Arnold Schwarzenegger
Governor

FIELD VALIDATION OF A MODEL OF GENERATION AND MIGRATION OF METHANE AND OTHER GASES IN LANDFILLS

INDEPENDENT ASSESSMENT AND FINAL EISG REPORT

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California Energy Commission
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Prepared By:
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ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM

INDEPENDENT ASSESSMENT REPORT (IAR)

FIELD VALIDATION OF A MODEL OF GENERATION AND MIGRATION OF METHANE AND OTHER GASES IN LANDFILLS

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PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable and reliable energy services and products to the marketplace. The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million of which 5% is allocated to the Energy Innovation Small Grant (EISG) Program. The EISG Program is administered by the San Diego State University Foundation through the California State University, which is under contract to the Commission.

The EISG Program conducts up to four solicitations a year and awards grants for promising proof-of-concept energy research.

PIER funding efforts are focused on the following seven RD&D program areas:

- Residential and Commercial Building End-Use Energy Efficiency
- Energy Innovations Small Grant Program
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally-Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies

The EISG Program Administrator is required by contract to generate and deliver to the Commission an Independent Assessment Report (IAR) on all completed grant projects. The purpose of the IAR is to provide a concise summary and independent assessment of the grant project in order to provide the Commission and the general public with information that would assist in making follow-on funding decisions. The IAR is organized into the following sections:

- Introduction
- Objectives
- Outcomes (relative to objectives)
- Conclusions
- Recommendations
- Benefits to California
- Overall Technology Assessment
- Appendices
  - Appendix A: Final Report (under separate cover)
  - Appendix B: Awardee Rebuttal to Independent Assessment (awardee option)

For more information on the EISG Program or to download a copy of the IAR, please visit the EISG program page on the Commission's Web site at:
http://www.energy.ca.gov/research/innovations

or contact the EISG Program Administrator at (619) 594-1049, or email at:
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For more information on the overall PIER Program, please visit the Commission's Web site at http://www.energy.ca.gov/research/index.html.

Field Validation of a Model of Generation and Migration of Methane and Other Gases in Landfills

EISG Grant #: 00-26

Awardee:	GC ENVIRONMENTAL, INC.
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Introduction

Solid waste deposited deep in a landfill decomposes by a process of anaerobic fermentation, creating gas with high methane content. If not otherwise controlled, this "landfill gas" works its way to the surface and enters the atmosphere as a greenhouse gas. When it is collected instead of released, landfill gas can serve as a fuel for electric generators. All of the many landfills in California generate these gasses, but inefficient collection of this potential fuel has limited its use to power electric generators. A better understanding of gas transport and generation processes in a typical landfill could lead to more efficient use of this renewable resource.

As of 2002, California generated 211 MW of electric power from landfill gasses. Currently, uncaptured gas produced by existing landfills in California is enough to fuel another 181 MW of electrical generation (Landfill Gas-to-Energy Potential in California, September 2002, CEC 500-02-041V1). In addition, California deposited 37,829,177 tons of taxable solid waste into landfills during 2002 (www.ciwmb.ca.gov/Landfills/LFData.html). The exact amount of gas generated varies greatly from landfill to landfill, but one estimate (www.forester.net/mw_0401_retail.html) suggests that each one-to-five million tons of waste can support a 1-MW power plant. Using an average of three million tons of solid waste per megawatt, we find that the amount of solid waste deposited annually in California will support an additional ~12 MW of electric generation capacity each year. Improved understanding of landfill gas generation and transport would accelerate the development of gas collection systems and enhance the use of these renewable resources.

This project proposed to test a model of gas transport and generation in a landfill using actual landfill data. The University of Southern California, (USC) in association with GC Environmental, Inc. (GCE), set out to develop a comprehensive, three-dimensional, computer gas-flow model to help predict gas generation and migration in heterogeneous landfills and the areas that surround them. Modern geo-statistical approaches for analyzing field data were used to map the heterogeneous structure of the landfill by calculating its various properties, such as its porosity and permeability distributions. This structure model, combined with a gas-generation simulator, would predict the rate of gas generation and migration. Also, it would predict the composition of the gas and air on the top surface of the landfill and in the surrounding soil, as well as the pressure build-up in the landfill. The researchers projected that the simulator could be helpful in predicting the amount of refuse that is lost to aerobic processes in the landfill surface layer.

Objectives

The goal of this project was to prove the feasibility of using a three-dimensional transport model to predict gas generation and migration in complex heterogeneous landfills. The researchers established the following project objectives:

1. Using data obtained from a large Southern California landfill, validate the predictive accuracy of a three-dimensional transport model to be within +/- 10% for gas GENERATION in complex heterogeneous landfills.

2. Using data obtained from a large Southern California landfill, validate the predictive accuracy of a three-dimensional transport model to be within +/- 10% for gas MIGRATION in complex heterogeneous landfills.

3. Provide specific recommendations to improve landfill gas-collection system designs to improve the quantity and quality of recovered landfill gas.

Outcomes

1. Data from the Kern County landfill was used. This landfill covered approximately 190 acres, with over 300 gas wells installed for collection. The landfill's size, complexity, and database provided adequate data to calibrate the model. The validated model was used to predict gas generation in the same field using the same data already used to validate the model, so it is not surprising that errors were low. The real test of the validated model requires its use to evaluate another well-documented landfill. Carbon/methane production ratios were found to vary greatly across the landfill. The researchers divided the landfill into five zones to account for this variability. In other cases, the researchers selected the data that would be used in the model validation and ignored other data.

2. The predicted gas migration was accurate within 10%. This, too, was not surprising since the model was calibrated using data from this landfill.

3. The researchers suggested several enhancements of the model, but none for gas-collection system designs that might improve the quantity and quality of recovered landfill gas.

Conclusions

1. Data from the Kern County landfill was used to validate the gas-generation part of the model. Some data points were ignored to facilitate computation. The true test of the model is to run it on another well-documented landfill. Understanding the complexities of landfills requires additional data evaluation. Permeability is just one of many factors that can affect gas generation and migration. Examination of more than one landfill will help determine if other factors apply.

2. The conclusion for the first objective applies to the second objective as well.

3. It is not yet clear how this model will improve the design of gas collection systems.

4. The feasibility of this model to improve the production and quality of landfill gas is not yet proven. Additional tests are required to validate the utility of this model at landfills that have been subjected to considerably less evaluation.

Recommendations

More data is needed to ascertain whether the validated model accurately predicts methane and carbon dioxide gas generation and pressure in the landfill where it was validated. A second recommendation is to test the validated model in another landfill that is well documented. Without more data and testing, the model's utility to ratepayers in California is difficult to ascertain. The researchers should devise/develop a critical test to demonstrate the value of the model to the landfill operators. Without that demonstration of value it is unlikely that the landfill operators will adopt the model.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is to increase the affordability of electricity in California by using landfill gas as a fuel for electric generators. This model, when fully developed and implemented, may help landfill operators capture and utilize an increased amount of the methane generated by solid waste. If not captured, this landfill gas contributes significantly to the inventory of greenhouse gasses. When utilized, it becomes a renewable resource for the production of electricity.

Overall Technology Development Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

If the model can be validated with additional data, the model can facilitate methane gas extraction from landfills. Improved methane gas extraction would provide more fuel for electricity generators in California. The researchers' company is in the business of providing consulting services to landfill operators. This is a sufficient market connection to take a completed model to the market. However, that company has not evaluated the size of the market.

Engineering/Technical

This project demonstrated a model for predicting the gas generation in a landfill. Actual field data were used to calibrate the model. Additional data are needed to verify the accuracy of this model. Otherwise, it is not possible to predict the utility of this model when applied to other landfills, or the impact to ratepayers in California.

Legal/Contractual

There are no known legal or contractual issues associated with this project. There is no evidence of intellectual property protection. The researcher stated that he has neither performed a patent search nor has he filed for a patent on the model.

Environmental, Safety, Risk Assessments/ Quality Plans

No environmental, safety, risk, or quality plans were addressed in this project.

Production Readiness/Commercialization

GC Environmental, Inc. has the capability to take a completed model to the market. However GC Environmental has not developed a business plan or commercialization plan for this model.

Appendix A: Final Report (under separate cover)

Appendix B: Awardee Rebuttal to Independent Assessment

Appendix A to IAR 00-26

ENERGY INNNOVATIONS SMALL GRANT (EISG) PROGRAM

EISG FINAL REPORT

FIELD VALIDATION OF A MODEL OF GENERATION AND MIGRATION OF METHANE AND OTHER GASES IN LANDFILLS

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Legal Notice

Inquiries related to this final report should be directed to the Awardee (see contact information on cover page) or the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

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Abstract

The **University of Southern California, (USC)** in association with **GC Environmental, Inc. (GCE)**, and under a grant from the California Energy Commission (Commission), has developed a comprehensive, three-dimensional computer gas flow model to help predict gas generation and migration in heterogeneous landfills and the areas that surround them. Specifically, the model uses modern geo-statistical approaches for analyzing field data in order to map the heterogeneous structure of the landfill, by analyzing it's various properties such as its porosity and permeability distributions. We have combined these with a gas generation simulator to predict the rate of gas generation and migration. The model also is able to evaluate composition of the gas and air on the top surface of the landfill and in the surrounding soil, and the pressure build-up in the landfill. Thus, the simulator can, in principle, be helpful in predicting the amount of refuse that is lost to aerobic processes in the landfill surface.

Keywords: Landfill, gas generation and migration, municipal solid waste

Executive Summary

1. Introduction

In order to implement gas collection and control in a landfill, and predict the behavior of a landfill over the course of several years, it is important to understand gas generation and transport within a landfill. Doing so can provide several advantages such as developing alternative sources of renewable energy and minimizing negative environmental impact. Landfill gas consists primarily of methane and carbon dioxide. The composition of the gaseous mixture depends on the conditions that affect the waste decomposition process, and the rate of transport of the gases on the landfill, which depend on the permeability and porosity distribution of the landfill.

The University of Southern California (USC) and GC Environmental, Inc., under a grant from the California Energy Commission have teamed to develop a comprehensive, three-dimensional model to assist in predicting gas generation and migration in heterogeneous landfills and areas that surround them. The model utilizes modern geostatistical approaches for analyzing field data to map the heterogeneous structure of the landfill, and evaluating its various properties such as porosity and permeability distribution throughout the landfill. These factors have been combined with a gas generation simulator to predict the rate of gas generation and migration.

2. Project Objectives

Many of the key parameters of a landfill that influence its behavior are either not known, or the data available is very limited or insufficient, or are not available to the public. In order to validate the model, a large Southern California landfill covering approximately 190 acres with over 300 gas wells was used. The site provided a large amount of data that could be used in the model. This site was selected to fit the model's parameters to the experimental data because of its complexity and complicated kinetics of waste biodegradation and the type and amount of gases that it produces, as well as it's large size and geometrical shape.

The primary objective of the project was to validate a comprehensive, three-dimensional model of gas generation and transport in landfills, developed by GCE and USC. The model allows for arbitrary distributions of the landfill heterogeneities (the distributions of its permeability and porosity), the reaction rates, a large number of reactants and products, and an arbitrary number of extraction wells distributed throughout the landfill, in addition to the factors listed above. If the model can be validated by applying it to a large and complex landfill in California, it can be used for studying the behavior of other landfills in California, and for making predictions for them, which can them be used in the planning and operation of such landfills.

3. Project Outcomes

Relative errors in reproducing the experimental data for the mole fraction of methane at the extraction and observation wells are presented in **Figure 3**. To compute these errors, the fitted parameters were used in the model. The error for the majority of the data is relatively small, while for a small minority of the data, the error is large.

After removing a few of the experimental data points from the fitting process and refitting the seven parameters to the rest of the data, we obtain the error plot shown in **Figure 4.** The error computing the mole fraction of methane at the point for which experimental data are available has been reduced. Thus, the quality and amount of experimental data that are used in the fitting process play a vital role in yielding accurate estimates for the fitted parameters. Numerical estimates of the two sets of the seven parameters obtained by fitting are shown in **Table 2**.

The distribution of the total (gauge) pressure in a plane at depth 9.114 meters (m), obtained by using the fitted parameters in the model, computed at the steady state are shown in **Figure 5. Figure 6** shows the corresponding distribution of methane at the same depth. It is clear that in a portion of the landfill, the mole fraction of methane is quite high, resulting in relatively high pressures. Evidently, we can compute the same distribution over a period of time in order to understand how these two distributions, which are important to the maintenance of a landfill, are built up.

The model results prove that the model could be used to provide reasonable answers concerning gas collection and pressure distribution inside and outside of a landfill. The model also allows soil gas flow rates to be calculated. This is helpful when evaluation off-site risk.

4. Conclusions

Provided there is a sufficient amount of data available for any given landfill, the parameters of the model can be accurately fit to the data. The fitted parameters can then be used for studying the behavior of the landfill and predicting its behavior, or the rates of gas generation and transport in the landfill over many years. Such a model could serve to be a valuable tool for planning the safe operation of a landfill.

5. Recommendations

It is clear that the work needs to be continued so that the model can be improved. The work completed so far provides the first steps for developing a predictive model of gas generation and transport in a landfill. Additional steps and improvements that can be undertaken to improve the model include using an optimization algorithm, such as the simulated annealing or the genetic algorithm to determine the distribution of permeability and porosity throughout the landfill, as opposed to assuming a fixed porosity and vertical and horizontal permeabilities in the landfill. Because of several factors, it is likely such distributions could be quite complex.

In addition, the model can be improved by treating the ratio of the production rates of carbon dioxide and methane as adjustable parameters. Our work indicates that the distribution of this quantity changes throughout the landfill and, therefore, similar to the permeabilities and porosities, must be determined by an optimization algorithm. These two problems pose a formidable computation problem, which can be solved, given our present knowledge.

Other mechanisms (kinetics) of reaction can also be examined in which the effect of moisture and the local composition are accounted for.

6. Public Benefits to California

Landfills can be a potential source for renewable energy, and need to be operated safely so as not to pose any threats to the environment. There are several thousands of landfills in the state of California. Currently, landfills are maintained and operated purely based on empiricism and "experience." There is no scientific basis to the operation of the landfills.

The model considered in this project is of fundamental importance to the operation of landfills and their use as a potential source of renewable energy. The model provides a sound scientific basis for such operations, and avoids many pitfalls that can result from purely empirically based operations. It can also predict the behavior of the landfill for several years to come, providing a sound basis for its planning and use.

Introduction

Understanding gas generation and transport in landfills is of fundamental importance to implementing landfill gas collection and control, and predicting the behavior of the landfill over a period of several years. This is important not only from an environmental view point, but also in terms of developing alternative sources of renewable energy. Landfill gas consists primarily of methane, carbon dioxide, oxygen, and nitrogen. The precise composition of the gaseous mixture depends on the conditions that affect the waste decomposition process, and on the rate of transport of the gases in the landfill; this, in turn, depends on the permeability and porosity distribution of the landfill. Hence, developing a comprehensive model of gas generation and transport in a landfill is of fundamental importance to predicting the behavior of the landfill.

Our group had previously developed such a comprehensive model [1]. It is a three-dimensional model that accounts for the effect of all the important factors, such as the geometry of the landfill, its permeability and porosity distributions, the spatial distribution of the extraction and observation wells, the kinetics of the reactions, and non-isothermal effects, as well as the effect of the surrounding soil, and the cover that is put on the top surface of the landfill.

Project Objectives

The primary objective of the project was to validate a three-dimensional, dynamic model of gas generation and transport in landfills, developed previously by our group. The model allows for arbitrary distributions of the landfill heterogeneities (that is, the distributions of its permeability and porosity), the reaction rates, a large number of reactants and products, and an arbitrary number of extraction wells distributed throughout the landfill, as well as other factors listed above. If the model can be validated by applying it to a large and complex landfill in California, it can then be used for studying the behavior of other landfills in California, and for making predictions for them, which can then be used in the planning and operation of such landfills.

Project Approach

Many of the key parameters of a landfill that influence its behavior are either not known or the data for them are very limited and insufficient, or are not available to the public. This presents a significant challenge in terms of validating a model, which is predictive of the landfill's behavior and past history. Over the past 18 months, our team has been working on fitting the model's parameters to the experimental data for one of the largest and most complex landfills in California. The complexity of this landfill is not only due to the complicated kinetics of waste biodegradation and the type and amount of the gases that it produces, but also due to its large size and complicated geometrical shape. It also contains 228 extraction wells, and many observation wells, scattered throughout the landfill. In addition, a large piece of land next to the landfill in utilized as natural gas storage. Some of the gas stored may, over time, have migrated towards the landfill, hence further complicating the task of interpreting the data collected at the observation and/or extraction wells at the landfill.

The dynamic model of gas generation and transport in landfills that we have developed contains several parameters. These are, (i) the three different fractions of the municipal solid waste (MSW) in the landfill (A_i), (ii) the three gas generations constants of each MSW fraction (λ_i), (iii) the prevailing temperature gradient in the landfill, (iv) the landfill's vertical and horizontal permeabilities, (v) the landfill's porosity and tortuosity factor, (vi) the surrounding soil's permeability and tortuosity factor, (vii) and the three gas generation potentials. In principle, all of these parameters affect the predictions of the model and, in particular, the amount and composition of the produced landfill gas. However, only limited experimental data for the amount and composition of the gas produced in the landfill were made available to us. Therefore, we did not attempt to fit simultaneously all the model parameters, as the uncertainty in the values of some of the parameters generated would have been too large, due to lack of sufficient amount of experimental data. Our approach, instead, was to fix the values of some of the parameters in the range, which based on prior literature information and our practical experiences, we thought to be reasonable and physically acceptable.

Even when one decides to focus attention during fitting on only a select number of parameters, one still runs into the problem that, the parameters to be fitted may not have the same values throughout the landfill; assigning a single value to them may, therefore, not reflect the practical reality. We know, for example, that due to compaction, the vertical permeability at the bottom of the landfill will be smaller than its value close to its top surface. Moreover, there are actually spatial distributions of the local permeabilities and porosity throughout the landfill. Attempting to fit all of these parameters, assuming that they are spatially-distributed, would entail estimating the values of thousands of parameters throughout the landfill. Although this problem can, in principle, be attacked and solved, if a sufficient amount of accurate experimental data were available, it would have been well beyond the scope of the present project. Instead, we have developed a unique method of incorporating the effect of the spatial distribution of the heterogeneities of the landfill (permeability and porosity) in the model and fitting the parameters of the model. This will be explained shortly.

The variables that we fit are, (1) the effective permeability in the vertical direction, as well as that in any horizontal plane in the landfill, since the model assumes that, due to compaction, the vertical permeability is different from the horizontal one; (2) the effective permeability of the soil that surrounds the landfill, since in the particular landfill the two appear to communicate with each other; (3) the effective porosities of the landfill and the surrounding soil, and (4) the tortuosities of the landfill and the soil. Therefore, we fit seven parameters that we believe to have the strongest influence on the rate of accumulation of methane in the landfill, and its migration toward the extraction and/or observation wells.

The data that were used for the fitting are the methane composition measured at the extraction and/or observation wells, taken from January through August during 2001. There are 228 extraction wells in this landfill, but composition data were only provided from 29 such wells. The rest of the experimental data were from the observation wells where gas probes take samples of the gas produced by the refuse; there were 38 such observation wells. We only used the experimental data available from the western part of the landfill. Although data were also made available to us from other parts of the landfill we did not use them, due to two main reasons.

The amount of the measured methane at some locations was essentially non detectable. Using these data creates severe numerical difficulty in fitting the parameters.

(1) There is evidence that the produced and measured methane at some of the locations in the landfill was due to thermogenic sources (for example, from natural and coal-bed gas) that had migrated to the landfill.

The numerical technique that we use to fit the parameters of the landfill is called the Marquardt-Levenberg (ML) method [2], which is, typically, used for fitting the parameters of a nonlinear model. In this method, the objective is to minimize a function, usually referred to as the Merit Function, which is defined by,

$$\chi^2(\mathbf{a}) = \sum_{i=1}^{N} \left[\frac{y_i - y(x_i;\mathbf{a})}{\sigma_i} \right]^2 \qquad (1)$$

where σ_i is the standard deviation. The experimental data are represented by y_i, while the theoretical data generated by the dynamic model are represented by y (x_i; **a**), with vector **a** denoting the parameters to be fitted. In the present problem, the function y(x, a1, a2, a3…..) represents the theoretically generated data (using some estimates for the fitted parameters) for those locations at which the experimental data were available and used in the fitting process. Since the model is nonlinear, the optimized values of the parameters are obtained after many iterations, beginning with some "guesses" for the values of the parameters to be fitted. Each iteration yields new estimates for the parameters that are calculated from the following equation,

$$\mathbf{a}_{\mathbf{next}} = \mathbf{a}_{\mathbf{cur}} - \text{constant} \times \nabla\chi^2(\mathbf{a}_{\mathbf{cur}}), \qquad (2)$$

where $\mathbf{a}_{\mathbf{cur}}$ represents the current estimates of the parameters. The constant in Eqn. (2) has a small value which does not affect the iteration procedure. Since the objective of iterative scheme is to determine those values of the parameters for which the Merit Function is minimum, the parameters must satisfy the set of equations that are obtained by taking the derivatives of the Merit Function with respect to the parameters. These equations are given by

$$\frac{\partial \chi^2}{\partial a_k} = -2\sum_{i=1}^{N} \frac{[y_i - y(x_i;\mathbf{a})]}{\sigma_i^2} \frac{\partial y(x_i;\mathbf{a})}{\partial a_k} \quad k = 1, 2, \ldots M, \qquad (3)$$

where N is the number of experimental data points used in the fitting and k is the number of the parameters to be fitted. In addition, due to the iteration procedure for a nonlinear model, we must compute the derivatives of the equations given by the set (3), implying that we must compute numerically the second derivatives of the Merit Function defined by Eqn. (1). Therefore, we must compute,

$$\frac{\partial^2 \chi^2}{\partial a_k \partial a_l} = 2\sum_{i=1}^{N} \frac{1}{\sigma_i^2}\left[\frac{\partial y(x_i;\mathbf{a})}{\partial a_k}\frac{\partial y(x_i;\mathbf{a})}{\partial a_l} - [y_i - y(x_i;\mathbf{a})]\frac{\partial^2 y(x_i;\mathbf{a})}{\partial a_l \partial a_k}\right] \quad (4)$$

The steepest descent method is then used for iterating the above equations, and determining their minima, hence estimating the optimized values of the fitting parameters. This method explores and computes the set of all the minima of the Merit function, and by eliminating the local minima locates the global minimum of the Merit Function. The iterative procedure is such that each calculated minimum is closer to the true minimum than the previous one.

The procedure to fit the parameters is as follows. The first step involves discretizing the equations that govern the dynamic model, in order to determine their numerical solutions. We use the finite-difference (FD) technique to discretize the governing equations. Hence, we first generate the grid structure that we use in the numerical solution of the dynamic model. The grid size is 113 x 213 x 33, where 33 represents the number of the grid points in the vertical direction. This represents an area with a size, 2727.96 x 3383.28 x 97.53, where the distances are measured in meters. Since we use a central-difference FD technique, the grid axes are along the cartesian coordinates, and the cells or blocks in the grid are cubes. The grid represents the landfill and the soil surrounding it.

Next, we identify, based on the map of the landfill that was available to us, that part of the overall grid that corresponds to the landfill itself; the rest of the grid represents the soil that surrounds the landfill. Since the boundaries of the landfill are completely irregular, adjusting the grid in order to produce approximate, yet accurate, boundaries of the landfill in the grid is a major problem. We spent a considerable amount of time in searching for the most efficient way of solving this problem.

We then assign the effective properties of the grid blocks, such as the porosity, permeabilities, the temperature distribution in the system, the initial estimates of the mole fractions of the gases that constitute the main components of the gaseous mixture of the landfill, the total pressure (the local partial pressures of the gases are computed by the model), the biodegradation time of each type of municipal solid wastes (MSW), and the type of grid block (landfill or soil). The assigned values, in the case of the parameters to be fitted, represent the initial guesses for their true values.

The grid contains, in general, four types of nodes, or equivalently grid blocks, which are those that are in the soil, in the landfill, in the air on top of the landfill, and in the wells, each of which is identified by a code number indicating their type, in addition to their spatial position. The parameters of the model, both those that are held fixed and those that we wish to fit, have different values for each type of node or grid block, but are assumed to be uniform throughout the landfill for each type of grid block.

The original model allows for the top cover of the landfill to be permeable. However, consultation with the landfill's operators indicates that it is their belief that very little (if any) gas escapes from the top and that the only way that methane could leave the landfill is through the extraction wells. We have no way of checking the validity of this claim, so during parameter fitting the top cover permeability was assigned a value of zero.

We assume that there are three types of MSW, and classify them as the readily biodegradable, moderately biodegradable, and least biodegradable wastes. We really have no information that this is indeed the case as we were not provided with any information concerning the exact composition of the waste that this landfill contains. The biodegradation of the three different classes of wastes is modeled as a substrate-limited version of the Monod equation, given by

$$\frac{d\Psi}{dt} = \frac{\kappa}{\kappa_s}\Phi\Psi \;\; ; \Psi << \kappa_s \tag{5}$$

which, when integrated for the three classes of wastes, yields the generation rate of each type of species produced in the landfill. In equation 5 κ is maximum rate of substrate, κ_s is half velocity coefficient, Φ is micro-organism concentration, and Ψ is the substrate concentration. We assume that the only gaseous species produced in the landfill are methane and carbon dioxide. The equation for the generation of each species in the landfill is given by (Eqn. 6 results from integration of Eqn. 5),

$$\alpha_k(t) = C_{Tk}\sum_{i=1}^{3} A_i \lambda_i e^{-\lambda_i t} \tag{6}$$

In equation 6 C_{Tk} is the total generation potential of species k, A_i is the fraction of MSW corresponding to MSW fraction i, λ_i is the generation rate constant of MSW i, and t is the time the waste spends in the landfill.

We were not given any information concerning the procedure and schedule by which this particular landfill was filled with municipal and/or other waste. In view of that we have utilized an empirical formulation to relate the depth where the particular waste is found and its age in the landfill. The time in the above equation is given as

$$t = t_o + t_f\left(\frac{Z}{L_Z}\right), \tag{7}$$

where t_o is the time that has passed since the top cover was placed on the landfill, t_f is the time it took to fill up the landfill, L_Z is the landfill total depth (at the particular x, y coordinate), and Z is the position where the waste lies in the vertical direction. Eqn. (7) is commonly utilized when modeling individual landfill cells and assumes that the MSW is placed at the landfill at regular intervals on a layer by layer basis. We like to emphasize that this is not a particular limitation of our model, but simply reflects the lack of knowledge about the schedule by which the waste was placed in this particular landfill.

The generation of the landfill model and the soil that surrounds it is now complete. The next step is then implementing the ML algorithm for determining the global minimum of the Merit Function, and hence the numerical values of the fitted parameters. In order to do this, the dynamic model must be solved over the grid structure that represents the landfill and the surrounding soil.

The dynamic model is based on the continuity equation for each component of the gaseous mixture in the landfill, accounting for both diffusion and convection of the gases, as well as their reactions. The continuity equation for species k in the landfill is given by

$$\varepsilon_l \frac{d\rho_k}{dt} + \nabla \cdot (\rho_k \mathbf{V}) = \alpha_k(Z) + \nabla \cdot (D_{km} \nabla \rho_k) , \qquad (8)$$

where ε_l is the local porosity, ρ_k is the mass concentration of gas k, V is the convective velocity, and D_{km} is the effective diffusivity of species k in the gas mixture.

We assume that Darcy's law represents the convective velocity of all the gases. During the iteration process, the continuity equations for all the gases are discretized and solved over the grid structure we have generated. We use finite-difference discretization of the governing equations, which corresponds to the grid structure that we have generated. A key feature of the dynamic model is its ability for accounting for nonisothermal effects in the landfill. We assume here a temperature gradient of 0.5 ^oC per meter of depth (in the vertical direction), and incorporate it into the dynamic model (the temperature at the bottom of the landfill is hotter than at the top). The effect of temperature gradient manifests itself, in terms of temperature-dependent properties of the gases, such as their density, viscosity, etc.

We first supply to the simulator the initial guesses for the parameters that are to be fitted, and then solve the governing equations numerically. Two distinct criteria have been used in order to determine the fitted values of the parameters.

(1) The numerical solution is compared with the experimental data at every grid point at which the data are available and are used for the fitting. If the difference between the experimental and computed mole fractions of methane at every one of these grid points is less than a few percent, then the current estimates of the fitted parameters are accepted, and the iterative process is terminated. This, in some sense, is the most stringent criterion, but it can rarely be satisfied, since all it takes to violate this criterion is having one experimental point that does not follow the general pattern in the rest of the data. Due to the unusual features of some of the experimental data (see below), this method could not yield accurate estimates of the parameters.

(2) In the second method, the convergence has been achieved if the estimates of the fitted parameters between two consecutive ML iterations do not vary by more than a few percent, or if the value of the Merit Function between the two iterations does not change by more than a few percent.

In both cases, if the convergence criterion has not been met, the ML algorithm evaluates the Merit Function at every point of the grid at which the experimental data are used for fitting the parameters, and its first- and second-order derivatives. It then computes new estimates for the fitting parameters, by the method described above, and supplies them to the simulator that solves for the solution of the dynamic model. The iterative procedure is repeated until the convergence criterion has been met. Some of the details of the numerical simulations are as follows.

The landfill simulator carries out transient simulation of gas generation and transport, assuming that the landfill is filled up with refuse, as the input to the simulator; one must also supply the ratio of the production rates of carbon dioxide and methane. Initially, we assumed that this ratio was 1. However, after some preliminary simulations, it was realized that not only this value is not realistic, but also it, in fact, varies throughout the landfill. Therefore, based on an analysis of the experimental data, we divided the landfill model into 5 regions, and assumed a reasonable ratio of the production rates of the two gases for each region. This greatly improved the quality of the fitting. Dividing the landfill into five regions also incorporates the effect of its heterogeneity in the model, since this ratio is, in some sense, a reflection of the distributions of the landfill's permeability and porosity, which control the rate of transport of the gases, as well as its reaction heterogeneity, which controls the amount of each gas produced in each region of the landfill. The **assumed values of the ratio of the production rates of carbon dioxide and methane** as are shown in **Table 1** below:

Table 1

Region Number	Methane to Carbon Dioxide Ratio
Region 1	1/5
Region 2	3/7
Region 3	1/1
Region 4	13/7
Region 5	3/1

Figure 1 shows the top view of the grid and that part of it that represents the top view of the landfill's boundaries. The different colors of the figures indicate the ratio of methane to carbon dioxide. Red indicates region 1, pink is region 2, gray is region 3, aqua is region 4 and green indicates region 5. The light grid blocks are the native areas around the landfill.

The simulator uses time steps of 0.1 yrs to determine the steady-state solution assuming that no wells exist in the landfill. This is in reality a pseudo-steady state solution as the gas generation rate declines with time (see Eqn. 6). The steady state is reached typically after about 9-10 months (after the landfill has been filled up); the simulator then takes the solution at that particular time and begins installing the extraction wells in the model, ten wells at a time. The simulator then determines the steady-state solution for the new configuration of the landfill with the first ten wells, and utilizes this solution as the initial guess for a landfill configuration in which the next 10 wells have been inserted into the landfill. The time is still taken to be the one at which the SS solution without any landfill wells had been reached, i.e., about 9-10 months after the landfill was filled up with refuse. This procedure is repeated until all of the 228 extraction wells have been introduced in the landfill's model. After the steady state solution has been determined for the landfill with all the 228 wells, the solution for the mole fractions of all the components at every point of the grid, as well as the spatial distribution of the total pressure in the landfill, are recorded. These solutions are then used in the ML iterative procedure as the initial guesses for starting the iteration process. The typical computation time for this part of the calculations is about two days.

The reason for installing the extraction wells in the model by an incremental approach is speeding up the computations. We can easily start with a model in which all the extraction wells have been included in the model, and in fact we have carried out extensive computations using this method. Depending on the accuracy of the initial guesses, the first run may take as little as 10 minutes or as much as a few days to be completed, if the wells are inserted in the model all at once. Inserting the wells by an incremental approach allows us to have better control on the convergence to the true solution, to avoid the uncertainty in the amount of time that might be needed for achieving convergence for a given run, and, most importantly, speeds up the computations.

Figure 2 presents the flow chart, showing how the ML iterative procedure is coupled with the landfill transient simulator in order to fit the parameters. The way the ML iterative process and the landfill simulator work simultaneously together is conceptually quite simple, since the ML technique only needs the computed values of the methane mole fractions, along with the partial derivatives of the Merit Functions with respect to each of the fitting parameters. The difficulty lies in the fact that we do not have an explicit analytical function for the solutions, but the numerical solutions.

Project Outcomes

Figure 3 presents the relative errors in reproducing the experimental data for the mole fraction of methane at the extraction and observation wells. To compute these errors, the fitted parameters were used in the dynamic model. As can be seen, the error for the majority of the data is relatively small, while for a small minority of the data it is large.

If we remove a few of the experimental data points from the fitting process, and refit the seven parameters to the rest of the data, we obtain the error plot shown in **Figure 4**. As can be seen in this case, the error in computing the mole fraction of methane at the points for which experimental data are available has been reduced drastically. Thus, as emphasized above, the quality and amount of the experimental data that are used in the fitting process play a crucial role in yielding accurate estimates for the fitted parameters.
We show in **Table 2 the numerical estimates of the two sets of the seven parameters obtained by fitting.**

Table 2

Parameter	Without Removing Points	With Removing Points
Horizontal Permeability	3.913 mD(miliDarcy)	3.985 mD
Vertical Permeability	0.961 mD	1.059 mD
Soil Permeability	0.345 mD	0.330 mD
Landfill Porosity	0.250	0.245
Landfill Tortuosity	2.173	1.884
Soil Porosity	0.130	.127
Soil Tortuosity	0.663	22.281

Figure 5 shows the distribution of the total (gauge) pressure in a plane at a depth of 9.114 m, obtained by using the fitted parameters in the dynamic model, computed at the steady state. The corresponding distribution of methane at the same depth is shown in **Figure 6**. Also shown is the region of the landfill for which the distribution is shown. It is clear that in a portion of the landfill the mole fraction of methane is quite high, resulting in relatively high pressures (see Figure 5). Clearly, we can compute the same distributions over a period of time in order to understand how these two distributions, which are vital to the maintenance of the landfill, are built up.

Conclusions

It is clear that, provided that a sufficient amount of experimental data are available for any given landfill, the parameters of the dynamic model can be accurately fitted to the data. The fitted parameters can then be used for studying the behavior of the landfill and predicting its behavior (that is, the rates of gas generation and transport in the landfill) over a period of many years. Such a model will then be a valuable tool for planning the safe operation of a landfill.

Recommendations and Future Work

The work done, so far, represents the first steps for developing a predictive model of gas generation and transport in a landfill. Clearly, the work needs to be continued, and the model can be improved. Some of these improvements include:

(1) Using an optimization algorithm, such as the simulated annealing or the genetic algorithm, one can determine the distributions of the permeabilities and porosities throughout the landfill, as opposed to assuming a fixed porosity everywhere in the landfill, and two fixed vertical and horizontal permeabilities. Due to a variety of factors, it is likely that such distributions may be quite complex.

(2) The ratio of the production rates of carbon dioxide and methane can also be treated as an adjustable parameter. It is likely, as our work indicates, that there is a distribution of this quantity throughout the landfill and, therefore, similar to the permeabilities and porosities, it must be determined by an optimization algorithm.

Together, these two problems pose a formidable computation problem which, however, can be solved, given our present knowledge.

(3) Other mechanisms (kinetics) of reaction can also be examined in which the effect of moisture and the local oxygen composition are accounted for.

Clearly, much work remains to be done.

Public Benefits to California

There are several thousands of landfills in California. On one hand, they need to be operated safely so as not to pose any threats to the environment. On the other hand, they can be potential source of renewable energy. Currently, landfills are maintained and operated purely based on empiricism and "experience." There is no fundamental scientific basis to their operations.

Development of the model considered in this work is of fundamental importance to operation of landfills and their use as a source of renewable energy. Not only it provides a sound scientific basis for such operations, hence avoiding many pitfalls that usually result from purely empirically-based operations, but it can also predict the behavior of the landfill for many years to come, and hence provides a sound basis for its planning and use.

References

M. Hashemi, H.I. Kavak, T.T. Tsotsis, and M. Sahimi, “Computer Simulation of Gas Generation and Transport in Landfill – I. Quasi-Steady-State Conditions,” Chem. Eng. Sci., vol. 57, 2475 (2002).

Marquardt, D.W 1963,” An Algorithm for Least-Square Estimation of Non linear Parameters”, Journal of Society of Industrial and Applied Mathematics, Vol. 11, pp 431-441

Figure 1
Top View of the Landfill

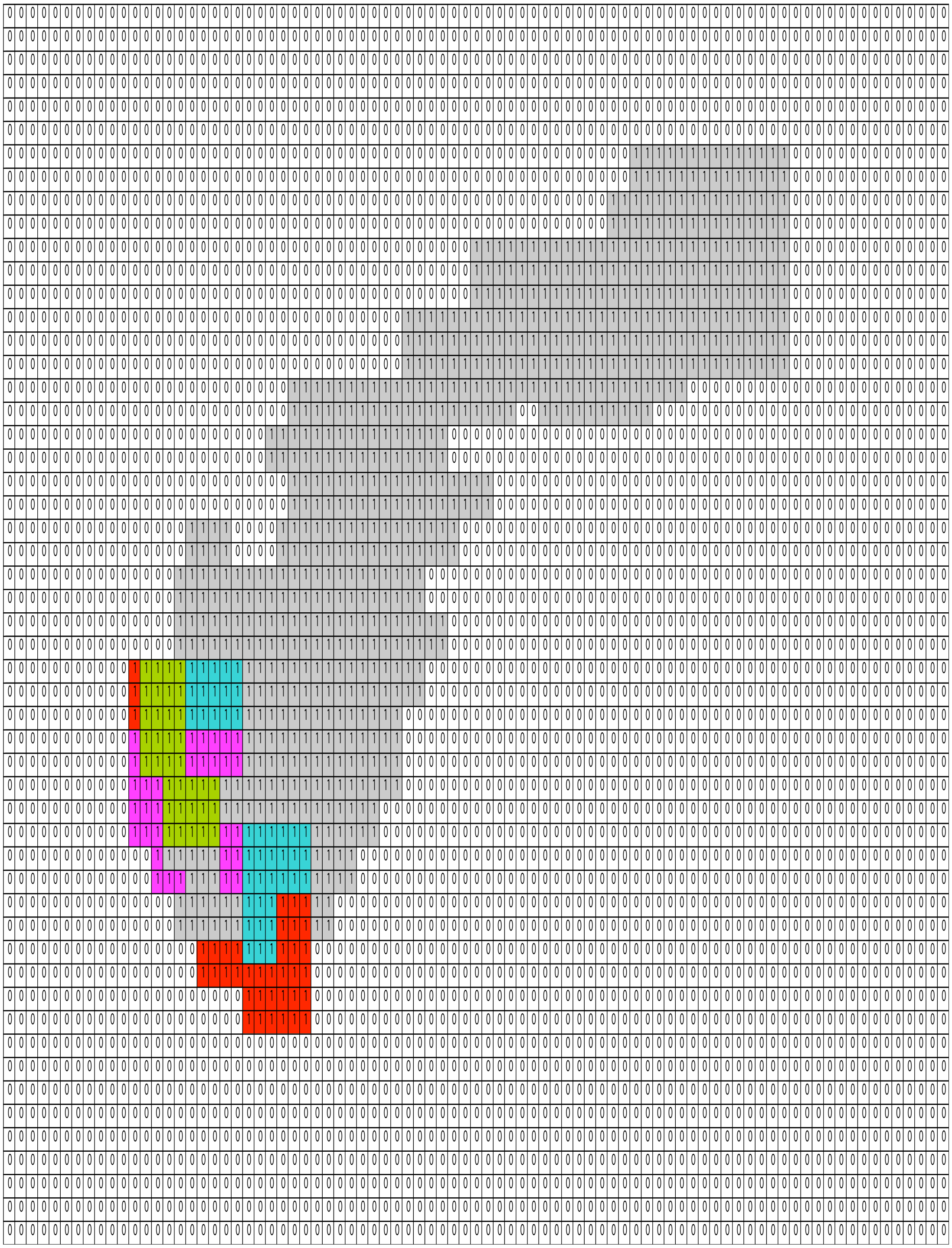


Figure 2
Flow Chart – ML Iterative Procedure Coupled with the Landfill Transient Simulator

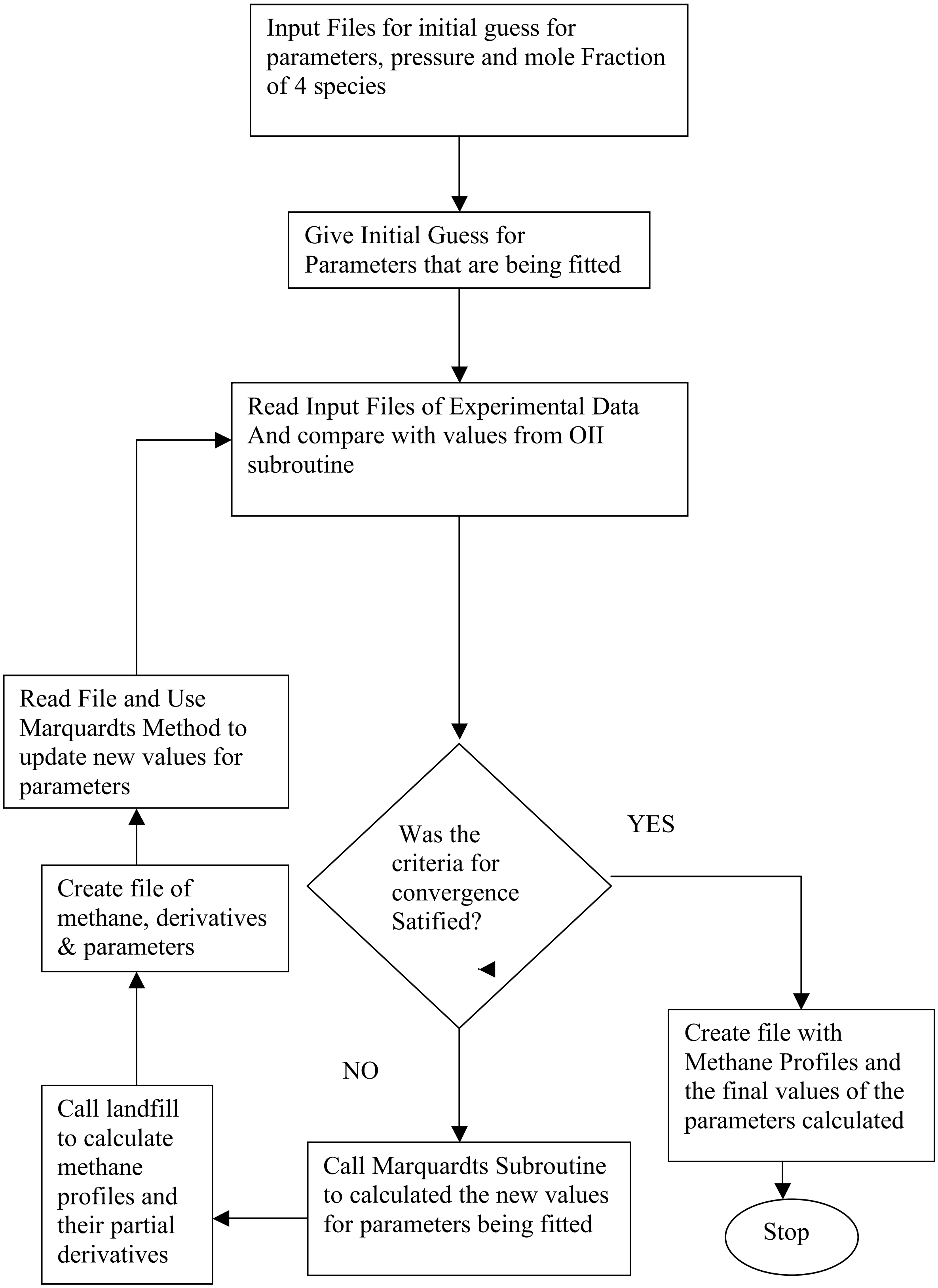


Figure 3
Relative Errors in Reproducing Experimental Data for the Mole Fraction of Methane at the Extraction and Observation Wells

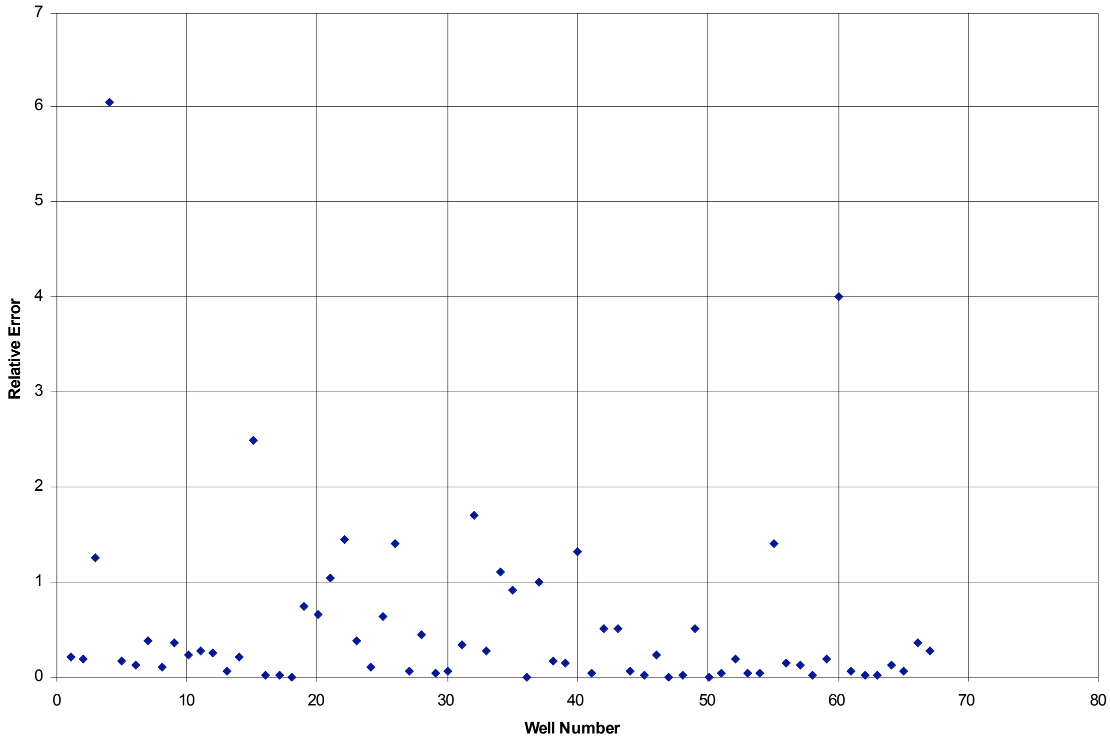


Figure 4
Error Plot in Computing the Mole Fraction of Methane at Points Where Experimental Data is Available

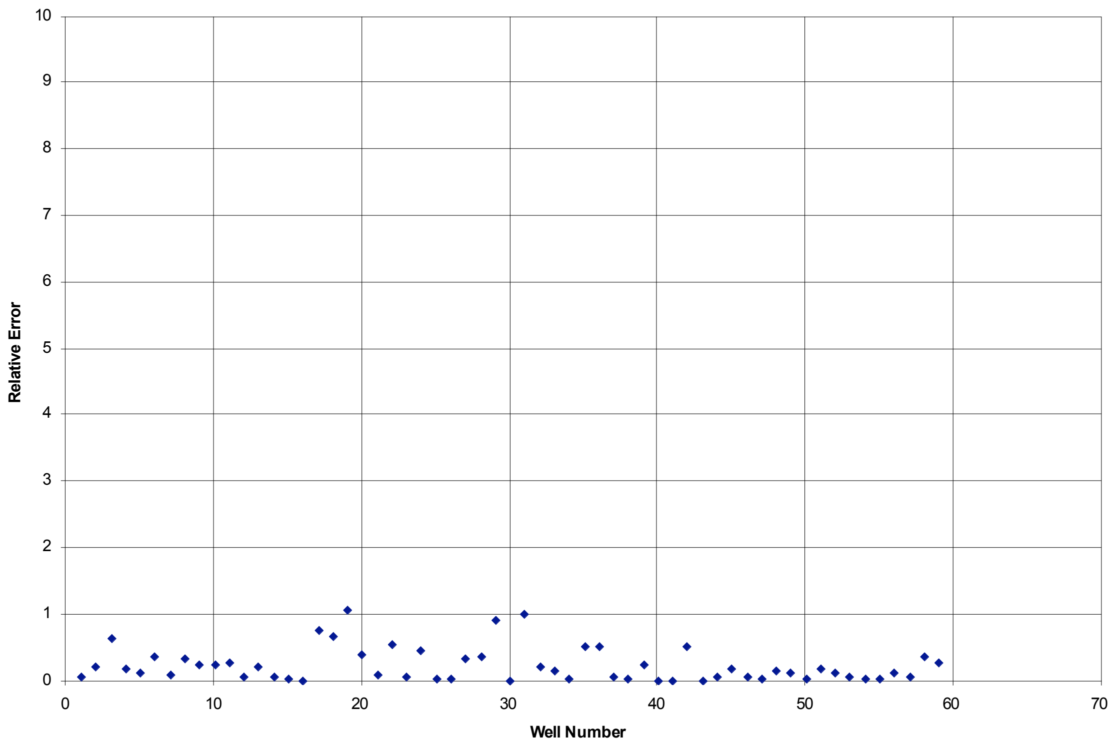


Figure 5
Distribution of the Total (Gauge) Pressure in a Plane at Depth 9.114 meters

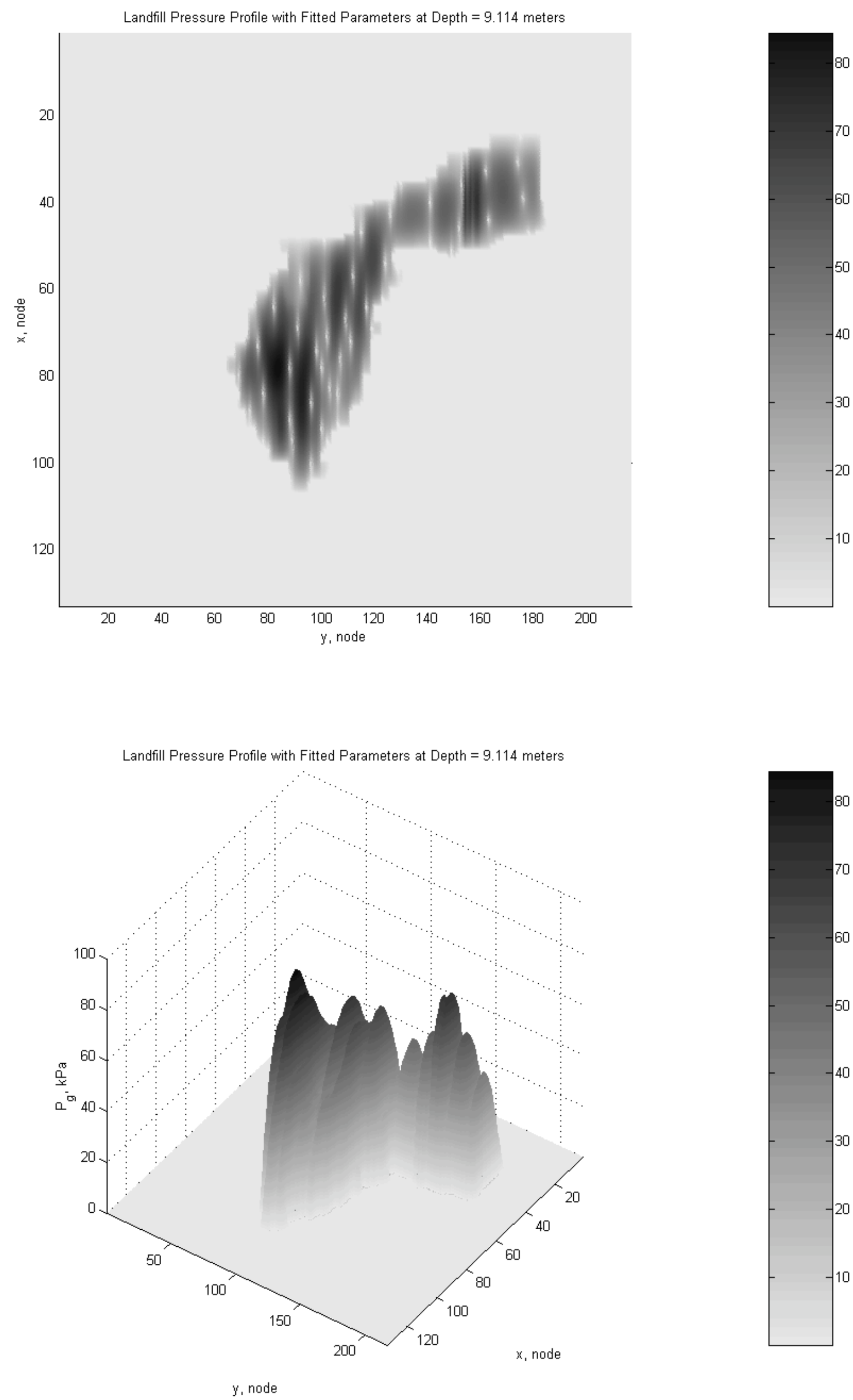
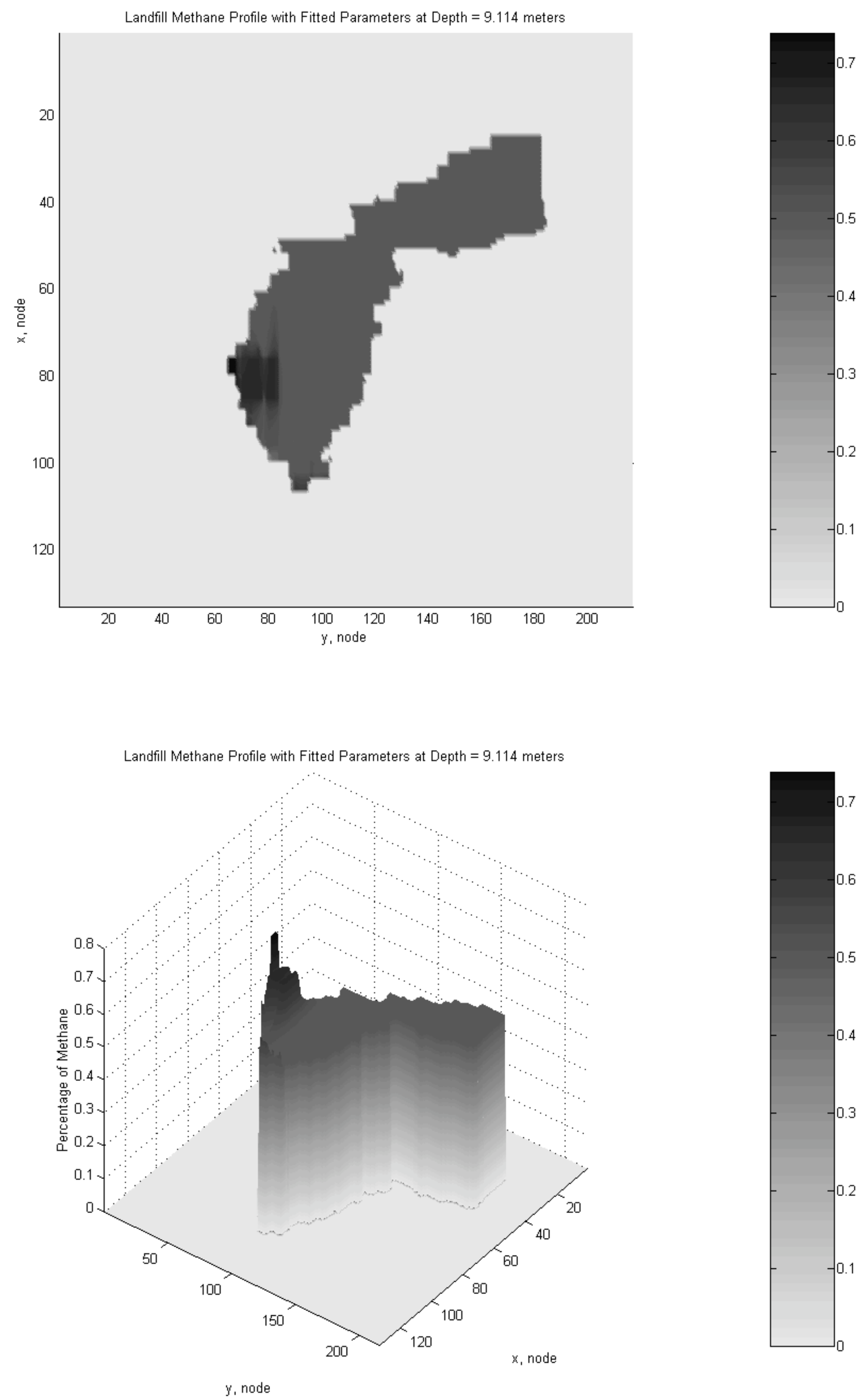


Figure 6
Distribution of Methane at depth 9.114 meters



California Energy Commission Energy Innovations Small Grant (EISG) Program **PROJECT DEVELOPMENT STATUS**	**Questionnaire**

Answer each question below and provide brief comments where appropriate to clarify status. If you are filling out this form in MS Word the comment block will expand to accommodate inserted text.

Questions	Comments:
Overall Status	
1) Do you consider that this research project proved the feasibility of your concept?	*Briefly state why.* **Yes, the merit function converged to reasonable values for the seven parameters.**
2) Do you intend to continue this development effort towards commercialization?	*If NO, indicate why and answer only those questions below that are still relevant.* **Yes.**
Engineering/Technical	
3) What are the key remaining technical or engineering obstacles that prevent product demonstration?	**We need better characterized landfills to continue to test and refine the model.**
4) Have you defined a development path from where you are to product demonstration?	**Yes, it is outlined in the "Future Work" section of the paper.**
5) How many years are required to complete product development and demonstration?	**Approximately 2 years.**
6) How much money is required to complete engineering development and demonstration?	*Do not include commercialization costs such as tooling.* **$15,000.00**
7) Do you have an engineering requirements specification for your potential product?	*This specification details engineering and manufacturing needs such as tolerances, materials, cost, stress etc. If NO indicate when you expect to have it completed.* **No, it is a computer model.**
Marketing	
8) What market does your concept serve?	*Residential, commercial, industrial, other.* **Industrial**
9) Is there a proven market need?	*If YES, what sources did you use to determine market need?* **Unknown**
10) Have you surveyed potential end users for interest in your product?	*If YES, the results of the survey should be discussed in the Final Report.* **No.**

11) Have you performed a market analysis that takes external factors into consideration?	*External factors include potential actions by competitors, other new technologies, or changes in regulations or laws that can impact market acceptance of your product?* **No.**
12) Have you compared your product with the competition in terms of cost, function, maintenance etc.?	**As far as we know, there are no completing technologies. General finite element/finite difference model may be adapted for this model.**
13) Have you identified any regulatory, institutional or legal barriers to product acceptance?	*If YES, how do you plan to overcome these barriers?* **No.**
14) What is the size of the potential market in California?	*Identify sources used to assess market size.* **Unknown.**
15) Have you clearly identified the technology that can be patented?	*If NO, how do you propose to protect your intellectual property?* **No. Not applicable.**
16) Have you performed a patent search?	*If YES, was it a self-search or professional search and did you determine if your product infringes or appears to infringe on any other active or expired patent?* **No.**
17) Have you applied for patents?	*If YES, provide the number of applications.* **No.**
18) Have you secured any patents?	*If YES, provide the patent numbers assigned and indicate if they are generic or application patents.* **No.**
19) Have you published any paper or publicly disclosed your concept in any way that would limit your ability to seek patent protection?	*If YES, is it your intent to put the intellectual property into the public domain?* **Yes?**

Commercialization Path

20) Can your organization develop and produce your product without partnering with another organization?	*If YES, indicate how you would accomplish that.* *If NO, indicate who would be the logical partners for development and manufacture of the product.*
21) Has an industrial or commercial company expressed interest in helping you take your technology to the market?	*If YES, are they a major player in the marketplace for your product?* **No.**

22) Have you developed a commercialization plan?	*If YES, has it been updated since completing your grant work?* **No.**
23) What are the commercialization risks?	*Risks are those factors particular to your concept that may delay or block commericialization.* **Lack of market.**
Financial Plan	
24) If you plan to continue development of your concept, do you have a plan for the required funding?	*Not at this time.*
25) Have you identified funding requirements for each of the development and commercialization phases?	*They have been estimated.*
26) Have you received any follow-on funding or commitments to fund the follow-on work to this grant?	*If YES, indicate the sources and the amount. If NO, indicate any potential sources of follow-on funding.* **No.**
27) Have you identified milestones or key go/no go decision points in your financial plan?	*Yes, the project has proven to be feasible and is awaiting funding.*
28) What are the financial risks?	**A lack of market for the software**
29) Have you developed a comprehensive business plan that incorporates the information requested in this questionnaire?	*If YES, can you attach a non-proprietary version of that plan to your final report?* **No.**
Public Benefits	
30) What sectors will receive the greatest benefits as a result of your concept?	*Residential, commercial, industrial, the environment, other* **Industrial, Environment.**
31) Identify the relevant savings to California in terms of kWh, cost, reliability, safety, environment etc.	*Show all assumptions used in calculations.* **This is difficult to quantify, however the software will be useful in identifying alternative energy projects for California**
32) Does the proposed technology impact emissions from power generation?	*If YES, calculate the quantify in total tons per year ot tons per year per relevant unit. Show all assumptions used in calculations.* **Yes, it encourages alternative energy projects using clean burning landfill gas.**
33) Are there any potential negative effects from the application of this technology with regard to public safety, environment etc.?	*If YES, please specify.* **NO.**

Competitive Analysis	
34) Identify the primary strengths of your technology with regard to the marketplace.	*Identify top 3.* *1) Accurate Model (as demonstrated with paper)* *2) Models heterogeneous conditions* *3) Adaptible and can model many differed landfill gas constituents and landfill geographies.*
35) Identify the primary weaknesses of your technology with regard to the marketplace.	*Identify top 3.* *1) The market for the model is difficult to quantify.* *2) Running the model requires some technical ability.*
36) What characteristics (function, performance, cost etc.) distinguishes your product from that of your competitors?	*The model is much more powerful than anything available in the market. It can model many different landfill geometries and heterogeneous conditions. Additionally, it models each gas constituent individually and provides a way to validate the input parameters.*
Development Assistance	
The EISG Program may in the future provide follow-on services to selected Awardees that would assist them in obtaining follow-on funding from the full range of funding sources (i.e. Partners, PIER, NSF, SBIR, DOE etc.). The types of services offered could include: (1) intellectual property assessment; (2) market assessment; (3) business plan development etc.	
37) If selected, would you be interested in receiving development assistance?	*If YES, indicate the type of assistance that you believe would be most useful in attracting follow-on funding.* *Yes, we would like assistance with market assessment.*

Appendix B
Rebuttal and Comments to the Independent Assessment Report (IAR)

Field Validation of a Model of Generation and Migration of Methane and Other Gases in Landfills

EISG Grant #00-26

The original modeling project was going to use data from a large landfill in Kern County. Early in the model development process the focus changed from a Kern County landfill to a large Southern California landfill. The landfill's name is omitted at the request of the owners. The landfill site change was made because the alternate landfill had substantially more data available for model calibration and verification.

The landfill tested was especially complicated because it accepted both class 3 municipal refuse and liquids. As stated in the Independent Assessment, this landfill had a wealth of data that aided in model calibration. Most sites do not have this much data. This limitation should not render the modeling program inadequate because modeling parameters can be modified to try and bracket the actual landfill conditions. This common engineering practice helps designers to gain a better understanding of the site and the possible limitations. We recognize the need for additional model validation and will continue this through application at other landfills.

The introduction section of the independent assessment shows a landfill fill rate of 37,829,177 tons during 2002. The Environmental Protection Agency (EPA) predicts a methane yield of 100 m^3/mg (1.6 ft^3/lb). Acknowledging that much of California is arid and that the yield will likely be reduced, a more practical statewide yield is 62.5 m^3/mg (1 ft^3 methane/lb refuse). If the refuse deposition remains constant then eventually the amount of refuse decomposed every year will equal the amount of refuse deposited. At the steady state condition, the calculated methane flow is:

$$\text{Methane} = \frac{37{,}829{,}177 \text{ tons}}{\text{year}} \times \frac{2{,}000 \text{ lbs.}}{\text{ton}} \times \frac{1 \text{ ft}^3 \text{ CH}_4}{\text{lb}} \times \frac{1 \text{ year}}{8{,}760 \text{ hours}} = \frac{8{,}637{,}000 \text{ ft}^3}{\text{hour}}$$

Methane has a lower heating value of about 909 BTU/ft^3 and a typical power plant has a heat rate between 10,000 and 12,000 BTU/KWH. The calculated power output for methane gas is:

$$\text{Power} = \frac{8{,}637{,}000 \text{ ft}^3}{\text{hour}} \times \frac{909 \text{ BTU}}{\text{ft}^3} \times \frac{\text{KWH}}{12{,}000 \text{ BTU}} \times \frac{1 \text{ MW}}{1{,}000 \text{ KW}} = 654 \text{ MW}$$

Given the existing power generation of 211 MW in the Independent Assessment, the future generation potential is over 400 MW.

Even modest increases in power generation could have a reasonably positive benefit to California.

The University of California (USC) and GC Environmental, Inc. (GCE) have met to discuss methods to market the model to the landfill industry. Because of the model complexity, it was thought that for the time being, it is best if USC sets up and executes the model. This work is ideal for graduate students because of their reduced billing rates through USC. GCE has proposed using the model at a number of landfills, but industry acceptance has been slow. We believe that this will change as people become aware of the benefit of the model and costs drop. One way we are attempting to enter the market is to use the model to aid in the protection of groundwater from landfill gas migration. Several jobs have been quoted with this objective. Once the model is established for this application, it will require small changes for the model to be used to help predict landfill behavior and methane collection.

For questions on the model, please contact Dick Prosser at GC Environmental, (714) 632-9969.