5	53.1	100.70
12/29/87	9.10	11.0	16.0	7.22	235.2	2715.0	18.2	27.0	27.3	42.6	3.1	43.6	100.93
01/12/88	9.06	8.0	14.0	6.94	149.0	1750.0	23.6	22.7	25.0	48.6	3.8	58.6	101.74
01/26/88	9.03	13.0	14.0	6.29	70.6	1083.0	38.8	22.5	25.0	48.3	4.3	75.5	102.45
02/09/88	8.90	14.5	10.0	5.97	53.8	1118.0	33.2	23.3	27.1	46.4	3.2	37.8	102.28
03/01/88	9.05	13.0	15.0	7.05	271.0	2952.0	69.2	24.3	26.6	46.1	3.0	45.9	102.21
03/29/88	8.88	13.0	14.0	6.93	182.6	1396.0	72.2	39.0	30.7	28.3	2.0	47.2	101.94
Maximum	9.11	18.0	25.0	7.95	406.0	4000.0	408.4	39.0	31.0	92.8	4.3	85.0	102.45
Minimum	8.80	8.0	10.0	5.97	53.8	1083.0	18.2	22.5	25.0	28.3	0.7	36.2	100.70
Mean	9.02	14.6	16.8	7.05	245.0	2738.7	139.2	26.8	28.2	45.7	2.7	60.4	101.79
Std. dev.	0.09	2.9	4.4	0.47	103.9	932.4	130.4	4.4	1.9	13.7	1.0	14.9	0.52
C.V.	0.98	19.9	25.9	6.71	42.4	34.0	93.7	16.3	6.7	30.0	38.6	24.6	0.51

APPENDIX D

APPENDIX D

DATE	W.L. (meters)	TEMP LEACH	TEMP GAS	pH	NH3-N LEACH (mg/L)	SPEC. CONDUCT. (umho/cm)	NH3-N GAS (ppb)	% CH4	% CO2	% N2	% O2	GAS FLOW (L/min)	BARO. PRESS. (KPa)
						F3 MATSQUI							
08/05/87	--	--	--	--	--	--	211.2	56.5	33.7	8.5	1.3	94.3	--
08/25/87	--	--	--	--	--	--	361.4	43.9	33.8	20.7	1.6	130.7	101.81
09/08/87	--	--	21.0	--	--	--	198.6	50.8	35.8	12.5	0.9	121.4	101.71
09/22/87	--	--	22.0	--	--	--	388.8	51.5	35.8	11.5	1.2	138.7	101.61
10/06/87	--	--	19.0	--	--	--	82.6	48.1	35.3	15.8	0.8	147.8	102.35
10/20/87	--	--	18.0	--	--	--	551.2	45.2	33.8	19.2	1.8	121.4	102.45
11/10/87	--	--	15.0	--	--	--	142.0	48.2	35.5	14.4	1.7	130.7	101.88
11/24/87	--	--	14.0	--	--	--	136.2	43.8	33.4	20.9	1.9	130.7	101.14
12/08/87	9.56	10.0	12.0	6.94	398.7	3400.0	19.8	45.5	32.6	19.2	2.7	100.0	100.70
12/29/87	9.58	10.0	12.0	6.85	285.6	3104.0	35.8	48.2	32.2	17.1	2.5	85.0	100.90
01/12/88	9.60	10.0	12.0	6.83	168.0	2054.0	26.8	43.5	33.8	19.8	2.9	115.6	101.68
01/26/88	9.58	14.0	13.0	6.60	142.8	1660.0	29.6	47.1	30.5	18.4	4.0	147.8	102.38
02/09/88	9.55	14.0	9.0	6.31	95.2	1680.0	52.0	24.5	23.6	46.7	5.2	47.2	102.25
03/01/88	9.60	17.0	13.0	5.86	88.5	1384.0	135.8	52.4	32.3	12.7	2.6	93.1	102.25
03/29/88	9.55	13.0	13.0	6.22	110.9	1298.0	44.8	44.9	29.7	23.1	2.3	103.6	101.94
Maximum	9.60	17.0	22.0	6.94	398.7	3400.0	551.2	56.5	35.8	46.7	5.2	147.8	102.45
Minimum	9.55	10.0	9.0	5.86	88.5	1298.0	19.8	24.5	23.6	8.5	0.8	47.2	100.70
Mean	9.57	12.6	14.8	6.52	184.2	2082.9	161.2	46.3	32.8	18.7	2.2	113.9	101.79
Std. Dev.	0.02	2.5	3.8	0.37	107.4	776.8	153.2	6.8	3.0	8.5	1.1	26.2	0.53
C.V.	0.21	19.9	25.5	5.68	58.3	37.3	95.1	14.7	9.2	45.2	51.3	23.0	0.53
						F4 MATSQU							
08/05/87	--	--	--	--	--	--	61.6	58.7	38.2	3.1	0.0	37.8	--
08/25/87	--	--	--	--	--	--	396.0	49.2	33.7	15.3	1.8	85.8	101.91
09/08/87	--	--	22.0	--	--	--	234.4	59.0	35.3	4.5	1.2	70.8	101.78
09/22/87	--	--	21.0	--	--	--	202.0	59.6	35.8	3.9	0.8	77.2	101.67
10/06/87	--	--	20.0	--	--	--	269.4	52.2	37.8	10.0	0.0	77.2	102.28
10/20/87	--	--	18.0	--	--	--	189.6	49.5	36.6	13.0	0.8	58.6	102.52
11/10/87	--	--	15.0	--	--	--	157.2	43.7	34.0	19.9	2.4	68.0	101.88
11/24/87	--	--	12.0	--	--	--	103.6	39.4	31.3	25.8	3.5	62.9	101.14
12/08/87	--	--	14.0	--	--	--	8.0	44.5	38.6	14.9	2.0	34.7	100.70
12/29/87	--	--	14.0	--	--	--	33.8	52.4	36.7	9.9	1.0	39.5	100.83
01/12/88	--	--	14.0	--	--	--	42.4	50.8	33.6	14.4	1.2	69.4	101.61
01/26/88	--	--	13.0	--	--	--	36.6	50.7	35.0	12.4	1.9	70.8	102.28
02/09/88	--	--	--	--	--	--	130.6	--	--	--	--	--	--
03/01/88	--	--	12.0	--	--	--	23.2	47.3	33.6	16.5	2.7	11.8	102.32
03/29/88	--	--	12.0	--	--	--	5.8	46.5	32.4	17.5	3.6	23.3	101.91
Maximum	--	--	22.0	--	--	--	396.5	59.6	38.6	25.8	3.6	85.8	102.52
Minimum	--	--	12.0	--	--	--	8.0	39.4	31.3	3.1	0.0	11.8	100.70
Mean	--	--	15.4	--	--	--	134.8	50.3	35.2	12.9	1.6	56.3	101.76
Std. Dev.	--	--	3.4	--	--	--	109.4	5.7	2.1	6.1	1.1	21.8	0.55
C.V.	--	--	22.3	--	--	--	81.1	11.4	6.1	47.4	67.0	38.8	0.54

APPENDIX D

DATE	W.L. (meters)	TEMP LEACH	TEMP GAS	pH	NH3-N LEACH (mg/L)	SPEC. CONDUCT. (umho/cm)	NH3-N GAS (ppb)	% CH4	% CO2	% N2	% O2	GAS FLOW (L/min)	BARO. PRESS. (KPa)
						F5 MATSQUI							
08/05/87	5.98	17.0	20.0	6.60	787.5	12000.0	22.0	38.7	33.8	26.4	1.1	34.0	--
08/25/87	5.98	18.0	21.0	6.82	1881.6	21913.0	601.6	56.9	43.1	0.0	0.0	18.9	101.98
09/08/87	5.98	17.0	20.0	6.85	1960.0	18500.0	76.0	56.9	43.1	0.0	0.0	18.3	101.88
09/22/85	5.96	17.0	25.0	6.75	1624.0	17546.0	143.8	57.0	43.0	0.0	0.0	23.6	101.54
10/06/87	5.97	18.0	22.0	6.86	1982.4	19207.0	99.2	54.0	40.2	4.7	1.2	40.5	102.25
10/20/87	5.88	17.0	20.0	6.78	1988.0	18877.0	276.8	58.9	35.9	4.7	0.4	21.8	102.49
11/10/87	6.08	15.0	14.0	6.81	397.6	5960.0	167.6	56.3	40.6	2.4	0.7	43.6	101.88
11/24/87	5.74	14.0	11.0	5.41	154.0	2906.0	37.4	37.9	27.4	27.1	7.6	N.D.	101.10
12/08/87	5.83	14.0	10.0	5.47	264.9	3200.0	13.6	48.0	37.5	12.0	2.5	8.6	100.73
12/29/87	5.83	14.0	8.0	6.74	1243.2	14746.0	73.0	56.3	37.7	4.6	1.3	10.0	100.80
01/12/88	6.44	13.5	12.0	6.86	1971.2	19132.0	30.8	51.9	33.9	11.5	2.7	41.4	101.57
01/26/88	5.61	14.5	8.0	6.17	300.6	4405.0	36.0	54.7	35.4	7.7	2.2	53.1	102.25
02/09/88	5.60	12.0	8.0	6.47	151.2	2864.0	--	--	--	--	--	--	--
03/01/88	5.73	15.0	12.0	6.59	778.1	9807.0	69.2	0.4	21.3	61.9	16.3	N.D.	101.94
03/29/88	5.54	14.0	10.0	6.37	478.8	6424.0	--	--	--	--	--	--	--
Maximum	6.44	18.0	25.0	6.86	1988.0	21913.0	601.6	58.9	43.1	61.9	16.3	53.1	102.49
Minimum	5.54	12.0	8.0	5.41	151.2	2864.0	13.6	0.4	21.3	0.0	0.0	N.D.	100.73
Mean	5.88	15.3	14.7	6.50	1064.2	11832.5	126.6	48.3	36.4	12.5	2.8	24.1	101.70
Std. Dev.	0.22	1.8	5.7	0.46	737.8	6841.9	154.2	15.3	6.1	16.7	4.4	16.5	0.55
C.V.	3.71	11.6	38.8	7.07	69.3	57.8	121.7	31.7	16.9	133.2	157.4	68.5	0.54
						F6 MATSQU							
08/05/87	--	--	--	--	--	--	92.4	35.5	23.0	33.1	8.5	5.0	--
08/25/87	--	--	--	--	--	--	447.4	--	--	--	--	6.9	102.05
09/08/87	--	--	--	--	--	--	83.6	40.4	27.3	25.4	6.8	N.D.	101.81
09/22/87	--	--	22.0	--	--	--	108.2	27.5	20.0	40.8	11.7	N.D.	101.54
10/06/87	--	--	19.0	--	--	--	N.D.	56.5	36.9	5.4	1.2	27.9	102.15
10/20/87	--	--	19.0	--	--	--	309.8	56.4	37.1	5.3	1.2	12.0	102.49
11/10/87	--	--	14.0	--	--	--	120.0	54.1	37.0	7.0	1.8	18.1	101.84
Maximum	--	--	22.0	--	--	--	449.2	56.5	37.1	40.8	11.7	27.9	102.49
Minimum	--	--	14.0	--	--	--	N.D.	27.5	20.0	5.3	1.2	N.D.	101.54
Mean	--	--	18.5	--	--	--	166.0	45.1	30.2	19.5	5.2	10.0	101.98
Std. Dev.	--	--	2.9	--	--	--	144.0	11.3	7.1	14.3	4.1	9.4	0.30
C.V.	--	--	15.5	--	--	--	86.8	25.0	23.5	73.4	78.2	94.6	0.29

APPENDIX D

DATE	W.L. (meters)	TEMP LEACH	TEMP GAS	pH	NH3-N LEACH (mg/L)	SPEC. CONDUCT. (umho/cm)	NH3-N GAS (ppb)	% CH4	% CO2	% N2	% O2	GAS FLOW (L/min)	BARO. PRESS. (KPa)
						F8 MATSQUI								
11/10/87	5.20	17.0	14.0	5.39	1.0	860.0	103.0	24.5	20.4	44.8	10.3	2.0	101.81
11/24/87	5.59	15.0	12.0	4.70	1.0	291.0	40.0	26.3	21.2	42.3	10.2	30.3	101.17
12/08/87	4.09	12.0	11.0	4.71	1.0	400.0	19.8	20.5	20.0	48.5	10.0	5.1	100.73
12/29/87	4.09	12.0	8.0	5.92	1.7	566.0	32.4	20.4	12.9	52.3	14.4	4.6	100.83
01/12/88	4.02	9.0	7.0	5.62	1.2	377.0	28.2	26.6	19.5	42.4	11.5	6.0	101.51
01/26/88	3.59	10.0	10.0	5.79	1.4	439.0	59.8	23.2	20.5	36.6	9.7	6.0	102.22
02/09/88	3.22	7.0	8.0	5.78	1.6	1023.0	27.2	35.7	18.6	35.6	10.1	5.0	102.23
03/01/88	3.78	11.0	11.0	5.74	N.D.	620.0	82.4	23.0	13.2	50.1	13.6	1.3	102.28
03/29/88	2.88	9.0	9.0	5.22	N.D.	243.0	70.4	23.6	18.7	47.7	10.0	1.3	101.94
Maximum	5.59	17.0	14.0	5.92	1.7	1023.0	103.0	35.7	21.2	52.3	14.4	30.3	102.28
Minimum	2.88	7.0	7.0	4.70	N.D.	243.0	19.8	20.4	12.9	35.6	9.7	1.3	100.73
Mean	4.05	11.3	10.0	5.43	1.0	535.4	51.4	24.9	18.3	44.5	11.1	6.8	101.64
Std. Dev.	0.82	2.9	2.1	0.44	0.6	247.0	27.2	4.3	2.9	5.5	1.6	8.5	0.57
C.V.	20.22	26.0	21.1	8.05	58.9	46.1	52.8	17.4	16.0	12.3	14.8	124.0	0.56

APPENDIX D

DATE	W.L. (meters)	TEMP LEACH	TEMP GAS	pH	NH3-N LEACH (mg/l)	SPEC. CONDUCT. (umho/cm)	NH3-N GAS (ppb)	% CH4	% CO2	% N2	% O2	GAS FLOW (L/min)	BARO. PRESS. (KPa)
						F2 STRIDE							
08/09/87	7.06	12.0	20.0	6.40	2.1	--	96.4	57.0	15.8	23.2	4.0	4.5	--
08/27/87	7.07	12.0	20.0	6.26	1.8	1182.0	101.2	55.6	16.1	26.3	2.0	2.0	101.78
09/10/87	7.11	12.0	18.0	6.33	4.1	1149.0	192.6	59.9	17.1	22.0	0.9	0.8	101.24
09/24/87	7.16	12.0	16.0	6.26	3.2	972.0	156.8	48.6	16.3	30.1	5.1	4.0	101.24
10/07/87	7.21	12.0	21.0	6.18	3.6	1167.0	209.4	56.3	27.9	14.7	1.2	2.4	101.91
10/22/87	7.32	12.0	16.0	6.18	1.1	1127.0	72.8	58.5	16.9	22.2	2.3	3.0	102.88
11/12/87	7.42	12.0	15.0	6.38	1.9	1107.0	98.8	55.6	15.9	25.3	3.3	6.0	101.81
11/26/87	7.01	11.5	13.0	5.67	0.7	952.0	74.6	59.6	15.7	22.9	1.9	12.0	102.21
12/15/87	6.78	11.5	12.0	5.47	1.0	786.0	42.6	32.0	15.4	48.9	3.6	5.0	100.90
12/31/87	6.77	11.5	11.0	6.22	2.4	1107.0	77.4	42.0	13.8	38.7	5.5	N.D.	101.78
01/14/88	6.76	11.5	8.0	6.20	2.6	1029.0	46.0	58.8	19.8	21.4	0.0	37.8	100.63
01/28/88	6.79	12.5	11.0	6.26	4.1	1270.0	101.6	22.8	20.2	50.3	6.8	5.4	101.44
02/11/88	7.00	12.0	12.0	6.32	4.6	1329.0	117.2	41.0	16.0	38.4	4.6	6.0	102.49
03/03/88	7.18	12.5	10.0	6.24	5.0	1245.0	86.0	8.8	3.7	69.4	18.1	N.D.	102.01
03/31/88	6.66	12.0	12.0	6.28	3.2	1341.0	91.0	29.9	18.1	52.0	0.0	1.9	102.55
Maximum	7.42	12.5	21.0	6.40	5.0	1341.0	209.4	59.9	27.9	69.4	18.1	37.8	102.88
Minimum	6.66	11.5	8.0	5.47	0.7	786.0	42.6	8.8	3.7	14.7	0.0	N.D.	100.63
Mean	7.02	11.9	14.3	6.18	2.8	1125.9	104.4	45.8	16.6	33.7	4.0	6.1	101.78
Std. Dev.	0.22	0.3	3.9	0.25	1.3	148.2	46.4	15.3	4.7	14.9	4.3	9.0	0.62
C.V.	3.11	2.6	27.2	4.03	47.2	13.2	44.4	33.5	28.4	44.1	107.7	148.3	0.61
						F3 STRIDE							
08/09/87	8.54	12.0	18.0	6.30	6.3	--	224.0	56.6	17.0	25.4	1.0	1.9	--
08/27/87	8.57	12.0	18.0	6.18	2.9	999.0	210.6	57.2	16.3	25.0	1.4	2.0	101.84
09/10/87	8.59	12.0	20.0	6.12	7.3	999.0	242.6	60.9	18.1	21.0	0.0	1.5	101.17
09/24/87	8.59	12.0	17.0	6.24	5.6	829.0	162.6	32.0	10.4	46.8	10.8	N.D.	101.24
10/07/87	8.60	12.0	17.0	6.13	6.4	1030.0	70.6	56.7	25.9	15.9	1.5	4.0	101.84
10/22/87	8.61	11.5	16.0	6.21	5.2	995.0	128.8	60.6	16.0	22.1	1.3	4.0	102.08
11/12/87	8.63	12.0	15.0	6.40	5.0	815.0	133.4	54.7	14.6	27.2	3.5	8.6	101.78
11/26/87	8.06	11.5	12.0	6.21	6.3	1982.0	110.4	58.0	15.4	24.2	2.4	10.0	102.25
12/15/87	7.30	12.0	11.0	5.84	9.1	1091.0	59.6	48.7	17.7	30.0	3.5	3.3	100.80
12/31/87	7.15	12.5	9.0	6.01	6.9	841.0	75.8	52.3	14.6	29.2	3.9	N.D.	101.78
01/14/88	7.14	12.0	10.0	5.92	2.3	497.0	56.4	48.6	13.5	32.7	5.2	1.9	100.53
01/28/88	7.10	12.5	13.0	6.14	7.1	977.0	215.4	25.4	7.9	54.3	12.4	1.3	101.47
02/22/88	6.82	12.5	12.0	6.17	5.6	835.0	62.2	34.5	9.6	46.2	9.7	3.3	102.45
03/03/88	7.53	12.0	12.0	6.32	5.2	600.0	53.8	17.1	4.9	61.8	16.2	N.D.	102.05
03/31/88	7.28	13.0	11.0	6.34	6.9	1018.0	77.8	24.6	12.1	57.5	5.8	2.0	102.59
Maximum	8.63	13.0	20.0	6.40	9.1	1982.0	242.6	60.9	25.9	61.8	16.2	10.0	102.59
Minimum	6.82	11.5	9.0	5.84	2.3	497.0	53.8	17.1	4.9	15.9	0.0	N.D.	100.53
Mean	7.90	12.1	14.1	6.17	5.9	964.9	125.8	45.9	14.3	34.6	5.2	2.9	101.71
Std. Dev.	0.69	0.4	3.3	0.15	1.6	325.8	66.6	14.4	4.8	14.2	4.7	2.8	0.58
C.V.	8.76	3.1	23.4	2.41	27.8	33.8	53.0	31.4	33.8	41.0	89.3	96.5	0.57

APPENDIX D

DATE	W.L. (meters)	TEMP LEACH	TEMP GAS	pH	NH3-N LEACH (mg/L)	SPEC. CONDUCT. (umho/cm)	NH3-N GAS (ppb)	% CH4	% CO2	% N2	% O2	GAS FLOW (L/min)	BARO. PRESS. (KPa)
						F6 STRIDE							
10/22/87	17.10	13.5	20.0	6.11	22.4	2098.0	113.6	22.9	16.3	48.7	12.2	2.4	102.15
11/12/87	16.28	14.0	15.0	6.08	15.3	934.0	245.4	7.6	3.5	70.1	18.8	3.0	101.74
11/26/87	16.10	12.5	10.0	5.35	19.0	1001.0	202.2	0.0	1.1	77.9	21.0	1.5	102.25
12/15/87	15.52	12.5	7.0	5.47	14.6	1066.0	82.2	0.0	0.4	78.2	21.4	1.3	100.77
12/31/87	16.32	10.0	8.0	5.89	15.0	753.0	60.2	0.0	0.0	78.3	21.7	1.1	101.81
01/14/88	16.43	10.0	8.0	5.71	14.8	746.0	35.6	0.0	11.0	78.6	20.4	4.6	100.50
01/28/88	15.75	11.5	10.0	5.88	15.4	839.0	257.4	0.0	1.2	21.1	21.1	2.0	101.54
02/11/88	15.39	11.0	8.0	5.78	20.2	983.0	--	--	--	--	--	--	--
03/03/88	15.68	11.5	10.0	5.85	15.7	829.0	65.2	0.0	0.0	78.6	21.4	N.D.	102.15
Maximum	17.10	14.0	20.0	6.11	22.4	2098.0	257.4	22.9	16.3	78.6	21.7	4.6	102.25
Minimum	15.39	10.0	7.0	5.35	14.6	746.0	35.6	0.0	0.0	21.1	12.2	N.D.	100.50
Mean	16.06	11.8	10.7	5.79	16.9	1027.7	132.8	3.8	4.2	66.4	19.8	2.0	101.61
Std. Dev.	0.51	1.3	4.0	0.24	2.7	392.8	83.2	7.6	5.7	19.7	3.0	1.3	0.61
C.V.	3.16	11.3	37.2	4.11	15.9	38.2	31.3	200.2	136.5	29.6	15.1	65.3	0.61
						F7 STRIDE							
08/27/87	18.05	14.0	18.0	6.25	15.4	1089.0	239.8	53.9	24.4	20.3	1.4	2.4	101.81
09/10/87	18.10	15.0	22.0	6.28	18.8	1055.0	244.4	56.7	22.6	18.5	2.1	3.0	101.24
09/24/87	18.16	14.0	17.0	6.16	14.0	894.0	120.8	--	--	--	--	--	101.27
10/07/87	18.19	12.0	20.0	6.17	13.4	970.0	97.4	62.2	23.1	13.4	1.3	8.6	101.78
10/22/87	18.27	14.0	17.0	6.16	11.6	978.0	179.0	60.9	23.1	14.5	1.5	14.9	102.11
11/12/87	18.25	13.0	17.0	6.37	12.3	845.0	193.8	52.5	25.8	20.2	1.6	24.6	101.74
11/26/87	18.27	13.0	15.0	5.40	10.0	644.0	228.2	44.8	23.2	30.0	2.0	34.0	102.25
12/15/87	17.54	15.0	9.0	6.18	14.0	1362.0	49.2	60.5	23.3	15.6	0.5	6.0	100.73
12/31/87	17.44	14.0	11.0	6.17	14.0	1245.0	42.8	43.2	21.2	31.2	4.5	N.D.	101.78
01/14/88	17.45	15.0	12.0	6.22	13.4	1167.0	43.6	51.4	22.5	26.0	0.0	3.7	100.50
01/28/88	17.08	14.0	12.0	6.31	9.5	1081.0	161.4	49.4	7.7	34.0	8.9	1.6	101.57
02/11/88	17.96	14.0	12.0	6.28	12.9	1301.0	299.4	69.7	10.1	16.3	3.9	7.5	102.45
03/03/88	18.33	14.5	12.0	6.31	35.3	1282.0	69.2	52.5	18.9	22.9	5.7	N.D.	102.11
03/31/88	18.11	14.5	12.0	6.27	20.7	1183.0	39.6	24.9	15.8	49.3	10.0	2.9	102.59
Maximum	18.19	15.0	22.0	6.28	18.8	1089.0	299.4	62.2	24.4	20.3	2.1	8.6	101.81
Minimum	17.08	12.0	9.0	5.40	9.5	644.0	39.6	24.9	7.7	13.4	0.0	N.D.	100.50
Mean	17.94	14.0	14.7	6.19	15.4	1078.3	142.4	52.5	20.1	23.0	3.3	8.4	101.71
Std. Dev.	0.38	0.8	3.7	0.23	6.2	192.3	85.8	10.6	5.4	9.7	3.0	9.9	0.59
C.V.	2.12	5.9	25.1	3.72	40.5	17.8	59.8	20.2	26.7	40.4	90.8	117.7	0.58

APPENDIX D

DATE	W.L. (meters)	TEMP LEACH	TEMP GAS	pH	NH3-N LEACH (mg/L)	SPEC. CONDUCT. (umho/cm)	NH3-N GAS (ppb)	% CH4	% CO2	% N2	% O2	GAS FLOW (L/min)	BARO. PRESS. (KPa)
						FB STRIDE							
08/27/87	—	--	20.0	--	--	--	184.6	52.7	24.6	20.8	1.9	2.6	101.91
09/10/87	—	--	26.0	--	--	--	354.8	57.6	24.7	16.2	1.5	2.3	101.24.
09/24/87	--	--	17.0	--	--	--	219.0	62.0	25.0	12.1	0.9	6.0	101.24
10/07/87	--	--	19.0	--	--	—	159.0	50.5	24.1	22.8	2.5	1.5	101.81
10/22/87	--	--	16.0	--	--	--	67.4	24.1	11.5	52.0	12.3	6.0	102.11
11/12/87	--	--	15.0	--	--	--	176.2	30.0	14.4	47.3	8.3	7.5	101.78
11/26/87	--	--	14.0	--	--	--	122.0	49.7	23.2	24.4	2.7	15.0	102.25
12/15/87	13.71	12.0	9.0	5.56	2.5	858.0	30.0	44.1	37.1	15.6	3.1	8.8	100.66
12/31/87	13.72	12.0	9.0	5.94	5.3	685.0	75.8	65.9	20.8	11.5	1.7	N.D.	101.78
01/14/88	13.69	12.0	8.0	5.97	6.7	740.0	50.8	66.4	26.3	7.3	0.0	15.4	100.50
01/28/88	13.69	12.0	11.0	5.86	2.8	763.0	188.4	54.3	20.9	19.9	4.9	4.3	101.64
02/11/88	13.94	10.0	9.0	5.65	2.5	610.0	71.2	60.7	14.1	20.5	4.8	8.6	102.45
03/03/88	14.00	12.0	11.0	5.78	2.0	557.0	69.8	--	--	--	--	N.D.	102.05
03/31/88	14.05	10.0	11.0	5.98	2.2	667.0	71.4	30.6	14.7	46.2	8.5	3.7	102.59
Maximum	14.05	12.0	26.0	5.98	6.7	858.0	354.8	66.4	37.1	52.0	12.3	15.4	102.60
Minimum	13.69	10.0	0.0	5.56	2.0	557.0	30.0	24.1	11.5	7.3	0.0	N.D.	100.50
Mean	13.83	11.4	10.8	5.82	3.4	697.1	131.4	49.9	21.6	24.4	4.1	5.8	101.70
Std.Dev.	0.15	0.9	7.3	0.15	1.7	92.8	85.2	13.4	6.6	14.1	3.5	4.7	0.60
C.V.	1.08	7.9	67.4	2.62	49.1	13.3	64.8	26.9	30.6	57.8	85.4	81.0	59.77
						10B STRIDE							
08/09/87	8.44	14.0	20.0	6.20	1.0	—	254.8	13.9	34.2	50.7	1.2	2.0	--
08/27/87	8.63	14.0	20.0	6.04	1.0	1377.0	278.8	17.7	29.7	49.9	2.6	N.D.	101.68
09/10/87	8.68	13.0	25.0	6.00	2.7	1465.0	283.0	19.3	29.8	47.7	3.2	1.0	101.10
09/24/87	8.79	13.0	19.0	6.14	1.0	1152.0	98.0	15.8	28.9	53.3	1.9	2.4	101.27
10/07/87	8.84	13.0	24.0	5.98	1.8	1463.0	112.0	22.4	31.0	43.9	2.7	2.0	101.74
Maximum	8.84	14.0	25.0	6.20	2.7	1465.0	70.8	22.4	34.2	53.3	3.2	2.4	101.74
Minimum	8.44	13.0	19.0	5.98	1.0	1152.0	24.5	13.9	28.9	43.9	1.2	N.D.	101.10
Mean	8.68	13.4	21.6	6.07	1.5	1364.3	51.4	17.8	30.7	49.1	2.3	1.5	101.45
Std. Dev.	0.14	0.5	2.4	0.08	0.7	127.6	20.7	2.9	1.9	3.2	0.7	0.9	0.27
C.V.	1.61	3.7	11.2	1.39	45.0	9.4	40.2	16.4	6.1	6.4	30.0	59.0	0.27

APPENDIX D

DATE	W.L. (meters)	TEMP LEACH	TEMP GAS	pH	NH3-N LEACH (mg/L)	SPEC. CONDUCT. (umho/cm)	NH3-N GAS (ppb)	% CH4	% CO2	% N2	% O2	GAS FLOW (L/min)	BARO. PRESS. (KPa)
							B8 RICHMOND						
08/14/87	3.36	19.0	23.0	6.36	100.8	--	33.0	55.0	41.9	2.8	0.3	6.0	--
09/01/87	3.47	20.0	29.0	6.40	122.1	3301.0	253.4	56.3	43.7	0.0	0.0	21.3	102.25
09/15/87	3.57	19.0	21.0	6.62	152.3	3865.0	75.4	53.8	42.0	3.4	0.9	15.1	101.84
09/29/87	3.51	20.0	24.0	6.51	153.4	3930.0	231.8	54.9	42.5	2.0	0.6	9.5	102.22
10/13/87	3.54	19.0	23.0	6.52	182.6	4798.0	102.8	53.5	42.1	3.5	0.9	10.9	101.91
11/03/87	3.55	20.0	18.0	6.83	183.7	4412.0	129.0	46.4	37.9	12.3	3.4	6.0	102.15
11/17/87	3.48	18.5	17.0	6.32	67.2	2630.0	N.D.	52.7	40.6	5.2	1.4	5.0	101.54
12/01/87	3.33	16.5	14.0	5.73	43.7	2109.0	N.D.	47.1	38.6	11.0	3.2	18.1	100.86
12/24/87	3.50	14.5	12.0	5.97	39.2	1712.0	29.2	43.1	34.7	17.3	4.9	58.6	102.05
01/06/88	3.26	15.0	9.0	6.08	46.1	1528.0	30.2	46.5	37.0	12.9	3.7	45.9	102.32
01/19/88	3.01	14.0	7.0	6.07	37.8	1370.0	36.4	50.4	39.3	8.2	2.1	27.4	101.98
02/02/88	2.88	10.5	7.0	6.16	58.2	1755.0	24.2	40.3	33.5	20.5	5.8	25.7	102.32
02/24/88	3.11	13.0	15.0	5.70	19.0	600.0	61.8	56.6	43.4	Tr	0.0	38.6	102.59
03/15/88	3.28	14.0	16.0	5.84	18.5	929.0	335.0	48.4	37.2	11.2	3.2	73.9	102.79
04/05/88	2.82	11.5	10.0	5.89	15.4	1105.0	19.6	50.7	40.6	8.8	0.0	56.6	102.11
Maximum	3.57	20.0	29.0	6.83	183.7	4798.0	335.0	56.6	43.7	20.5	5.8	73.9	102.79
Minimum	2.82	10.5	7.0	5.70	15.4	600.0	N.D.	40.3	33.5	0.0	0.0	5.0	100.86
Mean	3.31	16.3	16.3	6.20	82.7	2431.1	90.8	50.4	39.7	7.9	2.0	27.9	102.07
Std. Dev.	0.24	3.2	6.5	0.33	59.0	1336.8	99.4	4.8	3.0	6.0	1.8	21.2	0.45
C.V.	7.27	19.5	39.6	5.32	71.4	55.0	109.6	9.5	7.6	75.9	90.3	76.0	0.44
							D9 RICHMOND						
08/14/87	5.09	27.0	27.0	6.73	442.4	--	23.8	52.4	42.2	3.9	1.5	94.4	--
09/01/87	4.83	27.0	32.0	6.80	378.0	8347.0	280.2	52.4	41.8	4.5	1.2	106.2	102.28
09/15/87	4.40	26.0	25.0	6.72	411.6	8679.0	79.0	52.8	42.0	4.1	1.1	89.4	101.88
09/29/87	4.85	27.0	29.0	6.83	397.6	8135.0	118.6	51.9	41.2	5.5	1.5	94.4	102.28
10/13/87	4.93	26.0	31.0	7.57	406.0	7785.0	35.8	56.1	43.9	0.0	0.0	49.2	101.94
11/03/87	4.85	28.0	26.0	7.10	394.8	6566.0	72.6	44.5	36.9	14.6	4.0	73.9	102.11
11/17/87	4.99	28.0	27.0	6.86	318.2	5949.0	170.6	51.0	41.0	6.3	1.7	121.4	101.57
12/01/87	5.01	27.5	20.0	6.33	137.2	3229.0	N.D.	51.5	42.0	5.0	1.5	183.7	100.86
12/24/88	4.22	26.0	22.0	5.48	41.4	1251.0	39.8	48.0	37.2	11.6	3.3	141.6	102.05
01/06/88	4.31	26.0	22.0	6.72	327.6	5893.0	11.8	44.7	34.5	16.1	4.7	144.0	102.28
01/19/88	3.92	23.0	16.0	6.21	123.2	2673.0	44.6	52.5	39.0	6.7	1.7	94.4	102.08
02/02/88	3.92	24.0	17.0	6.81	425.6	7493.0	34.4	48.7	36.6	11.7	3.0	149.0	102.32
02/24/88	3.52	24.5	19.0	6.84	459.2	7980.0	N.D.	57.3	42.7	Tr	0.0	147.8	102.59
03/15/88	3.99	25.0	21.0	6.98	596.4	10493.0	205.8	49.1	35.8	11.9	3.1	174.3	102.92
04/05/88	3.19	20.0	16.0	6.64	232.4	5361.0	N.D.	44.8	34.7	16.2	4.3	163.4	102.11
Maximum	5.09	28.0	32.0	7.57	596.4	10493.0	280.2	57.3	43.9	16.2	4.7	183.7	102.92
Minimum	3.19	20.0	16.0	5.48	41.4	1251.0	N.D.	44.5	34.5	0.0	0.0	49.2	100.86
Mean	4.40	25.7	23.3	6.71	339.4	6415.7	74.4	50.5	39.4	7.9	2.2	121.8	102.09
Std. Dev.	0.58	2.1	5.1	0.44	142.5	2483.9	81.4	3.7	3.1	5.2	1.4	38.1	0.46
C.V.	13.08	8.0	21.8	6.61	42.0	38.7	109.2	7.4	7.8	66.4	65.5	31.2	0.45

APPENDIX D

DATE	W.L. (meters)	TEMP LEACH	TEMP GAS	pH	NH3-N LEACH (mg/L)	SPEC. CONDUCT. (umho/cm)	NH3-N GAS (ppb)	% CH4	% CO2	% N2	% O2	GAS FLOW (L/min)	BARO. PRESS. (KPa)
						C6 RICHMOND							
08/14/87	2.14	23.0	24.0	6.39	33.6	--	N.D.	54.2	42.5	2.6	0.7	130.7	--
09/01/87	2.07	24.0	26.0	6.42	23.5	2732.0	141.0	53.0	42.6	3.5	0.9	194.2	102.28
09/15/87	2.13	23.0	23.0	6.65	24.6	2826.0	77.6	55.4	44.6	0.0	0.0	44.7	101.88
09/29/87	2.22	23.0	26.0	6.23	8.4	2695.0	266.2	54.1	42.6	2.6	0.7	94.4	102.38
10/13/87	2.50	25.0	25.0	6.01	14.0	2982.0	119.2	55.8	44.2	0.0	0.0	58.6	101.84
11/03/87	2.69	24.0	24.0	6.43	33.9	2740.0	74.8	50.3	40.4	7.3	2.0	85.0	102.08
11/17/87	2.37	24.0	23.0	5.78	5.0	1633.0	73.4	53.0	41.2	4.5	1.2	169.9	101.61
12/01/87	2.04	18.5	25.0	5.90	8.4	1927.0	N.D.	50.5	39.6	7.6	2.3	51.5	100.83
12/24/87	2.23	14.5	9.0	6.28	9.0	1772.0	14.4	49.8	38.7	8.9	2.7	20.0	102.05
01/06/88	3.10	14.0	12.0	6.11	8.1	1544.0	11.4	47.7	35.9	12.9	3.5	18.5	102.25
01/19/88	2.26	16.0	12.0	6.24	9.5	1658.0	62.6	44.2	34.7	17.1	4.0	25.7	102.05
02/02/88	2.31	15.0	12.0	6.17	16.8	2177.0	14.8	44.2	34.5	16.9	4.4	236.0	102.29
02/24/88	2.48	15.0	17.0	6.24	16.8	1850.0	40.6	57.2	42.8	Tr	0.0	195.4	102.72
03/15/88	2.46	21.0	17.0	6.08	18.5	2268.0	119.0	57.2	42.8	Tr	0.0	288.0	102.96
04/05/88	2.69	16.0	12.0	5.70	9.8	2287.0	14.2	53.6	39.7	5.4	1.3	278.6	102.01
Maximum	3.10	25.0	26.0	6.65	33.9	2982.0	266.2	57.2	44.6	17.1	4.4	288.0	102.96
Minimum	2.04	14.0	9.0	5.70	5.0	1544.0	N.D.	44.2	34.5	0.0	0.0	18.5	100.83
Mean	2.38	19.7	19.1	6.18	16.0	2220.8	68.6	52.0	40.5	6.0	1.6	126.1	102.09
Std. Dev.	0.28	4.1	6.1	0.25	8.9	482.2	69.2	4.0	3.2	5.6	1.5	91.4	0.48
C.V.	11.59	20.7	31.8	4.00	55.9	21.7	100.8	7.8	7.8	94.8	92.0	72.5	0.47
						G7 RICHMOND							
08/14/87	3.96	21.0	23.0	6.58	44.8	--	156.6	53.2	40.2	6.0	1.6	10.5	--
09/01/87	4.05	22.0	29.0	6.48	73.9	3426.0	271.2	52.6	41.9	4.3	1.1	21.3	102.32
09/15/87	4.27	21.0	27.0	6.41	128.8	3810.0	80.4	56.6	43.4	0.0	0.0	4.0	101.88
09/29/87	4.27	22.0	25.0	6.53	123.2	3756.0	173.2	55.6	42.0	1.9	0.5	12.0	102.49
10/13/87	4.28	23.0	25.0	6.47	123.2	4023.0	124.8	52.6	40.7	5.6	1.5	8.6	101.88
11/03/87	4.41	22.0	23.0	6.64	166.9	4068.0	74.4	49.6	38.5	9.3	2.6	12.0	102.08
11/17/87	4.43	23.0	17.0	6.52	168.0	4166.0	18.8	47.4	38.0	11.5	3.1	25.7	101.57
12/01/87	4.20	19.5	14.0	6.12	52.6	2514.0	N.D.	49.4	38.2	9.6	2.8	12.0	100.86
12/24/87	4.15	15.0	8.0	6.13	14.6	1397.0	10.6	46.7	35.5	14.1	3.7	2.2	102.05
01/06/88	4.12	21.0	14.0	6.13	29.1	1460.0	25.2	46.0	38.2	12.4	3.4	12.0	102.22
01/19/88	4.10	20.0	14.0	6.02	28.0	1313.0	20.0	48.9	38.2	18.8	4.3	4.3	102.18
02/02/88	4.10	18.0	12.0	6.11	25.8	1835.0	N.D.	45.1	35.0	16.0	4.0	22.0	102.32
02/24/88	3.93	20.0	12.0	6.08	21.3	1152.0	--	45.2	34.5	16.3	4.0	8.6	102.65
03/15/88	3.55	20.0	16.0	6.03	26.9	1621.0	186.4	51.7	38.6	7.7	1.9	27.0	102.96
04/05/88	3.64	13.5	11.0	5.92	3.4	657.0	N.D.	--	--	--	--	2.4	101.98
Maximum	4.43	23.0	29.0	6.64	168.0	4166.0	271.2	56.6	43.4	18.8	4.3	27.0	102.96
Minimum	3.55	13.5	8.0	5.92	3.4	657.0	N.D.	45.1	34.5	0.0	0.0	2.2	100.86
Mean	4.10	20.1	18.0	6.28	68.7	2514.1	76.2	50.0	38.8	9.5	2.5	12.3	102.10
Std. Dev.	0.24	2.6	6.4	0.24	55.5	1248.9	83.6	3.6	2.6	5.4	1.3	7.9	0.48
C.V.	5.89	13.1	35.8	3.75	80.8	49.7	109.9	7.2	6.6	57.1	54.0	64.1	0.47

APPENDIX D

DATE	W.L. (meters)	TEMP LEACH	TEMP GAS	pH	NH3-N LEACH (mg/L)	SPEC. CONDUCT. (umho/cm)	NH3-N GAS (ppb)	% CH4	% CO2	% N2	% O2	GAS FLOW (L/min)	BARO. PRESS. (KPa)
						D.55 RICHMOND							
08/14/87	3.41	23.0	25.0	6.71	117.6	--	47.2	53.8	42.1	4.0	0.0	15.0	-
09/01/87	3.58	24.0	29.0	6.74	113.1	4243.0	156.8	53.6	40.3	4.8	1.3	35.4	102.15
09/15/87	3.75	24.0	26.0	6.50	134.4	4397.0	N.D.	57.2	42.8	0.0	0.0	85.0	102.11
09/29/87	3.82	25.0	29.0	6.54	121.0	4295.0	85.2	52.4	39.6	6.3	1.7	20.0	102.32
10/13/87	3.86	25.0	28.0	6.56	122.1	4579.0	101.8	54.2	41.7	4.0	0.0	12.0	102.00
11/03/87	4.08	25.0	22.0	6.72	114.2	4046.0	125.6	52.2	40.1	6.1	1.7	12.0	102.08
11/17/87	4.11	25.0	18.0	6.61	91.8	4219.0	19.4	50.7	39.2	7.9	2.2	35.4	101.57
12/01/87	3.60	20.0	16.0	6.62	110.9	3915.0	N.D.	53.8	41.3	3.8	1.2	15.0	100.89
12/24/87	3.01	21.0	12.0	6.68	81.8	3426.0	14.6	54.4	39.6	4.6	1.4	15.0	102.05
01/06/88	3.30	22.5	16.0	6.64	119.8	3776.0	36.6	42.4	41.1	13.1	3.3	8.6	102.22
01/19/88	3.26	21.0	14.0	6.55	113.1	3735.0	77.4	41.2	38.9	15.9	4.0	10.0	102.24
02/02/88	3.12	19.0	17.0	6.40	101.9	3965.0	29.2	43.7	37.7	14.9	4.7	15.0	102.29
02/24/88	3.00	21.0	19.0	6.62	87.4	3067.0	--	--	--	--	--	7.5	102.72
03/15/88	2.97	19.0	15.0	6.38	98.6	3496.0	74.2	56.8	41.1	2.1	0.0	47.2	102.92
04/05/88	2.99	15.5	12.0	6.14	26.3	1359.0	93.8	53.9	39.6	5.2	1.3	5.0	102.01
Maximum	4.11	25.0	29.0	6.74	134.4	4579.0	156.8	57.2	42.8	15.9	4.7	85.0	102.92
Minimum	2.97	15.5	12.0	6.14	26.3	1359.0	N.D.	41.2	37.7	0.0	0.0	5.0	100.89
Mean	3.46	22.0	19.9	6.56	103.6	3751.3	57.4	51.5	40.4	6.6	1.6	22.5	102.11
Std. Dev.	0.39	2.7	5.9	0.15	24.9	773.7	47.4	13.7	10.2	4.7	1.5	20.3	0.46
C.V.	11.26	12.4	29.8	2.33	24.0	20.6	82.6	28.5	26.9	76.5	95.7	90.1	0.45
						B.53 RICHMOND							
08/14/87	2.52	24.0	27.0	6.68	145.6	--	22.2	44.6	46.4	7.2	1.8	23.0	--
09/01/87	2.26	24.0	33.0	6.58	121.0	3432.0	203.8	49.5	39.8	8.4	2.3	18.9	102.11
09/15/87	2.43	25.0	27.0	6.56	145.6	3800.0	N.D.	50.9	40.8	6.6	1.8	13.6	102.11
09/29/87	2.23	25.0	28.0	6.49	112.0	3362.0	N.D.	55.0	42.5	1.9	0.5	12.1	102.32
10/13/87	2.40	24.0	27.0	6.30	98.6	3400.0	171.2	54.1	43.3	2.7	0.0	8.8	101.84
11/03/87	2.22	26.0	23.0	6.48	73.9	2620.0	29.6	52.8	41.2	4.7	1.3	7.0	102.05
11/17/87	2.33	25.0	20.0	6.45	108.6	2973.0	52.4	52.0	40.4	6.0	1.6	7.9	101.61
12/01/87	1.79	23.0	15.0	6.34	57.1	2410.0	N.D.	48.4	38.0	10.5	3.1	8.6	100.89
12/24/87	1.71	18.0	8.0	6.44	34.7	1972.0	20.4	21.1	14.8	50.2	13.9	1.7	102.05
01/06/88	2.70	18.0	10.0	6.38	43.7	1779.0	38.2	14.7	11.3	59.1	14.9	N.D.	102.18
01/19/88	2.68	14.0	14.0	6.33	48.2	1586.0	31.4	12.6	9.9	64.5	13.0	2.0	102.35
02/02/88	1.79	16.0	10.0	6.22	22.4	1394.0	17.0	Tr	2.2	77.9	19.9	1.5	102.25
02/24/88	2.06	17.5	14.0	6.46	7.8	654.0	--	0.0	0.0	78.5	21.5	N.D.	102.75
03/15/88	1.56	17.0	17.0	6.22	6.2	845.0	58.6	0.0	6.4	73.5	20.0	N.D.	102.92
04/05/88	1.67	14.5	8.0	6.20	3.6	821.0	--	--	--	--	--	--	--
Maximum	2.70	26.0	33.0	6.68	145.6	3800.0	203.8	55.0	46.4	78.5	21.5	23.0	102.92
Minimum	1.56	14.0	8.0	6.20	3.6	654.0	N.D.	0.0	0.0	1.9	0.0	N.D.	100.89
Mean	2.16	20.7	18.7	6.41	68.6	2217.7	46.0	32.6	26.9	32.3	8.3	7.5	102.11
Std. Dev.	0.36	4.2	8.0	0.14	48.5	1037.4	60.8	22.0	17.3	31.1	8.1	7.1	0.48
C.V.	16.74	20.3	42.7	2.14	70.7	46.8	132.1	67.7	64.3	96.5	97.8	94.2	0.47

APPENDIX D

DATE	W.L. (meters)	TEMP LEACH	TEMP GAS	pH	NH3-N LEACH (mg/L)	SPEC. CONDUCT. (umho/cm)	NH3-N GAS (ppb)	% CH4	% CO2	% N2	% O2	GAS FLOW (L/min)	BARO. PRESS. (KPa)
						P1 PREMIER							
08/20/87	13.48	22.0	23.0	6.72	213.9	6683.0	96.4	25.0	17.1	45.3	12.6	0.6	101.64
09/03/87	13.47	23.0	20.0	6.80	254.8	6512.0	81.6	28.9	21.5	39.4	10.2	0.6	102.43
09/17/87	13.48	24.0	20.0	6.47	285.6	6409.0	184.6	13.6	11.8	58.4	16.2	2.4	102.25
10/01/87	14.13	22.0	21.0	6.54	238.6	6264.0	111.4	33.1	24.9	33.5	8.6	3.0	101.78
10/15/87	14.28	22.0	18.0	6.57	233.3	6460.0	75.4	27.0	20.0	41.6	11.4	3.0	102.42
11/05/87	14.07	22.5	17.0	6.61	218.4	6537.0	141.6	30.3	22.3	37.1	10.2	2.4	101.78
11/19/87	13.82	22.0	15.0	6.48	212.8	6069.0	84.2	24.4	17.7	45.3	12.8	2.4	101.98
12/03/87	14.33	21.0	14.0	6.63	208.3	5470.0	17.8	7.2	6.4	67.9	18.8	1.3	100.83
12/22/87	13.40	21.5	10.0	6.72	235.2	6601.0	42.8	20.6	15.1	50.5	13.8	2.1	101.71
01/05/88	13.44	21.0	12.0	6.81	231.5	5622.0	63.8	12.1	10.5	60.5	16.9	1.3	101.84
01/20/88	13.70	22.5	11.0	6.69	246.4	5890.0	45.2	Tr	9.9	70.7	19.4	0.9	102.25
02/04/88	13.34	22.0	15.0	6.67	254.2	5915.0	58.8	4.7	3.9	72.5	18.6	3.3	103.00
02/23/88	13.32	22.5	12.0	6.56	246.4	5188.0	134.4	10.6	7.6	64.1	17.7	2.0	102.55
03/17/88	13.12	23.0	17.0	6.60	255.7	6063.0	82.8	18.0	13.3	54.2	14.4	1.5	102.86
04/07/88	13.34	22.0	12.0	6.54	175.5	5125.0	45.4	0.0	0.9	77.7	21.4	1.2	102.59
Maximum	14.33	24.0	23.0	6.81	285.6	6683.0	184.6	33.1	24.9	77.7	21.4	3.3	103.00
Minimum	13.12	21.0	10.0	6.47	175.5	5125.0	17.8	0.0	0.9	33.5	8.6	0.6	100.83
Mean	13.65	22.2	15.8	6.63	234.0	6053.9	84.4	17.0	13.5	54.6	14.9	1.9	102.13
Std. Dev.	0.37	0.7	3.9	0.10	25.2	494.0	42.4	10.7	6.9	13.6	3.8	0.9	0.54
C.V.	2.73	3.4	24.6	1.54	10.7	8.2	50.3	62.7	50.8	24.9	25.3	45.7	0.53
						P2 PREMIER							
08/20/87	11.04	23.0	20.0	6.74	221.8	6411.0	145.0	61.7	38.3	0.0	0.0	1.4	102.01
09/03/87	11.07	24.0	21.0	6.79	249.2	6350.0	86.0	58.8	36.9	3.4	0.9	1.4	102.35
09/17/87	11.19	25.0	23.0	6.54	280.0	6193.0	174.6	50.5	32.1	13.6	3.8	3.0	102.18
10/01/87	11.33	24.0	22.0	6.68	236.3	6180.0	N.D.	58.8	37.7	2.8	0.8	6.0	101.98
10/15/87	12.55	24.0	19.0	6.61	237.1	6467.0	112.4	52.4	34.2	10.4	2.9	5.0	102.52
11/05/87	11.94	24.0	21.0	6.63	234.1	6413.0	191.0	52.7	35.1	9.5	2.6	8.6	101.81
11/19/87	11.46	23.5	18.0	6.47	227.4	5633.0	48.4	35.5	23.5	32.1	8.9	3.3	101.98
12/03/87	10.68	21.0	13.0	6.60	173.6	4544.0	74.0	3.9	2.6	73.1	20.3	2.1	100.83
12/22/87	10.79	20.5	10.0	6.72	212.8	6601.0	44.2	20.7	13.8	51.5	14.0	1.5	101.71
01/05/88	10.04	23.0	15.0	6.76	201.6	4860.0	143.6	7.5	5.1	68.6	18.9	1.7	101.88
01/20/88	10.37	22.0	15.0	6.67	213.9	4873.0	32.2	Tr	4.2	75.2	20.6	1.3	102.15
02/04/88	10.28	22.0	12.0	6.75	231.8	5459.0	46.8	7.4	7.0	69.2	16.4	2.7	103.03
02/23/88	9.78	21.5	14.0	6.67	182.9	4009.0	43.0	Tr	13.5	68.1	18.5	3.3	102.59
03/17/88	9.79	22.0	15.0	6.66	242.7	5133.0	104.6	Tr	8.1	72.2	19.6	2.0	102.96
04/07/88	9.58	20.0	12.0	6.51	113.9	3743.0	29.6	Tr	2.0	76.8	21.2	1.7	102.59
Maximum	12.55	25.0	23.0	6.79	280.0	6601.0	191.0	61.7	38.3	76.8	21.2	8.6	103.03
Minimum	9.58	20.0	10.0	6.47	113.9	3743.0	N.D.	Tr	2.0	0.0	0.0	1.3	100.83
Mean	10.79	22.6	16.7	6.65	217.3	5524.6	85.0	27.3	19.6	41.8	11.3	3.0	102.17
Std. Dev.	0.81	1.4	4.0	0.09	37.4	918.2	56.0	25.0	14.2	30.7	8.3	2.0	0.53
C.V.	7.55	6.3	24.1	1.37	17.2	16.6	65.7	91.7	72.2	73.6	73.4	66.7	0.52

APPENDIX E - TABLES OF VARIABLES CALCULATED OR ESTIMATED
FROM BASIC DATA

DATE	N2/O2 RATIO	CH4 FLUX (kg CH4/ day-cm2)	CO2 FLUX (kg CO2/ day-cm2)	GAS DENSITY (kg/m3)	IONIC STRENGTH	ACTIVITY COEFF. gamma	pKa	pK1	pKw	NH3-N (molar W/ gamma)	NH3-N GAMMA (ug/L)
					F1 MATSQUI						
08/05/87	10.62	2.4132	5.6390	1.281	--	--	--	--	--	--	--
08/25/87	10.92	5.9866	12.2826	1.247	--	--	--	--	--	--	--
09/08/87	10.86	4.8962	10.7100	1.262	--	--	--	--	--	--	--
09/22/87	10.70	4.9803	11.3468	1.273	--	--	--	--	--	--	--
10/06/87	15.82	3.5527	8.3534	1.278	--	--	--	--	--	--	--
10/20/87	12.18	2.9773	6.8552	1.273	--	--	--	--	--	--	--
11/10/87	9.81	3.5430	8.3634	1.278	--	--	--	--	--	--	--
11/24/87	3.92	4.1266	9.1664	1.271	--	--	--	--	--	--	--
12/08/87	4.57	1.5385	3.2180	1.258	--	--	--	--	--	--	--
12/29/87	3.75	1.2970	2.5868	1.241	--	--	--	--	--	--	--
01/12/88	8.86	1.8128	5.4996	1.329	0.3846	0.64	9.84	4.87	14.71	4.95E-05	843.4
01/26/88	9.13	4.0341	11.6714	1.322	0.3392	0.65	9.70	4.86	14.56	4.95E-05	843.5
02/09/88	4.49	2.2008	4.3601	1.243	0.3608	0.64	9.72	4.86	14.58	3.83E-05	653.5
03/01/88	8.24	1.4104	2.6823	1.229	0.2606	0.68	9.60	4.86	14.46	3.66E-05	623.4
03/29/88	6.64	0.5491	1.1397	1.255	0.2564	0.68	9.70	4.86	14.56	2.45E-05	417.3
					F2 MATSQUI						
08/05/87	9.84	2.3305	5.7779	1.288	0.0640	0.79	9.50	4.85	14.35	8.33E-05	1419.7
08/25/87	38.67	3.3734	10.7900	1.948	0.0582	0.80	9.50	4.85	14.35	6.57E-05	1119.3
09/08/87	17.60	3.0726	9.4654	1.317	0.0544	0.80	9.47	4.85	14.32	8.95E-05	1524.6
09/22/87	33.50	3.9670	11.4527	1.310	0.0491	0.81	9.50	4.85	14.35	9.10E-05	1551.0
10/06/87	38.09	4.4313	13.1316	1.311	0.0578	0.80	9.47	4.85	14.32	1.14E-04	1940.5
10/20/87	59.86	3.5811	10.8311	1.315	0.0540	0.80	9.50	4.85	14.35	1.17E-04	1998.9
11/10/87	19.45	3.7221	11.2235	1.314	0.0539	0.80	9.54	4.85	14.39	1.46E-04	2491.3
11/24/87	12.49	3.1797	10.1509	1.322	0.0512	0.80	9.54	4.85	14.39	4.24E-04	7229.3
12/08/87	12.69	2.5878	7.6950	1.311	0.0384	0.82	9.70	4.86	14.56	4.25E-06	72.4
12/29/87	13.74	2.2630	6.2768	1.301	0.0434	0.82	9.70	4.86	14.56	4.17E-05	710.0
01/12/88	12.79	2.5750	7.7794	1.310	0.0280	0.84	9.81	4.86	14.67	1.13E-05	192.9
01/26/88	11.23	3.2884	10.0229	1.312	0.0173	0.87	9.64	4.86	14.49	1.83E-06	31.2
02/09/88	14.50	1.7290	5.5165	1.320	0.0179	0.87	9.59	4.86	14.44	7.48E-07	12.7
03/01/88	15.37	2.1516	6.4609	1.310	0.0472	0.81	9.64	4.86	14.49	3.78E-05	643.5
03/29/88	14.15	3.5634	7.6946	1.259	0.0223	0.86	9.64	4.86	14.49	2.04E-05	347.9

APPENDIX E

DATE	N2/O2 RATIO	CH4 FLUX (kg CH4/ day-cm2)	CO2 FLUX (kg CO2/ day-cm2)	GAS DENSITY (kg/m3)	IONIC STRENGTH	ACTIVITY COEFF. gamma	pKa	pK1	pKw	NH3-N (molar W/ gamma)	NH3-N GAMMA (ug/L)

F3 MATSQUI

08/05/87	6.54	10.0341	16.4176	1.185	--	--	--	--	--	--	--
08/25/87	12.94	10.8426	22.8999	1.254	--	--	--	--	--	--	--
09/08/87	13.89	11.6540	22.5291	1.230	--	--	--	--	--	--	--
09/22/87	9.58	13.4525	25.6523	1.226	--	--	--	--	--	--	--
10/06/87	19.75	13.5262	27.2305	1.240	--	--	--	--	--	--	--
10/20/87	10.67	10.4762	21.4898	1.247	--	--	--	--	--	--	--
11/10/87	8.47	12.1526	24.5528	1.240	--	--	--	--	--	--	--
11/24/87	11.00	11.0818	23.1808	1.252	--	--	--	--	--	--	--
12/08/87	7.11	8.8697	17.4326	1.239	0.0544	0.80	9.74	4.86	14.60	3.36E-05	572.7
12/29/87	6.84	7.9866	14.6359	1.221	0.0497	0.81	9.74	4.86	14.60	1.97E-05	336.2
01/12/88	6.83	9.8026	20.8939	1.258	0.0329	0.83	9.74	4.86	14.60	1.15E-05	195.4
01/26/88	4.60	13.5229	24.0213	1.218	0.0266	0.85	9.60	4.86	14.46	7.94E-06	135.4
02/09/88	8.98	2.2782	6.0200	1.292	0.0269	0.85	9.60	4.86	14.46	2.71E-06	46.2
03/01/88	4.88	9.4767	16.0242	1.200	0.0221	0.86	9.50	4.85	14.35	1.14E-06	19.4
03/29/88	10.04	9.0361	16.3960	1.221	0.0208	0.86	9.64	4.86	14.49	2.43E-06	41.4

F4 MATSQUI

08/05/87	--	4.2073	7.5106	1.203	--	--	--	--	--	--	--
08/25/87	8.50	7.9501	14.9377	1.225	--	--	--	--	--	--	--
09/08/87	3.75	7.8669	12.9114	1.183	--	--	--	--	--	--	--
09/22/87	4.88	8.6947	14.3266	1.184	--	--	--	--	--	--	--
10/06/87	--	7.6412	15.1786	1.235	--	--	--	--	--	--	--
10/20/87	16.25	5.5380	11.2325	1.241	--	--	--	--	--	--	--
11/10/87	8.29	5.7324	12.2344	1.258	--	--	--	--	--	--	--
11/24/87	7.37	4.8311	10.5278	1.264	--	--	--	--	--	--	--
12/08/87	7.45	2.9892	7.1125	1.285	--	--	--	--	--	--	--
12/29/87	9.90	4.0067	7.6979	1.228	--	--	--	--	--	--	--
01/12/88	12.00	6.8247	12.3824	1.215	--	--	--	--	--	--	--
01/26/88	6.53	6.9729	13.2046	1.226	--	--	--	--	--	--	--
02/09/88	--	--	--	--	--	--	--	--	--	--	--
03/01/88	6.11	1.0880	2.1201	1.237	--	--	--	--	--	--	--
03/29/88	4.86	2.1121	4.0369	1.234	--	--	--	--	--	--	--

APPENDIX E

DATE	N2/O2 RATIO	CH4 FLUX (kg CH4/ day-cm2)	CO2 FLUX (kg CO2/ day-cm2)	GAS DENSITY (kg/m3)	IONIC STRENGTH	ACTIVITY COEFF. gamma	pKa	pK1	pKw	NH3-N (molar W/ gamma)	NH3-N GAMMA (ug/L)
						F5 MATSQUI					
08/05/87	24.00	2.4950	5.9775	1.281	0.1920	0.70	9.50	4.85	14.35	4.53E-05	771.4
08/25/87	--	2.0322	4.2226	1.247	0.3506	0.65	9.47	4.85	14.32	1.79E-04	3045.0
09/08/87	--	1.9744	4.1025	1.247	0.2960	0.66	9.50	4.85	14.35	1.89E-04	3228.2
09/22/85	--	2.5079	5.1898	1.245	0.2807	0.67	9.50	4.85	14.35	1.26E-04	2139.7
10/06/87	3.92	4.1188	8.4110	1.245	0.3073	0.66	9.47	4.85	14.32	2.10E-04	3581.4
10/20/87	11.75	2.4347	4.0707	1.185	0.3020	0.66	9.50	4.85	14.35	1.63E-04	2779.2
11/10/87	3.43	4.7518	9.3998	1.234	0.0954	0.76	9.57	4.85	14.42	3.46E-05	589.2
11/24/87	3.57	--	--	1.252	0.0465	0.81	9.60	4.86	14.46	5.29E-07	9.0
12/08/87	4.80	0.8104	1.7367	1.259	0.0512	0.80	9.60	4.86	14.46	1.04E-06	17.7
12/29/87	3.54	1.1131	2.0447	1.213	0.2359	0.68	9.60	4.86	14.46	7.66E-05	1305.6
01/12/88	4.26	4.1885	7.5049	1.214	0.3061	0.66	9.62	4.86	14.48	1.49E-04	2537.8
01/26/88	3.50	5.7427	10.1948	1.208	0.0705	0.78	9.59	4.86	14.44	5.94E-06	101.3
02/09/88	--	--	--	--	0.0458	0.81	9.67	4.86	14.53	5.12E-06	87.3
03/01/88	3.80	0.0000	0.0000	1.323	0.1569	0.72	9.57	4.85	14.42	3.87E-05	660.2
03/29/88	--	--	--	--	0.1028	0.75	9.60	4.86	14.46	1.40E-05	237.9
						F6 MATSQUI					
08/05/87	3.89	0.3332	0.5921	1.236	--	--	--	--	--	--	--
08/25/87	--	--	--	--	--	--	--	--	--	--	--
09/08/87	3.74	0.0000	0.0000	1.235	--	--	--	--	--	--	--
09/22/85	3.49	0.0000	0.0000	1.262	--	--	--	--	--	--	--
10/06/87	4.50	2.9992	5.3732	1.207	--	--	--	--	--	--	--
10/20/87	4.42	1.2877	2.3236	1.209	--	--	--	--	--	--	--
11/10/87	3.89	1.8955	3.5562	1.221	--	--	--	--	--	--	--
						F8 MATSQUI					
11/10/87	4.35	0.0949	0.2167	1.279	0.0138	0.88	9.50	4.85	14.35	4.48E-09	0.1
11/24/87	4.15	1.5534	3.4350	1.275	0.0047	0.93	9.57	4.85	14.42	8.26E-10	0.0
12/08/87	4.85	0.2045	0.5474	1.284	0.0064	0.92	9.65	4.86	14.51	6.90E-10	0.0
12/29/87	3.63	0.1855	0.3218	1.255	0.0091	0.90	9.65	4.86	14.51	1.87E-08	0.3
01/12/88	3.69	0.3167	0.6368	1.263	0.0060	0.92	9.77	4.86	14.63	5.13E-09	0.1
01/26/88	3.77	0.2733	0.6624	1.161	0.0070	0.91	9.74	4.86	14.60	9.53E-09	0.2
02/09/88	3.52	0.3529	0.5044	1.206	0.0164	0.87	9.84	4.87	14.71	8.04E-09	0.1
03/01/88	3.68	0.0585	0.0921	1.241	0.0099	0.90	9.70	4.86	14.56	--	--
03/29/88	4.77	0.0604	0.1314	1.271	0.0039	0.93	9.77	4.86	14.63	--	--

APPENDIX E

DATE	N2/O2 RATIO	CH4 FLUX (kg CH4/ day-cm2)	CO2 FLUX (kg CO2/ day-cm2)	GAS DENSITY (kg/m3)	IONIC STRENGTH	ACTIVITY COEFF. gamma	pKa	pKl	pKw	NH3-N (molar W/ gamma)	NH3-N GAMMA (ug/L)
					F2 STRIDE						
08/09/87	5.80	0.4864	0.3698	1.062	--	--	9.67	4.86	14.53	7.45E-08	1.3
08/27/87	13.15	0.2109	0.1675	1.068	0.0189	0.87	9.60	4.86	14.46	4.68E-08	0.8
09/10/87	24.44	0.0915	0.0716	1.049	0.0184	0.87	9.60	4.86	14.46	1.25E-07	2.1
09/24/87	5.90	0.3737	0.3438	1.113	0.0156	0.88	9.57	4.85	14.42	9.09E-08	1.5
10/07/87	12.25	0.2553	0.3471	1.147	0.0187	0.87	9.60	4.86	14.46	7.79E-08	1.3
10/22/87	9.65	0.3374	0.2674	1.057	0.0180	0.87	9.67	4.86	14.53	2.05E-08	0.3
11/12/87	7.67	0.6435	0.5048	1.070	0.0177	0.87	9.67	4.86	14.53	5.61E-08	1.0
11/26/87	12.05	1.3893	1.0039	1.045	0.0152	0.88	9.69	4.86	14.55	3.91E-09	0.1
12/15/87	13.58	0.3119	0.4118	1.190	0.0126	0.89	9.69	4.86	14.55	3.56E-09	0.1
12/31/87	7.04	0.0000	0.0000	1.130	0.0177	0.87	9.69	4.86	14.55	4.71E-08	0.8
01/14/88	21.40	4.3944	4.0592	1.073	0.0165	0.87	9.69	4.86	14.55	4.90E-08	0.8
01/28/88	7.40	0.2409	0.5854	1.281	0.0203	0.86	9.65	4.86	14.51	9.46E-08	1.6
02/11/88	8.35	0.4795	0.5134	1.150	0.0213	0.86	9.67	4.86	14.53	1.17E-07	2.0
03/03/88	3.83	0.0000	0.0000	1.259	0.0199	0.87	9.65	4.86	14.51	1.11E-07	1.9
03/31/88	52.00	0.1107	0.1839	1.215	0.0215	0.86	9.67	4.86	14.53	7.43E-08	1.3
					F3 STRIDE						
08/09/87	25.40	0.2053	0.1692	1.067	--	--	9.67	4.86	14.53	1.78E-07	3.0
08/27/87	17.86	0.2184	0.1707	1.058	0.0160	0.88	9.67	4.86	14.53	5.43E-08	0.9
09/10/87	21.00	0.1732	0.1412	1.050	0.0160	0.88	9.67	4.86	14.53	1.19E-07	2.0
09/24/87	4.33	0.0000	0.0000	1.169	0.0133	0.89	9.64	4.86	14.49	1.32E-07	2.2
10/07/87	10.60	0.4345	0.5444	1.130	0.0165	0.87	9.67	4.86	14.53	1.07E-07	1.8
10/22/87	17.00	0.4660	0.3375	1.039	0.0159	0.88	9.69	4.86	14.55	1.00E-07	1.7
11/12/87	7.77	0.9075	0.6644	1.065	0.0130	0.89	9.67	4.86	14.53	1.57E-07	2.7
11/26/87	10.08	1.1306	0.8235	1.051	0.0317	0.84	9.69	4.86	14.55	1.16E-07	2.0
12/15/87	8.57	0.3144	0.3134	1.117	0.0175	0.87	9.67	4.86	14.53	7.75E-08	1.3
12/31/87	7.49	0.0000	0.0000	1.078	0.0135	0.88	9.65	4.86	14.51	9.17E-08	1.6
01/14/88	6.29	0.1813	0.1381	1.093	0.0080	0.91	9.67	4.86	14.53	2.45E-08	0.4
01/28/88	4.38	0.0641	0.0547	1.190	0.0156	0.88	9.65	4.86	14.51	1.26E-07	2.2
02/11/88	4.76	0.2219	0.1694	1.149	0.0134	0.89	9.65	4.86	14.51	1.08E-07	1.8
03/03/88	3.81	0.0000	0.0000	1.220	0.0096	0.90	9.67	4.86	14.53	1.38E-07	2.4
03/31/88	9.91	0.0962	0.1299	1.212	0.0163	0.88	9.64	4.86	14.49	2.02E-07	3.4
					F6 STRIDE						
10/22/87	3.99	0.1042	0.2035	1.263	0.0336	0.83	9.62	4.86	14.48	3.81E-07	6.5
11/12/87	3.73	0.0440	0.0556	1.266	0.0149	0.88	9.60	4.86	14.46	2.67E-07	4.5
11/26/87	3.71	0.0000	0.0089	1.293	0.0160	0.88	9.65	4.86	14.51	5.47E-08	0.9
12/15/87	3.65	0.0000	0.0028	1.289	0.0171	0.87	9.65	4.86	14.51	5.52E-08	0.9
12/31/87	3.61	0.0000	0.0000	1.287	0.0120	0.89	9.74	4.86	14.60	1.25E-07	2.1
01/14/88	3.85	0.0000	0.2744	1.487	0.0119	0.89	9.74	4.86	14.60	8.17E-08	1.4
01/28/88	--	0.0000	0.0129	0.588	0.0134	0.88	9.69	4.86	14.55	1.40E-07	2.4
02/11/88	--	--	--	--	0.0157	0.88	9.70	4.86	14.56	1.40E-07	2.4
03/03/88	3.67	0.0000	0.0000	1.286	0.0133	0.89	9.69	4.86	14.55	1.34E-07	2.3

APPENDIX E

DATE	N2/O2 RATIO	CH4 FLUX (kg CH4/ day-cm2)	CO2 FLUX (kg CO2/ day-cm2)	GAS DENSITY (kg/m3)	IONIC STRENGTH	ACTIVITY COEFF. gamma	pKa	pK1	pKw	NH3-N (molar W/ gamma)	NH3-N GAMMA (ug/L)
				F7 STRIDE							
08/27/87	14.50	0.2470	0.3067	1.134	0.0174	0.87	9.60	4.86	14.46	3.93E-07	6.7
09/10/87	8.81	0.3203	0.3503	1.106	0.0169	0.87	9.57	4.85	14.42	5.56E-07	9.5
09/24/87	--	--	--	--	0.0143	0.88	9.60	4.86	14.46	2.94E-07	5.0
10/07/87	10.31	1.0143	1.0333	1.080	0.0155	0.88	9.67	4.86	14.53	2.46E-07	4.2
10/22/87	9.67	1.7384	1.8088	1.088	0.0156	0.88	9.60	4.86	14.46	2.42E-07	4.1
11/12/87	12.62	2.4742	3.3354	1.153	0.0135	0.88	9.62	4.86	14.48	4.05E-07	6.9
11/26/87	15.00	2.9384	4.1741	1.175	0.0103	0.90	9.64	4.86	14.49	3.44E-08	0.6
12/15/87	31.20	0.7152	0.7555	1.088	0.0218	0.86	9.57	4.85	14.42	3.24E-07	5.5
12/31/87	6.93	0.0000	0.0000	1.175	0.0199	0.86	9.60	4.86	14.46	2.95E-07	5.0
01/14/88	--	0.3707	0.4452	1.130	0.0187	0.87	9.57	4.85	14.42	3.43E-07	5.8
01/28/88	3.82	0.1541	0.0659	1.054	0.0173	0.87	9.60	4.86	14.46	2.79E-07	4.7
02/11/88	4.18	1.0190	0.4051	0.954	0.0208	0.86	9.60	4.86	14.46	4.40E-07	7.5
03/03/88	4.02	0.0000	0.0000	1.111	0.0205	0.87	9.59	4.86	14.44	1.07E-06	18.2
03/31/88	4.93	0.1408	0.2450	1.244	0.0189	0.87	9.59	4.86	14.44	5.74E-07	9.8
				F8 STRIDE							
08/27/87	10.95	0.2598	0.3327	1.143	--	--	--	--	--	--	--
09/10/87	10.80	0.2462	0.2896	1.116	--	--	--	--	--	--	--
09/24/87	13.44	0.7127	0.7883	1.094	--	--	--	--	--	--	--
10/07/87	9.12	0.1441	0.1887	1.151	--	--	--	--	--	--	--
10/22/87	4.23	0.2780	0.3639	1.221	--	--	--	--	--	--	--
11/12/87	5.70	0.4340	0.5715	1.204	--	--	--	--	--	--	--
11/26/87	9.04	1.4431	1.8479	1.150	--	--	--	--	--	--	--
12/15/87	5.03	0.7646	1.7644	1.277	0.01	0.88	9.67	4.86	14.53	1.13E-08	0.2
12/31/87	6.76	0.0000	0.0000	1.044	0.01	0.89	9.67	4.86	14.53	5.83E-08	1.0
01/14/88	--	2.0217	2.1966	1.078	0.02	0.89	9.67	4.86	14.53	7.87E-08	1.3
01/28/88	4.06	0.4568	0.4823	1.114	0.01	0.89	9.67	4.86	14.53	2.55E-08	0.4
02/11/88	4.27	1.0284	0.6553	1.033	0.01	0.90	9.74	4.86	14.50	1.21E-08	0.2
03/03/88	--	--	--	--	0.01	0.94	9.67	4.86	14.53	1.54E-08	0.3
03/31/88	5.44	0.2215	0.2919	1.203	0.01	0.94	9.74	4.86	14.50	2.28E-08	0.4
				10B STRIDE							
08/09/87	42.25	0.0527	0.3558	1.416	--	--	9.60	4.86	14.46	2.61E-08	0.4
08/27/87	19.19	0.0000	0.0000	1.365	0.0220	0.86	9.60	4.86	14.46	1.55E-08	0.3
09/10/87	14.91	0.0360	0.1524	1.360	0.0234	0.86	9.64	4.86	14.49	3.52E-08	0.6
09/24/87	28.05	0.0721	0.3620	1.369	0.0184	0.87	9.64	4.86	14.49	1.83E-08	0.3
10/07/87	16.26	0.0838	0.3181	1.351	0.0234	0.86	9.64	4.86	14.49	2.24E-08	0.4

APPENDIX E

DATE	N2/O2 RATIO	CH4 FLUX (kg CH4/ day-cm2)	CO2 FLUX (kg CO2/ day-cm2)	GAS DENSITY (kg/m3)	IONIC STRENGTH	ACTIVITY COEFF. gamma	pKa	pK1	pKw	NH3-N (molar W/ gamma)	NH3-N GAMMA (ug/L)

B8 RICHMOND

DATE	N2/O2	CH4 FLUX	CO2 FLUX	GAS DENS	IONIC	ACT	pKa	pK1	pKw	NH3-N molar	NH3-N ug/L
08/14/87	9.33	0.6194	1.2944	1.249	--	--	9.44	4.84	14.28	5.54E-06	94.3
09/01/87	--	2.2061	4.6972	1.254	0.0528	0.80	9.41	4.84	14.25	6.35E-06	108.2
09/15/87	3.78	1.5352	3.2875	1.258	0.0618	0.79	9.44	4.84	14.28	1.20E-05	205.2
09/29/87	3.33	0.9756	2.0718	1.254	0.0629	0.79	9.41	4.84	14.25	1.01E-05	172.4
10/13/87	3.89	1.0945	2.3627	1.259	0.0768	0.77	9.44	4.84	14.28	1.12E-05	191.4
11/03/87	3.62	0.5315	1.1909	1.272	0.0706	0.78	9.41	4.84	14.25	2.50E-05	426.6
11/17/87	3.71	0.5048	1.0668	1.253	0.0421	0.82	9.46	4.85	14.30	2.66E-06	45.2
12/01/87	3.44	1.6503	3.7100	1.272	0.0336	0.83	9.52	4.85	14.37	3.89E-07	6.6
12/24/87	3.53	4.9235	10.8735	1.270	0.0274	0.85	9.59	4.86	14.44	5.30E-07	9.0
01/06/88	3.49	4.2049	9.1781	1.267	0.0244	0.85	9.57	4.85	14.42	8.40E-07	14.3
01/19/88	3.90	2.7110	5.7989	1.259	0.0219	0.86	9.60	4.86	14.46	6.29E-07	10.7
02/02/88	3.53	2.0550	4.6861	1.280	0.0281	0.84	9.72	4.86	14.58	8.93E-07	15.2
02/24/88	--	4.2146	8.8649	1.265	0.0096	0.90	9.64	4.86	14.49	1.31E-07	2.2
03/15/88	3.50	6.8759	14.4970	1.256	0.0149	0.88	9.60	4.86	14.46	1.86E-07	3.2
04/05/88	8.80	5.6335	12.3750	1.264	0.0177	0.87	9.69	4.86	14.55	1.42E-07	2.4

D9 RICHMOND

DATE	N2/O2	CH4 FLUX	CO2 FLUX	GAS DENS	IONIC	ACT	pKa	pK1	pKw	NH3-N molar	NH3-N ug/L
08/14/87	2.60	9.1606	20.2373	1.267	--	--	9.19	4.81	14.00	1.01E-04	1723.9
09/01/87	3.75	10.1367	22.1815	1.263	0.1336	0.73	9.19	4.81	14.00	7.41E-05	1262.8
09/15/87	3.73	8.8003	19.2026	1.263	0.1389	0.73	9.22	4.82	14.04	6.23E-05	1061.5
09/29/87	3.67	9.0131	19.6269	1.264	0.1302	0.73	9.19	4.81	14.00	8.38E-05	1427.5
10/13/87	--	5.0442	10.8279	1.257	0.1246	0.74	9.22	4.82	14.04	4.41E-04	7508.3
11/03/87	3.65	6.1105	13.8992	1.277	0.1051	0.75	9.22	4.82	14.04	1.48E-04	2520.8
11/17/87	3.71	11.4659	25.2854	1.267	0.0952	0.76	9.16	4.81	13.97	7.97E-05	1358.6
12/01/87	3.33	17.5201	39.1946	1.271	0.0517	0.80	9.17	4.81	13.98	1.04E-05	177.2
12/24/88	3.52	12.8878	27.3986	1.260	0.0200	0.86	9.22	4.82	14.04	4.29E-07	7.3
01/06/88	3.43	12.1224	25.6654	1.260	0.0943	0.76	9.22	4.82	14.04	5.18E-05	882.0
01/19/88	3.94	9.5274	19.4146	1.243	0.0428	0.82	9.31	4.83	14.14	5.24E-06	89.2
02/02/88	3.90	13.9014	28.6588	1.250	0.1199	0.74	9.28	4.83	14.11	7.00E-05	1192.0
02/24/88	--	16.1134	32.9389	1.242	0.1277	0.73	9.27	4.82	14.09	8.32E-05	1417.8
03/15/88	3.84	16.1723	32.3461	1.241	0.1679	0.71	9.25	4.82	14.07	1.50E-04	2563.9
04/05/88	3.77	14.0726	29.9001	1.260	0.0858	0.77	9.41	4.84	14.25	2.01E-05	343.3

APPENDIX E

DATE	N2/O2 RATIO	CH4 FLUX (kg CH4/ day-cm2)	CO2 FLUX (kg CO2/ day-cm2)	GAS DENSITY (kg/m3)	IONIC STRENGTH	ACTIVITY COEFF. gamma	pKa	pK1	pKw	NH3-N (molar W/ gamma)	NH3-N GAMMA (ug/L)

C6 RICHMOND

DATE	N2/O2 RATIO	CH4 FLUX	CO2 FLUX	GAS DENSITY	IONIC STRENGTH	ACTIVITY COEFF.	pKa	pK1	pKw	NH3-N (molar W/ gamma)	NH3-N GAMMA (ug/L)
08/14/87	3.71	13.2513	28.5034	1.258	--	--	9.31	4.83	14.14	2.65E-06	45.1
09/01/87	3.89	19.1247	42.1674	1.266	0.0437	0.82	9.28	4.83	14.11	1.74E-06	29.6
09/15/87	--	4.6480	10.2645	1.265	0.0452	0.81	9.31	4.83	14.14	2.87E-06	48.9
09/29/87	3.71	9.4894	20.4974	1.259	0.0431	0.82	9.31	4.83	14.14	3.74E-07	6.4
10/13/87	--	6.0962	13.2462	1.260	0.0477	0.81	9.25	4.82	14.07	4.29E-07	7.3
11/03/87	3.65	7.9978	17.6211	1.267	0.0438	0.82	9.28	4.83	14.11	2.56E-06	43.7
11/17/87	3.75	16.9012	36.0403	1.255	0.0261	0.85	9.28	4.83	14.11	8.81E-08	1.5
12/01/87	3.30	5.0170	10.7919	1.260	0.0308	0.84	9.46	4.85	14.30	1.29E-07	2.2
12/24/87	3.30	1.9622	4.1829	1.260	0.0284	0.84	9.59	4.86	14.44	2.48E-07	4.2
01/06/88	3.69	1.7202	3.5515	1.252	0.0247	0.85	9.60	4.86	14.46	1.47E-07	2.5
01/19/88	4.28	2.2144	4.7688	1.263	0.0265	0.85	9.54	4.85	14.39	2.68E-07	4.6
02/02/88	3.84	20.3343	43.5387	1.262	0.0348	0.83	9.57	4.85	14.42	3.67E-07	6.3
02/24/88	--	21.4123	43.9500	1.260	0.0296	0.84	9.57	4.85	14.42	4.37E-07	7.4
03/15/88	--	31.5596	64.7780	1.248	0.0363	0.83	9.38	4.84	14.21	5.13E-07	8.7
04/05/88	4.15	29.1100	59.1447	1.243	0.0366	0.83	9.54	4.85	14.39	7.82E-08	1.3

G7 RICHMOND

DATE	N2/O2 RATIO	CH4 FLUX	CO2 FLUX	GAS DENSITY	IONIC STRENGTH	ACTIVITY COEFF.	pKa	pK1	pKw	NH3-N (molar W/ gamma)	NH3-N GAMMA (ug/L)
08/14/87	3.75	1.0485	2.1733	1.261	--	--	9.38	4.84	14.21	4.73E-06	80.6
09/01/87	3.91	2.0611	4.5038	1.262	0.0548	0.80	9.34	4.83	14.18	5.33E-06	90.8
09/15/87	--	0.4193	0.8819	1.250	0.0610	0.79	9.38	4.84	14.21	7.28E-06	124.0
09/29/87	3.80	1.2439	2.5775	1.247	0.0601	0.79	9.34	4.83	14.18	9.88E-06	168.4
10/13/87	3.73	0.8434	1.7901	1.261	0.0644	0.79	9.31	4.83	14.14	9.19E-06	156.6
11/03/87	3.58	1.1172	2.3787	1.258	0.0651	0.79	9.34	4.83	14.18	1.71E-05	291.7
11/17/87	3.71	2.3337	5.1322	1.267	0.0667	0.79	9.31	4.83	14.14	1.40E-05	238.8
12/01/87	3.43	1.1475	2.4342	1.257	0.0402	0.82	9.42	4.84	14.27	1.42E-06	24.1
12/24/87	3.81	0.2031	0.4236	1.254	0.0224	0.86	9.57	4.85	14.42	3.00E-07	5.1
01/06/88	3.65	1.0686	2.4342	1.277	0.0234	0.86	9.38	4.84	14.21	9.32E-07	15.9
01/19/88	4.37	0.4070	0.8722	1.390	0.0210	0.86	9.41	4.84	14.25	6.52E-07	11.1
02/02/88	4.00	1.9342	4.1175	1.261	0.0294	0.84	9.47	4.85	14.32	6.23E-07	10.6
02/24/88	4.08	0.7578	1.5866	1.256	0.0184	0.87	9.41	4.84	14.25	5.74E-07	9.8
03/15/88	4.05	2.6835	5.4959	1.245	0.0259	0.85	9.41	4.84	14.25	6.34E-07	10.8
04/05/88	--	--	--	--	0.0105	0.90	9.62	4.86	14.48	4.03E-08	0.7

APPENDIX E

DATE	N2/O2 RATIO	CH4 FLUX (kg CH4/ day-cm2)	CO2 FLUX (kg CO2/ day-cm2)	GAS DENSITY (kg/m3)	IONIC STRENGTH	ACTIVITY COEFF. gamma	pKa	pK1	pKw	NH3-N (molar W/ gamma)	NH3-N GAMMA (ug/L)
					D.55 RICHMOND						
08/14/87	--	1.5045	3.2296	1.255	--	--	9.31	4.83	14.14	1.93E-05	329.7
09/01/87	3.69	3.4906	7.1993	1.247	0.0679	0.78	9.28	4.83	14.11	1.68E-05	286.1
09/15/87	--	9.0341	18.5430	1.243	0.0704	0.78	9.28	4.83	14.11	1.14E-05	195.0
09/29/87	3.71	1.9279	3.9968	1.249	0.0687	0.78	9.25	4.82	14.07	1.22E-05	207.1
10/13/87	--	1.2005	2.5336	1.250	0.0733	0.78	9.25	4.82	14.07	1.28E-05	217.5
11/03/87	3.59	1.1797	2.4860	1.255	0.0647	0.79	9.25	4.82	14.07	1.75E-05	297.6
11/17/87	3.59	3.4266	7.2675	1.256	0.0675	0.78	9.25	4.82	14.07	1.09E-05	184.9
12/01/87	3.17	1.5514	3.2669	1.254	0.0626	0.79	9.41	4.84	14.25	9.43E-06	160.6
12/24/87	3.29	1.5907	3.1764	1.238	0.0548	0.80	9.38	4.84	14.21	8.69E-06	148.1
01/06/88	3.97	0.7010	1.8639	1.315	0.0604	0.79	9.33	4.83	14.16	1.28E-05	218.6
01/19/88	3.98	0.7975	2.0656	1.308	0.0598	0.79	9.38	4.84	14.21	8.84E-06	150.6
02/02/88	3.17	1.2558	2.9718	1.300	0.0634	0.79	9.44	4.84	14.28	4.84E-06	82.5
02/24/88	--	0.0000	0.5245	1.288	0.0491	0.81	9.38	4.84	14.21	8.17E-06	139.2
03/15/88	--	5.1718	10.2655	1.233	0.0559	0.80	9.44	4.84	14.28	4.55E-06	77.5
04/05/88	4.00	0.5254	1.0588	1.240	0.0217	0.86	9.55	4.85	14.41	5.78E-07	9.8
					B.53 RICHMOND						
08/14/87	4.00	1.8997	5.4214	1.339	--	--	9.28	4.83	14.11	2.40E-05	409.2
09/01/87	3.65	1.6986	3.7464	1.267	0.0549	0.80	9.28	4.83	14.11	1.27E-05	216.0
09/15/87	3.67	1.2820	2.8188	1.267	0.0608	0.79	9.25	4.82	14.07	1.55E-05	264.0
09/29/87	3.80	1.2284	2.6037	1.252	0.0538	0.80	9.25	4.82	14.07	1.03E-05	174.8
10/13/87	--	0.8817	1.9357	1.264	0.0544	0.80	9.28	4.83	14.11	5.42E-06	92.4
11/03/87	3.62	0.6937	1.4849	1.258	0.0419	0.82	9.22	4.82	14.04	7.25E-06	123.6
11/17/87	3.75	0.7789	1.6601	1.257	0.0476	0.81	9.25	4.82	14.07	9.17E-06	156.3
12/01/87	3.39	0.8030	1.7293	1.262	0.0386	0.82	9.31	4.83	14.14	3.30E-06	56.3
12/24/87	3.61	0.0709	0.1365	1.264	0.0316	0.84	9.47	4.85	14.32	1.78E-06	30.4
01/06/88	3.97	0.0000	0.0000	1.275	0.0285	0.84	9.47	4.85	14.32	1.97E-06	33.6
01/19/88	4.96	0.0488	0.1051	1.273	0.0254	0.85	9.60	4.86	14.46	1.44E-06	24.6
02/02/88	3.91	0.0000	0.0178	1.276	0.0223	0.86	9.54	4.85	14.39	6.12E-07	10.4
02/24/88	3.65	0.0000	0.0000	1.286	0.0105	0.90	9.49	4.85	14.34	4.33E-07	7.4
03/15/88	3.68	0.0000	0.0000	1.327	0.0135	0.89	9.50	4.85	14.35	1.89E-07	3.2
04/05/88	--	--	--	--	0.0131	0.89	9.59	4.86	14.44	8.67E-08	1.5

APPENDIX E

DATE	N2/O2 RATIO	CH4 FLUX (kg CH4/ day-cm2)	CO2 FLUX (kg CO2/ day-cm2)	GAS DENSITY (kg/m3)	IONIC STRENGTH	ACTIVITY COEFF. gamma	pKa	pK1	pKw	NH3-N (molar W/ gamma)	NH3-N GAMMA (ug/L)

P1 PREMIER

DATE	N2/O2	CH4 FLUX	CO2 FLUX	GAS DENSITY	IONIC	ACTIVITY	pKa	pK1	pKw	NH3-N molar	NH3-N GAMMA
08/20/87	3.60	0.0282	0.0528	1.259	0.1069	0.75	9.34	4.83	14.18	2.51E-05	427.2
09/03/87	3.86	0.0329	0.0671	1.263	0.1042	0.75	9.31	4.83	14.14	3.87E-05	659.4
09/17/87	3.60	0.0619	0.1473	1.287	0.1025	0.75	9.28	4.83	14.11	2.18E-05	371.9
10/01/87	3.90	0.1876	0.3872	1.263	0.1002	0.75	9.34	4.83	14.18	1.86E-05	317.0
10/15/87	3.65	0.1546	0.3142	1.265	0.1034	0.75	9.34	4.83	14.18	1.94E-05	331.1
11/05/87	3.64	0.1393	0.2813	1.260	0.1046	0.75	9.33	4.83	14.16	2.06E-05	351.9
11/19/87	3.54	0.1130	0.2248	1.267	0.0971	0.76	9.34	4.83	14.18	1.45E-05	247.1
12/03/87	3.61	0.0181	0.0442	1.292	0.0875	0.76	9.38	4.84	14.21	1.89E-05	321.3
12/22/87	3.66	0.0849	0.1708	1.269	0.1056	0.75	9.36	4.84	14.20	2.66E-05	453.7
01/05/88	3.58	0.0307	0.0730	1.287	0.0900	0.76	9.38	4.84	14.21	3.16E-05	538.9
01/20/88	3.64	0.0000	0.0478	1.295	0.0942	0.76	9.33	4.83	14.16	2.83E-05	482.6
02/04/88	3.90	0.0299	0.0681	1.280	0.0946	0.76	9.34	4.83	14.18	2.69E-05	458.5
02/23/88	3.62	0.0413	0.0813	1.276	0.0830	0.77	9.33	4.83	14.16	2.13E-05	362.5
03/17/88	3.76	0.0517	0.1048	1.270	0.0970	0.76	9.31	4.83	14.14	2.48E-05	422.7
04/07/88	3.63	0.0000	0.0058	1.293	0.0820	0.77	9.34	4.83	14.18	1.40E-05	239.2

P2 PREMIER

DATE	N2/O2	CH4 FLUX	CO2 FLUX	GAS DENSITY	IONIC	ACTIVITY	pKa	pK1	pKw	NH3-N molar	NH3-N GAMMA
08/20/87	3.78	0.1638	0.2789	1.187	0.1026	0.75	9.31	4.83	14.14	2.94E-05	500.8
09/03/87	3.58	0.1556	0.2678	1.195	0.1016	0.75	9.28	4.83	14.11	3.98E-05	678.8
09/17/87	3.50	0.2844	0.4958	1.210	0.0991	0.75	9.25	4.82	14.07	2.71E-05	461.6
10/01/87	3.59	0.6644	1.1686	1.201	0.0989	0.75	9.28	4.83	14.11	2.94E-05	501.1
10/15/87	3.65	0.4985	0.8925	1.212	0.1035	0.75	9.28	4.83	14.11	2.50E-05	425.8
11/05/87	3.61	0.8565	1.5648	1.216	0.1026	0.75	9.28	4.83	14.11	2.59E-05	440.6
11/19/87	3.60	0.2237	0.4061	1.239	0.0901	0.76	9.30	4.83	14.12	1.70E-05	289.7
12/03/87	3.68	0.0159	0.0291	1.281	0.0727	0.78	9.38	4.84	14.21	1.49E-05	254.6
12/22/87	3.63	0.0610	0.1115	1.259	0.1056	0.75	9.39	4.84	14.23	2.24E-05	381.7
01/05/88	3.65	0.0246	0.0459	1.279	0.0778	0.77	9.31	4.83	14.14	2.88E-05	490.6
01/20/88	4.22	0.0000	0.0289	1.318	0.0780	0.77	9.34	4.83	14.18	2.31E-05	393.6
02/04/88	3.68	0.0389	0.1011	1.287	0.0873	0.76	9.34	4.83	14.18	2.97E-05	506.9
02/23/88	3.68	0.0000	0.2366	1.315	0.0641	0.79	9.36	4.84	14.20	1.94E-05	330.8
03/17/88	3.62	0.0000	0.0857	1.310	0.0821	0.77	9.34	4.83	14.18	2.56E-05	436.1
04/07/88	3.68	0.0000	0.0182	1.308	0.0599	0.80	9.41	4.84	14.25	7.58E-06	129.1

MATSQUI PRECIP.		STRIDE PRECIP.		RICHMOND PRECIP.		PREMIER ST. PRECIP	
08/05/87	15.4	08/09/87	6.4	08/14/87	25.8	08/20/87	15.2
08/25/87	15.2	08/27/87	25.8	09/01/87	0.0	09/03/87	11.4
09/08/87	11.6	09/10/87	13.2	09/15/87	22.8	09/17/87	11.1
09/22/87	12.0	09/24/87	11.8	09/29/87	5.6	10/01/87	5.6
10/06/87	3.0	10/07/87	3.6	10/13/87	0.2	10/15/87	1.2
10/20/87	0.0	10/27/87	0.0	11/03/87	20.2	11/05/87	36.2
11/10/87	30.0	11/12/87	56.0	11/17/87	74.4	11/19/87	92.6
11/24/87	99.1	11/26/87	98.6	12/01/87	61.2	12/03/87	123.8
12/08/87	96.0	12/15/87	121.8	12/24/87	136.0	12/22/87	114.8
12/29/87	116.7	12/31/87	30.2	01/06/88	13.6	01/05/88	10.6
01/12/88	23.0	01/14/88	39.6	01/19/88	44.2	01/20/88	101.8
01/26/88	69.0	01/28/88	23.4	02/02/88	23.3	02/04/88	33.9
02/09/88	76.2	02/11/88	38.1	02/24/88	67.0	02/23/88	110.7
03/01/88	51.1	03/03/88	51.8	03/15/88	51.8	03/17/88	73.4
03/29/88	121.4	03/31/88	123.4	04/05/88	118.2	04/07/88	222.9

APPENDIX F.1. - Precipitation data (in millimeters) used in Statistical analysis

MATSQUI ALL N = 49

VARIABLE	MEAN	STD. DIV.	K-S Z STAT.	2 TAILED PROB.
PRECIP	58.33	40.81	1.151	0.141
W.L.	7.43	2.21	1.977	0.001
TW	13.61	3.15	1.014	0.256
TG	14.02	4.80	1.369	0.047
PH	6.4575	0.7086	0.871	0.434
NH3-N LEACH	648.88	827.00	2.308	0.000
NH3-N GAS	197.33	236.06	1.747	0.004
FLOW	43.16	35.00	0.762	0.608
PRESSURE	101.80	0.578	1.046	0.224
% CH4	35.76	13.71	1.247	0.089
CH4 FLUX	3.10	2.96	1.215	0.105
CO2 FLUX	7.03	5.77	0.782	0.574
IONIC ST.	0.10	0.12	2.191	0.000

STRIDE AVE. ALL N = 44

VARIABLE	MEAN	STD. DIV.	K-S Z STAT.	2 TAILED PROB.
PRECIP	43.74	40.09	1.328	0.059
W.L.	10.80	4.98	2.322	0.000
TW	12.65	1.09	1.941	0.001
TG	14.36	3.69	1.437	0.032
PH	6.18	0.22	1.746	0.005
NH3-N LEACH	7.83	6.56	1.271	0.079
NH3-N GAS	248.04	140.7	1.131	0.155
FLOW	5.54	8.13	1.810	0.003
PRESSURE	101.74	0.59	0.906	0.384
% CH4	46.75	15.81	1.365	0.048
CH4 FLUX	0.56	0.86	1.899	0.001
CO2 FLUX	0.58	0.97	1.94	0.001
IONIC ST.	0.02	0.01	0.703	0.707

RICHMOND ALL N = 86

VARIABLE	MEAN	STD. DIV.	K-S Z STAT.	2 TAILED PROB.
PRECIP	42.31	40.14	2.020	0.001
W.L.	3.33	0.89	0.791	0.558
TW	20.87	4.34	1.209	0.108
TG	19.51	6.76	1.074	0.199
PH	6.39	0.34	0.533	0.939
NH3-N LEACH	117.03	128.3	1.979	0.001
NH3-N GAS	143.17	155.34	1.654	0.008
FLOW	55.22	67.09	2.246	0.000
PRESSURE	102.09	0.45	1.505	0.022
% CH4	47.96	11.94	2.303	0.000
CH4 FLUX	5.37	6.71	2.169	0.000
CO2 FLUX	11.43	14.05	2.180	0.000
IONIC ST.	0.05	0.03	1.140	0.149

PREMIER ST. ALL N = 30

VARIABLE	MEAN	STD. DIV.	K-S Z STAT.	2 TAILED PROB.
PRECIP	64.35	62.01	1.141	0.148
W.L.	12.22	1.59	1.217	0.103
TW	22.42	1.18	0.937	0.344
TG	16.23	4.04	0.839	0.482
PH	6.64	0.10	0.485	0.973
NH3-N LEACH	225.7	33.54	0.826	0.503
NH3-N GAS	169.4	101.0	0.716	0.685
FLOW	2.43	1.67	1.104	0.174
PRESSURE	102.15	0.54	0.595	0.871
% CH4	22.2	20.3	0.750	0.627
CH4 FLUX	0.1320	0.2034	1.413	0.037
CO2 FLUX	0.2601	0.3572	1.331	0.058
IONIC ST.	0.0926	0.0127	0.918	0.0368

APPENDIX F.2.- Results of Kolmogorov-Smirov Goodness of Fit Test

APPENDIX F.3 - MATRIX RESULTS OF PEARSON PRODUCT-MOMENT CORRELATIONS

F1 MATSQUI

VARIABLES	ppt.	W.L.	Tw	Tg	pH	NH3-N Leach	NH3-N Gas	FLOW	PRESS.	% CH4	CH4 FLUX	CO2 FLUX	IONIC ST.
	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13
V1	X	X	X	-0.7618	X	X	-0.5791	X	X	X	X	X	X
V2	X	X	X	X	X	X	X	X	X	X	X	X	X
V3	X	X	X	X	X	X	X	X	X	X	X	X	X
V4	-0.7618	X	X	X	X	X	0.7672	0.5878	X	X	0.6933	0.6236	X
V5	X	X	X	X	X	X	0.6439	X	X	X	X	X	X
V6	X	X	X	X	X	X	X	X	X	X	X	X	X
V7	-0.5791	X	X	0.7672	X	X	X	0.6439	X	X	0.7944	0.6763	X
V8	X	X	X	0.5878	X	X	X	X	X	X	0.9637	0.9444	X
V9	X	X	X	X	X	X	X	X	X	X	X	X	X
V10	X	X	X	X	X	X	X	X	X	X	X	X	X
V11	X	X	X	0.6933	X	X	0.7944	0.9637	X	X	X	0.9700	X
V12	X	X	X	0.6236	X	X	0.6763	0.9944	X	X	0.9700	X	X
V13	X	X	X	X	X	X	X	X	X	X	X	X	X

F2 MATSQUI

	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13
V1	X	X	X	-0.6265	X	X	-0.6602	X	X	X	X	X	-0.5741
V2	X	X	X	X	X	X	X	0.6341	X	-0.5886	X	X	X
V3	X	X	X	0.6277	X	0.6826	0.7105	X	X	X	X	X	0.6559
V4	-0.6265	X	0.6277	X	X	0.7387	0.8925	X	X	X	X	X	0.6959
V5	X	X	X	X	X	0.7757	X	X	X	X	X	X	-0.7375
V6	X	X	0.6826	0.7387	0.7757	X	X	X	X	X	X	X	0.9123
V7	-0.6602	X	0.7105	0.8925	X	0.5605	X	X	X	X	X	X	0.6026
V8	X	0.6341	X	X	X	X	X	X	X	X	0.8497	0.9712	X
V9	X	X	X	X	X	X	X	X	X	X	X	X	X
V10	X	-0.5886	X	X	X	X	X	X	X	X	X	X	X
V11	X	X	X	X	X	X	X	0.8497	X	X	X	0.9258	X
V12	X	X	X	X	X	X	X	0.9712	X	X	0.9258	X	X
V13	-0.5741	X	0.6559	0.6962	0.7375	0.9123	0.6026	X	X	X	X	X	X

F3 MATSQUI

	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13
V1	X	X	X	-0.7325	X	X	X	X	X	X	X	X	X
V2	X	X	X	X	X	X	X	X	X	X	X	X	X
V3	X	X	X	X	X	X	X	X	X	X	X	X	X
V4	-0.7325	X	X	X	X	X	0.6834	X	X	0.6047	0.6112	X	X
V5	X	X	X	X	X	X	X	X	X	X	X	X	X
V6	X	X	X	X	X	X	X	X	X	X	X	X	X
V7	-0.6275	X	X	0.6834	X	X	X	X	X	X	X	X	X
V8	X	X	X	X	X	X	X	X	X	X	0.9524	0.9828	X
V9	X	X	X	X	X	X	X	X	X	X	X	X	X
V10	X	X	X	0.6047	X	X	X	X	X	X	0.7097	X	X
V11	X	X	X	0.6112	X	X	X	0.9524	X	0.7097	X	0.9551	X
V12	X	X	X	0.5727	X	X	X	0.9828	X	X	0.9551	X	X
V13	X	X	X	X	X	X	X	X	1	X	X	X	X

APPENDIX F.3

F4 MATSQUI

VARIABLES	ppt.	W.L.	Tw	Tg	pH	NH3-N Leach	NH3-N Gas	FLOW	PRESS.	%CH4	CH4 FLUX	CO2 FLUX	IONIC ST.
	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13
V1	X	X	X	-0.7669	X	X	-0.6714	X	-0.6268	X	-0.6377	-0.5940	X
V2	X	X	X	X	X	X	X	X	X	X	X	X	X
V3	X	X	X	X	X	X	X	X	X	X	X	X	X
V4	-0.7669	X	X	X	X	X	0.2503	X	X	0.7034	0.6905	0.6087	X
V5	X	X	X	X	X	X	X	X	X	X	X	X	X
V6	X	X	X	X	X	X	X	X	X	X	X	X	X
V7	-0.6714	X	X	0.7503	X	X	X	0.6149	X	X	0.6049	0.5998	X
V8	X	X	X	X	X	X	0.6149	X	X	X	0.9613	0.9905	X
V9	-0.6268	X	X	X	X	X	X	X	X	X	X	X	X
V10	X	X	X	0.7034	X	X	X	X	X	X	X	X	X
V11	-0.6377	X	X	0.6908	X	X	0.6049	0.9613	X	X	X	0.9700	X
V12	-0.5940	X	X	0.6087	X	X	0.5998	0.9905	X	X	0.9700	X	X
V13	X	X	X	X	X	X	X	X	X	X	X	X	X

F5 MATSQUI

VARIABLES	ppt.	W.L.	Tw	Tg	pH	NH3-N Leach	NH3-N Gas	FLOW	PRESS.	%CH4	CH4 FLUX	CO2 FLUX	IONIC ST.
	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13
V1	X	X	-0.7720	-0.8416	-0.6988	-0.6955	X	X	-0.7707	X	X	X	-0.6762
V2	X	X	X	X	X	X	X	X	X	X	X	X	X
V3	-0.7720	X	X	0.9167	X	X	X	X	0.6297	X	X	X	0.6427
V4	-0.8416	X	0.9167	X	X	0.6456	X	X	X	X	X	X	0.6768
V5	-0.6988	X	X	X	X	0.7459	X	X	X	X	X	X	0.7929
V6	-0.6755	X	X	0.6456	0.7459	X	X	X	X	X	X	X	0.9782
V7	X	X	X	X	X	X	X	X	X	X	X	X	X
V8	X	X	X	X	X	X	X	X	X	X	0.9840	0.9905	X
V9	-0.7707	X	-0.6297	X	X	X	X	X	X	X	X	X	X
V10	X	X	X	X	X	X	X	X	X	X	X	X	X
V11	X	X	X	X	X	X	X	0.9540	X	X	X	0.9882	X
V12	X	X	X	X	X	X	X	0.9905	0.5581	X	0.9882	X	X
V13	-0.6762	X	0.6427	0.6768	0.7929	0.9782	X	X	X	X	X	X	X

APPENDIX F.3

F2 STRIDE

VARIABLES	ppt.	W.L.	Tw	Tg	pH	NH3-N Leach	NH3-N Gas	FLOW	PRESS.	% CH4	CH4 FLUX	CO2 FLUX	IONIC ST.
	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13
V1	X	X	X	X	-0.6251	X	X	X	X	X	X	X	X
V2	X	X	X	X	X	X	X	X	X	X	X	X	X
V3	X	X	X	X	X	0.6558	X	X	X	X	X	X	0.6730
V4	X	X	X	X	X	X	0.6477	X	X	X	X	X	X
V5	-0.6251	X	X	X	X	X	X	X	X	X	X	X	0.7464
V6	X	X	0.6558	X	X	X	X	X	X	X	X	X	0.6550
V7	X	X	X	0.6377	X	X	X	X	X	X	X	X	X
V8	X	X	X	X	X	X	X	X	X	X	0.9943	0.9960	X
V9	X	X	X	X	X	X	X	X	X	X	X	X	X
V10	X	X	X	X	X	X	X	X	X	X	X	X	X
V11	X	X	X	X	X	X	X	0.9943	X	X	X	0.9909	X
V12	X	X	X	X	X	X	X	0.9960	X	X	0.9909	X	X
V13	X	X	0.6730	X	0.7464	0.6550	X	X	X	X	X	X	X

F3 STRIDE

VARIABLES	ppt.	W.L.	Tw	Tg	pH	NH3-N Leach	NH3-N Gas	FLOW	PRESS.	% CH4	CH4 FLUX	CO2 FLUX	IONIC ST.
	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13
V1	X	X	X	-0.6022	X	X	X	X	X	X	X	X	X
V2	X	X	-0.6101	0.8627	X	X	X	X	X	X	X	X	X
V3	X	-0.6101	X	X	X	X	X	X	X	-0.5867	X	X	X
V4	-0.6022	0.8627	X	X	X	X	0.7519	X	X	X	X	X	X
V5	X	X	X	X	X	X	X	X	0.6171	X	X	X	X
V6	X	X	X	X	X	X	X	X	X	X	X	X	X
V7	X	X	X	0.7519	X	X	X	X	X	X	X	X	X
V8	X	X	X	X	X	X	X	X	X	X	0.9879	0.9624	0.6424
V9	X	X	X	X	0.6171	X	X	X	X	X	X	X	X
V10	X	X	-0.5867	X	X	X	X	X	X	X	X	X	X
V11	X	X	X	X	X	X	X	0.9579	X	X	X	0.9710	0.6617
V12	X	X	X	X	X	X	X	0.9624	X	X	0.9710	X	0.6554
V13	X	X	X	X	X	X	X	0.6424	X	X	0.6617	0.6554	X

APPENDIX F.3

F7 STRIDE

VARIABLES	ppt.	W.L.	Tw	Tg	pH	NH3-N Leach	NH3-N Gas	FLOW	PRESS.	%CH4	CH4 FLUX	CO2 FLUX	IONIC ST.
	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13
V1	X	X	X	X	X	X	X	X	X	X	X	X	X
V2	X	X	X	X	X	X	X	X	X	X	X	X	X
V3	X	X	X	X	X	X	X	X	X	X	X	X	0.6280
V4	X	X	X	X	X	X	X	X	X	X	X	X	-0.5983
V5	X	X	X	X	X	X	X	-0.6505	X	X	X	-0.6367	0.6156
V6	X	X	X	X	X	X	X	X	X	X	X	X	X
V7	X	X	X	X	X	X	X	X	X	X	X	X	X
V8	X	X	X	X	-0.6505	X	X	X	X	X	-0.9858	0.9921	-0.7215
V9	X	X	X	X	X	X	X	X	X	X	X	X	X
V10	X	X	X	X	X	X	X	X	X	X	X	X	X
V11	X	X	X	X	X	X	X	0.9858	X	X	X	0.9738	-0.6731
V12	X	X	X	X	-0.6367	X	X	0.9921	X	X	0.9738	X	0.7442
V13	X	X	0.6280	-0.5983	0.6156	X	X	-0.7215	X	X	-0.6731	-0.7442	X

F8 STRIDE

VARIABLES	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13
V1	X	X	X	X	X	X	X	X	X	X	X	X	X
V2	X	X	X	X	X	X	X	X	X	X	X	X	X
V3	X	X	X	X	X	X	X	X	X	X	X	X	X
V4	X	X	X	X	X	X	0.8442	X	X	X	X	X	X
V5	X	X	X	X	X	X	X	X	X	X	X	X	X
V6	X	X	X	X	X	X	X	X	X	X	X	X	X
V7	X	X	X	0.8442	X	X	X	X	X	X	X	X	X
V8	X	X	X	X	X	X	X	X	X	X	0.9236	X	X
V9	X	X	X	X	X	X	X	X	X	X	X	X	X
V10	X	X	X	X	X	X	X	X	X	X	X	X	X
V11	X	X	X	X	X	X	X	0.9457	X	X	0.9128	X	X
V12	X	X	X	X	X	X	X	0.9236	X	X	X	X	X
V13	X	X	X	X	X	X	X	X	X	X	X	X	X

APPENDIX F.3

B8 RICHMOND

VARIABLES	ppt.	W.L.	Tw	Tg	pH	NH3-N Leach	NH3-N Gas	FLOW	PRESS.	% CH4	CH4 FLUX	CO2 FLUX	IONIC ST.
	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13
V1	X	X	X	X	-0.6083	-0.6672	X	X	X	X	X	X	-0.6002
V2	X	X	0.8766	0.7210	0.6107	0.6965	X	X	X	X	X	X	0.7355
V3	X	0.8766	X	0.8434	0.7568	0.8186	X	-0.7031	X	X	-0.6985	-0.7102	0.8628
V4	X	0.7210	0.8434	X	0.5781	0.7056	0.5418	X	X	0.6989	X	X	0.7264
V5	-0.6083	0.6107	0.7568	0.5781	X	0.9278	X	-0.6971	X	X	-0.7133	-0.7156	0.9054
V6	-0.6672	0.6965	X	0.7056	0.9278	X	X	-0.7198	X	X	-0.7263	X	0.9775
V7	X	X	X	X	X	X	X	X	X	X	X	-0.7304	X
V8	0.5625	X	0.8186	X	-0.6971	-0.7195	X	X	X	X	0.9914	X	-0.7653
V9	X	X	X	X	X	X	X	X	X	X	X	0.9934	X
V10	X	X	X	0.6989	X	X	X	X	X	X	X	X	X
V11	X	X	-0.7031	X	-0.7133	-0.7263	X	0.9914	X	X	X	0.9993	-0.7799
V12	0.5624	X	-0.6985	X	-0.7156	-0.7304	X	0.9934	X	X	0.9993	X	-0.7817
V13	-0.6002	0.7355	-0.7002	0.7264	0.9054	0.9775	X	-0.7653	X	X	-0.7799	-0.7817	X

D9 RICHMOND

VARIABLES	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13
V1	X	X	X	X	-0.6559	X	X	X	X	X	X	X	-0.5882
V2	X	X	0.8957	0.7899	X	X	X	X	X	X	X	X	X
V3	X	0.8957	X	0.7179	X	X	X	X	X	X	X	X	X
V4	X	0.7899	0.7179	X	X	X	X	-0.6548	X	X	-0.6451	-0.6024	X
V5	-0.6559	X	X	X	X	0.7823	X	X	X	X	X	X	0.7696
V6	X	X	X	X	0.7823	X	X	X	0.6075	X	X	X	0.9723
V7	X	X	X	X	X	X	X	X	X	X	X	X	X
V8	X	X	X	X	X	X	X	X	X	X	0.9718	0.9667	X
V9	X	X	X	X	X	0.6075	X	X	X	X	X	X	X
V10	X	X	X	X	X	X	X	X	X	X	X	X	X
V11	X	X	X	X	X	X	X	0.9718	X	X	X	0.9919	X
V12	X	X	X	X	X	X	X	0.9667	X	X	0.9919	X	X
V13	-0.5882	X	X	X	0.7696	0.9723	X	X	X	X	X	X	X

C6 RICHMOND

VARIABLES	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13
V1	X	X	X	X	X	X	X	X	X	X	X	X	X
V2	X	X	X	X	X	X	X	X	X	X	X	X	X
V3	X	X	X	0.8833	X	X	0.5767	X	X	X	X	X	0.7276
V4	X	X	0.8833	X	X	X	X	X	X	X	X	X	0.6454
V5	X	X	X	X	X	0.6850	X	X	X	X	X	X	X
V6	X	X	X	X	0.6850	X	X	X	X	X	X	X	0.6544
V7	X	X	0.5767	X	X	X	X	X	X	X	X	X	X
V8	X	X	X	X	X	X	X	X	X	X	0.9918	0.9943	X
V9	X	X	X	X	X	X	X	X	X	X	X	X	X
V10	X	X	X	X	X	X	X	X	X	X	X	X	X
V11	X	X	X	X	X	X	X	0.9918	X	X	X	0.9991	X
V12	X	X	X	X	X	X	X	0.9943	X	X	0.9991	X	X
V13	X	X	0.7276	0.6454	X	0.6544	X	X	X	X	X	X	X

APPENDIX F.3

67 RICHMOND

VARIABLES	ppt.	W.L.	Tv	Tg	pH	NH3-N Leach	NH3-N Gas	FLOW	PRESS.	% CH4	CH4 FLUX	CO2 FLUX	IONIC ST.
	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13
V1	X	X	-0.7703	-0.7256	X	X	X	X	X	-0.5881	X	X	X
V2	X	X	X	X	0.6282	0.7449	X	X	X	X	X	X	0.6761
V3	-0.7703	X	X	0.7404	0.7364	0.7294	X	X	X	0.7335	X	X	0.7985
V4	-0.7256	X	0.7404	X	0.8025	0.6595	0.7600	0.9930	X	X	X	X	0.8196
V5	X	0.6282	0.7364	0.8025	X	0.8216	X	X	X	X	X	X	0.9444
V6	X	0.7449	0.7294	0.6595	0.8216	X	X	X	X	X	X	X	0.9079
V7	X	X	X	0.7600	X	X	X	X	X	X	X	X	X
V8	X	X	X	X	X	X	X	X	X	X	0.9930	0.9947	X
V9	X	X	X	X	X	X	X	X	X	X	X	X	X
V10	-0.5881	X	0.7335	X	X	X	X	X	X	X	X	X	X
V11	X	X	X	X	X	X	X	X	X	X	X	0.9984	X
V12	X	X	X	X	X	X	X	0.9947	X	X	0.9984	X	X
V13	X	0.6761	X	0.8196	0.9444	0.9079	X	X	X	X	X	X	X

0.55 RICHMOND

	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13
V1	X	X	X	-0.7509	X	-0.7862	X	X	X	X	X	X	-0.6996
V2	X	X	0.8381	0.6430	X	X	X	X	X	X	X	X	0.6264
V3	X	0.8381	X	0.7528	0.7288	0.7250	X	X	X	X	X	X	0.8275
V4	-0.7509	0.6430	0.7528	X	X	0.6271	X	X	X	X	X	X	0.6729
V5	X	X	0.7288	X	X	0.6354	X	X	X	X	X	X	0.7051
V6	0.7862	X	0.7250	0.6271	0.6352	X	X	X	X	X	X	X	0.9170
V7	X	X	X	X	X	X	X	X	X	X	X	X	X
V8	X	X	X	X	X	X	X	X	X	X	0.9981	X	X
V9	X	X	X	X	X	X	X	X	X	X	X	X	X
V10	X	X	X	X	X	X	X	X	X	X	X	X	X
V11	X	X	X	X	X	X	X	0.9981	X	X	X	0.9991	X
V12	X	X	X	X	X	X	X	0.9993	X	X	0.9991	X	X
V13	-0.6996	0.6264	0.8275	0.6729	0.7051	0.9170	X	X	X	X	X	X	X

B.53 RICHMOND

	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13
V1	X	X	X	X	X	X	X	X	X	X	X	X	X
V2	X	X	X	X	X	X	X	X	X	X	X	X	X
V3	X	X	X	0.7271	X	0.7974	X	0.7204	X	0.9473	0.7978	0.7289	0.8685
V4	X	X	0.7721	X	0.6199	0.8353	X	0.8357	X	0.7534	0.8818	0.8244	0.8243
V5	X	X	0.6423	0.6199	X	0.8306	X	0.8304	X	0.6587	0.8173	0.8292	0.7604
V6	X	X	0.7974	0.8353	0.8306	X	X	0.8966	X	0.8229	0.9196	0.8927	0.9589
V7	X	X	X	X	X	X	X	X	X	X	X	X	X
V8	X	X	0.7204	0.8557	0.8304	0.8966	X	X	X	0.7191	0.9897	0.9937	0.8466
V9	X	X	X	X	X	X	X	X	X	X	X	X	X
V10	X	X	0.9473	0.7534	0.6387	0.8229	X	0.7191	X	X	0.7925	0.7133	0.9122
V11	X	X	0.7978	0.8818	0.8173	0.9196	X	0.9897	X	0.7925	0.9835	0.9835	0.8917
V12	X	X	0.7289	0.8244	0.8292	0.8927	X	0.9937	X	0.7133	0.8917	X	0.8356
V13	X	X	0.8688	0.8243	0.7604	0.9589	X	0.8466	X	0.9122	X	0.8356	X

APPENDIX F.3

P1 PREMIER

VARIABLES	ppt.	W.L.	Tv	Tg	pH	NH3-N Leach	NH3-N Gas	FLOW	PRESS.	% CH4	CH4 FLUX	CO2 FLUX	IONIC ST.
	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13
V1	I	I	I	-0.6810	I	-0.5734	I	I	I	-0.6108	I	I	-0.6612
V2	I	I	I	I	I	I	I	I	-0.5994	I	0.5740	0.5468	I
V3	I	I	I	I	I	0.6296	0.7086	I	I	I	I	I	0.6162
V4	-0.6810	I	I	I	I	I	I	I	I	0.6521	I	I	I
V5	I	I	I	I	I	I	I	I	I	I	I	I	I
V6	-0.5754	I	0.6296	I	I	I	I	I	I	I	I	I	I
V7	I	I	0.7086	I	I	I	I	I	I	I	I	I	I
V8	I	I	I	I	I	I	I	I	I	I	0.6941	0.6979	I
V9	I	-0.5994	I	I	I	I	I	I	I	I	I	I	I
V10	-0.6108	I	I	0.6521	I	I	I	I	I	I	0.7794	I	0.7452
V11	I	0.5740	I	I	I	I	I	0.6941	I	0.7794	I	0.9939	I
V12	I	0.5968	0.5968	I	I	I	I	0.6979	I	0.7406	0.9939	I	I
V13	-0.6612	I	I	0.6102	I	I	I	I	I	0.7452	I	I	I

P2 PREMIER

VARIABLES	ppt.	W.L.	Tv	Tg	pH	NH3-N Leach	NH3-N Gas	FLOW	PRESS.	% CH4	CH4 FLUX	CO2 FLUX	IONIC ST.
	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13
V1	I	-0.5622	-0.8416	-0.6922	I	-0.8211	I	I	I	-0.6737	I	I	-0.7026
V2	-0.5622	I	0.6960	0.6565	I	I	I	0.6192	I	0.8153	0.7925	0.7512	0.7861
V3	-0.8416	0.6960	I	0.9250	I	0.7984	I	I	I	0.7900	0.6669	0.6410	0.6445
V4	-0.6922	0.6565	0.9250	I	I	0.6528	I	I	I	0.8578	0.7055	0.6818	0.5866
V5	I	I	I	I	I	I	I	I	I	I	I	I	I
V6	-0.8211	I	0.6528	0.6528	I	I	I	I	I	0.6012	I	I	0.7667
V7	I	I	I	I	I	I	I	I	I	I	I	I	I
V8	I	0.6192	I	I	I	I	I	I	I	I	0.9204	0.9519	I
V9	I	I	I	I	I	I	I	I	I	I	I	I	I
V10	-0.6737	0.8153	0.8578	0.8578	I	0.6012	I	I	I	0.7367	0.7367	I	0.8368
V11	I	0.7925	0.7055	0.7055	I	I	I	0.9204	I	I	I	0.9913	0.6096
V12	I	0.7511	0.6818	0.6818	I	I	I	0.9519	I	0.9913	0.9913	I	0.5539
V13	-0.7026	0.7861	0.5866	0.5866	I	0.7667	I	I	I	0.6096	0.6096	I	I