ANALYSIS OF CHANGES IN LANDFILL GAS OUTPUT AND THE ECONOMIC POTENTIAL FOR DEVELOPMENT OF A LANDFILL GAS CONTROL PROTOTYPE

A Thesis
by
DAVID JUSTIN HARRILL

Submitted to the Graduate School
Appalachian State University
in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE

May 2014
Department of Technology and Environmental Design

ANALYSIS OF CHANGES IN LANDFILL GAS OUTPUT AND THE ECONOMIC POTENTIAL FOR DEVELOPMENT OF A LANDFILL GAS CONTROL PROTOTYPE

A Thesis
by
DAVID JUSTIN HARRILL
May 2014

APPROVED BY:

Ok-Youn Yu
Chairperson, Thesis Committee

Brian W. Raichle
Member, Thesis Committee

Jeffrey E. Ramsdell
Member, Thesis Committee

Marie C. Hoepfl
Member, Thesis Committee

Jeff S. Tiller
Chairperson, Department of Technology and Environmental Design

Edelma D. Huntley
Dean, Cratis Williams Graduate School

Abstract

Analysis of Changes in Landfill Gas Output and the Economic Potential for Development of a Landfill Gas Control Prototype

David Justin Harrill
B.S., Electrical Engineering, University of Iowa
M.B.A., Governors State University

Chairperson: Ok-Youn Yu

The demand for methane gas extracted from landfill gases as a renewable energy source is significantly increasing throughout the world. As a result, the scientific and engineering communities are attempting to improve landfill operations in a way that will maximize the electrical generation produced. The amount of methane gas that is collected from a landfill is dependent on various factors including the types of waste contained in the landfill, the system used to collect the landfill gases, and the real time atmospheric conditions. The equipment selected to convert the methane gas to useful electrical power is dependent on the amount and quality of the methane gas that can be collected from the landfill.

The relationship between changes in local atmospheric conditions and the performance of the landfill gas collection system installed at the Rockingham County (NC) municipal solid waste landfill was studied. This work consisted of a statistical analysis of the relationship between atmospheric pressure and two critical landfill gas extraction performance metrics: total landfill gas flow and methane gas (percentage) in the collected landfill gases.

An economic and energy analysis on the operation of a theoretical landfill gas-to-energy (LFGE) facility control prototype was performed to show the possible economic benefits of such a system. This study examined the wellhead variability at the Watauga County, North Carolina landfill using data collected twice a month from August 2007 to October 2013.

Results show some trends with atmospheric conditions, mainly ambient air temperature and performance metrics studied. Also, the theoretical landfill control device shows strong potential for wellhead control and shows benefits with regards to the energy and economics of the landfill performance.

Acknowledgments

I would like to express the deepest appreciation to my committee chair, Professor Ok-Youn Yu, who has shown the attitude and the substance of a genius: he continually and persuasively conveyed a spirit of adventure in regard to research and scholarship, and an excitement in regard to teaching. Without his supervision and constant help this thesis would not have been possible.

I would like to thank my committee members, Professor Brian W. Raichle, Professor Jeffrey E. Ramsdell, and Professor Marie C. Hoepfl, whose work demonstrated to me that concern for global affairs supported by an "engagement" in modern technology should always transcend academia and provide a quest for our times.

I am also grateful to Jason W. Hoyle, Research Analyst, from the Appalachian Energy Center for all of his assistance and help throughout this work.

I would also like to thank the operating and support personnel at the Rockingham County (NC) and Watauga County (NC) municipal solid waste landfills for their support.

Dedication

I dedicate my thesis work to my family and many friends.

I have a special feeling of gratitude to my loving parents, Mike and Helen Harrill, whose words of encouragement and push for tenacity ring in my ears as I write.

My sister Jessica deserves recognition as she has never left my side and is very special and supportive in her own way.

I dedicate this work and give special thanks to my friend Greg Bricker for being there for me throughout the entire master's program.

I dedicate and give thanks to Andrew and Dana Halper for always being there and being able to make me smile when I needed it the most.

Table of Contents

CHAPTER 1
INTRODUCTION

People throughout the world create waste products as they carry out their daily activities. In the United States one person creates, on average, 4.38 pounds of waste per day (United States Environmental Protection Agency [USEPA], 2014). Two hundred fifty-one million tons of waste were created and disposed of in landfills in 2013 (USEPA, 2014). Modern landfills are designed and constructed to safely store wastes for long periods of time. However, landfill wastes can be used as a source of energy to produce electrical power. Municipal solid wastes that are placed in landfills naturally decompose. As the organic materials within this solid waste decompose in the absence of oxygen, several gases are created in the landfill. Landfill gas is a mixture of carbon dioxide, methane, and other trace components, generated from bacterial decomposition of organics. Methane is the second most common source of greenhouse gases, about 9% of the total. Landfills contribute 17% of greenhouse emissions (USEPA, 2013b). Methane is also a combustible gas that can be used as a fuel source; this can be used directly to generate heat or to fuel a combustion engine to power a generator that produces electricity and thermal energy. Currently in the United States there are 621 operational projects generating 1,978 megawatts (MW) of electrical power by landfill gas to energy (LFGE) systems (USEPA, 2013a). With the potential of 850 megawatts of electrical power in 450 candidate landfills across the country, this energy source has some room to grow (USEPA, 2013a).

The relationship between changes in the local atmospheric conditions and the performance of the landfill gas collection system installed at the municipal solid waste landfill in Rockingham County, North Carolina was studied. This work consisted of a statistical analysis of the relationship between the atmospheric pressure and two critical landfill gas extraction performance metrics at this landfill: total landfill gas flow and methane gas (percentage) in the collected landfill gases.

In addition, an economic and energy analysis on the operation of a theoretical LFGE facility flow control prototype was performed to show the possible economic benefits based on wellhead variability at the municipal landfill in Watauga County, North Carolina. This analysis used data collected twice a month from August 2007 to October 2013.

Statement of the Problem

With the potential of generating approximately 850 megawatts using methane recovered from 450 candidate landfills, LFGE is an underutilized renewable energy source in the United States (USEPA, 2013a). Developing new technologies and/or improving existing operations will improve the economics for smaller LFGE systems. The objective of this work was to use data gathered from currently operating small LFGE facilities to determine the following:

- The relationship or correlation between measured LFG performance metrics and local atmospheric conditions at the Rockingham County (NC) landfill.
- The potential economic benefit of the Rockingham County (NC) landfill including the sale of carbon credits.

- Variability in measured wellhead LFG performance metrics at the Watauga County (NC) landfill.
- The potential effects of installing a wellhead control system on the electrical production capacity of these landfills.
- The effect on revenue generation of a proposed wellhead LFG flow control system.

The results of this work can be introduced to the LFGE community and used as a basis for further LFGE research and to influence the design of LFG collection and control systems.

Purpose of the Study

The purpose of this study was to address four key areas that may affect the operation of LFGE facilities. The first objective of this study was to examine the relationship between changes in the atmospheric conditions and the performance of the landfill gas collection system installed at the Rockingham County (NC) municipal solid waste landfill. Specifically, this examination focused on the relationship between local atmospheric pressure and two key LFG collection performance metrics: total landfill gas flow collected and methane gas (percentage) in the collected landfill gases.

The second objective was to determine the variability of measured wellhead LFG operating characteristics at the Watauga County (NC) landfill. This analysis examined the range and averages of important LFG variables collected at each wellhead at the Watauga County (NC) landfill from August 2007 to December 2013. These data formed the basis for a discussion about the potential impact of including a wellhead gas flow rate control system on the landfill’s wellheads.

The third objective of this work was to calculate the economic and energy benefits of a theoretical wellhead LFG flow control device at the Rockingham County landfill. The fourth and last objective of this study was to use the information obtained from the first three objectives to discuss the implications and limitations of the design, construction, and operation of a landfill wellhead control system.

Research Questions

To be able to successfully accomplish the goals of this study the following questions had to be addressed:

1. What is the correlation between atmospheric conditions (temperature and barometric pressure) and the measured LFG production (including total flow and methane percentage) from the landfill at the Rockingham County, North Carolina landfill?
2. What is the temporal variability output (total LFG flow and methane percentage) from individual well heads at the Watauga County, North Carolina landfill?
3. If flow rate from individual well heads was controlled to optimize methane content and flow, what effect could this theoretically have on energy conversion from a LFGE system?
4. What are the economic implications of carrying out this type of control for optimization in a LFGE system?
5. What are the implications of these findings for design of a landfill gas control system? In other words, based on the research and development carried out to date at the Watauga County landfill and based on the economic analysis of the

Rockingham County landfill data, what lessons have been learned that could enhance development of a landfill gas control and monitoring system?

Limitations of the Study

The main limitation of this research study focuses on LFGE operating data being used for the analysis. The data that was used for this study was collected by others (Rockingham landfill by Rockingham County, Watauga landfill by Eric McGee, and the weather data by National Oceanic and Atmospheric Administration) meaning that the data cannot be verified for accuracy.

Significance of the Study

The results of this study can be used to inform future development of wellhead control systems that might enhance the recovery of energy from landfills.

This research is significant because it provides needed information on LFGE gas flow control and may stimulate future research and development in this area, resulting in potentially improved economics at smaller landfill sites and an increase in the number of LFGE projects.

CHAPTER 2
REVIEW OF LITERATURE

The Production of Landfill Gas

Background

All people create waste products as they carry out their daily activities. The wastes produced are in many forms, such as biological and by-product waste, and much of this waste is disposed of in landfills. Modern landfills are designed and constructed to safely store wastes for long periods of time. However, landfill wastes can also be used to create a renewable source of energy. Municipal solid wastes that are placed in landfills naturally decompose. As the biological solid wastes decompose several gases are created, including carbon dioxide, methane, and other trace components, generated from bacterial decomposition of organics. Methane is a combustible gas (a renewable energy source) that can be used as a fuel source for a combustion engine to power a generator that produces electricity to power consumer devices or manufacturing processes. By applying current technology, a LFGE system can be constructed and operated to reduce the existing demands on other types of energy. A LFGE system is an economical and easy to operate energy system. In addition, LFGE operations can be constructed and operated at any major landfill. Depending on the size of the landfill an LFGE operation can convert methane gas to energy at a rate of 150 kilowatts or more (Rajaram, Siddiqui, & Khan, 2012).

Landfill Gas Creation

The first step of an LFGE system is to understand the chemical process that takes place in the landfill to create the combustible gas. There are three major processes that form landfill gases.

Bacterial decomposition. During this process organic waste is broken down and goes through four phases of decomposition. The bacterial decomposition process creates the majority of the gases that are generated in the landfill. During the first phase of decomposition, the aerobic bacteria (i.e., need oxygen to live) begin to absorb the oxygen that remains inside the landfill after the landfill has been capped. During this phase the chemical reactions create large amounts of carbon dioxide gas. The first phase continues until all of the oxygen in the landfill is consumed by the aerobic bacteria. Once all of the oxygen is utilized the first phase ends and phase two begins. Phase two is the point in the bacterial decomposition process where the anaerobic bacteria begin to function. During this phase the anaerobic bacteria start to break down the compounds into acids (lactic, formic, etc.) and alcohols (methanol and ethanol.) The acids then begin to mix with moisture in the landfill, causing nutrients to dissolve and in turn creating nitrogen and phosphorus. The gaseous by-products of this process are carbon dioxide and hydrogen. Phase three begins when other anaerobic bacteria start to consume the acids created in phase two, creating a more neutral environment in the landfill. This is when the methane-producing bacteria start to take over the landfill. After the methane-producing bacteria begin to dominate the landfill, the production of by-products becomes more stable and constant, allowing the fourth and final phase to initiate. Phase four decomposition begins and the collection of methane gas starts. The landfill gases can contain 45% to 60% of useable methane gas. Landfills will create usable methane gas for about 20 years, with some landfills creating usable methane gas for up to 50 years (Agency for Toxic Substances and Disease Registry [ATSDR], 2001).

Volatilization. This is the process during landfill gas production when organic wastes change form, from a liquid or solid into vapor. This is the process that creates most of the Non-Methane Organic Compounds (NMOCs) that are contained inside a landfill (ATSDR, 2001).

Chemical reactions. Some landfill gas, including some NMOCs, can be created by the chemical reactions that can take place inside the landfill. The wastes placed in the landfill contain chemicals. When these chemicals react with each other, the results may take the form of a landfill gas. If chemicals not normally found in landfills come into contact with other chemicals in the landfill they may react with each other and create potentially toxic by-products that are not commonly in landfill gas. This may mean certain safety precautions have to be implemented (ATSDR, 2001).

These three processes of decomposition produce the landfill gas mixture.

Common Components of Landfill Gas

This section discusses the most commonly occurring gases found in mature landfills.

Methane. The most common gas found inside a landfill is methane. Methane gas is the desired component because of its potential as an energy source. Methane gas is combustible and can be used to fuel an engine-generator to produce electrical power. Methane gas makes up 45% - 60% of the landfill gas. Methane gas is colorless and odorless. Landfills are the largest generator of methane gas in the United States (ATSDR, 2001).

Carbon dioxide. Another naturally forming gas during the anaerobic process is carbon dioxide. Carbon dioxide makes up around 40% - 60% of the gas in a landfill. Carbon dioxide is also odorless, colorless, and acidic (ATSDR, 2001).

Smaller components of landfill gas. Methane and carbon dioxide gases make up the largest percentage of landfill gas, but there are other gases that make up smaller percentages of the landfill gas. The smaller components of landfill gas may include (ATSDR, 2001):

- Nitrogen - 2% - 5%
- Oxygen – 0.1% - 1 %
- Ammonia – 0.1% - 1 %
- NMOCs – 0.01% - 0.06 %
- Sulfides – 0% - 1%
- Hydrogen – 0% - 0.2 %
- Carbon Monoxide – 0% - 0.2 %

Non-methane organic compounds. NMOCs are compounds that contain carbon. These can occur naturally in the process of landfill gas creation, but might also be formed by synthetic chemical processes. Some of the most common NMOC that are found inside a landfill are benzene, carbonyl sulfide, and hexane (ATSDR, 2001).

Factors Affecting Gas Production

Some of the major factors that affect the production of landfill gas are the waste composition, moisture content, oxygen content, temperature, and age of waste in the landfill. Waste composition affects the components of the landfill gas. The more organic wastes in the landfill the more bacterial decomposition takes place. The more bacterial decomposition, the more methane and carbon dioxide gas are produced. If large amounts of chemicals are in the landfill, then more NMOC gases are produced (ATSDR, 2001).

A second factor affecting the amount of gas a landfill produced is the moisture content found in the landfill. When moisture is present, it aids in the bacterial decomposition. Higher moisture content in the landfill also increases the chances for chemical reactions that produce landfill gas (ATSDR, 2001).

Another factor affecting the gases produced by a landfill is the oxygen content in the landfill. The lower the oxygen content of the landfill the more methane gas can be collected. Methane gas can only be produced in the landfill in the absence of oxygen (ATSDR, 2001).

Also, the internal temperature of the landfill can affect the amount of landfill gas produced. Higher temperatures can increase bacterial decomposition, volatilization, and chemical reactions; all of these can increase the landfill gas produced by the landfill (ATSDR, 2001).

The last major factor affecting gas production is the age of the refuse. The newer the waste contained in the landfill, the more landfill gas will be produced. Landfills produce most of the landfill gases when the landfill has been operating for five to seven years (ATSDR, 2001).

Landfill Gas Movement

The natural movement of landfill gas is a very important consideration when designing a new LFGE system. Since methane gas is lighter than air, the methane gas tends to move towards voids in the landfill and then migrate upwards to the top of the landfill. When the upward flow can no longer take place, the landfill gas will generally move horizontally to fill other voids or find an exit from the landfill (such as through a wellhead.)

Other factors that can affect the movement of gas inside the landfill are diffusion, pressure, and permeability. Diffusion is the natural tendency of the landfill gas to move throughout the landfill in a manner that will create a uniform landfill gas concentration in the landfill. Pressure inside and outside the landfill can affect the movement of the gas inside the landfill. If there is a higher area of pressure in an area of the landfill and there is a dense waste area located in the natural flow path of the landfill gas, this higher pressure area can act as a plug and stop the natural movement of gas in the landfill. The natural flow of the landfill gas will be from the higher pressure area to the lower pressure. When the pressure of the entire landfill gets too high the landfill gas will try to move outside of the landfill into the ambient air – the lower pressure area. The last factor affecting the movement of landfill gas is permeability. Permeability is a measure of flow through the voids in the landfill. If there are large voids (holes) inside the landfill, the landfill gas will move towards those voids and create the uniform concentration of landfill gas throughout the landfill. Permeability can also affect the amount of landfill gas that can seep through the soil and into the ambient air (ATSDR, 2001).

Factors Affecting Gas Movement

Several factors can affect the movement of gas throughout the landfill.

Landfill cover type. The landfill cover type can change the movement of the landfill gas with respect to the ambient air and how the gas moves inside the landfill. If the landfill cover type is a permeable material, the landfill gas will migrate through the cover and escape the landfill (ATSDR, 2001).

Pathways. Man-made paths (drains, trenches, etc.) or natural pathways inside the landfill are the most common paths of gas flow inside the landfill (ATSDR, 2001). This can include constructed pathways, or wells, associated with wellhead systems designed to capture landfill gas for use.

Wind speed and direction. The velocity and direction of the wind can affect the flow of landfill gas. If the landfill is vented, the wind's movement will create a chimney effect and actually pull the landfill gas from the landfill (ATSDR, 2001).

Moisture. Wet soil conditions can act as a cover for the landfill and prevent the landfill gas from making its way to the top of the landfill (ATSDR, 2001).

Groundwater levels. Rising groundwater levels can affect the landfill gas movement in the landfill by forcing the landfill gas upward in the landfill (ATSDR, 2001).

Temperature. The gas movement is also dependent on the temperature. Higher temperatures can improve the movement of landfill gas in the landfill (ATSDR, 2001).

Pressure. The difference between the barometric pressure and the soil gas pressure can allow the gas to move in any direction within the landfill based on the difference between the two pressures (ATSDR, 2001).

Landfill Gas to Energy (LFGE) Systems

The process of creating a LFGE system starts with the landfill. The size of the landfill can range from the small, such as the one in Watauga County, to the very large. Using a LFGE system has several benefits. First, as mentioned earlier, using the methane gas from a landfill reduces the demand on other energy sources such as fossil fuels. Another major benefit is the positive impact on the environment. Methane gas is the second largest contributor to greenhouse gases (GHG) in the atmosphere. Methane gas has a negative impact on the environment because methane gas has a life span in the atmosphere of 12 years

(USEPA, 2013b). Landfills are a significant contributor of methane gas to the atmosphere because they contain municipal solid wastes (MSW) and MSW is one of the highest contributors to global methane emissions at 17 % of the total (USEPA, 2013b). Converting methane gas from landfill gas to electrical energy via combustion in an engine generator within a LFGE facility reduces the methane gas released to the environment, thus reducing GHG.

LFGE Construction

The following is a high level summary of how a LFGE system is constructed. A more detailed description of the major equipment pieces and design considerations will follow. First, the landfill needs to be enclosed or “capped” in some manner. “Capping” the landfill is required, by law, because there has to be a way to capture the methane gas as the MSW decomposes. Next, wellheads have to be constructed. The wellheads provide a way for the methane gas to flow through a pipeline to the LFGE plant. After this segment of the construction is complete, the “capped” landfill is now a self-filling, pressurized “tank” that has to be monitored just like any other tank under pressure. Some of the more critical operating parameters that have to be monitored are temperature, flow rates, pressure, and methane gas percentage. So, one of the last construction activities that has to be completed at the landfill is the installation of monitoring probes, which are usually installed in smaller monitoring wells distributed in a pattern outside the landfill’s cap (Rajaram et al., 2012).

LFGE Equipment

Several types of major equipment pieces are used in the construction of a LFGE facility.

Extraction wells. These wells are used as the extraction points for the landfill gas being collected. Extraction wells consist of slotted pipe that is surrounded by porous materials. The extraction wells are bored down into the waste below the landfill. Each wellhead usually has a vacuum adjustment at the top, which is used to monitor flow. Depending on the purpose of the extraction wells and the age of the landfill, the extraction wells can be positioned in a vertical or horizontal orientation. Following is a description of each type of well (Global Methane Initiative [GMI], 2012).

***Vertical wells*.** This type of well is generally placed in landfills that have stopped receiving waste. The major components of a vertical well are the pipe, backfill, bentonite plug, and the wellhead. The pipe is typically made up of either polyvinyl chloride (PVC) or high density polyethylene (HDPE). The type of pipe used can change from landfill to landfill and depends on the conditions inside the landfill and other factors. The plug is used to prevent the gas from infiltrating the surface. The placement of the wells throughout the landfill depends on numerous factors including waste depth, compaction of the waste, and the presence of the final cap (GMI, 2012).

Horizontal wells. These are most commonly used in landfills that are still collecting waste because they allow the landfill gas to be collected before the landfill is closed. Horizontal wells are placed in trenches that are embedded in the waste. A fabric is placed on top of the pipe to help prevent blockage. Most horizontal wells are spaced about 30 to 40 meters apart (GMI, 2012).

Wellhead components. Wellheads are found on most extraction wells and are usually at the surface to allow for maintenance and routine operations. Several of the components included on the wellhead are vacuum adjustment, monitoring ports, and the option to measure flow.

The vacuum adjustment gives the technician the ability to adjust the vacuum on each individual wellhead in the landfill. The monitoring ports are used by the technician to monitor gas specifics in each area of the landfill. Monitoring ports are also used to track operation data and help identify potential problems, such as leaks or broken pipes. The flow measurement option consists of either pitot tubes or orifice plates. Gas flow measurements can be used to monitor the total LFG flow and allow the technician to calculate other key performance indicators. There is also a removable cap on each wellhead that allows technicians to perform maintenance activities (GMI, 2012).

Lateral and header piping. These are the pipes that are used to transport the gas throughout the landfill to the collection system and towards either the flame tower or engine-generator. Lateral and header piping is typically designed for the maximum expected flow rate and are either placed above ground or below the surface, depending on the budget or size of the landfill (GMI, 2012).

Moisture management system. The moisture that is created during the decomposition process should be taken into consideration when designing and constructing a landfill system. The pipes should have a drainage system to allow moisture to drain to the lower points in the landfill. Here the moisture can be removed from the landfill. Another reason to consider the moisture content is due to the existence of the flare (flame tower). For the flare to work properly the landfill gas has to have very low moisture content. This is typically attained with the inclusion of a moisture separator. A moisture separator lowers the landfill gas flow rate to the flare, which allows moisture to drain out of the gas (GMI, 2012).

Blower. The blower provides the vacuum that is used to collect the gas and drive it towards the flare or the engine-generator. There are adjustments that can be made at the blower to allow the LFG flow rate to meet the operating requirements of the flare or the engine-generator. The blower location is also where the total LFG flow rate can be measured using a flow meter. A Landtec field analytical unit can also be used at this location to gather other vital information such as total methane percentage and other operational gas data. These data are very useful when entering into contracts to sell carbon credits (GMI, 2012).

Flare. Flares are used at the landfill to burn the excess or all of the landfill gas. There are two major types of flares that are commonly used on a landfill. Open flares can achieve up to 98% destruction efficiency, are smaller, and less costly. Enclosed flares can achieve up to 99% destruction efficiency, are larger, and have a major drawback of higher installation cost (GMI, 2012).

LFG utilization technologies. In addition to using an internal combustion engine-generator to combust the landfill gas and create electricity, there are many other technologies that can be used to convert the gas to another usable energy form (Rajaram et al., 2012). These include:

- Micro turbines
- Stirling Cycle Engines
- Steam Turbines
- Alternate Fuels
- Boilers
- Fuel Cells

LFGE Plant Construction

The most common facility constructed to use an LFGE's methane gas as a fuel is a plant that uses internal combustion (IC) engines to generate electrical power (Rajaram et al., 2012). One reason for this is that the gas mixture exiting the landfill will not always contain a very high percentage of methane, but this mixture is still volatile enough to be used as a fuel for IC engines (Kohn, 2011). The energy obtained from the consumed methane is then converted to electricity using a generator set (or “genset”). The major reason that IC engines are the favored conversion equipment is primarily due to IC engines’ low installation cost, low operating and maintenance costs, and because they need less methane to produce energy than many of the other devices (Hodge, 2010). The power produced is then used internally or sent to the electric grid where the owners are then compensated based upon power purchase contracts established with the local utilities or electrical coops.

LFGE systems can also utilize other types of operating plants to harness the power of the methane in landfills. These range from natural gas boilers to heat fluids for space heating to even using bottled methane gas as fuel for vehicles. To generate electrical power, in addition to IC engines other conversion machinery may be used such as large turbines or micro-turbines, depending on the user requirements.

Efficiency of LFGE Systems

The efficiency of an LFGE system depends on a combination of many different operating criteria. These range from the cover of the landfill, the contents inside, to the equipment used to generate power (Barlaz, 2009). Possible efficiency improvements range from flow rate control and energy recovery projects to ways to accelerate generation (Ritchie & McBean, 2011). These are just some of the improvements that can be controlled or monitored to allow the LFGE system to run more efficiently, thus making the business case for LFGE systems even stronger.

Prevalence of LFGE Systems

At this time there are LFGE systems operating all over the world. Although there are many LFGE systems operating in the United States, many more LFGE systems could be put in place to convert landfill gas energy to electricity. The expanded use of LFGE systems in the United States is a partial answer to the country's waste management and energy supply problems.

United States

Currently in the United States 2,700 MW are being generated by LFGE systems (Caterpillar, 2008). While the generated amount is relatively small when compared to other energy sources, the use of these LFGE systems has reduced the use of other energy sources, and proved to be beneficial to the environment and to the communities where LFGE systems were built. There are many landfills across the country that have the potential to be used for LFGE systems (USEPA, 2013a), and Waste Management has stated they want to increase their 115 systems to over 160 by the end of 2013 (Koch, 2010).

Some organizations in the United States do not support LFGE projects. Criticisms include a belief that using LFGE projects promotes not recycling and building up trash to be used for energy, when the better method is to recycle so that GHG can be prevented in the first place instead of using trash to generate electricity (Club, n.d.). Besides that, some do not consider LFGE to be a green source of green energy primarily due to the potential health impacts from burning the gas, the sustainability of operation, and the belief that LFGE promotes landfilling waste materials instead of recycling (Chen, 2003).

Around the World

The LFGE system technology is being used all over the world. There are many LFGE systems being constructed in Asia and Canada. Overall, the global contribution of LFGE systems is at least 9,000 MW and growing (Caterpillar, 2008). A program has been created by the USEPA called the Landfill Methane Outreach Program (LMOP) that is going across the globe promoting LFGE systems and designing projects (Ludwig, n.d.). Locations for new LFGE facilities can be identified using the information obtained by this initiative.

Other Countries

Some of the major LFGE challenges that are being discovered around the world are in developing countries. These challenges are primarily due to economic limitations of the developing country's power grid interconnection systems. Some of the other major hurdles that countries are addressing are their national policies regarding the use of this type of energy resource. The main problem is that the policies are too hard to follow in a manner that allows for successful project completion, or the policies just flat out discourage the construction of LFGE systems (Rajaram et al., 2012).

Landfill Gas Modeling

There are various types of models that are used to calculate the potential gas production from landfills. Gas models are used to calculate the long term gas production potential. They are also used in designing and building the landfill site, and determining how the energy is to be utilized.

LandGEM Model

This is the model that was utilized in this study. The LandGEM model is very useful and is one used by the LFG industry. This model was created by the United States EPA and provides an estimate of air emissions from a municipal solid waste landfill. The model is based on a first-order decomposition equation. This software allows a user to estimate emission over time using known landfill characteristics such as capacity, amount of waste in place, waste acceptance rate, and methane production rate.

There are two different equations that can be used to estimate the gas emissions. If the year-to-year waste acceptance rate, from opening date to closing or to present, is unknown, one equation is used. If the year-to-year acceptance rate is known, the other equation is used. The one drawback of using the LandGEM model is that software assumes one year between acceptances, while in reality as little as six months is needed for enough landfill gas to generate power (Rajaram et al., 2012).

CHAPTER 3
RESEARCH METHODOLOGY

In order to complete this body of work, four separate analyses were performed. The following sections describe the methodology used to complete each of the four analyses.

Relationship between LFG and Atmospheric Conditions Analysis

The Rockingham County data was collected in 20-minute intervals by Rockingham County employees using Landtec's FAU-TDL and Thermal Instruments model 9500 flow meters. The weather data was collected from nearby (6 miles) Shiloh airport from a National Oceanic and Atmospheric Administration (NOAA) website. Next, an analysis of the Rockingham County landfill and the weather data was conducted to determine if there was any correlation between atmospheric conditions and landfill gas production. The following actions were performed to complete the analysis:

1. **Clean the data** – The data were scrubbed by eliminating any incorrect data or data points that didn't have all variables.
2. **Determine the relationships to be examined** – The following relationships were studied:
    a. Atmospheric Pressure vs Methane Concentration
    b. Pressure vs Landfill Gas Flow
    c. Ambient Air Temperature vs Concentration
    d. Temperature vs Landfill Gas Flow

3. **Build datasets and analyze the data** – The following analyses were performed:
    1. Regression Analysis
    2. Time Shift Regressions
    3. Monthly Regressions
4. **Determine if there is a correlation among the parameters** – Next, the sample size for the statistical analysis was established. After running several scenarios, it was determined that a 95% confidence level with a 5% interval should be used for the analysis. The information was then studied to determine any correlations.

Wellhead LFG Variability Analysis

The second analysis determined the variability of LFG output between the individual wellheads at the Watauga County, North Carolina landfill based on bi-weekly gas flow and composition data collected by Eric McGee of McGee Environmental using a Gem 5000 meter. The following actions were performed to complete the analysis:

1. **Collect the data** – Electronic copies of Watauga County's wellhead field logs were obtained. The data sheets contained information about the wellheads and the header of the landfill. Metrics include methane concentration, oxygen concentration, carbon dioxide concentration, balance gas, and flow rates. The data was then manually put into Excel.
2. **Determine the variability of the parameters** – The change in methane flow between wellhead readings was calculated and displayed in graphical form. Also, the change in methane content between adjustments and before and after wellhead adjustments at the header were calculated and displayed in graphical form.

LFGE System Energy Analysis

The third analysis examined the potential LFGE system energy potential based on available gas in relation to the LFGE system parameters. This analysis included the following steps:

1. **Methane gas flow was calculated** by multiplying the total landfill gas flow in SCFM by the methane percentage for each 20-minute interval for the entire twelve month period.
2. The kW for each time interval was calculated by using the energy density value of 18.05, 1027 Btu per SCFM (American Gas Association [AGA], 2014) multiplied by 60 minutes per hour divided by 3412.14 (Rapid Tables, n.d.), multiplied by the methane gas flow, in SCFM.
3. The efficiency of the combustion engine generator set was then used to **calculate the generator's electrical output** in kW by multiplying the efficiency of the combustion engine generator set by the available electrical energy (kW.)
4. If the calculated **electrical output was greater** than the generator's rated output capacity, then it was determined that the excess gas would have to be consumed by using the blower flare to comply with USEPA-mandated methane emissions requirements. In addition, the gas collected during generator shutdowns (which occurs if the LFG methane concentration is below 40%) would also have to be sent to the blower flare (Packham, 2007).
5. Then **energy (kWh)** was calculated by multiplying each time interval by 1/3.
6. The energy (kWh) for each time interval was summed to find the **total energy (kWh) produced by the LFGE facility.**

Economic Analysis

The last analysis was the economic analysis. This analysis was performed using standard economic analysis equations: internal rate of return, net present value, and simple payback. The economic analysis was performed using the following steps:

1. Use total kWh that can be generated and the amount of kWh flared in the flame tower from the energy analysis to determine the revenue for the calculations.
2. Collect the following financial data for the project:
    a. Initial Cost of the Project – This includes all permitting and engineering expenditures.
    b. Installation Cost – This includes all equipment and construction expenditures.
    c. O&M Cost – This includes all normal operating and maintenance expenditures over the life of the facility.
    d. Salvage – Estimate of the salvage value of the equipment when the facility is retired.
    e. Power Costs – Price per kWh.
3. Calculate carbon credits using the guidelines provided by Climate Action Reserve documentation (Climate Action Reserve [CAR], 2011).
4. Create a cash flow diagram - Use 20 years for the life of the facility. Twenty years is the expected life of the combustion engine and generator that converts the gas to electricity.
5. Using standard economic analysis techniques and the cash flow diagram calculate the following:
    a. Internal Rate of Return (IRR)

    b. Net Present Value (NPV)
    c. Return on Investment (ROI)
6. Determine the number of scenarios to analyze.
7. Perform economic calculations on each scenario.
8. Based on results, determine the best scenario to implement.

CHAPTER 4
RESEARCH FINDINGS

There are four separate types of findings for this study and the following sections review the results of the analyses:

- Atmospheric Conditions
- Wellhead Variability
- LFGE System Energy
- Economics

Atmospheric Conditions

Atmospheric data was collected at the Rockingham County landfill in North Carolina. Data was collected for 12 months beginning in July 2012 and ending in June 2013.
Review of the atmospheric data indicated that the data contained extraneous information not pertinent to this work. Formatting of the data was also required to allow for the analysis to be completed using Excel. After the data set was scrubbed to remove the invalid data and to standardize the formatting, the analysis of the data was initiated. First, the methane gas flow was calculated by multiplying the total gas flow by the percentage of methane gas found in the total gas flow. This calculation yielded the amount of methane gas that is available for consumption. These results were then used with the NOAA weather data to perform the calculations (using Excel spreadsheets) resulting in the following charts.

Weather Characteristics

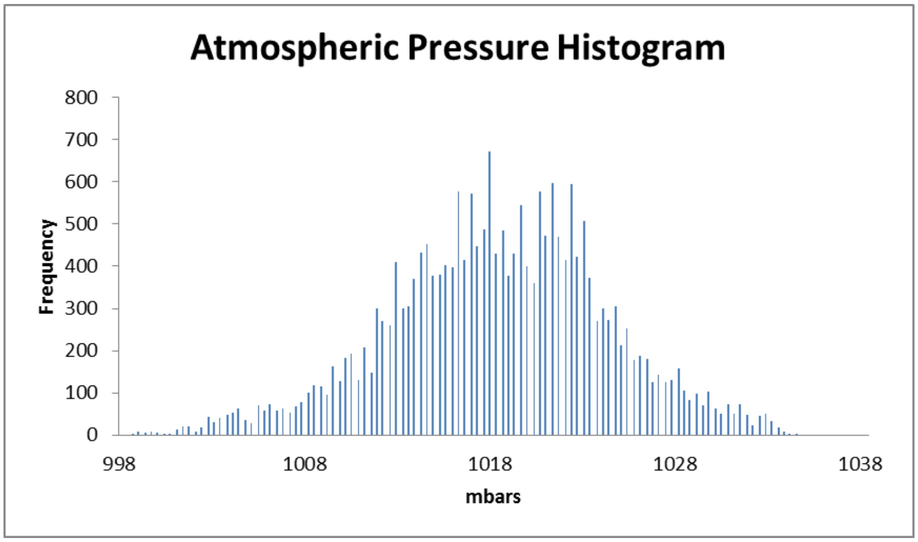


Figure 1. Atmospheric pressure histogram.

The pressure histogram shown in Figure 1 displays the number of occurrences for each atmospheric pressure reading. The counting bins were established for every 0.1 mbars, thus ensuring that the data would yield an accurate distribution. The most frequently used bin was at 1018 mbars with almost 700 occurrences at this pressure. The range of the pressure occurrences is from 998 mbars to 1038 mbars.

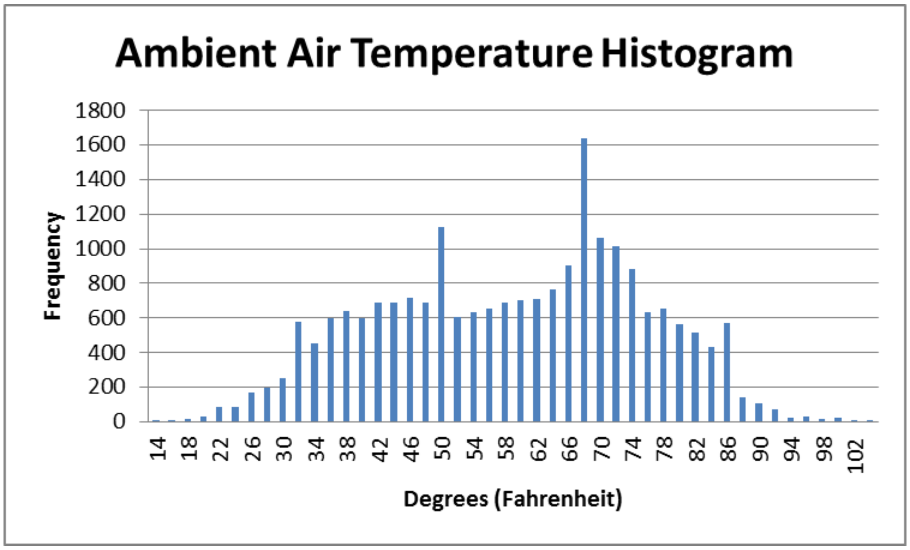


*Figure 2***.** Ambient air temperature histogram.

The temperature histogram (Figure 2) was created with bin sizes of two degrees Fahrenheit. Most of the temperature readings taken were in the 20 degrees Fahrenheit to 85 degrees Fahrenheit range. However, there were a significant number of outliers below 20 degrees Fahrenheit and above 85 degrees Fahrenheit. The maximum temperature reading was 103 degrees Fahrenheit. The lowest temperature reading was 14 degrees Fahrenheit. The most frequent temperature reading was 70 degrees Fahrenheit.

Gas Characteristics

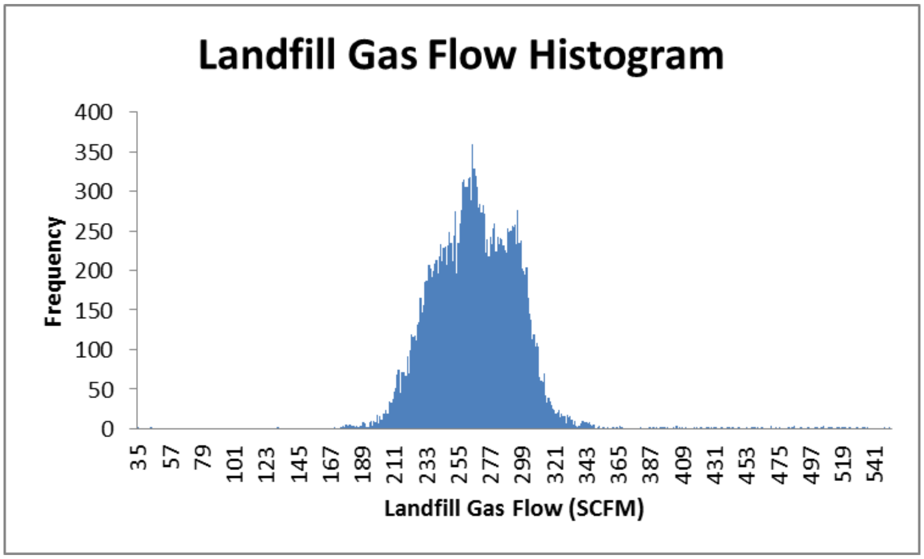


*Figure 3***.** Landfill gas flow histogram.

The landfill gas flow histogram (Figure 3) displays the frequency of flow readings taken at the landfill. The histogram was created using bin sizes of 1 SCFM. The flow readings range from 35 SCFM to 541 SCFM. There were a significant number of flow readings in the 196 SCFM to 334 SCFM range. The most common reading was 260 SCFM with almost 400 readings taken during the 12 month period.

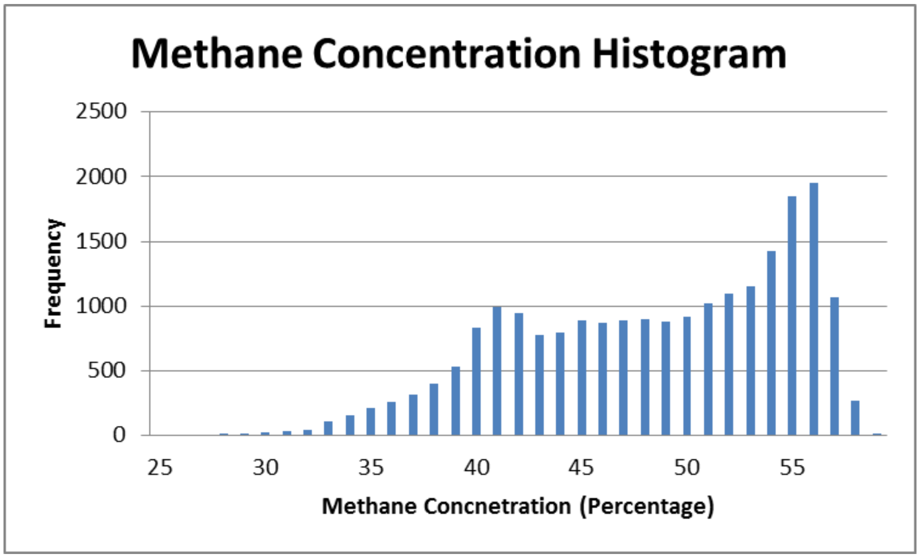


*Figure 4***.** Methane concentration histogram.

The histogram for methane gas percentage (Figure 4) was created by using bin sizes of 1%. The histogram shows the methane gas percentage ranges from 25% methane to 59% methane. The histogram also shows that the most frequent methane gas percentage reading is around 57% methane gas with almost 2000 readings.

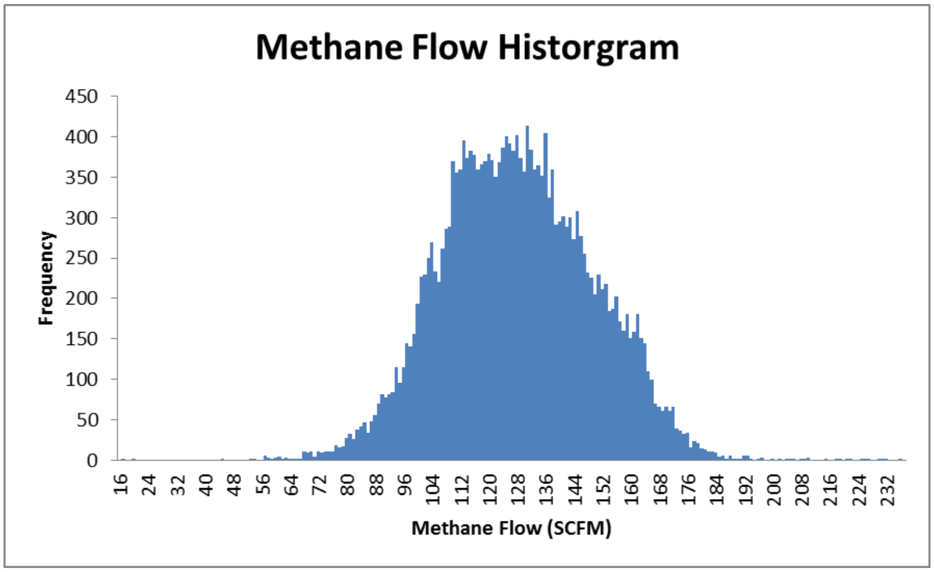


*Figure 5***.** Methane flow histogram.

The methane gas flow histogram (Figure 5) was created using bin sizes of 1 SCFM and shows that the range is from 72 SCFM to 184 SCFM. The most frequent reading takes place at 126 SCFM with around 400 readings.

Time Characteristics

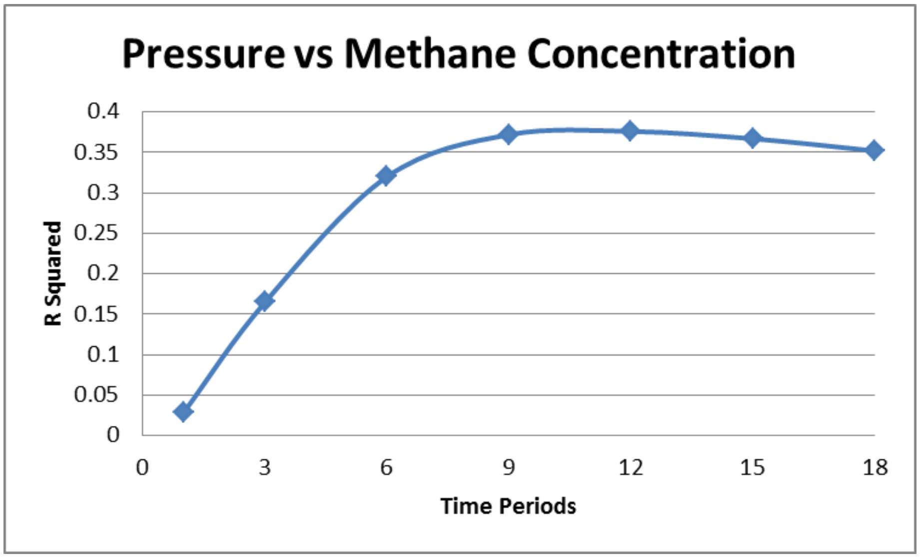


*Figure 6***.** Changes in pressure vs changes in concentration.

Figure 6 shows the change in pressure versus the change in methane concentration over certain time lengths. The R-squared values between the parameters steadily rise until it peaks at nine time periods (3 hours, time interval nine minus time interval one throughout the whole data set) and starts to drop off again.

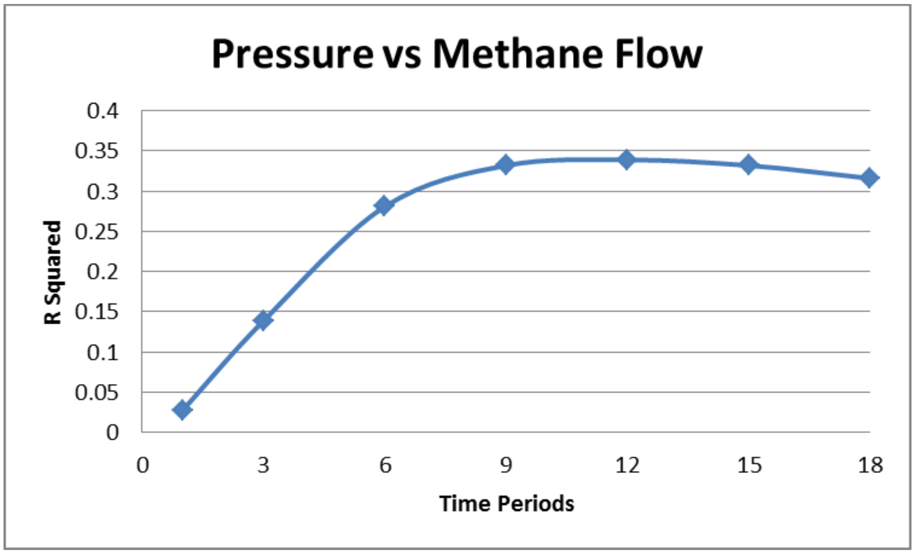


*Figure 7***.** Changes in pressure vs changes in methane flow.

Changes in pressure versus the changes in methane flow over time periods is shown in Figure 7. Similarly with Figure 6 it shows that the R-squared values peak at nine time periods (3 hours) and drop back down afterwards.

Monthly Trend Plots

Next, the data were analyzed to determine if there was any seasonality. Displayed in Figure 8 are two of the twelve months that were analyzed. They show the monthly trend line plots for each of the compared metrics.

August 2012.

August and September were used to display the following graphs due to the fact they are the better looking months from the 12 months data that is used in this analysis. Two months were used to to compare the trends.

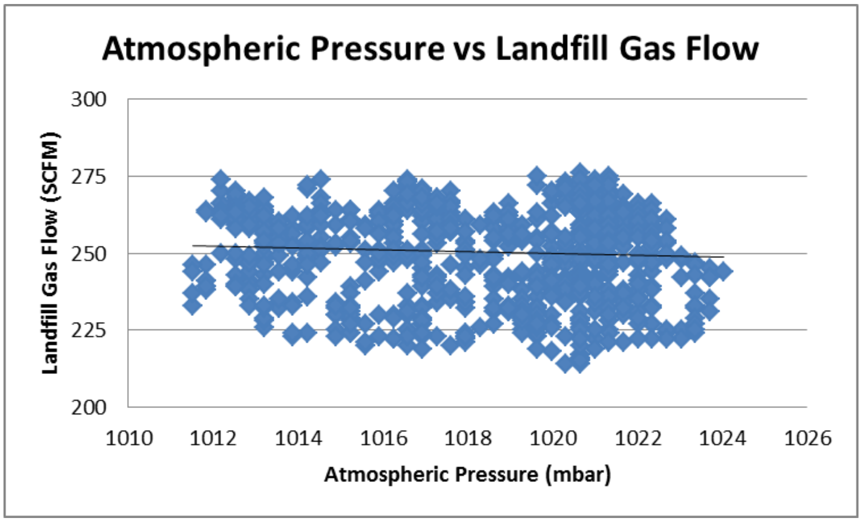


*Figure 8***.** Atmospheric pressure vs landfill gas flow.

Figure 8 shows the atmospheric pressure plotted versus the total gas flow of the system. It shows a very slight negative trend line that has an R-squared value of 0.0045. The analysis shows a trend between the two variables, but the R-squared shows that the trend is not very strong.

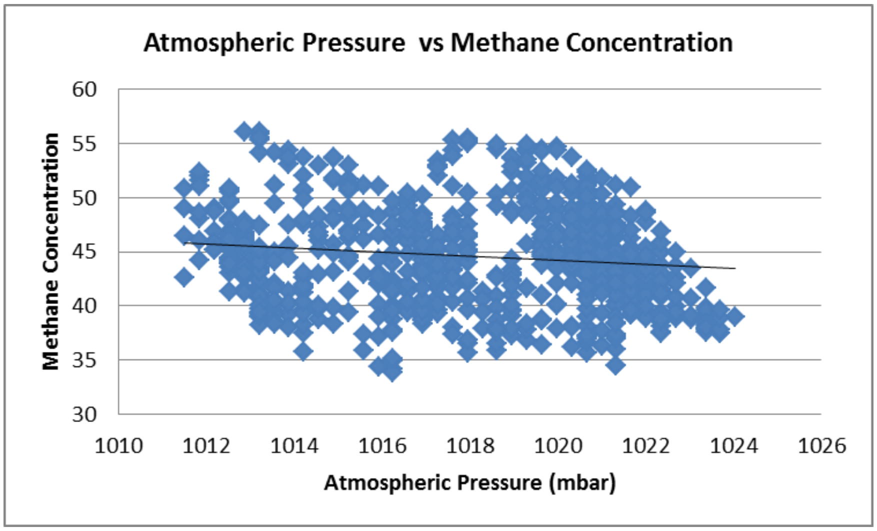


*Figure 9***.** Atmospheric pressure vs methane concentration.

Atmospheric pressure and methane concentration show a similar negative trend with a very low R-squared value of 0.0201. The trend is shown to have a weak negative relationship (Figure 9).

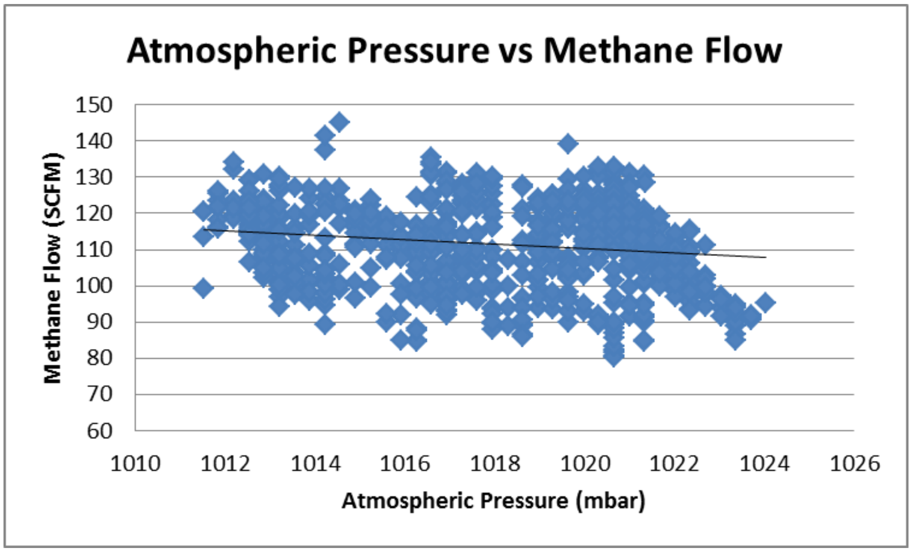


*Figure 10***.** Atmospheric pressure vs methane flow.

The last metric looked at was atmospheric pressure in relation to methane flow (Figure 10). The analysis shows a similar negative trend and a low R-squared of 0.0304. The negative trend and a low R-squared show a trend that is not very strong, like the rest of the atmospheric pressure trends.

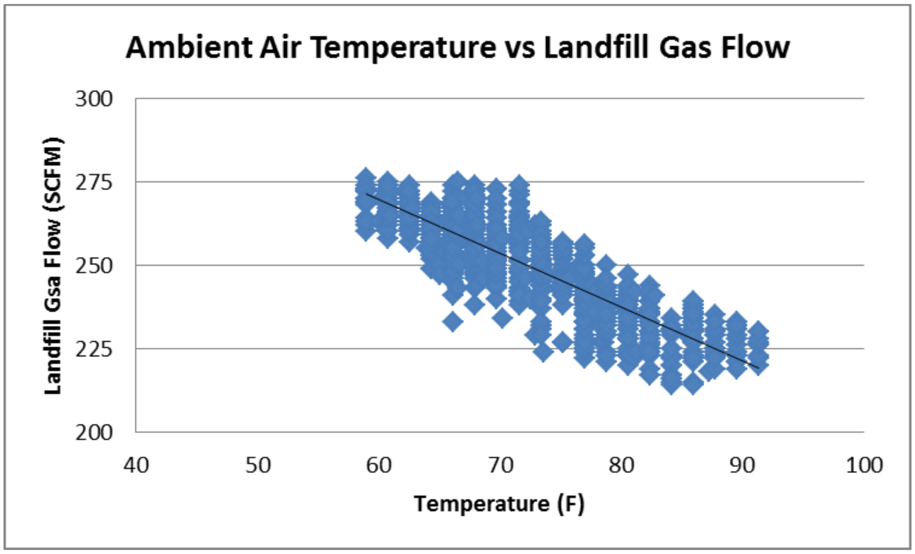


Figure 11. Ambient air temperature vs landfill gas flow.

Ambient temperature in relation to total gas flow, as displayed in Figure 11, showed a strong negative trend and an R-squared of 0.7581.

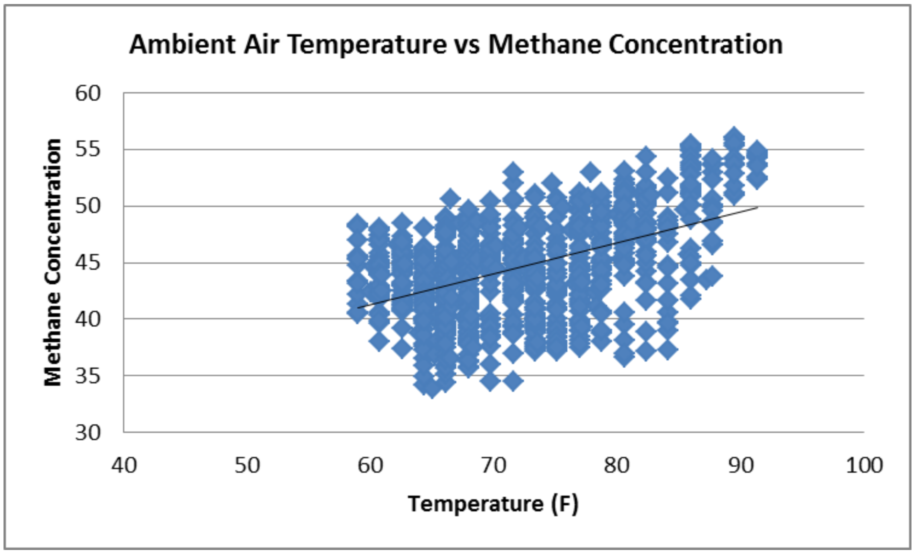


Figure 12. Ambient air temperature vs methane concentration.

The trend for the variables of ambient temperature and methane concentration showed a moderate positive trend with an R-squared value of 0.2474 (Figure 12).

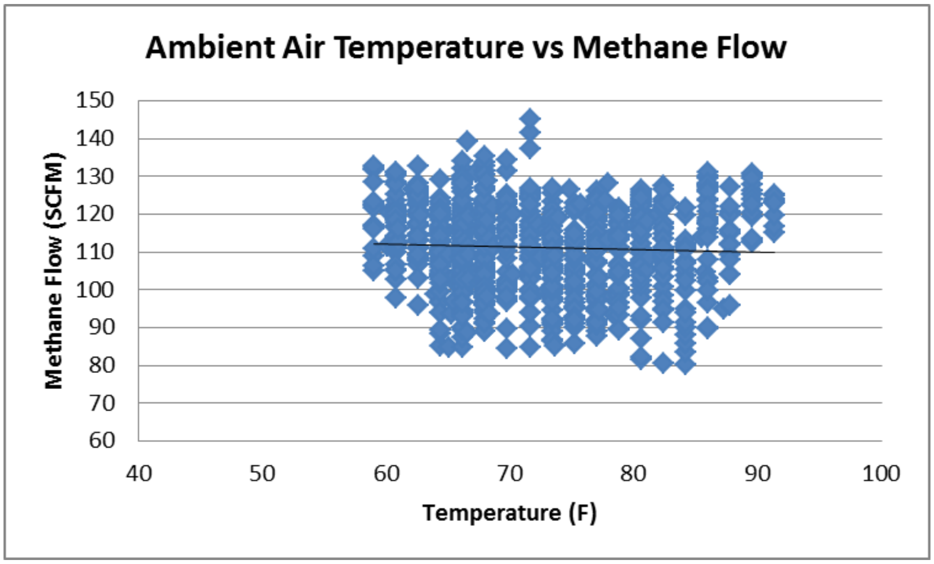


Figure 13. Ambient air temperature vs methane flow.

Ambient temperature and methane flow seems to have no relationship, with an R-squared value of 0.0022 (Figure 13).

September 2012.

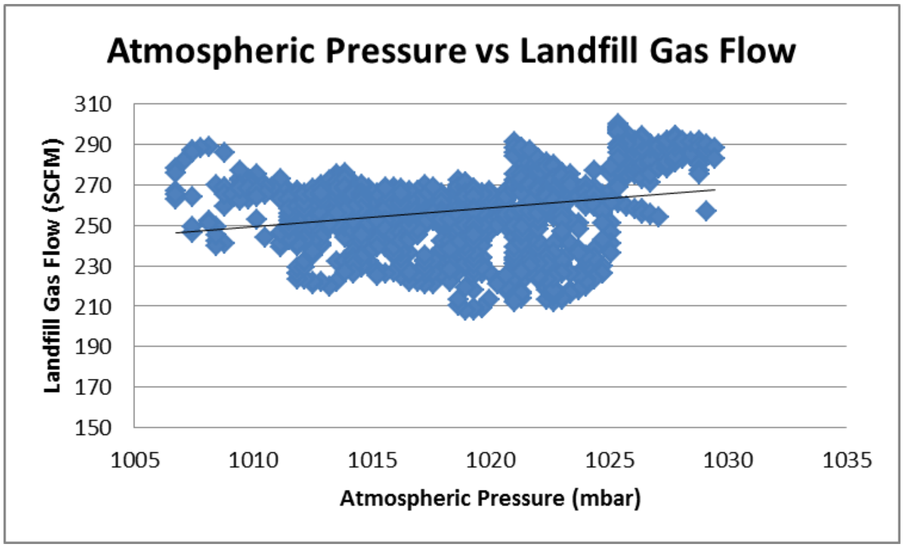


Figure 14. Atmospheric pressure vs total gas flow.

Atmospheric pressure and gas flow for the month of September, 2012 showed a slight positive trend compared to the previous month (Figure 14). It had a weak strength with an R-squared value of 0.0615.

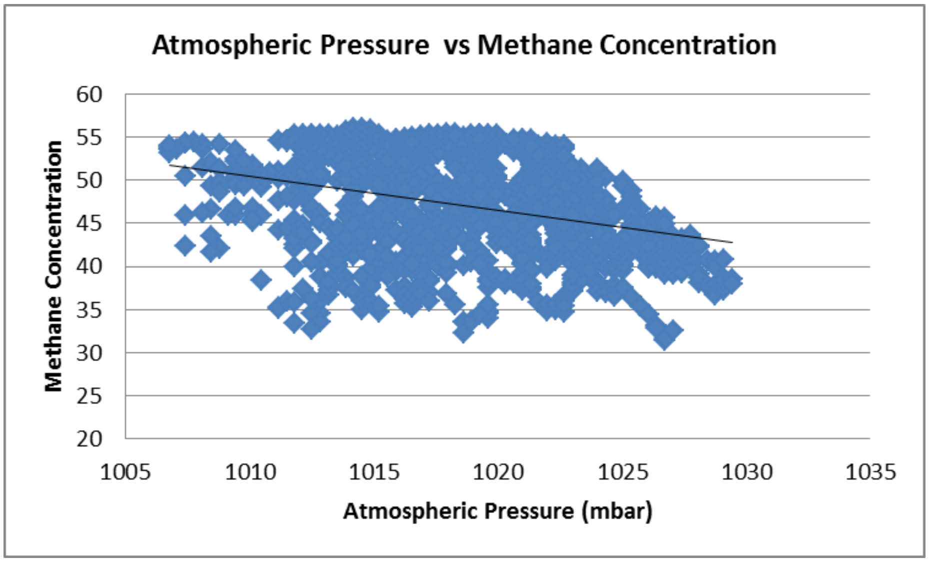


*Figure 15***.** Atmospheric pressure vs methane concentration.

The trend between atmospheric pressure and methane concentration showed a slight negative trend with a weak R-squared of 0.1112 (Figure 15). This trend is similar to the previous month shown.

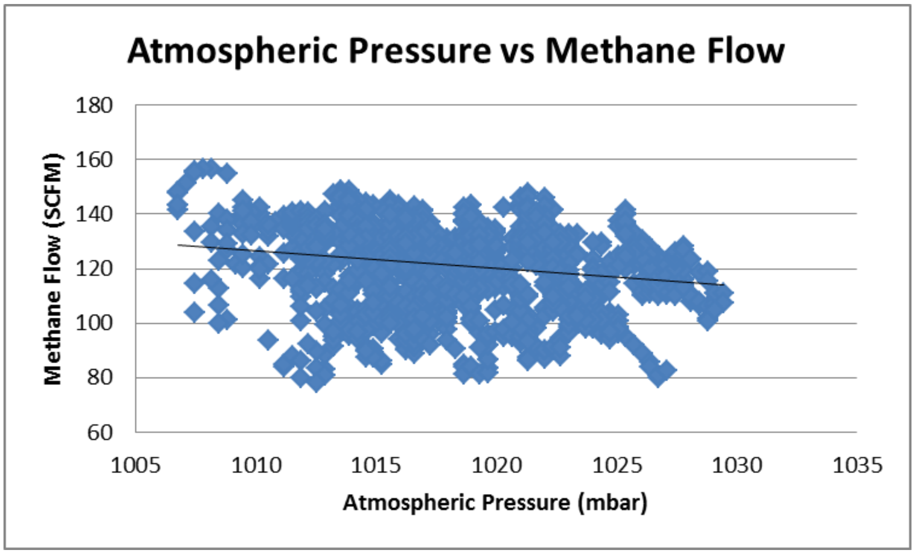


*Figure 16***.** Atmospheric pressure vs methane flow.

Similar to the last month, the trend for atmospheric pressure and methane flow was negative and had a very weak R-squared of 0.0408 (Figure 16).

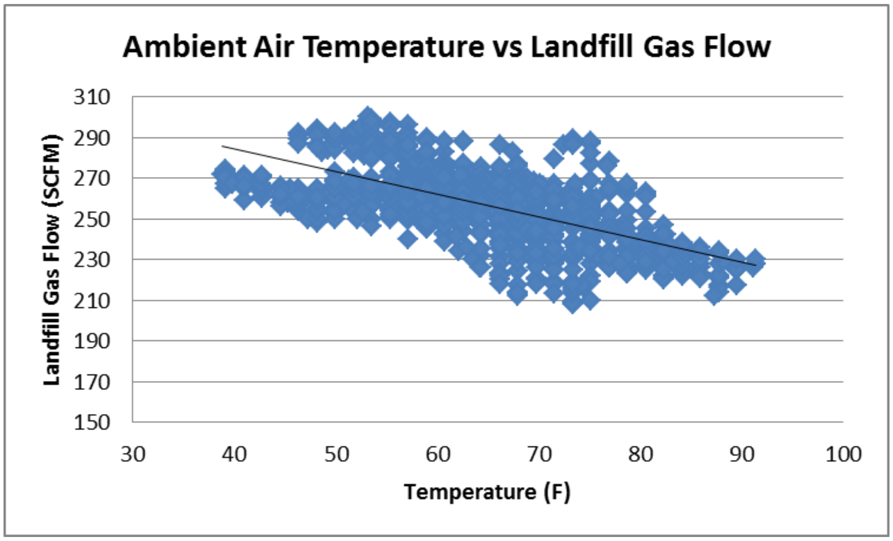


*Figure 17***.** Ambient air temperature vs total gas flow.

Ambient temperature and gas flow showed a moderate negative trend with a relatively high R-squared value of 0.4292 (Figure 17). This trend was similar to the previous month.

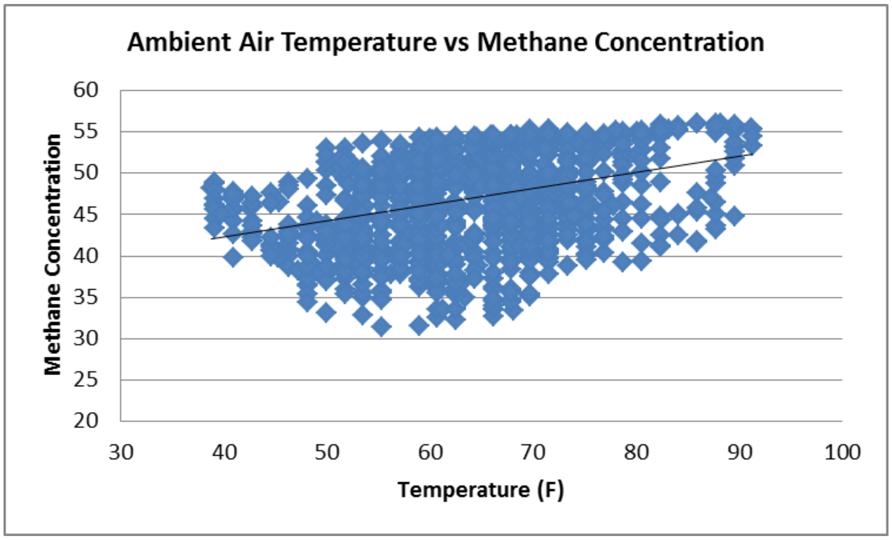


Figure 18. Ambient air temperature vs methane concentration.

Ambient temperature and methane concentration (Figure 18) showed a positive trend, which was similar to the previous month, but had a weak R-squared of 0.1344.

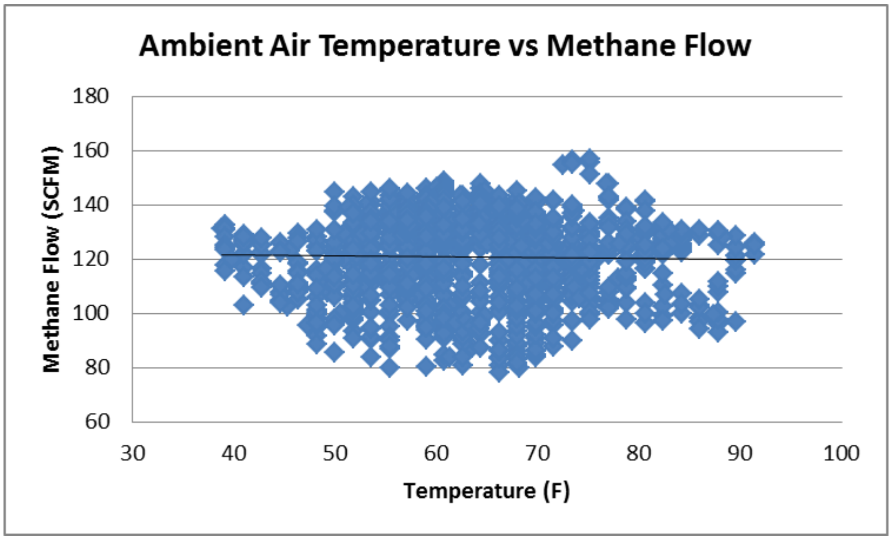


Figure 19. Ambient air temperature vs methane flow.

Along with the trend shown in August, the methane flow and ambient temperature trend of near-neutral had an R-squared of 0.0005.

Overall, the graphs for the months shown above have similar trends with each other and with the rest of the months throughout the year (Appendix A). Atmospheric pressure has some differences like shown above with the different trends for gas flow.

Wellhead Variability

The data collected at the Watauga County landfill consisted of wellhead logs dating from 2007 to 2013, with some exceptions (2010). The technician took readings every month at each of the 22 wellheads that make up the landfill system and sent reports to the County. The data consisted of various performance metrics; the parameters used for this study were methane percent, carbon dioxide percent, oxygen percent, balance gas percent, initial flow, and adjusted flow. Balance gas consists of the other gases that are not CH4, O2, or CO2. The five best performing wellheads at Watauga County were number 3 (average of 2.67 SCFM of methane), 11 (average of 4.05 SCFM of methane), 17 (average of 4.06 SCFM of methane), 18 (average of 5.96 SCFM of methane), and 21 (average of 7.92 SCFM of methane). Using the data from Watauga County, Figures 20 through 24 were created to display the methane flow changes between readings (the gaps in the Figure 20 through Figure 24 are from when no readings are taken).

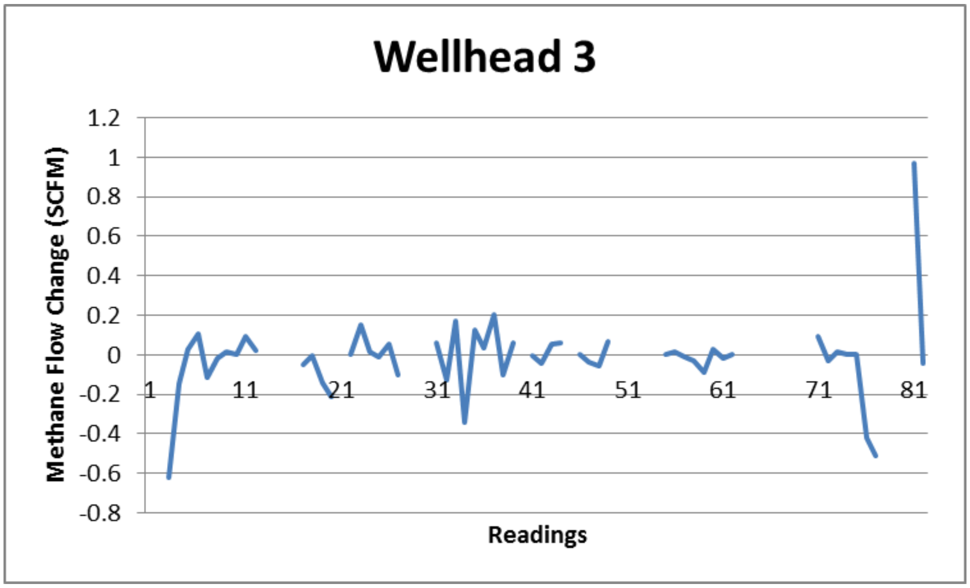


*Figure 20***.** Wellhead 3 methane flow variation between readings.

Wellhead 3 (Figure 20) had a methane flow change ranging from a gain of 1 SCFM to a loss of 0.6 SCFM.

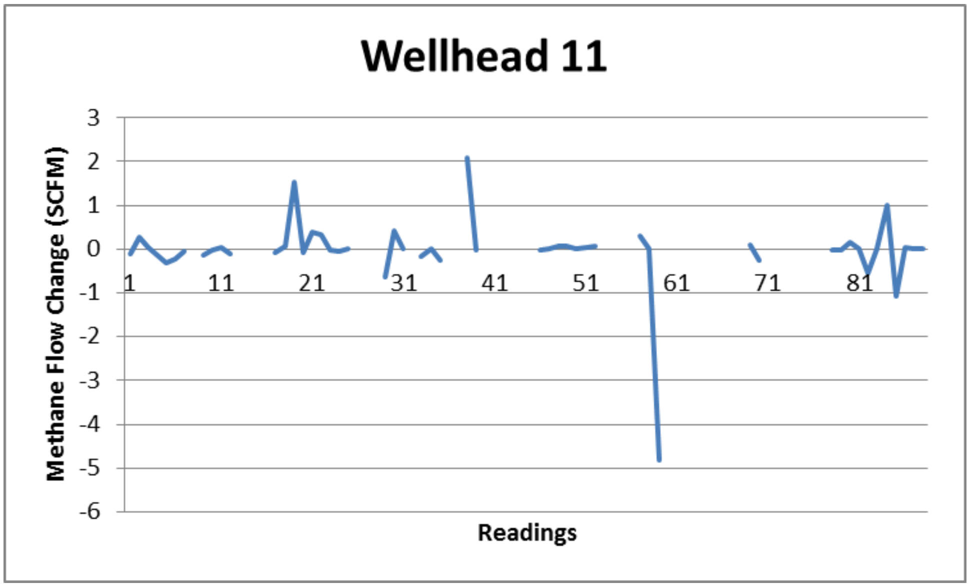


*Figure 21***.** Wellhead 11 methane flow variation between readings.

Wellhead 11 (Figure 21) had a methane flow change ranging from a gain of over 2 SCFM to a loss of almost 5 SCFM.

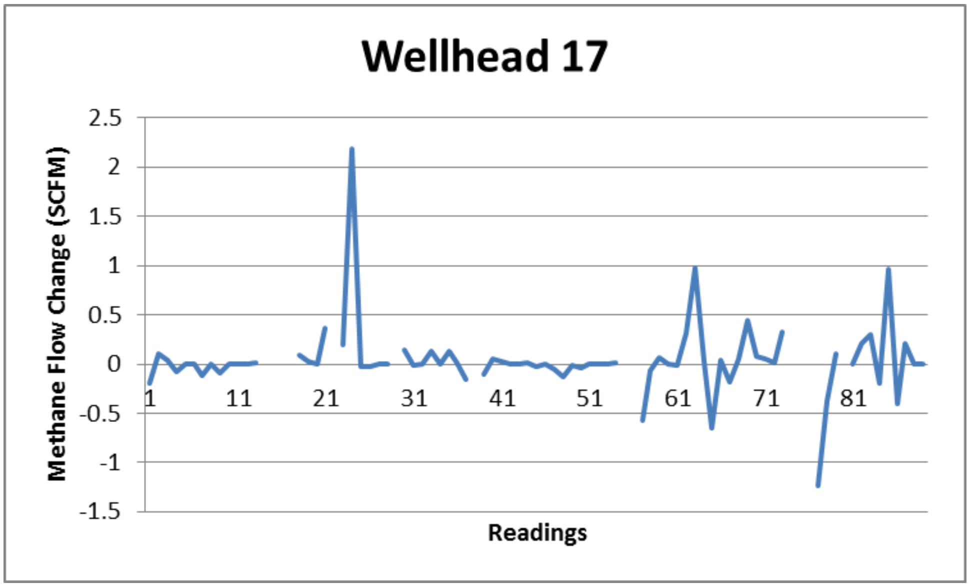


*Figure 22***.** Wellhead 17 methane flow variation between readings.

Wellhead 17 (Figure 22) had a methane flow change ranging from a gain of over 2 SCFM to a loss of over 1 SCFM.

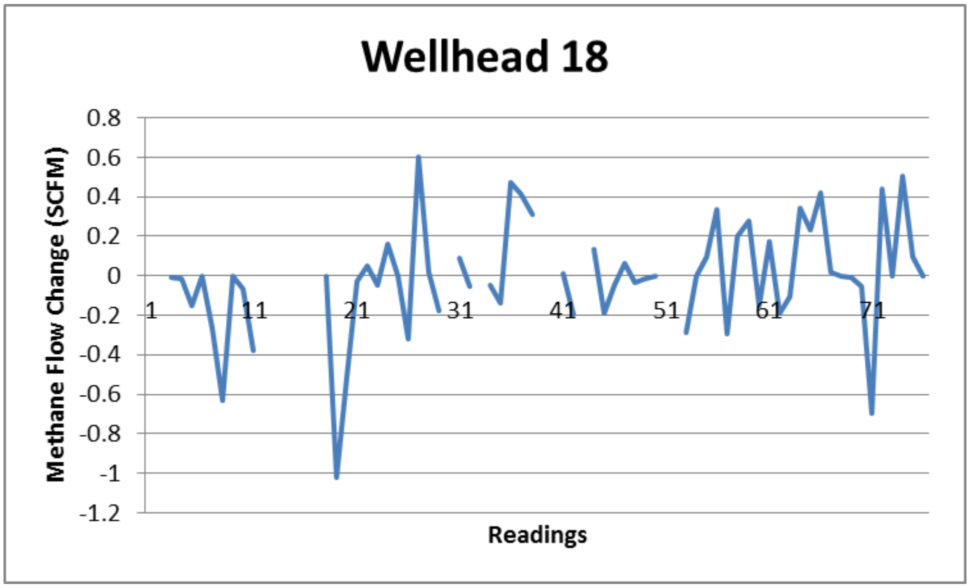


*Figure 23***.** Wellhead 18 methane flow variation between readings.

Wellhead 18 (Figure 23) had a methane flow change ranging from a gain of 0.6 SCFM to a loss of over 1 SCFM.

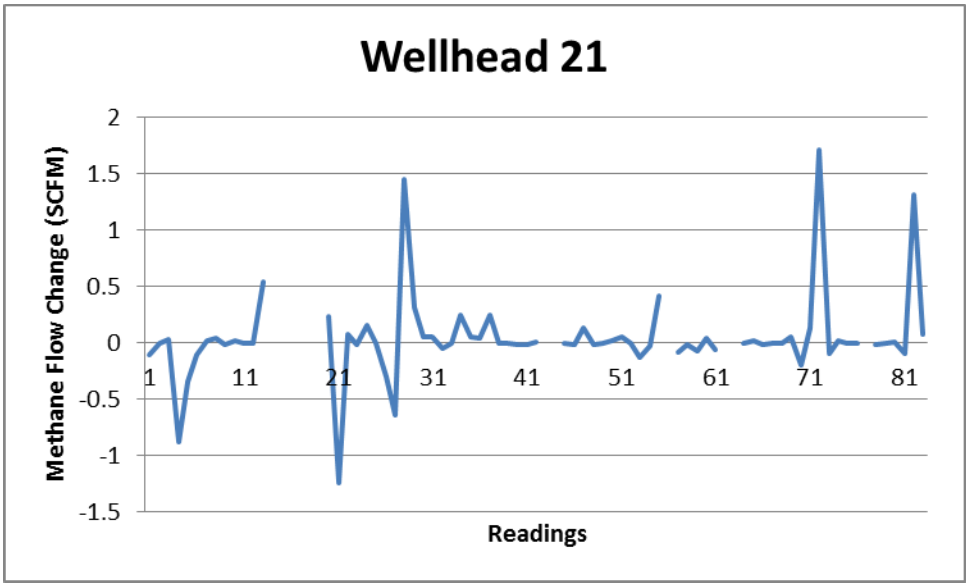


*Figure 24***.** Wellhead 21 methane flow variation between readings.

Wellhead 21 (Figure 24) had a methane flow change ranging from a gain of over 1.5 SCFM to a loss of over 1 SCFM.

Figure 25 shows the change in total flow at the header before and after wellhead adjustments. Figure 26 shows the change in total flow at the header between the readings.

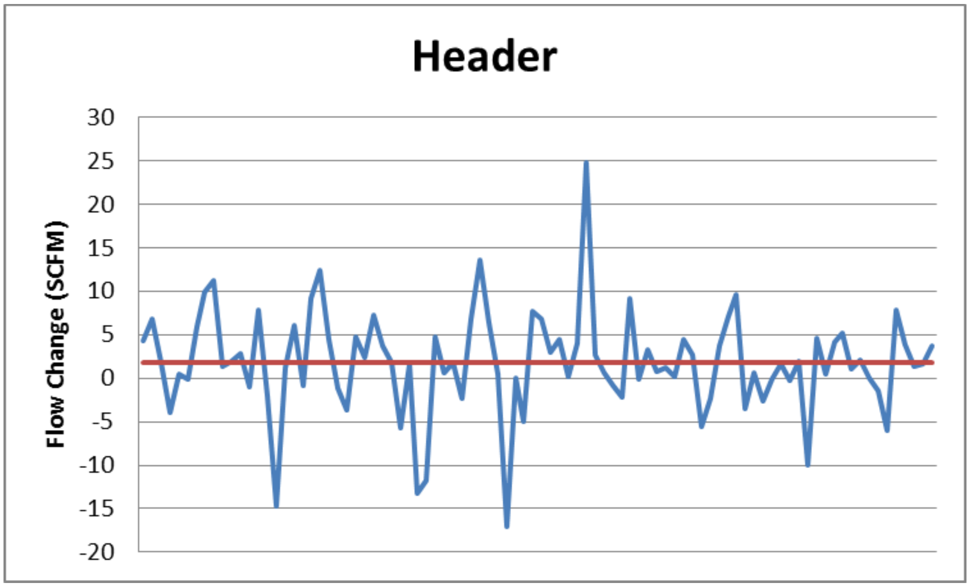


*Figure 25***.** Header flow variation before and after wellhead adjustments.

The header readings before and after wellhead adjustments (Figure 25) showed a flow change ranging from a gain of 25 SCFM to a loss of over 15 SCFM.

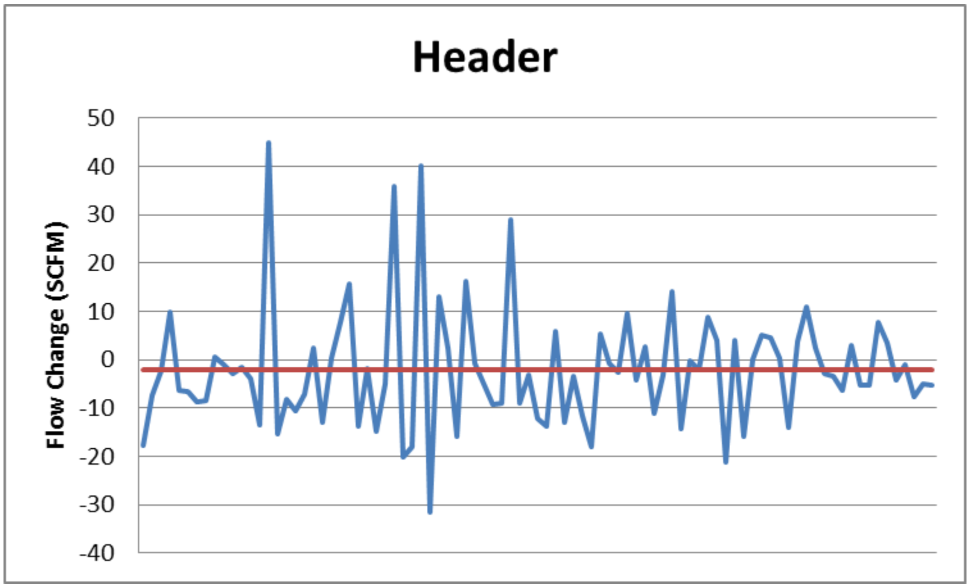


*Figure 26***.** Header flow variation between readings.

The header readings of between adjustments (Figure 26) showed a flow change ranging from a gain of 45 SCFM to a loss of over 30 SCFM.

The wellhead data show that there can be a large variation in gas flow between readings. The straight line in Figure 25 and 26 shows the average for the entire time series. Figure 25 shows that on average the wellhead adjustments gain 1.8 SCFM of flow while Figure 26 shows that 2.1 SCFM of flow is lost in between readings at the header. It shows that the adjustments are doing their purpose and having a gain in flow and shows that the flow drops before the next reading. These data suggest there is a strong potential benefit from a wellhead control device to keep the flow steady, which could enhance the engine efficiency and help prevent shut downs.

LFGE System Energy

When sizing a genset it is common practice to use a landfill gas model. For this particular analysis the LandGEM model created by the USEPA was used. The data from Rockingham County's records were used to create a model to estimate the amount of methane gas that will be created in the future (Figure 27). The estimated amount of methane gas was then used to specify the size of the genset to be installed at a particular landfill. Starting in 1985 and ending in 2008 Rockingham County waste input to the landfill waste ranged from 31,920 Mg per year to 80,077 Mg per year. Using this data and inventory conventional default parameters in the LandGEM model one can estimate that in 2024 there will be an average yearly total gas flow of 154.14 SCFM and methane flow rate of 77 SCFM. The planned installation of the genset in 2014 will use information from LMOP's *Project Development Handbook* (2010) stipulating that engine sizing should be based off of the landfill expectations 10 years from installation.

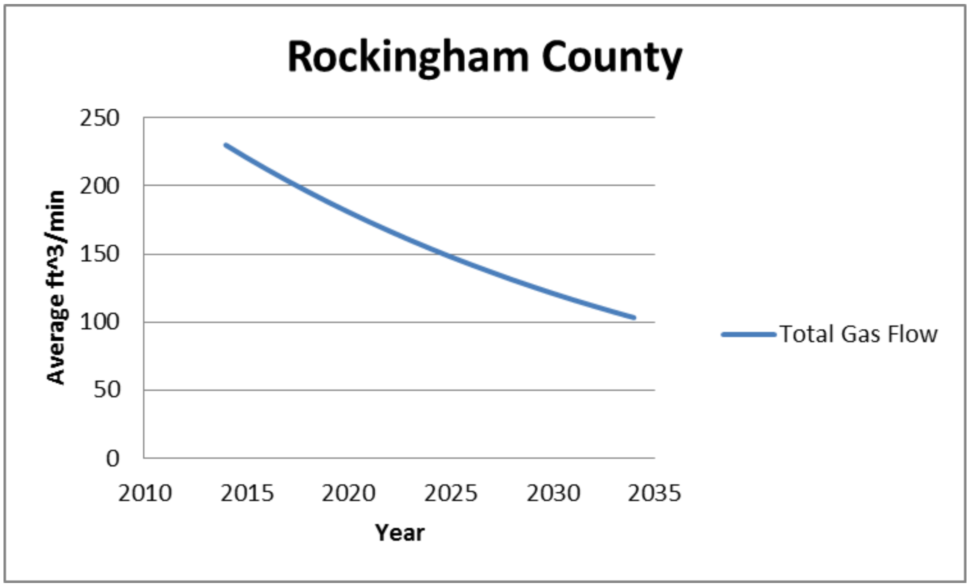


Figure 27. Rockingham County LandGEM model.

Next, the estimated 77 SCFM of methane gas was converted into kilowatts resulting in a potential of 562 kilowatts that can be generated by the facility. Then, using this kilowatt load to size the genset and examining the specifications of several off-the-shelf manufactured gensets, two of the Jenbacher J208 engines were chosen for this study. The Jenbacher J208 has an efficiency of 41% (General Electric [GE], 2014) and a capacity of 250-350 kilowatts (330 kW was used for this analysis due to typical output according to a specification sheet).

Two gensets were chosen for this analysis because of the ability to keep one of the gensets going if the other needs maintenance or shuts down for another reason. Also, with two gensets the ability to use the gas flow near the end of the genset's lifespan increases because the smaller gensets can use a lower flow intake compared to a larger genset.

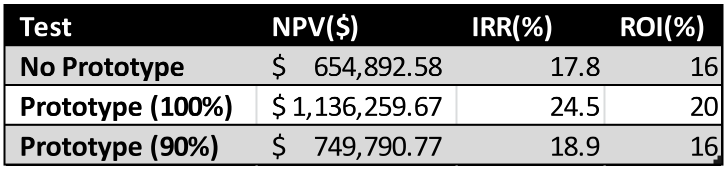
This analysis also examined two operating options. The purpose was to select the operating option that had the best operating and financial performance. The two operating options for the landfill were the following:

1. Leaving the landfill as is when connecting the generator sets.
2. Using a landfill wellhead control device to maintain a steady methane flow.

For the analysis of the landfill without the wellhead control system the 12-month data from Rockingham County was not altered. The number of engine shutdowns was calculated, meaning any 20-minute interval that has a methane concentration below 40% would cause the engine to shut down. For the entire year data for Rockingham County a total of 40.99 days the engine would be shut down was calculated. This is just an estimate of the number of days the engines might be shut down. The 40.99 days is the total number of 20 minute intervals that were below the desired methane concentration, but in reality the engine would not be able to start back up during the next 20-minute interval and the engine could actually be off for days and not minutes. The analysis used the number of kilowatt-hours generated without any adjustments.

The wellhead control system option used a wellhead control device to maintain a specified flow and methane percentage. There were two different parts of this analysis. For the first analysis, it was assumed the wellhead control system would operate at 100% accuracy while maintaining the methane gas flow and concentration at the optimal level. For the second analysis it was assumed the wellhead control system would operate at 90% accuracy. The first analysis with the annual average was determined to be the best scenario for the wellhead control system to operate. For this landfill the annual averages calculated were 266.8 SCFM and a methane percentage of 47.9 %. When calculating the total amount of kilowatt hours that could be generated by the system, the annual average was assumed for an every 20 minute interval, and it had the same amount of intervals that the Rockingham County data provided. The 90% analysis was used to help show a range of potential, depending on the accuracy of the prototype, and was calculated at 90% of the 100% prototype. Table 1 shows the output of the energy analysis.

Table 1. *Energy Analysis Results*

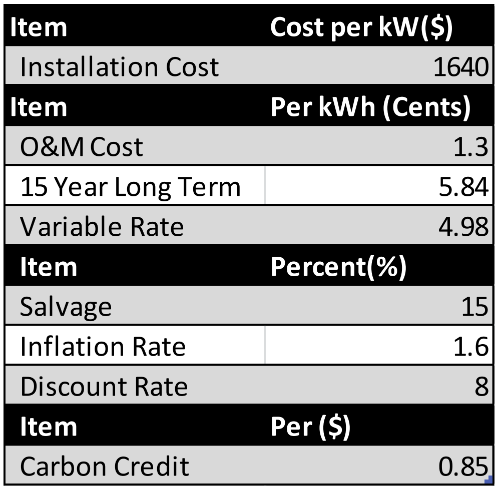


Test	NPV($)	IRR(%)	ROI(%)
No Prototype	$ 654,892.58	17.8	16
Prototype (100%)	$ 1,136,259.67	24.5	20
Prototype (90%)	$ 749,790.77	18.9	16

Economics

Using the genset sizing information and the data gathered from the energy analysis, an economic analysis was performed to determine which of the two options were the most beneficial in terms of profit. Data were gathered from the USEPA with regards to installation and operation and maintenance cost (USEPA, 2008); from Duke Energy for the 15-year long-term agreement price per kWh and their variable price per kWh for the final 5 years of the analysis (Duke Energy, 2013); and from Rockingham County representatives for their budgeted cost per carbon credit (Jason Hoyle, personal interview, April 15, 2014). Table 2 was developed to summarize the parameters for determining the potential yearly cash flows.

Table 2. *Prices Used Per Item*

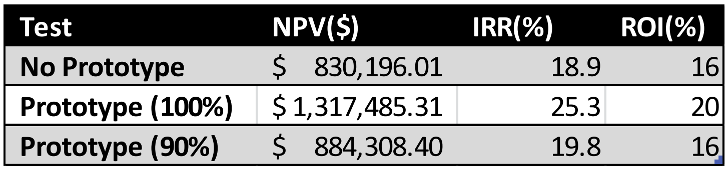


Item	Cost per kW($)
Installation Cost	1640
Item	**Per kWh (Cents)**
O&M Cost	1.3
15 Year Long Term	5.84
Variable Rate	4.98
Item	**Percent(%)**
Salvage	15
Inflation Rate	1.6
Discount Rate	8
Item	**Per ($)**
Carbon Credit	0.85

Using the figures in Table 2, the cash flow tables (Table 4 through Table 6 in Appendix B) were created for each individual test. These cash flow tables show the estimated cash flow for 20 years, which is the expected life-span of one of the proposed gensets. Since the genset was sized for 10 years after installation years 11through 20 the genset will not be running at full capacity. Using the size of the genset and the output from the LandGEM model one can get percentage of capacity that will be used in the economic analysis. That will be used to calculate the amount of kWh instead of using the full capacity amount. The values range from 82 % of capacity in year 11 to 57 percent of capacity in year 20.

Table 6 shows the economic analysis for each test and the results to determine the potential economic benefit for the tests with the prototype.

Table 3. *Economic Analysis Results*



Test	NPV($)	IRR(%)	ROI(%)
No Prototype	$ 830,196.01	18.9	16
Prototype (100%)	$ 1,317,485.31	25.3	20
Prototype (90%)	$ 884,308.40	19.8	16

Implications for the Design of Prototype

One of the major purposes of this study was to take the information gathered and become more informed with regards to the opportunities that a gas flow control prototype might be able to unlock. The potential for landfill gas as a renewable energy source is very high and the more that can be learned about this form of energy the better it can be utilized. This prototype could help make this form of energy a more reliable and efficient renewable energy.

Energy Analysis

Table 1 shows the results for the energy analysis. Using the information from Rockingham County one can see the potential the prototype might have on a landfill's total energy production by controlling gas flow so more gas gets sent to the genset rather than being flared, thus creating a more efficient system.

Economic Analysis

The economic analysis (Table 6) shows that there is potential for a large monetary gain from a prototype like the one envisioned by this researcher. Using the information from Rockingham County and the known amount of wellheads at the site, I estimated that a range of approximately $7,299.86 to $37,028.24 per wellhead per prototype could be invested for the 20 year period before the benefit of the prototype becomes null (90 % NPV minus no prototype NPV divided by 13 wellheads to 100% NPV minus no prototype NPV divided by 13 wellheads).

Development

Progress on a gas control prototype has been made over the time of this study and can be used to inform efforts to create a better prototype in the future. Using data loggers at various wellheads at Watauga County landfill, a number of sensors have been tested to try and find ones that would work well with the landfill gas and the weather in the area. Dynamet sensors have been used for methane and carbon dioxide; and although they worked for a short while they eventually became corroded and died out. Pressure transducers were used to calculate the flow rate using the pitot tubes on the Landtec wellheads, but the tubes to the sensor and the pitot tube became sun-dyed and brittle. Once the winter came around the pressure sensors were found to not work well in the colder weather. The moisture from the air caused the diaphragm in the sensor to freeze, after which they could not calculate the correct pressure. Arduino microcontrollers have been tested to use as the control device for the prototype. They can be used for the prototype, but there need to be more attachments for data logging and weather protection.

CHAPTER 5
CONCLUSIONS AND DISCUSSION

Atmospheric Condition Results

The analysis of the atmospheric conditions shows no meaningful conclusion can be found with regards to atmospheric pressure and landfill operating metrics, but some possible trends with regards to ambient air temperature and the landfill gas metrics have shown up across the months. In addition to monthly trends, a stronger correlation between changes in pressure over time and changes in methane concentration and methane flow was shown. This information could become more useful if more information is known and further research is conducted.

Wellhead Results

The findings show that at Watauga County the variation in change in methane flow in between readings at each wellhead (especially the best performing wellheads) varied greatly, and as Figure 25 shows this can alter the total flow at the header. Figure 26 shows that between readings the total flow fluctuated just like the wellheads. Using this information and further research at the wellhead level of a landfill, a wellhead control device could greatly change the performance of a landfill and keep the methane flow steady.

Energy and Economics Analysis Results

The energy and economic analysis shows the potential of a landfill using a wellhead control device. Table 1 shows that using the device could help produce more kWh and lower the amount of gas flared. The economic variables calculated in Table 6 show that there is potential for economic benefit with the installation of a wellhead control device, and provides a range of money that could be spent per prototype per wellhead for the 20 years taken into account ($4,162 to $37,483).

Future Studies

The results of this study lead me to conclude that there is need for further research within the LFGE system community. Using this study as a background and justification, the effects of ambient air temperature and atmospheric pressure should be studied using a larger sample size and in more detail. These studies would determine different operational parameters for LFGE systems. In addition to the atmospheric conditions, other parameters should be studied. For example, ground temperature and precipitation are two factors about which a better understanding could lead to a better knowledge of how time factors into the effects on the landfill performance. To further help with the production of a wellhead control device, research conducted on site-specific wellheads would need to be conducted to help determine an algorithm for the device.

REFERENCES

Agency for Toxic Substances and Disease Registry [ATSDR]. (2001). *Landfill gas primer: An overview for environmental health professionals*. Retrieved from http://www.atsdr.cdc.gov/HAC/landfill/html/intro.html

American Gas Association [AGA]. (2014). *How to measure natural gas*. Retrieved from http://www.aga.org/KC/ABOUTNATURALGAS/ADDITIONAL/Pages/HowtoMeasureNaturalGas.aspx

Barlaz, M. A. (2009). Controls on landfill gas collection efficiency: Instantaneous and lifetime performance. *Journal of the Air & Waste Management Association*, *59*(12), 1399-1404.

Caterpillar. (2008). *Landfill gas to electricity*. Retrieved from http://www.myfoleyinc.com/foleyinc/files/chp_CAT%20Marketing%20Piece_Brochure_Landfill%20Gas%20Applications_LEDE4554-01.pdf

Climate Action Reserve [CAR]. (2011, June 29). *U.S. landfill project protocol*. Retrieved from http://www.climateactionreserve.org/how/protocols/us-landfill

Chen, C. (2003). Is landfill gas green energy? Arlington, VA: Natural Resources Defense Council. Retrieved from http://www.nrdc.org/air/energy/lfg/lfg.pdf

Club, S. (n.d.). *The danger of corporate landfill gas to energy scehemes and how to fix it.* Retrieved from http://www.teamster.org/sites/teamster.org/files/6310GreenhouseGasReportrevisedlowres.pdf

Duke Energy. (2014, March 13). *Docket No. E-100, Sub 136.* Retrieved from http://starw1.ncuc.net/NCUC/ViewFile.aspx?Id=7e8b2aa8-20a5-45e8-9f17-5ee4bcc4522d

General Electric [GE]. (2014). *Jenbacher Type 2.* Retrieved from https://www.ge-distributedpower.com/news-media/customer-magazine/engine-sheet-type-2-e

Global Methane Initiative [GMI]. (2012). *International best practices guide for landfill gas to energy (LFGE) projects.* Retrieved from https://www.globalmethane.org/documents/toolsres_lfg_IBPGcomplete.pdf

Hodge, B. (2010). *Alternative energy systems and applications.* Danvers, MA: Wiley and Sons.

Koch, W. (2010). *Landfill projects on the rise*. Retrieved from http://usatoday30.usatoday.com/money/industries/energy/2010-02-24-landfill-energy_N.htm

Kohn, M. P. (2011). Performance of an internal combustion engine operating on landfill gas and the effect of syngas addition. *Industrial & Engineering Chemistry Research*, *50*(6), 3570-3579.

Landfill Methane Outreach Program [LMOP]. (2010). Project development handbook. Retrieved from http://www.epa.gov/lmop/publications-tools/handbook.html#01

Ludwig, V. (n.d.). Going abroad with landfill gas energy: Taking the success of direct use in the United States to the international community. Retrieved from http://www.scsengineers.com/Papers/Dieleman-Going_Abroad_with_LFGE.pdf

Packham, K. (2007). *The case for waste to energy: Utilizing low-Btu reciprocating gas engine generators.* Retrieved from http://www.camelottech.com/CMFiles/Docs/F-6015-waste-to-energy.pdf

Rajaram, V., Siddiqui, F.Z., Khan, M.E. (2012). *From landfill gas to energy: Technologies and challenges.* Leiden: CRC Press.

Rapid Tables. (n.d.). *BTU/hr to kilowatts (kW) conversion*. Retrieved from http://www.rapidtables.com/convert/power/BTU_to_kW.htm

Ritchie, S., & McBean, E. (2011). Assessment of operations and design strategy controls to improve landfill gas utilization opportunities. *Canadian Journal of Civil Engineering, 38*(5), 519-529.

United States Environmental Protection Agency (USEPA). (2008). *Technology characterization: Reciprocating engines.* Retrieved from http://www.epa.gov/chp/documents/catalog_chptech_reciprocating_engines.pdf

United States Environmental Protection Agency (USEPA). (2013a). *An overview of landfill gas.* Retrieved from http://epa.gov/lmop/documents/pdfs/overview.pdf

United States Environmental Protection Agency (USEPA). (2013b). *Overview of greenhouse gases.* Retrieved from http://epa.gov/climatechange/ghgemissions/gases/ch4.html

United States Environmental Protection Agency (USEPA). (2014). *Municipal solid waste*. Retrieved from http://www.epa.gov/waste/nonhaz/municipal/

APPENDICES

APPENDIX A

Monthly Trend Graphs

July 2012

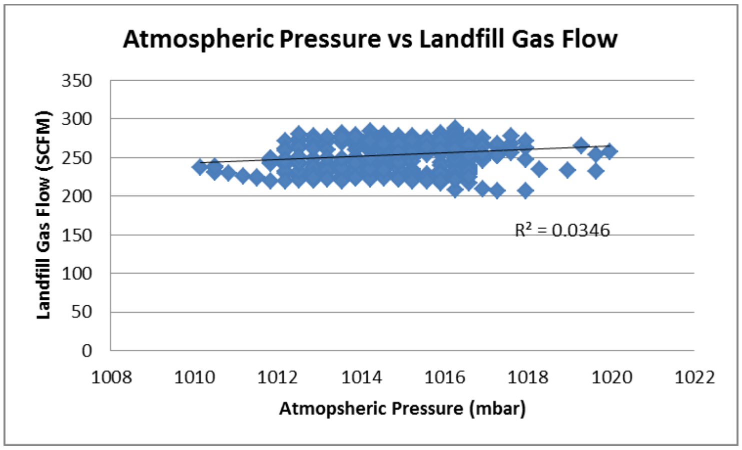


Figure 28. Atmospheric pressure vs landfill gas flow.

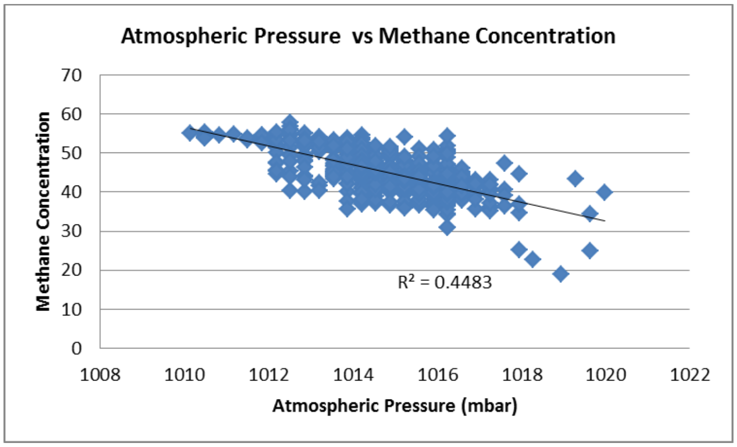


Figure 29. Atmospheric pressure vs methane concentration.

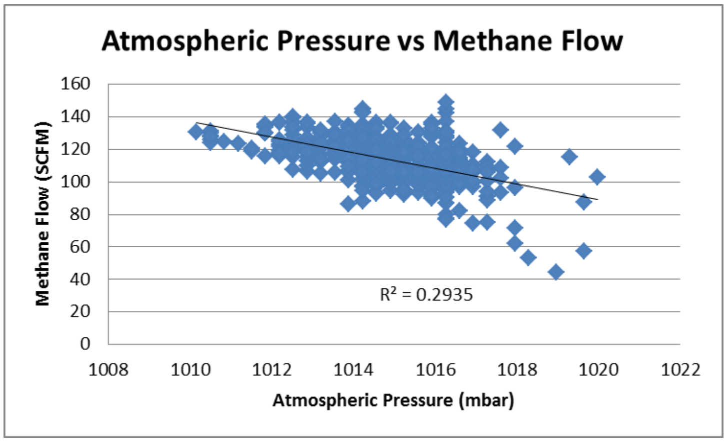


Figure 30. Atmospheric pressure vs methane flow.

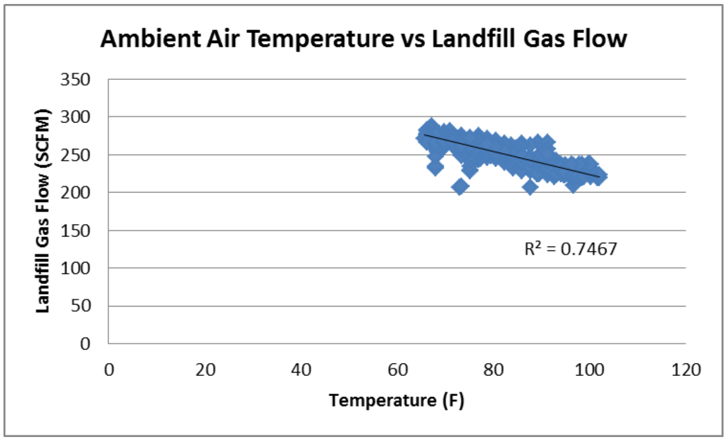


Figure 31. Ambient air temperature vs landfill gas flow.

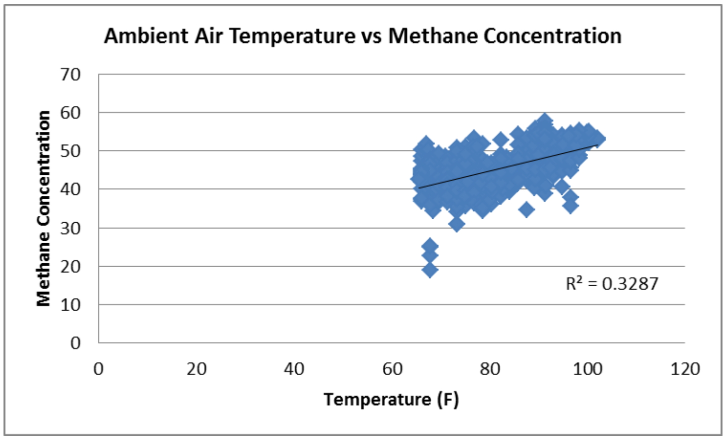


Figure 32. Ambient air temperature vs methane concentration.

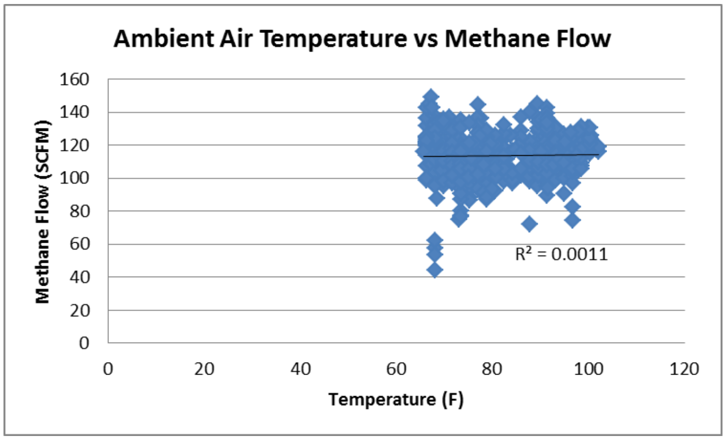


Figure 33. Ambient air temperature vs methane flow.

October 2012

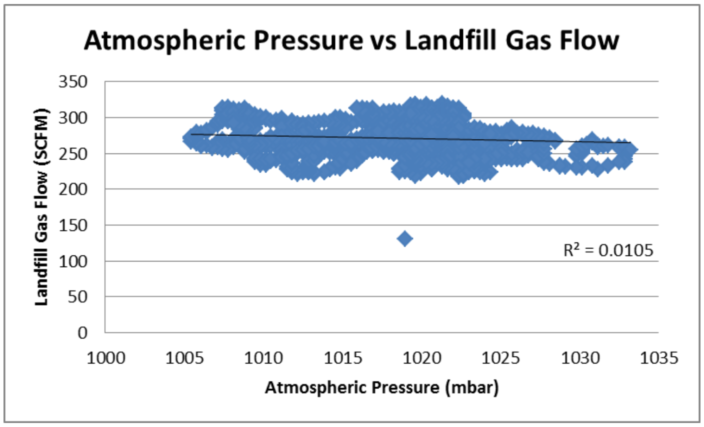


Figure 34. Atmospheric pressure vs landfill gas flow.

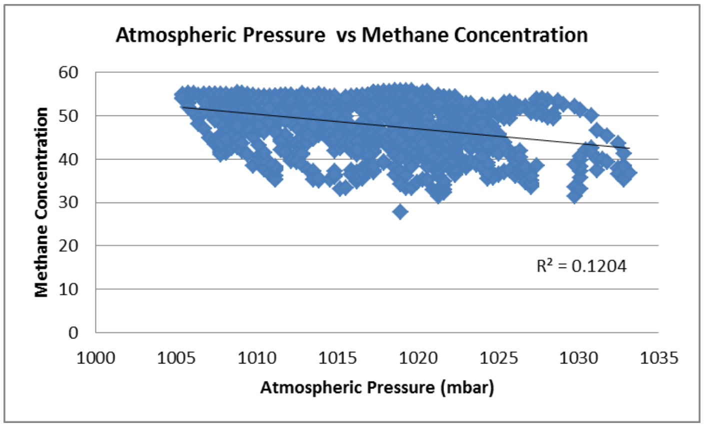


Figure 35. Atmospheric pressure vs methane concentration.

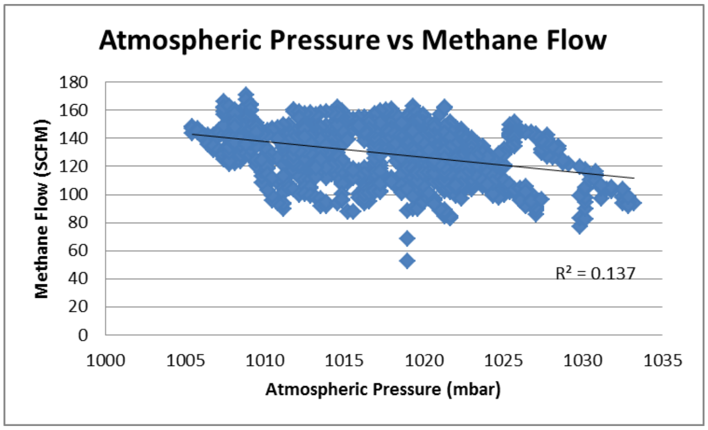


Figure 36. Atmospheric pressure vs methane flow.

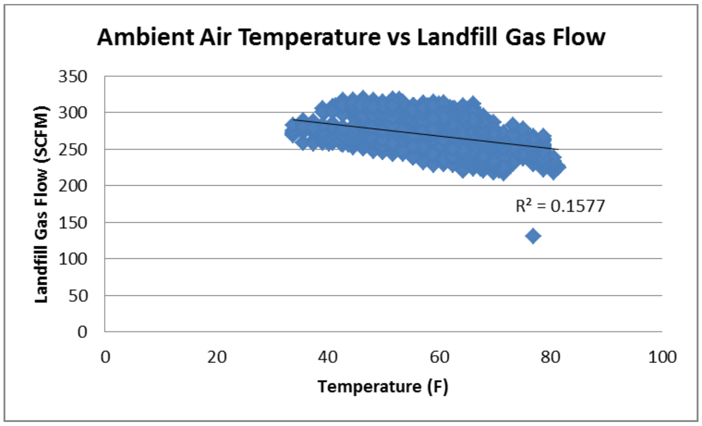


Figure 37. Ambient air temperature vs landfill gas flow.

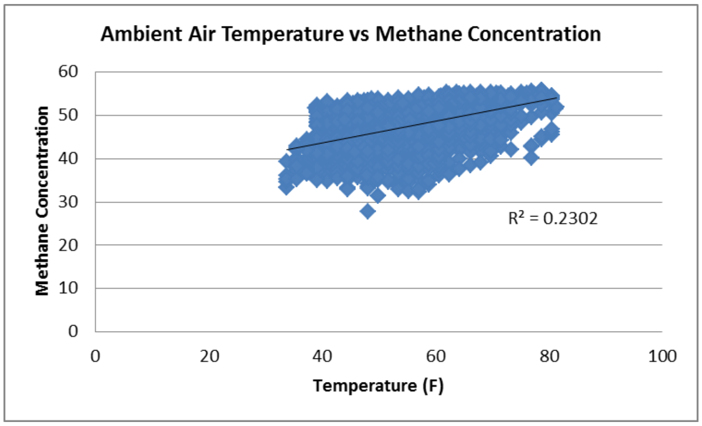


Figure 38. Ambient air temperature vs methane concentration.

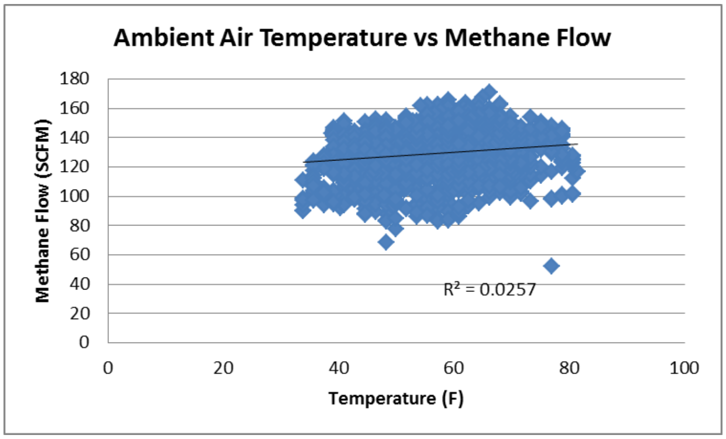


Figure 39. Ambient air temperature vs methane flow.

November 2012

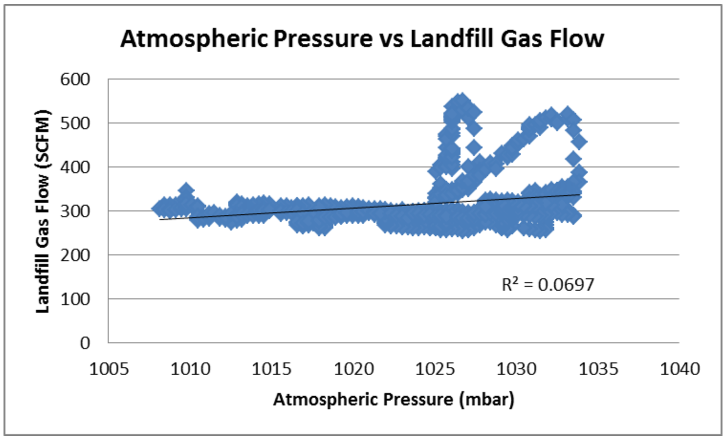


Figure 40. Atmospheric pressure vs landfill gas flow.

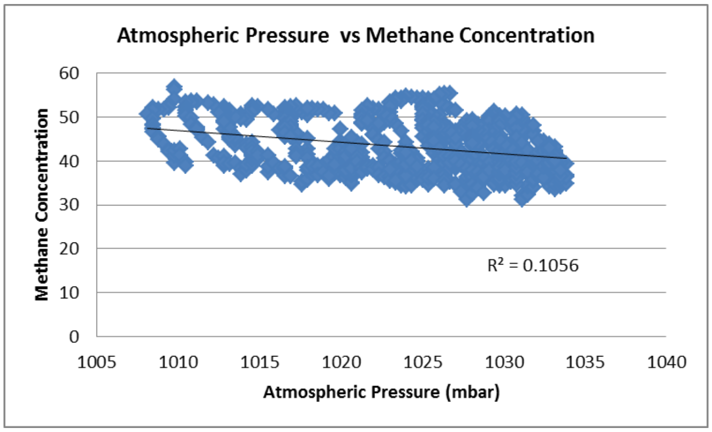


Figure 41. Atmospheric pressure vs methane concentration.

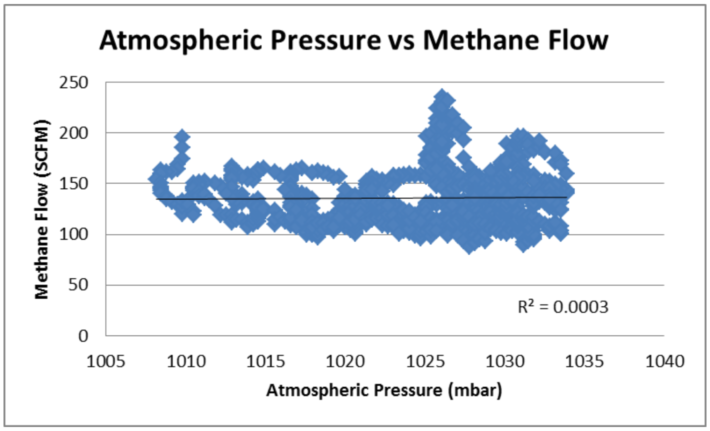


Figure 42. Atmospheric pressure vs methane flow.

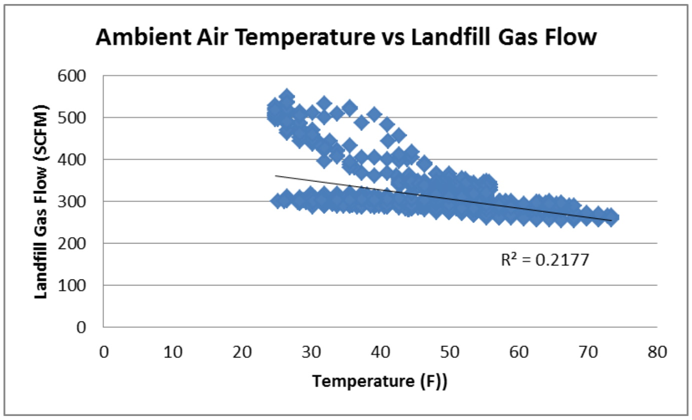


Figure 43. Ambient air temperature vs landfill gas flow.

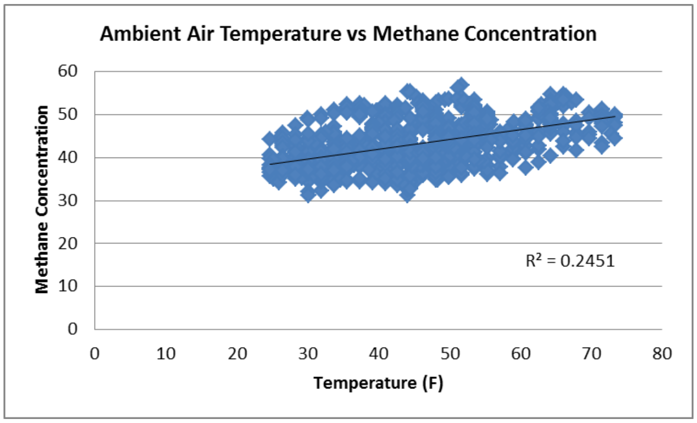


Figure 44. Ambient air temperature vs methane concentration.

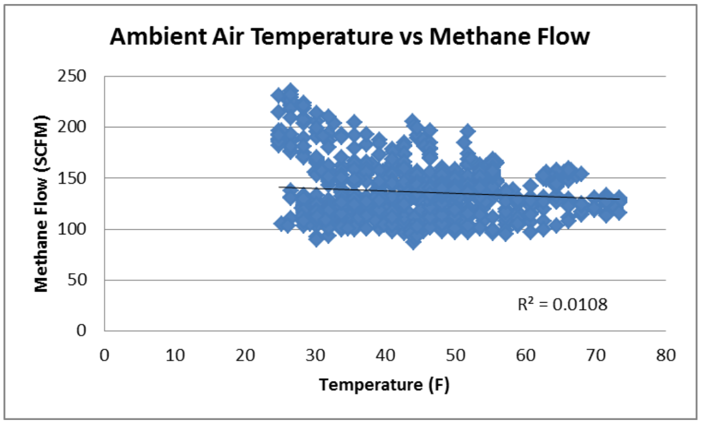


Figure 45. Ambient air temperature vs methane flow.

December 2012

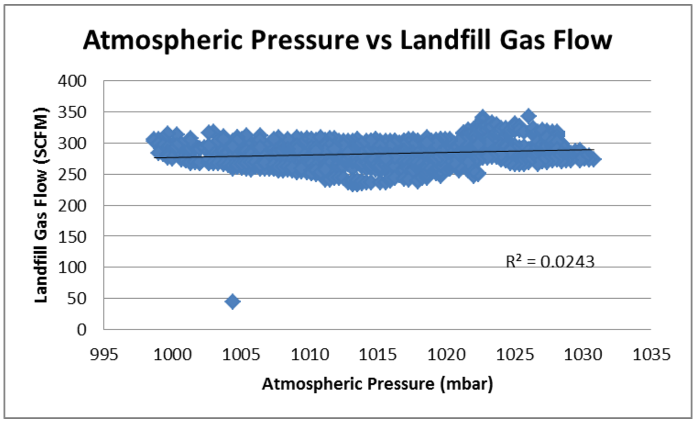


Figure 46. Atmospheric pressure vs landfill gas flow.

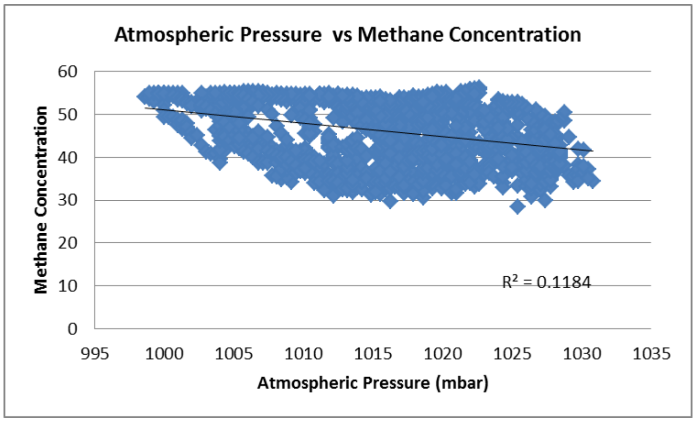


Figure 47. Atmospheric pressure vs methane concentration.

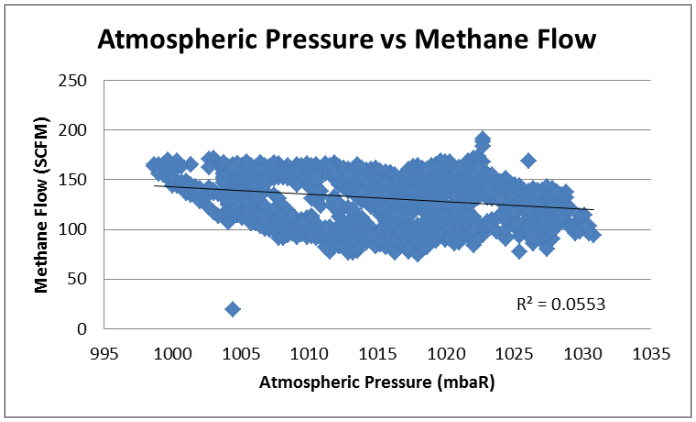


Figure 48. Atmospheric pressure vs methane flow.

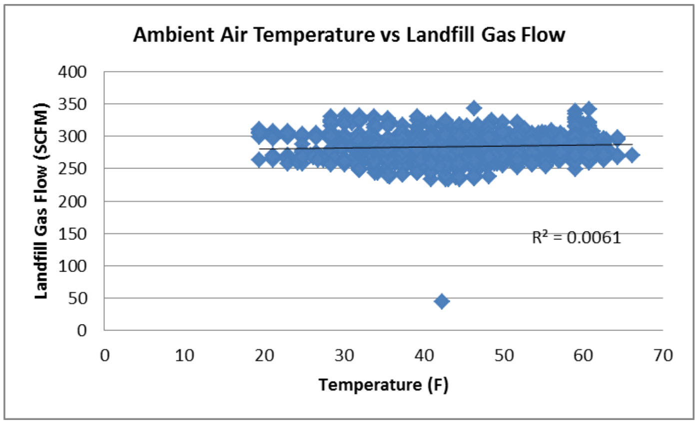


Figure 49. Ambient air temperature vs landfill gas flow.

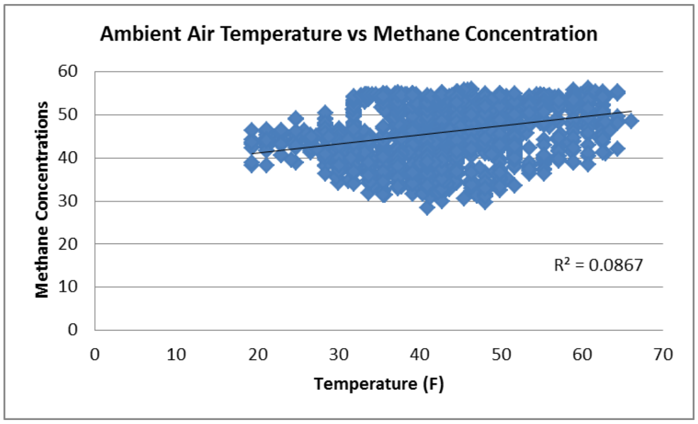


Figure 50. Ambient air temperature vs methane concentration.

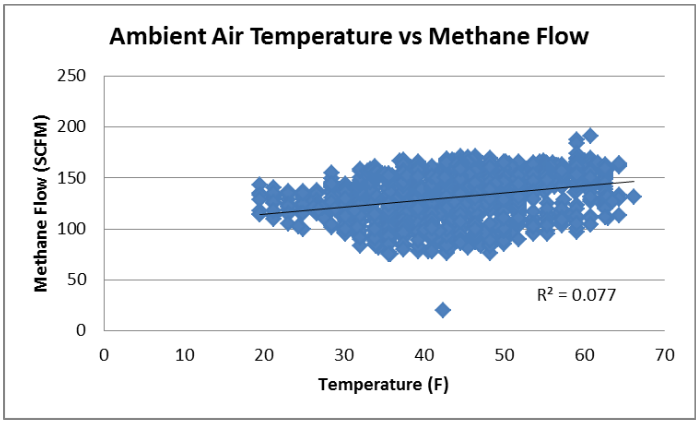


Figure 51. Ambient air temperature vs methane flow.

January 2013

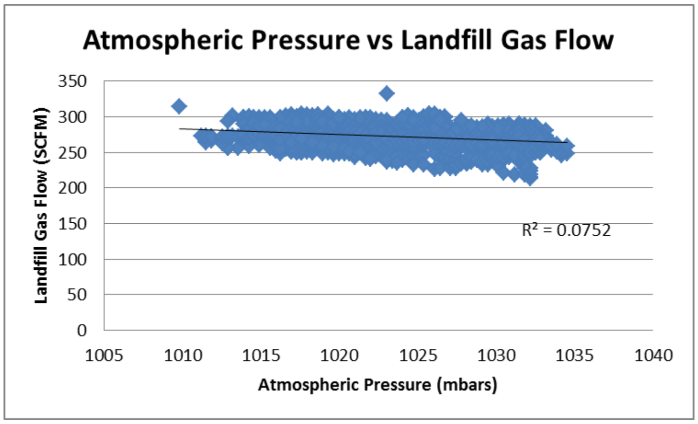


Figure 52. Atmospheric pressure vs landfill gas flow.

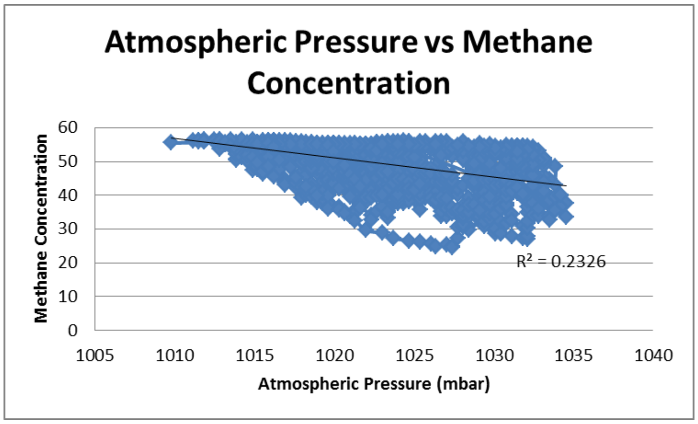


Figure 53. Atmospheric pressure vs methane concentration.

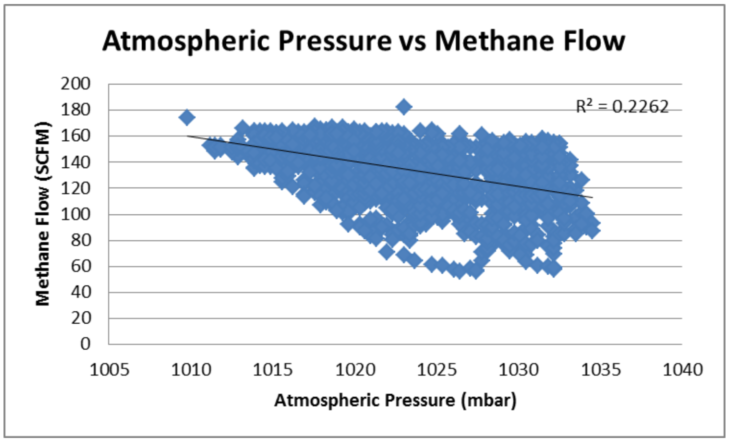


Figure 54. Atmospheric pressure vs methane flow.

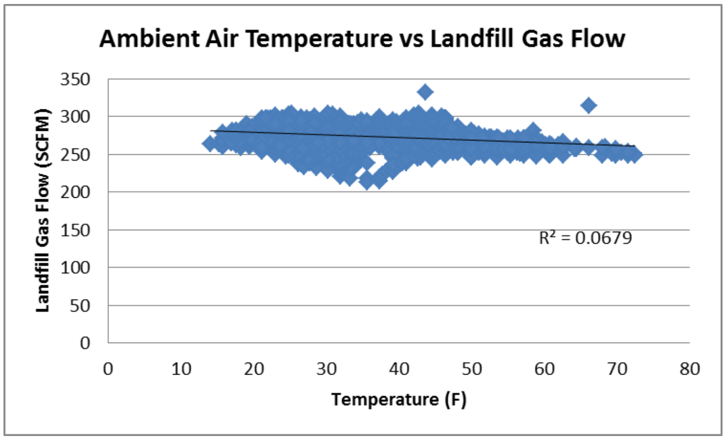


Figure 55. Ambient air temperature vs landfill gas flow.

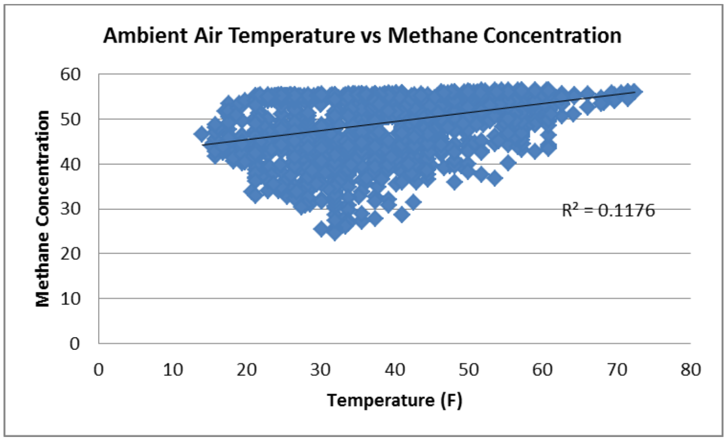


Figure 56. Ambient air temperature vs methane concentration.

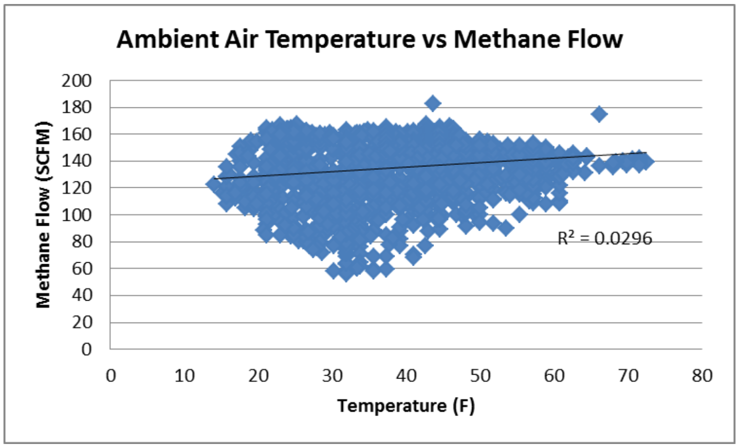


Figure 57. Ambient air temperature vs methane flow.

February 2013

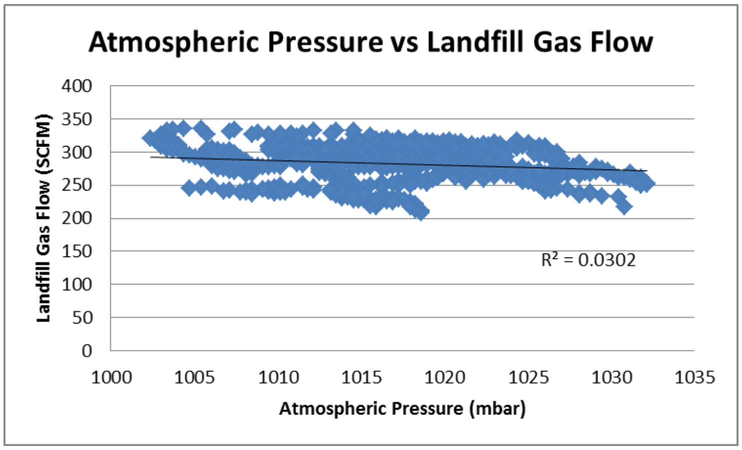


Figure 58. Atmospheric pressure vs landfill gas flow.

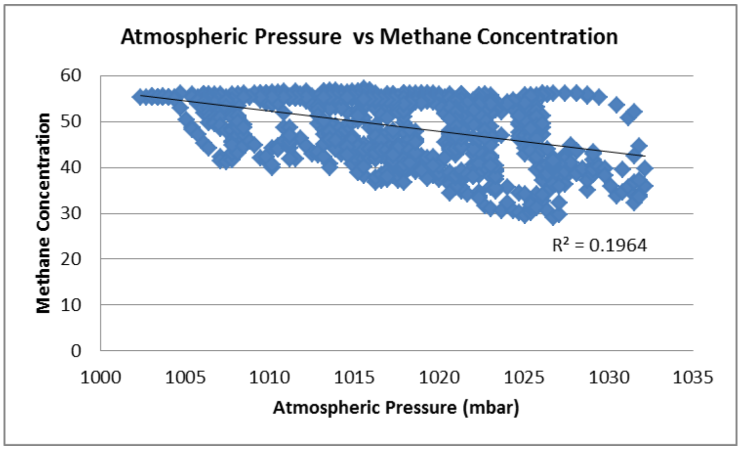


Figure 59. Atmospheric pressure vs methane concentration.

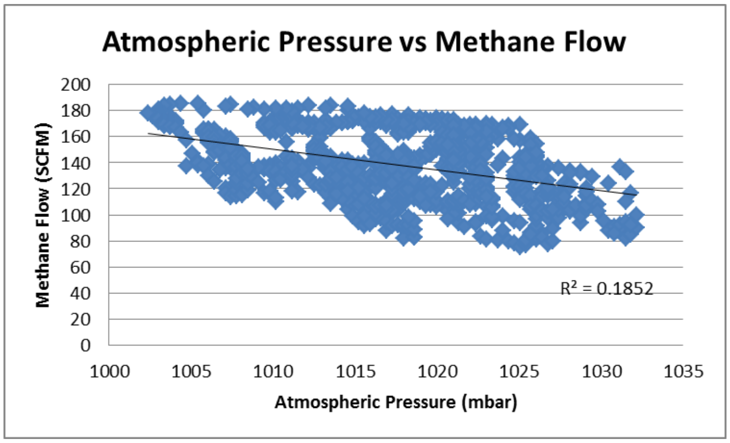


Figure 60. Atmospheric pressure vs methane flow.

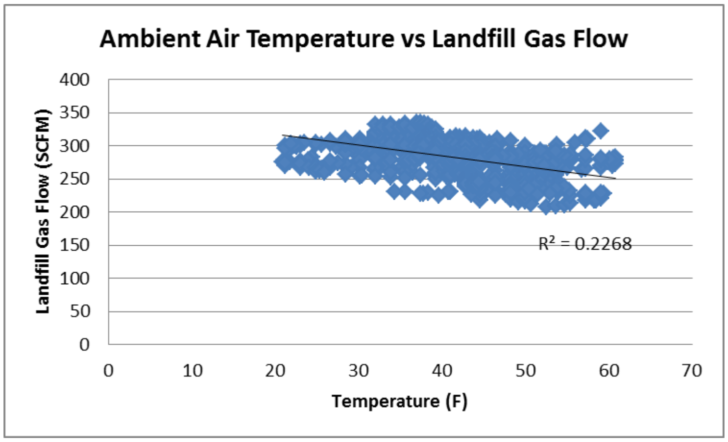


Figure 61. Ambient air temperature vs landfill gas flow.

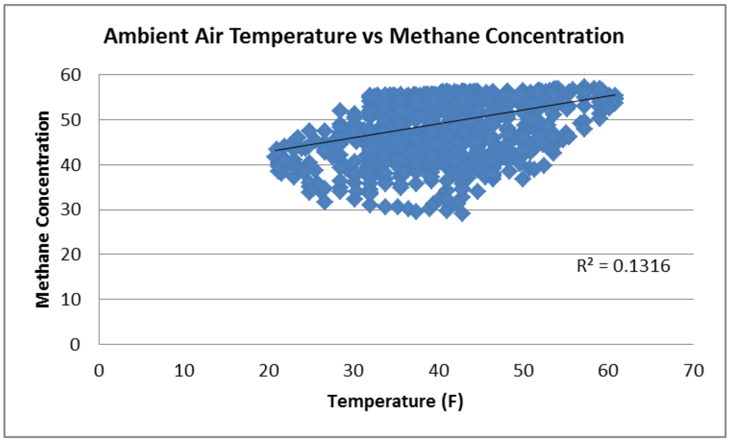


Figure 62. Ambient air temperature vs methane concentration.

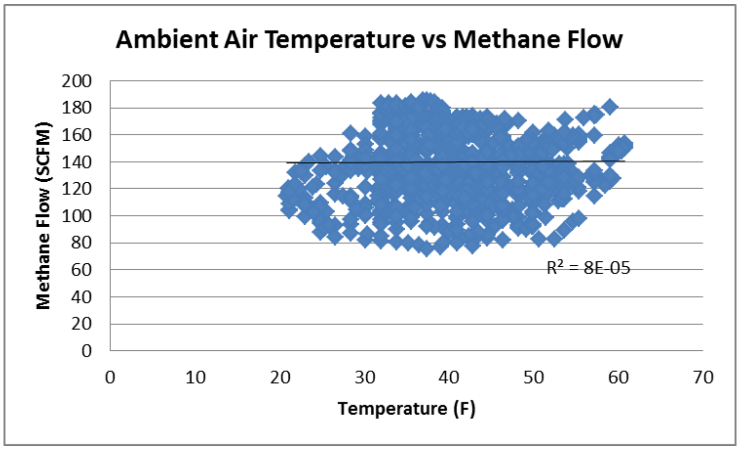


Figure 63. Ambient air temperature vs methane flow.

March 2013

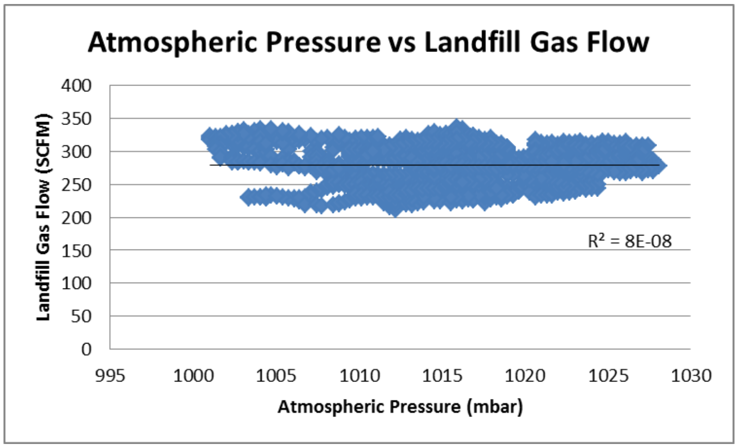


Figure 64. Atmospheric pressure vs landfill gas flow.

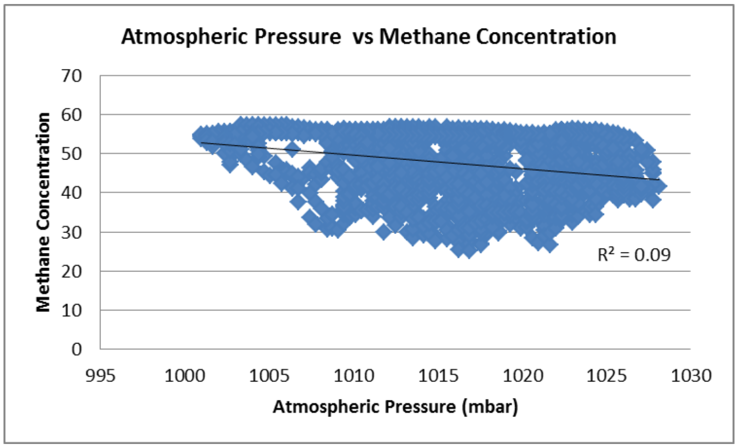


Figure 65. Atmospheric pressure vs methane concentration.

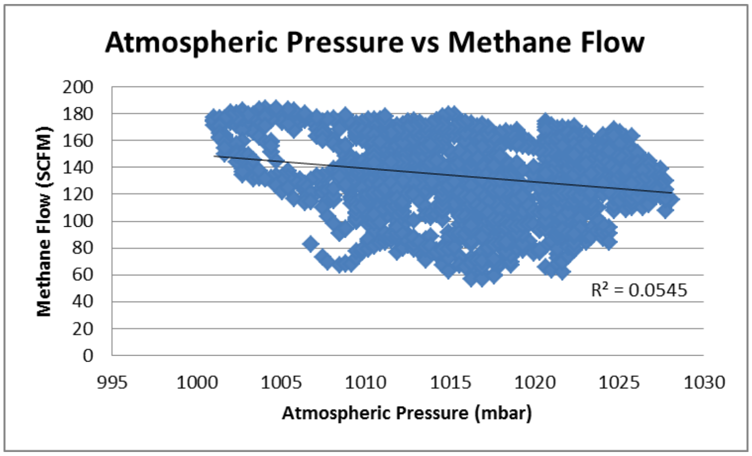


Figure 66. Atmospheric pressure vs methane flow.

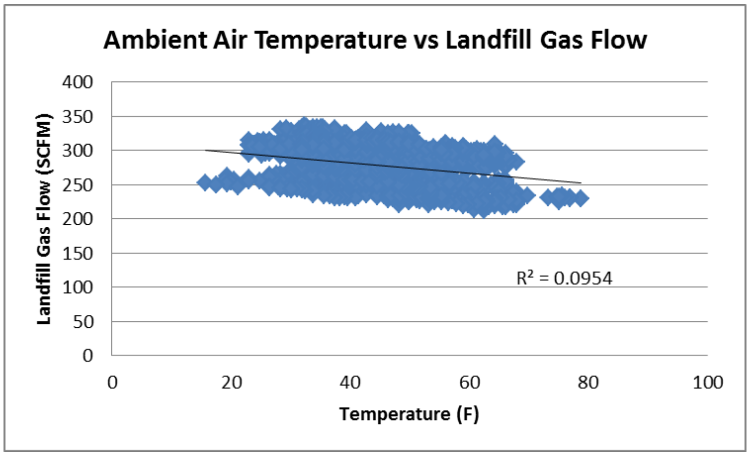


Figure 67. Ambient air temperature vs landfill gas flow.

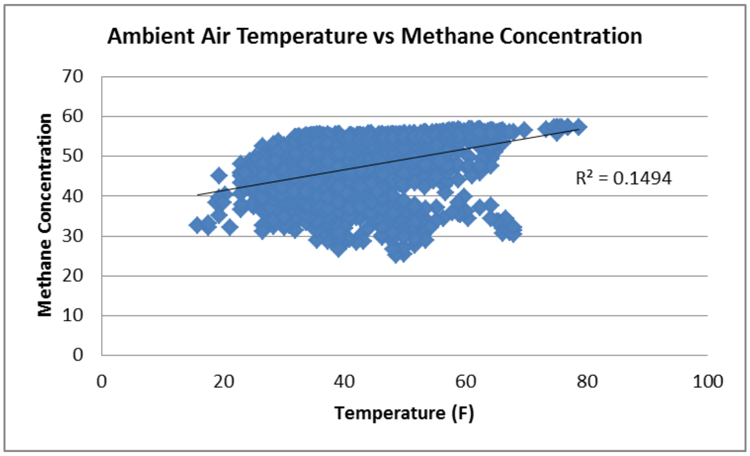


Figure 68. Ambient air temperature vs methane concentration.

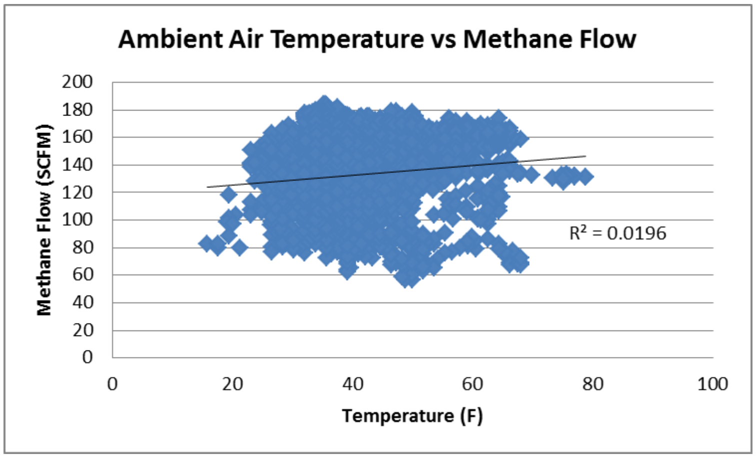


Figure 69. Ambient air temperature vs methane flow.

April 2013

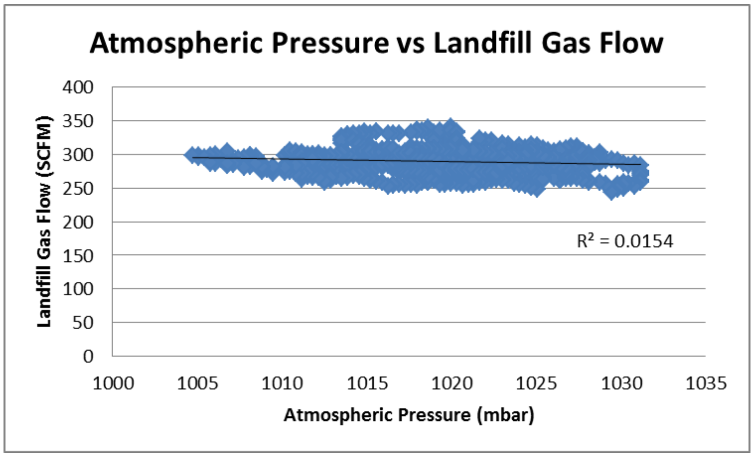


Figure 70. Atmospheric pressure vs landfill gas flow.

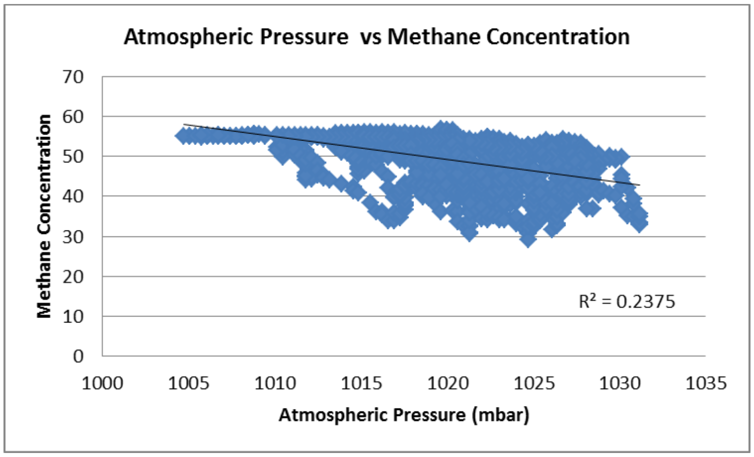


Figure 71. Atmospheric pressure vs methane concentration.

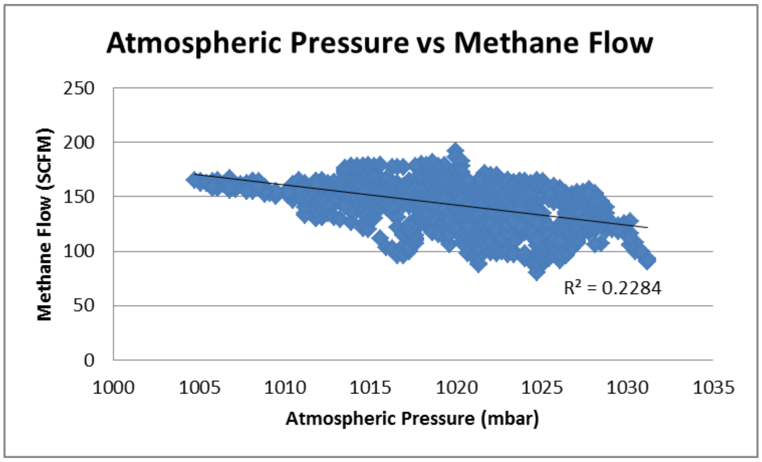


Figure 72. Atmospheric pressure vs methane flow.

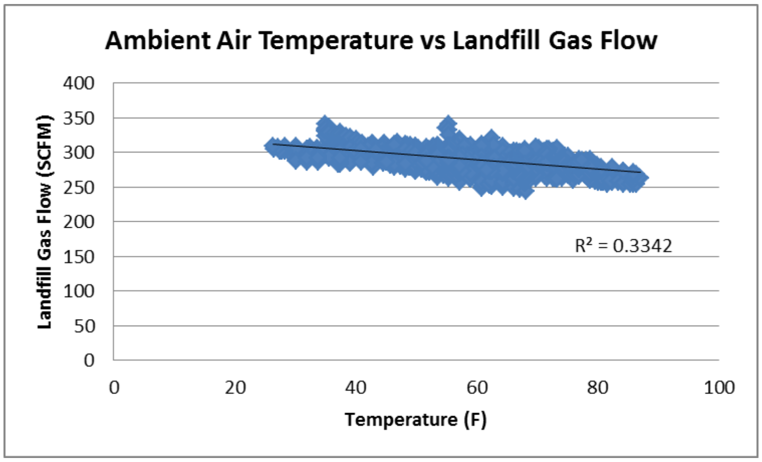


Figure 73. Ambient air temperature vs landfill gas flow.

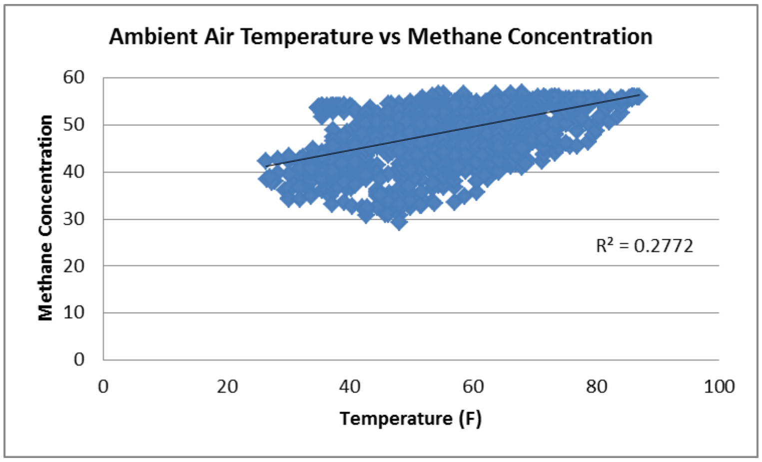


Figure 74. Ambient air temperature vs methane concentration.

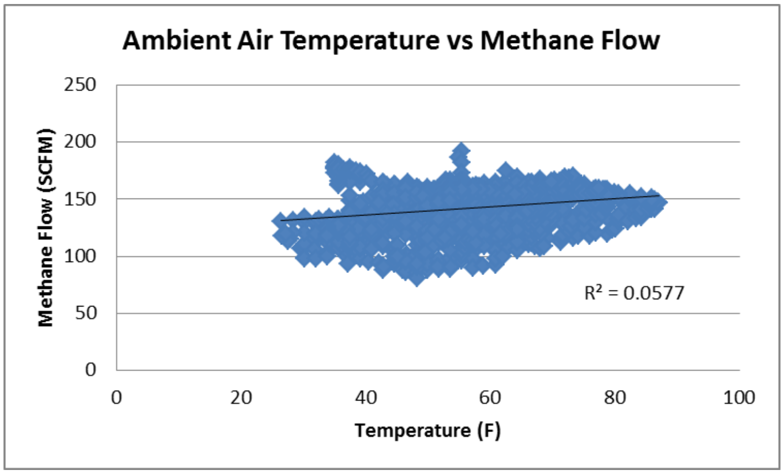


Figure 75. Ambient air temperature vs methane flow.

May 2013

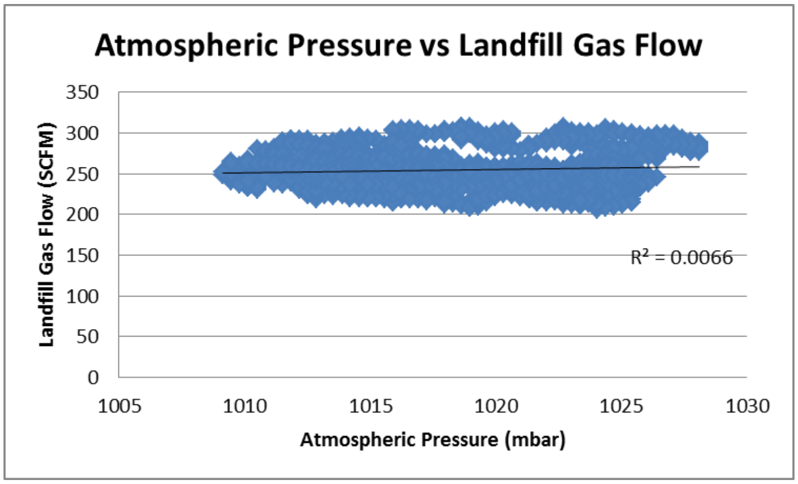


Figure 76. Atmospheric pressure vs landfill gas flow.

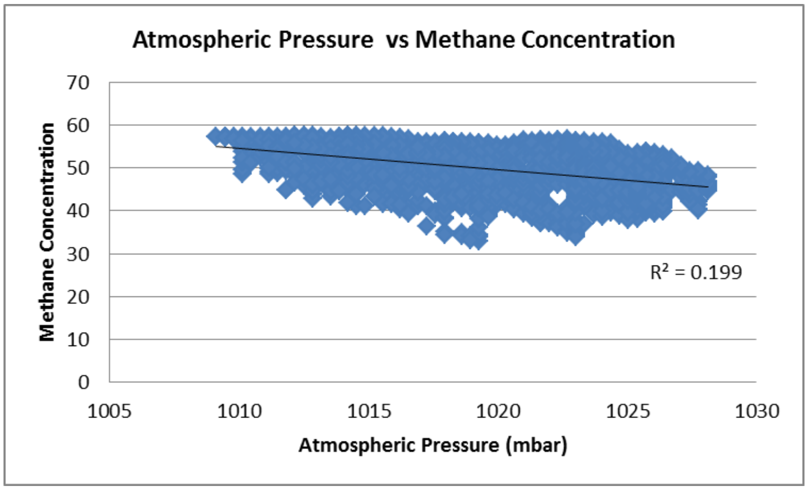


Figure 77. Atmospheric pressure vs methane concentration.

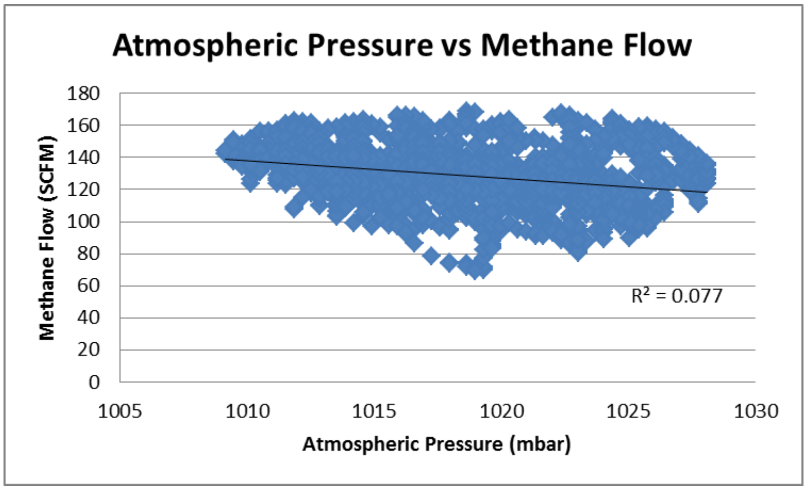


Figure 78. Atmospheric pressure vs methane flow.

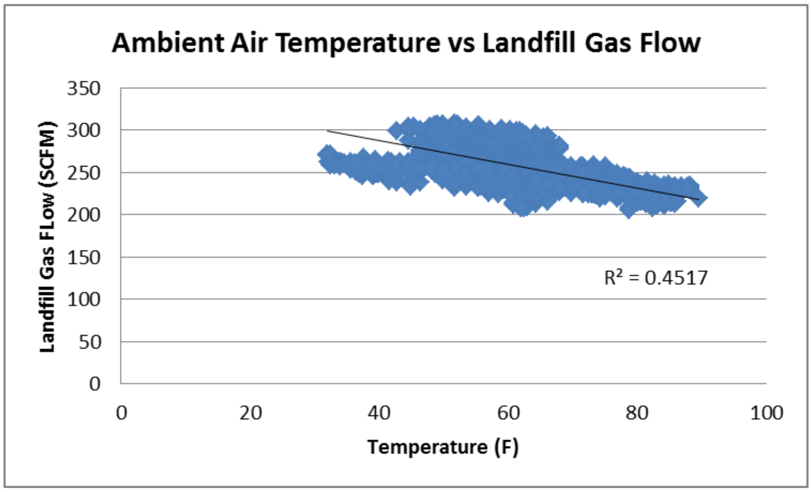


Figure 79. Ambient air temperature vs landfill gas flow.

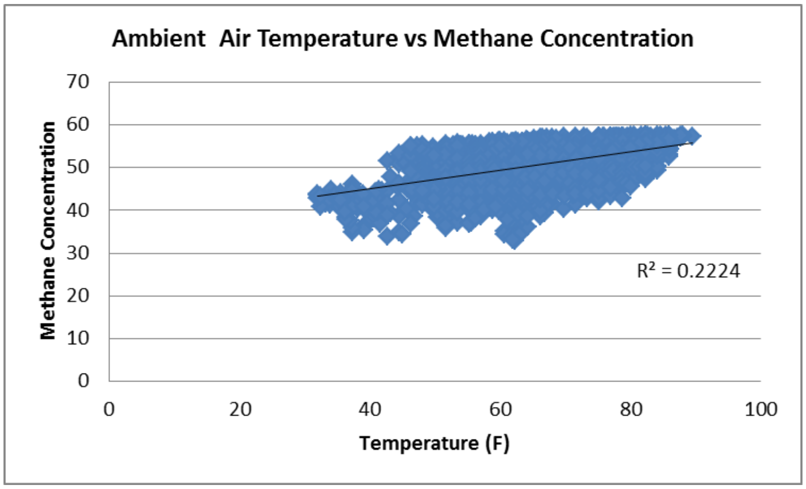


Figure 80. Ambient air temperature vs methane concentration.

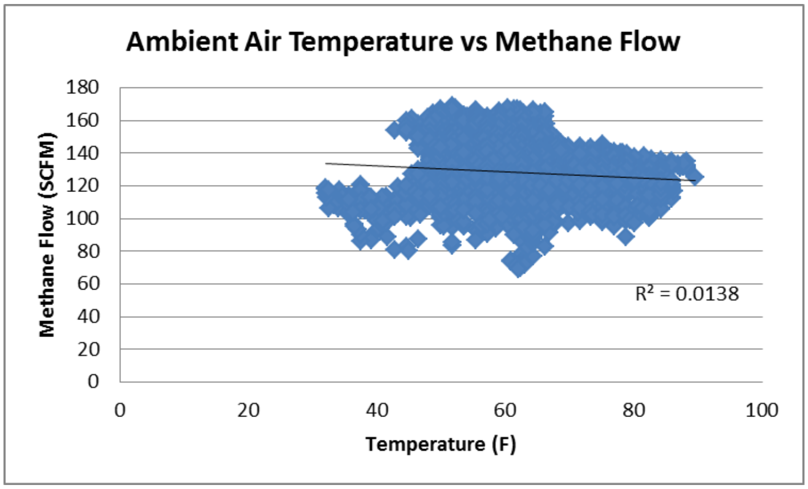


Figure 81. Ambient air temperature vs methane flow.

June 2013

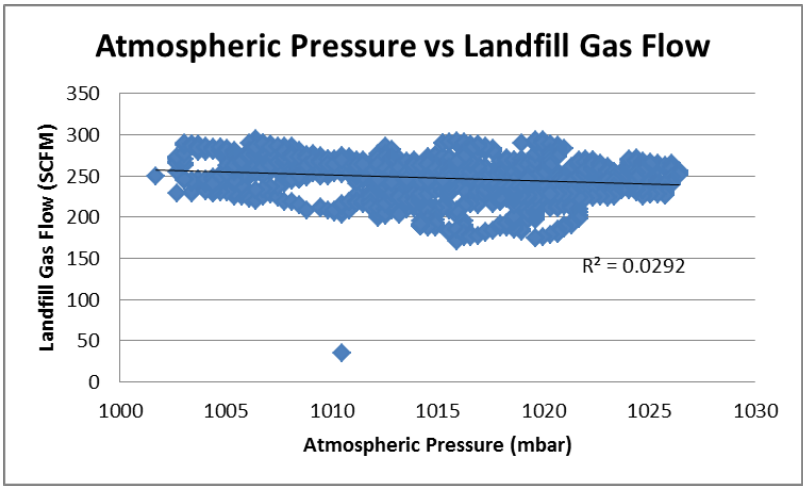


Figure 82. Atmospheric pressure vs landfill gas flow.

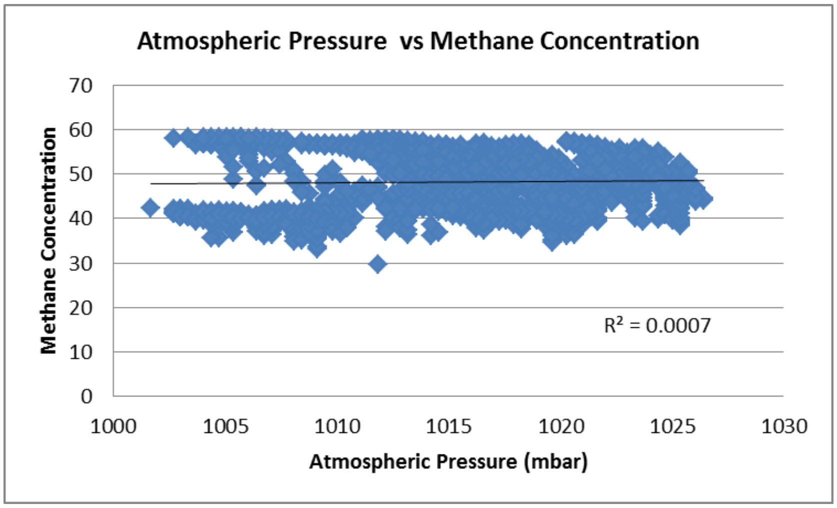


Figure 83. Atmospheric pressure vs methane concentration.

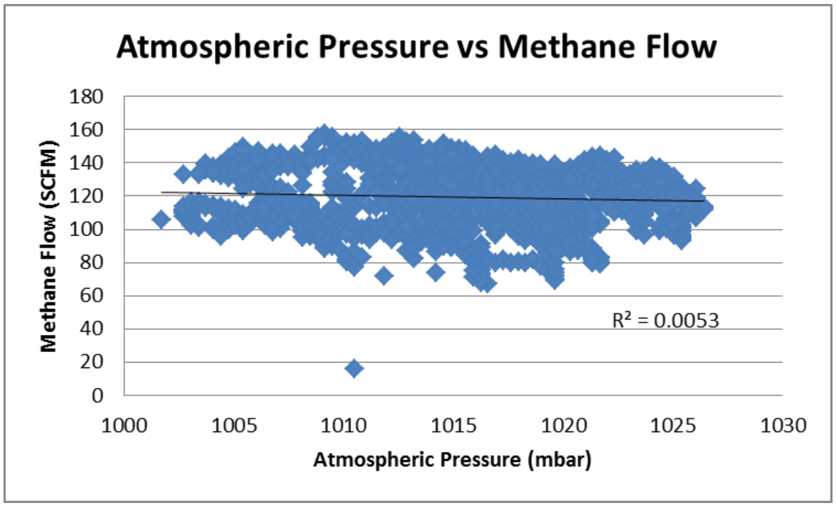


Figure 84. Atmospheric pressure vs methane flow.

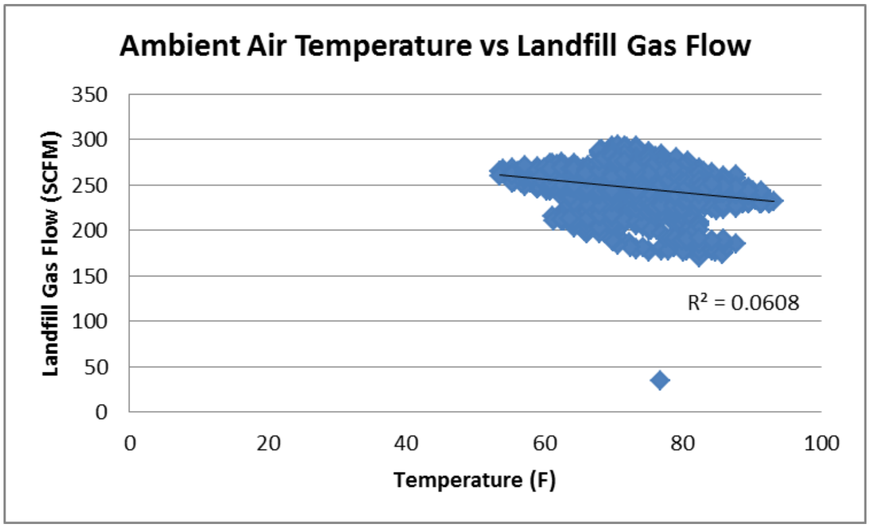


Figure 85. Ambient air temperature vs landfill gas flow.

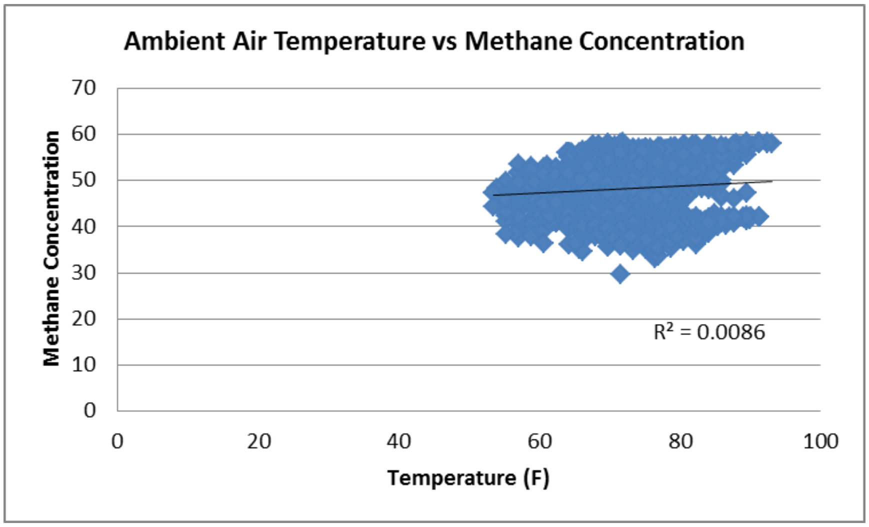


Figure 86. Ambient air temperature vs methane concentration.

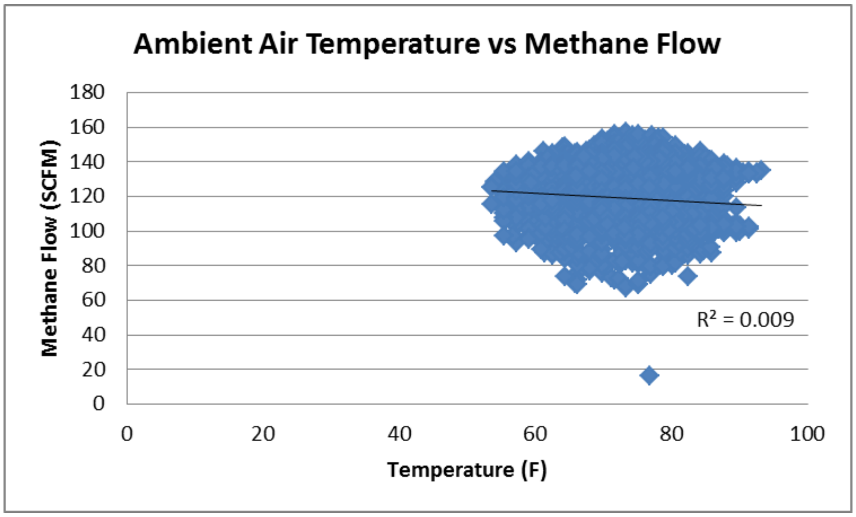
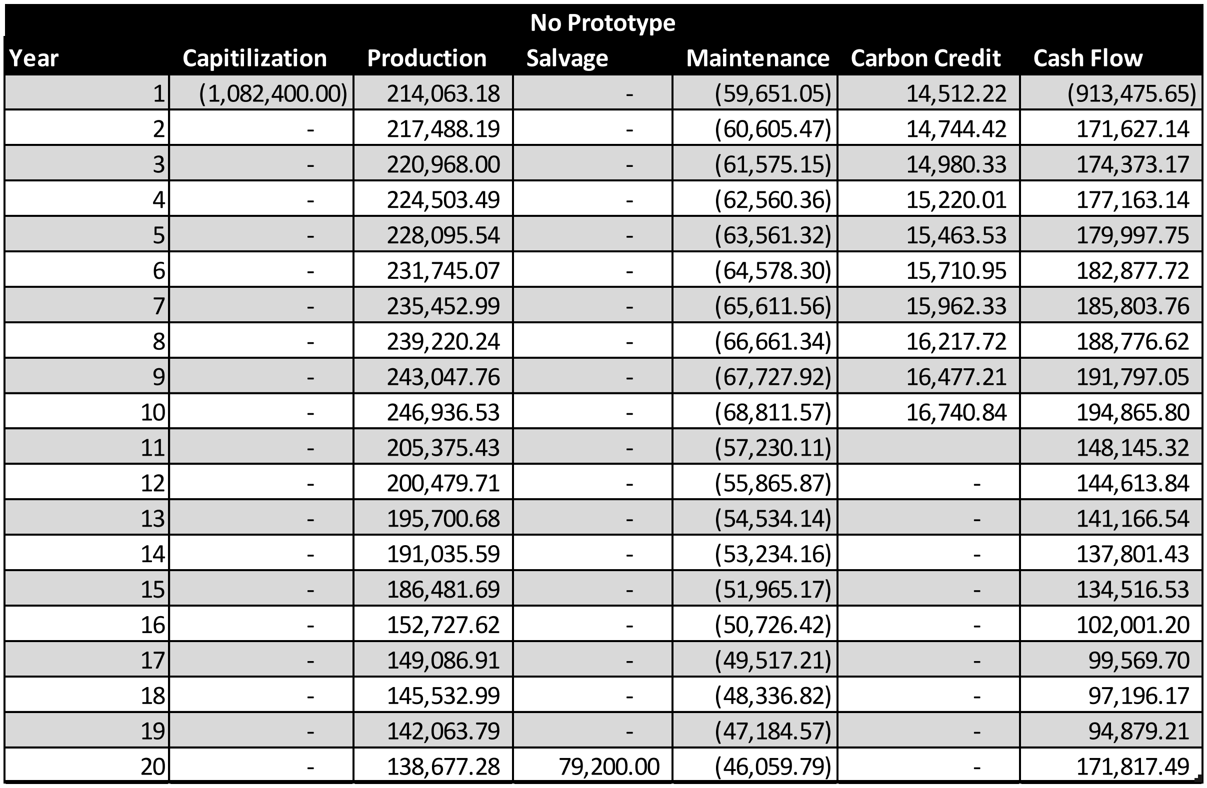


Figure 87. Ambient air temperature vs methane flow.

APPENDIX B

Cash Flow Tables

Table 4. *No Prototype 20 Year Cash Flow Diagram*



			No Prototype			
Year	Capitilization	Production	Salvage	Maintenance	Carbon Credit	Cash Flow
1	(1,082,400.00)	214,063.18	-	(59,651.05)	14,512.22	(913,475.65)
2	-	217,488.19	-	(60,605.47)	14,744.42	171,627.14
3	-	220,968.00	-	(61,575.15)	14,980.33	174,373.17
4	-	224,503.49	-	(62,560.36)	15,220.01	177,163.14
5	-	228,095.54	-	(63,561.32)	15,463.53	179,997.75
6	-	231,745.07	-	(64,578.30)	15,710.95	182,877.72
7	-	235,452.99	-	(65,611.56)	15,962.33	185,803.76
8	-	239,220.24	-	(66,661.34)	16,217.72	188,776.62
9	-	243,047.76	-	(67,727.92)	16,477.21	191,797.05
10	-	246,936.53	-	(68,811.57)	16,740.84	194,865.80
11	-	205,375.43	-	(57,230.11)		148,145.32
12	-	200,479.71	-	(55,865.87)	-	144,613.84
13	-	195,700.68	-	(54,534.14)	-	141,166.54
14	-	191,035.59	-	(53,234.16)	-	137,801.43
15	-	186,481.69	-	(51,965.17)	-	134,516.53
16	-	152,727.62	-	(50,726.42)	-	102,001.20
17	-	149,086.91	-	(49,517.21)	-	99,569.70
18	-	145,532.99	-	(48,336.82)	-	97,196.17
19	-	142,063.79	-	(47,184.57)	-	94,879.21
20	-	138,677.28	79,200.00	(46,059.79)	-	171,817.49

Table 5. *With prototype (100%) 20 year cash flow diagram*

No Prototype						
Year	Capitilization	Production	Salvage	Maintenance	Carbon Credit	Cash Flow
1	(1,082,400.00)	214,063.18	-	(59,651.05)	14,512.22	(913,475.65)
2	-	217,488.19	-	(60,605.47)	14,744.42	171,627.14
3	-	220,968.00	-	(61,575.15)	14,980.33	174,373.17
4	-	224,503.49	-	(62,560.36)	15,220.01	177,163.14
5	-	228,095.54	-	(63,561.32)	15,463.53	179,997.75
6	-	231,745.07	-	(64,578.30)	15,710.95	182,877.72
7	-	235,452.99	-	(65,611.56)	15,962.33	185,803.76
8	-	239,220.24	-	(66,661.34)	16,217.72	188,776.62
9	-	243,047.76	-	(67,727.92)	16,477.21	191,797.05
10	-	246,936.53	-	(68,811.57)	16,740.84	194,865.80
11	-	205,375.43	-	(57,230.11)		148,145.32
12	-	200,479.71	-	(55,865.87)	-	144,613.84
13	-	195,700.68	-	(54,534.14)	-	141,166.54
14	-	191,035.59	-	(53,234.16)	-	137,801.43
15	-	186,481.69	-	(51,965.17)	-	134,516.53
16	-	152,727.62	-	(50,726.42)	-	102,001.20
17	-	149,086.91	-	(49,517.21)	-	99,569.70
18	-	145,532.99	-	(48,336.82)	-	97,196.17
19	-	142,063.79	-	(47,184.57)	-	94,879.21
20	-	138,677.28	79,200.00	(46,059.79)	-	171,817.49

Table 6. *With prototype (90%) 20 year cash flow diagram*

No Prototype						
Year	Capitilization	Production	Salvage	Maintenance	Carbon Credit	Cash Flow
1	(1,082,400.00)	214,063.18	-	(59,651.05)	14,512.22	(913,475.65)
2	-	217,488.19	-	(60,605.47)	14,744.42	171,627.14
3	-	220,968.00	-	(61,575.15)	14,980.33	174,373.17
4	-	224,503.49	-	(62,560.36)	15,220.01	177,163.14
5	-	228,095.54	-	(63,561.32)	15,463.53	179,997.75
6	-	231,745.07	-	(64,578.30)	15,710.95	182,877.72
7	-	235,452.99	-	(65,611.56)	15,962.33	185,803.76
8	-	239,220.24	-	(66,661.34)	16,217.72	188,776.62
9	-	243,047.76	-	(67,727.92)	16,477.21	191,797.05
10	-	246,936.53	-	(68,811.57)	16,740.84	194,865.80
11	-	205,375.43	-	(57,230.11)		148,145.32
12	-	200,479.71	-	(55,865.87)	-	144,613.84
13	-	195,700.68	-	(54,534.14)	-	141,166.54
14	-	191,035.59	-	(53,234.16)	-	137,801.43
15	-	186,481.69	-	(51,965.17)	-	134,516.53
16	-	152,727.62	-	(50,726.42)	-	102,001.20
17	-	149,086.91	-	(49,517.21)	-	99,569.70
18	-	145,532.99	-	(48,336.82)	-	97,196.17
19	-	142,063.79	-	(47,184.57)	-	94,879.21
20	-	138,677.28	79,200.00	(46,059.79)	-	171,817.49

Vita

David Justin Harrill was born in Augusta, Georgia, to Michael and Helen Harrill. He graduated from Morris Community High School in Morris, Illinois in June 2006. The following autumn, he entered University of Iowa to study Electrical Engineering with an emphasis on computers, and in May 2010 he was awarded the Bachelor of Science degree with minors in Mathematics and Computer Science. In the fall of 2010, he entered the Master's in Business Administration program at Governors State University and began work toward an M.B.A. degree. The M.B.A. was awarded in May 2012. In August, 2012, Mr. Harrill commenced work toward his second Master's degree, the Master of Science in Technology with a concentration in Renewable Energy Engineering at Appalachian State University. Mr. Harrill is an Eagle Scout and plans to stay active in the Scouting program. He resides in Morris, Illinois, with his parents and younger sister.