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Landfill Odor Generation Estimates for Odor Control at Sanitary Landfills

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Abstract

This landfill odor characterization model (LOCM) provides a unique screening tool for design, evaluation and agency review of sanitary landfill odor impacts prior to landfill construction. Assuming the site specific effect of waste composition, surface environment (e.g. moisture content, temperature, pH, etc.), and cover characteristics, the total gas generation rate based on Palos Verdes kinetic model is predicted and could be used to estimate surface velocities from odor sources at landfills in Michigan. Consequently, this modeling for gas generation estimates will provide the preliminary guideline in predicting the odor control episodes, or in determining design and operational conditions that will eliminate the off-site transport of odors.

THEORETICAL BACKGROUND

The emission rate from sanitary landfills is determined by the gas generation mechanism and means of transport [1-4]. Gas generation mechanism includes biological decomposition, vaporization, and chemical reaction. Transport mechanism includes convection, molecular diffusion and displacement.

For emissions to occur, the volatile organic must first be present in gaseous form. The gaseous organic compound must then be transported to atmosphere above the landfill. Either mechanism can limit the emission rate. However, transport appears to be the limiting emission mechanism.

1. Landfill Gas Generation Mechanism

Landfill gas, consisting primarily of CH_4 and CO_2, is produced by microorganism in the landfill under anaerobic non-methanogenic unstable conditions [1-4]. The methane potential of each refuse component was calculated based on complete conversion of a degradable constituent to CH_4 and CO_2, using the stoichiometry given by Parkin and Owen [5]:

$$C_aH_bO_cN_d + \left[\frac{(4a - b - 2c + 3d)}{4}\right] H_2O \Rightarrow \left[\frac{(4a + b - 2c - 3d)}{8}\right] CH_4 + \left[\frac{(4a - b + 2c - 3d)}{8}\right] CO_2 + dNH_3 \qquad (1)$$

Anaerobic decomposition of complex organic material is normally a two-stage process [1-4, 6]. In the first stage (no methane production), the complex organics (e.g., cellulose, fats, proteins, and carbohydrates) are hydrolyzed, fermented, and biologically converted to simple organic fatty acids by a group of acid-forming anaerobic bacteria. During the second stage of methane fermentation, the organic acids are consumed by methanogenic anaerobic bacteria and converted into CH_4 and CO_2 [1-4, 6].

The stages of organic decomposition have been the subject of a number of investigations [3, 7, 8]. Two of these have attempted to associate the various stages of organic decomposition with gas procudtion [1, 3, 4, 7].

The first source, Pohland and Harper, identified five stages of gas production as determined from indicators in leachate and gas compositions [1, 3, 7]. The five stages of Pohland and Harper decomposition model shown in Figure 1 are categorized as follows [1, 3]:

(1) Initial Adjustment Stage (Aerobic)

The first stage includes the initial placement and covering of waste as well as preliminary moisture accumulation.

(2) Transition Stage

The second stage is characterized by moisture accumulation to the point that the field capacity of the waste is exceeded and leachate is formed. During this stage, there is a trend towards reduction (anaerobic decomposition) and volatile organic fatty acids first begin to appear in the leachate of the landfill.

(3) Acid Formation Stage (Anaerobic, Non-Methanogenic)

The third stage is marked with the massive production of volatile fatty acids and a sharp decline of pH in the wastes. Hydrogen may appear during this stage of decomposition.

(4) Methane Fermentation Stage (Anaerobic, Unstable Methanogenic)

The fourth stage is characterized by the onset of methane generation and an increasing rate of carbon dioxide production.

Total gas production rate reaches its mamximum during this stage.

The second source, EMCON Associates [1-4] identifies four stages of organic decomposition and gas generation as shown in Figure 2. These stages were determined by using the analysis of gas samples taken from test lysimeters, and from extraction wells in sanitary landfills [1-3]. The four stages of biological organic decomposition identified by EMCON Associates are as follows:

(1) Aerobic Decomposition Stage

When oxygen exists in landfills, aerobic organic decomposition begins producing mainly CO_2 gas.

(2) Anaerobic, Non-Methanogenic Decomposition Stage

When oxygen has been depleted; anaerobic organic decomposition begins producing a larger amount of CO_2 gas and also a relatively small amount of H_2 gas.

(3) Anaerobic, Unstable Methanogenic Decomposition Stage

The CH_4 gas may appear with the reduction in amount of H_2 gas produced until the H_2 gas is depleted.

(4) Anaerobic, Stable Methanogenic Decomposition Stage

This stage reaches steady state conditions with a decline in total gas production. During this stage, only CH_4 and CO_2 are produced until the organic fraction of the waste is depleted. At this time, landfill gas production ceases.

2. Factors Affecting On Landfill Gas Generation

Biological decomposition produces by far the greatest volume of gases emitted from sanitary landfills, and appear to be the most important factor in determining total emission rates [1, 2, 4, 6]. Landfill gas generation rate is a function of the following factors [1-4]:

- Availability of oxygen
- Quantity and composition of the refuse
- Moisture content of the waste
- Age of the waste
- Temperature inside the landfill
- pH and alkalinity of the refuse environment inside the landfill
- Quantity and quality of nutrients in the refuse
- Presence or absence of compounds that are toxic to bacteria

First, oxygen has a direct effect on gas generation rate. When oxygen is available in a landfill there is aerobic decomposition which produces mainly carbon dioxide [7]. After oxygen has been depleted, anaerobic decomposition begins and greater total gas generation appears.

Second, the quantity and composition of landfill refuse can affect on the landfill gas generation rate. The more waste that is available for decomposition, the greater potential gas generation [2]. The higher the percentage of biodegradable materials in the refuse (e.g. food waste and other organic materials), the higher the landfill gas generation rate. In some landfills, such as Ann Arbor study site, the percentage of available materials may also depend on the amount of daily cover that remains in place (approximately 5-10%).

Third, the amount of moisture in landfill waste will affect landfill gas generation, and therefore, generation rates throughout the biologically active life of a landfill [2]. According to the source [2], a 60-90% moisture content will produce the highest gas generation rate in landfill waste. Another source [3] indicates that a 60-80% moisture content is optimum for total gas generation. However, landfill waste typically has a 25% moisture content when it is dumped [2].

Fourth, the age of a sanitary landfill also plays a major role in governing gas generation rate [7]. This is directly related to the stage of decomposition in the landfill.

Fifth, the temperature of the landfill can also affect gas generation rate. For example, one source indicates that the optimum temperature for anaerobic decomposition (and methane production) in a landfill is 29℃ to 38℃ for mesophilic bacteria and 49℃ to 57℃ for thermophilic bacteria [1]. At temperatures below 10℃, there is a dramatic drop in the gas generation rate [1]. Another source states that the optimum temperature, on a short term basis, for methane generation in waste samples from landfills is 41℃. In addition, it was indicated that methane generation ceased at temperatures between 48℃ and 55℃.

Sixth, the pH of landfill liquids is another factor that affects gas generation rates [2]. Optimal pH for methane fermentation is neutral to slightly alkaline (7.0-7.2) [1]. Most landfills have an acidic environment for the first seven years.

Finally, gas production is reduced by compounds that are toxic to bacteria [2]. These compounds may be present in sanitary landfills as a result of the disposal of household chemicals or small quantity hazardous wastes, or reactions between chemical species.

3. Landfill Gas Generation Rate Modeling

The state-of-the-art for measuring air pollutants from waste landfills is inadequate, expensive, and time-consuming. Studies have been made to estimate the waste landfill gas emissions by theoretical calculations. Therefore, it has been necessary to develop empirical models to predict gas generation. Estimation of landfill gas emissions requires the estimation of both pollutant concentration and landfill gas flow rate.

The estimate of landfill gas emissions is developed using the following gas generation kinetic models [1-4]: Palos Verdes model, Sheldon-Arleta model, and Scholl Canyon model.

The Palos Verdes model is a two-stage, first-order mathematical model to represent the kinetics of landfill gas production. This model can be mathematically described as follows [1-4]:

First Stage: for $t_x \leq t_{1/2}$,

$$\frac{dG}{dt} = k_1 \cdot L_o \cdot \left(\frac{1}{P}\right) \cdot N_x \, \{\exp[-k_1 (t_{1/2} - t_x)]\} \tag{2}$$

Second Stage: for $t_x > t_{1/2}$,

$$\frac{dL}{dt} = k_2 \cdot L_o \cdot \left(\frac{1}{P}\right) \cdot N_x \, \{\exp[-k_2 (t_x - t_{1/2})]\} \tag{3}$$

Where,

$$k_1 = \frac{\ln(50)}{t_{1/2}} \tag{4}$$

$$k_2 = \frac{\ln(50)}{t_{99/100} - t_{1/2}} \tag{5}$$

It is needed to use other gas generation kinetic model for model validation. For this purpose the Scholl Canyon model is recommended, which is the simplest methane generation model selected by the USEPA in evaluating regulatory impacts [1-4]. This model can be expressed as follows [4, 9]:

$$Q_{CH4} = L_o \cdot V_x \, \{\exp(-k\tau) - \exp(-kt)\} \tag{6}$$

In order to use this model, two input constants, k and L_o, are required as well as the landfill age, average acceptance rate, and time since closure (0 if still active) [9]. The methane generation rate constant, k, is a measure of how quickly the methane generation rate decreases, once it reaches the peak rate. A reasonable estimate of gas generation emission rate can be obtained using the model with typical or median values of k (=0.02) and L_o [9].

USEPA used the Scholl Canyon model for estimation of landfill gas emissions based on landfill gas flow and concentration measurements of non-methanogenic organic compound (NMOC). The NMOC emission rate is to be determined using the tiered approach developed by USEPA [2]. Assuming the average annual acceptance rate is constant from year to year, the NMOC emission rate is as follows [2]:

$$M_{NMOC} = 2\,L_o \cdot V_R \cdot \{\exp(-k\tau) - \exp(-kt)\} \cdot C_{NMOC} \cdot Z \qquad (7)$$

The averaged acceptance rate (V_R) can be determined by dividing the refuse in place by the age of the landfill. This method for determining the emission rate should only be used for landfills with little or no knowledge of the actual year-by-year refuse acceptance rate. If refuse acceptance rate information is available, the landfill owner should determine the methane generation rate for each yearly submass of refuse to obtain an accurate overall landfill emission rate. The following equation can be used for submass approach [2]:

$$Q_i = 2\,k \cdot L_o \cdot M_i \cdot \{\exp(-kt_i))\} \cdot C_{NMOC} \cdot Z \qquad (8)$$

Regardless of which method is chosen, the nondegradable refuse, such as demolition refuse, should be subtracted from the mass or acceptance rate to avoid overestimating the landfill emission rate. A combination of the two methods may be used if acceptance rate information, such as gate receipts, is only available for a limited time period.

Recently, EMCON Associates developed the MGM gas generation model [2, 10] to estimate methane production for three types of decomposable waste: rapidly decomposable, moderately decomposable, and slowly decomposable wastes.

LANDFILL GAS GENERATION RATE ESTIMATES

1. Landfill Gas Emissions Data Survey

Based on avaialble data, the rate of landfill gas generation rate appears to range from 0.75 to 34 (*l*/kg of wet refuse/yr). This range is based on data from three sources.

An investigation of eight landfills in California indicates that 1.2 to 7.5 (*l* of CH_4/kg of wet refuse/yr) were produced for wastes with 25% moisture content [1, 3]. Since landfill gas is typically 50% CH_4, these rates represent a total landfill gas generation rate of 2.4 to 15 (*l*/kg of wet refuse/yr) [2].

In another study, conducted by USEPA' s Office of Solid Waste (OSW), total landfill gas production rates of 0.45 to 20.0 (*l*/*l* of refuse/yr) for 12-53% moisture content have also been reported [2]. Assuming a refuse density of 0.6 (kg/*l*), this corresponds to 0.75 to

34 (*l*/kg of wet refuse/yr) [2]. One important finding of this study was the correlation between gas generation and moisture content.

Another USEPA study [1, 7] reports landfill gas production rate from landfills in California ranging from 1 to 8 (*l*/kg of dry refuse/yr). Assuming that this refuse had a 25% moisture content, the total landfill gas production rate would correspond to 0.75 to 6 (*l*/kg of wet refuse/yr). Methane production rates of 2.5 to 3.7 (*l*/kg of wet refuse/yr) for 25% moisture content are commonly reported within a few years after refuse placement [3]. Assuming the landfill gas is 50% methane, this corresponds to a total gas production rate of 5 to 7.4 (*l*/kg of wet refuse/yr).

2. Model Input and Assumptions

There is very little quantitative data in the literature on emission rates. However, information on gas production can be used to estimate landfill gas emission rates. For this study, landfill site survey was provided to 105 operating landfills in Michigan [6, 11]. This survey identified the ranges of design and operating criteria that most affect odor generation and transport [6, 11].

Data inputs have been reduced to twelve variables by assuming that some landfill conditions are consistent across Michigan, and that changes in some of the conditions will not significantly affect gas generation or transport.

Based on landfill survey in Michigan, the model assumed variables include [6, 11]:

- Percent methane content (P): 50%
- In-place volume of refuse (L_o): 208.4 *l*/kg of refuse
- Density of in-place refuse (D): 0.654 kg/*l*
- Moisture content of refuse: 33%
- Organic fraction of refuse (N_T): 95%
  - Organic fraction of readily decomposable refuse: 30%
  - Organic fraction of moderately decomposable refuse: 61%
  - Organic fraction of minimally decomposable refuse: 4%
  - Non-decomposable fraction of refuse: 5%
- $t_{1/2}$ (yr) and $t_{99/100}$ (yr)
  - Readily decomposable refuse: $t_{1/2}=1$ and $t_{99/100}=3.5$
  - Moderately decomposable refuse: $t_{1/2}=2$ and $t_{99/100}=6$
  - Minimally decomposable refuse: $t_{1/2}=20$ and $t_{99/100}=60$

This landfill survey provides that P ranges from 50% to 72%, L_o from 42.5 *l*/kg refuse to 245.0 *l*/kg refuse, and D from 0.3 kg/*l* to 1.2 kg/*l*. Typical value of L_o may range from 1 ft^3 CH_4/*lb* refuse (62.4 *l*/kg refuse) to 3 ft^3 CH_4/*lb* refuse (125 *l*/kg refuse) depending on the refuse composition [3]. For this study, the model assumes that the organic portion of the waste is composed of three main fractions; 30% readily decomposable, 61% moderately decomposable, and 4% minimally decomposable.

For this study, all waste for a given year was assumed to be placed on January 1 of that year, and gas generation rates for that waste were assumed to be constant for any given year [6, 11-13]. All gas generated was assumed to exit through the landfill surface with no lateral imigration, and the surface velocity of that gas was also assumed to be uniform over the entire area [6, 11-13]. Chemical reactions and synergistic effects between chemicals in the landfill gas are assumed not to occur [6, 11-13]. In addition, the internal conditions of the landfill (i.e. temperature, percent moisture, leachate composition) were assumed not to be a limiting factor in the waste decomposition [6, 11-13].

Based on this information and the assumptions described above, the gas production rate of any fraction in the year being evaluated is calculated by using equations (2) through (5) based on Palos Verdes kinetic model [2-4, 6, 11]. However, the assumed constants can be changed based on site specific conditions [6, 11-13].

RESULTS AND DISCUSSIONS

Using the model assumed variables based on landfill site survey in landfills across Michigan and typical values for $t_{1/2}$ and $t_{99/100}$ based on the Palos Verdes study [2-4], the gas generation rate could be calculated. Figure 3 illustrates the simulation of gas generation for 30% readily decomposable, 61% moderately decomposable, and 4% minimally decomposable organic refuse.

Figures 4 and 5 graphically depict total gas production rate and the fraction of gas produced per unit mass of refuse, as estimated by Palos Verdes kinetic model using assumed model variables. These schematic curves as shown in Figure 5 show that the readily decomposables provide 36% of the total gas production; the moderately decomposables, 59%; and the minimally decomposables 5%. And also these results predict that a landfill reaches its maximum gas generation rate after about 3.5 years for readily decomposable organics and about 6 years for moderately decomposable organics, and about 60 years for minimally decomposable organics refuse [3].

Checking the model assumed half life ($t_{1/2}$), the calculated second stage rate constant (k_2) would be underestimated compared to the reported rate constant (k_2) based on Palos Verdes study [3]. Some investigations indicated that the economical gas generation life of a "typical" landfill is probably significantly greater than the 6 years reported in the Palos Verdes study [3]. However, from the comparison of observed and reported estimation, this result has a good consistency with the Palos Verdes study.

From the landfill site survey and site modeling, predictions of total gas generation could be used to estimate surface velocities. For the City of Ann Arbor Sanitary Landfill, the landfill odor characterization model (LOCM) predicts surface velocities similar to those determined during the site specific sampling and evaluation [6, 11]:

Source	Average Surface Velocity (ft/min)	
	Sampled	Model Prediction
Open Tipping Face	9.9×10^{-3}	7.6×10^{-3}
Temporary Cover	3.6×10^{-3}	7.6×10^{-3}
Final Cover	2.5×10^{-6}	1.1×10^{-4}

It was found that differences between sampled and modeled predictions at landfills in Michigan will be more dependent on site configuration and operating procedures [1]. From the result, it appears that the production of sanitary landfill gases with greatest odor intensity occurs primarily at the open tipping face and the temporary cover with freshly deposited and recently covered refuse [1]. However, due to transport of a higher volume of total gases, it was found that odors produced from older waste have a more predominant and widespread influence at adjacent receptors [1]. Thus, these variations in predicted values result from the site specific effect of waste composi-tion, surface environment (e.g. moisture content, temperature, pH, etc.), and cover characteristics, among other factors [1].

Literature review states that sanitary landfills emit 0.75 to 34 (*l* of total gas/kg of wet refuse/yr), and that the total volume of odorous emissions from sanitary landfills can be estimated at less than 0.075 to 0.34 *l*/kg of refuse/yr (assuming 12-53% moisture content and 1% tracer concentration). From the result of this study at Ann Arbor sanitary landfills in Michigan, the total gas generation rate using Palos Verdes kinetic model could be predicted at about 30 (*l* of total gas/kg of refuse/yr), and the total volume of odorous emissions from sanitary landfills could be estimated at about 0.3 *l*/kg of refuse/yr (assuming 33% moisture content and 1% tracer concentration).

CONCLUSION

This landfill odor characterization model (LOCM) provides a unique screening tool for design, evaluation and agency review of sanitary landfill odor impacts prior to landfill construction. Assuming the site specific effect of waste composition, surface environment (e.g. moisture content, temperature, pH, etc.), and cover characteristics, predictions of total gas generation could be used to estimate surface velocities. For Ann Arbor sanitary landfills in Michigan, the landfill odor characterization model (LOCM) predicts surface velocities similar to those determined during the site specific sampling and evaluation.

It was found that differences between sampled and modeled predictions at study sites will be more dependent on site configuration and operating procedures. Thus, these variations in predicted values result from the site specific effect of waste composition, surface environ-ment (e.g. moisture content, temperature, pH, etc.), and cover characteristics, among other factors [1].

Consequently, this modeling for gas generation estimates will provide the preliminary guideline in predicting the odor control episodes, or in determining design and operational conditions that will eliminate the off-site transport of odors.

NOMENCLATURE

a,b,c,d : Stoichiometry constants [-].
C_{NMOC} : Concentration of NMOC [ppm].

D : Density of in-place refuse [kg/l].
k : Methane generation rate constant [l/yr].
k_1 : First stage rate constant [l/yr].
k_2 : Second stage rate constant [l/yr].
L_0 : Potential CH_4 generation capacity of the refuse [ft^3/Mg refuse].
M_i : Mass of ith section [Mg].
M_{NMOC} : Mass emission rate of NMOC [Mg/yr].
N_x : Percent of each decomposable organic fraction [%].
N_1 : Percent of organic fraction that is readily decomposable [%].
N_2 : Percent of organic fraction that is moderately decomposable [%].
N_3 : Percent of organic fraction that is minimally decomposable [%].
N_T : Percent of total organic fraction that is decomposable in refuse [%]: $N_T = N_1 + N_2 + N_3$
P : Percentage CH_4 content of the refuse [%].
Q_{CH4} : CH_4 gas generation rate at time t [ft^3/yr].
Q_i : NMOC emission rate from the ith section [Mg/yr].
Q_{sxtx} : Total gas generated from source S_x at time t_x [ft^3/min].
t : Time since the initial refuse placement [yr].
$t_{1/2}$: Half life [yr].
$t_{99/100}$: Time required to achieve 99% of ultimate CH_4 production [yr].
t_i : Age of the ith section [yr].
t_x : Time chosen for evaluation of source S_x [yr].
V_R : Average annual refuse acceptance rate during the active life [Mg/yr].
V_{sxtx} : Surface velocity for S_x at time t_x [ft/min].
Z : Conversion factor (3.595×10^{-9}).
τ : Time since landfill closure [yr] ($\tau = 0$ for active landfills).
dG/dt : First stage CH_4 gas production rate [ft^3/ton of refuse/yr].
dL/dt : Second stage CH_4 gas procudtion rate [ft^3/ton of refuse/yr].

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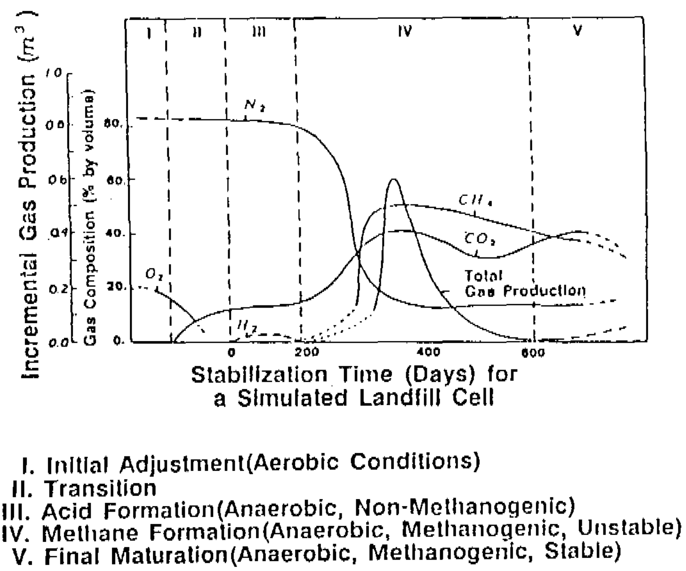

Fig. 1. Gas production rates, Pohland and Harper model [1]

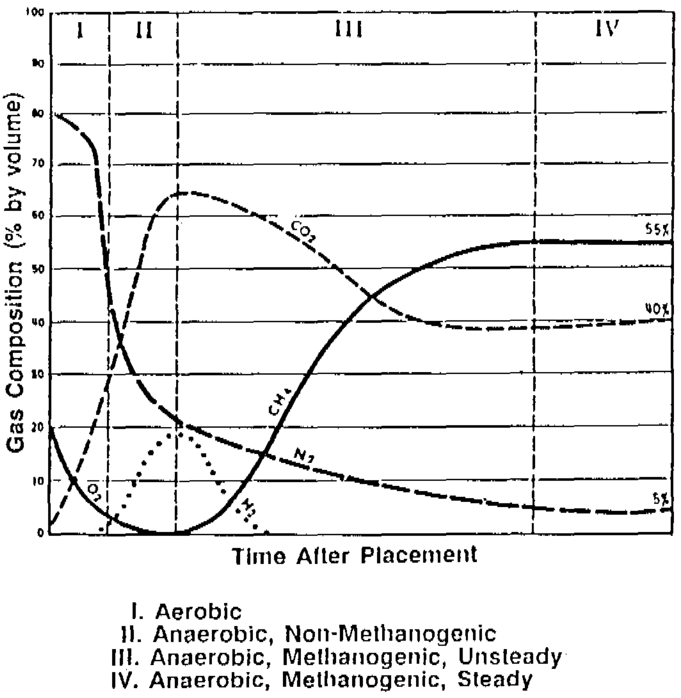

Fig. 2. Gas production rates, EMCON Associates model [1, 3]

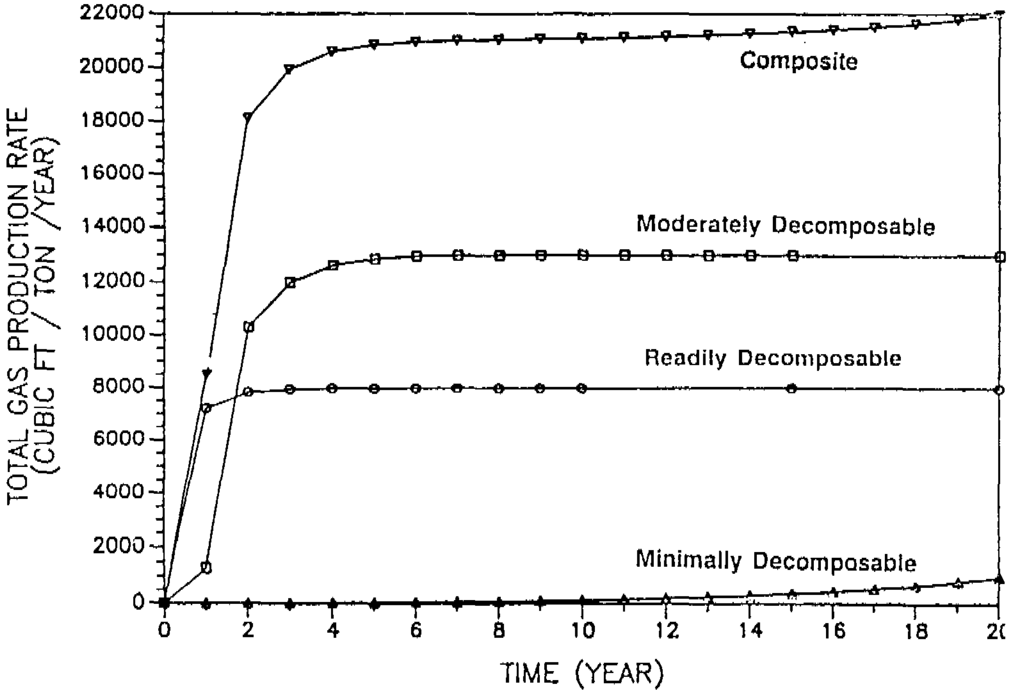

Fig. 3. Total gas production rate as a function of time

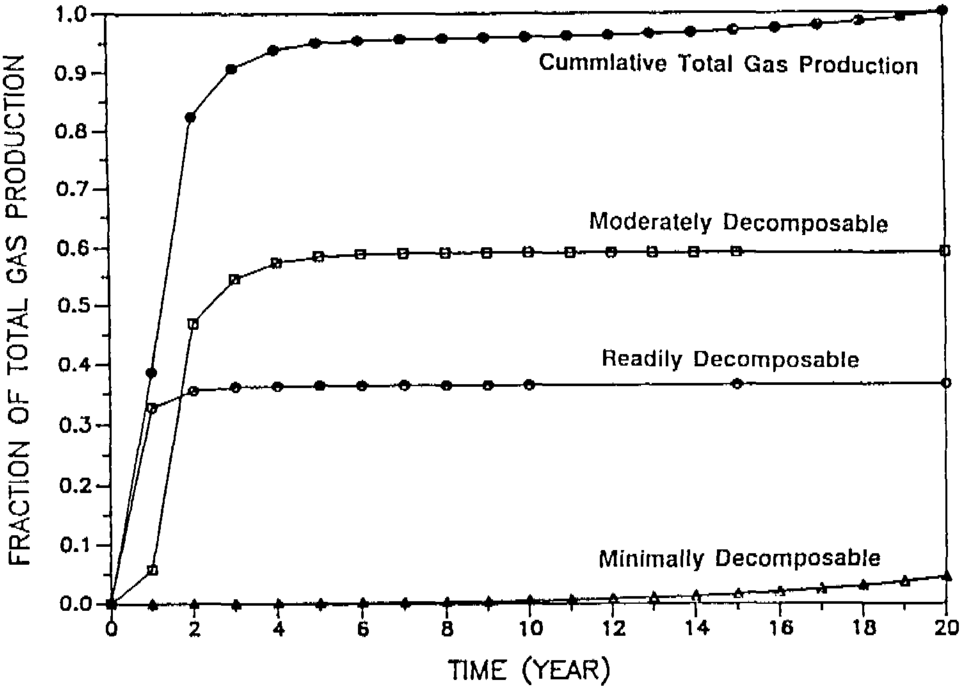

Fig. 4. Cummulative total gas production rate
(Palos Verdes kinetic model)

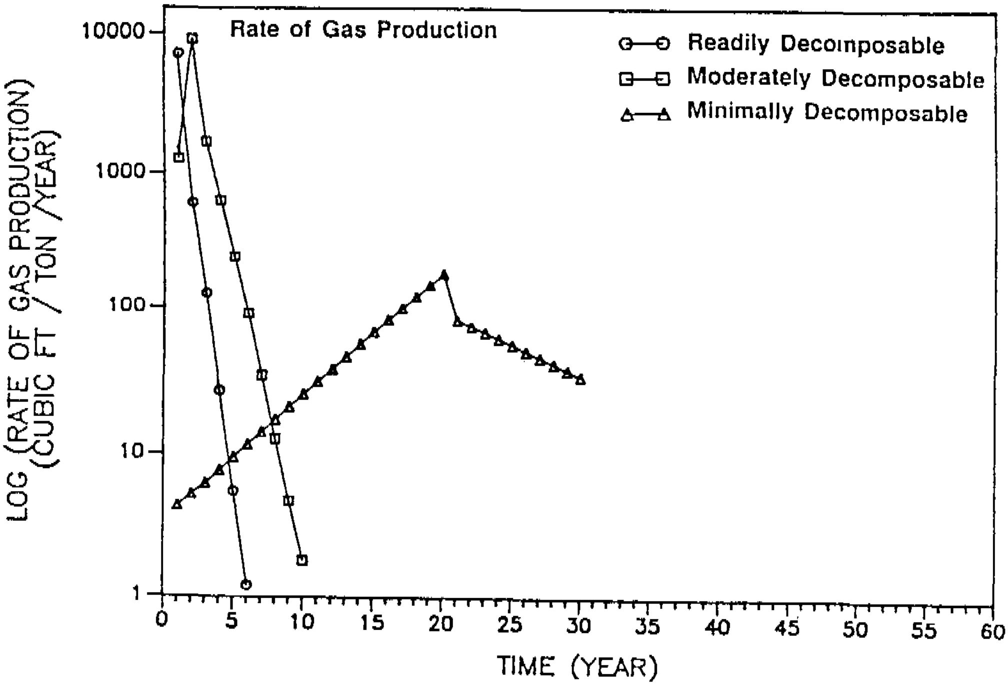

Fig. 5. Rate of gas production as a function of time