

Modeling of Hydrogen Sulfide Generation from Landfills Beneficially Utilizing Processed Construction and Demolition Materials

Russell Anderson
Senior Project Professional
SCS Engineers, PC
Providence, Rhode Island
randerson@scsengineers.com

Jenna R. Jambeck, Ph.D.
Faculty of Engineering
University of Georgia
jjambeck@engr.uga.edu

Gregory P. McCarron, PE
Vice President
SCS Engineers, PC
Valley Cottage, New York
gmccarron@scsengineers.com

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Executive summary

Recycling of construction and demolition (C&D) debris has increased in recent times, with positive environmental and economic benefits being realized from utilizing C&D “waste” materials as resources. Resulting policies at the federal and state levels and economic structures have supported this increase in recycling. For example, tipping fees and regulatory structure (waste bans in Massachusetts) have expanded the C&D processing industry in the northeast. One of the products produced from C&D recycling is C&D fines, which often include some quantity of sulfate from gypsum drywall. Use of fines containing sulfate in an anaerobic environment can result in the formation of hydrogen sulfide (H₂S). Because of H₂S concerns, there is a growing problem in the Northeast relative to recycling or disposal of C&D fines. The long term focus of Massachusetts Department of Environmental Protection (MassDEP) and other state solid waste regulators in the Northeast is to improve management of C&D fines and to develop improved end markets that are less dependent on landfills. In the short term, however, regulators must continue to work with C&D processors and landfill operators to improve the management of C&D fines and residuals at active and inactive landfills.

Increasingly over the past decade, C&D debris processing residuals and fines have been used as landfill daily cover material and to close and cap old landfills. C&D debris processing residuals and fines (C&D fines) are favored by numerous landfill operators as an alternate daily cover material (ADC) as they are superior in many ways to traditional soil cover materials. However, one potential issue with use of C&D fines has been the increase in landfill gas (LFG) odors due to production of H₂S and other reduced sulfur compounds. Increases in generation of reduced sulfur compounds in the LFG stems from the small pieces of gypsum wallboard contained in the fines. These LFG issues were unexpected and many landfill operations had to increase resources in LFG management and odor abatement as a result. Regulators have become involved in several states, implementing policies for use of C&D fines, management of LFG and control of odors. As a result, some landfills have stopped utilizing C&D fines altogether.

This research project had the following objectives:

- Compile and evaluate existing LFG, hydrogen sulfide and C&D fines data at nine northeastern landfills.
- Where necessary, conduct supplemental testing of H₂S gas concentrations and determine sulfate content of C&D fines, if still being accepted by the site.
- From the empirical data, develop a first order model to predict H₂S generation in MSW landfills in the northeast resulting from disposal or use of C&D fines in the landfill.

For this study, total sulfate content data was obtained from MassDEP for seven different C&D processing facilities in New England that provide C&D fines for beneficial use in Massachusetts. This data consisted of 81 samples collected and analyzed in various months of 2007 (about equal amount of data from each facility). In addition to this data compilation, samples were collected from fines accepted at two of the landfill study sites for a total of eight additional samples. For two facilities, sulfate content data was provided for samples analyzed from 2004 through 2008. This data set was not included in the aggregated data as it would bias the overall mean to these two facilities' sulfate concentrations. However, the trend of the data was

examined to determine if concentrations had changed historically. Table ES-1 contains the C&D processing facilities, the source and number of sulfate results obtained, as well as the range and mean sulfate concentration.

Table ES-1. Sulfate Content of C&D Fines in the Northeast

Facility	n	Sulfate Concentration (%)	
		Range	Mean
NE_1 ^a	6	3.1-3.6%	3.3%
NE_2 ^{a,b}	14	0.17-3.8%	1.6%
NE_3 ^a	12	1.2-9.3%	4.4%
NE_4 ^a	12	2.8-5.4%	3.6%
NE_5 ^a	12	5-12%	8.7%
NE_6 ^a	10	4.4-12%	6.8%
NE_7 ^a	20	0.22-8.9%	3.2%
NE_8 ^b	3	2.4-3.6%	3.1%
Overall	89	0.17-12%	4.3%

^aSulfate data from MADEP BUD Permits;

^bSulfate data from UNH analysis

The total amount of fines used in each landfill, as well as the corresponding amount of sulfur deposited as a consequence, is summarized in Table ES-2.

Table ES-2. Quantity of C&D Debris Fines used at each Landfill and resulting Sulfur Deposited

Landfill	C&D Debris Fines (Tons)	Sulfur (Tons)
A	87,000	1100
B	1,054,000	11,415
C	446,000	6400
D	37,000	530
E	100,000	1600
F	19,000	270
G	137,600	1638
H	33,800	484
I	214,000	3100

A first-order decay model was developed for six (6) of the nine (9) landfills based upon compiled data (Landfills A, C, D, G, H, and I). The other three study sites, for which modeling results did not correlate as well to the actual data, also provided valuable information and insight into H₂S generation trends and the complexity of modeling this component of LFG. Information on these three landfills (B, E and F) is contained in Appendix A. Each landfill site was modeled separately to develop site specific model inputs and a site specific model. A spreadsheet was developed which utilized a first order model equation similar to the LandGem used for estimating methane generation.

The model equation is as follows:

$$Q_{H_2S} = \sum_{i=1}^n k S_0 M_i (e^{-kt_i})$$

where,

Q_{H_2S} = H₂S generation rate from the landfill, cf

k = H₂S generation rate constant, 1/yr

S_0 = H₂S generation potential, CuFt/ton sulfur

M_i = mass of sulfur from C&D Fines deposited in the i^{th} section, tons

t_i = age of the i^{th} section, months

i = section number

The modeling for each site was developed in three steps:

1. Derive site specific H₂S generation rate constant k (or decay rate) from H₂S recovery trend data
2. Using the site specific k and sulfur inputs into the model equation, derive a specific S_0 value using a 'best fit' approach
3. Check the 'best fit' S_0 value by balancing the model outputs (cubic feet per month of H₂S) to the actual H₂S recovery data for the same months and years.

Table ES-3 provides a summary of the values determined for each parameter of the model for each landfill modeled.

Table ES-3. Summary of Model Results (k and S_0 Values)

Landfill	k	S_0 (ft ³ /Ton)	Model Results Correlated to Actual Data (R-SQ)
Landfill A	0.54	3186	0.92
Landfill C	0.56	7634	0.93
Landfill D	0.50	1885	0.64
Landfill G	0.83	4548	0.95
Landfill H	0.52	2176	0.89
Landfill I	0.88	6430	0.96

There was a correlation between the site specific decay rate (k) derived from the exponential trend and the actual H₂S recovery trend data with R-squared values between 0.86 and 0.99 for Landfills A, B, C, G, H and I. The model results also correlated well with the actual H₂S recovery trend data with R-squared values between 0.89 and 0.97. Four of the six study sites (Landfill A, C, G and I) with correlation between the model and actual data were MSW landfills which used C&D fines as ADC. Modeling of these four sites resulted in a range of decay rates 1/time (k) of between 0.54 and 0.88, with an average k for these four sites of 0.702 and a range of H₂S

generating potential in ft^3 of H_2S per ton sulfur as sulfate (S_0) of between 3186 Ft^3/ton and 7184 Ft^3/ton with an average S_0 value of 5360 Ft^3/ton . The other two sites (Landfill B and H) with correlation between the model and actual data were landfills in which C&D fines were segregated from MSW as monofill. Modeling of these two sites resulted in a range of decay rates $1/\text{time}$ (k) of between 0.166 and 0.515, with an average k for these two sites of 0.34 and a range of H_2S generating potential in ft^3 of H_2S per ton sulfur as sulfate (S_0) of between 2704 Ft^3/ton and 4548 Ft^3/ton with an average S_0 value of 3626 Ft^3/ton . The average k value for all six landfills was 0.64. The average S_0 value for all six landfills was 4310 Ft^3/ton .

Based on the results of the data analysis and the model, H_2S generation in an MSW landfill resulting from C&D fines is expected to peak and decline much more rapidly than for methane. Additionally, the model results indicate that C&D fines used as ADC in MSW landfill environments are expected to decay more rapidly (higher k value) and produce more H_2S per ton of sulfate deposited in the Landfill (higher S_0 value) than C&D fines that are monofilled. Further, based on the model results of Landfill B which in addition to monofilling the C&D fines also mixed C&D fines with soils to reduce H_2S generating potential, there is some preliminary evidence that by mixing or layering C&D fines with the right kind of soil in a monofill environment, the H_2S generating potential of the fines can be reduced. Additional study is needed in this area.

In order to more accurately model H_2S from C&D fines, the inputs into the model are important, including the total mass of sulfur input into the landfill from C&D fines tonnage *and* sulfate composition of the fines. Both of these parameters are needed to evaluate the H_2S generation potential of the site through this modeling approach. Landfill F illustrates a case where not all sulfate sources are known, resulting in a poor fit and unusable model. Representative samples and the correct test method (i.e., the Musson et al., 2008 method) are important. In addition to this data, numerous and reliable H_2S characterization data from the landfill will provide calibration data for the model, allowing site-specific k values to be derived, which makes the model more accurate. In the absence of site-specific data, this research shows a k value of 0.34 for monofilled C&D fines and a k value of 0.70 for C&D fines in an MSW landfill setting are appropriate in the Northeast US.

This modeling approach could be used as a tool used to determine the amount of C&D fines that can be accepted/utilized as ADC or fill based upon the acceptable generation of H_2S (e.g., Landfill E illustrates this principle). While H_2S contributes to odor, it should be noted that this model is not an odor model. Odor can be an issue because of landfill gas management issues even with very low concentrations of H_2S . Conversely several hundred or even thousand ppm of H_2S might not be an odor problem with an active LFG collection system. However, sometimes gas-to-energy or SO_x emissions limit the amount of H_2S that is allowable. In addition to acceptable fines quantities and H_2S generation, this modeling approach could be valuable for landfills to estimate the cost of C&D fines in terms of LFG management and treatment. Estimation of H_2S concentrations in LFG could also be accomplished through this model by combining the H_2S model results with the results of an LFG generation model, adjusted to the site specific methane concentration projected.

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Introduction

Increasingly over the past decade, construction and demolition (C&D) debris processing residuals and fines have been used as landfill daily cover material and to close and cap old landfills. C&D debris processing residuals and fines (C&D fines) are favored by numerous landfill operators as an alternate daily cover material (ADC) as they are superior in many ways to traditional soil cover materials. However, one potential issue with use of C&D fines has been the increase in landfill gas (LFG) odors due to production of hydrogen sulfide (H_2S) and other reduced sulfur compounds. Increases in generation of reduced sulfur compounds in the LFG stems from the small pieces of gypsum wallboard contained in the fines. These LFG issues were unexpected and many landfill operations had to increase resources in LFG management and odor abatement as a result. Regulators have become involved in several states, implementing policies for use of C&D fines, management of LFG and control of odors. As a result, many landfills have stopped utilizing C&D fines altogether. Because of tipping fees and regulatory structure (e.g., state and federal endorsement C&D debris recycling and waste bans in Massachusetts) the C&D processing industry has expanded in the northeast. However, because of H_2S concerns, there is a growing problem in the Northeast relative to recycling or disposal of C&D fines. The long term focus of Massachusetts Department of Environmental Protection (MassDEP) and other State solid waste regulators in the Northeast is to improve management of C&D fines and to develop improved end markets that are less dependent on landfills. In the short term, however, regulators must continue to work with C&D processors and landfill operators to improve the management of C&D fines and residuals at active and inactive landfills.

Significant amounts of H_2S can be generated in a landfill environment when waste with high sulfur content such as gypsum wallboard and other calcium sulfate containing products are accepted. In a landfill environment, sulfur reducing bacteria use sulfate as their terminal electron acceptor during decomposition and release hydrogen sulfide gas. This has been shown to occur at locations throughout the U.S (Lee et al., 2006; Eun et al., 2007). The potential for H_2S generation in a landfill depends on a number of factors, including sulfate quantities, moisture content, pH, and the quantity of degradable organic matter available (Yang, 2000). Construction and demolition (C&D) materials are heterogeneous and specifically depend on the type of building and activity (construction or demolition), but on average contain 14 percent (by weight) of gypsum drywall (Jang and Townsend, 2003). C&D material is targeted for recycling and often processed at materials recovery facilities with hand (e.g., picking line) and/or mechanical (e.g., screening) methods. Additionally, a ban on landfill disposal of some C&D materials in Massachusetts essentially mandates recycling or processing of C&D materials, so growth in the recycling industry, as well as the need for markets for materials produced, is great in Massachusetts and surrounding states. At recycling facilities, materials are separated out for recycling and reuse (e.g., metals, wood), while producing a fines and/or residual fraction. This fraction can range from 6-inch minus to $\frac{3}{4}$ -inch sizes, depending on the operation of the processing facility. The reduced size of C&D fines has small pieces of gypsum, providing greater surface area and potentially allowing for more rapid production of H_2S than non-size reduced C&D debris. Because other fractions of the C&D materials have been removed, but the

gypsum remains, the C&D fines can also have a higher sulfate content in comparison to bulk C&D waste (Note: states such as Massachusetts and New Hampshire require up-front removal of gypsum drywall from the process when feasible).

H₂S and other reduced sulfur compounds are odiferous. Generation of reduced sulfur compounds in a landfill is one of the most common causes of landfill related odors. H₂S has a low odor detection threshold; the lowest reported odors derived from H₂S have been detected at concentrations as low as 0.5 ppb by 2 percent of the population in study groups, with the lowest detection at 0.43 ppb (Collins and Lewis, 2000). In the northeast, landfills that have experienced serious odor issues related to H₂S have improved LFG collection through system expansions and increased operations and maintenance of existing LFG systems. H₂S testing programs were implemented at many of the landfill sites in an attempt to qualify H₂S concentrations. Testing programs varied from site to site but in many cases involved use of field indicator tubes in combination with periodic analysis of gas samples at testing laboratories. In some cases, testing was conducted to quantify potential stack emissions (e.g., SO₂) or to size H₂S treatment systems. In other cases, LFG testing for H₂S is a requirement of the facility permit. As a result, for a number of landfill sites in the northeast which accepted C&D fines, there is a large amount of LFG recovery and H₂S testing data available. In some cases, the data spans several years and shows clear trends in H₂S concentrations, which can be correlated to historic acceptance and cessation of C&D fines. For several landfills, SCS Engineers, an environmental consulting and contracting firm, initially developed a basic working model to predict hydrogen sulfide generation, based on the amount of sulfate deposited in the landfill in the form of C&D fines. Although the initial H₂S generation model utilizes a zero order decay equation, because H₂S generation originates from a biological process, it was expected that generation is best modeled with a first order decay equation, similar to the EPA landfill gas generation model (LandGem model).

Development of a model to predict H₂S generation resulting from acceptance of C&D fines in a typical MSW landfill provides valuable information for C&D processors, landfill operators and regulators. Since the model is based upon total sulfur input, C&D processors can refine their operations to reduce gypsum content in fines or reduce the production of fines. Landfill operators can better evaluate allowable quantities of C&D fines that may not impact LFG significantly or weigh the potential impacts of increased LFG management against the economic benefits of accepting the fines.

This research project had the following objectives:

1. Compile and evaluate existing LFG, hydrogen sulfide and C&D fines data at nine northeastern landfills.
2. Where necessary, conduct supplemental testing of H₂S gas concentrations and determine sulfate content of C&D fines, if still being accepted by the site.
3. From the empirical data, develop a first order model to predict H₂S generation in MSW landfills in the northeast resulting from disposal or use of C&D fines in the landfill.

Results and Discussion

Sulfate Content of Fines

C&D fines are required to be analyzed in some states (e.g., Massachusetts) for a number of parameters on a regular basis in accordance with beneficial use determination (BUD) permits issued by the regulatory agencies. In accordance with BUD permits, EPA Method 300 (quantification of sulfate by ion chromatography) is used. For this analysis, sulfate must be in solution (the sulfate must be extracted from the solid into a liquid). Contract labs report extracting sulfate from the solid to the liquid by adding 100 ml of deionized water to 10 g of sample (C&D fines or residuals) and mixing for one hour. The liquid extract is then analyzed by ion chromatography to determine the sulfate concentration (EPA Method 300). This concentration (in mg/L) is related to the solid and liquid fraction used in the procedure (10 g/100 ml) to determine the amount of total sulfate in mg/kg in the solid sample.

For this study, total sulfate content data was obtained from MassDEP for seven different C&D processing facilities in New England that provide C&D fines for beneficial use in Massachusetts. This data consisted of 81 samples collected and analyzed in various months of 2007 (about equal amount of data from each facility). In addition to this data compilation, samples were collected from fines accepted at two of the landfill study sites for a total of eight additional samples. For two facilities, sulfate content data was provided for samples analyzed from 2004 through 2008. This data set was not included in the aggregated data as it would bias the overall mean to these two facilities' sulfate concentrations. However, the trend of the data was examined to determine if concentrations had changed historically. Table 1 contains the C&D processing facilities, the source and number of sulfate results obtained, as well as the range and mean sulfate concentration. Figure 1 illustrates how sulfate content varies over time at one of these facilities. While sulfate content can be variable, it does not have a clear increasing or decreasing trend.

Table 1. Sulfate Content of C&D Fines in the Northeast

Facility	n	Sulfate Concentration (%)	
		Range	Mean
NE_1 ^a	6	3.1-3.6%	3.3%
NE_2 ^{a,b}	14	0.17-3.8%	1.6%
NE_3 ^a	12	1.2-9.3%	4.4%
NE_4 ^a	12	2.8-5.4%	3.6%
NE_5 ^a	12	5-12%	8.7%
NE_6 ^a	10	4.4-12%	6.8%
NE_7 ^a	20	0.22-8.9%	3.2%
NE_8 ^b	3	2.4-3.6%	3.1%
Overall	89	0.17-12%	4.3%

^aSulfate data from MADEP BUD Permits;

^bSulfate data from UNH analysis

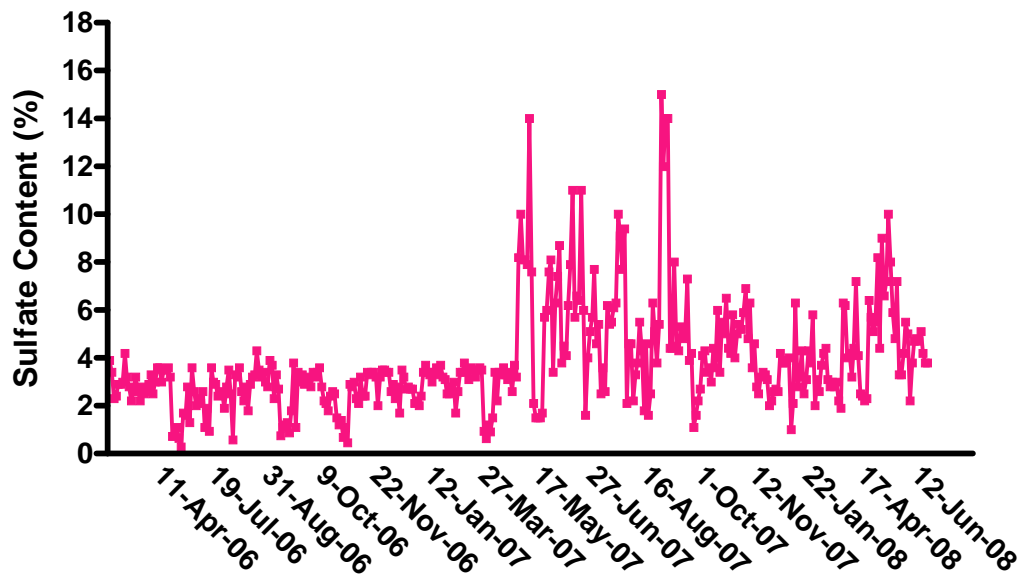


Figure 1. Sulfate Content at C&D Processing Facility NE_3

For landfills accepting C&D fines from other facilities where only 2007 data was available, 2007 data was used. Sulfate content can vary with time (e.g., Figure 1), and could change significantly with materials accepted, processing techniques (which often evolve over time) and active removal of wallboard. Some of these changes could increase or decrease sulfate content of the C&D fines. However, it is not possible to extrapolate the sulfate concentration historically based upon trends or variability. 2007 data was used to represent all years of data when this is the only data that was available. The aggregated data was examined to determine if it was normal or log-normal. The data appeared to be normally distributed and so the arithmetic mean was utilized.

Sulfate content data was used to calculate total sulfur deposited each year from C&D fines. Because complete C&D fines source information and sulfate content data was not available for all C&D fines received, the following methodology was employed to estimate sulfate content of the C&D fines received at each study site:

- For C&D processing facilities providing data from 2004-2007 (two facilities), this data was entered corresponding to tonnage of fines accepted from these facilities at each study site landfill.
- For C&D processing facilities that provided BUD data for 2007, the mean of this data was used for the corresponding tonnage accepted at a study site landfill (e.g., NE_4 = 3.6%).
- For those processing facilities where no source information or sulfate content data was available, the mean of the aggregated data (89 samples) was used (4.3%).

The total amount of fines used in each landfill, as well as the corresponding amount of sulfur deposited as a consequence, is summarized in Table 2.

Table 2. Quantity of C&D Debris Fines used at each Landfill and resulting Sulfur Deposited

Landfill	C&D Debris Fines (Tons)	Sulfur (Tons)
A	87,000	1100
B	1,054,000	11,415
C	446,000	6400
D	37,000	530
E	100,000	1600
F	19,000	270
G	137,600	1638
H	33,800	484
I	214,000	3100

Model Development

This section presents those landfills where model development was feasible (Landfill A, C, D, G, H and I). Appendix A contains the details of each of these landfill sites (e.g., design and operation of the landfill gas system). The other three study sites, for which modeling results did not correlate as well to the actual data, also provided valuable information and insight into H₂S generation trends and the complexity of modeling this component of LFG. Details on these three landfills are included in Appendix A. A first-order decay model was developed for each landfill based upon compiled data. Each landfill site was modeled separately to develop site specific model inputs and a site specific model. A spreadsheet was developed which utilized a first order model equation similar to the LandGem used for estimating methane generation.

The model equation is as follows:

$$Q_{H_2S} = \sum_{i=1}^n k S_0 M_i (e^{-kt_i})$$

where,

Q_{H_2S} = H₂S generation rate from the landfill, cf

k = H₂S generation rate constant, 1/yr

S_0 = H₂S generation potential, CuFt/ton sulfur

M_i = mass of sulfur from C&D Fines deposited in the i^{th} section, tons

t_i = age of the i^{th} section, months

i = section number

The modeling for each site was developed in three steps:

1. Derive site specific H₂S generation rate constant k (or decay rate) from H₂S recovery trend data
2. Using the site specific k and sulfur inputs into the model equation, derive a specific S_0 value using a 'best fit' approach
3. Check the 'best fit' S_0 value by balancing the model outputs (cubic feet per month of H₂S) to the actual H₂S recovery data for the same months and years.

Sulfur Input/Output

A sulfur mass input and output was developed for each landfill based upon sulfur input from sulfate as C&D fines and out as H₂S in the LFG (in pounds per month) (Figure 2). The sulfur input was the total pounds (or tons) of sulfur calculated for each month, based on the tons of C&D fines received and the sulfate concentration of the C&D fines. For some sites annual or monthly average sulfate concentration data was available for C&D fines produced by processing

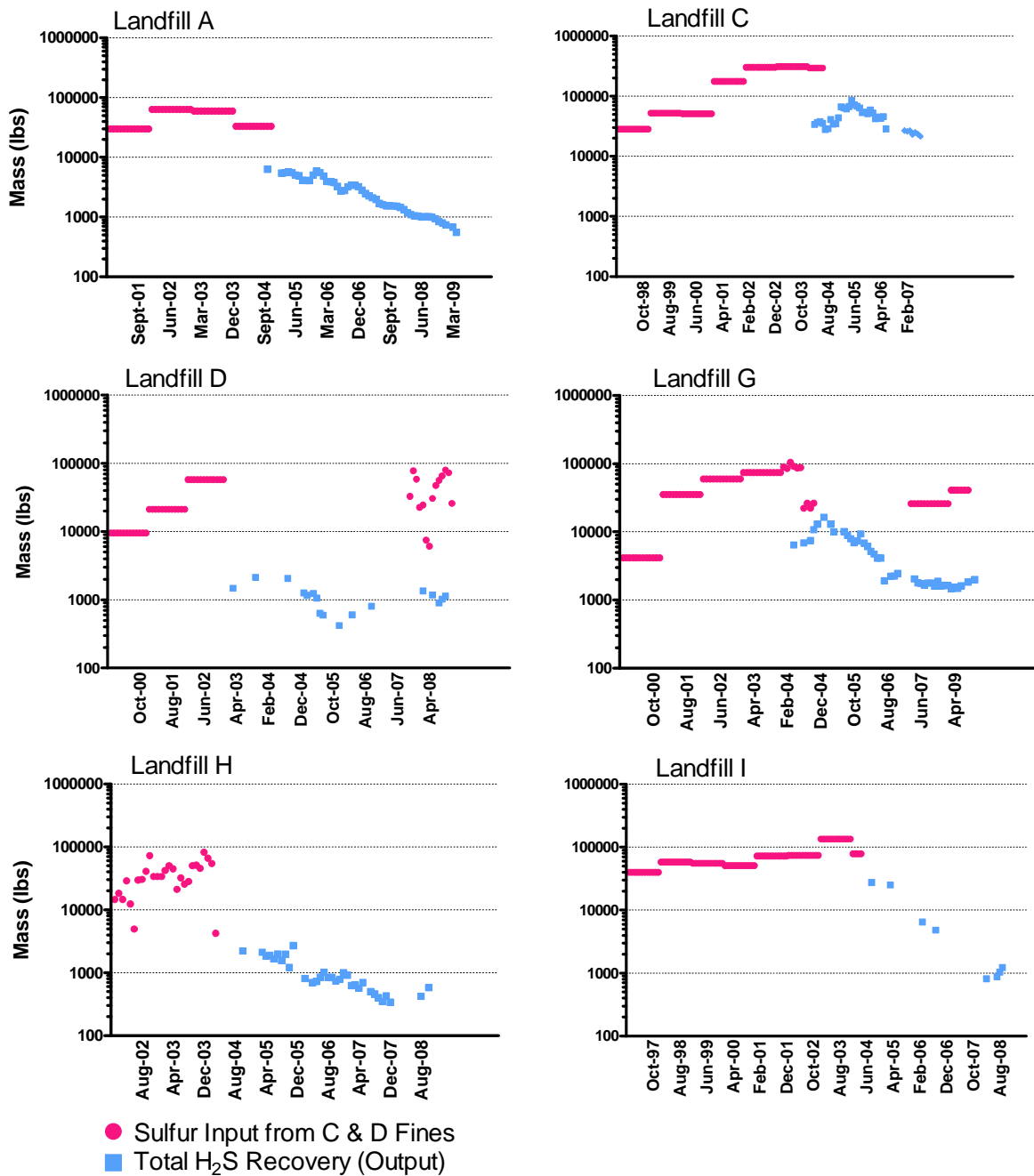


Figure 2. Landfill Sulfur Input/Output

facilities. For other sites only regional data was available. Likewise, for some landfill sites the quantity of C&D fines received was available on a monthly basis. For other sites the annual total C&D fines received was distributed evenly throughout the year. All the landfill sites in the study provided tonnage for all of C&D fines materials accepted. Therefore, for all the study sites a sulfur 'input' from C&D fines was available all months that C&D fines were received. The sulfur output was the total mass H₂S recovered from the LFG collection and control system. The sulfur output as H₂S, in contrast to sulfate input as fines, was not available for many of the months since C&D fines were initially accepted. As previously mentioned, there was no H₂S recovery total available for any of the study sites from before C&D fines were accepted. For most cases, there was also little or no H₂S recovery data available at all until after C&D fines were no longer being accepted. Therefore, a true mass balance of sulfate in and H₂S out could not be completed. The months with reliable H₂S recovery totals (in total cubic feet H₂S recovered) were used as a reference to provide calibration points for the model.

Hydrogen Sulfide Data Trends

Hydrogen sulfide data trends are presented in Figure 3 (Landfill G is then further split into sections based upon fines deposition, further explained in Appendix A). The H₂S test data available from each month was normalized to 50 percent methane. For purposes of the model input, both field test results and lab results were used for each Landfill where available since this produced the most robust data. All of the field test results for a given month, at 50 percent methane equivalent, were averaged to obtain a single monthly average field test H₂S concentration. The same was then done for all of the laboratory H₂S test data for each month. The field test data average and the lab test data average were then combined for a single monthly average concentration with field test data average and lab test data average weighted equally, regardless of the number of sample events available in each data set. In almost all the cases when there was both lab data and field data available for a single month, there was usually more field data available, therefore biasing monthly concentration data in favor of the lab test data. This is appropriate since the laboratory test method is generally considered to provide higher quality data. The monthly values for H₂S concentration were then used with the monthly LFG recovery totals for each month (also normalized to 50 percent methane) in order to calculate the total flow of H₂S, in both pounds and cubic feet.

H₂S Generation Rate (k)

In order to derive the site specific H₂S generation rate (k), the historic H₂S recovery trend (in cubic feet per month) was plotted from the actual data (Figure 4). A specific period of historic H₂S recovery data was selected to coincide with a period starting at least 6 months after acceptance C&D fines had ceased and any further acceptance of C&D fines resumed (Landfill B was an exception to this). The actual data trend line used to derive k was therefore representative of the decay trend of declining H₂S generation observed at the sites. To compensate for variability in the H₂S recovery trend, such as may be encountered in LFG operations, difference in the number of days per month etc., a three month moving average of the H₂S recovery data was used for the model. An automated exponential

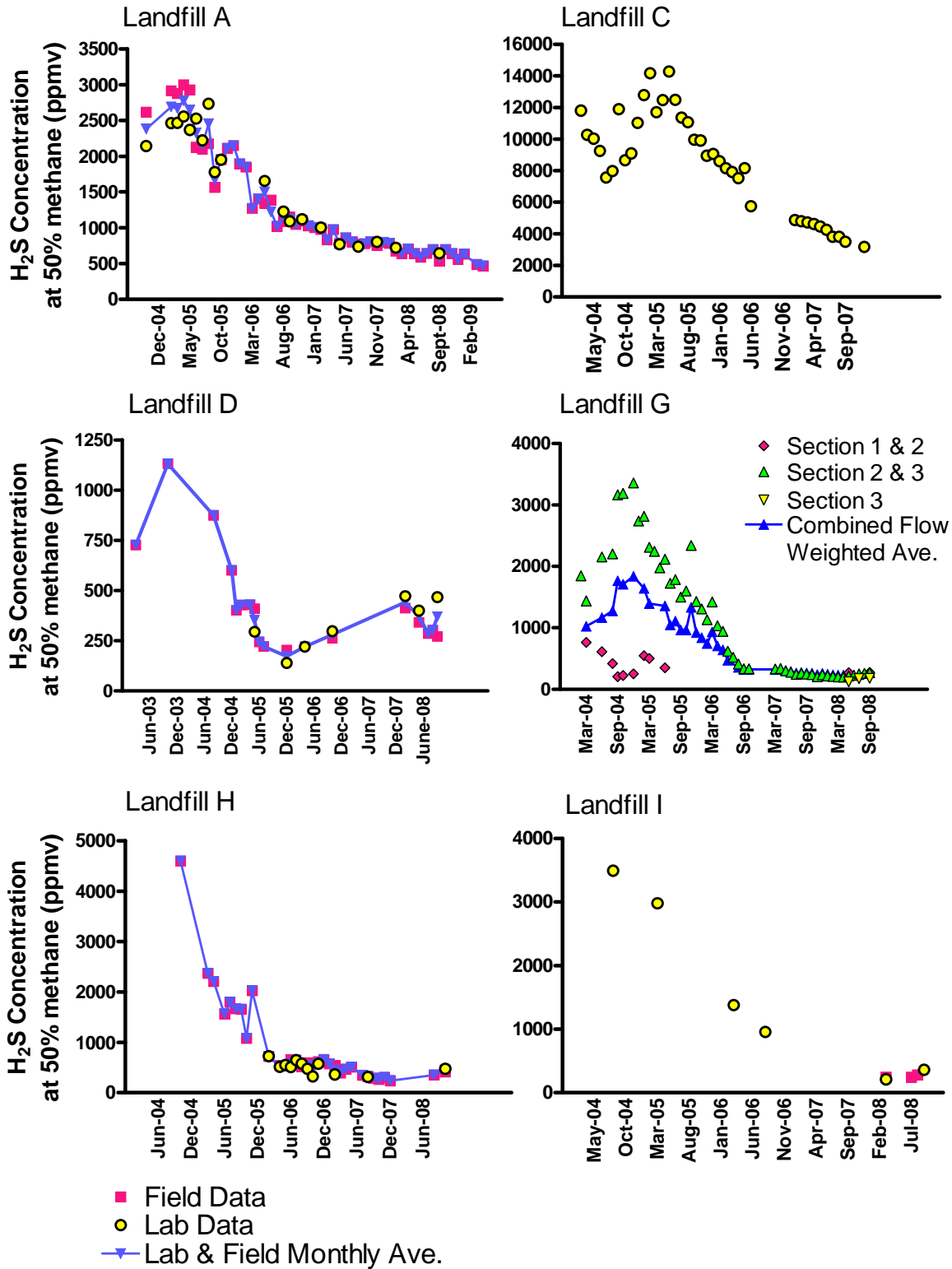


Figure 3. Landfill Hydrogen Sulfide Data Trends

trendline (using Microsoft Excel®) was then fitted to the H₂S recovery data. The exponent of the natural log in the exponential trendline equation generated by Excel, was selected as the site specific k value. The R-Squared value correlating the exponential trend line to the actual data was evaluated to determine the fit of the data to the derived site specific k value. Generally an R-Squared value of 0.90 or greater was interpreted as representing a reasonably good derivation of k from the data.

H₂S Generation Potential (S₀)

Model projections versus actual H₂S recovery data is presented in Figure 5. After a k value was determined from the trendline, M_i was taken from the sulfur input and these site specific variables were input to the model. S₀ was estimated by plotting the results of the model to the months of H₂S recovery data available (using the three month average value). In this case all of the H₂S recovery data available (of acceptable quality) was utilized for the model, including recovery data representing periods during C&D fines acceptance. S₀ was refined through iterations of the model until the model had the best fit with the empirical data. This fit was evaluated through a linear regression of the model results versus actual H₂S recovery data using an X-Y plot and setting slope to approximately 1. The R-Squared value correlating the model to the actual data was evaluated to determine the fit of the data to the model results (Figure 6). Generally an R-Squared value of 0.90 or greater was interpreted as representing a reasonably good fit of the model to the data.

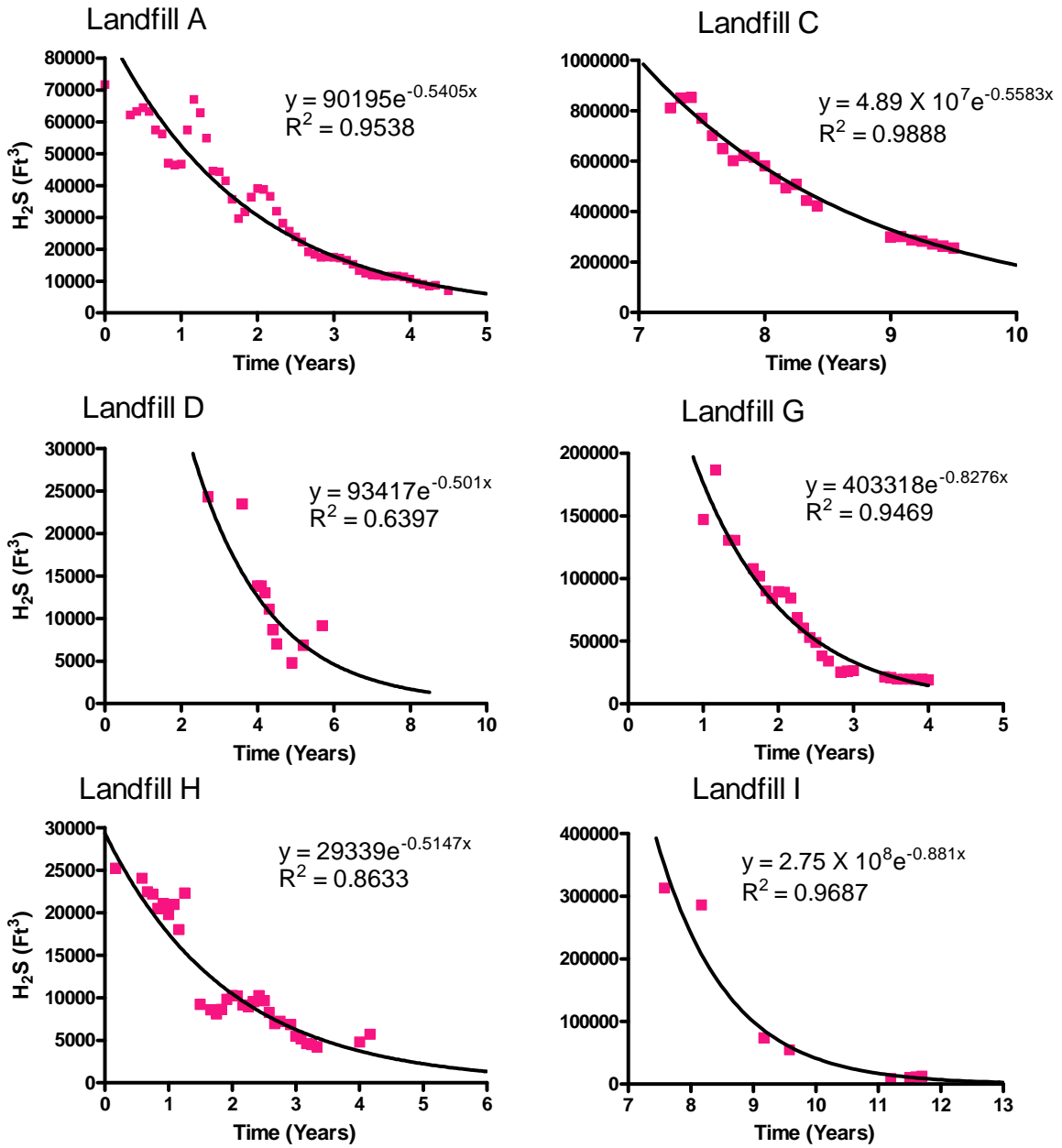


Figure 4. Development of Decay-rate Constant (k)

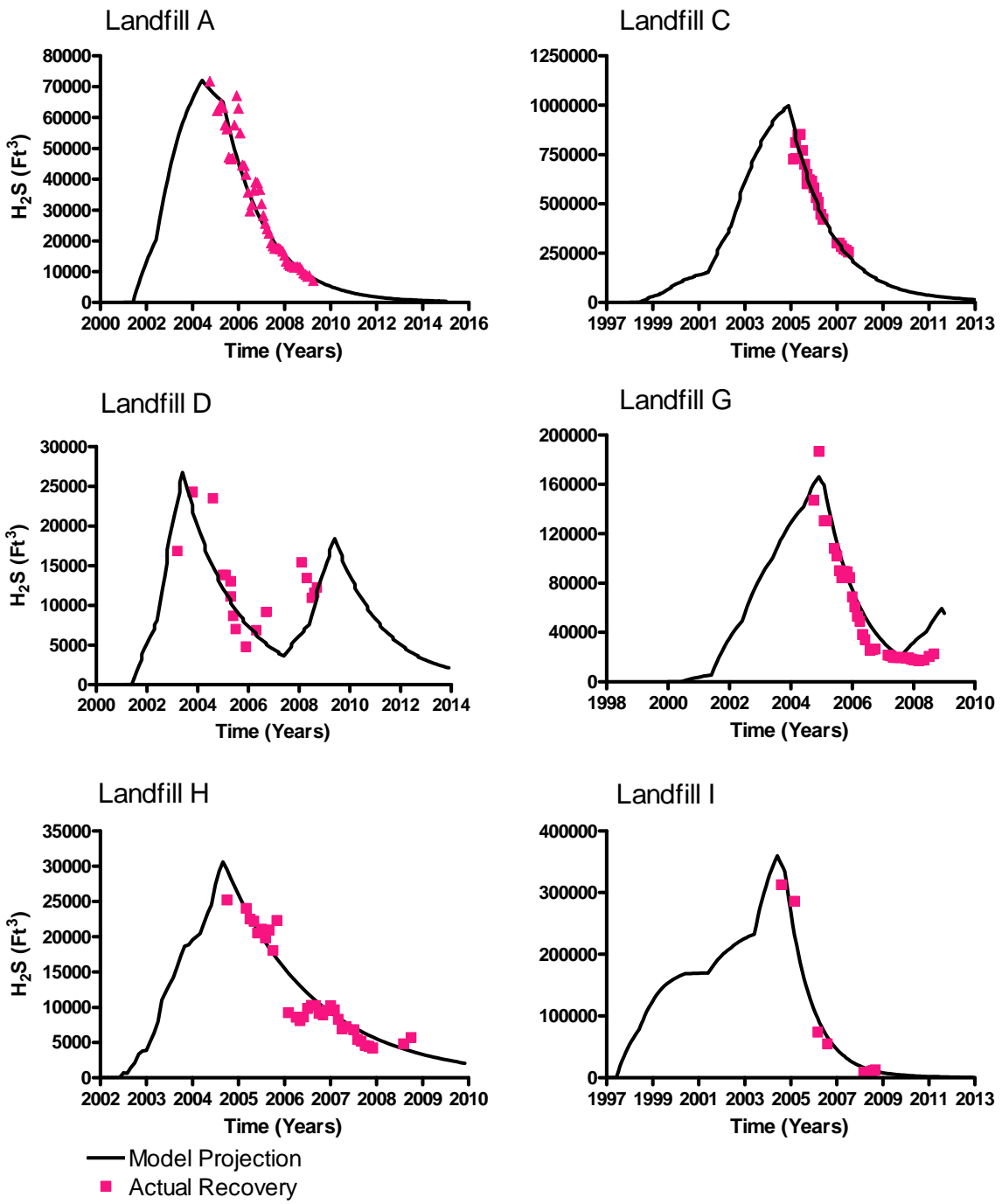


Figure 5. Model Projection versus Actual H₂S Recovery

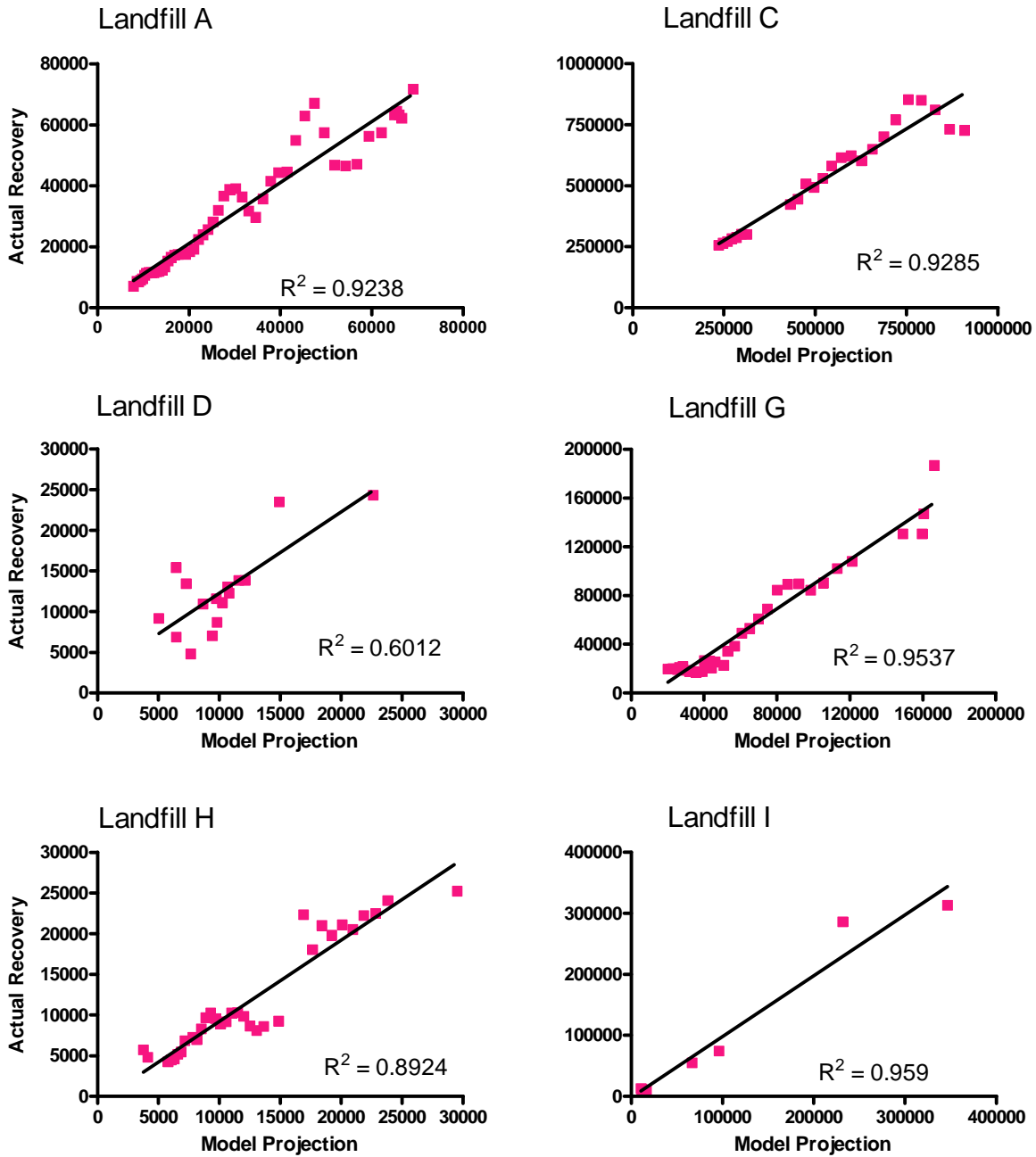


Figure 6. Model to Actual H₂S Recovery Data Correlation

Check of H₂S Generation Potential (S₀)

As a check, the monthly H₂S recovery totals use to calibrate the model to an S₀ value (see above) was subtracted from the model resulting H₂S flow totals for each respective month. The total difference between the actual recovery data and the H₂S flow total from the respective months generated by the model was then evaluated. S₀ was refined through iterations of the model until the difference in flow between the actual data and the respective months generated by the model was approximately equal to zero. The percent difference between the

two S_0 values, one generated by the X-Y plot and the other by the model versus actual data difference, was then evaluated. A large difference between the two S_0 values being another indication of accuracy of the model compared with actual data.

Summary of Model Results

Table 3 provides a summary of the values determined for each parameter of the model for each landfill modeled.

Table 3. Summary of Model Results (k and S_0 Values)

Landfill	k	S_0 (ft ³ /Ton)	Model Results Correlated to Actual Data (R-SQ)
Landfill A	0.54	3186	0.92
Landfill C	0.56	7634	0.93
Landfill D	0.50	1885	0.64
Landfill G	0.83	4548	0.95
Landfill H	0.52	2176	0.89
Landfill I	0.88	6430	0.96

There was a correlation between the site specific decay rate (k) derived from the exponential trend and the actual H₂S recovery trend data with R-squared values between 0.86 and 0.99 for Landfills A, B, C, G, H and I. The model results also correlated well with the actual H₂S recovery trend data with R-squared values between 0.89 and 0.97. Four of the six study sites (Landfill A, C, G and I) with correlation between the model and actual data were MSW landfills which used C&D fines as ADC. Modeling of these four sites resulted in a range of decay rates 1/time (k) of between 0.54 and 0.88, with an average k for these four sites of 0.702 and a range of H₂S generating potential in ft³ of H₂S per ton sulfur as sulfate (S_0) of between 3186 Ft³/ton and 7184 Ft³/ton with an average S_0 value of 5360 Ft³/ton.

The other two sites (Landfill B and H) with correlation between the model and actual data were landfills in which C&D fines were segregated from MSW as monofill. Modeling of these two sites resulted in a range of decay rates 1/time (k) of between 0.166 and 0.515, with an average k for these two sites of 0.34 and a range of H₂S generating potential in ft³ of H₂S per ton sulfur as sulfate (S_0) of between 2704 Ft³/ton and 4548 Ft³/ton with an average S_0 value of 3626 Ft³/ton. The average k value for all six landfills was 0.64. The average S_0 value for all six landfills was 4310 Ft³/ton.

Conclusions

Based on the results of the data analysis and the preliminary model, H₂S generation in an MSW landfill resulting from C&D fines is expected to peak and decline much more rapidly than for methane. Additionally, the model results indicate that C&D fines used as ADC in MSW landfill environments are expected to decay more rapidly (higher k value) and produce more H₂S per ton of sulfate deposited in the Landfill (higher S_0 value) than C&D fines that are monofilled.

Further, based on the model results of Landfill B which in addition to monofilling the C&D fines also mixed C&D fines with soils to reduce H₂S generating potential, there is some preliminary evidence that by mixing or layering C&D fines with the right kind of soil in a monofill environment, the H₂S generating potential of the fines can be reduced. Additional study is needed in this area.

In order to more accurately model H₂S from C&D fines, the inputs into the model are important, including the total mass of sulfur input into the landfill from C&D fines tonnage *and* sulfate composition of the fines. Both of these parameters are needed to evaluate the H₂S generation potential of the site through this modeling approach. Landfill F illustrates a case where not all sulfate sources are known, resulting in a poor fit and unusable model. Representative samples and the correct test method (i.e., the Musson et al., 2008 method) are important. In addition to this data, numerous and reliable H₂S characterization data from the landfill will provide calibration data for the model, allowing site-specific k values to be derived, which makes the model more accurate. In the absence of site-specific data, this research shows a k value of 0.34 for monofilled C&D fines and a k value of 0.70 for C&D fines in an MSW landfill setting are appropriate in the Northeast US.

This modeling approach could be used as a tool used to determine the amount of C&D fines that can be accepted/utilized as ADC or fill based upon the acceptable generation of H₂S (e.g., Landfill E illustrates this principle). While H₂S contributes to odor, it should be noted that this model is not an odor model. Odor can be an issue because of landfill gas management issues even with very low concentrations of H₂S. Conversely several hundred or even thousand ppm of H₂S might not be an odor problem with an active LFG collection system. However, sometimes gas-to-energy or SO_x emissions limit the amount of H₂S that is allowable. In addition to acceptable fines quantities and H₂S generation, this modeling approach could be valuable for landfills to estimate the cost of C&D fines in terms of LFG management and treatment. Estimation of H₂S concentrations in LFG could also be accomplished through this model by combining the H₂S model results with the results of an LFG generation model, adjusted to the site specific methane concentration projected.

Materials and Methods

Selection of Study sites

Approximately 20 potential MSW landfill study sites, all located in the Northeast US, were pre-selected for the study based on relevant criteria. Landfill study candidates were given the option to remain anonymous. The common factors among all of the potential study sites was that they had all accepted some processed C&D material within the past ten years, they had active LFG collection systems in place, elevated H₂S concentrations were exhibited in LFG recovered, and the sites had conducted some testing of H₂S concentrations. Thirteen landfills initially agreed to participate in the study. Based on preliminary data screening (e.g., site characteristics and the availability, quantity and quality of data), nine of the thirteen sites were selected for use in the study. Of the nine study sites selected, seven are MSW landfills which previously used C&D fines as an alternative daily cover, one is landfill site which used C&D fines

as shaping and grading material during closure, and one is an MSW landfill which disposed of C&D fines as waste, partially segregated from MSW disposal areas.

Compilation and Analysis of Data

A common element shared by all the study sites was the challenge of odor control related to H₂S at some point in the landfill's past. The time at which odor problems typically started to occur correlates within one to two years of the initial acceptance of C&D fines. A common response among the landfills which were experiencing problems was to increase LFG collection and control measures, which included expansions to LFG collection system soon after waste deposit, increased operations, maintenance and monitoring of LFG collection, and monitoring H₂S concentrations in the LFG. As a result, LFG recovery data is available including LFG flow, gas composition and H₂S concentrations. Similarly, with regular LFG system expansions and increased LFG management, LFG collection system coverage was quite high, assumed to be greater than 90 percent in those areas of the landfills which used C&D fines and were odor problems.

Historical waste tonnage was well documented at the study sites (including C&D fines). However, older 'baseline' LFG recovery data from before C&D fines acceptance, before odor issues began to drive LFG management, is lacking. Therefore, there is little or no baseline H₂S data available from the study site landfills before the acceptance of C&D fines and odor problems occurred.

Site specific data was compiled from the study sites by month and year (as available) and includes the following:

- LFG recovery data.
- H₂S concentration data.
- Waste composition and tonnage data.
- C&D fines tonnage data, and sources where available).
- Sulfate content of fines (where available).

Data was compiled for each study site into spreadsheets. For each site, sulfur input into the landfill in the form of sulfate from C&D fines and sulfur output from the landfill as H₂S was calculated on a monthly basis. In addition, the study involved compilation of sulfate content data obtained from C&D processing facilities (regionally) to use in modeling sites which did not have site specific sulfate test data (true for most of the study sites). Additional discussion of the data is provided in subsequent sections.

Waste Composition and Tonnage Data

Waste characterization and tonnages were provided for each site on either an annual or a monthly basis. Waste was separated by major type (wherever data was available), including MSW, unprocessed C&D waste, sludge, and processed C&D waste (i.e., C&D fines, C&D residuals). Waste type predominately fit into three categories for most of the study sites: MSW, unprocessed C&D bulk waste and C&D fines/residuals waste (sometimes as ADC). Waste data provided as annual tonnage was equally distributed for the 12 months of that year. Total

tonnage of MSW, C&D waste, and other waste were compiled for use as reference, to provide a general comparison of H₂S trends and waste profile between the different study sites. C&D fines tonnage data was further evaluated, as described in the following section.

C&D Fines Tonnage

C&D fines tonnage data was available for each site on either an annual, quarterly or a monthly basis. The sources of C&D fines received (i.e., the processing facility) was available for most of the study sites. Several sites had detailed records available including the tonnages received each month from each C&D processing facility. C&D fines tonnage data provided as annual tonnage was equally distributed for the 12 months of that year or for the portion of the year that C&D fines was known to have been accepted. The C&D fines tonnage data (along with the sulfate content discussed below) was used to estimate the input of sulfur into the landfill.

LFG Recovery Data

LFG recovery data was available from flow meter readings and recorder devices for each LFG control point at the site (e.g., flares, energy facility). Methane concentration data was also available from facility LFG monitoring records. Total monthly LFG recovery from all control points was combined to get total cubic feet per month of LFG, which was then normalized to 50 percent methane using the monthly average of methane concentration data. LFG recovery data was compared with historic landfill operations and the coverage of the LFG collection system present for each year and month. Periods in which system coverage was known to be incomplete and LFG recovery data which appeared irregular or spurious were noted. Months when there was incomplete system coverage or with unreliable LFG data were not used in the model.

Historic Hydrogen Sulfide Data

H₂S concentration data consisted of two types of data collected: laboratory analysis and field data collected with indicator tubes (e.g., Gastec[®] tubes, Draeger[®] tubes). In most cases, H₂S data was collected by the site on a regular frequency such as weekly, monthly, quarterly, or annually. The amount of available historic H₂S data varied from site to site, sometimes consisting of field indicator tube data and sometimes analytical data. For several of the study sites, there was both analytical data and field data taken together side by side on a consistent basis, which allowed for a comparison of field and analytical data which is discussed later in this report.

Supplemental Hydrogen Sulfide Testing

As a part of the study, supplemental H₂S testing was conducted at several of the study sites. For several study sites, there was a significant amount of historic H₂S testing data available during the time period when odor issues were occurring but no recent data. It was typical for landfills to scale back or abandon H₂S testing programs when improved LFG management and/or reduced acceptance of C&D fines reduced or eliminated odor problems. As a result, this study includes additional H₂S testing at six of the sites. A total of twelve supplemental test events were performed at six of the study sites between February and September of 2008. Sampling events consisted of the following:

- Field testing of H₂S concentrations using a Gastec[®] H₂S indicator tube (3 to 4 tubes used for each event).
- Field testing of LFG composition using a GEM 500/200 LFG field analyzer.
- Collection of LFG samples into 1-liter tedlar bags which were then shipped to the testing lab.

Laboratory samples were analyzed for hydrogen sulfide, total reduced sulfur compounds and permanent gases (methane, carbon dioxide, oxygen and nitrogen). Hydrogen sulfide was analyzed via Method 14 or 307.91 (gas chromatography) and reduced sulfur compounds (8 compounds) were analyzed via Method 15 or 307.91 (gas chromatography/Mass spectrometry). Permanent gases were analyzed by Method 3C or ASTM 1945 (thermal conductivity/gas chromatography). For the test sites that had multiple gas control points, testing was conducted at all control points during each sample event.

The methods followed in this supplemental testing program were essentially the same methods employed in the various sites historically. Therefore, a large portion of the historic test data for several of the study sites is considered of comparable quality.

Acknowledgements

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Appendices

APPENDIX A – Modeled Landfill Details

Landfill A

Landfill A is a Massachusetts landfill site that conducted H₂S testing consistently over a four year period. The LFG collection system at the site was well-managed and LFG recovery data was generally of high quality. C&D fines data, including processing source data, was also available. The quality and quantity of data available from this site made it the best candidate for initial analysis of H₂S data trends and development of an initial H₂S model.

Site Background

Landfill A is a closed and capped MSW landfill with approximately 2.5 million tons of waste in place. There were two principal phases of landfill operation and development, the original landfill area and an expansion area. The original landfill area was a 29-acre unlined facility, operated since the 1940s. The original landfill was closed in 1999 and capped with geomembrane (i.e., high density polyethylene) cap in 2001. The second phase of the landfill development was a 10-acre expansion, constructed with a geomembrane base liner system and a leachate collection system. The expansion area was constructed over a portion of the original landfill with a geomembrane liner. The landfill expansion was operated from 2000 to 2005, and was then closed and capped with a geomembrane cap system in 2006.

Waste composition deposited in the original landfill consisted of waste categorized in records as MSW and C&D waste (unprocessed). The C&D waste component was known to be primarily comprised of wood waste from a large furniture industry which was historically present in the region. Therefore, the C&D portion of the waste in the original landfill areas is not believed to have contained an elevated portion of gypsum wallboard or other high sulfate bearing waste (similar to typical MSW waste streams for that era). C&D fines were not used in the original landfill. Waste deposited in the expansion area consisted predominately of MSW with approximately 5 percent unprocessed C&D waste. Between 2000 and closure at the end of 2005, the expansion area accepted approximately 400,000 tons of MSW waste, 20,000 tons of unprocessed C&D waste and 87,000 tons of C&D fines from various regional processors. The Landfill expansion area accepted C&D fines waste as alternative daily cover between 2001 and 2004, with peak C&D fines acceptance between 2002 and 2004. Use of C&D fines as alternative daily cover was discontinued in November 2004.

LFG Management and Historic H₂S Data

Prior to 2003, LFG management in the original landfill area was accomplished via passive vent flares, connected to gas wells and leachate system vents. In 2003, a comprehensive LFG collection system was installed in the original landfill area. The permanent LFG flare system was installed and an active LFG collection and control system was started in October of 2003. The LFG collection system was expanded into the active landfill expansion area in phases during 2004 and 2005, with addition of collection system piping, leachate cleanouts and vertical wells as waste filling progressed. In December 2004, an additional temporary LFG flare was installed

to supplement the existing permanent LFG flare at the facility. Installation of all collection wells and most of the permanent LFG collection system piping was completed in the expansion area in the fall of 2005. Use of the temporary flare system was discontinued in April 2007, due to declining LFG recovery rates.

The gas collection and flare system has been operated on a 24 hour per day, 7 day per week basis since commissioning in October, 2003. Operation, monitoring and maintenance (OM&M) of the LFG collection and control system has been performed on a regular basis. LFG recovery flow rates at both flares were measured by permanent flow metering devices. LFG composition at the flares was measured with a portable LFG analyzer on a once per week basis (minimum). Flare device run times and total LFG flow rates were documented.

The first hydrogen sulfide concentration data sampled at the LFG collection system was in late 2004, consisting of one analytical test sample and several field test events. An H₂S testing and monitoring program was implemented at the site in 2005 to evaluate the source of odors and H₂S concentration trends. Between 2005 and 2007, LFG samples were collected regularly from the two flare devices for laboratory analysis, initially on a monthly basis and later reduced to quarterly. Field testing of H₂S was also conducted at the two flares on a weekly basis starting in 2005 and including through most of 2008. Field test data was also obtained at the time of each lab sample collection event for a side by side comparison. Two supplemental samples were collected for laboratory analysis in 2008 as part of this study. A summary of the number of H₂S sampling data points available for Landfill A are presented in Table A-1.

Table A-1. H₂S Sample Data for Landfill A

Year	Flare 1		Flare 2		Combined Total	
	Lab Analysis	Field Tests	Lab Analysis	Field Tests	Lab Analysis	Field Tests
2004	1	3	0	0	1	3
2005	9	71	9	88	18	159
2006	7	96	5	94	12	190
2007	4	103	1	24	5	127
2008	2	75	0	0	2	75

Review and Analysis of Hydrogen Sulfide Data from Landfill A

The H₂S data available for Landfill A was reviewed in order to identify the H₂S generation trend over time and a comparison of field data results with analytical data results. The H₂S concentration data was reviewed as three different sets, divided as follows:

1. Monthly Averages of Field Testing Results
 - a. Flare 1
 - b. Flare 2
 - c. Flare 1 & 2 combined
2. Monthly Average of Laboratory Testing Results
 - a. Flare 1
 - b. Flare 2
 - c. Flare 1 & 2 combined
3. Field test results taken concurrently with Laboratory Test samples

- a. Flare 1
- b. Flare 2
- c. Flare 1 & 2 combined

Field test events were typically conducted on three to five different days each month with two or three replicates conducted for each event. Laboratory analysis sample collection was conducted once per month or quarter, and was completed in combination with field testing. The field data results and the lab data results were compared as a quality control step and in order to evaluate differences in results between the two H₂S testing methods (i.e., laboratory analysis versus field test data). For each month, analytical testing results were compared both to the field test results data from the same sample event day and to the average of all of the field test data for collected for the month. All H₂S test data, both analytical and field data, was normalized to 50 percent methane equivalent, based on the same day methane concentration data. The combined flare H₂S concentrations were calculated as a flow weighted average of H₂S concentration data from both flares, also normalized to 50 percent methane.

Analytical data and field data were compared as a percent of the ratio of analytical test results divided by field test results, for each month. The standard deviation and average deviation from mean was then calculated for all of the monthly analytical data results/field data results monthly ratios. A summary of data analysis is provided in Table A-2.

Table A-2. Data Analysis Results of Field and Laboratory H₂S Concentrations for Landfill A

H ₂ S test data Years 2004- 2008	Flare 1		Flare 2		Combined Flare Data ⁽⁴⁾
	Lab Test Results with Same day Field Test results	Lab Test Results with Monthly Average Field Test results	Lab Test Results with Same day Field Test results	Lab Test Results with Monthly Average Field Test results	Lab Test Results with Monthly Average Field Test results
Number of sample days	20	184	14	105	184
Number of field samples	40	348	28	206	554
Number of lab samples	20	22	14	15	37
Ratio Lab results/Field results ⁽¹⁾	104.5%	107.1%	96.3%	98.3%	101.1%
Average Deviation % ⁽²⁾	13.9%	19.0%	11.6%	13.9%	12.5%
Standard Deviation % ⁽³⁾	19.9%	25.8%	17.3%	17.6%	15.2%

(1) Ratio of lab data to field data is the H₂S concentration of lab result divided by the H₂S concentration of field result, presented as a average percent for all months of data

(2) Average deviation of ratio between lab results and field results = $1/n \sum \text{abs}(x - x_{\text{mean}})$, calculated for all months of data

(3) Standard deviation of ration between lab results and field results = $(\sum (x - x_{\text{mean}})^2) / (n-1)^{1/2}$, calculated for all months of data

(4) Combined monthly average of all field test results and lab results, flow weighted for each collection point at 50 percent methane

In summary, the lowest standard deviation observed between the laboratory data and field data sets was exhibited by the data set for combined flare, flow weighted H₂S concentrations. A correlation was then made of the combined flare analytical H₂S concentration results and the monthly average of combined flare field test H₂S concentration results. The sum of squares value for the resultant regression line was calculated at R² = .87 (Figure A-1).

In addition to the H₂S testing conducted at the flares, testing of H₂S concentrations at individual gas wells using field indicator tubes was also conducted during April of 2005. Approximately 25 gas collectors in the original landfill area and 10 gas collectors in the expansion area were individually field tested for H₂S concentration. Average results from the 25 gas collectors in the original landfill area, where no C&D fines were received, was approximately 90 ppmv, with results at individual wells ranging from 0 to the highest value observed at 450 ppmv. The gas collectors tested in the expansion area, were observed to have concentrations between the 300 ppmv to over 10,000 ppmv. During the same month, average H₂S concentrations measured at the flares (combined weighted average normalized to 50 percent methane) was approximately 2,800 ppmv. At the time of the testing, approximately half of the total gas recovery from the landfill is estimated from each the original landfill and expansion area.

Although the field test data collected at individual wells is not quantitative in terms of providing data for a landfill sulfur balance, it does provide important qualitative information, indicating that the source of elevated H₂S was from the expansion areas where C&D fines were used as alternative daily cover and that baseline H₂S concentration in the LFG generated in waste that did not receive C&D fines are fairly low (i.e., about 100 ppmv). Figure A-1 presents the correlation between the field and the laboratory results of H₂S data analysis; the slope of the linear fitted line is 0.82 with R² of 0.87 indicating strong correlation between the two types of test. There is no clear trend in the difference between field data results and test data results, such as one test method consistently providing a lower value. Because of the strong correlation, no correction factor needed to coordinate the data collected with either method. For purposes of the model input, the average of all the monthly field results was averaged with the lab results (where available) providing a more robust combined data set.

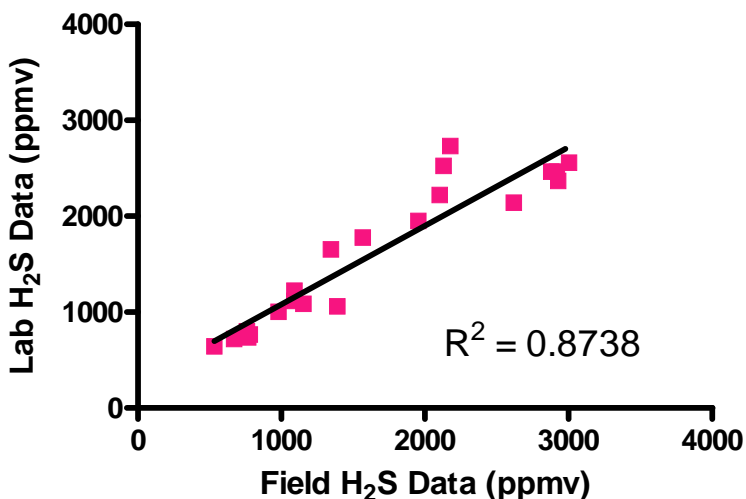


Figure A-1. Correlation between Lab and Field Test H₂S Results for Landfill A

Sulfur Inputs and Outputs for Landfill A

Based on C&D fines and sulfate data, 1,100 tons of sulfur, from the 87,000 tons of C&D fines, was deposited as ADC over a four-year period (2000 through 2004). An estimated 142,000 pounds of H₂S was collected during 50 months of available data between October 2004 and April 2009.

Landfill A Model

An exponential trendline (using MS excel) was fit to the volume of H₂S produced over time to estimate a decay rate (k value). A three month rolling average of the H₂S monthly flow rate, from the 50 months of available data between October 2004 and April 2009, was used to account for any month to month variability in LFG recovery such as may be encountered in LFG operations, difference in the number of days per month, etc.

For the Landfill A model, k value of 0.54 was used, which was found from the trendline fit to the H₂S data, M_i was from sulfur input and S₀ was estimated by plotting the results of the model to actual H₂S recovery data. S₀ was refined through iterations of the model until the model had the best fit with the empirical data. An S₀ value of 3186 Ft³/ton (90 M³/Megagram) was estimated using this method. This fit was evaluated through a linear regression of the predicted H₂S generation (cubic feet H₂S per month) from the model versus actual H₂S recovery data (cubic feet H₂S per month, 3-month average) resulting in an R-squared of .924.

The S₀ value was then checked by solving for S₀ (using the same k value) by setting the total volume of H₂S estimated by the model equal to the total volume of H₂S represented by the actual H₂S flow data for all of the available data used for the model. The derived S₀ value using the volume approach was 3295 Ft³/ton, approximately 3.5 percent higher than the best fit S₀ value.

Discussion – Landfill A

The spike and then rapid declining trends in H₂S concentrations and recovery at Landfill A are indicative of a rapid conversion of sulfate containing waste to H₂S. The extensive H₂S testing program conducted over a number of years and the stable operation of the LFG collection system provided a well-defined data trend to illustrate declines in H₂S generation. During 2001 through 2004, C&D fines material was used as ADC in the expansion area with the C&D fines tonnage equaling between 15 and 26 percent of the total waste accepted, which was primarily MSW. The landfill is located in an area with relatively high annual precipitation (45 to 50 inches year). The moisture and C&D fines mixed with MSW waste in the landfill expansion area is believed to have created advantageous conditions for both methane producing and sulfur reducing bacteria.

In addition to the H₂S testing conducted at the flares, testing of H₂S concentrations at individual gas wells was conducted using field indicator tubes during April of 2005. Approximately 25 gas collectors in the original landfill area and 10 gas collectors in the expansion area were individually field tested for H₂S concentration. Average results from the 25 gas collectors in the

original landfill area, where no C&D fines were received, was approximately 90 ppmv, with results at individual wells ranging from 0 to the highest value observed at 450 ppmv. The gas collectors tested in the expansion area, were observed to have concentrations between the 300 ppmv to over 10,000 ppmv. During the same month, average H₂S concentrations measured at the flares (combined weighted average normalized to 50 percent methane) was approximately 2,800 ppmv. At the time of the testing in 2005, approximately half of the total gas recovery from the landfill is estimated from each the original landfill and expansion area.

Although the field test data collected at individual wells is not quantitative in terms of providing data for a landfill sulfur balance, it does provide important qualitative information, indicating that the source of elevated H₂S was from the expansion areas where C&D fines were used as alternative daily cover and that baseline H₂S concentration in the LFG generated in waste that did not receive C&D fines are fairly low (e.g., about 100 ppmv).

Landfill C

Landfill C is an active, MSW landfill located in New Jersey. Analytical testing of H₂S concentrations in the recovered LFG has been conducted consistently at the landfill on a once per month basis since 2004. During the period of the H₂S testing program, the LFG collection system in areas receiving C&D fines has been for the most part comprehensive, well-managed and LFG recovery data was generally of high quality. Annual totals of C&D fines tonnage received was made available for this study, however C&D fine processing source information was not available. The quality and quantity of data available from this site made it a good candidate for initial analysis of H₂S data trends and development of a site specific H₂S model.

Site Background

The landfill has been developed as five lined cells with a total footprint of 38 acres. The five cells form one contiguous mound. The Landfill is permitted for the disposal of MSW originating from residential, commercial and industrial sources as well as ash and construction and demolition debris. Through 1997, the Landfill accepted primarily ash, with the balance being mostly bulky waste and some bypass MSW waste. In 1997, the landfill began to accept larger quantities of MSW and bulky waste, comprised of approximately 40 percent MSW and 60 percent bulky (unprocessed) C&D waste.

The landfill also began to accept C&D processing fines in 1998. C&D fines were deposited primarily as alternative daily cover but some C&D fines material may have also been accepted for landfill disposal. Approximately 447,000 tons of C&D fines material were accepted between 1998 and 2004, equivalent to between 9 and 27 percent of total waste acceptance each year by weight; an average of 16 percent of the waste acceptance during the seven-year period. Acceptance of C & D fines was discontinued in May 2004. The landfill continues to receive primarily MSW through the present time. Total waste tonnage (all types) received by the landfill through 2008 is approximately 2.8 million tons.

LFG Management and Historic H₂S Data

LFG odors issues initially began to be a problem at the landfill in November, 2002. LFG collection system equipment, including wells, leachate cleanout connections, gas conveyance piping and flare equipment, was installed at the Landfill incrementally between March 2003 and January 2005 in order to improve LFG system coverage. Since February 2005, after the commissioning of the permanent blower/flare system, the LFG collection system coverage has generally been comprehensive throughout the site and has been expanded on a regular basis to maintain comprehensive LFG collection system coverage. As of 2008, the LFG collection system was comprised of 54 vertical wells, 1 horizontal collector, 23 leachate cleanout connections and a 12-inch perimeter header, system extending around the north, east and south sides of the Landfill.

Temporary blower/flare stations were initially installed at the Landfill, which included utility flares. A 350-scfm flare was originally installed in March 2003. This flare was replaced with a 750-scfm flare (nominal rating) in March 2004. This flare was then replaced in February 2005 with the permanent 2,200 scfm blower/flare station referenced above. An electrical generation and gas treatment system was then added in October 2006. The LFG control equipment at the landfill utilize a common collection header and blower system. Therefore, H₂S testing data is representative of H₂S concentrations in LFG recovered from the landfill overall.

The gas collection and flare system has been operated on a 24 hour per day, 7 day per week basis since 2003. OM&M of the LFG collection and control system has been performed on a regular basis. LFG recovery flow rates at the flares and electrical generation plant were measured by permanent flow metering devices. LFG composition was measured with a portable LFG analyzer (approximately on a once per week basis) prior to 2006, but has utilized a continuous methane analyzer since commissioning of the electrical generation plant in October, 2006.

The Landfill has conducted regular, once per month, analytical testing of H₂S concentrations in the recovered LFG since March of 2004. The following sampling data was made available by the landfill for use in this study, summarized in Table C-1 below:

Table C-1. H₂S Sample Data for Landfill C

Year	Number of Monthly Lab Analytical Results Available
2004	12
2005	12
2006	6
2007	10

Field testing of H₂S concentrations was not conducted at the site. Supplemental testing was not performed as part of this study due to the quantity lab analytical data that was already available.

Sulfur Inputs and Outputs for Landfill C

Based on C&D fines and sulfate data, 6,400 tons of sulfur, from the 446,000 tons of C&D fines, were deposited, chiefly as ADC, over a seven-year period (1998 through 2004). An estimated 1.55 million pounds of H₂S was collected during 35 months of available data between March 2004 and July 2007.

Landfill C Model

An exponential trendline (using MS excel) was fit to the volume of H₂S produced over time to estimate a decay rate (k value). The trend line was fitted for the period starting with the peak H₂S recovery, which was approximately May of 2005 through July of 2007, the most recent data available. The peak of H₂S recovery in May 2005 is approximately 12 months after the last C&D fines material was accepted at the landfill. A three month rolling average of the H₂S monthly flow rate was used for modeling in order to account for any month to month variability in recovery such as may be encountered in LFG operations, difference in the number of days per month, etc.

For the Landfill C model, k value was set to 0.558, which was found from the trendline fit to the H₂S data. The actual H₂S data correlated to the exponential trendline with an R-squared of 0.99. M_i was from sulfur input and S₀ was estimated by plotting the results of the model to actual H₂S recovery data. S₀ was refined through iterations of the model until the model had the best fit with the empirical data. To calibrate the model to S₀, the data period used was February 2005 through July of 2007, which corresponds to the time period starting with comprehensive system coverage (i.e., when the permanent blower/flare system was commissioned) through the most recent data available. A three month rolling average of the H₂S monthly flow rate was used for modeling in order to account for any month to month variability in recovery such as may be encountered in LFG operations, difference in the number of days per month etc. A S₀ value of 7634 Ft³/ton (182 M³/Megagram) was estimated using this method. This fit was evaluated through a linear regression of the predicted versus actual H₂S recovery data with an R-squared of .93.

The S₀ value was then checked by solving for S₀ (using the same k value) by setting the total volume of H₂S estimated by the model equal to the total volume of H₂S represented by the actual H₂S flow data for all of the available data used for the model (24 months of data). The derived S₀ value using the volume approach was 7734 Ft³/ton, approximately 1.3 percent higher than the best fit S₀ value.

Discussion – Landfill C

This landfill has the largest data set of lab analytical test data, providing lab verified H₂S concentration data for 40 months over a 5-year period. Landfill C exhibits a spike and then rapidly declining trends in both H₂S concentrations and total recovery as mass. This is also observed at other Landfills which accepted large amounts of sulfate containing C&D fines for use as ADC. This landfill case presents a good correlation between the actual data trends and the model projections as exhibited by the R-squared value of 0.99 correlating the actual recovery data to the exponential decay trend (k) and a R-squared value of 0.93 correlating the

actual recovery data to the model. The model variables (i.e., model equation k and S_0 inputs) for landfill C are also similar to other landfills in this study which used C&D fines materials as ADC. This study site is also able to indicate through the data trends a peak in H_2S recovery and concentrations lagging 6 to 12 months after acceptance of C&D fines was halted.

Landfill D

Landfill D is a Massachusetts landfill site that conducted H_2S testing during a 3-year period following use of C&D fine materials. During the period which most of the H_2S testing was conducted, the LFG collection system had complete system coverage throughout those areas which had disposed C&D fines material. The LFG collection system at the site was therefore comprehensive, well-managed and LFG recovery data was generally of high quality. C&D fines data, including annual tonnage and processing facility source data, was also available. The quality and quantity of data available from this site made it a good candidate for initial analysis of H_2S data trends and development of a site specific H_2S model.

Site Background

Landfill D is an open landfill facility which primarily accepts MSW. The landfill has been developed in three separate, non-contiguous, landfill areas; two of which are now closed to waste disposal. The third, active landfill area has a separate LFG collection and control system from the other two landfill areas and is the only landfill area which has accepted C&D fines, and therefore is the subject area for this study. The active landfill has been operated since approximately 1996, is lined and currently has approximately 1.1 million tons of waste in place. A leachate recirculation system was installed in 2001 and operated for approximately one and a half years. Leachate recirculation was discontinued in 2002 due to problems related to LFG management and wet conditions within the landfill. Completed areas of the landfill, already at final grades, have been capped incrementally with a geosynthetic cap system. Approximately one-third of the landfill has been capped.

During the previous 10 years of operating life, the landfill accepted on average approximately 70 percent MSW and 30 percent unprocessed C&D waste (excluding C&D fines). The facility accepted C&D fines as alternative daily cover (ADC) between 2000 and 2002. Approximately 37,000 tons of C&D fines material was accepted during the three-year period. Acceptance of C&D fines material was discontinued at the end of 2002 due to concerns over contribution of C&D fines to hydrogen sulfide generation and odor problems. Acceptance of C&D processing residuals for use as ADC was resumed in October 2007. The landfill has since accepted approximately 26,000 tons of C&D fines materials between October 2007 and November 2008.

LFG Management and Historic H_2S Data

Odor issues, related to elevated H_2S concentrations in the landfill gas, first became a concern in 2002. Incomplete LFG collection system coverage was compounded by leachate recirculation activities which increased LFG generation and reduced LFG system performance. Expansion of the gas collection system, discontinuing leachate recirculation and partial capping of landfill side slopes improved gas collection at the landfill, eventually providing comprehensive collection system coverage and control of odors by mid-2004. There were some continuing LFG

odor issues related to LFG system coverage and system performance issues during the second half of 2005 and at the end of 2006. These performance issues were in part caused by wet conditions within the waste mass, watered in collectors etc. Issues were also resolved through expansions of the LFG collection system and incremental capping of the landfill. The LFG collection system has been expanded incrementally as filling progresses.

The current LFG collection system includes header piping, vertical wells, leachate cleanout connections, horizontal collectors and condensate management components. A utility flare is used to combust the LFG collected from this landfill area. The LFG collection and flare system has been operated on a 24 hour per day, 7 day per week basis. OM&M of the LFG collection and control system has been performed on a regular basis since 2004. LFG recovery flow rate at the flare is measured by permanent flow metering device. LFG composition at the flare has been measured with a portable LFG analyzer on a once per week basis (minimum). A small amount of LFG (estimated at 50 cubic feet per minute flow rate) is also diverted from the flare system blower, through a 2-inch pipe, as supplemental fuel for a small electrical generation plant. Flare device run times and total LFG flow rates were documented.

The first hydrogen sulfide concentration data sampled at the LFG collection system was in March 2003, consisting two field test events. An H₂S testing and monitoring program was implemented at the site in 2004 to evaluate the source of odors and H₂S concentration trends. During 2004, field testing was completed at the flare approximately twice per month. The testing program was changed to include only quarterly analytical testing between 2005 and 2006. No test data was available for 2007, however four field testing events and 3 analytical test events were conducted in 2008, including two supplemental samples collected for laboratory analysis as part of this study. A summary of the number of H₂S sampling data points available for Landfill D are presented in Table D-1.

Table D-1. H₂S Sample Data for Landfill D

Year	Flare 1	
	Lab Analysis	Field Tests
2003	0	2
2004	0	23
2005	2	12
2006	2	1
2007	0	0
2008	3	5

Sulfur Inputs and Outputs for Landfill D

Based on C&D fines and sulfate data, 530 tons of sulfur, from the 37,000 tons of C&D fines, was deposited as ADC over a three-year period (2000 through 2002) and another 300 tons of sulfur, from the 26,000 tons of C&D fines, was deposited as ADC between October 2007 and November 2008. An estimated 17,500 pounds of H₂S was collected during the 17 months with available H₂S recovery data between March 2003 and September 2008.

Landfill D Model

An exponential trendline (using MS excel) was fit to the volume of H₂S produced over time to estimate a decay rate (k value). A three month rolling average of the H₂S monthly flow rate, was used to account for any month to month variability in LFG recovery such as may be encountered in LFG operations, difference in the number of days per month, etc. The 11 months of H₂S recovery data between October 2003 and October 2006 was used to derive the k value since this represents the time with comprehensive LFG system coverage, but before acceptance of C&D fines was resumed.

For the Landfill D model, k value was set to 0.501, which was found from the trendline fit to the H₂S data, M_i was from sulfur input and S₀ was estimated by plotting the results of the model to actual H₂S recovery data. S₀ was refined through iterations of the model until the model had the best fit with the empirical data. A S₀ value of 1885 Ft³/ton (53 M³/Megagram) was estimated using this method. This fit was evaluated through a linear regression of the predicted H₂S generation (cubic feet H₂S per month) from the model versus actual H₂S recovery data (cubic feet H₂S per month, 3-month average) resulting in an R-squared of .601.

The S₀ value was then checked by solving for S₀ (using the same k value) by setting the total volume of H₂S estimated by the model equal to the total volume of H₂S represented by the actual H₂S flow data for all of the available data used for the model. The derived S₀ value using the volume approach was 2305 Ft³/ton, approximately 22 percent higher than the best fit S₀ value.

Discussion – Landfill D

The spike and then rapid declining trends in H₂S concentrations and recovery at Landfill D are indicative of a rapid conversion of sulfate containing waste to H₂S. However, the results of the H₂S trend data, including concentration trends and volumetric H₂S recovery data, does not follow the expected trends as closely as for some of the other study sites. The resulting exponential trendline, used to derive k, and the relationship between the modeled results and the actual trend data are therefore less than optimal, with R-squared values of .64 and .60 respectively. The S₀ value (i.e. hydrogen sulfide generating potential) was also lower than other, similar MSW landfills in the study, which had also used C&D fines as ADC.

After declining rapidly between 2004 to 2006, the H₂S concentrations at the landfill were observed to 'rebound' over the following two years (three sample events), increasing from a low of approximately 170 ppmv (at 50 percent methane equivalent) in December 2005 to over 440 ppmv in February 2008. The rebound in H₂S recovery observed in the trend data cannot be attributed to the resumed use of C&D fines as ADC in October 2007, as the C&D fines material was less than 6 months in age and would not yet contribute to H₂S generation, assuming a 6 month delay between placement of fines and initial generation of H₂S).

The reason for the inconsistencies is attributed to several potential causes including:

- Wet conditions within the Landfill,
- Inconsistent collection system coverage/performance during the period,
- Insufficient number of data points for several years,
- Differences between the actual and assumed sulfate concentration in the C&D fines material.

The landfill is located in an area with relatively high annual precipitation (45 to 50 inches year), the impact of which is further increased by leachate recirculation during 2001 and 2002. There were significant operational problems related to wet conditions and elevated leachate levels.

Landfill G

Landfill G is a Massachusetts landfill site that conducted extensive H₂S testing over the past five year period. LFG collection systems at the site was for the most part comprehensive, well-managed and LFG recovery data was generally of high quality. However initially, during 2004, significant improvements and expansions of the LFG system were completed. Therefore, LFG collection system coverage during 2004 was incomplete, making LFG and H₂S recovery data from most of 2004 and earlier unusable. This is documented by odor problems and operational issues that the site experienced prior to 2005. C&D fines data, including annual tonnage and processing facility source data, was also available. The quality and quantity of data available from this site made it a good candidate for analysis of H₂S data trends and development of a site specific H₂S model.

Site Background

Landfill G is an operating MSW landfill with approximately 4.0 million tons of waste in place and a total design capacity of approximately 9.0 million tons. The Landfill has been developed in 3 main Sections (Sections 1, 2 and 3). Section 1, approximately 25 unlined acres, began receiving waste in 1972 and is currently closed to filling. A final cover system has been installed over the entire Section 1 area. Section 2, initially constructed in 1994, consists of four lined phases totaling approximately 24 acres in size plus 3 acres of overfill over Section 1. Section 2 ceased waste acceptance in August of 2004 with capping completed during 2005. Section 3 is the currently active Landfill area, consisting of 2 lined phases (1 and 2) with two additional phases (3&4) planned for the future. The landfill currently accepts between 300,000 and 400,000 tons of waste per a year.

Waste composition deposited in the landfill during the past 10 years of operation has consisted mostly of MSW (90 percent) with the balance consisting mostly of C&D waste (unprocessed). C&D fines were used as alternative daily cover (ADC) in Section 2 between January of 2000 and August of 2004 at which time their use was discontinued. C&D fines were not used in the Section 1 landfill. Use of fines as ADC in Section 3 resumed in March 2007 and continues through present day. . Between 2000 and July of 2004, approximately 110,000 tons of C&D fines were placed in the Section 2 landfill. A small amount of C&D fines were also placed in Section 3 initially during July and August of 2004 and approximately 27,000 tons of C&D fines were deposited in Section 3 between March of 2007 and June of 2008.

LFG Management and Historic H₂S Data

The Landfill currently has a comprehensive LFG collection system in place, which was installed in phases during the past 12 years of landfill operation and expansion. The gas collection system is installed throughout all areas of the Landfill area, including closed Sections 1 and 2 and the active areas of Section 3. Prior to 2004, LFG was collected from Section 1 and portions of Section 2 and then conveyed offsite for use as fuel in a biomass power generation facility. This original gas collection system is referred to as the Section 1/2 collection system. Odor issues, resulting from incomplete collection system coverage in Section 2, required that additional gas collection and controls be installed in Section 2. A separate gas collection system was installed in Section 2 to convey LFG to a new flare, commissioned in early 2004. Expansions to the Section 2 LFG system and improvements in LFG management during 2004 resulted in comprehensive LFG collection throughout all areas of the Landfill by the end of 2004. The LFG collection system was expanded incrementally in Section 2 as waste filling progressed until closure in mid-2004. The gas system was expanded into Section 3 during 2005 and 2006, initially tying into Section 3 leachate cleanouts. The Section 3 LFG collection system has been expanded incrementally since that time, continuing to provide comprehensive LFG collection coverage at the active sections of the landfill. Currently LFG collected in Section 3 and much of the LFG collected from Section 2 (Section 2/3 collection system) is conveyed to an on-site electrical generation plant and back up flare. LFG in Section 1 and the older portions of Section 2 are still collected separately and delivered for offsite use.

The gas collection and control system has been operated on a 24 hour per day, 7 day per week. OM&M of the LFG collection and control system has been performed on a regular basis. LFG recovery flow rates from both collection systems are measured by permanent flow metering devices. LFG composition from both collection systems are currently measured with a continuous gas analyzer. A portable LFG analyzer was used to measure LFG composition on a once per week basis (minimum) at the Section 2/3 flare prior to the commissioning of the electrical generation plant. LFG control device run times and total LFG flow rates were well documented.

The first hydrogen sulfide concentration data sampled at the landfill was in early 2004, consisting of one analytical test sample and several field test events at both the Section 1/2 collection system header and the Section 2/3 collection system header (then collecting LFG from only the newer portions of Section 2). An H₂S testing and monitoring program was implemented at the site to evaluate the source of odors and H₂S concentration trends. H₂S concentrations from the Section 2 system were initially observed to be elevated, between 2000 and 3000 parts per million volume (ppmv), however H₂S concentrations at the Section 1/2 system were much lower, generally between 200 and 500 ppmv. Testing at the Section 1/2 system initially consisted of field tests conducted twice monthly, however testing at this system was discontinued after June of 2005. At the Section 2/3 system, LFG samples were collected monthly during 2005 and 2006, including field tests and laboratory analysis, on a monthly basis (later reduced to quarterly). Field testing of H₂S was also conducted on a weekly basis starting in 2005 which has continued through the present day. Field testing is conducted at the inlet of the electrical generation plant on a weekly basis (minimum). Field test data was also obtained at the time of each lab sample collection event for a side by side comparison.

Six supplemental samples were collected for laboratory analysis in May and September 2008; two samples each from the Section 1/2 LFG system, the Section 2/3 LFG system and from the Section 3 LFG system (prior to mixing with Section 2 LFG). A summary of the number of H₂S sampling data points available for Landfill G are presented in Table G-1.

Table G-1. H₂S Sample Data for Landfill G

Year	Section 1/2 System		Section 2/3 System		Combined Total	
	Lab Analysis	Field Tests	Lab Analysis	Field Tests	Lab Analysis	Field Tests
2004	1	8	2	17	3	25
2005	0	4	11	32	11	36
2006	0	0	9	14	9	14
2007	0	0	0	>150	0	>150
2008 (Sept.)	2	4	2	54	2	58

One testing event, including a lab analysis and field test data, was conducted in January 2006 when all LFG collected from Sections 1, 2 and 3 was directed to a single point (a flare). This test event data point (780 ppmv) correlates with the estimated H₂S concentration calculated by averaging LFG flow weighted test results from Section 2/3 and Section 1/2. Analytical testing conducted at the Section 3 system in May and September of 2008 resulted in H₂S concentrations of 120 ppmv and 179 ppmv respectively which were lower than the results of analytical testing conducted at the 2/3 system on the same dates (207 ppmv and 277 ppmv respectively).

Hydrogen Sulfide Data Trends for Landfill G

The monthly average H₂S concentration for each of the two collection systems combined (Section 1/2 and Section 2/3) were used with the monthly LFG flow rate for each collection system (normalized to 50 percent methane) in order to calculate a flow weighted H₂S concentration for the entire landfill collection system. In order to supplement the missing H₂S concentration data for the Section 1/2 collection system between June 2005 and the supplemental testing conducted in 2008, an assumed H₂S value of 308 ppmv was used. The value of 308 ppmv is based on the average of 349 ppmv from June 2005 testing and 267 ppmv from the May 2008 test event. It was necessary to use this estimated H₂S value to supplement the missing data for the Section 1/2 collection system in order to calculate a total monthly flow of H₂S, (presented either in pounds or cubic feet) for the entire Landfill during those years. Because the LFG flow rates and H₂S concentration at the Section 1/2 system are significantly lower, compared with the Section 2/3 system, potential error in the model resulting from using this assumed H₂S concentration value (as opposed to using only months with actual direct test data) is considered appropriate and within an acceptable margin of error.

Sulfur Inputs and Outputs for Landfill G

Based on C&D fines and sulfate data, 1,360 tons of sulfur, from the 110,000 tons of C&D fines, was deposited as ADC over a four-year period (2000 through 2004) and 278 tons sulfur were placed in Section 3 from the 27, 600 tons of C&D fines as ADC between January 2007 and July

2008. An estimated 203,000 pounds of H₂S was collected during 50 months of available data between October 2004 and April 2009.

Landfill G Model

An exponential trendline (using MS excel) was fit to the volume of H₂S produced over time to estimate a decay rate (k value). A three month rolling average of the H₂S monthly flow rate, from the 28 months of available data between October 2004 and October 2007, was used to account for any month to month variability in LFG recovery such as may be encountered in LFG operations, difference in the number of days per month, etc. H₂S flow trend data after October 2007 was not used to trend the H₂S decay curve because for 6 months prior to October, C&D fines materials had been placed in Section 3. This new material could contribute to the total H₂S flow rate from the site and, in turn, affect the slope of the decay curve (and derived k value). The objective is to obtain a k value which represents the decay rate of H₂S during the period of time after placement of sulfate bearing materials had ceased.

For the Landfill G model, k value was set to 0.828, which was found from the trendline fit to the H₂S data, M_i was from sulfur input and S₀ was estimated by plotting the results of the model to actual H₂S recovery data. S₀ was refined through iterations of the model until the model had the best fit with the empirical data. A S₀ value of 4548 Ft³/ton (129 M³/Megagram) was estimated using this method. This fit was evaluated through a linear regression of the predicted H₂S generation (cubic feet H₂S per month) from the model versus actual H₂S recovery data (cubic feet H₂S per month, 3-month average) resulting in an R-squared of 0.954.

The S₀ value was then checked by solving for S₀ (using the same k value) by setting the total volume of H₂S estimated by the model equal to the total volume of H₂S represented by the actual H₂S flow data for all of the available data. The derived S₀ value using the volume approach was 3764 Ft³/ton, approximately 21 percent lower than the best fit S₀ value.

Discussion – Landfill G

The spike and then rapid declining trends in H₂S concentrations and recovery at Landfill G are indicative of a rapid conversion of sulfate containing C&D fines waste to H₂S. During the years 2001 through 2004, when the largest quantities of C&D fines material were used as ADC in Section 2, the C&D fines tonnage equaled between 10 and 15 percent of the total waste accepted, which was chiefly MSW. The landfill is located in an area with fairly high annual precipitation (45 to 50 inches year), the impact of which is further increased by the use of C&D fines as ADC which may increase infiltration rate at the landfill surface.

Therefore, the moisture and ratio of C&D fines mixed with MSW waste in the Section 2 landfill is believed to have created advantageous conditions for both methane producing and sulfur reducing bacteria. This results in slightly higher k and S₀ values for H₂S than may otherwise be observed under somewhat different conditions. Although Landfill Section 3 has also accepted a significant quantity of C&D fines material since early 2007, this has not yet resulted in the same 'spike' in H₂S generation as was observed from fines deposited in Section 2. This can be observed in the model based on a decay rate and S₀ values calibrated to H₂S from the Section 2 area. This may be a result of several variables including differences in the sulfate content of the

C&D fines material now being accepted, differences in landfill operational practice and a lower ratio of C&D fines to total waste disposal as the C&D fines used as ADC in Section 3 was between 4 and 7 percent in 2007 and 2008.

Landfill H

Landfill H is a Connecticut landfill site that conducted H₂S testing consistently over a three year period. During the period which most of the H₂S testing was conducted, the LFG collection system had complete system coverage throughout those areas which had accepted C&D fines material. The LFG collection system at the site was therefore comprehensive, well-managed and LFG recovery data was generally of high quality. C&D fines data, including quarterly tonnage and processing facility source data, was also available. The quality and quantity of data available from this site made it a good candidate for initial analysis of H₂S data trends and development of a site specific H₂S model.

Site Background

Landfill H is an active landfill which accepts both MSW and Bulky C&D waste. The landfill is unlined with approximately 2.0 million tons of waste in place and has approximately 2 years of operating life remaining, after which it will be closed and capped. The site is permitted to dispose MSW, including bulky waste and C&D debris (C&D waste), on a 65-acre portion of the site. Waste has historically covered a 50-acre footprint at the site. The Landfill area is divided into 4 cells (A, B, C and D). Cells A and B, comprising the northern portion of the Landfill footprint, contain the oldest waste and have not received any new waste for over 9 years. Cells C and D are currently open to active filling. The Landfill topography is fairly flat with moderate slopes and shallow waste depth with maximum waste depth between 50 and 60 feet.

C&D waste disposal, including C&D fines disposal when that material was being accepted, is segregated from MSW waste disposal, disposed in a 5-acre area of the southeastern portion of the site permitted for bulky waste and C&D debris. Although C&D fines materials were mono-filled in the C&D waste disposal area, separately from MSW disposal, the MSW disposal areas and C&D waste disposal areas were not separated by a liner system, or other physical barrier. Therefore, there is contact and mixing of C&D and MSW, particularly along the perimeter of the C&D disposal area. C&D fines waste material was not used as alternative daily cover in MSW disposal areas.

Prior to 1994, the Landfill received only MSW at an average rate of approximately 60,000 tons per year. In 1994, the landfill began to track acceptance of construction and demolition waste or 'bulky waste' separately from MSW waste. Waste accepted per year between 1994 and 2001 averaged approximately 45,000 tons, with an average of 4,000 tons per year of that total consisting of bulky waste. Between 2002 and 2007, the Landfill accepted an average of 70,000 tons waste per year, including approximately 60 percent MSW and 40 percent C&D waste (including C&D fines).

In July 2002, the Landfill started accepting processed construction and demolition residual fines (C&D fines) from a single C&D processing facility. The C&D fines contained elevated sulfate content from gypsum drywall material components. From August 2002 through November

2004, the Landfill accepted approximately 34,000 tons of C&D fines materials. Acceptance of C&D fines material was discontinued in November 2004, when the Landfill placed a ban on construction and demolition gypsum, including C&D fines materials. In 2006, the ban on C&D gypsum was lifted, but the landfill has not accepted additional C&D fines due to concerns over contribution of C&D fines to hydrogen sulfide generation and odor problems.

LFG Management and Historic H₂S Data

Odor issues, related to elevated hydrogen sulfide in the landfill gas, first became a concern in the mid-2003, approximately 9 to 12 months after initial acceptance of C&D fines. The initial phase of the LFG collection system was installed in the C&D waste disposal area, completed in December 2003. The collection system was subsequently expanded into Cells C and D during April of 2004 and again between November 2004 and January 2005, as part of a continuing effort to control LFG odors at the site. The first and second installations of the LFG collection system (December 2003 and April 2004) represented approximately half of the currently existing gas collection system in terms of landfill coverage area. The third and most recent system expansion (November 2004) added gas collectors throughout the remainder of the bulky waste and MSW areas along the southern edge of Cell D. The most recent expansion provides 100 percent system coverage in all bulky waste areas, as well as additional collectors in Cell C and D MSW areas.

The LFG collection system includes header piping, vertical wells, horizontal collectors and condensate management components. There are 43 vertical extraction wells and 7 horizontal collection wells installed in portions of Cells C and D. A utility flare is used to combust the LFG collected. The LFG collection and flare system was initially operated on a timer during 2004 but since mid-2004 the system has been operated on a 24 hour per day, 7 day per week basis. OM&M of the LFG collection and control system has been performed on a regular basis. LFG recovery flow rate at the flare is measured by permanent flow metering device. LFG composition at the flares has been measured with a portable LFG analyzer on a once per week basis (minimum). Flare device run times and total LFG flow rates were documented. LFG odors have been controlled at the site since the early 2005. As a result, no additional expansions of the collection system have been necessary since that time.

The first hydrogen sulfide concentration data sampled at the LFG collection system was in late 2004, consisting of one analytical test sample and several field test events. An H₂S testing and monitoring program was implemented at the site in 2005 to evaluate the source of odors and H₂S concentration trends. Between 2005 and 2007, field testing H₂S at the flare was conducted on a regular basis, several times per a month. During 2006 and 2007 LFG samples were also collected for laboratory analysis, initially on a monthly basis and later reduced to quarterly. Regular testing of H₂S was discontinued in 2008 after odors problems were under control and H₂S concentrations had been observed to be reduced. Field test data was obtained at the time of each lab sample collection event for a side by side comparison. Two supplemental samples were collected for laboratory analysis in 2008 as part of this study. A summary of the number of H₂S sampling data points available for Landfill H are presented in Table H-1.

Table H-1. H₂S Sample Data for Landfill H

Year	Flare 1	
	Lab Analysis	Field Tests
2004	0	4
2005	1*	29
2006	9	24
2007	2	17
2008	2	2

*Data was excluded because it was erroneous.

One testing event conducted in May of 2005 included a lab analysis and field test data. The laboratory result for H₂S and other gas components was an outlier from the field results and the data set overall. Based on lab results this data point is suspected of being erroneous and therefore was not included in the modeling data base.

Hydrogen Sulfide Data Trends for Landfill H

The monthly values for H₂S concentration were used with the monthly LFG flow rate (normalized to 50 percent methane) to calculate the total monthly flow of H₂S. For purposes of the model input, the average of all the monthly field results was averaged with the lab results (where available) since this data set was the most robust. The laboratory result obtained in May 2005 was an outlier, suspected of being erroneous and therefore was not used for the model data base.

Sulfur Inputs and Outputs for Landfill H

Based on C&D fines and sulfate data, 484 tons of sulfur, from the 33,800 tons of C&D fines, was deposited as ADC over a four-year period (2000 through 2004). An estimated 34,400 pounds of H₂S was collected during 33 months of available data between October 2004 and October 2008.

Landfill H Model

An exponential trendline (using MS excel) was fit to the volume of H₂S produced over time to estimate a decay rate (k value). A three month rolling average of the H₂S monthly flow rate, from the 50 months of available data between October 2004 and October 2008, was used to account for any month to month variability in LFG recovery such as may be encountered in LFG operations, difference in the number of days per month, etc.

For the Landfill H model, k value was set to 0.515, which was found from the trendline fit to the H₂S data, M_i was from sulfur input and S₀ was estimated by plotting the results of the model to actual H₂S recovery data. S₀ was refined through iterations of the model until the model had the best fit with the empirical data. A S₀ value of 2176 Ft³/ton (62 M³/Megagram) was estimated using this method. This fit was evaluated through a linear regression of the predicted H₂S generation (cubic feet H₂S per month) from the model versus actual H₂S recovery data (cubic feet H₂S per month, 3-month average) resulting in an R-squared of .892.

The S_0 value was then checked by solving for S_0 (using the same k value) by setting the total volume of H_2S estimated by the model equal to the total volume of H_2S represented by the actual H_2S flow data for all of the available data used for the model. The derived S_0 value using the volume approach was 2023 Ft^3/ton , approximately 7.5 percent lower than the best fit S_0 value.

Discussion – Landfill H

Although C&D fines materials in Landfill H were mono-filled, there was direct contact between MSW and some of the C&D fines material. In addition, the landfill was generally wet with elevated leachate levels in some areas of the waste and high infiltration rate of surface water caused by generally flat topography and landfill operations. Therefore, the moisture and organic materials content in the C&D disposal areas, available for both methane producing and sulfur reducing bacteria, was higher at Landfill H than in a typical C&D monofill landfill.

The acceptance of a significant portion of unprocessed C&D 'bulky' waste at the Landfill is also suspected to contribute to the overall generation of H_2S at the site, however C&D fines was clearly the cause of odors and elevated H_2S concentrations early on. Testing at individual gas wells in 2005 indicates that H_2S concentrations at the wells installed in C&D bulky waste areas which did not accept C&D fines materials were higher (typically 100-1000 ppmv) than H_2S concentrations at wells installed in MSW waste (< 100ppmv). However LFG flow rates from wells installed in C&D bulky waste areas were generally much lower. At wells installed in C&D waste areas which accepted C&D fines materials however, H_2S concentrations were consistently elevated, in some cases as high as 20,000 ppmv or more. LFG recovery from some of the well in C&D fines disposal areas also typically exhibited higher LFG flow rates than wells in bulky only C&D waste areas.

The 'spike' in H_2S recovery was observed during 2004 and 2005 which, subsequently declined through mid-2007, when it reached the current, generally stable H_2S concentrations at between 200 and 400 ppmv. Due to the presence and continued acceptance of C&D bulky waste the current trend of a 'baseline' H_2S concentration between 200 and 400 ppm is not attributed to C&D fines disposal and is expected to remain constant at the landfill.

Landfill I

Landfill I is an active, MSW Landfill located in New York. H_2S testing was conducted on a once or twice per a year basis for four out of the past five years. During the period which H_2S testing was conducted the LFG collection system in areas receiving C&D fines was for the most part comprehensive, well-managed and LFG recovery data was generally of high quality. C&D fines tonnage and source data is also available, with most of the C&D fines originating from a single processing facility located in NY. The quality and quantity of data available from this site made it a good candidate for initial analysis of H_2S data trends and development of a site specific H_2S model. Background information on Landfill I and the results of data analysis and subsequent model development, are outlined here.

Site Background

From 1962 through 1994 the landfill facility operated two, discrete landfill areas at the site. The two original unlined landfill areas did not utilize or receive C&D fines for disposal and are now closed and capped. Therefore, these two older landfill areas were not included in this study. A third, active landfill area (Landfill I) has been in operation since 1994 and consists of six double lined cells located on approximately 45 acres. Currently, 31 acres have been closed and capped with a plastic cap system. The remaining landfill areas are in various stages of filling with additional capping expected to be completed incrementally as filling progresses. Landfill I has approximately 2.5 million tons of waste in place, based on end of 2007 waste data.

Waste composition historically deposited in the landfill consists of waste categorized in records as MSW, sludge and bulky C&D waste (unprocessed). Approximately 80 percent of the waste received was MSW with between 0 and 40 percent of the waste each year (20 percent average) consisting of bulky C&D waste. The C&D waste component is assumed to be primarily construction debris and could contain gypsum wallboard or other high sulfate bearing waste (i.e. similar to typical MSW waste streams for the era). Only a small amount of the total waste received was classified as sludge.

C&D fines, along with auto fluff and ash were used as alternative daily cover (ADC). The C&D fines were used as ADC between 1997 and 2004, with peak C&D fines acceptance in 2003. Approximately 214,000 tons of C&D fines were accepted during the eight year period. The tonnage of C&D fines utilized as ADC was between 7 and 18 percent of the total annual waste deposited, with an average of 10-11 percent each year. Some C&D fines may have also been used as final grading and shaping materials during capping/ closure of areas during 2002, 2003 and 2004. Use of C&D fines as alternative daily cover was discontinued in 2004.

LFG Management and Historic H₂S Data

Prior to 2002, LFG management in the active landfill was accomplished via horizontal collectors and leachate system vents and one utility flare. In 2002, a portion of the landfill was capped and vertical extraction wells were installed within that cap area. A second utility flare was added in May 2003. Additional vertical extraction wells were installed in 2004 in the uncapped areas of the landfill. The LFG collection system was expanded in the active landfill area incrementally in phases in 2006 and 2008, with addition of collection system piping, horizontal collectors, leachate cleanouts and vertical wells as waste filling progressed. Additional temporary LFG flares were installed to supplement the existing permanent LFG flare at the facility in October 2003 and April 2004. Use of the temporary flare system was discontinued in mid-2006, due to declining LFG recovery rates.

The gas collection and flare system has been operated on a 24 hour per day, 7 day per week basis since 2002. Operation, monitoring and maintenance (OM&M) of the LFG collection and control system has been performed on a regular basis. LFG recovery flow rates at the flares were measured by permanent flow metering devices. LFG composition at the flares was measured with a portable LFG analyzer on a once per week basis (minimum). Flare device run times were documented. LFG recovery data for 2003, 2004, 2007 and 2008 were obtained from the average flow reading taken from instantaneous readings at all operating flare (up to three

at a time) between once and 20 times per month. LFG flow totalizer data was available for years 2005 and 2006.

The first hydrogen sulfide concentration data sampled at the LFG collection system was in August 2004, consisting of one analytical test sample. One analytical test sample was obtained in 2005 (March) and two in 2006 (March & August). No testing was performed in 2007. In 2008 four test events were performed. H₂S testing in 2008 included one analytical test and field test in March and supplemental testing, performed as part of this study in July, August and September, including one analytical test sample (September) and two field sample events (July & August). A summary of the number of H₂S sampling data points available for Landfill I is presented in Table I-1.

Table I-1. H₂S Sample Data for Landfill I

Year	Flare Inlet	
	Lab Analysis	Field Tests
2004	1	0
2005	1	0
2006	2	0
2007	0	0
2008	2	3

Hydrogen Sulfide Data Trends for Landfill I

For purposes of the model, the average of all the H₂S concentration monthly field test results was averaged with the lab result for the same month so that field data results and lab data results are weighted equally. For Landfill I, both field data and lab data were available for only one month (March 2008).

Sulfur Inputs and Outputs for Landfill I

Based on C&D fines and sulfate data, 3,100 tons of sulfur, from the 214,000 tons of C&D fines, was deposited as ADC over an eight-year period (1997 through 2004). An estimated 68,000 pounds of H₂S was collected during 8 months of available data between August 2004 and September 2008.

Landfill I Model

An exponential trendline (using MS excel) was fit to the volume of H₂S produced over time to estimate a decay rate (k value). A three month rolling average of the H₂S monthly flow rate was used to account for any month to month variability in recovery such as may be encountered in LFG operations, difference in the number of days per month, etc. For the Landfill I model, k value was set to 0.881, which was found from the trendline fit to the H₂S data. The actual H₂S data correlated to the exponential trendline with an R-squared of 0.97. M_i was from sulfur input and S₀ was estimated by plotting the results of the model to actual H₂S recovery data. S₀ was refined through iterations of the model until the model had the best fit with the empirical data. A S₀ value of 6430 Ft³/ton (182 M³/Megagram) was estimated using this method. This fit was evaluated through a linear regression of the predicted versus actual H₂S recovery data with an R-squared of 0.96. The S₀ value was then checked by solving for S₀ (using the same k value)

by setting the total volume of H₂S estimated by the model equal to the total volume of H₂S represented by the actual H₂S flow data for all of the available data used for the model (8 months of data). The derived S₀ value using the volume approach was 6282 Ft³/ton, approximately 3.3 percent lower than the best fit S₀ value.

Discussion – Landfill I

Landfill I exhibits the spike and then rapidly declining trends in H₂S concentrations and recovery observed at other Landfills which accepted large amounts of sulfate containing, C&D fines waste for use as ADC. The actual data trends correlate very well with the model projections as exhibited by high R-squared values. The model variables (i.e., model equation k and S₀ inputs) for landfill I are also similar to other MSW landfills in this study which used C&D fines materials as ADC. The principal uncertainty present in this Landfill's H₂S modeling results is the limited amount of H₂S concentration testing data available. However, the validity of this model results is reinforced by the similarities in model inputs derived, compared with the other, similar landfill cases examined in this study.

Landfill B

Landfill B is a Massachusetts landfill site that has conducted consistent (daily) H₂S testing of the LFG recovered since January 2006. This Landfill was different from the other landfill sites in the study since it was not an MSW landfill but a landfill closure project which used C&D fines and processing residuals extensively as shaping and grading materials. During the period which H₂S testing was conducted, the LFG collection system had system coverage throughout most areas where C&D fines material were disposed. The LFG collection system at the site was therefore generally well-managed and LFG recovery data was generally of high quality. C&D fines data, including annual tonnage and processing facility source data, was also available. The quality and quantity of data available from this site made it a good candidate for initial analysis of H₂S data trends and development of a site specific H₂S model. Background information on Landfill B and the results of data analysis and subsequent model development, are outlined here.

Site Background

Landfill B was a landfill closure project which consisted of using C&D fines, processing residuals and soils as shaping and grading materials to properly close an old municipal landfill site which had not been properly closed and capped. The original landfill site was a municipal landfill operated during the 1960s and 70s located within a wet (swampy) parcel, which is now in an urbanized area. The original landfill area is estimated to have approximately 1 million tons of solid waste in place, covering an area of approximately 40 acres. The closure project involved shaping and grading the existing landfill site with C&D residuals and soil materials and then permanently closing the landfill with a plastic cap and final cover system. The project had three stages of filling which involved bringing different sections of the original landfill site up to final design grades.

The first stage of the landfill project began to receive C&D fines and processing residuals in April of 2003. Between April 2003 and July 2004 the site received approximately 230,000 tons of C&D fines, residuals etc. In addition to C&D fines, the landfill also accepted approximately 110,000 tons of soil material (including contaminated soils) between April 2003 and July 2004.

Soils were used principally on side slope areas and as grading material prior to capping. Odor issues had already begun to occur at the end of 2003, initiating the installation of several gas wells, gas piping and a small portable blower flare system in March 2004. Capping of the first stage was completed in October 2004.

Filling in the second stage of the landfill project began in July of 2004. The second stage accepted approximately 400,000 tons of C&D fines materials and 300,000 tons soils materials between July 2004 and November 2005. The gas system had been expanded during that period with the addition of vertical and horizontal collectors installed in Stages 1 and 2 and the installation of a permanent utility flare system in September, 2005. The facility was forced to temporarily cease landfill activities in November 2005, largely due to concerns over odors caused by H₂S emissions. Between September 2005 and March 2006, the landfill increased LFG collection system coverage throughout the landfill by expanding the collection system, improving landfill cover and capping completed areas.

In February 2006, the Landfill resumed operations, however C&D fines materials were thereafter mixed with soils material by layering the materials in lifts during the fill process. The method consisted of a layer of C&D fines waste (5 to 10 feet) covered with approximately one half the volume by soils material. This resulted in an approximately 2:1 ratio of C&D fines to soils on a volumetric basis or approximately 1:1 ratio by weight.

Between February 2006 and December 2007, Landfill stages 2 and 3 accepted approximately 420,000 tons of C&D fines materials and 700,000 tons of soil materials. In addition, the landfill also accepted approximately 38,000 tons of short paper fiber and 39,000 tons of unprocessed C&D waste material. Over the four year period of operation, the landfill accepted approximately 1,050,000 tons of C&D fines and residuals.

Between 2006 and the end of 2007, the LFG system was expanded incrementally with a system of horizontal collectors and vertical wells. Horizontal collectors installed at lower elevations in 2005 and 2006 were eventually abandoned in place due to the very wet conditions present in the lower elevation of the landfill. Capping of landfill areas at final grades in stages 2 and 3 was completed in 2005, 2006, 2007 and 2008 with the largest area (20 acres) completed in 2007.

LFG Management and Historic H₂S Data

Control of odors, related to hydrogen sulfide emissions, was a driving force behind the expansions and operation of the LFG collection system. From October 2005 through present, the collection system coverage area has been comprehensive and LFG odors and emissions have generally been controlled, as evidenced by an extensive ambient air monitoring program. The gas collection and flare system has been operated on a 24 hour per day, 7 day per week basis since October, 2005. OM&M of the LFG collection and control system has been performed on a daily basis. LFG recovery flow rates at the flares were measured by permanent flow metering devices and LFG composition was measured with a portable LFG analyzer on a once per day basis, minimum.

However, despite intensive LFG management at the landfill, the historic trends observed in LFG recovery since January 2006, including methane concentrations and volumetric flow rates, are

not consistent. Typically, landfills with comprehensive, well managed LFG collection systems exhibit a consistent LFG recovery trend over time with some fluctuations in methane concentrations and volumetric flow rates from month to month but overall, remaining fairly stable over the course of a year. The LFG recovery trend for Landfill B however shows significant spikes and drops in recovery. It is noted that the decreases in recovery for some periods of months does not correlate with odor issues or other indications of poor LFG recovery. A summary of LFG flow total results for Landfill B is presented below in Figure B-1 (I).

The fluctuations in LFG recovery can be explained by a number of factors including:

- Operation of the system with high vacuum to control odors, which introduced air in the landfill prior to capping in mid-2007
- Wet conditions in the landfill, which may have submerged waste at lower elevations and affected performance of horizontal collectors
- Changes in operational strategy of the LFG collection system such as operating at high vacuum for periods and then reducing vacuum to decrease air infiltration
- Rapid pace of waste filling, LFG system expansions and capping which was ongoing during the last two years of operation
- Potential gaps or omissions in the recovery data provided

In order to analyze and model H₂S recovery trends, LFG recovery needs to be fairly consistent. Review of the landfill operational history and LFG recovery data indicates that there were two periods of time when LFG recovery was reliable and consistent: 1) between January 2006 and June 2006 and, 2) from April 2008 through March 2009 (most recent data available). Prior to January 2006 facility installed a new flare, expanded the LFG collection system and improved LFG system operations. In addition, the landfill was closed for a 3-month period with no new waste accepted. The LFG system was operated consistently until July of 2006 when impacts from ongoing fill operations and new expansions to the LFG system may have affected consistency of LFG recovery. Since April of 2008, the LFG system has been operated under post closure conditions with some improvements to LFG operation implemented in March. In addition, the landfill was no longer receiving C&D fines or residuals waste after December 2007 and expansions to the LFG collection system and the landfill cover system had been completed.

Hydrogen Sulfide Data Trends for Landfill B

The landfill conducted twice daily (week days) measurement of H₂S concentrations using field indicator tubes since January 2006. Measurements of H₂S were obtained consistently from the inlet of the blower/flare system. Therefore, H₂S testing data is representative of H₂S concentrations in LFG recovered from the landfill overall. Over 500 field test events were conducted per year over a three year period including in 2006, 2007, 2008 and the first quarter of 2009. Due to the quantity of field test data available, supplemental testing was not performed as part of this study. A summary of H₂S testing results (normalized to 50 percent methane) for Landfill B is presented in Figure B-1 (II). The H₂S concentration data was used with the LFG data available for the same months (normalized to 50 percent methane) in order to calculate the total flow of H₂S. Actual recovery of H₂S is presented in Figure B-1 (III) as cubic feet per month.

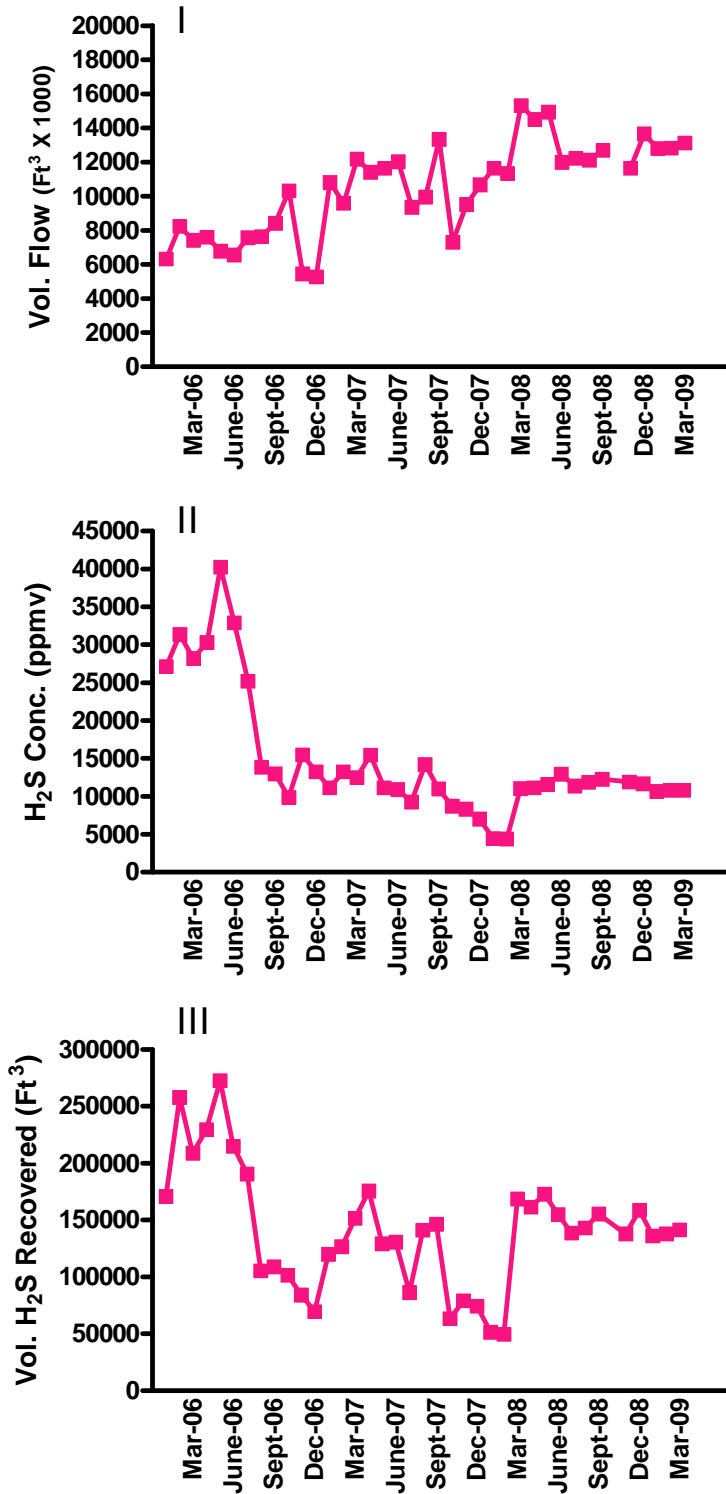


Figure B-1 (I-III). Landfill B - H₂S Model Projections Versus Actual Recovery

Sulfur Inputs and Outputs for Landfill B

Figure B-2 (I) presents the sulfur inputs and outputs for Landfill B, based on input of sulfur into the landfill from sulfate as C&D fines/residuals and output of H₂S from the landfill as LFG, in pounds per month.

Based on C&D fines and sulfate data, 11,415 tons of sulfur, from the 1,054,000 tons of C&D fines, was deposited between 2003 and 2007). Approximately 60 percent of the C&D fines/residuals received (634,636 tons) were deposited as monofill prior to 2006 and approximately 40 percent of the C&D fines/residuals received (419,613 tons) were deposited as soils/fines mix during 2006 and 2007. An estimated 470,000 pounds of H₂S was collected during the 39 months between January 2006 and March 2009.

Landfill B Model

Landfill B was modeled using two different approaches. The first approach (Case 1) was the same as for the other landfill models presented in this study. M_i was from sulfur input from all C&D fines received and S_0 was estimated by plotting the results of the model to actual H₂S recovery data. S_0 was refined through iterations of the model until the model had the best fit with the empirical data. To calibrate the model to S_0 , the same data period was utilized, January 2006 through June 2006 and April 2008 through March 2009 (19 months of data) with the derived k value input of 0.166. This approach (Case 1B) resulted in spurious results with a poor apparent match between the actual data and the model results. Similar spurious results were obtained by calibrating the model to S_0 using the entire data set (Case 1A), January 2006 through March 2009 (39 months of data) with a derived k value input of 0.101.

The second modeling approach (Case 2) utilized two different S_0 values: one S_0 for C&D fines waste which was deposited basically as monofill, prior to November 2005, and a second S_0 for C&D waste which was deposited mixed (layered) with soil materials at an approximately 1:1 ratio (by weight). The S_0 for C&D fines waste mixed with soils was set equal to 10 percent (10%) for the S_0 value for C&D fines waste which was monofilled. Reducing the H₂S producing potential (S_0), through mixing with soil has been demonstrated in previous studies in the laboratory. Melendez, 2008 showed an order of magnitude reduction in H₂S concentration when 2:1 and 3:1 soil:fines (by mass) mixtures were used. Similar to Case 1, Case 2 calibrated the model to S_0 , refined through iterations of the model until the model had the best fit with the empirical data.

Case 2 also was modeled to two data sets: Case 2B utilized the January 2006 through June 2006 and April 2008 through March 2009 data (17 months of data) with a k value input of 0.166 and Case 2A utilized the entire data set January 2006 through March 2009 (39 months of data) with a k value input of 0.101. The best results using this method of two S_0 values were obtained from Case 2B. A S_0 value of 4189 Ft³/ton (182 M³/Megagram) was estimated for monofilled C&D fines waste deposited prior to 2006 and 419 Ft³/ton was assumed for soils:fines mixed waste deposits post-2006. This fit was evaluated through a linear regression of the predicted versus actual H₂S recovery data with an R-squared of 0.97.

The S_0 value for Case 2B was then checked by solving for S_0 (using the same k value) by setting the total volume of H_2S estimated by the model equal to the total volume of H_2S represented by the actual H_2S flow data used for the model (17 months of data). The derived S_0 value using the volume approach was $2704 \text{ Ft}^3/\text{ton}$ ($270 \text{ Ft}^3/\text{ton}$ for soil:fines mix deposits after January 2006) which is significantly lower, (approximately 35 percent) than the best fit S_0 value using X-Y plot approach. Based on apparent fit of the model to this data set and the differences in S_0 between the two methods, the volume method was determined to be a closer fit and is the S_0 value presented in Figure B-2(III) below (i.e. 2704 & $270 \text{ Ft}^3/\text{ton}$). Figure B-2 (III) presents the model results for case 2B described above with default inputs plotted along with the actual H_2S recovery. Figure B-2(IV) presents a correlation between the model results and the actual recovery data plotted on X-Y axis. Modeling results for cases 1A, 1B and 2A are provided in Figures B-3(I-III) and B-4(I-IV).

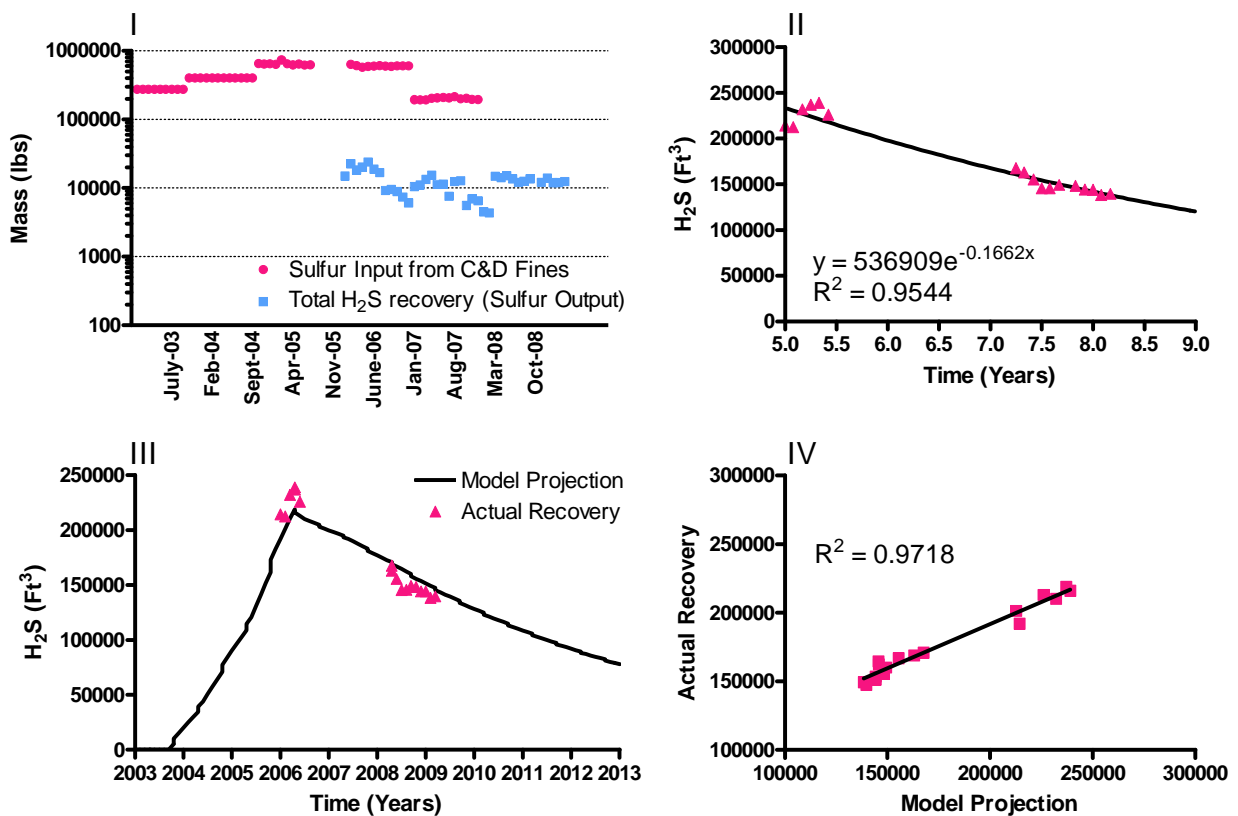


Figure B-2 (I-IV). Landfill B Sulfur Inputs/Outputs and Model Development/Results

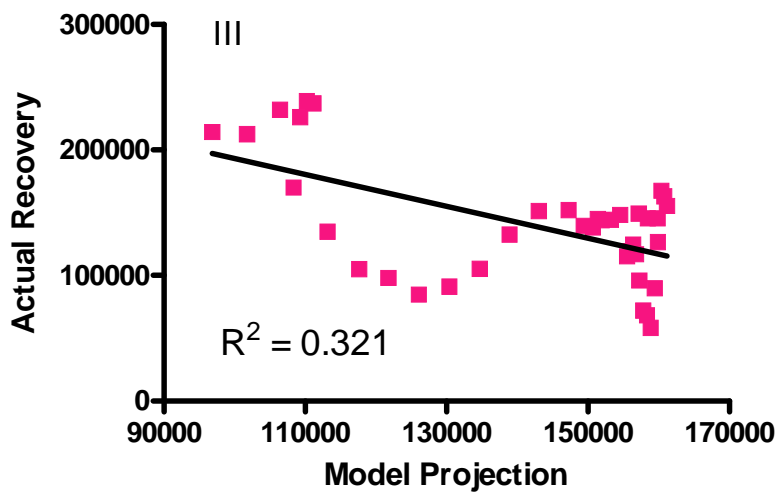
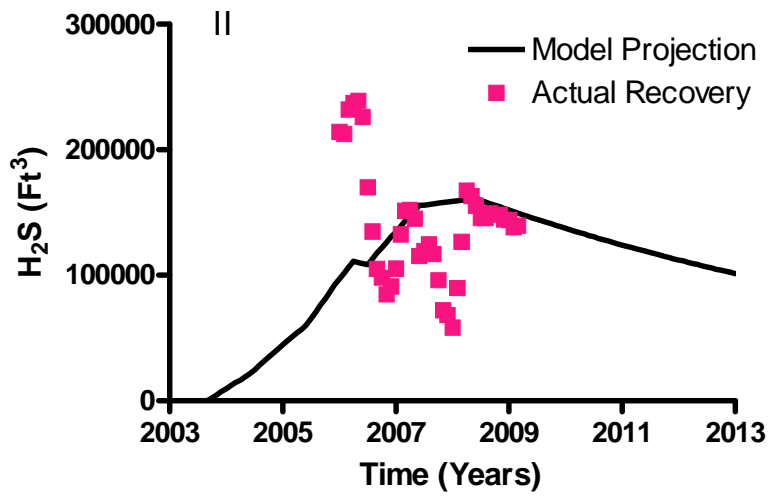
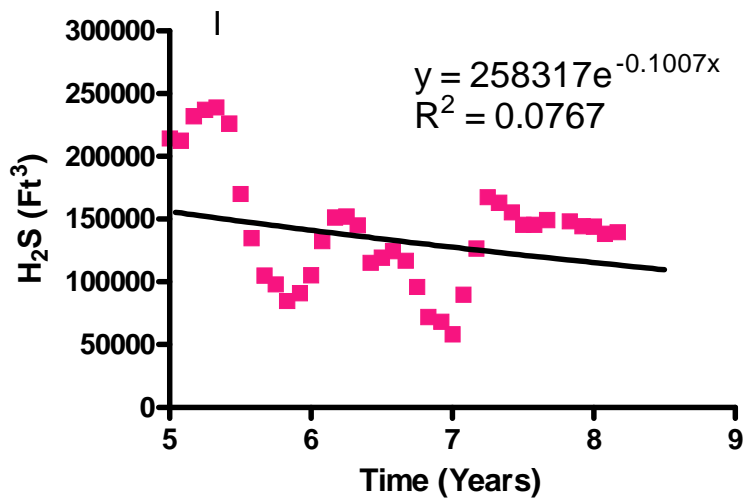


Figure B-3 (I-III). Landfill B – Case 1 H₂S Model Projections

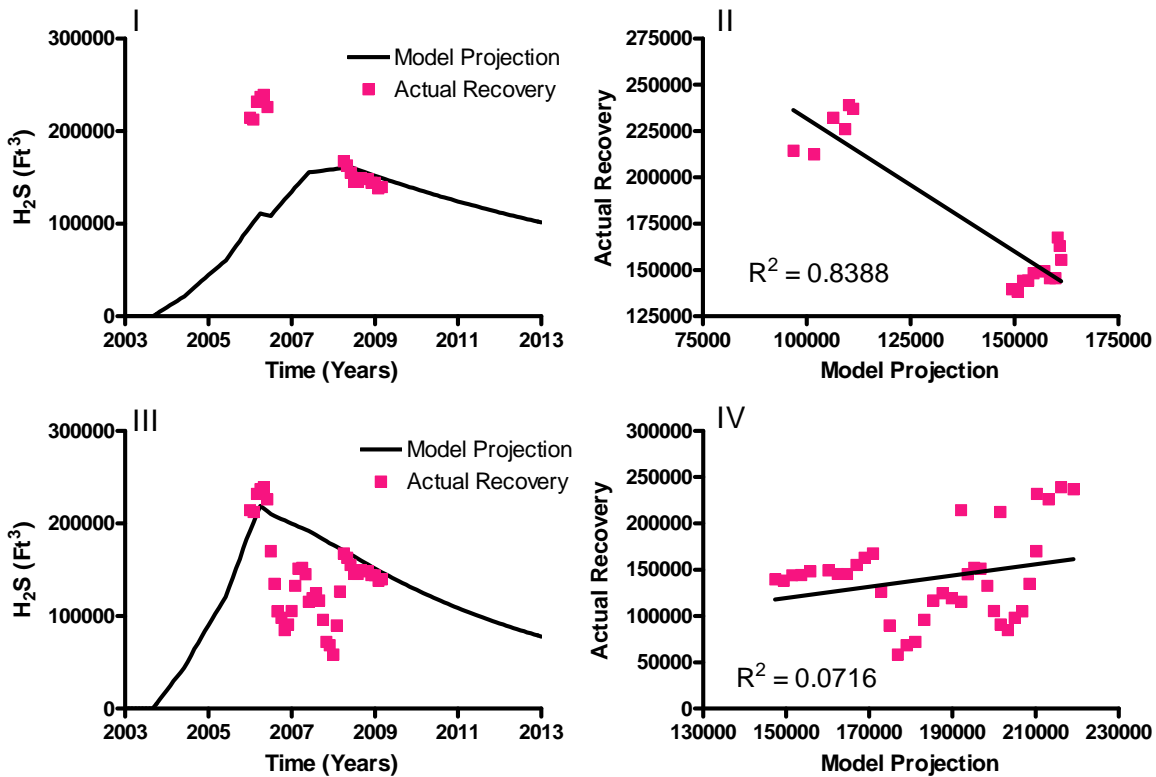


Figure B-4 (I-IV). Landfill B – Case 2 H₂S Model Projections

Discussion – Landfill B

Landfill B presents some important observations made during this study. Importantly, it provides an example of a different landfill type than the other landfills presented, where C&D fines are monofilled and not deposited with MSW or used as alternative daily cover. Although not fully conclusive, based on the model results for landfill B, the decay rate (k) and H₂S producing potential (S_0) appear to be lower than in the landfill cases where C&D fines are used in MSW landfills. Inconsistencies observed in the LFG recovery trends and significant differences in the derived S_0 values for modeling Case 2B require that additional evaluation be completed before definitive conclusions can be made regarding the dual S_0 modeling approach used for the mono-filled and mixed fill C&D fines waste in the landfill. Landfill B modeling also presents some evidence that the right kind of soils mixed with C&D fines/residuals in a non-MSW landfill may provide a significant reduction in the H₂S producing potential; this is supported by other studies completed (Melendez, 2008) and is recommended for additional analysis and study.

Landfill E

Landfill E is an active, MSW landfill located in Massachusetts. H₂S testing has been conducted on a monthly basis for the past two years and on a less frequent basis going back five years. During the period which H₂S testing was conducted, the LFG collection system has been comprehensive, well-managed and LFG recovery data is generally of high quality. C&D fines tonnage and source data is also available. This landfill also presents a somewhat different case than most of the other Landfills because the landfill has continued to accept and use C&D fines as alternative daily cover for the past 10 years without interruption.

The quality and quantity of data available from this site made it a good candidate for initial analysis of H₂S data trends and development of a site specific H₂S model. Background information on Landfill E and the results of data analysis and subsequent model development, are outlined here.

Site Background

Landfill E comprises a 152-acre parcel of land with approximately 70 acres used for solid waste disposal since 1995, receiving approximately 120,000 tons of waste per year on average. The landfill is a lined facility developed in several phases and incorporates a bottom liner with leachate collection and a geomembrane cap in closed areas. The first phase, comprising a footprint of 20 acres commenced operations in 1995 and was partially filled prior to operations moving to the second phase area in 2002. The second phase, which consists of approximately 10 acres, was opened in 2002. The Landfill has received approximately 1.6 million tons of solid waste since opening in 1995 and has approximately 15 years of operating life remaining.

The waste stream has been composed of municipal solid waste and construction and demolition debris. The exact ratio of MSW to C&D bulky waste historically received by the landfill was not made available for this study but the waste stream is believed to consist of approximately 80 percent MSW on average. C&D fines have been accepted and used as alternative daily cover since opening in 1995 and, have been used consistently since that time except for one year (1999) when the site did not receive C&D fines materials.

Approximately 100,000 tons of C&D fines have been accepted at the landfill since 1995, with two processing sources identified. The tonnage of C&D fines utilized as ADC was between 2 and 15 percent of the total annual waste deposited, with an average of 5 percent each year. The peak usage of C&D fines as ADC was between 2000 and 2002 when approximately 55,000 tons of fines were received averaging 10 to 15 percent of the total waste received by the landfill. Since 2004 acceptance of C&D fines has been significantly reduced, with the tonnage of C&D fines utilized as ADC between 2 and 3 percent of the total annual waste deposited.

LFG Management and Historic H₂S Data

The Landfill was originally designed and permitted to incorporate only passive gas vents for LFG control. Odor issues began to develop at the site between 1998 and 2000, therefore an active LFG collection system was installed in 2000 to enhance LFG control. The LFG collection system consists of a network of vertical and horizontal wells, laterals and header pipes to extract the

LFG , and a utility blower/flare system to combust LFG. The facility currently utilizes an electrical generation plant which was commissioned in 2006.

The gas collection and flare system has been operated on a 24 hour per day, 7 day per week basis since 2000. OM&M of the LFG collection and control system has been performed on a regular basis. LFG recovery flow rates at the flare and electrical generation plant were measured by permanent flow metering devices. LFG composition at the flares was measured with a portable LFG analyzer on a once per week basis (minimum) prior to 2006. The electrical generation plant has utilized a continuous methane analyzer since 2006. LFG recovery data from the landfill was available back to 2001 including LFG flow rate and methane content.

The first hydrogen sulfide concentration data sampled at the LFG collection system was in March 2004, consisting of one analytical test sample. Additional field test sample data was available for several months in 2005 and 2006, and available consistently on a monthly basis for 2007 and 2008. One supplemental test event was performed as a part of this study in October 2008. A summary of the number of H₂S sampling data points available for Landfill E are presented in Table E-1.

Table E-1. H₂S Sample Data for Landfill E

Year	Lab Analysis	Field Tests
2004	1	0
2005	0	2
2006	0	6
2007	0	10
2008	1	8

Hydrogen Sulfide Data Trends for Landfill E

H₂S testing has historically been completed at either the inlet of the flare or at the main LFG collection system blowers at the inlet to the electrical generation plant, and is representative of average H₂S concentrations in the total recovered LFG. A summary of H₂S testing results (normalized to 50 percent methane) for Landfill E is presented in Figure E-1 (I). The H₂S concentration data available was used with the LFG data available for the same months (normalized to 50 percent methane) in order to calculate the total flow of H₂S. For purposes of the model, the average of all the H₂S concentration monthly field test results was averaged with the lab result for the same months so that field data results and lab data results are weighted equally. For Landfill E, both field data and lab data were available for only one month (October 2008). A three month rolling average of the H₂S monthly flow rate was used to account for any month to month variability in recovery such as may be encountered in LFG operations, difference in the number of days per month, etc. Total H₂S recovery in cubic feet per month is presented in Figure E-1 (IV).

The linear trend line indicates a fairly flat level (no change) in H₂S recovery rate for the period. LFG recovery from the landfill has a similar flat trend line, with fairly steady LFG recovery rates observed for the past 3 to 4 years.

Sulfur Inputs and Outputs for Landfill E

Figure E-1 (I) presents the sulfur inputs and outputs for Landfill E, based on mass of sulfur into the landfill from sulfate as C&D fines and mass of H₂S out of the landfill as LFG, in pounds per month. Based on C&D fines and sulfate data, 1,600 tons of sulfur, from the 100,000 tons of C&D fines, was deposited as ADC over a fourteen-year period (1995 through 2008). An estimated 15,600 pounds of H₂S was collected during 27 months of available data between March 2004 and October 2008.

Landfill E Model

An exponential trendline (using MS excel) could not be fit to the volume of H₂S produced over time because the data set had no clear decay trend (See figure E-2) and therefore a site specific decay rate (k value) could not be obtained. This is expected since the landfill has received C&D fines consistently and usage of fines during the past 5 years has been limited to a very small tonnage (2 to 3 percent) compared with total waste.

Therefore, for Landfill E, k value was set to 0.64, which was the average of the k values obtained for landfills A, C, D, H, G and I. M_i was from sulfur input and S_0 was estimated by plotting the results of the model to actual H₂S recovery data. S_0 was refined through iterations of the model until the model had the best fit with the empirical data. A S_0 value of 1150 Ft³/ton (33 M³/Megagram) was estimated using this method. The data set did not correlate well with the model and linear regression of the predicted versus actual H₂S recovery data produced a very low R-squared (< .1). Figure E-4 presents the model results using the above default inputs plotted along with the actual H₂S recovery.

Discussion – Landfill E

It was not possible to derive a reasonable predictive model for Landfill E for several reasons. The first reason is that the precision of testing low levels of H₂S using field indicator tubes is not adequate to draw meaningful data from concentration changes less than 100 ppmv from a LFG collection system. This is due to limitations of the test equipment and the affect of 'normal' fluctuations in H₂S concentration in the LFG which are expected to occur month to month or even day to day in an LFG recovery system. At sites with high concentrations (>1,000), small month to month fluctuations in H₂S concentration do not significantly impact the overall trends. However, at landfill E the average H₂S concentrations were observed between 100 and 200 ppmv which impacted the affect of 'normal' fluctuations and test method accuracy. Therefore, based on the test data available, H₂S recovery at landfill E is considered to be more or less steady (see linear trend line Figure E-1 (III)), currently neither increasing or decreasing at a quantifiable rate.

The second reason is that the landfill continues to receive C&D fines at a fairly steady, but low acceptance rate. Waste receipts at the landfill are also fairly consistent keeping the overall ratio of C&D fines to total waste very low (2 to 3 percent by weight). This is by design, as the landfill operators became aware of the impact of accepting too much C&D fines material early on and have moderated intake of the materials very carefully during the past 5 to 6 years. Therefore, although a model for H₂S could not be derived for this landfill based on the data, this landfill case provides an example of how acceptance and use of C&D fines materials can be effectively managed in order to limit H₂S generation to manageable levels.

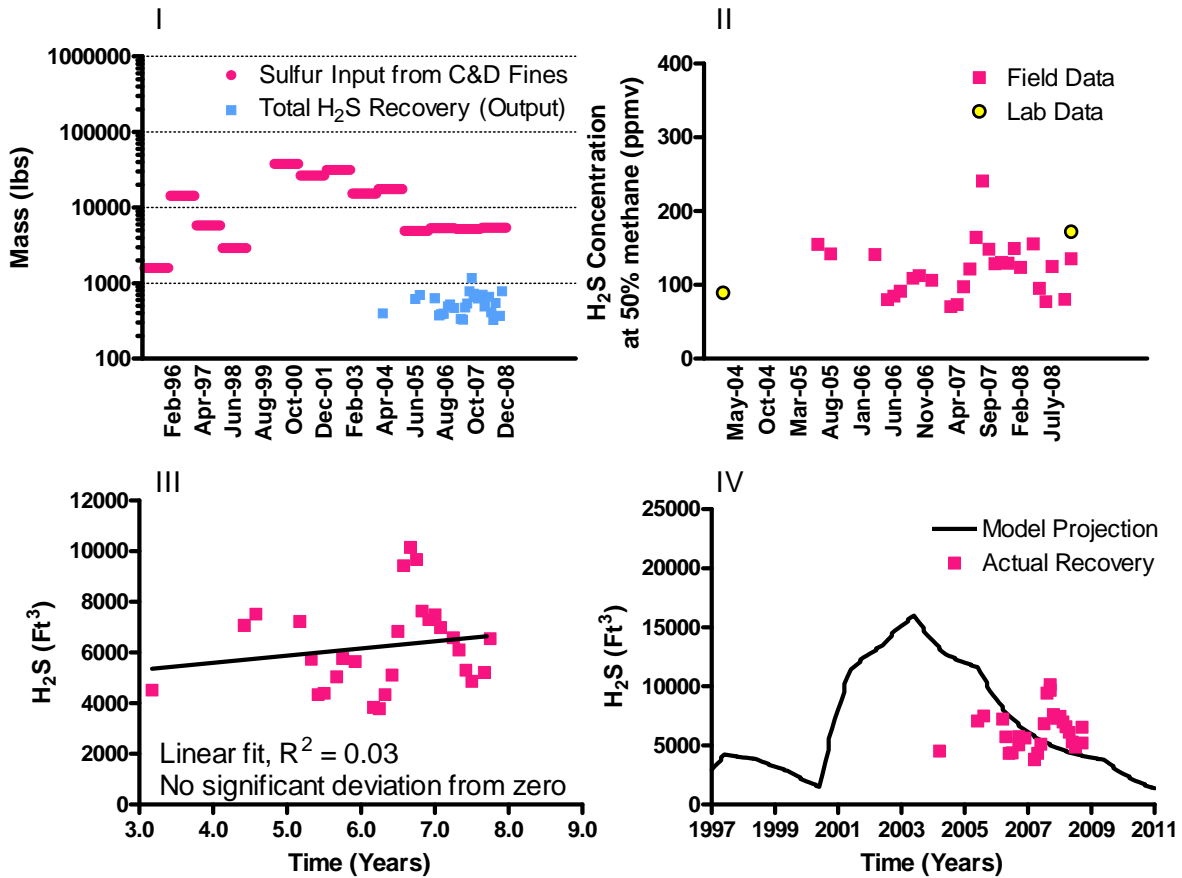


Figure E-1 (I-IV). Landfill E Model Development

Landfill F

Landfill F is a New Jersey landfill site that has conducted H₂S testing sporadically over a five-year period. H₂S testing has been conducted on a monthly basis for the past two years and on a less frequent basis going back five years. During the past two to three year period, the LFG collection system has been comprehensive, well-managed and LFG recovery data is generally of good quality. C&D fines tonnage was available (termed "Barrier material" by landfill staff) however source data was not available. The quality available from this site was believed to be

good, therefore it was selected as a candidate for initial analysis of H₂S data trends and development of a site specific H₂S model. Background information on Landfill F and the results of data analysis and subsequent model development, are outlined here.

Site Background

The landfill was originally permitted in 1992 to receive bulky, non processed C&D waste and dry industrial wastes. The original Landfill permit was for a 77-acre facility then consisting of 10 planned cells, utilizing a double-composite liner system. In 1998, the Landfill began to also receive MSW waste. The average waste composition since 2001 has been approximately 70 percent MSW and 30 percent C&D/bulky waste. The landfill currently accepts approximately 275,000 tons per year and has approximately 3.6 million tons of waste in place.

The landfill accepted a type of C&D fines/processing residuals referred to as “barrier material” for a twelve month period in 2003 and 2004. “Barrier material” was placed principally within two cells (Cells 6 and 7) and was believed to contain a particularly elevated content of gypsum materials (i.e., sulfate). Based on individual well readings taken in March 2008, the highest H₂S concentrations were generally observed in or near Cells 6 and 7. As such, the data suggests that the source of elevated H₂S concentrations in LFG is the barrier material in Cells 6 and 7. A total of 19,000 tons of the “Barrier material” was deposited in 2003 and 2004. This comprises approximately 1 to 4 percent of the total waste received by the landfill during those two years. According to the landfill, no other C&D fines material has been accepted since that time.

LFG Management and Historic H₂S Data

The LFG collection system was originally installed in 2004 and included 18 LFG wells, connecting piping, flare and blowers. This system became operational in mid-August 2004. In 2005, 11 additional wells were installed, 9 of which were new wells and 2 of which were "redrills" of previously installed wells. The "redrills" were connected to the existing piping network. Additional LFG collection system infrastructure was installed throughout Cells 3 through 8 during 2006 including 24 vertical wells and 3 horizontal collectors. There were significant gaps in the LFG system coverage throughout the landfill prior to 2007. The gaps in coverage were primarily in Cells 6, 7 and 8 where the bulk of C&D fines materials are believed to have been placed. Additional LFG collection system expansions have been completed in 2007 and 2008 as waste filling progressed.

The collected LFG is routed to the permanent blower/flare and energy recovery facility at the southwest corner of the landfill and a temporary blower/flare station located at the southeast corner of the landfill. The temporary flare has been operated intermittently since November 2007 as required for supplement LFG control. The gas collection and control system has been operated on a 24 hour per day, 7 day per week basis since commissioning in August 2004. OM&M of the LFG collection and control system has been performed on a regular basis. LFG recovery flow rates at both the flares and energy recovery station are measured by permanent flow metering devices. LFG composition at the flares was measured with a portable LFG analyzer. Flare device run times and total LFG flow rates were documented.

LFG recovery flow data from the landfill was available back to 2005 and methane content data was available back to January 2007. The first hydrogen sulfide concentration data sampled at the LFG collection system was in December 2005, consisting of one analytical test sample. Additional field test event and analytical test event was conducted in 2006. Five analytical test sample events were conducted in 2007 and 12 field test sample events were conducted in 2008 and 2009. One supplemental test event was performed as a part of this study in September 2008. A summary of the number of H₂S sampling data points available for Landfill F are presented in Table F-1.

Table F-1. H₂S Sample Data for Landfill F

Year	Lab Analysis	Field Tests
2005	1	0
2006	1	1
2007	5	0
2008	0	10
2009	1	2

Hydrogen Sulfide Data Trends for Landfill F

A summary of H₂S testing results (normalized to 50 percent methane) for Landfill F is presented in Figure F-1(I). Data collected prior to 2007 was determined to not be representative since LFG collection system coverage was incomplete in the areas where C&D fines waste had been deposited. The H₂S concentration data available for the periods with comprehensive coverage in place, was used with the LFG data available for the same months (normalized to 50 percent methane) in order to calculate the total flow of H₂S, presented either in pounds or cubic feet. For purposes of the model, the field test results and the lab result were weighted equally to provide a larger data set.

Sulfur Inputs and Outputs for Landfill F

Figure F-1(II) presents the sulfur inputs and outputs for Landfill F, based on mass of sulfur into the landfill from sulfate as C&D fines and mass of H₂S out of the landfill as LFG, in pounds per month. LFG recovery and H₂S test data available from prior to 2007 was not utilized. Based on C&D fines and sulfate data, 270 tons of sulfur, from the 19,000 tons of C&D fines, was deposited as ADC over a twelve-month period (2003 and 2004). An estimated 136,000 pounds of H₂S was collected during 17 months of available data between July 2007 and February 2009.

Landfill F Model

An exponential trendline (using MS excel) was fit to the volume of H₂S produced over time to estimate a decay rate (k value) (Figure F-1 (III)) using the data available between July 2007 and February 2009. A three month rolling average of the H₂S monthly flow rate was used to account for any month to month variability in recovery such as may be encountered in LFG operations, difference in the number of days per month, etc.

For the Landfill F model, k value was set to 0.236, which was found from the trendline fit to the H₂S data. The correlation of the actual H₂S data to the exponential trendline was found to be marginal, with an R-squared of 0.47. M_i was from sulfur input and S₀ was estimated by plotting the results of the model to actual H₂S recovery data. S₀ was refined through iterations of the model until the model had the best fit with the empirical data. To calibrate the model to S₀, the same data period was used (from July 2007 through February 2009).

A S₀ value of approximately 39,660 Ft³/ton (1224 M³/Megagram) was estimated using this method. This fit was evaluated through a linear regression of the predicted versus actual H₂S recovery data with an R-squared of 0.52. The S₀ value was also checked by solving for S₀ (using the same k value) by setting the total volume of H₂S estimated by the model equal to the total volume of H₂S represented by the actual H₂S flow data for all of the available data used for the model (17 months of data). The derived S₀ value using the volume approach was 39,685 Ft³/ton, approximately 0.1 percent higher than the best fit S₀ value. Figure F-1 (IV) presents the model results using the above default inputs plotted along with the actual H₂S recovery. Figure F-1 (V) presents a correlation between the model results and the actual recovery data plotted on X-Y axis.

Discussion – Landfill F

The derived S₀ value for the landfill model is an order of magnitude higher than that derived for the other landfill cases in this study. It is likely that a large amount of sulfate containing waste was deposited in the landfill and not accounted for. The results of the modeling performed for this landfill study site exemplifies the importance of having accurate fines tons and sulfate concentration data in order to make meaningful estimates of H₂S generation.

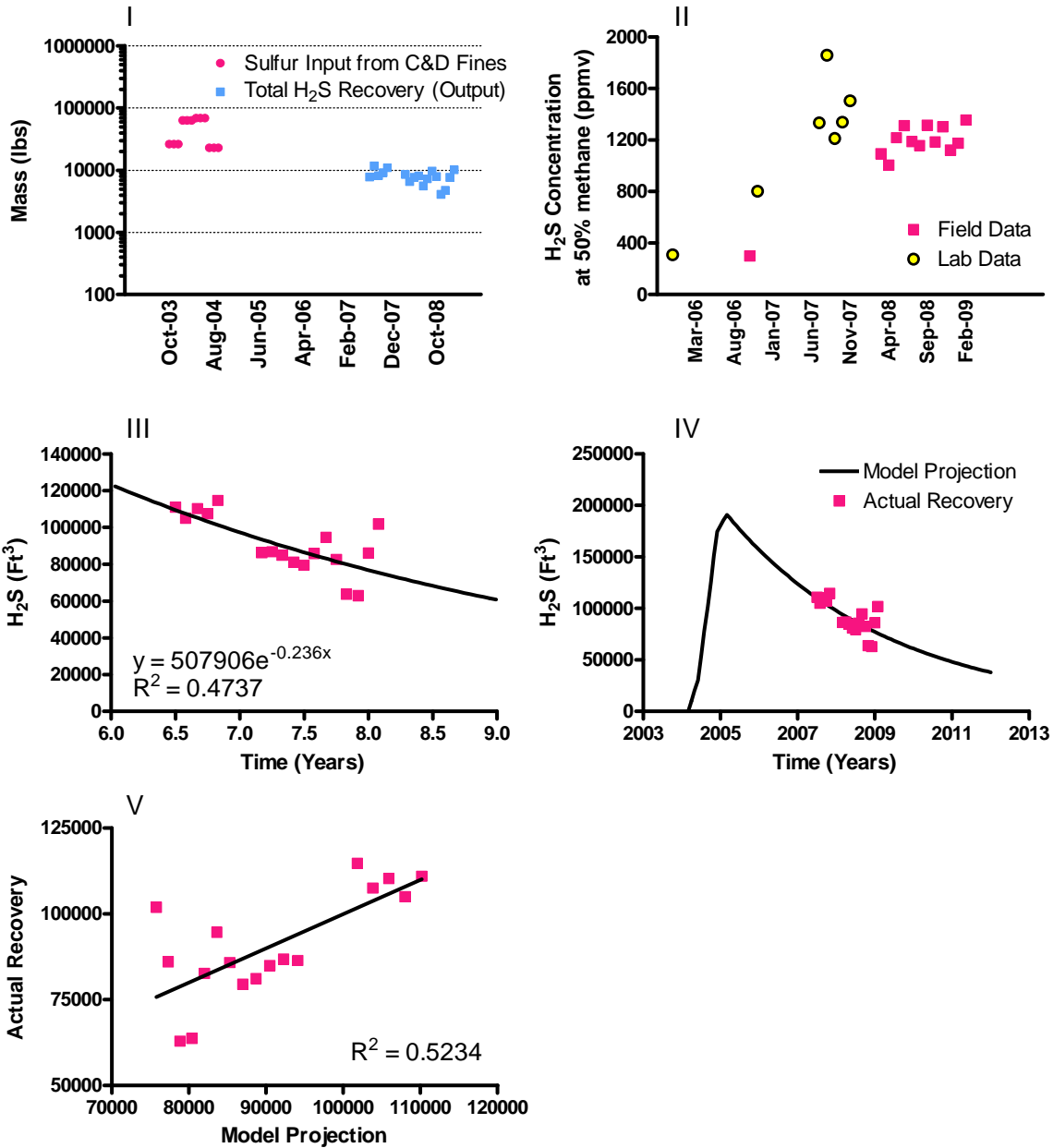


Figure F-5 (I-V). Landfill F Model Development

APPENDIX B – Other Project Deliverables

Anderson, R., Jambeck, J., McCarron, G. (2009), "Modeling of Hydrogen Sulfide Generation from Processed Construction and Demolition Materials in Landfills," SWANA Landfill Gas Symposium, Atlanta, GA.