FINAL REPORT

COMPARISON OF MODELS FOR PREDICTING LANDFILL METHANE RECOVERY

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EXECUTIVE SUMMARY

Introduction

Landfill methane models are tools used to project methane generation over time from a mass of landfilled waste. These models are used for sizing landfill gas (LFG) collection systems, evaluations and projections of LFG energy uses, and regulatory purposes. Compared to other alternatives (such as installation of a full-scale LFG recovery system or the use of test wells and the performance of a pump-test program), models have advantages in terms of low cost and relatively rapid results.

Improvement of landfill methane models has been a priority for the LFG industry. The literature is not replete with models that have been compared or calibrated with landfill methane field data and modeling of methane generation and recovery is not sufficiently advanced. Current landfill methane models are uncertain. However, as more LFG collection systems are installed (for regulatory and other reasons) and operated within lined landfills, better landfill data will become available for modeling. As a result, model uncertainties probably can be reduced.

The objective of this project was to select various landfill methane models and to provide a comparison of model outputs to actual long-term gas recovery data from a number of well managed and suitable landfills. Another objective was to use these data to develop better estimates of confidence limits that can be assigned to model projections.

Approach

This project assessed trial model forms against field data from available landfills where methane extraction was maximized, waste filling history was well-documented, and other pertinent site information was of superior quality. Date were obtained from 18 U.S. landfills. Four landfill methane models were compared: a zero-order, a simple first order, a modified first order, and a multi-phase first order model. Models were adjusted for "best fit" to field data to yield parameter combinations based on the minimized residual errors between predicted and experienced methane recovery. The models were optimized in this way using two data treatments: absolute value of the differences (arithmetic error minimization) and absolute value of the natural log of the ratios (logarithmic error minimization).

Results

Application of the two data treatments yielded parameter combinations which were model dependent and similar to those used in the LFG industry. Values for Lo, the methane yield potential, were consistent for the three first-order models under the arithmetic error optimization function, ranging from 2,100 to 2,200 cubic feet of methane per ton of landfilled waste. Under the logarithmic function, at least one parameter combination for each of the four models resulted in an Lo within the 2,000 to 2,200 cubic feet of methane range. Values for k, the first order decay rate constant, were more varied and model dependent. Under the arithmetic optimization , k values ranged from 0.05 to 0.08 per year; under the logarithmic optimization, k values ranged from 0.03 to 0.06 per year.

Minimization of logarithmic error gave better results than those demonstrated by arithmetic error minimization in the form of a narrow, more specific band of parameter combinations for best fit optimization.

Regression coefficients (r^2) were calculated to compare modeled versus actual methane recovery. Results for r^2 ranged from 0.928 to 0.937 for the arithmetically optimized models; for the models optimized logarithmically, the r^2 values ranged from 0.914 to 0.955, indicative of reasonable correlations. Similarity of the regression coefficient results indicates that the four models were similar in predictive ability.

The four landfill methane models also were compared through examination of data distributions of the numerical ratios of the measured methane recovery values to the modeled recovery over the spectrum of data points established for the study landfills. Plots were developed to show 10 and 90 percent probability limits around median values based on minimization of arithmetic and logarithmic errors.

Generally, the set of study landfills showed rather wide probability limits, meaning the models could project methane recovery within a factor of about 1.5 for 80 percent of the landfill data points. The spread or dispersion was greater for the remaining data points. Furthermore, the probability limits for the models optimized via logarithmic minimization were narrower than those established with the arithmetic optimization.

A simple computer program was developed for each of the four study models which accepts keyboard inputs for model parameters in order project methane generation over time. For one model form the program provides probability limits (upper and lower bounds) based on the minimization of arithmetic error procedures described in the report.

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SECTION 1

INTRODUCTION

LANDFILL METHANE MODELS

A landfill methane model is a tool used to project methane generation over time from a mass of waste. In its simplest form, a model predicts methane generation or recovery from a single batch of waste, landfilled at a single given point in time. Total methane generation or recovery from a landfill (or a portion of the waste mass) is then the sum of outputs from all batches in the landfill. Typically, the unit for the parameter time is a year.

Typical components of models may include an interval before methane generation starts (lag time) and subsequent intervals of rising, constant, and falling production, depending on the model. A simplified example of a model profile from a single waste batch is illustrated in Figure 1, showing a 1-year lag time and estimated methane generation over a 45-year period. Although Figure 1 shows a single line for simplicity, model projections are inherently "probabilistic", and confidence limits should be assigned to their projections.

Landfill gas (LFG) models are used for:

- Sizing landfill gas collection systems. LFG collection and treatment equipment must be installed at most larger landfills in response to regulatory requirements under the Clean Air Act. In addition, landfill sites often require such systems for purposes of subsurface migration control, odor control, and other reasons. Modeling can be an effective tool to appropriately size the wellfield and associated LFG collection, treatment, and/or recovery equipment.

- Evaluations and projections of landfill gas energy uses. With knowledge of equipment and operating costs, unit energy revenues, and other key factors, "probabilistic" model projections can be used to estimate the LFG or methane yields of landfills, size equipment, estimate costs, and evaluate the spectrum of likely investment returns.

- Regulatory purposes. Model projections have been used to calculate landfill emissions and to support establishment of LFG and methane emission requirements.

Figure 2 shows steps in a hypothetical model application for an energy project. The top illustration shows three curves for a hypothetical model which projects likelihood that gas recovery will exceed given values at a landfill site. The lowest curve is a recovery value which might be exceeded 90 percent of the time; the middle curve is the median (where gas recovery might be exceeded 50 percent of the time) and the top curve is the recovery that would be attained 10 percent of the time.

The middle illustration of Figure 2 represents equipment performance for two different capacities (or gas usage rates) compared to a gas recovery projection at the 50 percent

level. Similarly, the bottom illustration represents the same set of equipment capacities compared to more conservative gas recovery estimates (i.e., methane recovery that would be realized or exceeded 90 percent of the time).

Solid waste industry investments and expenses associated with LFG control and recovery are significant. For example, the capital cost of equipment to produce 1,000 Mwe of electricity from LFG would exceed $1 billion (EPRI, 1992; EPA, 1993). Both EPA (1993) and EPRI (1992) estimate LFG electric potential at 5000+ MWe, given adequate electricity sale prices. Furthermore, given the implementation of current Clean Air Act requirements, the costs for LFG controls are expected to rise in the future.

Theoretically, as landfill methane models are refined and improved, their use should reduce errors in sizing of energy and recovery equipment, yield improved cost-benefit calculations, and reduce project risks. Such models would provide significant added value annually to the LFG industry and the public.

Compared to other alternatives, models have advantages in terms of low cost and relatively rapid results. To estimate a landfill's methane generation, one alternative to models (short of installing a full-scale recovery system) is the use of test wells and the performance of a pump-test program. However, costs for pump tests can exceed $100,000 and require three months or more to accomplish; the tests have inherent imprecisions; and the field results represent points in time for the test location(s) in the landfill rather than long-term projections for the entire landfill. A goal for landfill methane models is to provide information of comparable accuracy to extrapolations of pump test results for the entire landfill.

Although models have the potential to provide these benefits, advantages of models can be realized only to the extent models are sufficiently developed. Modeling of landfill methane generation and recovery is not sufficiently advanced.

PREVIOUS MODELING STUDIES

Model development for prediction of gas recovery and other purposes began with the increase in sanitary landfilling in the 1970's. The first "modeling" consisted of the application of "rules of thumb", and such estimates (albeit refined) continue to be used in the LFG industry (Walsh, 1994) . Qualitative descriptions of the LFG generation process also were developed by Farquhar and Rovers in 1973. Other investigators attempted more rational bases for prediction of LFG or methane on the basis of available but limited landfill data (Alpern, 1973; Ham, 1979; and Ham, et. al., 1979). Around the same time, more quantitative model predictions were first attempted in the Los Angeles basin in the U. S.

Numerous variables affect waste decomposition in landfills and the subsequent production of methane. The "standard" analytical models, such as the Monod, that predict performance of microbial processes under defined temperature, nutrient, and other biological conditions, cannot be applied effectively to landfills. Researchers have found it difficult to obtain field data from a unique batch of waste to compare with a model's predicted methane generation curve. In part, this difficulty occurs because methane recovery from landfills typically is aggregated output from many years of waste placement, rather than from individual batches of waste within the landfill.

Model development mostly has been empirical; it has consisted of the application or the testing of a wide range of postulated generation curves (i.e., variations on the curve of Figure 1). Forms of such curves have been assumed on various bases including mechanistic assumptions about decomposition (Van Zanten and Scheepers, 1995; Zison, 1990; Augenstein and Pacey, 1991).

The literature is not replete with landfill methane models that have been compared or calibrated with field data. The following summarizes some of the published and unpublished work:

- Good data are becoming available from landfills operated in Southern California by the Sanitation Districts of Los Angeles. These landfills have accurate waste placement, composition, methane recovery, and other relevant data, and are yielding promising model forms to predict methane recovery.

- Several proprietary models exist and are applied by engineering firms and others. However, the development details largely are unknown and little published information is available which compares the proprietary models' predictions with field experience.

- Oonk, et. al. (1994) examined methane recovery from landfills in Holland. This work correlated four trial models with a moderate amount of data from 12 landfills and showed good "fit" of postulated models with site data. However, methane generation data were short term-- three years, maximum.

- Peer, et. al. (1992) for the U. S. EPA examined methane recovery from a set of 21 U.S. landfills. One recovery rate was measured at a single "point in time" (the study year) for each landfill. Peer, et. al. found recovery to be correlated with waste in place, by what was termed an "emission factor"; i.e., methane recoverable per unit of waste per unit of time, determined for each individual study landfill. Correlations were not made with waste age (i.e., time since filling) or other variables such as rainfall or temperature. For the study landfills, the emission factor ranged from 2.5 to 6.5 cubic meters of methane per minute per million metric tons of waste in place.

- Augenstein and Pacey (1991) showed comparisons of two landfills' data to a proprietary model which suggest conformance of gas generation/recovery to first order kinetics. This paper also presented data from Zison (1990) wherein a similar model gave reasonable results (recovery ranging from -30 to +50 percent of predicted) for three of four Southern California landfills.

Current landfill methane models are uncertain. These uncertainties are due to several factors, including:

- Sparseness and quality of the data used for model development and calibration;
- Limited time frames for the available field data used;
- Inappropriate application of available data:
- Varying geographic/climatic conditions; and
- Other factors specific to the landfill design and operations such as landfill depth, liners, and leachate recirculation.

As more LFG collection systems are installed and operated within lined landfills, better landfill data likely will become available for modeling. As a result, model uncertainties probably can be reduced.

Given the present status of landfill methane models and the utility of such models to landfill operators, LFG-to-energy developers, and regulators, the National Renewable Energy Laboratory (NREL) funded this project through a contract with the Solid Waste Association of North America (SWANA). SWANA subsequently retained SCS Engineers and the Institute for Environmental Management to perform this study and prepare this report.

PROJECT OBJECTIVES

The purpose of this project was to select various landfill methane models and to provide a comparison of model outputs to actual gas recovery data from a number of well managed and suitable landfills. Specific objectives included:

- Identify U.S. landfills with available operational and gas recovery data suitable for model comparisons and obtain data from them;
- Select trial model forms to test against landfill data;
- Use landfill data to adjust model parameters and assess the reasonableness of the trial models;
- Identify confidence limits which can be assigned to models;
- Assess the effect of site variables on methane generation and recovery;
- Make available the study's findings in the form of an easy-to-use computer program; and
- Make recommendations for future study.

Comparison of landfill methane models involves a number of complex issues and choices as to procedures to be used. This report provides detail on the background and reasoning as to why certain approaches were taken and discusses advantages and limitations of the findings with respect to methane model users in the LFG industry.

REPORT ORGANIZATION AND CONTENT

The remaining sections of the report are organized as follows:

- Section 2 presents background on landfill methane generation and the selection of landfill methane models for further evaluation;
- Section 3 discusses the approach used for comparison of model outputs to actual gas recovery data;
- Section 4 presents results of the model comparisons and derivations for parameter values of the optimized models. It also presents error and confidence limits based on data from the study landfills;
- Section 5 discusses the computer program developed for users to create outputs from the four models evaluated;
- Section 6 presents recommendations for further study, based on the findings and analytical results; and
- Section 7 lists literature references noted in the report.

Supplemental information is appended as referenced herein.

FIGURE 1
HYPOTHETICAL METHANE GENERATION PROFILE FROM LANDFILL WASTE

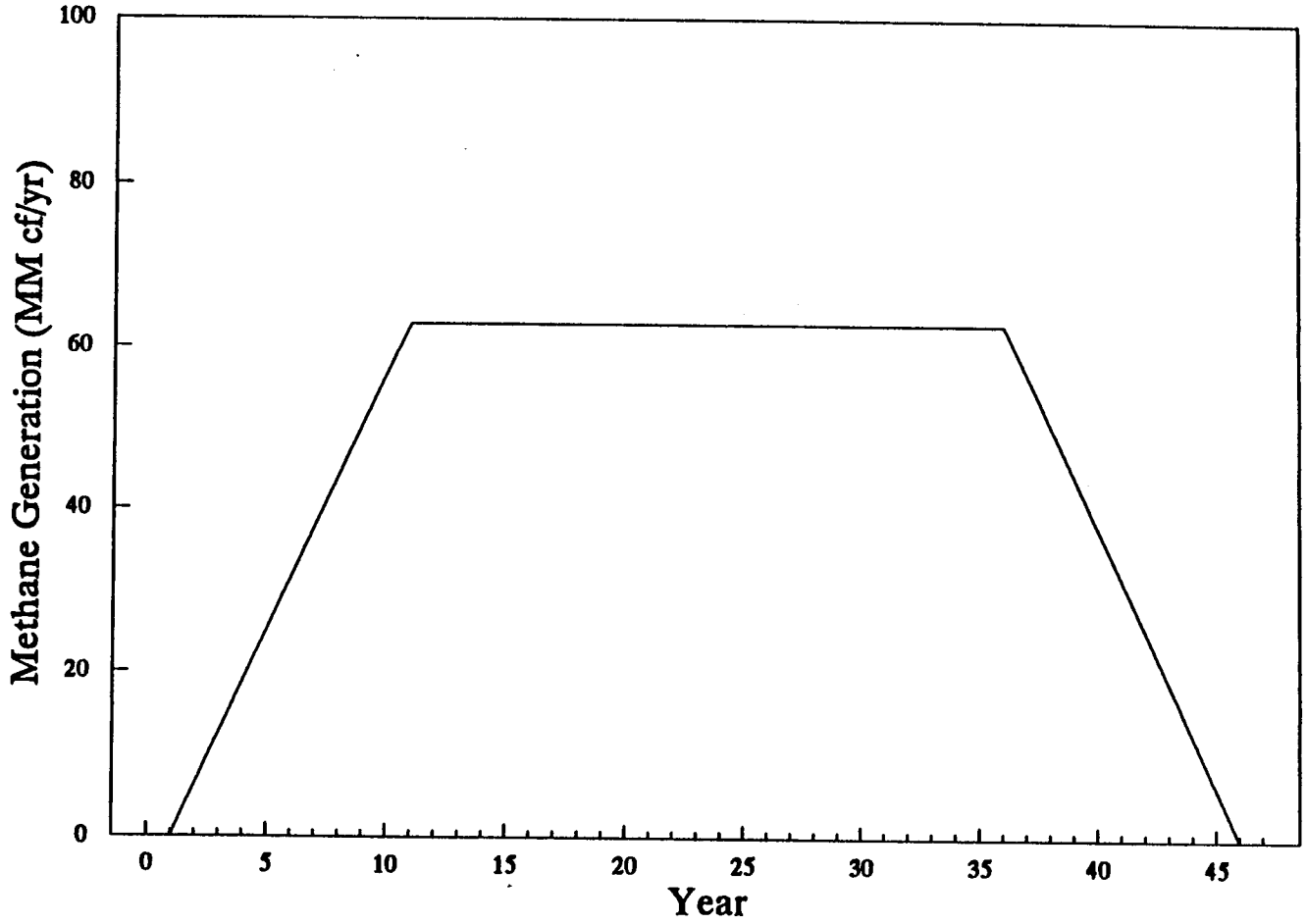
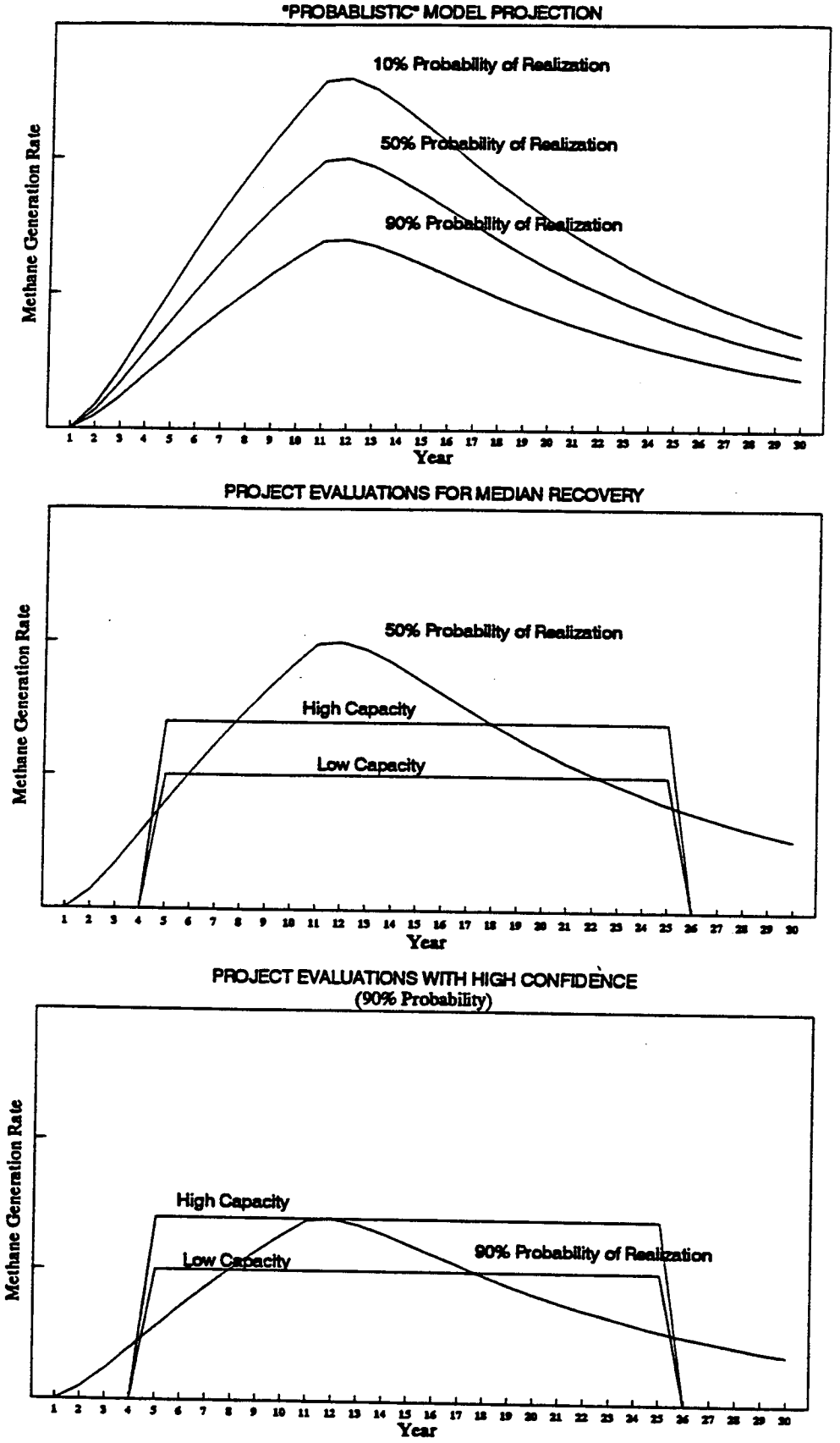


FIGURE 2
USE OF METHANE PROFILES TO EVALUATE ENERGY APPLICATIONS



SECTION 2

SELECTION OF STUDY LANDFILLS AND METHANE MODELS

This section reviews LFG generation as it relates to predictive modeling. Variables and uncertainties inherent in both the development of models and their application are discussed, as well as the criteria used in to select this study's landfills for model development. Finally, this section discusses the basis for the landfill methane models selected for further examination.

BACKGROUND

The approach for this study was to compare selected landfill methane models (model curves) with gas recovery field data from several landfills so as to yield the best predictions, or "best fits". An underlying assumption to this approach is that there is an "average" curve that can best represent and predict methane generation and/or recovery, and that curve-fitting procedures can identify one or more "best" models closest to this average curve. This approach has been applied in previous studies (Oonk, 1994; Zison, 1991; and Augenstein and Pacey, 1991).

Certain terms are used in this report specific to LFG models. Models may refer to either total gas (i.e., LFG) or methane. Because methane is normally the component of interest, this report refers to landfill methane (unless otherwise specified). The term generation refers to the methane generated within the waste mass. Recovery refers to the methane recovered from the waste mass because it is a parameter that can be measured. (This avoids the ambiguous term "production" which can to refer to either methane generation or the actual fraction of methane recovered from that generated).

Landfill Gas Generation

Landfill gas is the mixture of carbon dioxide and methane, and other trace components, generated from waste by bacterial decomposition of waste organics. For cellulose, the principal source of gas from landfilled waste, the conversion reaction is:

$$\underset{\text{cellulose monomer}}{(C_6H_{10}O_5)_n} + n\,H_2O \xrightarrow[\text{bacteria}]{} 3n\,CH_4 + 3n\,CO_2$$

Discussions of landfilled waste decomposition are found in a number of references, including Halvadakis, et. al. (1983), Barlaz (1990), Ham and co-workers (several papers), Pohland and co-workers (several papers), and Augenstein and Pacey (1991).

Several factors govern waste decomposition. Moisture level commonly is considered of greatest importance. Another factor, well-established on fundamental grounds and from laboratory tests (but largely neglected in modeling), is temperature. Figures 3 and 4 show the pronounced effects of moisture and temperature, respectively, from work of Halvadakis, et. al. (1983) and Ashare, et. al. (1993), respectively.

Other factors also affect the rate and quantity of methane generation from wastes. These can include waste composition, waste nutrient level, and the presence or absence of

buffering agents (which may be provided from such sources as cover soils). Landfill operational factors, such as air intrusion, landfill covers, waste compaction, and leachate recirculation also can impact methane generation. Because factors tend to vary from landfill to landfill, some degree of modeling uncertainty is a given.

Sources of Uncertainty in Model Development and Application

Factors giving rise to uncertainties in methane models include:

- Variation in generation due to factors mentioned above;
- Measurement inaccuracies or errors;
- Recovery efficiency variables;
- Substantial variation of relevant parameters spatially within the landfill, becoming more significant with increasing moisture and temperature in certain "pockets" or zones; and
- Discrepancies between the model form chosen and the "true" underlying average generation within a given dataset used to estimate model parameters.

For example, recovery efficiency is a source of variability. It likely varies with the landfill geometry; liner and cover materials (e.g., clay or membrane); cover maintenance; design, installation, and maintenance of the LFG extraction system; and other factors. Recovery efficiency can change with time during active landfilling, with lower recovery expected in the first few years, higher recoveries expected after closure, and levels somewhere in between during the interim years.

Landfill-to-landfill variations in methane generation and recovery occur for reasons that are evident. For example, precipitation/infiltration through cover soils may be greater into some landfills than others, and subsequent methane generation may be accelerated where there is more infiltration. However, excessive oxygen infiltration into the waste mass impedes methane production. Also, warm region landfills decompose more rapidly than cold region landfills. While landfills self-warm as methane generation occurs, heat dissipation rates vary.

What is important for modeling is not so much the source of uncertainties but their effect in the aggregate. In aggregate the uncertainties create deviations between any model's prediction and subsequent field experience. This deviation is referred to as "model error" or "uncertainty" in this report. The degree of model error intrinsic to a given model is important to describe, but has not been explicitly characterized for any large database in landfill methane model work to date. There exist "probabilistic" ways of expressing probability of methane recovery lying within any given set of bounds. Identification and expression of these bounds were project objectives.

Some uncertainties can be reduced. One way is to select landfills with superior data. Uncertainties also can be compensated for or reduced by establishing correlations between site factors and gas recovery.

The value of reliable methane recovery data and corresponding reliable site factors was illustrated by Oonk, et. al. (1994). Using data from 12 Dutch landfills with good apparent recovery and good knowledge of site history and site factors (e.g. annual waste placement, design, extraction monitoring, etc.), three different trial models "fit" recovery with similar accuracy (by statistical indices). Maximum error of about 30 percent was reported, generally better than reported by U.S. experience[1].

SELECTION OF STUDY LANDFILLS

Candidate landfills for this study ("study landfills") were sought with the following characteristics:

- Gas recovery efficiency is maximized. This was considered associated with as many as possible of the following features:
  - Scavenging of LFG for energy-limited equipment;
  - Well-maintained covers (clay or synthetic) and frequent well monitoring;
  - Good well density;
  - "Efficient" well configuration in terms of close spacing, greater (rather than lesser) depth;
  - Wellhead and header pipeline methane contents at 40 to 50 percent (rather than 50 to 60 percent), suggesting tuning of wells for maximum recovery;
  - Maintenance of methane below regulatory limits by surface scan (now mandated in many regions of the country); and
  - Maintenance of odors below odor thresholds.
- Accurate waste gate receipt and placement history.

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[1] Such "goodness of fit" may relate to the relative uniformity of Dutch landfills and wastes, but nonetheless supports use of the best site data.

- Methane recovery over significant durations. Typically, methane has been recovered at U.S. landfills for only a portion of the time needed for complete generation. Also, little information exists on methane recovery after closure of the landfill. Consequently, study landfills were sought with long-term recovery data.

- Other site features known. These include waste composition (for example, presence of unusual quantities of inerts or degradable materials), knowledge of leachate quantities (a surrogate for waste moisture), degrees of compaction, internal temperature, site geology/soils (for example, clay layers which would tend to prevent lateral migration), rainfall, and other features which might affect or correlate with methane generation and recovery.

- Measurements of methane recovery by methods accepted as accurate.

- Ready accessibility of records.

An initial goal of the project was to elicit site information relevant to methane generation and recovery through a questionnaire which was prepared and mailed to selected landfill owners/operators. A copy of this questionnaire is included as Appendix B.

Many of the questionnaires were not returned, perhaps because they required significant input from respondents. In other cases, limited, partial, or no answers were given for the questions. Site data that were sought were fragmentary or lacking, such as in-waste temperature, in-waste moisture, and corrections to gate tonnage for factors affecting levels of decomposable material. Follow-up communications filled some data gaps; overall, site information provided was limited.

Several factors were grounds for exclusion of a landfill from the study. The principal (and frequently encountered) reason for exclusion of a landfill was that methane recovery was not maximized (for many landfills, only enough methane was recovered to support energy equipment. These landfills were unsuitable because total recoverable methane was unknown). Another reason was absence of gate tonnage data (volume receipts alone were not considered accurate enough for study purposes).

Table 1 presents the list of landfills screened and from which the study landfills were selected. Of the 26 landfills considered, 18 were ultimately judged to have acceptable characteristics for inclusion in the study. Waste placement data obtained for each site are given in Appendix A. Some landfill owners allowed use of their data only on the condition of anonymity. Accordingly, the selected landfills were identified by code letters.

Most of the landfill sites selected had good waste placement history and waste tonnages. For some landfills filling histories for early years relied on staffs' estimates of placement based on filled waste volumes. Although long-term methane recovery data were sought, only a few landfills (in California) had recovery histories of ten years or more. East Coast landfills had fill data on the order of a few years.

In essence, "perfect" landfill sites were not found in terms of meeting most of the desirable criteria for model comparisons. Field data typically are much less than ideal and

often are incomplete. Generally, the best data were obtained from the landfill sites operated by the Sanitation Districts of Los Angeles.

Because this study represents a limited set of landfills, data from landfills not typical of the study landfills may not be comparable. However, efforts were made to include a cross-section of U.S. landfills (with the normal uncertainties and methane recovery variations) so as to allow basic comparisons in model outputs (including predictive ability and confidence limits) to "average" or "typical" U.S. landfills. Models limited to this predictive ability still represent a significant advance over previous published work.

SELECTION OF LANDFILL METHANE MODELS

Landfill methane models considered for the study were based on previous studies and usage in the LFG industry. Some models were not selected for inclusion (examples are certain model forms proposed in Zison [1990]). Kinetic estimates (which have significant "guess" components, precedent, and field experience) are important model forms in the industry. Model forms that are commonly considered are discussed in Van Zanten and Scheepers (1995) and in Augenstein and Pacey (1991).

A goal of the project was to select landfill methane models with fairly simple structures and are easy to use. In part, this is because any model of sufficient complexity--with sufficient adjustable parameters--can be fit to any dataset. Yet, ability to obtain a perfect fit does not confirm a model's correctness.

Certain field measurements should (in principle) provide ideal methane generation profiles upon which to base model forms. For example, an ideal measurement for purposes of model development would be of long-term methane generation/recovery for a landfill cell filled over a short interval, with known relevant parameters (such as moisture content, etc.). The cell could be monitored closely over time so that total methane output could be assumed to represent a batch methane generation profile and thus, provide a "true" model curve for landfilled wastes under a given set of conditions.

There have been some measurements of methane generation from single batches along these lines. The results are informative, but less than helpful with respect to ideals of modelers. In one case a completely enclosed control cell was operated as part of a landfill test project (Augenstein and Pacey, 1991). The generation curve from this enclosed cell is shown in Figure 5.

In another case, gas recovery data were collected from five waste cells at a California landfill (Yolo Central) over a six-year interval. These data yield normalized methane per year per ton of waste in place for each of the five cells as a function of time since waste placement. These results are depicted in Figure 6.

Both Figures 5 and 6 should represent a close match of an ideal batch generation profile (i.e., the "model curve") for the particular waste masses measured. However, the generation and/or recovery field data are irregular over time, with many short-term

variations that are difficult to explain. In essence, field data typically do not match mathematical model curves in the published literature.

As landfilling proceeds over a longer time and more waste is added which contributes to the landfill's generation/recovery profile, short-term fluctuations in generation from individual waste lots average out. Even if a postulated model form does not match the generation profile of a single waste batch exactly, it can be useful to replicate the longer term generation profiles of "real" landfills.

With these issues in mind, four model forms (taking the form of mathematical expressions) were selected for evaluation and comparison. The background and basis for each model choice are discussed briefly below.

With each model, parameters which can be adjusted to optimize the model are shown in boxes beneath the model equations. Each model requires input values for adjusted waste placement data and the noted parameters to make projections for a given model year. Because the model equations for the value G (methane generation by volume) are for individual "batches" or years, the batches must be summed for the years desired to provide the gas generation time curve. Mathematical expressions for the models are as follows:

<u>Model 1: Zero Order Model</u>

$$G = \frac{W L_o}{(t_l - t_f)} \quad \text{for } t_l<t<t_f$$

Where:

G = methane generation, million cubic feet per year;
W = waste in place, tons;
L_o = methane yield potential, cubic feet methane per ton of waste;
t = time, years;
t_l = lag time (between placement and start of generation); and
t_f = time to endpoint of generation.

Parameters adjustable to fit field data for optimization: t_l and t_f (or the interval t_f-t_l).

This model is used fairly extensively in the landfill gas industry.

Model 2: Simple First Order Model

$$G = W L_o k e^{-k(t-t_l)}$$

Where:

G = methane generation, million cubic feet per year;
W = waste in place, tons;
L_o = methane yield potential, cubic feet methane per ton of waste;;
t = time after waste placement, years;
t_l = lag time (between placement and start of generation); and
k = first order rate constant.

Parameters to vary initially for best fit to field data: k and t_L

Variants of this model are used extensively. A public domain computer version is available from EPA.

Model 3: Modified First Order Model

$$G = W L_o \frac{k+s}{s} (1-e^{-s(t-t_l)}) (k e^{-k(t-t_l)})$$

Where:

G = methane generation, million cubic feet per year;
W = waste in place, tons;
L_o = methane yield potential, cubic feet methane per ton of waste:
t = time after waste placement, years;
t_l = lag time (between placement and start of generation);
k = first order decay rate constant; and
s = first order rise phase rate constant.

Parameters to adjust to fit field data: t_l, k, and s.

This model is described by Van Zanten and Scheepers (1995). The model form assumes that methane generation/recovery initially may be low (i.e., there is a "lag"). Recovery then rises to a peak before declining in what is essentially exponential fashion.

Model 4: First Order Multi-Phase Model

$$G = W L_o [F_{(r)} (k_{(r)} e^{-k_{(r)}(t-t_l)}) + F_{(s)} (k_{(s)} e^{-k_{(s)}(t-t_l)})]$$

Where:

G = methane generation, million cubic feet per year;
W = waste in place, tons;
L_o = methane yield potential, cubic feet methane per ton of waste;
t = time after waste placement, years;
t_l = lag time (between placement and start of generation);
$k_{(r)}$ = first order decay rate constant for rapidly decomposable waste;
$k_{(s)}$ = first order decay constant for slowly decomposable waste;
$F_{(r)}$ = fraction of rapidly decomposable waste; and
$F_{(s)}$ = fraction of slowly decomposable waste.

Parameters to adjust to fit field data: t_l, k(r),k(s), F(r) , and F(s).

Model 4 is a refinement of Model 3 (the modified first order model) above. Its assumptions are the same, except that differing waste fractions are assumed to decompose at different rates. Variants of this model are applied commercially. This model gave the best results (by narrow margin) in modeling work of Oonk, et. al. (1994).

Parameter Sensitivity

To estimate annual methane emissions, each model accepts inputs for the refuse filling history and methane generation parameters. Some input parameters are used by several models; others are specific to one particular model. To illustrate model outputs and the effects of varying parameters, trial runs of the four models were used to estimate methane emissions from an example landfill. Parameter sensitivity was ascertained by varying one parameter with selected values while keeping other parameters constant.

The example landfill for this parameter sensitivity effort received 100,000 tons of refuse per year for 10 years (i.e., resultant waste-in-place is 1 million tons).

Model 1 --

The Zero Order Model has two parameters: the methane yield potential (Lo) and duration of methane generation (time in years). A graphic summary of the sensitivity for these two parameters is shown in Figure 7 (for Lo) and Figure 8 (for time).

As shown in Figure 7, the impact of varying Lo in Model 1 is direct: during peak methane generation periods (i.e., the flat peak of the curve), cubic feet of methane per year vary inversely with Lo.

Model 2 --

The Simplified First Order Model has two parameters: the methane yield potential (Lo) and the decay rate (k). Figures 9 and 10 show sensitivity to the parameters Lo and k.

As shown in Figure 9, the impact of varying Lo in Model 2 is significant: the estimated rate has a direct relationship to the selected value for Lo. Similarly, Figure 10 shows that as k is increased, recovery increases and time span decreases. The rate of falloff for methane generation increases markedly with increasing k.

Model 3 --

The Modified First Order Model has three parameters: the methane yield potential (Lo), the decay rate (k), and the rise phase constant (s). Sensitivity testing is illustrated as follows:

Figure 11 depicts the effects of varying Lo;
Figure 12 depicts the effects of varying k; and
Figure 13 depicts the effects of varying s.

The impact of varying Lo in Model 3, as with Model 2, is to increase generation proportionally to Lo. Effect of varying k in Model 3 is similar to the effect exhibited in Model 2. These results are not surprising, given similarities between Models 2 and 3.

Figure 13 depicts the effect of varying "s" in the Modified First Order Model. In this model, values for "s" fix the rate of rise in methane generation/recovery after filling. (As noted above, the justification for this model form is that such a rise from initially low rates of recovery is commonly observed in the field.) Figure 13 shows the effect of the rise phase constant "s" on the time to reach peak generation, and the peak rate at which methane is generated. The rise phase constant also has a minor effect in the rate of decay from peak generation.

Model 4 --

The Multi-Phase First Order Model has four parameters: the methane yield potential (Lo); the fraction of rapidly decomposing refuse, F(r); the decay rate of rapidly decomposing refuse, k(r); and the decay rate of slowly decomposing refuse, k(s).

A graphic summary of sensitivity testing for this model is summarized by parameter as follows:

Figure 14 depicts the effects of varying Lo;
Figure 15 depicts the effects of varying k(r);
Figure 16 depicts the effects of varying k(s); and
Figure 17 depicts the effects of varying waste composition.

Methane recovery at any given time is directly proportional to Lo; that is, doubling the selected value for Lo will double the estimated peak generation rate. Of the two decay values, variations in k(r) has a minimal effect on the generation pattern while changes to

k(s) have a more pronounced effect on model results.

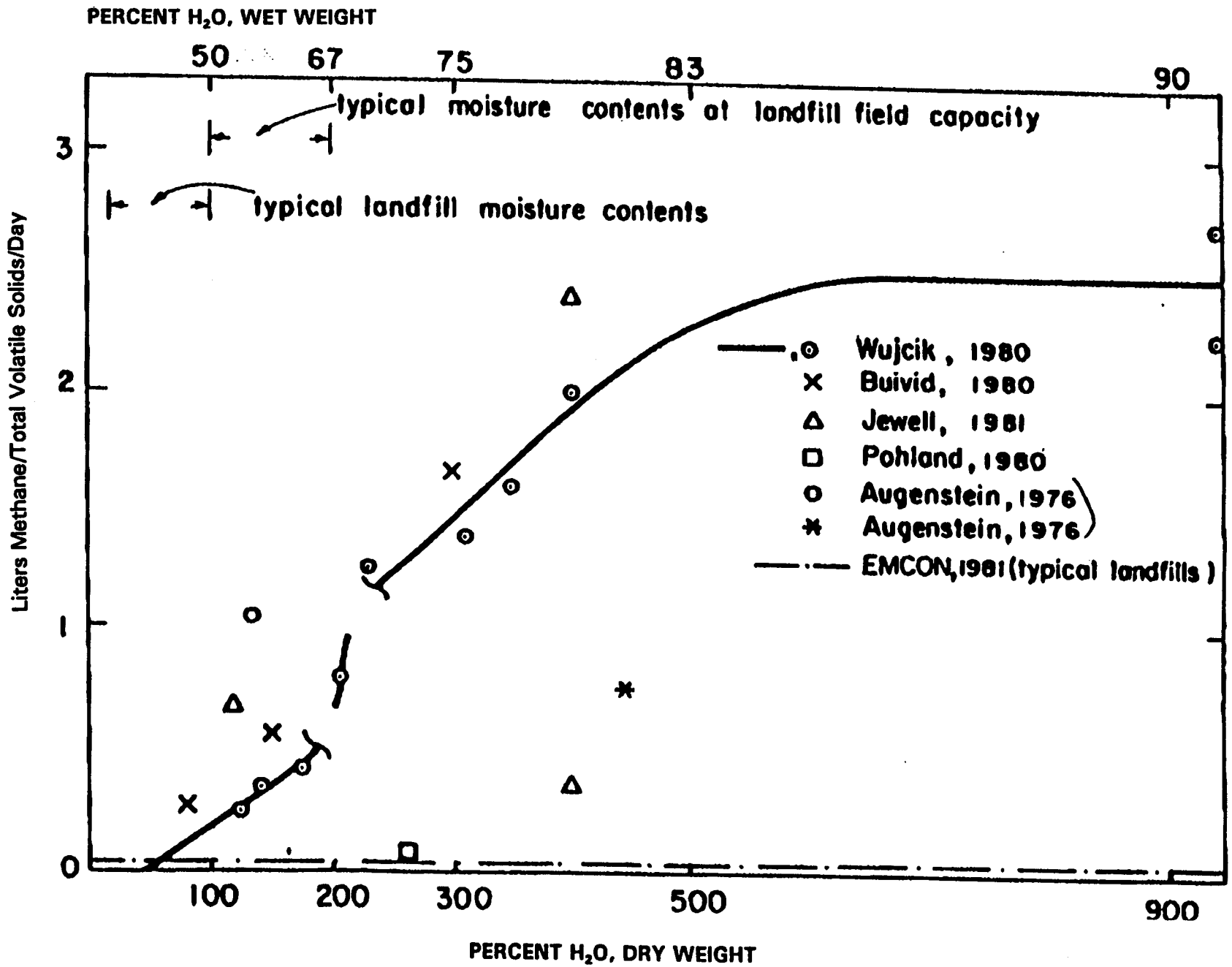
As might be anticipated, Model 4 will be sensitive to changes in waste composition. As the selected value for F(s) is increased, peak generation (and time to reach this state) is decreased. However, the rate of tail-off in recovery is correspondingly less pronounced when a high fraction of slower decaying waste is assumed.

The procedures to estimate "best" values for model parameters and to allow comparisons between the four models are discussed in Section 3.

TABLE 1
SELECTION OF LANDFILL SITES

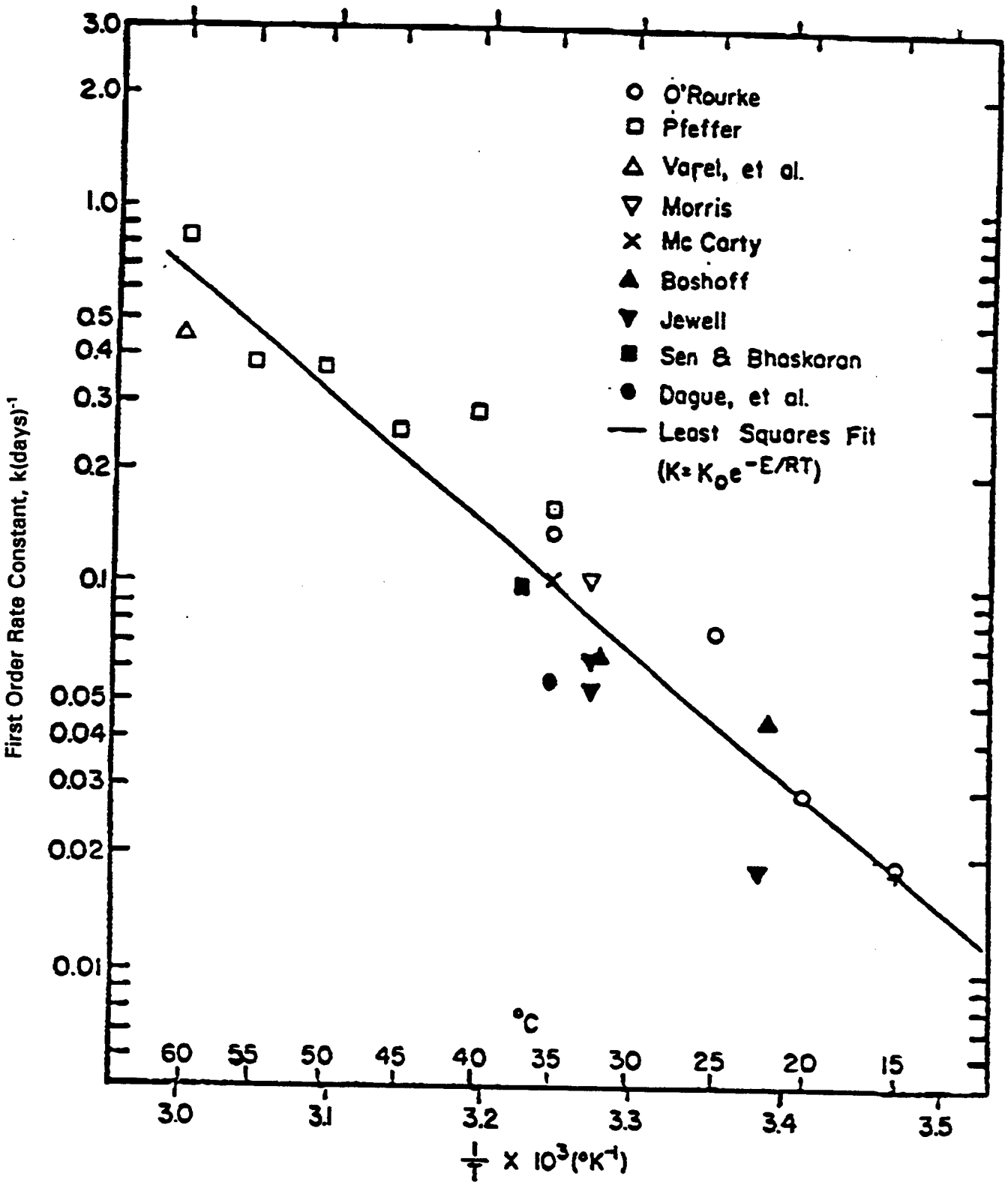
Landfill Sites Considered	Landfill Sites Selected
American Canyon Landfill, CA	
Calabasas Landfill, CA	Calabasas Landfill, CA
Marina Landfill, CA	
Marsh Road Landfill, CA	
Mission Canyon Landfill, CA	Mission Canyon Landfill, CA
Newby Island Landfill, CA	
Palos Verdes Landfill, CA	Palos Verdes Landfill, CA
Penrose Landfill, CA	
Puente Hills Landfill, CA	Puente Hills Landfill, CA
Scholl Canyon Landfill, CA	Scholl Canyon Landfill, CA
Spadra Landfill, CA	Spadra Landfill, CA
Toyon Landfill, CA	
Yolo County Landfill, CA	Yolo County Landfill, CA
City Sand Landfill, MI	City Sand Landfill, MI
Dunbarton Landfill, NH	Dunbarton Landfill, NH
Hamm's Landfill, NJ	Hamm's Landfill, NJ
Kinsley Landfill, NJ	Kinsley Landfill, NJ
Oceanside Landfill, NY	Oceanside Landfill, NY
Onondaga Landfill, NY	Onondaga Landfill, NY
Old Bethpage Landfill, NY	Old Bethpage Landfill, NY
Smithtown Landfill, NY	Smithtown Landfill, NY
Elda Landfill, OH	
Amity Landfill, PA	Amity Landfill, PA
Intervale Landfill, VT	Intervale Landfill, VT
Cathcart Landfill, WA	
Spokane South Landfill, WA	Spokane South Landfill, WA

FIGURE 3
EFFECTS OF MOISTURE ON METHANE GENERATION



Source: Malvadr... t. al. (1983).

FIGURE 4
EFFECTS OF TEMPERATURE ON METHANE GENERATION



Source: Ashare, et. al. (1993).

FIGURE 5
METHANE RECOVERY FROM MOUNTAIN VIEW LANDFILL TEST CELL

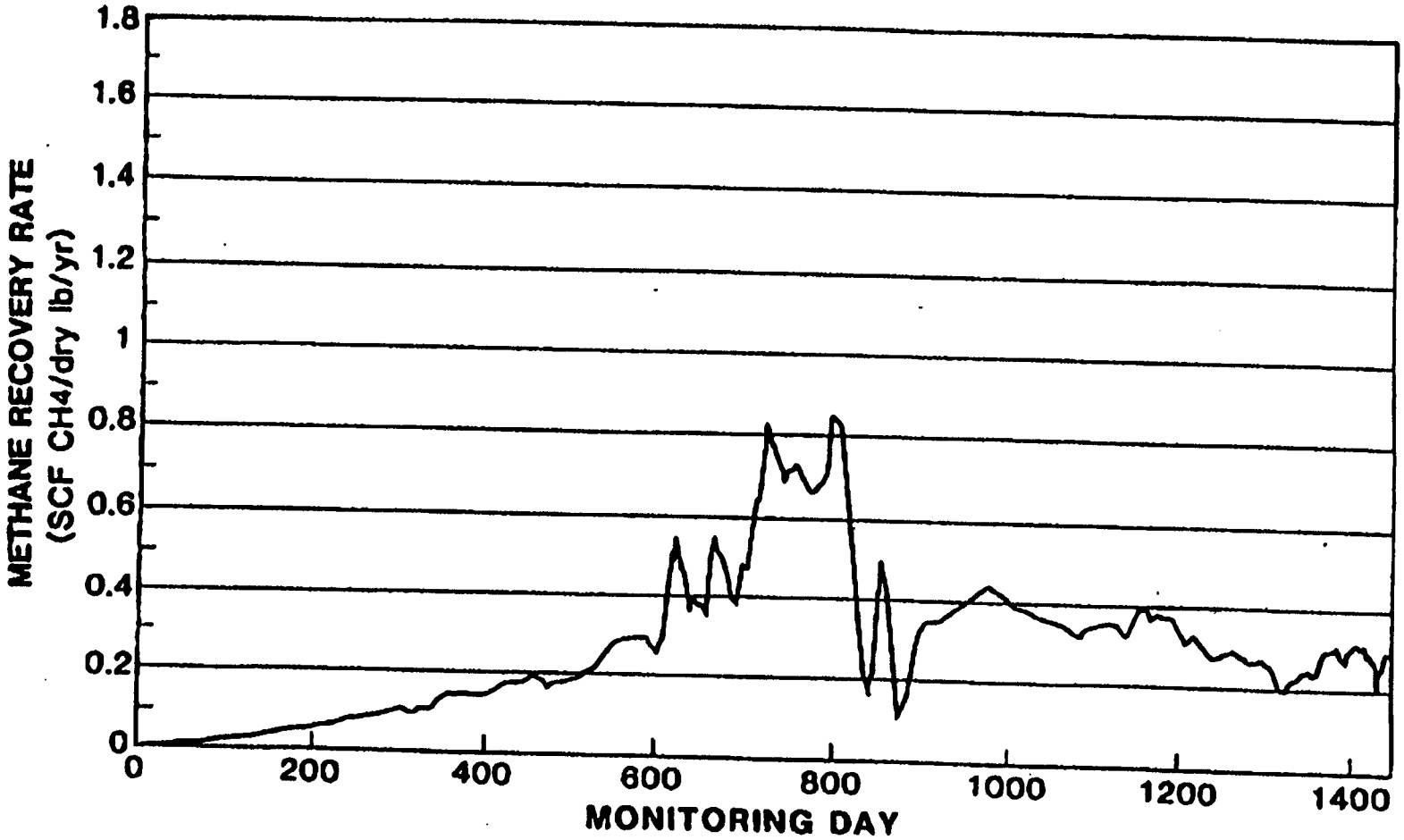


FIGURE 6
METHANE RECOVERY FROM YOLO COUNTY LANDFILL TEST CELLS

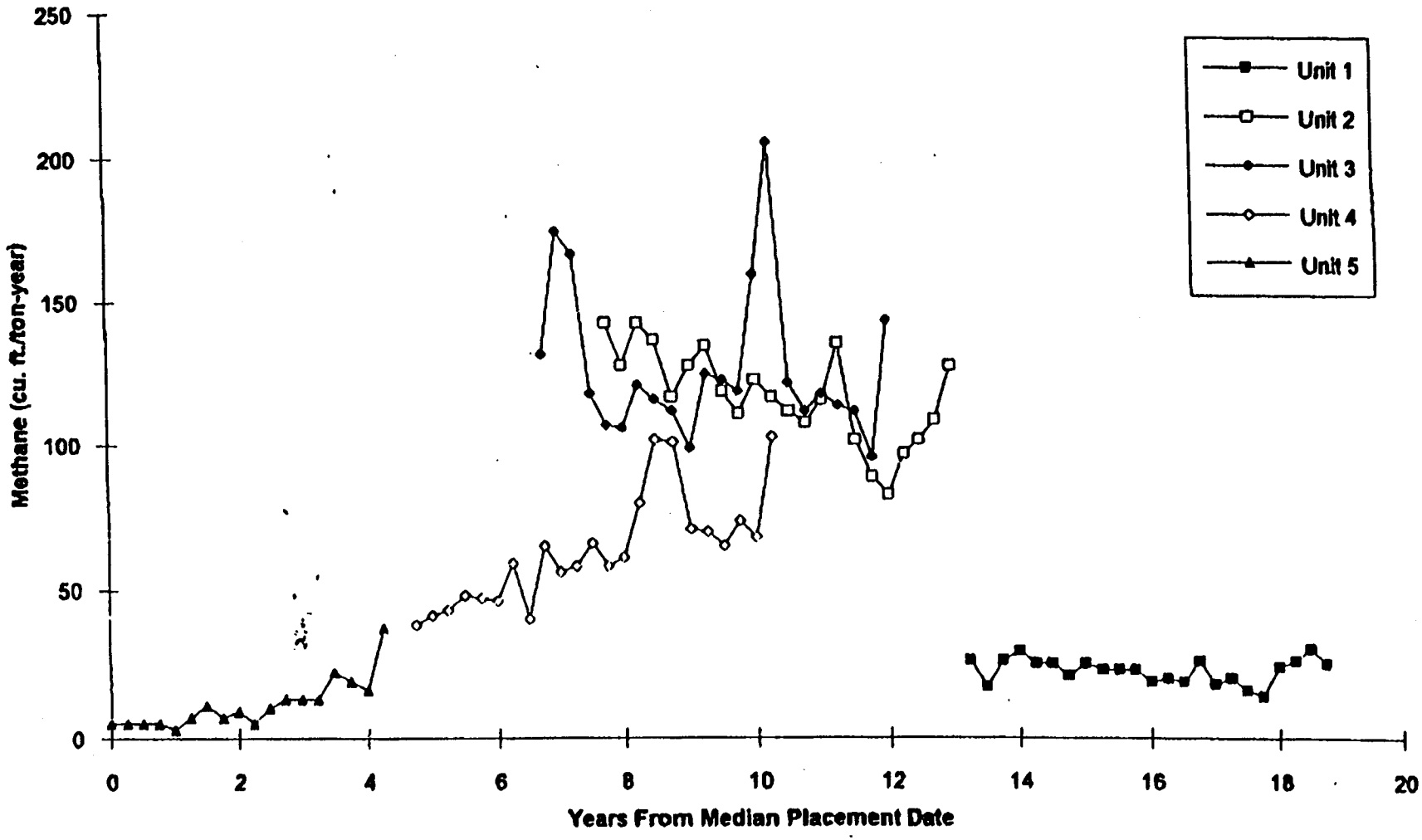
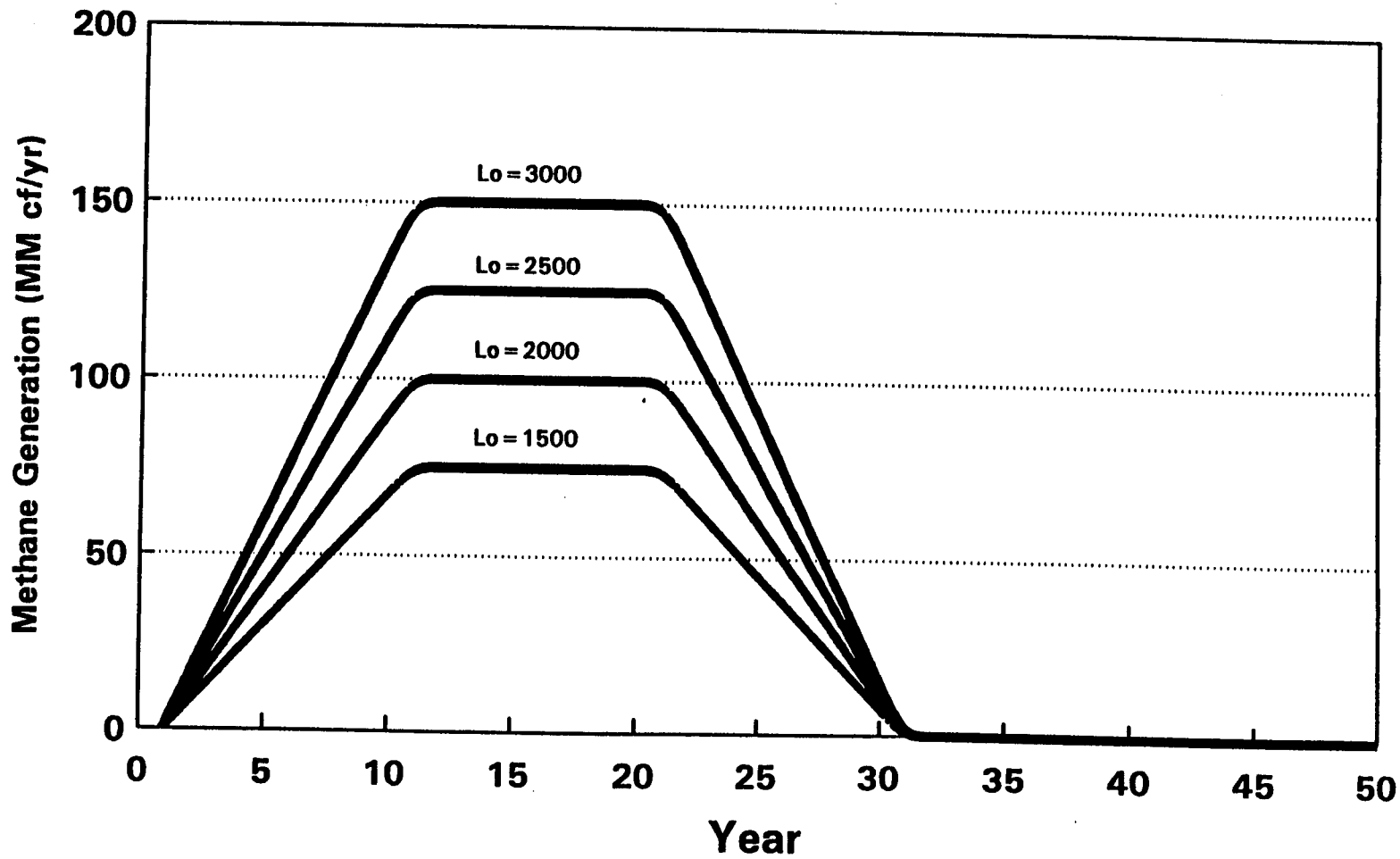


FIGURE 7
MODEL 1 (Zero Order Model)
EFFECTS OF VARYING L_o
ON METHANE GENERATION



Lo = Methane Yield Potential (cubic feet CH4/ton refuse)

FIGURE 8
MODEL 1 (Zero Order Model)
EFFECTS OF VARYING TIME
ON METHANE GENERATION

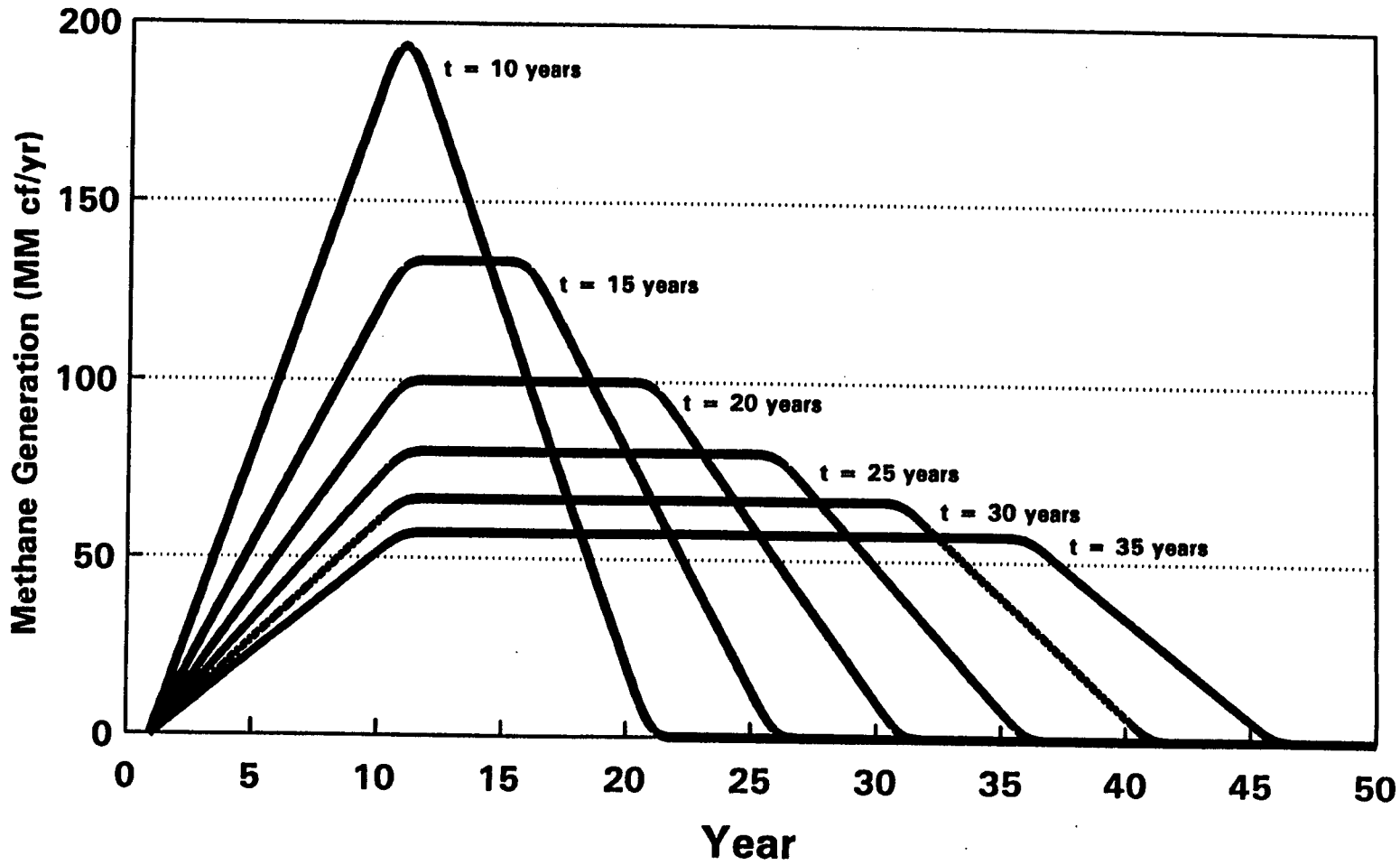
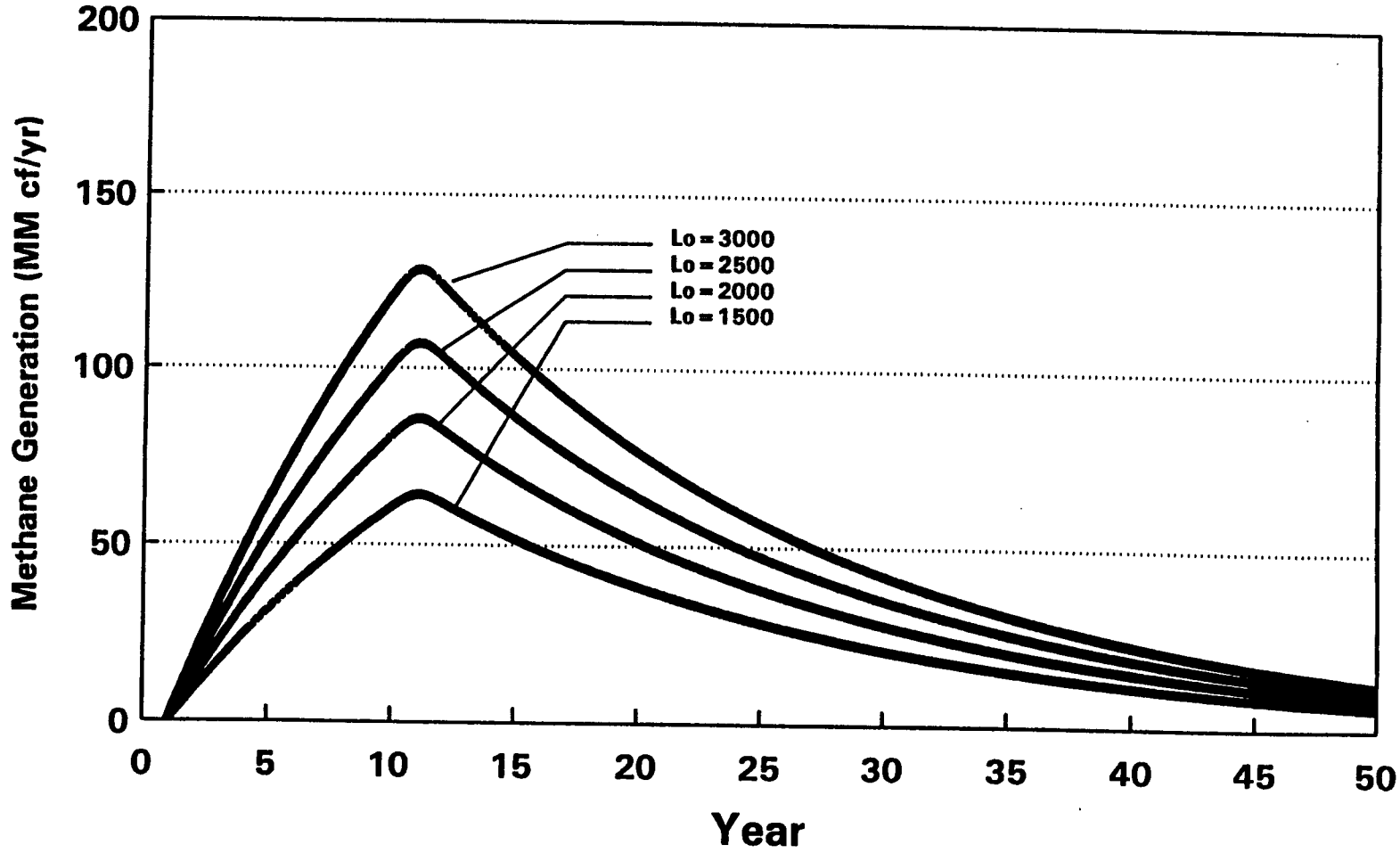
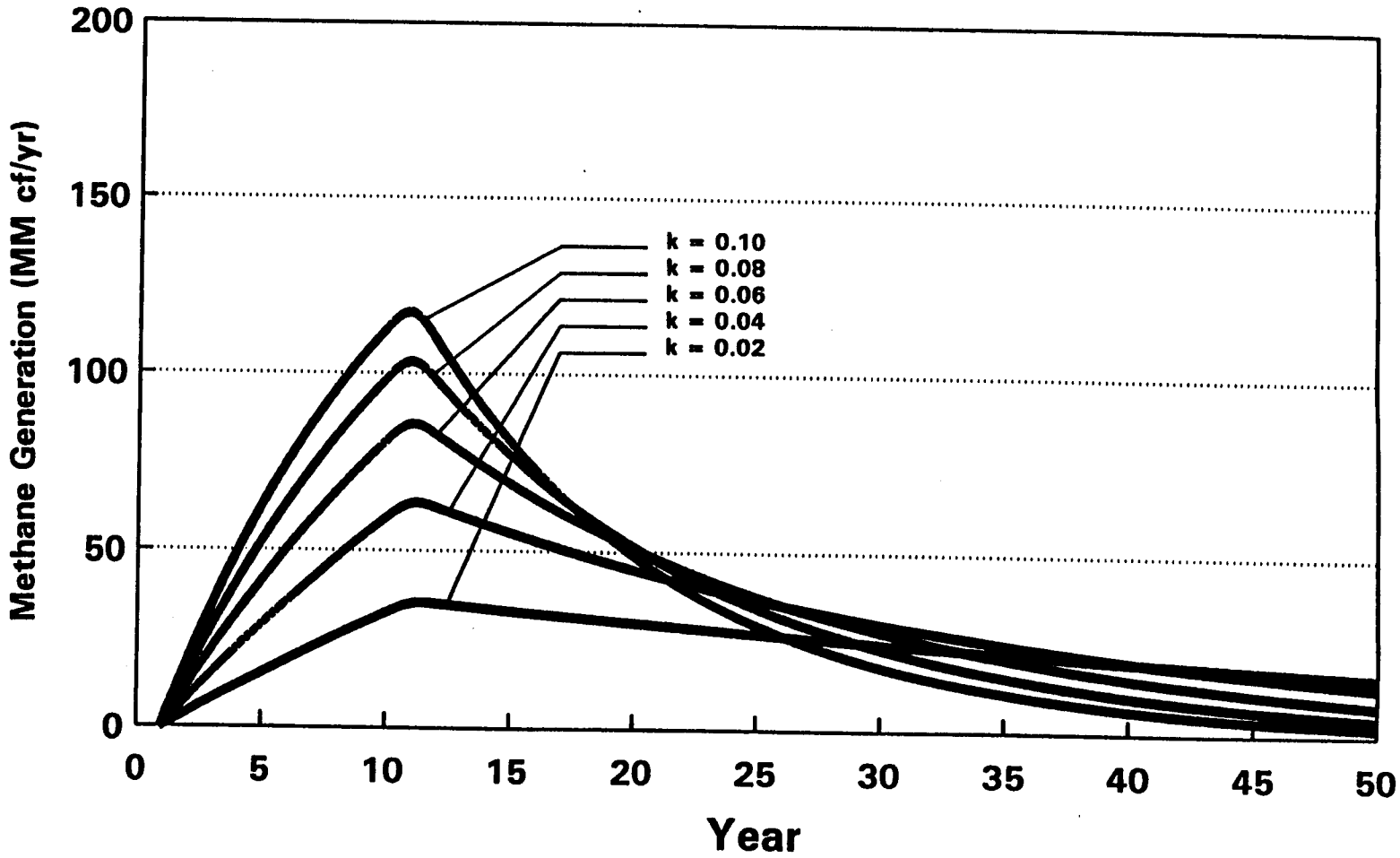


FIGURE 9
MODEL 2 (Simple First Order Model)
EFFECTS OF VARYING L_o
ON METHANE GENERATION



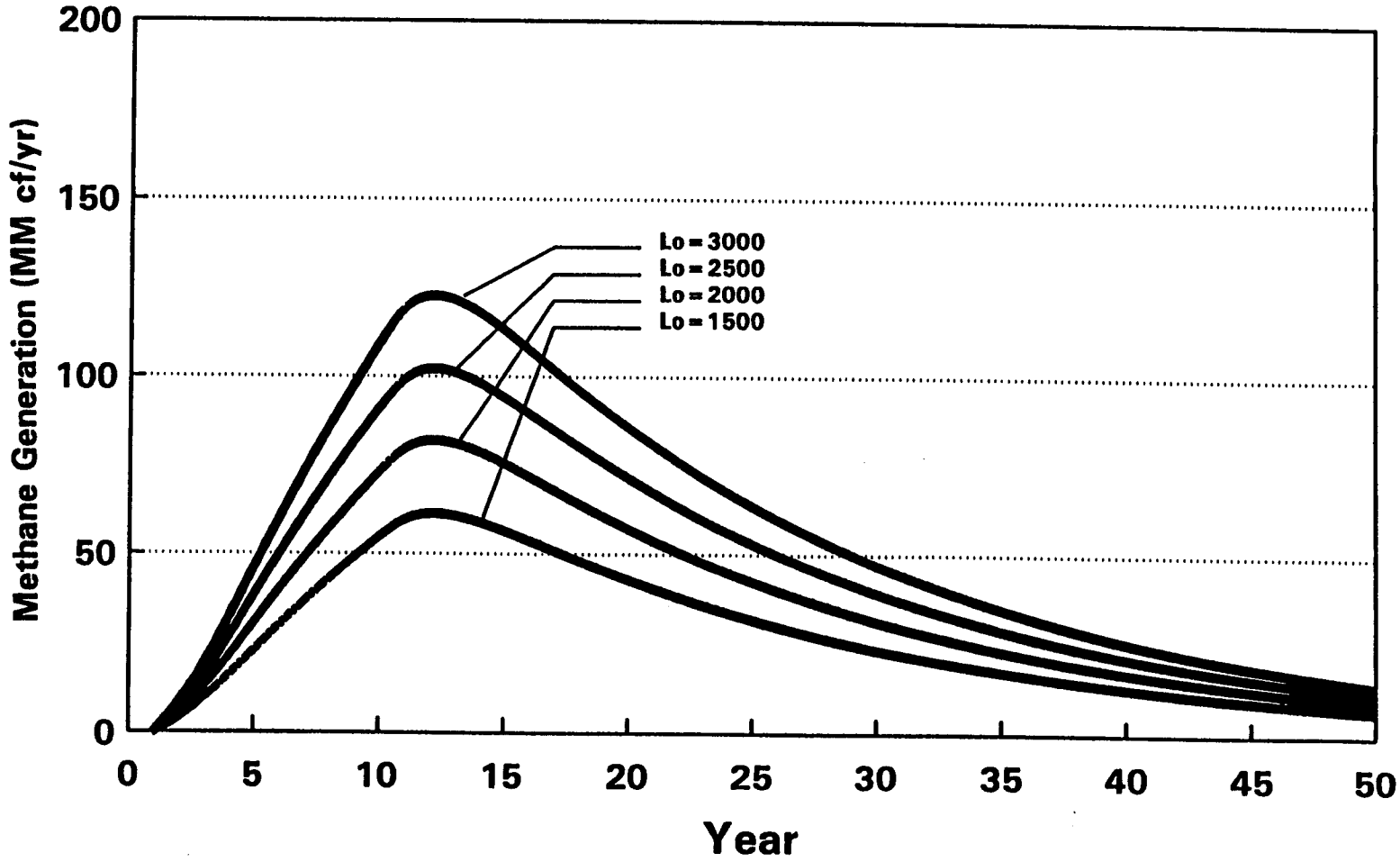
Lo = Methane Yield Potential (cubic feet CH4/ton refuse)

FIGURE 10
MODEL 2 (Simple First Order Model)
EFFECTS OF VARYING k
ON METHANE GENERATION



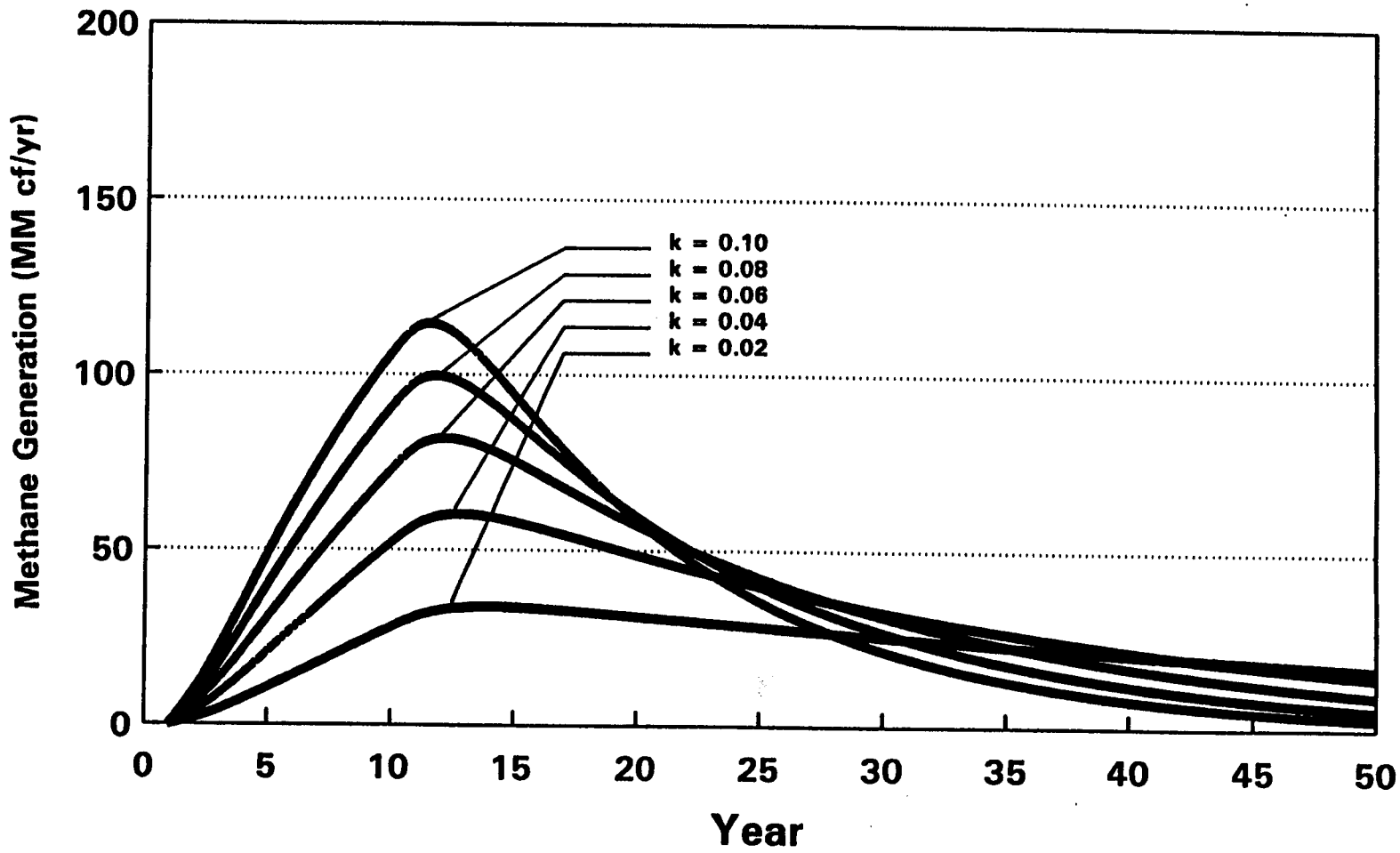
k = First Order Decay Rate per year

FIGURE 11
MODEL 3 (Modified First Order Model)
EFFECTS OF VARYING L_o
ON METHANE GENERATION



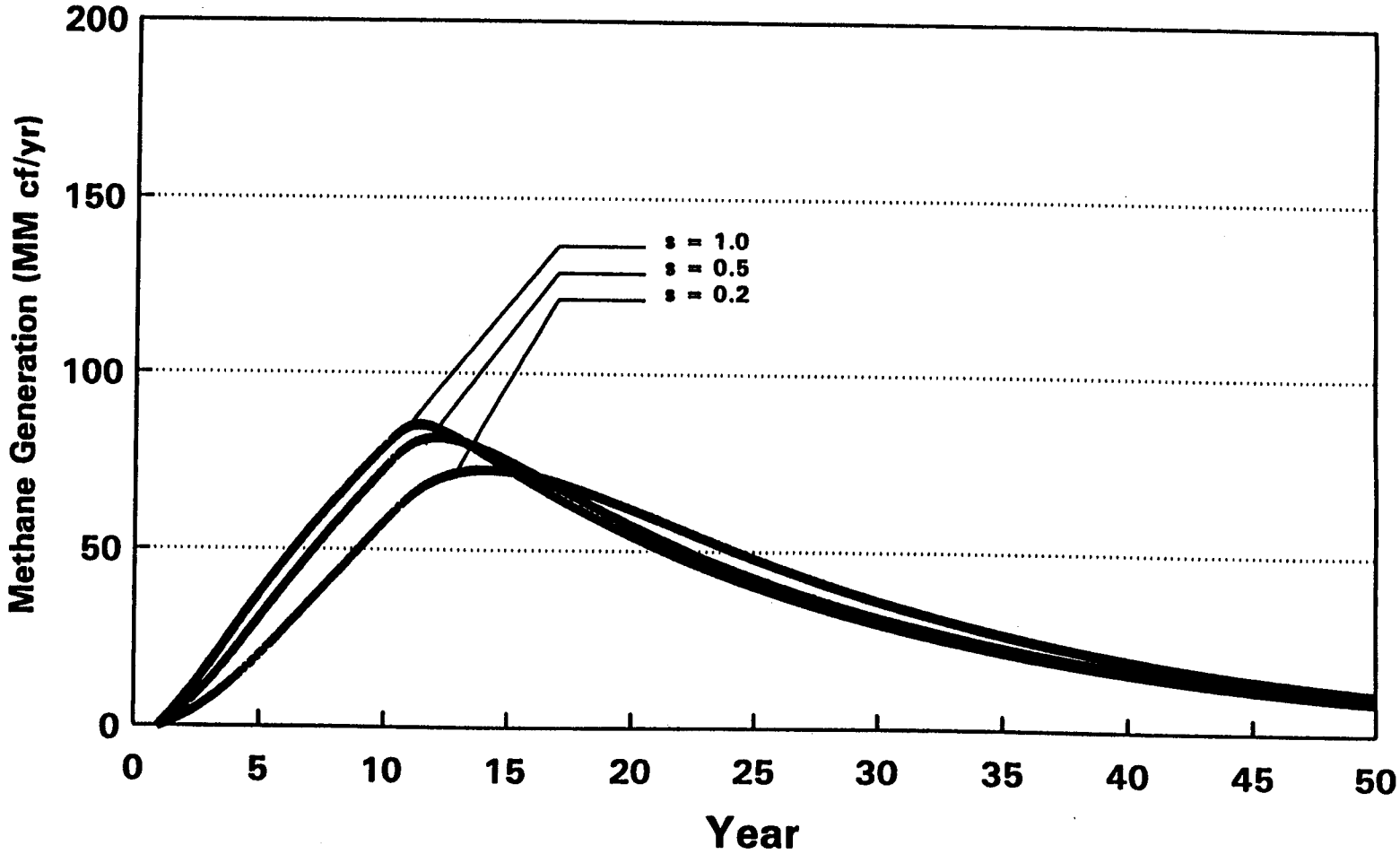
Lo = Methane Yield Potential (cubic feet CH4/ton refuse)

FIGURE 12
MODEL 3 (Modified First Order Model)
EFFECTS OF VARYING k
ON METHANE GENERATION



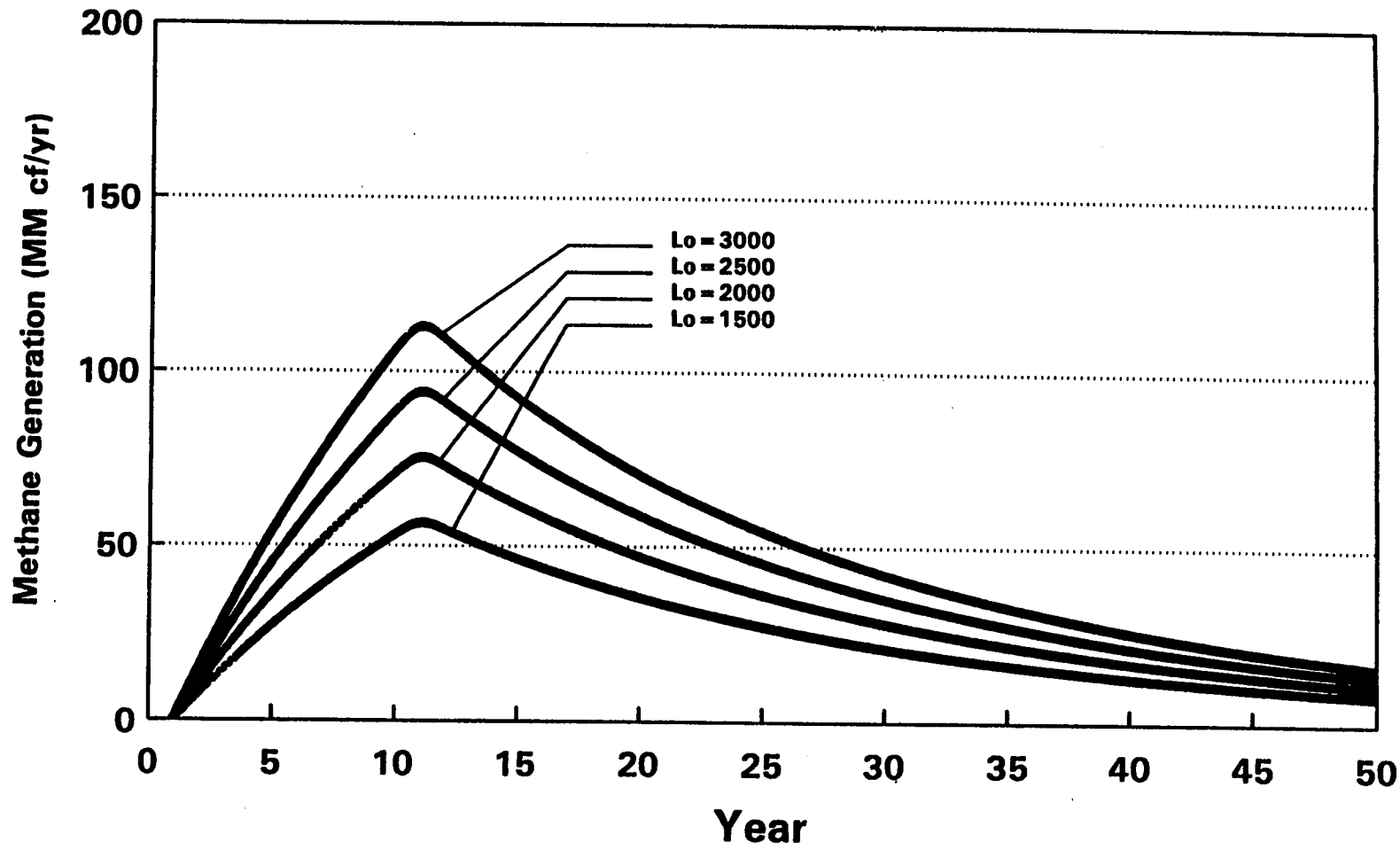
k = First Order Decay Rate per year

FIGURE 13
MODEL 3 (Modified First Order Model)
EFFECTS OF VARYING s
ON METHANE GENERATION



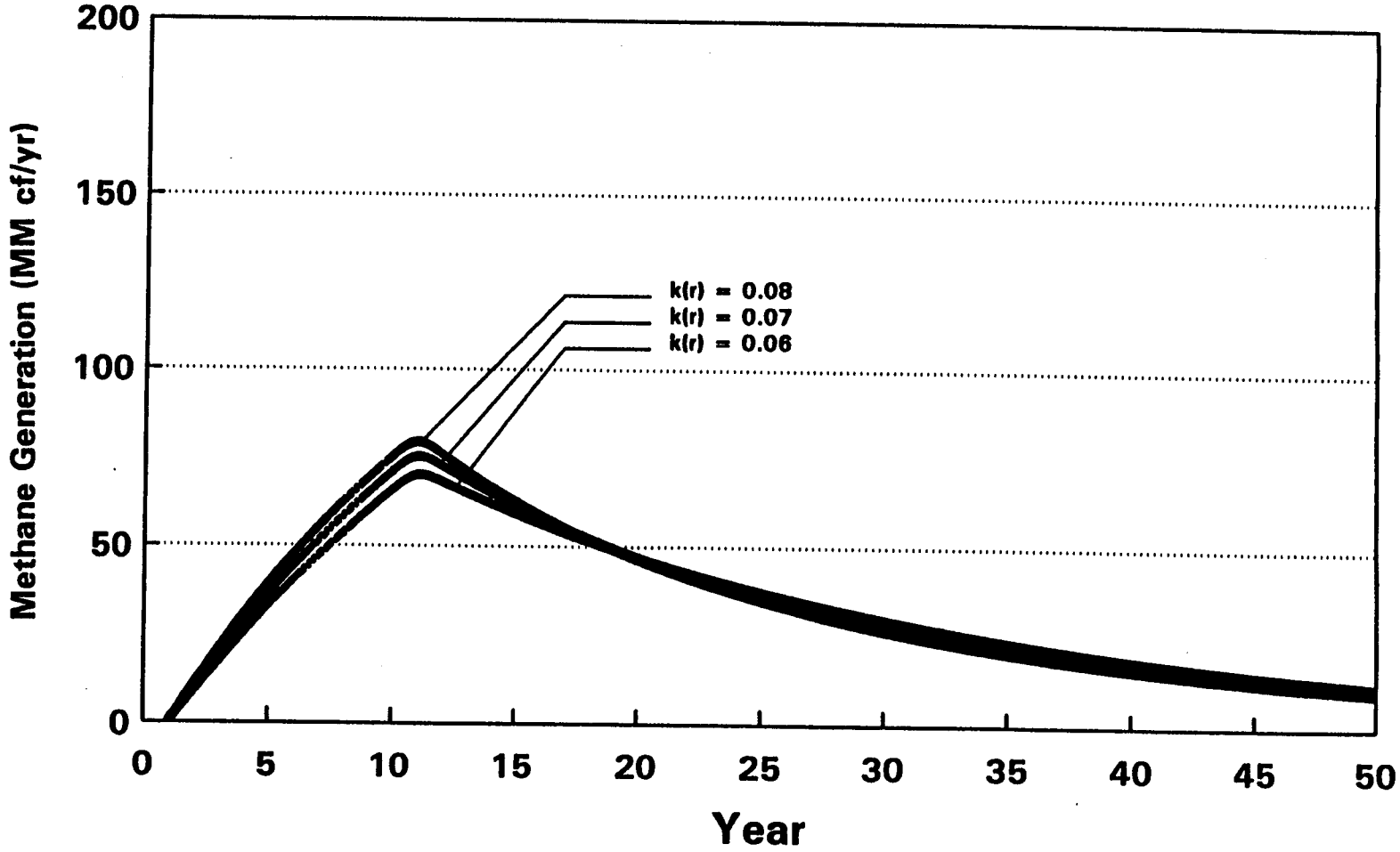
s = First Order Rise Phase Rate Constant per year

FIGURE 14
MODEL 4 (Multi-Phase First Order Model)
EFFECTS OF VARYING L_o
ON METHANE GENERATION



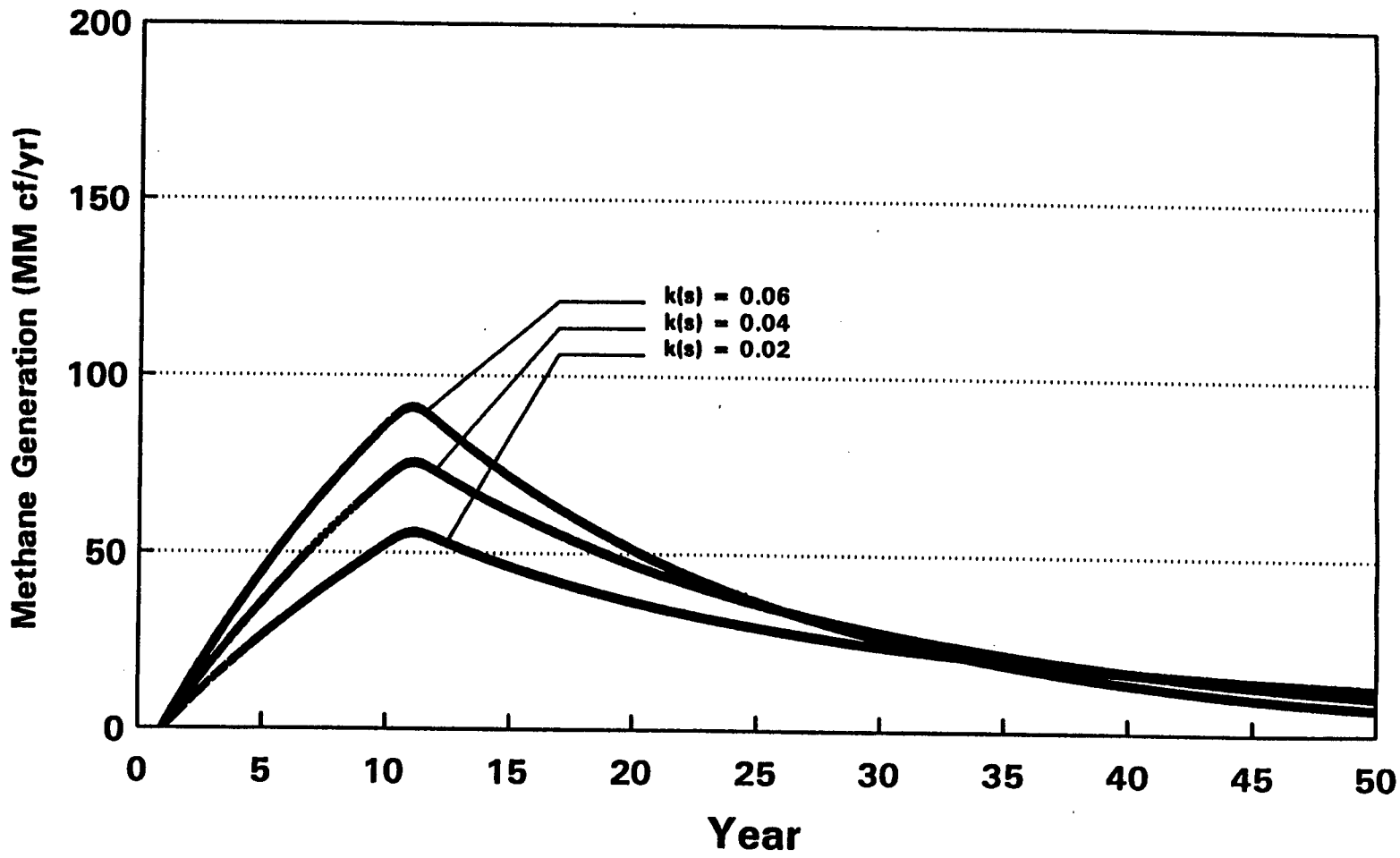
Lo = Methane Yield Potential (cubic feet CH4/ton refuse)

FIGURE 15
MODEL 4 (Multi-Phase First Order Model)
EFFECTS OF VARYING $k_{(r)}$
ON METHANE GENERATION



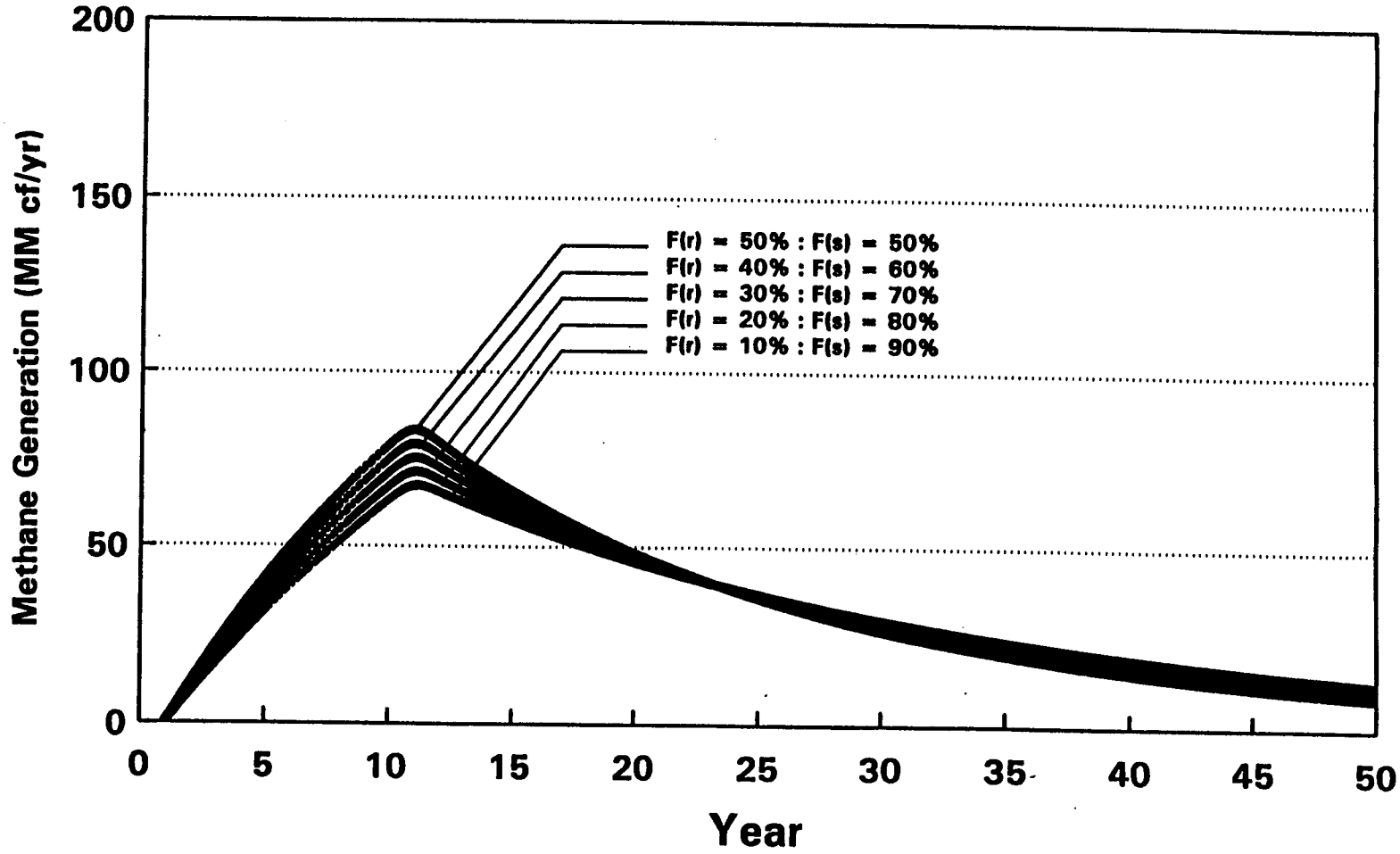
k(r) = Annual Decay Rate for rapidly decomposing refuse

FIGURE 16
MODEL 4 (Multi-Phase First Order Model)
EFFECTS OF VARYING $k_{(s)}$
ON METHANE GENERATION



k(s) = Annual Decay Rate for slowly decomposing refuse

FIGURE 17
MODEL 4 (Multi-Phase First Order Model)
EFFECTS OF VARYING WASTE COMPOSITION
ON METHANE GENERATION



F(r) = Fraction of rapidly decomposing refuse;
F(s) = Fraction of slowly decomposing refuse.

SECTION 3

APPROACH FOR MODEL OPTIMIZATION AND COMPARISON

OVERVIEW OF APPROACH

This section presents the approaches considered for model optimization and subsequent methods for model comparison. Model optimization sought to calibrate the selected landfill methane models through varying key model parameters to obtain the "best fit" to field results for each model.

There can be different definitions of "best fit", and several approaches exist for this kind of data analysis and model calibration. Typical optimization functions are based on the differences (or residuals) between projected methane recovery and measured field data, or on the ratios of projected methane recovery to measured field data. Model optimization approaches considered for this study were:

- Use of absolute filling and recovery data;
- Use of normalized filling and recovery data;
- Fitting of filling/recovery data to trial models;
- Minimization of arithmetic error:
  - use of absolute value of the differences;
  - use of square of the differences (i.e., least squares);
- Minimization of logarithmic error:
  - use of the natural log of the ratios;
  - use of absolute value of the natural log of the ratios; and
  - use of square of the natural log of the ratios.

Of these data treatment choices considered, two were selected for application and subsequent model comparisons in accordance with the scope of the study. The first calibration method was minimization of arithmetic error through use of the absolute value of the differences; the second method was minimization of logarithmic error through the use of the absolute value of the natural log of the ratios.

Minimization of arithmetic and logarithmic residuals has certain advantages and disadvantages. Minimization of arithmetic residuals weights according to actual waste quantities and gas recoveries. For example, large model errors at high recovery rates are more important than smaller model errors at lower recovery rates. In contrast, an advantage of the logarithmic optimization is in normalizing, so that both large and small landfills' data count equally. But, logarithmic optimization might give less weight to an important discrepancy between prediction and experience. For example, it will give equal weight to the $\log_{10}$ spreads between a 50,000 cfm predicted versus 5,000 cfm experienced ratio and to a 500 cfm predicted versus 50 cfm experienced ratio.

Another consequence of minimizing logarithmic rather than arithmetic residuals is that the optimized prediction will tend toward the log mean rather than the arithmetic mean of projections. For data with a significant amount of scatter, the log mean recovery may be

significantly less than the arithmetic. One consequence is that the model obtained by minimizing logarithmic residuals may underpredict recovery.

MODEL OPTIMIZATION PROCEDURE

Each model calibration method adjusted parameters for each of the four models to minimize model error (and thus, obtain one form of "best fit") between predictions of the trial model at hand and the gas recovery data set from the 18 landfills. The calibration methods weighted data in accordance with waste placement magnitude and methane recovery.

Modeled methane generation for a landfill site was assumed to be equivalent to methane recovery experienced. In addition, a time mesh or interval of one year for methane recovery was used for model optimization. Lastly, it was assumed that for each landfill site, gas recovery during any one-year period would count as one value in the optimization process. Thus, landfills with fewer recovery values contributed less to the project results than landfills with more recovery values.

For minimization of arithmetic error, the model optimization procedure was:

- Based on the waste filling history for each of the study landfills, establish parameter values for time (t) and waste in place (W). For each model, calculate methane generation (G) over time using a probable combination of remaining parameter values (e.g., k and Lo). (Parameters varied for each model were identified in Section 2.)

- Run iterative calculations of G over time for the varied parameters through small adjustments of the parameters over a wide range of numerical values. These iterations yield a series of model recovery projections, one for each combination of model parameters.

- For each trial model and parameter combination leading to a projection, calculate the absolute arithmetic difference between the model projection data points for methane generation (G) and the experienced methane gas recovery from the study landfill dataset.

- Sum the arithmetic differences (or residuals) between projections and experienced methane recoveries for the study landfill to obtain a total "sum of residuals" or total arithmetic error. The "calibrated" (or optimized) model is simply the trial model form with parameter combinations that give the minimum arithmetic error, and thus, the "best" predictions.

Procedures for minimization of logarithmic error were similar to the above except that the logarithms of waste placement and gas recovery were used, and minimization was performed on the absolute values of the residuals (differences in the natural logs of the ratios of gas recovery predicted versus gas recovery experienced).

ILLUSTRATION OF TRIAL MODEL OPTIMIZATION

As noted earlier, each of the four models (zero order, simple first order, modified first order, and multi-phase first order) was tested by the above procedures. For illustration of how the two optimization functions were applied, Figures 18 and 19 show examples carried out for Model 2 (simple first order model) with the study landfill data set.

For Model 2, parameters which can vary are the estimated recovery yield, Lo, and the first-order decay rate constant, k. (Note that for Models 1, 2, and 4, the lag time was set at zero to simplify the evaluation. This does not result in significant error). For Figures 18 and 19, the values of Lo were varied within a range considered likely (i.e., from 1,500 to 3,000 cubic feet of methane per ton of refuse, at intervals of 100), and the values for k were varied between 0.02 $year^{-1}$ and 0.10 $year^{-1}$, at intervals of 0.02.

Examination of Figure 18 for the arithmetic optimization function shows that several Lo and k parameter combinations yielded similar minimized residuals, at around 30,000 (the units of error are arbitrary). Calculated values for the same (not shown in Figure 18) allowed more specific comparisons. For example, the lowest sum of arithmetic error obtained for Figure 18 was with Lo = 2,000 and k = 0.08; the sum of residuals was 26,767. Other parameter combinations had low sums of arithmetic error as well: the residuals sum at Lo = 2,200 and k = 0.06 was 26,993; and a similar residual value was obtained for Lo of 2,500 and k of 0.04. While an advantage could be assumed because error was minimized with Lo and k at 2,000 and 0.08, respectively, it is not likely this parameter combination is unique or statistically significant for establishment of the only or "best" parameter set for Model 2.

Examination of Figure 19 for the logarithmic optimization function shows greater specificity for establishment of the "best" parameter set for Model 2. As shown, the sum of the natural log of the ratios was minimized at 24 (again, units of error are arbitrary) and this occurred with Lo at 2,200 and k at 0.04. Figure 19 is useful because it indicates that values of k = 0.06, 0.08, and 0.10 do not yield best fits under any combinations within the range of Lo values tested, that k = 0.02 may yield a best fit combination outside of the Lo range tested (i.e., at Lo values greater than 3,000), and that k = 0.04 provides several Lo values with minimized error near the best fit parameter combination (e.g., Lo = 2,100 or 2,300).

Based on these examples, the optimization process leaves some uncertainty as to "best" parameter combinations. Ambiguity as to the best Lo and k combinations arises because of the relatively short term of much of the gas recovery data for the study landfills. Longer term gas recovery data would tend to provide improved values of Lo, which would in turn fix k values more exactly. This is true because Lo by definition becomes better defined as gas is recovered over a greater fraction of the generation cycle.

For purposes of this report, the parameter combinations which resulted in minimum error (even if the combination has only a small advantage over other combinations for the same trial model) were used to describe the best fit for the model at hand and for further comparative purposes.

FIGURE 18
EXAMPLE SUM OF RESIDUALS: ARITHMETIC

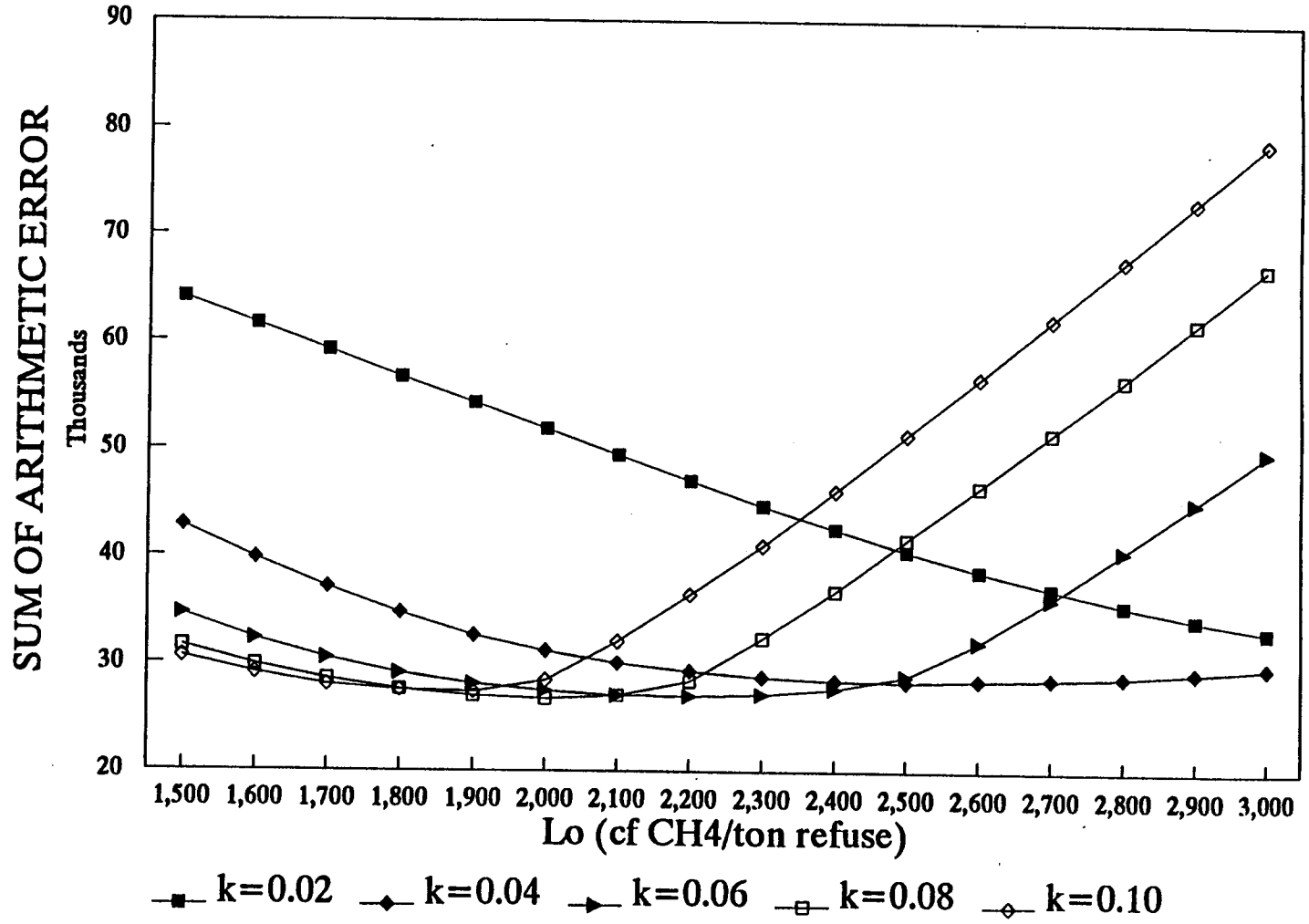
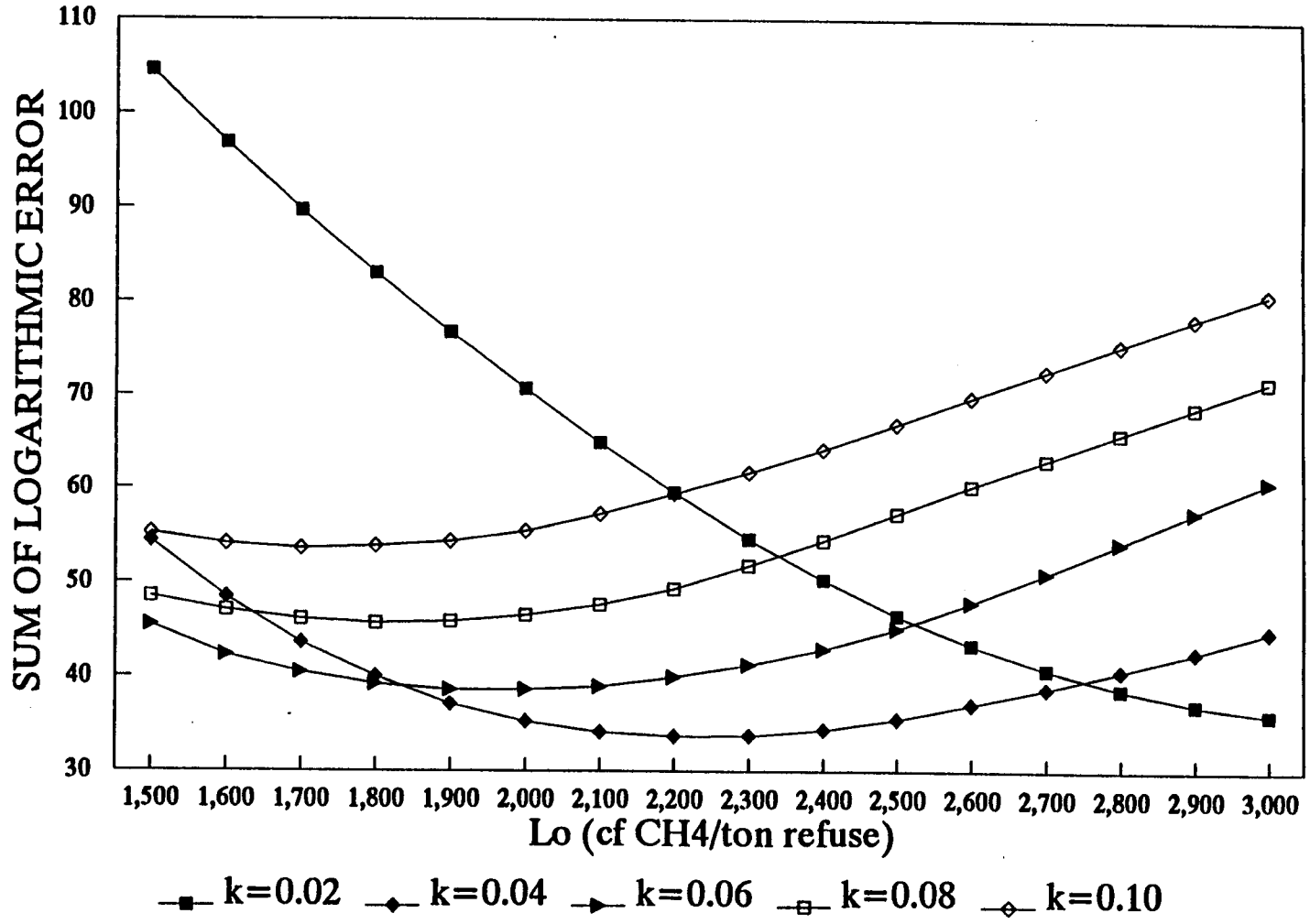


FIGURE 19
EXAMPLE SUM OF RESIDUALS: LOGARITHMIC



SECTION 4

RESULTS

PARAMETER COMBINATIONS DERIVED FROM MINIMIZED ERROR

Numerous computer runs were made to calculate the residuals for possible parameter combinations for:

- the ranges of parameter values selected;
- the four models and 18 landfill sites evaluated in this study; and
- the two optimization functions selected.

Results from these computer runs were scanned visually for optimal results and compared numerically for the lowest minimized error. Table 2 presents the resulting parameter combinations by landfill methane model and by optimization function. Application of the data treatment of absolute value of the logarithmic error produced two different parameter combinations (each had an equivalent lowest minimized error) under each of Models 1, 2, and 3.

As indicated in Table 2, values for Lo, the methane yield potential, were consistent for the three first-order models (i.e., Models 2, 3, and 4) under the arithmetic error optimization function, ranging from 2,100 to 2,200 cubic feet of methane per ton of landfilled waste. Under the logarithmic function, at least one parameter combination for each of the four models resulted in an Lo within the 2,000 to 2,200 cubic feet of methane range.

Values for k, the first order decay rate constant, were more varied and model dependent. Under the arithmetic optimization function, k values ranged from 0.05/year to 0.08/year for Models 2, 3, and 4; under the logarithmic optimization function, k values ranged from 0.03/year to 0.06/year.

MODEL COMPARISONS

Comparisons of the study landfill data to the optimized (or best fit) models were developed. In brief, model parameter combinations obtained through minimization of arithmetic residuals (see Table 2) were used to develop generation curves; these data sets then were plotted against the actual methane recovery data from the 18 study landfills. Results of these plots are shown in Figures 20 through 23 for Models 1 through 4, respectively. In these figures the fit of each model is illustrated by comparison of optimized model predictions for methane generation with the measured methane recovery for all data points obtained from the study landfills. The model parameter combinations from Table 2 used to develop the predicted methane generation data (i.e., the x-axis) are shown on the figures as well.

Similarly, comparisons were made for each of the four models to show the results of optimization via minimization of logarithmic residuals, as described in the previous section. Figures 24 through 27 provide tabular and graphic results from the optimization procedure for Models 1 through 4, respectively. The parameter combinations derived from minimizing logarithmic error (given for each model in Table 2) are indicated on the figures as well.

This use of differing weighting yielded, in several cases, similar parameter combinations to the arithmetic results. Furthermore, minimization of logarithmic error gave better results than those demonstrated by arithmetic error minimization by producing a narrow, more specific band of parameter combinations for best fit optimization. As a result, other combinations could be eliminated. For example, parameter combinations which included values of t = 15 years and t = 25 years for the zero order model (Model 1) clearly could not result in the lowest minimized error (see Figure 24). The same conclusion could be drawn for parameter combinations which included:

- Values of k = 0.07, 0.08, 0.09, and 0.10 for Model 2 (see Figure 25);
- Values of k = 0.07 and 0.09 for Model 3 (see Figure 26); and
- Values of k(r) and k(s) = 0.06, k(r) = 0.07 and k(s) = 0.06, and k(r) = 0.08 and k(s) = 0.06, for Model 4 (see Figure 27).

<u>Comparisons By Correlation</u>

Figures 20 through 23 also allow model comparisons of predicted versus actual methane recovery in terms of the variance of landfill data points from the straight line (the straight line represents an exact correlation). A commonly-applied statistical measure for good correlation or "goodness of fit" for modeled data is the regression coefficient, r^2. Regression coefficients were calculated for the plots shown in Figures 20 through 23 (based on arithmetic optimization) and for similar data based on logarithmic optimization. Results are presented in Table 3.

Generally, regression coefficient values based on arithmetic optimization were similar for all four models, ranging from 0.928 to 0.937, depending on the model. This could be considered reasonable correlation. By one interpretation, such a regression coefficient might indicate that from 92.8 to 93.7 percent of the variation in methane recovery could be attributed to parameter values and inputs of the optimized model. Table 3 shows that regression coefficients for the logarithmic data treatment showed high correlations as well, ranging from 0.914 to 0.955. Similarity of the regression coefficient results indicates that the four models are similar in predictive ability.

However, the assumptions implicit in the use of the regression coefficient may not correspond exactly to landfill methane modeling. Where the regression coefficient is applied, an assumption is that an underlying "true" model exists, correlated to the extent

indicated by r^2 to model variables. Deviations between the model prediction and measured methane recovery are otherwise assumed to be due to unknown factors or random errors (such as in field measurements made).

This base assumption may not be valid if a much higher fraction of the discrepancy between the modeled and experienced values is not random, but due to unquantified real biases. An example of such bias that could show as "random" error would be where one landfill yields much greater methane recovery over time (essentially, a greater Lo value) than another because of greater moisture infiltration and distribution within the waste mass.

Comparisons By Probability Limits

The four landfill methane models also were compared through examination of data distributions of the numerical ratios of the measured methane recovery values to the modeled recovery over the spectrum of data points established for the study landfills. For each model and each optimization function (arithmetic and logarithmic), plots were developed to show distributions around median values for modeled versus actual methane recovery values.

Figures 28 through 31 provide distribution plots for Models 1 through 4, respectively, based on the minimization of arithmetic error. Similarly, Figures 32 through 35 provide distribution plots for Models 1 through 4, respectively, based on the minimization of logarithmic error.

For these figures, a "perfect" model correlation would be represented by a vertical line of the landfill data points at 100 percent of actual recovery (the x-axis). Data "scatter" or dispersion from a perfect correlation are illustrated on the figures with bounds shown by vertical lines. These bounds represent the 10 and 90 percent probability (or confidence) limits. In other words, the cumulated fraction of points lying within any particular boundary, in terms of percentages of the modeled prediction, indicates the dispersion of experienced recovery about the model prediction.

Overall, Figures 28 through 35 show rather wide probability limits for the set of study landfills, meaning the models could project methane recovery within a factor of about 1.5 for 80 percent of the landfill data points. The spread or dispersion was greater for the remaining data points. Note that this is the first time that methane recovery probability limits have been developed in association with projections for U.S. landfills. (Where landfills share common filling histories and operational features, a narrower range for the limits might be expected).

Comparison of the two groups of figures representing arithmetic versus logarithmic data treatments (Figures 28 through 31 and Figures 32 through 35, respectively) indicates that the probability limits for the models optimized via logarithmic minimization are narrower than those established with the arithmetic optimization.

Comparison Of Model Parameters With Other Work

Parameter combinations developed for the study landfill data set were compared in a limited manner with other published values. As shown in Table 2 for the Simple First Order Model (Model 2), study landfill results had three parameter combinations associated with minimized error: Lo = 2,100 and k = 0.07/year; Lo = 2,200 and k = 0.04/year; and Lo = 2,500 and k = 0.03/year. The U.S. EPA has published regulatory values based on reported literature values for Lo and k and its first order landfill methane emissions model. The regulatory values are Lo = 4,010 cubic feet methane per refuse ton, k (for wet sites) = 0.04, and k (for dry sites) = 0.02, from Compilation of Air Pollutant Emission Factors, Stationary Point and Area Sources, July 1993 (AP-42). It is assumed that EPA's Lo value was selected to be higher than reported typical landfill values in order to be conservative for regulatory purposes.

For other published model work, some interpretive calculations were made to compare with this work's findings. For example, Oonk, et. al. (1994) based methane yield on an assumed waste degradable carbon content. Based on average Dutch waste composition, the first order Lo from Oonk can be calculated to be about 2,200 cubic feet of methane per ton, and a first order rate constant, k, of 0.09/years.

Another commercial model reported by Augenstein (1992) and (Augenstein and Pacey, 1991) based projections on dry waste of assumed composition. An assumed 25 percent waste moisture content for this model gave an Lo value 2,100 cubic feet of methane per ton, and k values near 0.07/year.

TABLE 2
METHANE MODEL PARAMETER COMBINATIONS YIELDING MINIMIZED ERROR

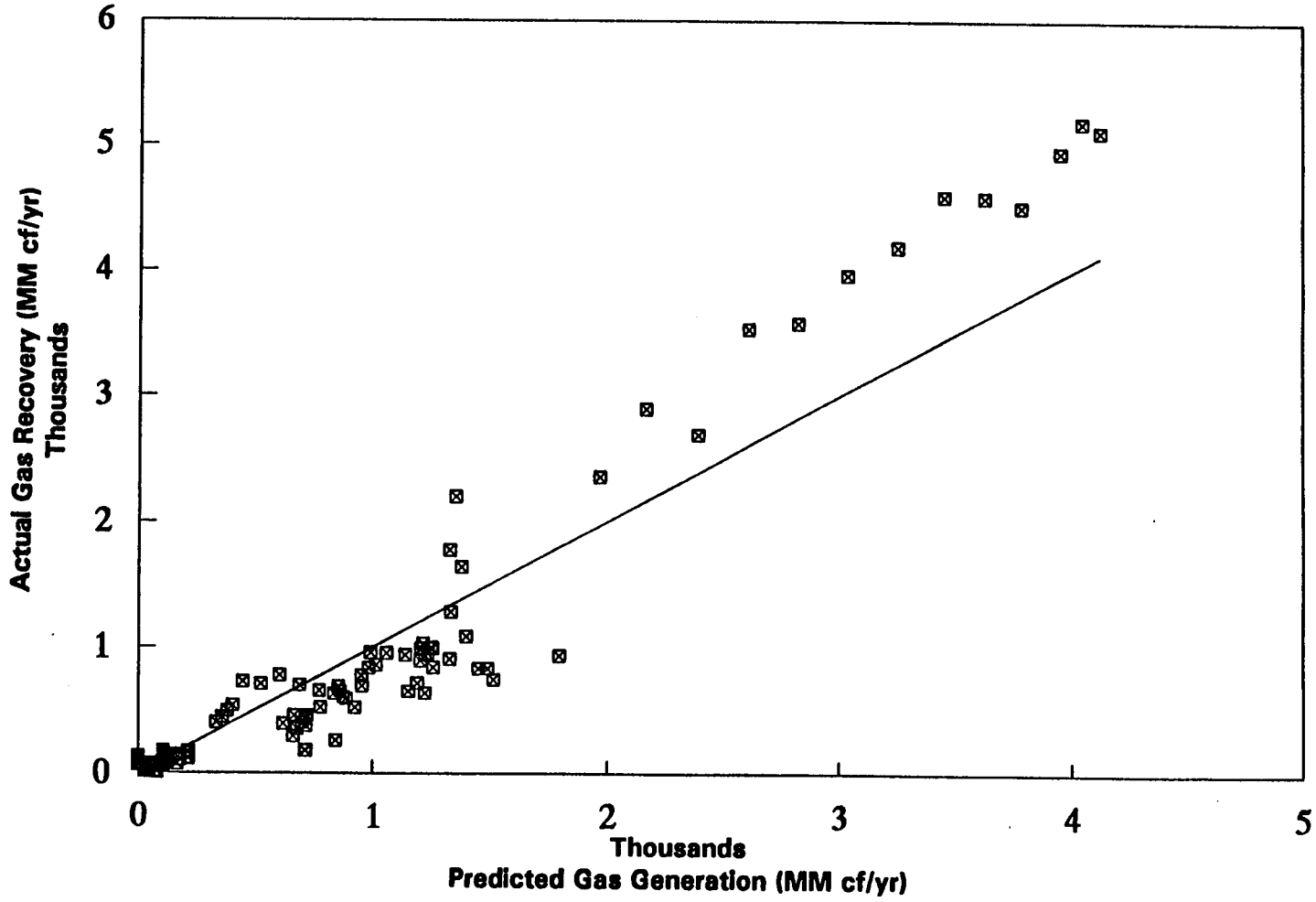
Optimization Function	Parameter Combinations*			
	Model 1: Zero Order	Model 2: Simple First Order	Model 3: Modified First Order	Model 4: First Order Multi-Phase
I. Minimization of Absolute Value of Arithmetic Error	Lo = 1,600 t = 20 years	Lo = 2,100 k = 0.07/year	Lo = 2,200 k = 0.05/year s = 1.0	Lo = 2,100 $k_{(r)}$ = 0.08 $k_{(s)}$ = 0.06 $F_{(r)}$ = 40% $F_{(s)}$ = 60%
II. Minimization of Absolute Value of Logarithmic Error	Lo = 1,700 t = 35 years AND Lo = 2,200 t = 45 years	Lo = 2,200 k = 0.04/year AND Lo = 2,500 k = 0.03/year	Lo = 2,000 k = 0.05/year s = 0.2 AND Lo = 2,500 k = 0.03/year s = 1.0	Lo = 2,200 $k_{(r)}$ = 0.06 $k_{(s)}$ = 0.04 $F_{(r)}$ = 20% $F_{(s)}$ = 80%

* Units for Lo, methane yield potential, are cubic feet methane gas per ton of waste landfilled.

TABLE 3
REGRESSION COEFFICIENT VALUES FOR METHANE MODEL COMPARISONS

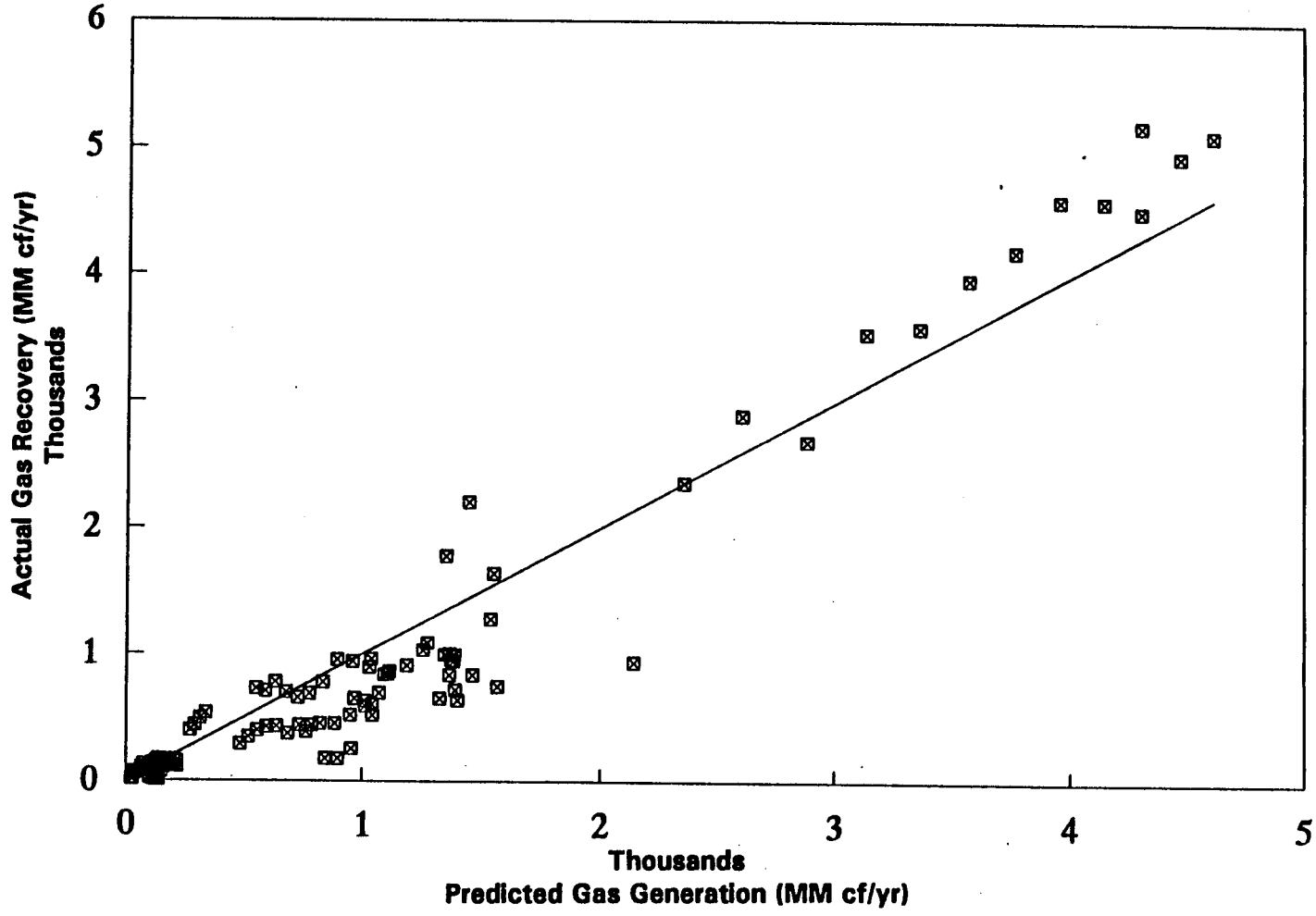
Landfill Methane Model	Regression Coefficient (r^2) by Optimization Function	
	Arithmetic	Logarithmic
Model 1: Zero Order	0.928	0.914
Model 2: Simple First Order	0.937	0.955
Model 3: Modified First Order	0.937	0.918
Model 4: First Order Multi-Phase	0.937	0.939

FIGURE 20
MODEL 1: ZERO ORDER
PREDICTED GAS GENERATION VERSUS ACTUAL GAS RECOVERY



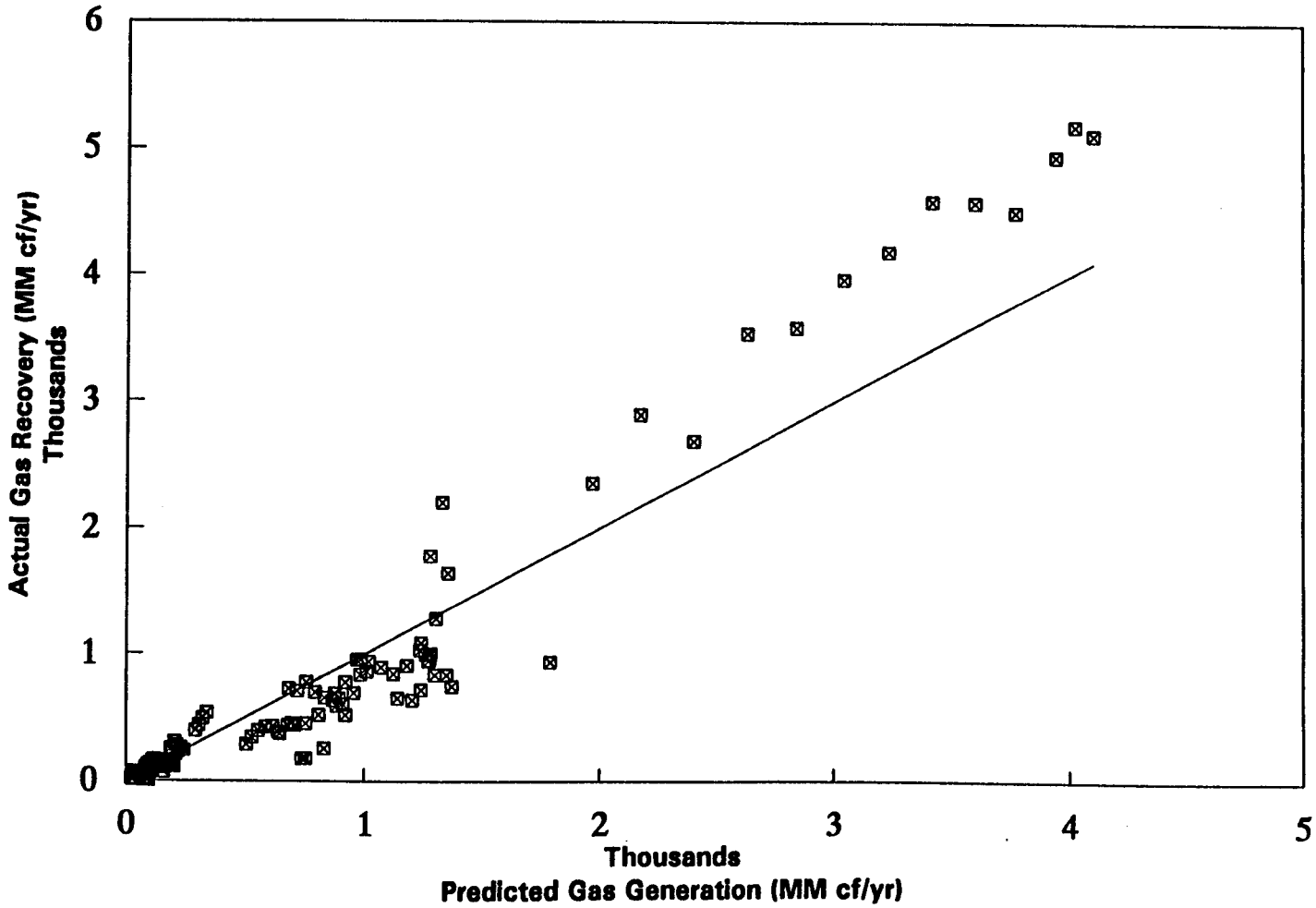
Minimizing Parameters: Lo = 1,600 of CH4/ton refuse; time = 20 years.

FIGURE 21
MODEL 2: SIMPLE FIRST ORDER
PREDICTED GAS GENERATION VERSUS ACTUAL GAS RECOVERY



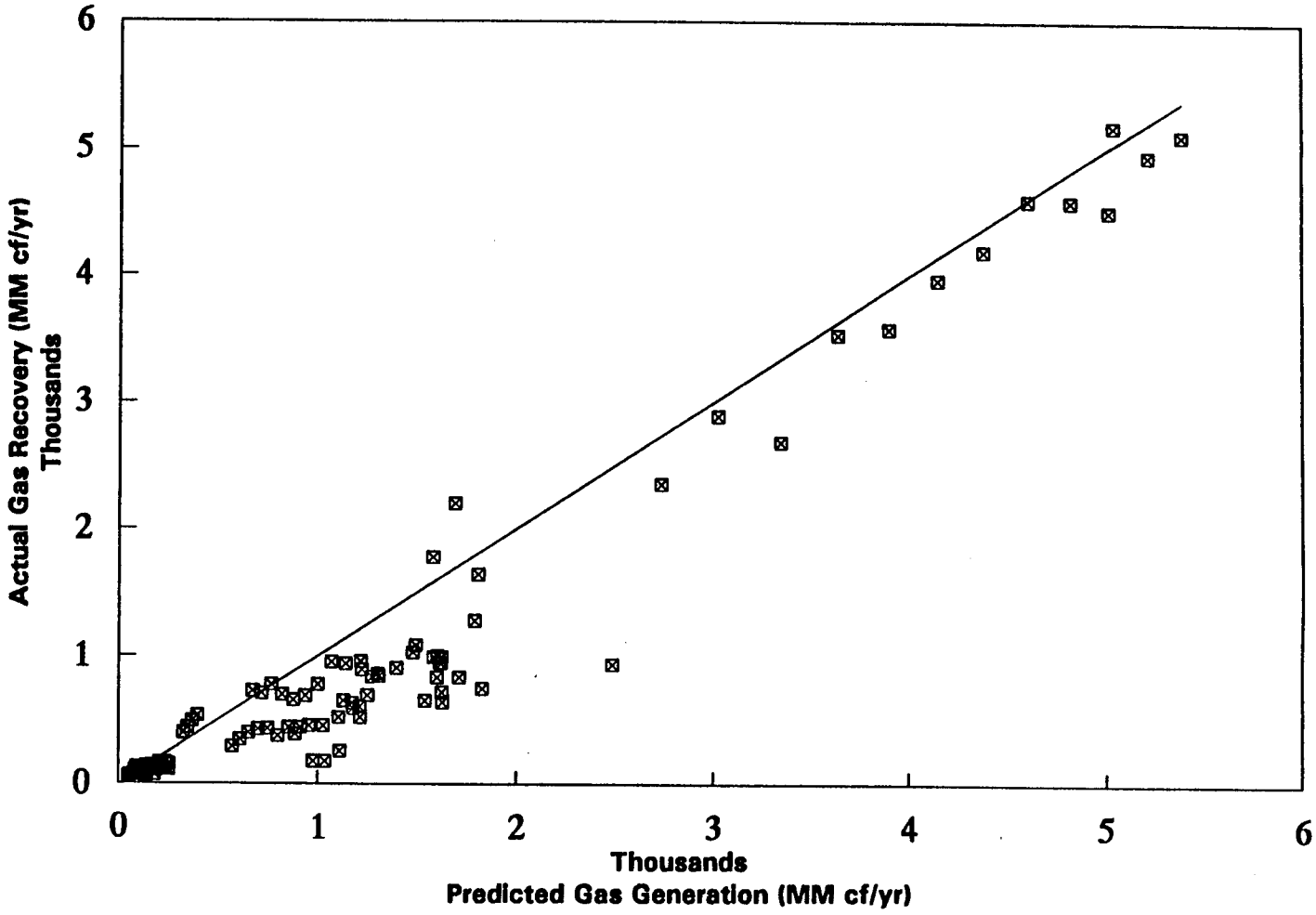
Minimizing Parameters: Lo = 1,600 of CH4/ton refuse; time = 20 years.

FIGURE 22
MODEL 3: MODIFIED FIRST ORDER
PREDICTED GAS GENERATION VERSUS ACTUAL GAS RECOVERY



Minimizing Parameters: Lo = 1,600 of CH4/ton refuse; time = 20 years.

FIGURE 23
MODEL 4: FIRST ORDER MULTI-PHASE
PREDICTED GAS GENERATION VERSUS ACTUAL GAS RECOVERY



Minimizing Parameters: Lo = 1,600 of CH4/ton refuse; time = 20 years.

FIGURE 24
MODEL 1: ZERO ORDER
SUMMARY OF LOGARITHMIC ERROR MINIMIZATION

	Sum of Absolute Natural Logs of (Predicted/Actual)							
Lo	t=10 yrs	t=15 yrs	t=20 yrs	t=25 yrs	t=30 yrs	t=35 yrs	t=40 yrs	t=45 yrs
1,500	147 *	105 *	88 *	63 *	45 *	43	53	64
1,600	150	108	91	64	45	40	48	58
1,700	153	111	94	65	46	39 *	44	52
1,800	156	115	97	67	47	40	41	48
1,900	159	119	100	70	48	40	40	44
2,000	162	123	103	73	50	41	40 *	41
2,100	165	127	107	75	52	43	40	40
2,200	169	131	111	79	54	44	41	39 *
2,300	172	135	116	83	57	46	42	40
2,400	175	139	120	87	60	48	43	40
2,500	178	144	125	91	63	50	44	41
2,600	181	148	129	96	66	52	45	42
2,700	184	152	133	100	70	54	47	43
2,800	187	156	137	104	74	57	49	44
2,900	190	159	141	108	78	60	51	45
3,000	193	163	145	112	82	63	53	47

* Denotes the minimum sum for each value of t

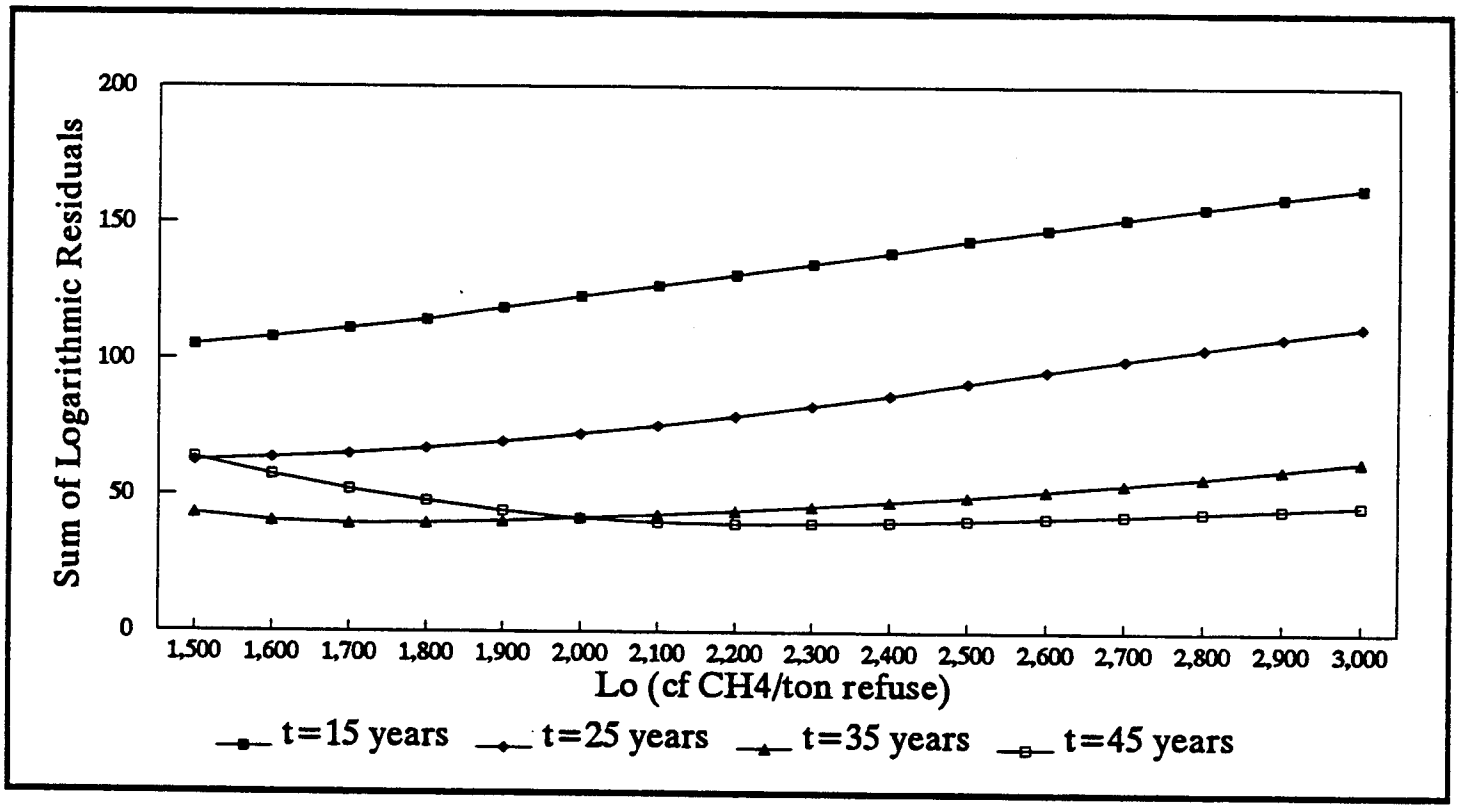


FIGURE 25
MODEL 2: SIMPLE FIRST ORDER
SUMMARY OF LOGARITHMIC ERROR MINIMIZATION

	Sum of Absolute Error								
Lo	k=0.02	k=0.03	k=0.04	k=0.05	k=0.06	k=0.07	k=0.08	k=0.09	k=0.10
1,500	105	72	54	47	46	46	49	52	55
1,600	97	65	48	43	42	44	47	50	54
1,700	90	58	44	40	40	43	46	50	54 *
1,800	83	52	40	38	39	42	46 *	50 *	54
1,900	77	46	37	36	39	42 *	46	50	54
2,000	71	42	35	36	39 *	42	46	51	55
2,100	65	39	34	36 *	39	43	48	52	57
2,200	60	36	34 *	36	40	45	49	55	59
2,300	55	35	34	37	41	46	52	57	62
2,400	50	34	34	38	43	49	55	60	64
2,500	47	34 *	36	40	45	51	57	62	67
2,600	43	34	37	42	48	54	60	65	70
2,700	41	35	39	44	51	57	63	68	73
2,800	39	35	41	47	54	60	66	71	75
2,900	37	36	43	50	58	63	69	74	78
3,000	36 *	37	45	54	61	67	72	76	81

* Denotes the minimum sum for each value of k

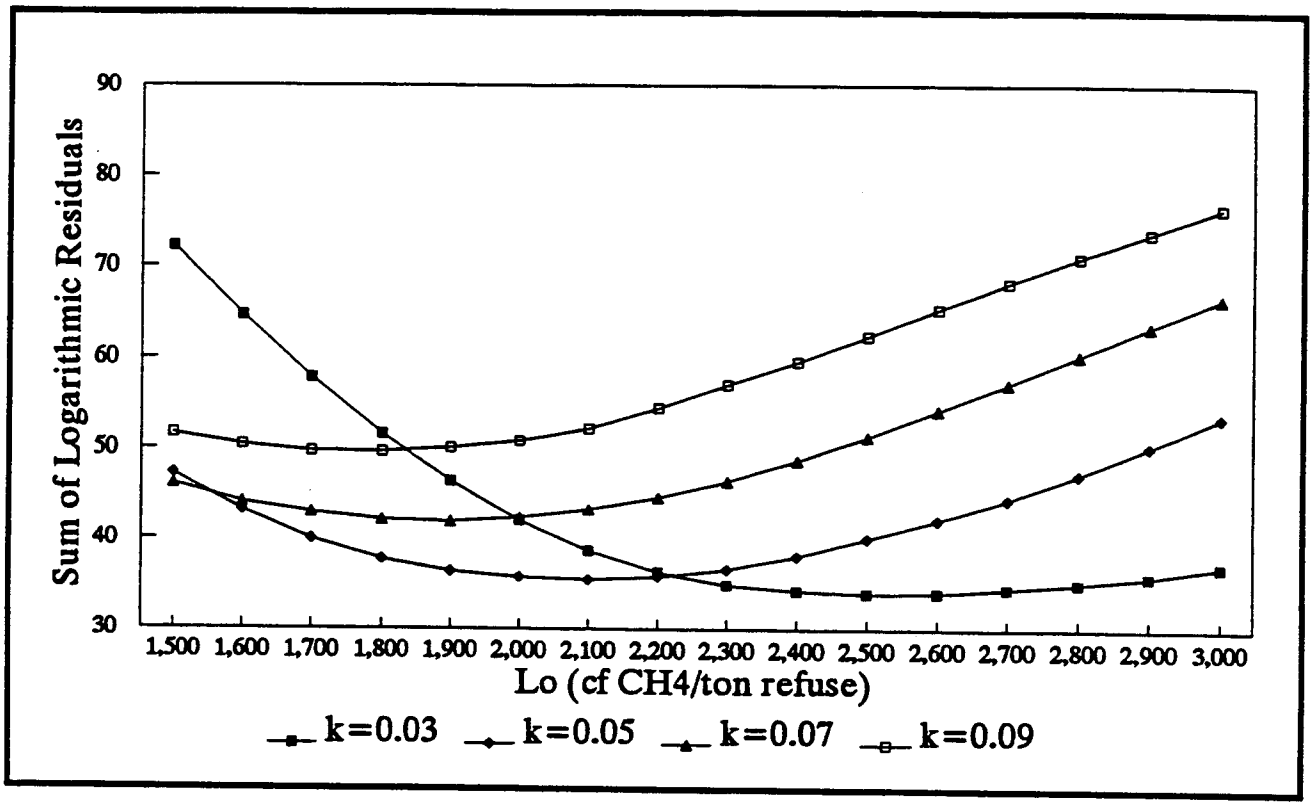


FIGURE 26
MODEL 3: MODIFIED FIRST ORDER
SUMMARY OF LOGARITHMIC ERROR MINIMIZATION

	Sum of Absolute Natural Logs of (Predicted/Actual)											
	k=0.03			k=0.05			k=0.07			k=0.09		
Lo	s=0.2	s=0.5	s=1	s=0.2	s=0.5	s=1	s=0.2	s=0.5	s=1	s=0.2	s=0.5	s=1
1,500	82	73	71	46	44	45	40	42	44	42	47	49
1,600	74	65	64	42	40	41	38	40	42	41 *	46 *	48
1,700	67	58	57	38	38	38	37	40	41	41	46	48 *
1,800	61	52	51	35	36	37	37 *	39 *	41 *	42	47	49
1,900	55	47	45	34	35	35	37	40	41	44	48	50
2,000	50	42	41	34 *	35 *	35 *	38	41	42	46	50	51
2,100	46	39	38	35	35	35	39	43	44	48	52	53
2,200	43	37	36	36	36	36	41	45	45	50	55	56
2,300	41	35	35	37	37	37	44	47	47	53	58	59
2,400	39	35	34	39	39	39	46	49	50	56	61	62
2,500	38	35 *	34 *	41	41	41	49	52	53	59	64	65
2,600	37 *	35	34	42	44	44	52	56	56	63	67	68
2,700	37	35	35	45	46	46	56	59	60	67	71	71
2,800	37	36	36	47	49	49	59	63	63	71	74	74
2,900	38	37	37	50	52	52	64	67	66	75	77	77
3,000	39	38	38	52	55	56	68	70	70	78	81	80

* Denotes the minimum sum for each value of k and s.

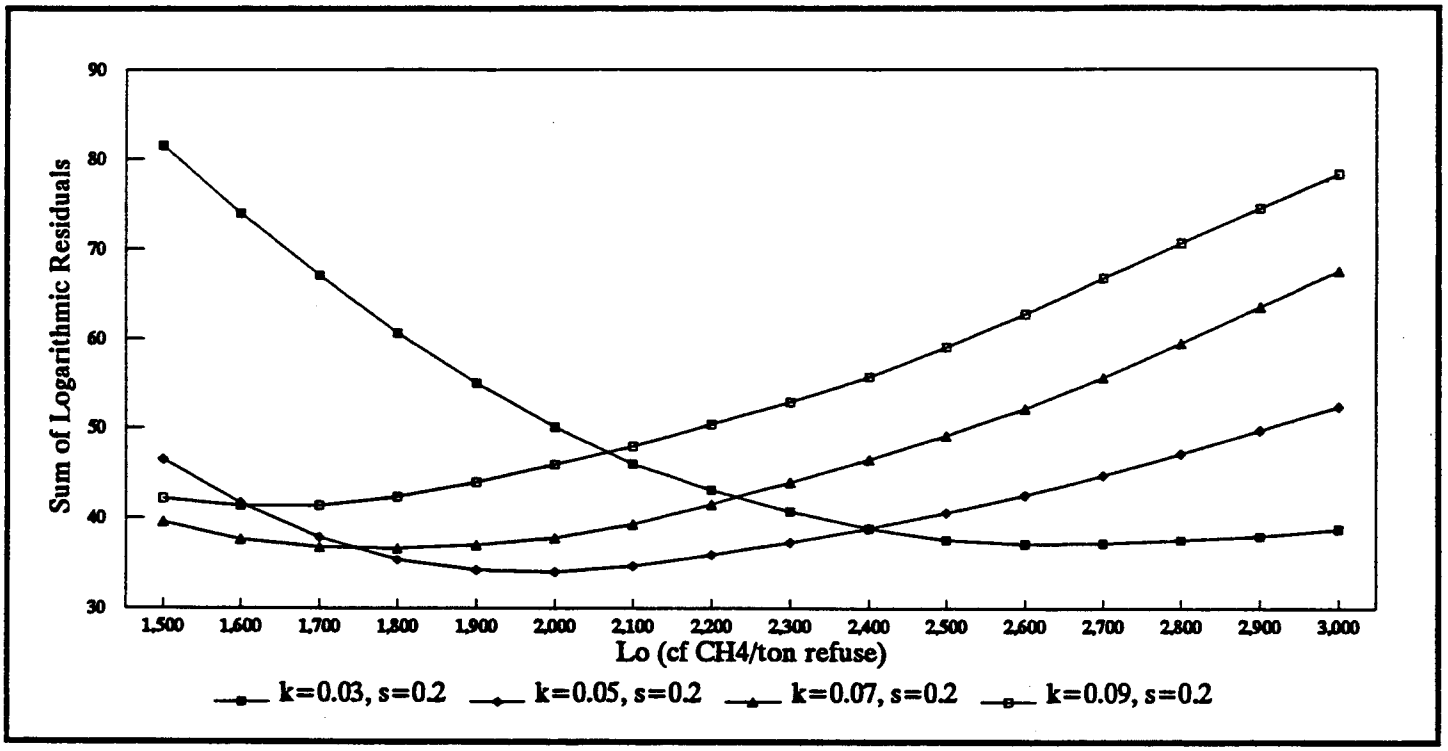


FIGURE 27
MODEL 4: FIRST ORDER MULTI-PHASE
SUMMARY OF LOGARITHMIC ERROR MINIMIZATION

	Sum of Absolute Natural Logs of (Predicted/Actual)								
	k(r)=0.06			k(r)=0.07			k(r)=0.08		
Lo	k(s)=.04	k(s)=.05	k(s)=.06	k(s)=.04	k(s)=.05	k(s)=.06	k(s)=.04	k(s)=.05	k(s)=.06
1,500	52	47	46	51	47	46	51	47	46
1,600	46	43	42	46	43	43	46	43	43
1,700	42	40	40	42	40	41	42	40	41
1,800	39	38	39	39	38	40	39	39	40
1,900	37	37	39	37	37	39 *	37	38	40 *
2,000	35	36	39 *	36	37	39	36	37 *	40
2,100	34	36 *	39	35	37 *	40	35	37	40
2,200	34 *	36	40	35 *	37	41	35 *	38	42
2,300	34	37	41	35	38	42	35	39	43
2,400	35	39	43	36	40	44	36	40	45
2,500	37	41	45	37	42	46	38	42	47
2,600	39	43	48	39	44	49	40	44	50
2,700	41	46	51	41	46	52	42	47	53
2,800	43	48	54	43	50	55	44	50	56
2,900	45	52	58	46	53	59	46	54	60
3,000	47	55	61	48	56	62	49	57	63

* Denotes the minimum sum for each value of $k_{(r)}$ and $k_{(s)}$.

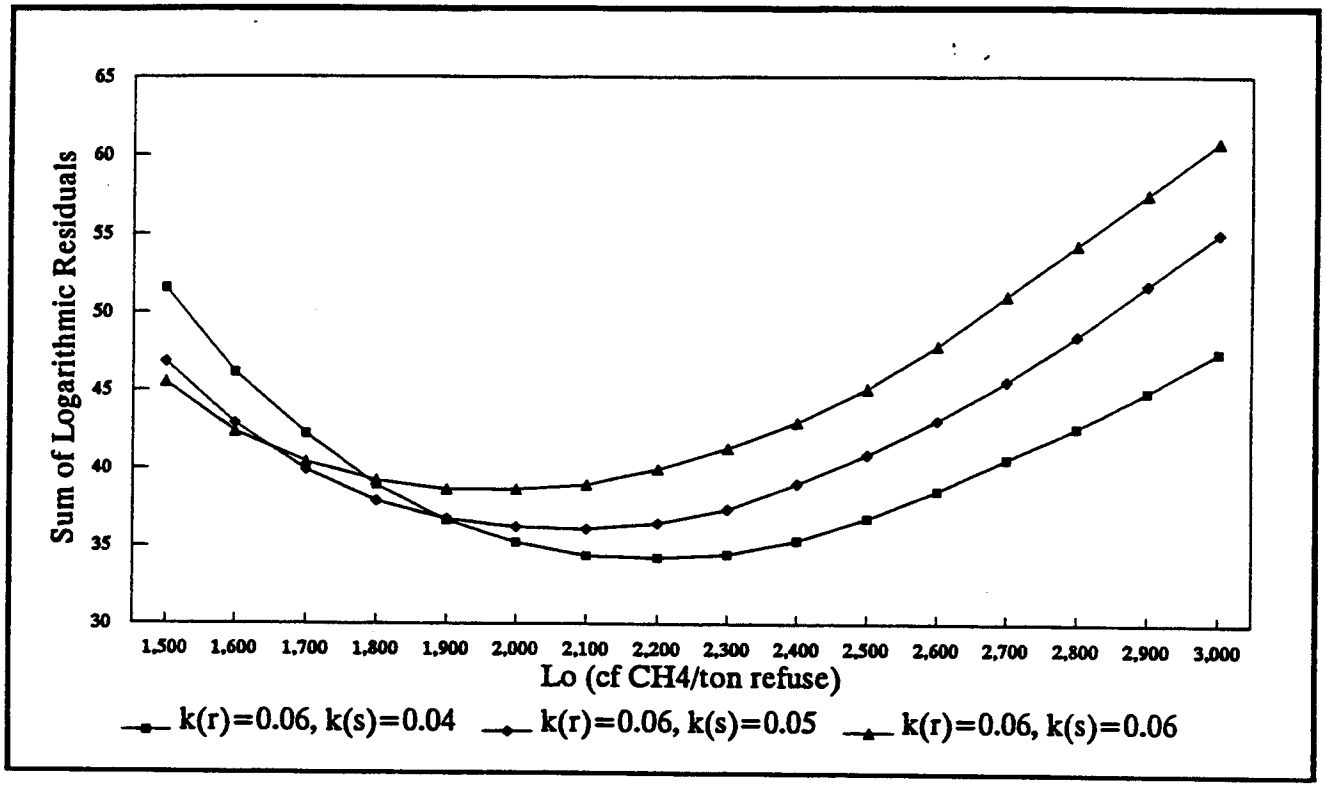


FIGURE 32
ZERO ORDER MODEL: LOGARITHMIC DISPERSIONS AND CONFIDENCE LIMITS

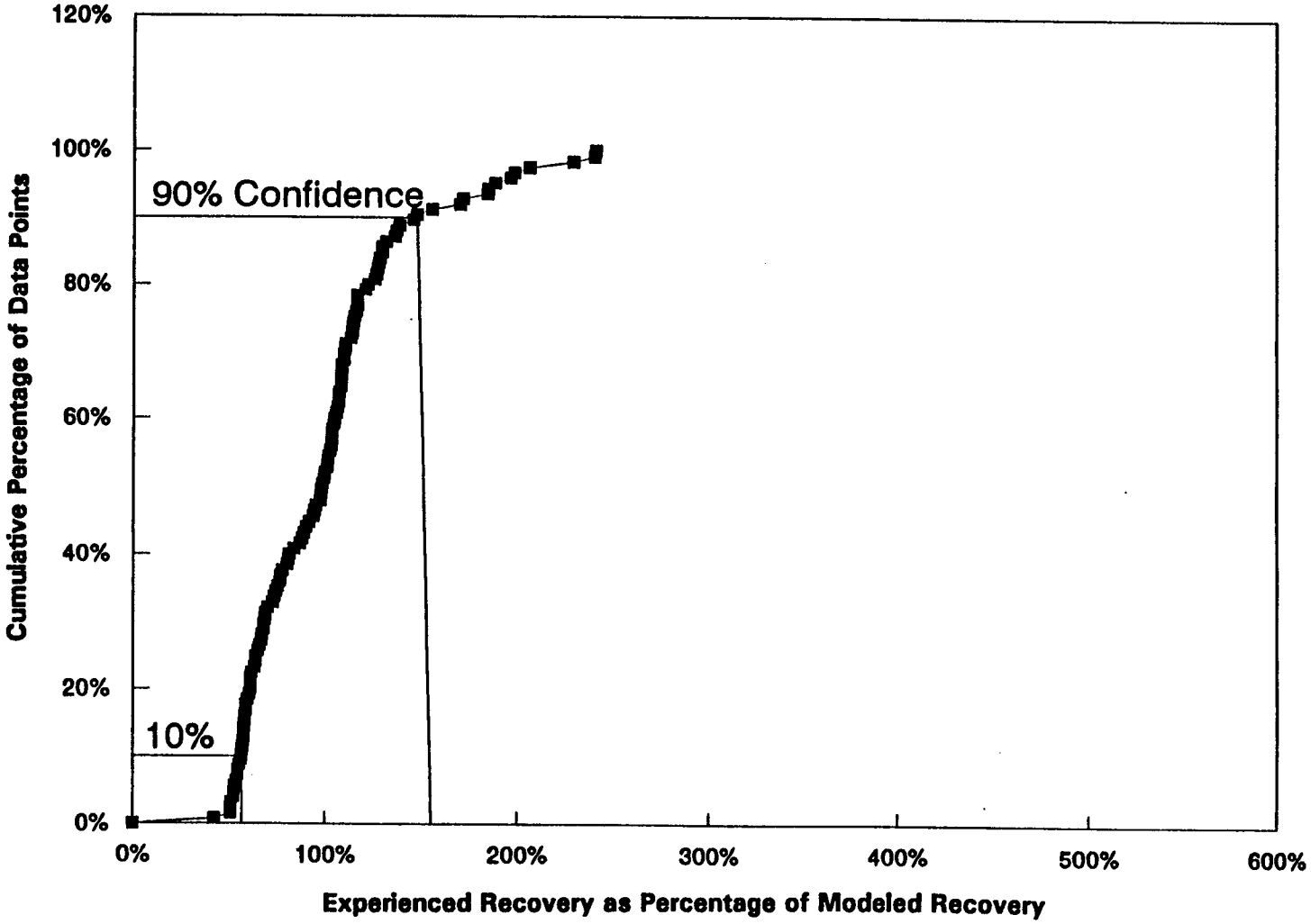


FIGURE 33
MODEL 2: SIMPLE FIRST ORDER: LOGARITHMIC DISPERSIONS AND CONFIDENCE LIMITS

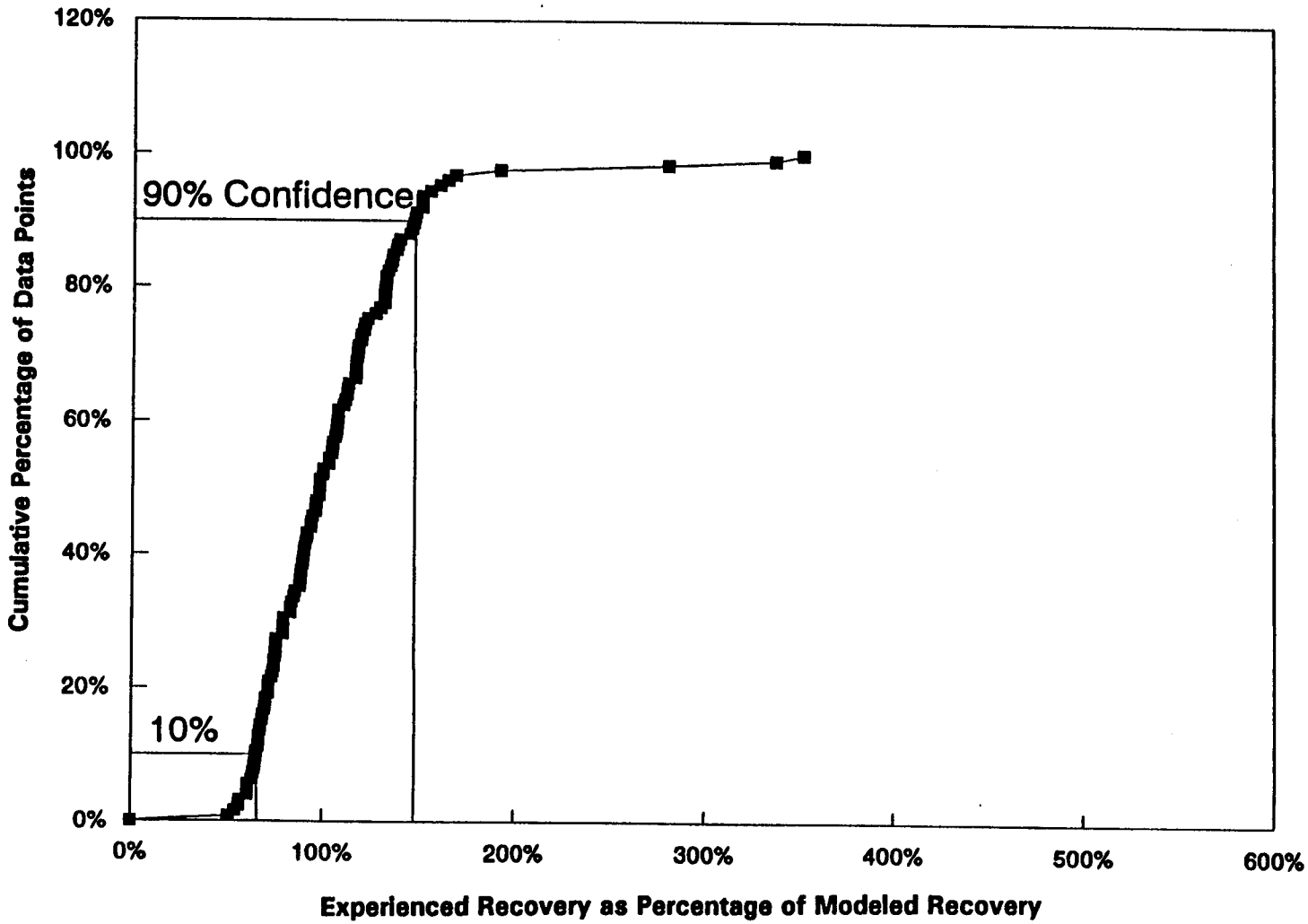


FIGURE 34
MODIFIED FIRST ORDER MODEL: LOGARITHMIC DISPERSIONS AND CONFIDENCE LIMITS

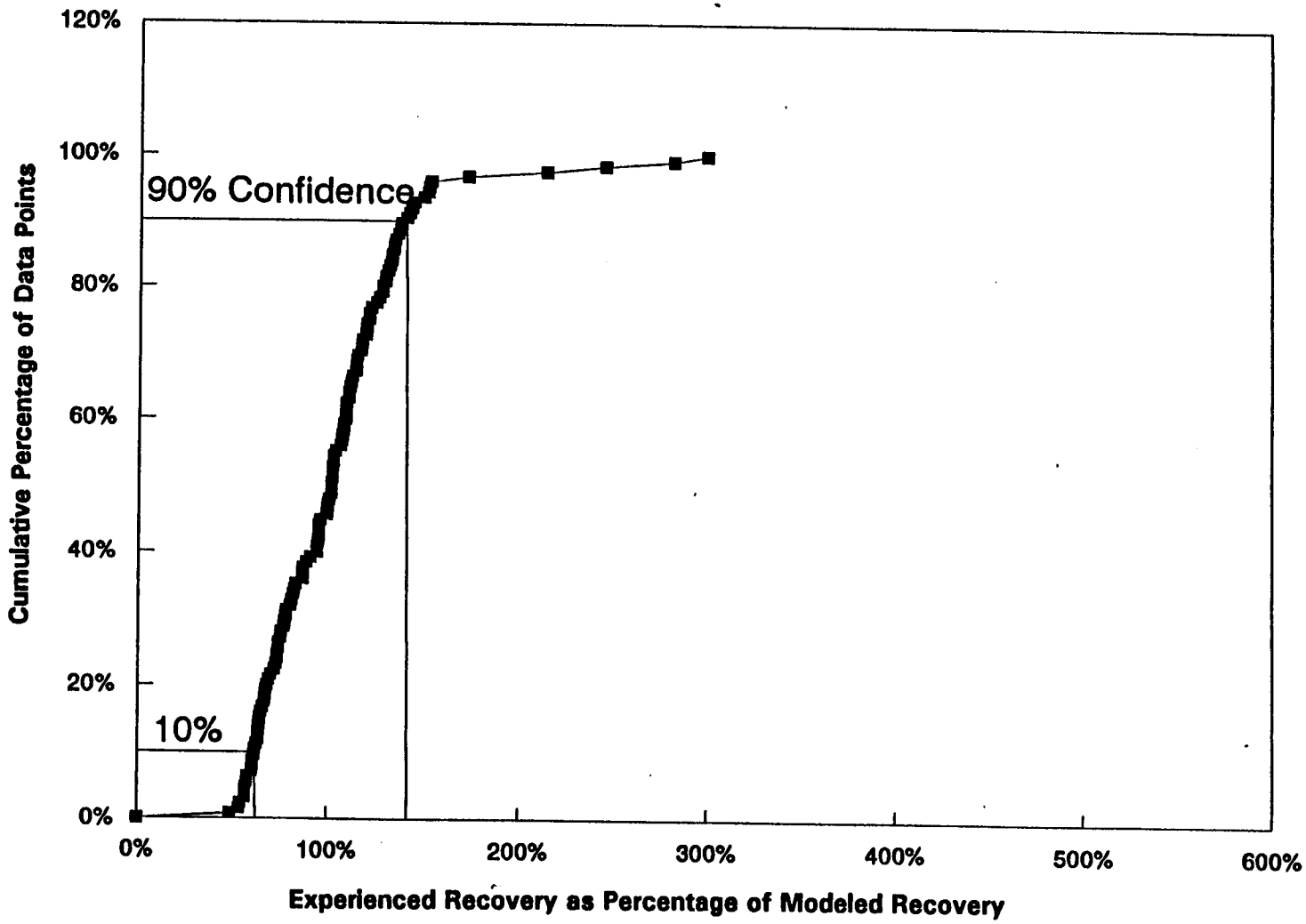
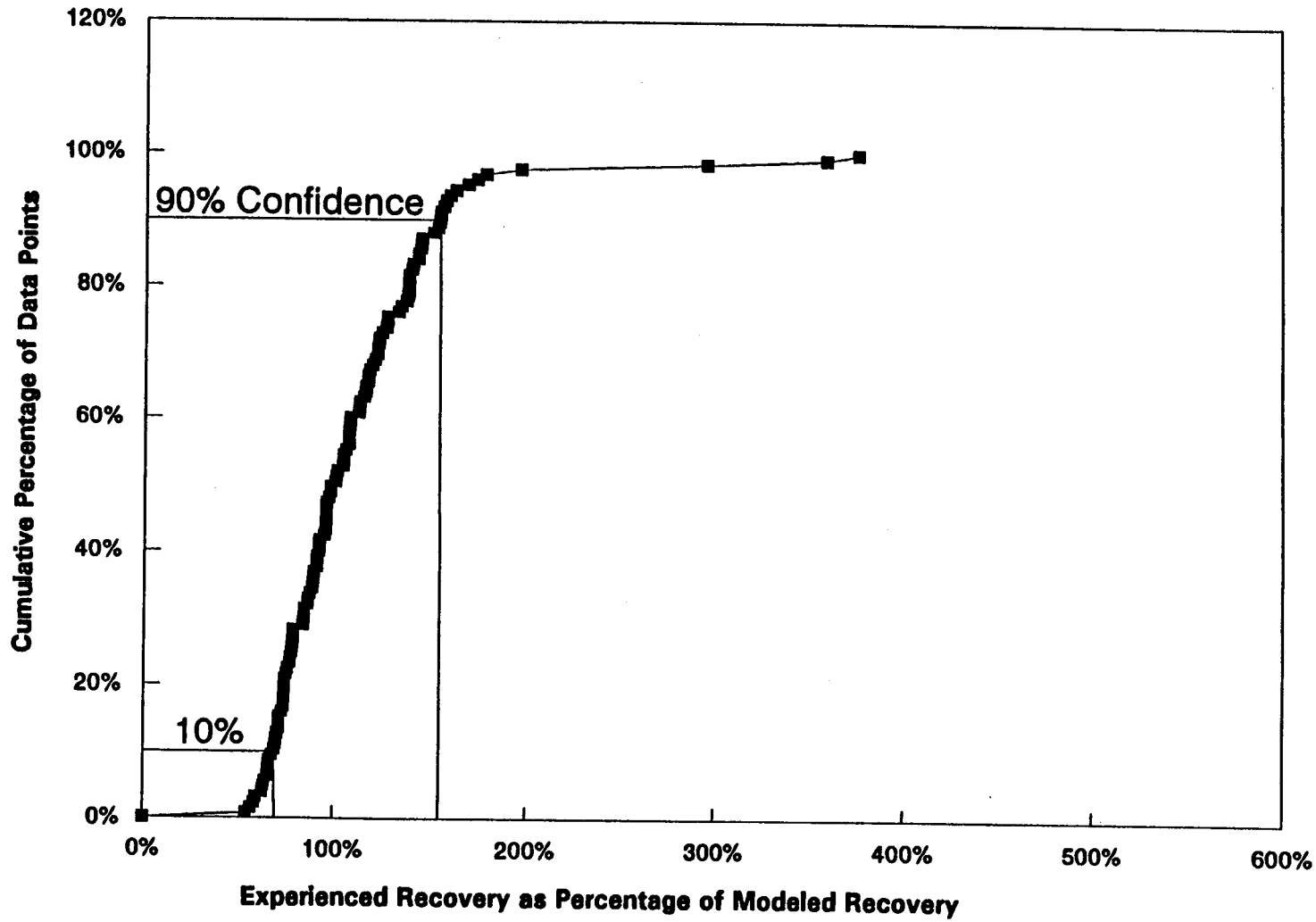


FIGURE 35
FIRST ORDER MULTI-PHASE MODEL: LOGARITHMIC DISPERSIONS AND CONFIDENCE LIMITS



SECTION 5

COMPUTER PROGRAM FOR LANDFILL METHANE MODELS

Based on this report's findings, a simple computer program was developed for each of the four models discussed herein. Titled as "Methane Gas Recovery Program (MEGAREP), Version 1.1", the program presumes a landfill has characteristics typical of the study landfills. This program is included herein as a diskette in Appendix C.

MEGAREP accepts keyboard data to a standard spreadsheet application (Corel ® Quattro Pro ®, version 6.0). The file can be read into similar spreadsheet programs. User inputs include landfill site name, the landfill waste filling history on an annual basis (i.e., tons of waste per year), and parameter combinations for each selected model. The user can input model parameter combinations from Table 2 (as derived from the report's procedures to optimize models through minimization of error), or other parameter combinations as desired.

MEGAREP outputs from each of the four models are tabular data and plots for estimated methane generation over time. For purposes of the program, methane generation estimates were treated as equivalent to expected methane recovery. Other program outputs are probability limits (or uncertainty bounds). The probability limits (upper and lower bounds) are calculated (tabular data) and plotted for the simple first order model (Model 2). These limits are based on the minimization of arithmetic error procedures described in the report. Example input forms and program outputs for the four models are presented in Appendix C.

Probability limits are expressed in terms of the likelihood of seeing predicted gas recovery levels. For example, model outputs provide expected gas recovery levels that would be seen 90 percent of the time, 50 percent of the time, and 10 percent of the time. Users can decide what limits are reasonable or acceptable as the basis for design and sizing of a landfill gas collection and recovery system.

Note that this is the first time that methane recovery probability limits have been available in association with projections for U.S. landfills.

SECTION 6

RECOMMENDATIONS FOR FURTHER WORK

This section recommends further work that could be carried out to improve the utility and confidence limits of the landfill methane models discussed herein.

1. Develop More Complete Landfill Site Characterization

Notwithstanding past results,[1] more detailed site data from study landfills should help to improve modeling accuracy. Landfill site characterization information was considered in questions of the project questionnaire (Appendix B). Except for the Sanitation Districts of Southern California landfills, limited information was obtained from the study landfills other than gate waste tonnage and methane recovery information. In other projects, an interview and information exchange process has been successful in eliciting additional detailed information (U.S. EPA, 1995). Should additional site information be developed for the study landfills to test for improved correlations, the conduct of follow-up interviews is recommended.

2. Continue Accumulation of Data for Study Landfills

Collection of study landfills' data should continue, particularly waste filling and methane recovery information. Working relationships established with the landfill owners/operators should help with collection of future data as they become available. Such future data will better define "real" parameter combinations; that is, those that best explain the long-term methane generation/recovery profile.

3. Add More Landfills to the Study Data Set

Addition of landfills to the study's data set will expand the usefulness and application of the model comparisons. Furthermore, model calibration is needed for groups of landfills located in distinct geographic/climate regions. A larger data set should allow better evaluation for such groups of landfills, such as those in Eastern regions and hot, humid climate regions.

4. Examine Other Data Treatment Approaches

Four landfill methane models were compared through the use of two optimization functions. Other optimization functions were identified but not applied (such as

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1 For example, in work of Peer, et. al. (1992), little correlation was seen between recovery and variables normally expected to influence it [meteorological factors (rainfall, humidity, temperature), design features (depth, etc.) and factors such as waste age].

minimization of arithmetic error by least squares, minimization of logarithmic error by the natural log of the ratios or the square of the natural log of the ratios). These choices for data treatment may be a useful step to further compare methane models and to better distinguish predictive abilities.

5. Examine Other Landfill Methane Models

Other trial model forms could be examined similar to the procedures presented in the study. Examples include multi-phase zero-order and second order models. It is possible that other models could be better in terms of reducing the discrepancies between model projections and field experience.

6. Incorporate Estimates For Methane Recovery Efficiency

The landfill methane models examined treated methane generation as equivalent to methane recovery; estimates for actual methane recovery efficiencies are not model parameters. Because recovery efficiency can affect significantly the actual methane recovered, users of methane models should be experienced and familiar with LFG collection systems so as to apply proper judgement to the model results obtained. Incorporation of the parameter, methane recovery efficiency, to the study's computer program (MEGAREP, v.1.1) is recommended as an initial step to allow users of methane models to discount predicted methane generation as appropriate.

SECTION 7

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APPENDIX A

PROJECT LANDFILL SITE DATA

LANDFILL A
WASTE PLACEMENT DATA

Year	Refuse (Tons/year)	Methane Recovery (MM cf/year)
1955		
1956		
1957		
1958		
1959		
1960		
1961		
1962		
1963		
1964		
1965		
1966		
1967	310,000	
1968	310,000	
1969	310,000	
1970	310,000	
1971	310,000	
1972	310,000	
1973	310,000	
1974	310,000	
1975	310,000	
1976	470,000	
1977	470,000	
1978	470,000	
1979	470,000	
1980	720,000	
1981	750,000	
1982	770,000	
1983	800,000	
1984	830,000	
1985	1,260,000	
1986	1,490,000	
1987	1,530,000	
1988	1,050,000	
1989	870,000	
1990	900,000	652
1991	1,200,000	637
1992	1,700,000	1,281
1993	850,000	1,637
1994		2,201
1995		1,776

LANDFILL B
WASTE PLACEMENT DATA

Year	Refuse (Tons/year)	Methane Recovery (MM cf/year)
1955		
1956		
1957		
1958		
1959		
1960		
1961		
1962		
1963		
1964		
1965		
1966		
1967		
1968		
1969		
1970		
1971		
1972		
1973	213,000	
1974	232,000	
1975	232,000	
1976	232,000	
1977	232,000	
1978	232,000	
1979	508,000	
1980	711,000	
1981	1,114,000	
1982	1,265,000	
1983	1,528,000	
1984	1,484,000	
1985	593,000	
1986	287,000	179
1987	41,000	180
1988		441
1989		443
1990		373
1991		433
1992		426
1993		400
1994		344
1995		293

LANDFILL C
WASTE PLACEMENT DATA

Year	Refuse (Tons/year)	Methane Recovery (MM cf/year)
1955		
1956		
1957		
1958		
1959		
1960		
1961		
1962		
1963		
1964		
1965		
1966		
1967		
1968		
1969		
1970		
1971		
1972		
1973	10,000	
1974	30,000	
1975	40,000	
1976	50,000	
1977	70,000	
1978	90,000	
1979	100,000	
1980	190,000	
1981	210,000	
1982	250,000	
1983	200,000	
1984	320,000	
1985	450,000	
1986	450,000	
1987	70,000	
1988	90,000	
1989	40,000	
1990	10,000	
1991		154.50
1992		169.50
1993		166.83
1994		171.86
1995		

LANDFILL D
WASTE PLACEMENT DATA

Year	Refuse (Tons/year)	Methane Recovery (MM cf/year)
1955		
1956		
1957		
1958		
1959		
1960		
1961		
1962		
1963		
1964		
1965		
1966		
1967		
1968		
1969		
1970		
1971		
1972		
1973		
1974	24,000	
1975	25,000	
1976	27,000	
1977	74,000	
1978	72,000	
1979	74,000	
1980	77,000	
1981	82,000	
1982	82,000	
1983	88,000	
1984	94,000	
1985	99,000	
1986	105,000	
1987	109,000	
1988	108,000	
1989	100,000	88.44
1990	100,000	60.20
1991	69,000	85.39
1992	63,000	70.89
1993	62,000	72.07
1994	60,000	89.19
1995		

LANDFILL E
WASTE PLACEMENT DATA

Year	Refuse (Tons/year)	Methane Recovery (MM cf/year)
1955		
1956		
1957		
1958		
1959		
1960		
1961		
1962		
1963		
1964		
1965		
1966		
1967		
1968		
1969		
1970		
1971		
1972		
1973	10,000	
1974	30,000	
1975	40,000	
1976	50,000	
1977	70,000	
1978	90,000	
1979	100,000	
1980	190,000	
1981	210,000	
1982	250,000	
1983	200,000	
1984	320,000	
1985	450,000	
1986	450,000	
1987	70,000	
1988	90,000	
1989	40,000	
1990	10,000	
1991		112.67
1992		118.44
1993		118.44
1994		119.63
1995		

LANDFILL F
WASTE PLACEMENT DATA

Year	Refuse (Tons/year)	Methane Recovery (MM cf/year)
1955		
1956		
1957		
1958		
1959		
1960		
1961		
1962		
1963		
1964		
1965	26,000	
1966	27,000	
1967	27,000	
1968	28,000	
1969	28,000	
1970	29,000	
1971	30,000	
1972	30,000	
1973	31,000	
1974	32,000	
1975	32,000	
1976	33,000	
1977	34,000	
1978	34,000	
1979	35,000	
1980	36,000	
1981	36,000	
1982	37,000	
1983	38,000	
1984	39,000	
1985	39,000	
1986	40,000	
1987	41,000	
1988	46,000	
1989	38,000	
1990		
1991		
1992		
1993		66.83
1994		61.39
1995		

LANDFILL G
WASTE PLACEMENT DATA

Year	Refuse (Tons/year)	Methane Recovery (MM cf/year)
1955		
1956		
1957		
1958		
1959		
1960		
1961		
1962		
1963		
1964		
1965		
1966		
1967		
1968		
1969		
1970	300,000	
1971	300,000	
1972	300,000	
1973	300,000	
1974	300,000	
1975	300,000	
1976	300,000	
1977	300,000	
1978	300,000	
1979	300,000	
1980	400,000	
1981	400,000	
1982	400,000	
1983	459,000	
1984	440,000	
1985	411,000	
1986	111,000	
1987		
1988		
1989		
1990		
1991		532.81
1992		492.56
1993		440.56
1994		399.52
1995		

LANDFILL H
WASTE PLACEMENT DATA

Year	Refuse (Tons/year)	Methane Recovery (MM cf/year)
1955		
1956		
1957		
1958		
1959		
1960		
1961		
1962		
1963		
1964		
1965		
1966		
1967		
1968		
1969		
1970		
1971		
1972		
1973		
1974		
1975	50,000	
1976	50,000	
1977	50,000	
1978	195,000	
1979	195,000	
1980	195,000	
1981	195,000	
1982	195,000	
1983	195,000	
1984	195,000	
1985	195,000	
1986		
1987		
1988		
1989		
1990		
1991		142.50
1992		130.92
1993		107.85
1994		114.35
1995		

LANDFILL I
WASTE PLACEMENT DATA

Year	Refuse (Tons/year)	Methane Recovery (MM cf/year)
1955		
1956		
1957		
1958	25,000	
1959	25,000	
1960	25,000	
1961	25,000	
1962	25,000	
1963	25,000	
1964	25,000	
1965	25,000	
1966	25,000	
1967	25,000	
1968	25,000	
1969	119,000	
1970	138,000	
1971	160,000	
1972	134,000	
1973	122,000	
1974	119,000	
1975	101,000	
1976	71,000	
1977	102,000	
1978	160,000	
1979	155,000	
1980	143,000	
1981	174,000	
1982	216,000	
1983	206,000	
1984	228,000	
1985	213,000	
1986	57,000	
1987		
1988		
1989		
1990		
1991		102.67
1992		71.56
1993		147.62
1994		132.16
1995		

LANDFILL L
WASTE PLACEMENT DATA

Year	Refuse (Tons/year)	Methane Recovery (MM cf/year)
1955		
1956		
1957		
1958		
1959		
1960	34000	
1961	669000	
1962	379000	
1963	519000	
1964	929000	
1965		
1966		
1967		
1968		
1969		
1970		
1971		
1972		
1973		
1974		
1975		
1976		
1977		
1978		
1979		
1980		
1981		
1982		
1983		
1984		115
1985		131
1986		111
1987		107
1988		79
1989		72
1990		67
1991		62
1992		66
1993		72
1994		65
1995		59

LANDFILL M
WASTE PLACEMENT DATA

Year	Refuse (Tons/year)	Methane Recovery (MM cf/year)
1955		
1956		
1957	86,000	
1958	161,200	
1959	194,800	
1960	220,950	
1961	317,800	
1962	477,700	
1963	683,300	
1964	878,350	
1965	852,100	
1966	703,300	
1967	785,450	
1968	998,572	
1969	1,355,925	
1970	1,215,841	
1971	1,045,424	
1972	1,044,948	
1973	1,062,961	
1974	1,002,844	
1975	983,190	
1976	938,401	
1977	1,052,020	
1978	1,187,187	
1979	1,176,457	
1980	1,177,953	746
1981		833
1982		836
1983		1,083
1984		907
1985		841
1986		896
1987		939
1988		957
1989		778
1990		686
1991		654
1992		697
1993		778
1994		708
1995		728

LANDFILL N
WASTE PLACEMENT DATA

Year	Refuse (Tons/year)	Methane Recovery (MM cf/year)
1955		
1956		
1957	58,410	
1958	500,665	
1959	500,665	
1960	500,665	
1961	500,665	
1962	500,665	
1963	500,665	
1964	500,665	
1965	500,665	
1966	500,665	
1967	500,665	
1968	500,665	
1969	500,665	
1970	773,610	
1971	1,125,496	
1972	1,254,809	
1973	1,277,047	
1974	1,119,786	
1975	946,242	
1976	988,526	
1977	1,333,620	
1978	1,696,837	
1979	1,864,517	
1980	2,046,014	
1981	2,311,218	
1982	2,223,459	939
1983	2,614,426	2,353
1984	2,982,347	2,892
1985	3,282,641	2,687
1986	3,241,095	3,535
1987	3,182,169	3,580
1988	3,184,345	3,961
1989	3,202,556	4,190
1990	3,259,157	4,590
1991	3,285,964	4,580
1992	3,228,554	4,508
1993	3,338,185	4,939
1994	3,245,187	5,109
1995		5,180

LANDFILL O
WASTE PLACEMENT DATA

Year	Refuse (Tons/year)	Methane Recovery (MM cf/year)
1955		
1956		
1957		
1958		
1959		
1960		
1961	205,000	
1962	334,000	
1963	394,000	
1964	481,000	
1965	493,000	
1966	495,000	
1967	512,000	
1968	495,000	
1969	499,000	
1970	475,000	
1971	458,400	
1972	453,000	
1973	431,000	
1974	462,000	
1975	493,000	
1976	440,700	
1977	498,500	
1978	610,300	
1979	691,400	
1980	750,800	
1981	817,500	
1982	867,700	
1983	895,300	
1984	879,000	
1985	1,062,900	
1986	1,527,100	
1987	1,620,200	
1988	683,900	
1989	763,012	718
1990	673,623	993
1991	653,697	942
1992	607,714	952
1993	611,901	1,002
1994	532,240	995
1995		1,032

LANDFILL P
WASTE PLACEMENT DATA

Year	Refuse (Tons/year)	Methane Recovery (MM cf/year)
1955		
1956		
1957	34,560	
1958	75,300	
1959	75,300	
1960	75,300	
1961	89,250	
1962	122,621	
1963	152,404	
1964	160,412	
1965	166,768	
1966	157,428	
1967	147,900	
1968	162,022	
1969	177,606	
1970	184,304	
1971	183,223	
1972	196,010	
1973	205,116	
1974	187,832	
1975	179,883	
1976	178,004	
1977	206,995	
1978	251,992	
1979	283,572	
1980	286,528	
1981	341,519	
1982	364,070	
1983	422,212	
1984	490,617	
1985	553,469	
1986	774,962	
1987	709,519	
1988	770,192	
1989	915,626	387
1990	808,052	452
1991	862,684	456
1992	909,172	519
1993	913,908	632
1994	706,255	602
1995		652

LANDFILL Q
WASTE PLACEMENT DATA

Year	Refuse (Tons/year)	Methane Recovery (MM cf/year)
1955		
1956		
1957		
1958		
1959		
1960		
1961		
1962		
1963		
1964		
1965		
1966		
1967		
1968		
1969		
1970		
1971		
1972		
1973		
1974		
1975	220,000	
1976	220,000	
1977	110,000	
1978	275,000	
1979	275,000	
1980	275,000	
1981	441,667	
1982	166,667	
1983	166,667	
1984	100,000	
1985	100,000	
1986	100,000	
1987		
1988	250,000	
1989	250,000	
1990	250,000	268.2605
1991	250,000	243.2414
1992		241.8708
1993		262.1037
1994		227.9036
1995		205.8382

LANDFILL R
WASTE PLACEMENT DATA

Year	Refuse (Tons/year)	Methane Recovery (MM cf/year)
1955		
1956		
1957		
1958		
1959		
1960		
1961		
1962	80,000	
1963	82,000	
1964	84,000	
1965	86,000	
1966	88,000	
1967	90,000	
1968	92,000	
1969	94,000	
1970	96,000	
1971	98,000	
1972	100,000	
1973	102,000	
1974	104,000	
1975	106,000	
1976	108,000	
1977	110,000	
1978	112,000	
1979	114,000	
1980	116,000	
1981	118,000	
1982	120,000	
1983	122,000	
1984	124,000	
1985	103,428	
1986	110,944	
1987	175,000	
1988	168,766	
1989	190,657	
1990	202,000	
1991	204,000	
1992		284
1993		310
1994		228
1995		257

APPENDIX B

PROJECT QUESTIONNAIRE

APPENDIX B

QUESTIONNAIRE ON LANDFILL SITE FEATURES

As background to readers of this report, landfills initially were identified and screened as suitable for study based on features enumerated in Section 2. This questionnaire was then distributed to staff of selected landfills for information gathering purposes.

SWANA/NREL/DOE LANDFILL METHANE MODEL PROJECT

QUESTIONNAIRE FOR SITE AND GAS RECOVERY DATA

INTRODUCTION

This detailed questionnaire requests landfill and gas recovery information to help develop better landfill gas models. Data will be used in developing models which will be publicly available, for use of everyone in the solid waste community.

Questions below will normally be asked as part of interviews. The questionnaire is intended to be a thorough "checklist" so that important information is not missed. Much information may be pertinent depending on circumstances. However, it is recognized that answers to many questions may be partial or unavailable. Some information may be proprietary. Respondents are asked to answer questions as they are able, and their cooperation is greatly appreciated.

The questions below may pertain to a landfill as a whole. However, if you have and are willing to give data below by landfill sectors it would also be extremely valuable for purposes of developing a model. Questions below may also apply to a single landfill sector.

GENERAL SITE DATA

Name of Landfill Site:

Location:

Year Landfill Started:

Meteorological Data:

Average Annual Rainfall

Average Annual Temperature

Maximum summer daily average

Minimum winter daily average

LANDFILL CONFIGURATION AND OPERATION

(NOTE: THE FOLLOWING QUESTIONS ARE INTENDED TO DETERMINE RELEVANT LANDFILL CONFIGURATION (CELL, MODULE, ETC.) AND OPERATING PROCEDURES.)

Type of fill, (i.e., canyon, mound, etc.):

Waste tonnage since landfill start:

Is waste filled into separate and independent modules? If so, how many and what is configuration and size of the modules?

What is total area ("footprint") of waste now landfilled? If only part of area is decomposable (gas-generating) waste, what is that area? (i.e., eliminate non-decomposable waste areas like demo debris, ash, etc. from total)

Is schematic of fill available (attach, if practical):

Is demolition/inert waste filled separately from organics containing decomposable MSW?

Would you summarize the landfill operating procedure as filling proceeds? (i.e., how do you build new landfill sections and place waste? For example, you might say "fill xxx acre sectors at a time. Sector filling proceeds by placing approximately 10-foot deep compacted layers over sector, repeating until xx foot plan depth is reached").

Would you characterize a typical "cell" dimension resulting from daily filling? (for example 50 x 40 x 8 feet deep, side slope 30°to 60° from horizontal)?

What is the waste compaction practice during filling?

Final cover material: clay or soil? Is membrane used? over what areas?

Is cover cracked? If so is cover repaired?

What is intermediate cover material or practice, i.e.,: permeable soil? Is any greenwaste used for temporary cover? Other temporary cover used, like foams?

Typical intermediate cover soil depth:

(optional) Is the cover soil calcareous, that is containing limestone?

Has cover approach changed over past years? how?

WASTE COMPOSITION CHARACTERIZATION

(NOTE: THE PURPOSE OF THE FOLLOWING QUESTIONS IS TO GENERALLY DETERMINE THE PERCENTAGE AND TYPE OF DECOMPOSABLE WASTE THAT IS LANDFILLED. RELEVANT INFORMATION ALSO REQUESTED AND IS TO BE SUPPLIED IN TABLE 1.)

Can you estimate (from areas served) or otherwise characterize the percentages landfilled of (a) incoming waste that is "normal" household-- paper and putrescibles like food and yard wastes and everything else. (b) percentage that is business/office/commercial--principally paper and including putrescibles such as grocery and restaurant wastes, and (c) inert non-decomposables--these include wood, demolition debris like asphalt, ash, inert non-decomposable manufacturing wastes of various sorts.

Has any waste characterization been performed, i.e., % paper, food, plastic, metal, inerts?

Are there any "atypical" wastes--for example these could be large amounts of food processing or grocery wastes, paper mill and sewage sludges?

Are there significant "unusual" wastes—such as food processing plant wastes, decomposable byproducts of industrial processes, etc.?

Is there baling of waste? Is any waste shredding practiced? Are plastic bags and containers opened before placement? (This does not count compaction.) If so, specify.

Are there significant hazardous wastes (filled in past or components possibly seen in gas from older sectors)?

Is yard waste separated and composted?

What materials are recovered at landfill? For example:

Appliances	Tires	Paper
Tramp iron (cans), metals	Cardboard	Other

WASTE MOISTURE ESTIMATION

(NOTE: THE PURPOSE OF THE FOLLOWING QUESTIONS IS TO DETERMINE THE LIKELY MOISTURE CONTENT AND INFILTRATION AT SITE--WHEN AND WHAT AMOUNT OF WASTE INFLUENCED, AND DEGREE OF SATURATION.)

Do you have moisture data on waste in the landfill? Or, what is moisture addition history at landfill--for example flooding or run-on events, liquid additions by waste type?

Is the cover material porous, allowing precipitation infiltration, or clay (and shedding most precipitation)?

Is waste saturated in any part of landfill (indicated by liquid at base of wells, etc.)

Is leachate generated? If so how much and from where?

Is leachate recycled?

Leachate characteristics:

leachate pH ?

other characteristics (i.e., alkalinity, nutrients) if known.

GAS RECOVERY DATA

(THE PURPOSE OF QUESTIONS BELOW IS TO CHARACTERIZE GAS RECOVERY METHODS AND FLOW AND COMPOSITION MEASUREMENTS)

Are you supplying an energy system? If so, is the energy system gas limited? And, are you trying to maximize recovery for it?

Recovery system characteristics

Vertical well? If so,

- Is layout triangular, square, or mix (irregular)
- Ratio of well depth/waste depth____/____
- Slotline or perforation extent: from ____ depth to ____ (___ above bottom)
- Ratio of well perforation depth to well separation

Trench?

- Trench depth/waste depth
- Trench depth/trench separation
- Length of typical trenches

Membrane cover present?

What is methane measurement method?

- Infrared absorption (Landtech®) meter?
- Thermal conductivity (Gastech® or MSA®) meter?
- Gas chromatograph (model/make if possible)?

Do you measure oxygen or nitrogen at all?

What is the flow measurement method? (Pitot tube, orifice meter, hot-wire anemometer, other)

Is recovery system tuned for maximum recovery? (i.e.,, throttle wells below 50% concentration, increase flow from wells over 50% concentration, etc.)

If system is tuned, what is the methane "set point", i.e., concentration goal on adjustment? (__)% Methane normally observed? (__)% Time interval between adjustments?_____

Is surface scan performed for methane concentration? If so, concentration criterion for control (for example: added control needed if scan shows over 1000 ppm as methane)

Are any other criteria used for extraction adjustment, i.e., surface pressure drop?

Is welling of decomposable waste total (i.e., all welled within 3-5 years from waste placement) or partial? If partial, can you estimate the fraction of decomposable waste that is <u>not</u> welled three or more years after placement?

Wellhead gas temperature: What are values if you have them and, do these vary from new to old sectors of the landfill?

(NOTE: PLEASE FILL OUT TABLE 1. THE MORE ACCURATE THE INFORMATION YOU PROVIDE, THE BETTER.)

TABLE 1

WASTE PLACEMENT AND GAS RECOVERY DATA FOR _____ LANDFILL
(see explanations and instructions)

DESCRIPTION OF LANDFILL SECTOR (IF APPLICABLE) _____ or, N. A.
(check here)

YEAR	Annual Gate Gate Receipts:	Compost, recycl, inert adjustm. see	Waste in place, not yet welled	Adjusted annual waste placement	Gas flow (give units)	Percent methane	Annual Methane Generation	Comments on data/calcs (use later note page[s] also)
1995								
1994								
1993								
1992								
1991								
1990								
1989								
1988								
1987								
1986								
1985								
1984								
1983								
1982								
1981								
1980								
1979								
1978								

Attach data for earlier years if relevant

NOTES/EXPLANATIONS TO TABLE 1.

1. If you can do so, please provide the gate waste tonnage receipts, in terms of total gate waste tons for each year. (for example: 500 tons/day x 300 days open per year would be 150,000 tons.) We want to base the model on yearly gate tonnages since this is information landfill operators are most likely to have.

2. We want to adjust so that the basis for gas generation is only tonnage of "typical" municipal waste whose decomposable organics are actually buried in the landfill, and from which gas is being extracted. Thus several corrections may be needed. From gate tonnage figures that you report, would you please designate and quantify as well as possible any of the tonnage of

   (a) Gate decomposable waste that is not filled but instead composted, including yard waste and other greenwaste, food, paper.

   (b) Gate decomposable waste tonnage that is not filled but recycled--paper, cardboard.

   - Report estimated tonnage for atypically large amounts of inert waste--for example amounts of demolition waste over 20% of the total tonnage received, asphalt and concrete discards, etc. Please count wood waste as inert.

   (d) Report as well, waste tonnage filled but not yet welled (in the next column provided).

   NOTE: Items a and b above--food and paper diverted after the gate (such as for recycling or composting) are especially important. These materials are normally the source of a major part of landfill gas. Their diversions (from filling) represent loss of gas generation potential. If you don't have exact numbers for various materials, provide estimates if you think they are reasonably accurate, and just note these as estimates ("est.").

   You do not have to adjust for glass, metal, or normal demo debris (even if demo debris is placed separately, or some glass or metal are recycled) since these are normally present in "typical" waste that all landfills receive. "Normal" demo debris is up to 15% of waste weight

3. After the adjustments this value should be the gate waste tonnage with remaining decomposables actually landfilled within the year.

4. This figure should be based on the maximum sustainable gas recovery rate you observe (over a month or more in the year) with the gas system working optimally. If there is winter to summer variation you can average and note that. You can report gas recovery rates in your own units (cfm, etc.) and percentage methane and we will work out the rest. We can discuss.

5. Put any comments you think appropriate about waste placement or methane or other data here--just for example "percent methane varied between 45-55%" or " 15% of gas wells down all year" or anything else you think might affect accuracy. Use note section following for longer notes.

There are likely to be questions in many cases. Please call Don Augenstein at 415-856-2850 or Greg Vogt at SCS Engineers, (703) 471-6150. We can also discuss in interviews. Thanks for your help.

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APPENDIX C

METHANE GAS RECOVERY PROGRAM
VERSION 1.1

- Example Program Input Forms and Outputs
- Program Disk

MEGAREP

METHANE GAS RECOVERY PROGRAM
VERSION 1.1, March 1997

This program was developed as part of:

Comparison of Models for Predicting Landfill Methane Recovery,
SCS Engineers, 1997

This program, designed to make estimates for methane emissions from landfills, is organized as follows:

Introductory Screen (Introduction)
Model 1: Methane Generation Coefficients (Gas Coefficients 1)
Model 1: Inputs and Methane Generation Estimates (Input 1)
Model 1: Graph of Estimated Methane Emissions (Model 1)
Model 2: Methane Generation Coefficients (Gas Coefficients 2)
Model 2: Inputs and Methane Generation Estimates (Input 2)
Model 2: Graph of Estimated Methane Emissions (Model 2)
Model 3: Methane Generation Coefficients (Gas Coefficients 3)
Model 3: Inputs and Methane Generation Estimates (Input 3)
Model 3: Graph of Estimated Methane Emissions (Model 3)
Model 4: Methane Generation Coefficients (Gas Coefficients 4)
Model 4: Inputs and Methane Generation Estimates (Input 4)
Model 4: Graph of Estimated Methane Emissions (Model 4)

Individual sheets were relabeled to correspond with the sheet's contents. Sheet names are presented above in parentheses.

Data entry only is to be performed within the input sheets (e.g., 1 through 4). Each cell (highlighted in red) must have an entry for the model to properly function. After data entry, touch the F9 (function key) to recalculate the spreadsheets and update the graphs.

All cells, other than input cells, have been protected.

ABC LANDFILL

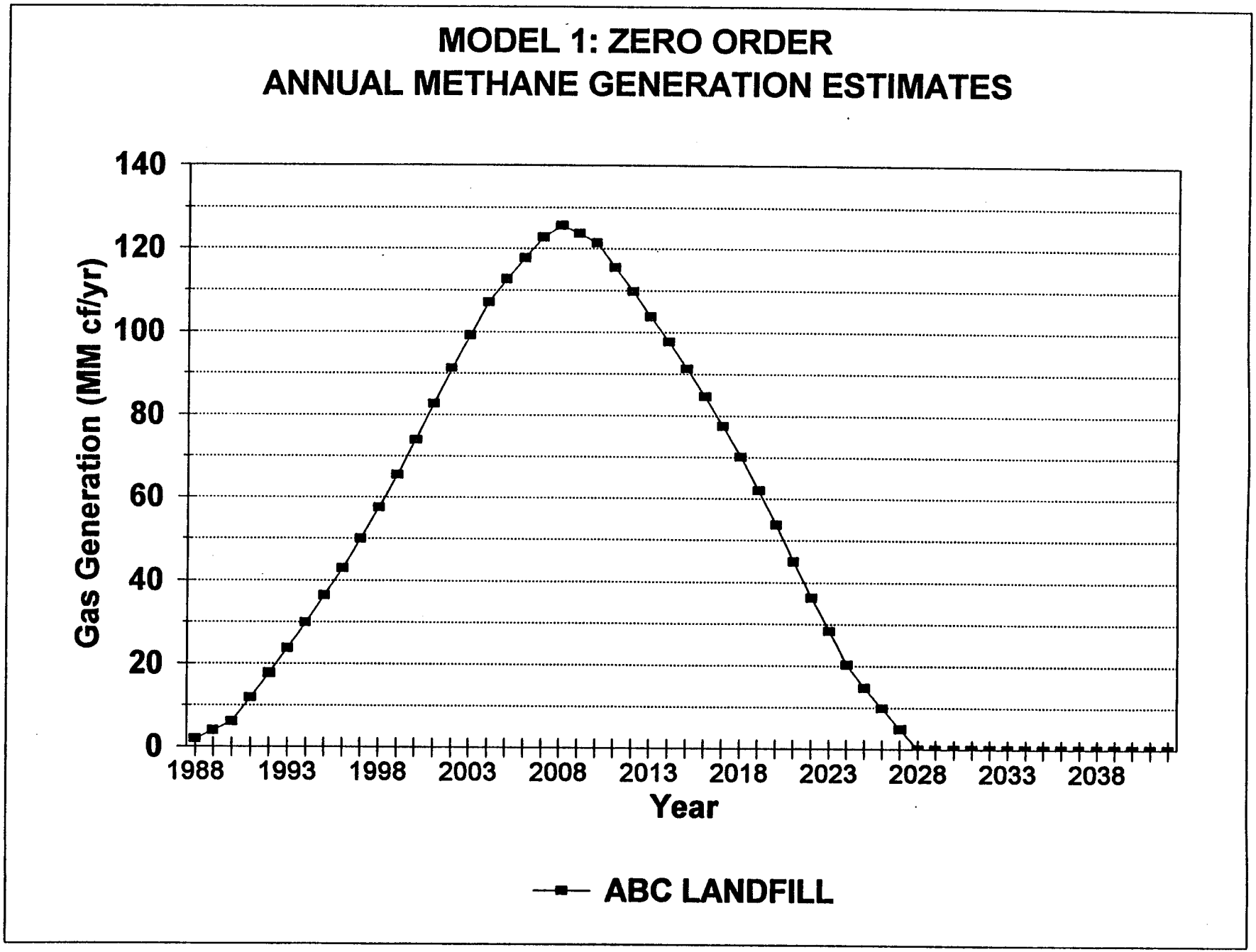
Model 1: Parameters
Zero Order

Start Year No.	**0**	
End Year No.	**20**	
Lo:	**1,600**	cubic feet Methane/ton refuse

Lag time between placement and start of generation is assumed to be zero.

Methane Generation

Year	Annual Refuse (Tons)	Methane Generation (Million cubic feet / year)
1988	**24,000**	2
1989	**25,000**	4
1990	**27,000**	6
1991	**74,000**	12
1992	**72,000**	18
1993	**74,000**	24
1994	**77,000**	30
1995	**82,000**	36
1996	**82,000**	43
1997	**88,000**	50
1998	**94,000**	58
1999	**99,000**	65
2000	**105,000**	74
2001	**109,000**	83
2002	**108,000**	91
2003	**100,000**	99
2004	**100,000**	107
2005	**69,000**	113
2006	**63,000**	118
2007	**62,000**	123
2008	**60,000**	126
2009	**0**	124
2010	**0**	121


MODEL 1: ZERO ORDER
ANNUAL METHANE GENERATION ESTIMATES
Gas Generation (MM cf/yr)
140
120
100
80
60
40
20
0
1988
1993
1998
2003
2008
2013
2018
2023
2028
2033
2038
Year
ABC LANDFILL

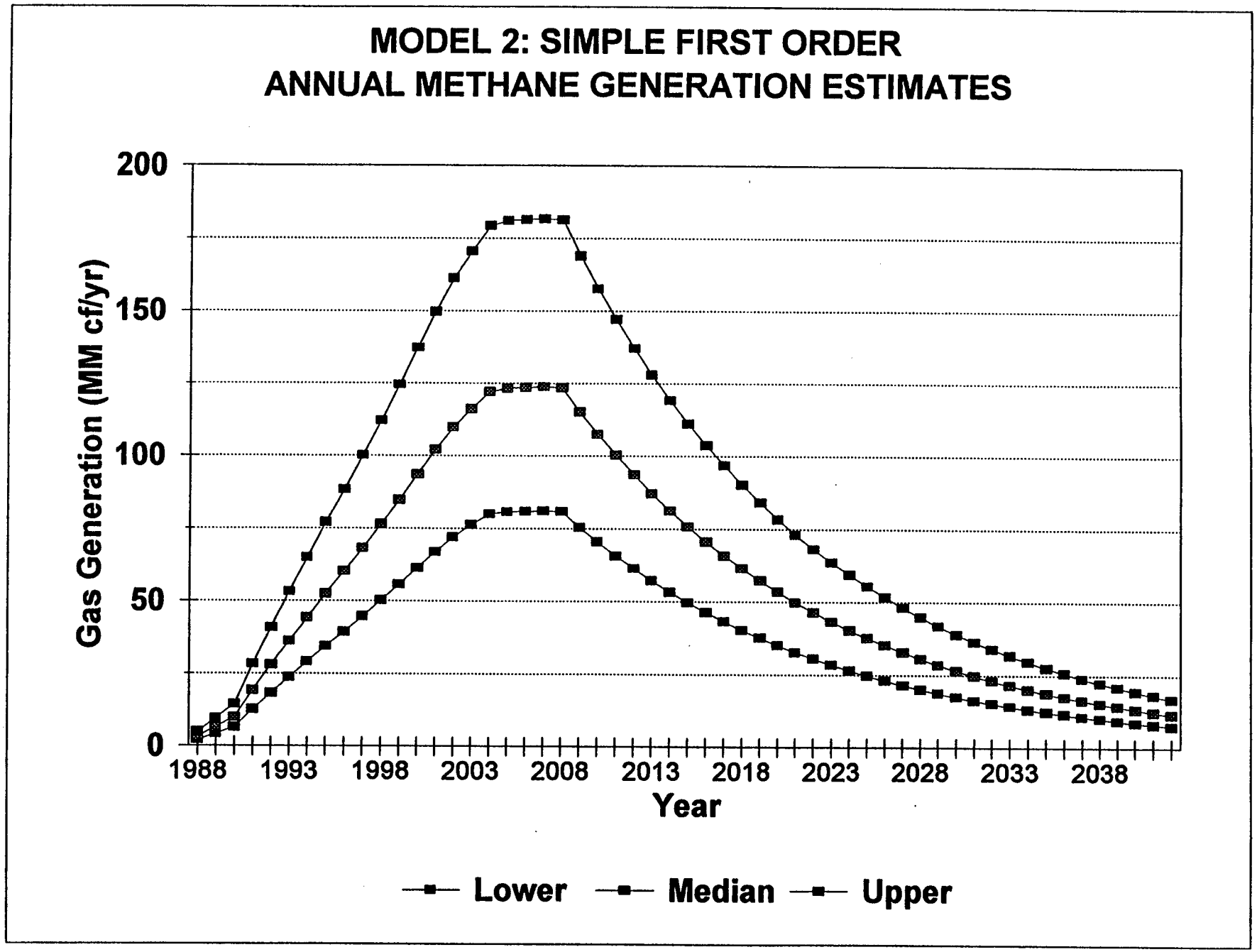
ABC LANDFILL

Model 2: Parameters
Simple First Order

Lo: **2,100** cubic feet Methane/ton refuse
k: **0.07** /year

Methane Generation

Year	Annual Refuse (Tons)	Methane Generation (Million cubic feet / year) Lower Limit	Median	Upper Limit
1988	**24,000**	2	3	5
1989	**25,000**	4	6	10
1990	**27,000**	6	10	14
1991	**74,000**	13	19	28
1992	**72,000**	18	28	41
1993	**74,000**	24	36	53
1994	**77,000**	29	44	65
1995	**82,000**	34	52	77
1996	**82,000**	39	60	88
1997	**88,000**	45	68	100
1998	**94,000**	50	76	112
1999	**99,000**	56	85	125
2000	**105,000**	61	93	137
2001	**109,000**	67	102	150
2002	**108,000**	72	110	162
2003	**100,000**	76	116	171
2004	**100,000**	80	122	179
2005	**69,000**	81	123	181
2006	**63,000**	81	124	182
2007	**62,000**	81	124	182
2008	**60,000**	81	124	182
2009	**0**	75	115	169
2010	**0**	70	107	158


MODEL 2: SIMPLE FIRST ORDER
ANNUAL METHANE GENERATION ESTIMATES
Gas Generation (MM cf/yr)
200
150
100
50
0
1988
1993
1998
2003
2008
2013
2018
2023
2028
2033
2038
Year
Lower
Median
Upper

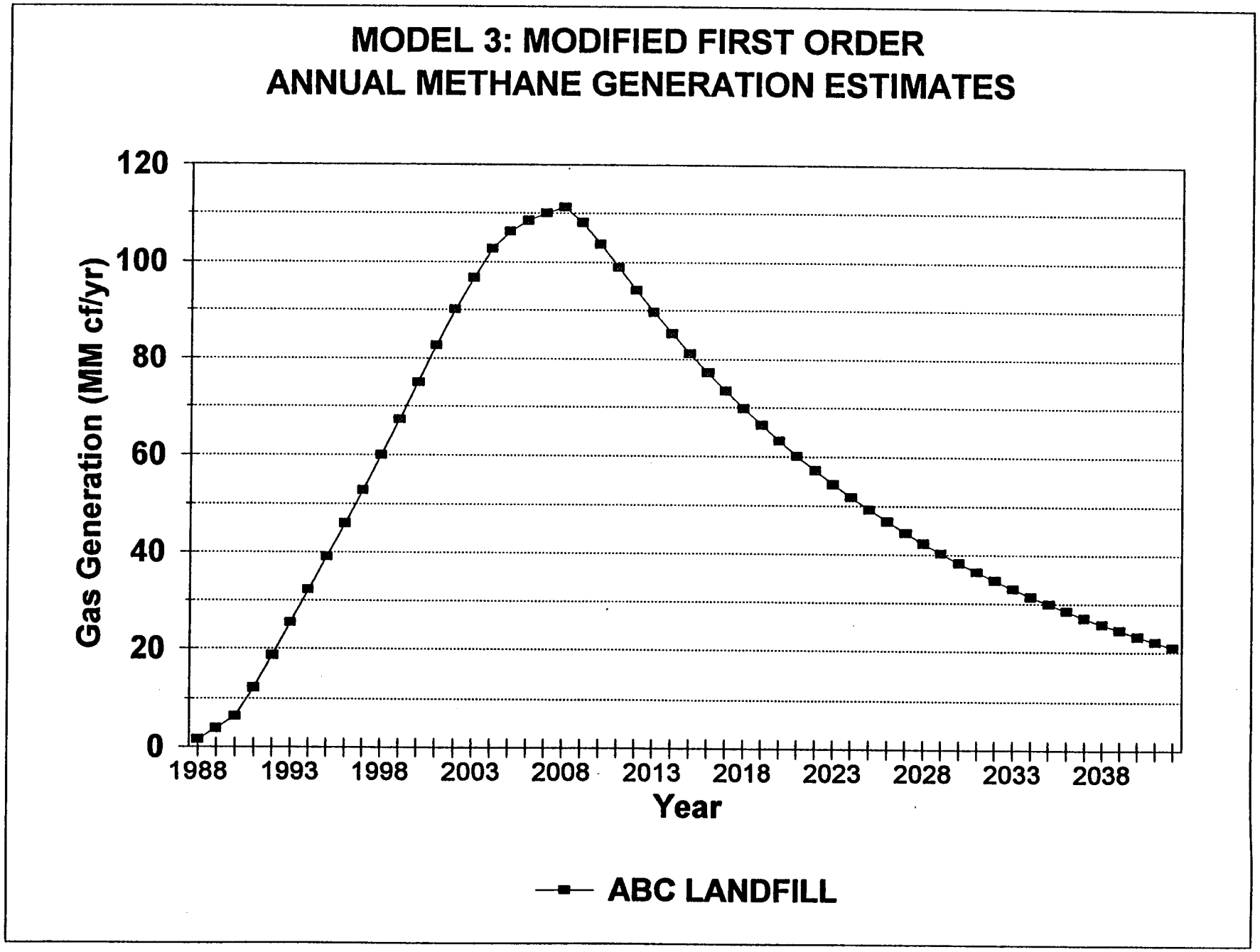
ABC LANDFILL

Model 3: Parameters
Modified First Order

s:	**1.00**	
Lo:	**2,200**	cubic feet Methane/ton refuse
k:	**0.05**	/year

Methane Generation

Year	Annual Refuse (Tons)	Methane Generation (Million cubic feet / year)
1988	**24,000**	2
1989	**25,000**	4
1990	**27,000**	6
1991	**74,000**	12
1992	**72,000**	19
1993	**74,000**	25
1994	**77,000**	32
1995	**82,000**	39
1996	**82,000**	46
1997	**88,000**	53
1998	**94,000**	60
1999	**99,000**	67
2000	**105,000**	75
2001	**109,000**	83
2002	**108,000**	90
2003	**100,000**	97
2004	**100,000**	103
2005	**69,000**	106
2006	**63,000**	108
2007	**62,000**	110
2008	**60,000**	111
2009	**0**	108
2010	**0**	104


MODEL 3: MODIFIED FIRST ORDER
ANNUAL METHANE GENERATION ESTIMATES
Gas Generation (MM cf/yr)
120
100
80
60
40
20
0
1988
1993
1998
2003
2008
2013
2018
2023
2028
2033
2038
Year
ABC LANDFILL

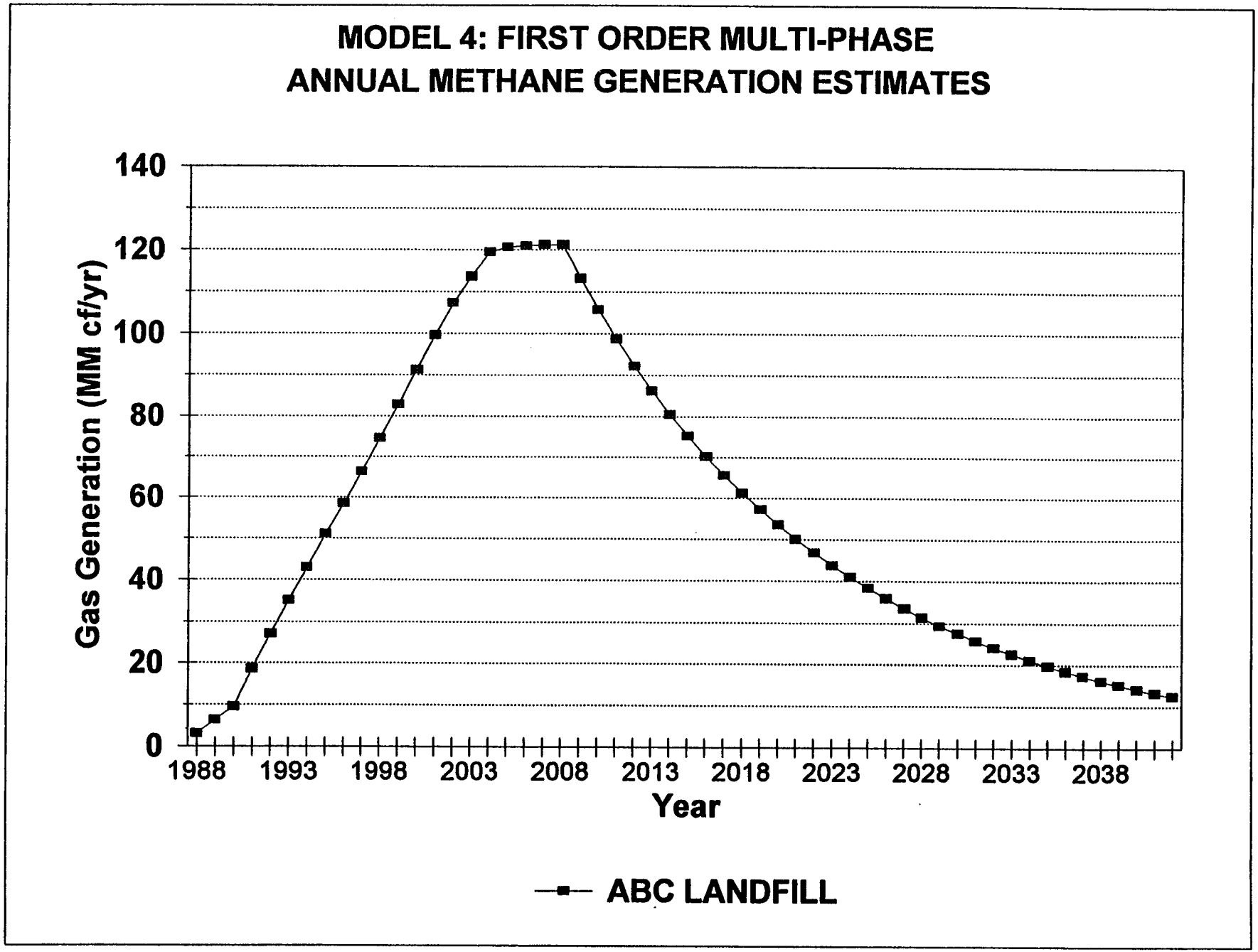
ABC LANDFILL

Model 4: Parameters
First Order Multi-Phase

k-Constant (for rapid)	**0.08**	Decay Rate of Rapidly Decomposables
k-Constant (for slow)	**0.06**	Decay Rate of Slowly Decomposables
Fraction fast decomposing	**40%**	Fraction of Rapidly Decomposing Waste
Fraction slow decomposing	**60%**	Fraction of Slowly Decomposing Waste
Lo-Constant	**2,100**	cubic feet Methane/ton refuse

Methane Generation

Year	Annual Refuse (Tons)	Methane Generation (Million cubic feet / year)
1988	**24,000**	3
1989	**25,000**	6
1990	**27,000**	9
1991	**74,000**	19
1992	**72,000**	27
1993	**74,000**	35
1994	**77,000**	43
1995	**82,000**	51
1996	**82,000**	59
1997	**88,000**	66
1998	**94,000**	75
1999	**99,000**	83
2000	**105,000**	91
2001	**109,000**	100
2002	**108,000**	107
2003	**100,000**	114
2004	**100,000**	119
2005	**69,000**	121
2006	**63,000**	121
2007	**62,000**	121
2008	**60,000**	121
2009	**0**	113
2010	**0**	106


MODEL 4: FIRST ORDER MULTI-PHASE
ANNUAL METHANE GENERATION ESTIMATES
Gas Generation (MM cf/yr)
140
120
100
80
60
40
20
0
1988
1993
1998
2003
2008
2013
2018
2023
2028
2033
2038
Year
ABC LANDFILL