Post-Perforation Technology for Rehabilitating Vertical Methane Extraction Wells at Municipal Solid Waste Facilities

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Post-Perforation Technology for Rehabilitating Vertical Methane Extraction Wells at Municipal Solid Waste Facilities

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Abstract

The capture of methane from waste disposal facilities can have a significant impact on the reduction of anthropogenic methane emissions. In the United States, more than six hundred facilities are capturing approximately 26.3 MMTCO$_2$e methane annually (U.S. EPA, 2015). The importance of the capture is two-fold: reduction of greenhouse gases and the exploitation of a beneficial energy source.

Yet methane capture efficiencies have been moderate due to many logistical issues. Few methods currently exist to rehabilitate marginally producing extraction wells at landfills. This study was designed to test whether post-perforation technology, invented in 2009, is effective in increasing the efficiency of gas capture from marginally producing wells.

This study examined the effectiveness of post-perforation technology to improve the environmental and energy benefits associated with additional methane capture. Post perforation technology was designed and developed to rehabilitate marginal extraction wells. The technology creates new openings to allow more methane to enter an extraction well. Prior to this technology low yield or marginal extraction wells were abandoned and new extraction wells were drilled and installed.

The study consisted of gathering data from nine existing municipal solid waste facilities that had extraction wells previously post-perforated. After review, five of the nine facilities were selected for the study. For adequate sample size, facilities with nine or more post-perforated extraction wells were included in this study. The number of post-

perforated wells from the five facilities ranged from 9 to 19. All facilities were from Texas or Florida. Post-perforation at these facilities was conducted between September 2009 and October 2014. The number of methane extraction wells from the five facilities ranged from 49 to 138. Measurements for % methane (CH_4), initial flow (standard cubic feet per minute scfm) and adjusted flow (scfm) were obtained at each extraction well at least on a monthly basis. One year's worth of data was obtained at each facility, six months prior and six month after post-perforation for each extraction well.

All extraction at each of the five facilities wells were categorized into one of three groups for analyses based on the following criteria. If the initial flow was ≤2 (scfm) or the % methane was <50% the extraction well was a candidate for post-perforation. If this type of extraction well was subsequently post-perforated, it was categorized into group 1, but if not selected for post-perforation it was categorized into group 2, serving as a control group within that landfill. However, if the initial flow was >3 (scfm) the extraction wells was categorized into group 3. The total sample size for group 1 was 67, group 2 contained 165, and group 3 contained 261 extraction wells.

The results of the analyses demonstrated a statistical effect after post-perforation on the initial flow (scfm) and on adjusted flow (scfm) in Group 1, the treatment group. The mean initial flow after post-perforation increased from 16.9 to 28.5 scfm ($t = 3.05$; $p = 0.016$; $n=67$), and the adjusted flow increased from 16.8 to 30.1 scfm ($t = 3.66$; $p = 0.002$; $n=67$). Group 2 and Group 3 mean values also increased after the time of perforation of Group 1 wells, but with not as large an increase in either variable.

The added methane capture from landfills yielded substantial environmental and energy benefits. Four facilities yielded mean flow increases of methane at 125, 157, 120 and 558 scfm, for a total 960 scfm methane. The increase from those four facilities represents a total equivalent emission reduction of 0.1329 $MMTCO_2E$/year, equivalent to 5,336 tons of CH_4/year or 13,171 tons of CO_2/ year. The energy benefit from 960 scfm could heat 3,315 homes for a year.

This study demonstrates that post-perforation does increase the capture of methane in extraction wells at municipal solid waste facilities. Furthermore, this study demonstrated the advantages to be gained from any methodology or innovation that decreases fugitive emissions from landfills. Further research is required to increase the efficiency of methane capture. Industry change is slow due to the inconsistencies between federal, state and local regulatory requirements, but this study helps point the way.

Biographical Sketch

Stefan Stamoulis is President and Principal Hydrogeologist of Hydrogeologic/ Environmental Testing (H/ET), in Alvin, Texas. As President/ Principal Hydrogeologist he manages operations at the company. Mr. Stamoulis leads a second geotechnical drilling company (Malibu Drilling) that provides drilling services to the Geotechnical Engineering Industry. He is a noted inventor, currently holding three patents with the United States Patent and Trademark Office (USPTO). These patents encompass the technology evaluated in this thesis. Prior to founding H/ET in 1993, Mr. Stamoulis was a hydrogeologist at two of the foremost environmental engineering firms in Texas, providing consulting services to the waste management industry.

Mr. Stamoulis holds a bachelor's of business administration from Texas Wesleyan University, in Fort Worth, Texas (1984) and a bachelor's of science in geology from Tarleton State University, in Stephenville, Texas (1986). In 2007, he earned a master's of business administration, from Pepperdine University, in Malibu, California.

His credentials include a Geoscience (Geology) registration in the State of Louisiana (LA-502), in the State of Texas, (TX-333), a license in the State of Texas as a Master Water Well Driller (TX-54882), and an additional Master Water Well Driller certification in the State of New Mexico (WD-1576).

He sits on the seven-member Board of the Moody Endowment of Galveston, Texas. The endowment was established to support research into traumatic brain injury rehabilitation. In addition to management of the portfolio, the board oversees the disbursement of research grants in appropriate field of medicine. In related service, Mr. Stamoulis sits on the board of the Transitional Learning Center (TLC) of Galveston, Texas as one of its eight members. The Transitional Learning Center is one of the leading traumatic brain injury (TBI) rehabilitation facilities in the United States. The Transitional Learning Center, established in 1982, is a non-profit organization with the sole purpose of providing post-acute traumatic brain injury rehabilitation. The Transitional Learning Center's support comes from the Moody Endowment and the Moody Foundation, both of Galveston, Texas. Mr. Stamoulis sits as the Chairman of the on the audit committee at the Moody Endowment and the Transitional Learning Center.

Dedication

I dedicated this thesis with love to my beautiful bride and soul mate Joanna Stamoulis, and our newborn baby girl Katina Mirka Stamoulis. In addition, I dedicate this to my sister Mary Kay Bishop and my entire staff and employees at Hydrogeologic/ Environmental Testing and Malibu Drilling. This thesis would not have been possible without my classmates and professors at Harvard University and the Harvard Extension School. My sanity would have crumbled if not for the support of my loyal friends: Roger Quiroga, Don Suderman, Sonny Milos and Paul Dimarco. They supported my educational efforts, mentored me during the rough patches and helped me laugh during the smooth times.

More importantly, I dedicate this scientific endeavor to all non-believers, sceptics and deniers because, without this fraction of society, research, science and innovation would not progress.

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Any educational endeavor requires moral support from family, friends, and colleagues. My educational preparation and the completion of this thesis was no different. I am rich in indebtedness.

God has blessed me with a wife whose love and support sustains my drive. She has filled my life with joy and happiness. Without her, I could not have continued on and completed this program. She amazes me every day with her laughter, critical acuity and sense of humor. She has endured the disruptions of a move from Europe to Texas and carried our child through a period of immense sacrifice while we mastered the bureaucratic processes that now allow us to be together. My love for her assisted in completing this thesis.

I am grateful to all my classmates in the Sustainability and Environmental Management Program at the Harvard Extension School, especially Romilly Cavanaugh, Nicole Amalfitano, Jennifer Tracey and Chryssa Gardner. I would like to acknowledge Tak Makino for his assistance with the statistical analysis portion of this thesis. Last, but not least, I would like to acknowledge Dr. John Gorman for his editorial assistance on the fundamentals of syntax and the elements of style.

Most of all, I wish to thank Dr. Mark Leighton, who advised me along the course of this process and kept me on the path to completion. His ability to guide, mentor and direct had a profound impact on the outcome and overall final product.

Table of Contents

List of Tables

List of Figures

Definition of Terms

Annulus: The space between two concentric objects, such as that between the wellbore and casing or between casing and tubing, where fluid can flow. Pipe may consist of drill collars, drill pipe, casing or tubing.

Apertures: An aperture is a hole or an opening through which gas can travel.

Balance gas: The quantity of gases other than CH_4, CO_2, and O_2 measured in a GEM 2000 gas meter is expressed as balance gas and displayed as nitrogen (N).

Barometric pressure/Atmospheric pressure is the force per unit area exerted on a surface by the weight of air above that surface in the atmosphere of Earth.

Clean Air Act: In the U.S.A. the original Clean Air Act was passed in 1963, but our national air pollution control program is based on the 1970 version of the law. The 1990 Clean Air Act Amendments are the most far-reaching revisions of the 1970 law. In this summary, we refer to the 1990 amendments as the 1990 Clean Air Act.

CO_2e: (CDE) and Equivalent carbon dioxide (e) are two related, but distinct measures for describing how much global warming a given type and amount of greenhouse gas may cause, using the functionally equivalent amount or concentration of carbon dioxide as the reference.

Comprehensive Environmental Response, Compensation and Liability Act (CERCLA): enacted in 1980 by the U.S. Congress to deal with historic and abandoned sites.

Device ID: ID code in a Landtec GEM 2000 for a extraction well location, the ID can be stored along with the data measurements. Subsequently, the data can be retrieved and uploaded to a database.

Gas Collection and Control Systems: Well-designed active collection systems are considered the most effective means of landfill gas collection. Active gas collection systems include vertical and horizontal gas collection wells similar to passive collection systems. Unlike the gas collection wells in a passive system, however, wells in the active system should have valves to regulate gas flow and to serve as a sampling port. Sampling allows the system operator to measure gas generation, composition, and pressure. Active gas collection systems include vacuums or pumps to move gas out of the landfill and piping that connects the collection wells to the vacuum. Vacuums or pumps pull gas from the landfill by creating low pressure within the gas collection wells. The low pressure in the wells creates a preferred migration pathway for the landfill gas. The size, type, and number of vacuums required in an active system to pull the gas from the landfill depend on the amount of gas being produced. With information about landfill gas generation, composition, and pressure, a landfill operator can assess gas production and distribution changes and modify the pumping system and collection well valves to achieve maximum efficiency in running an active gas collection system. The system design should account for future gas management needs, such as those associated with landfill expansion.

Gas Flow: An orifice plate is a device used to measuring flow rate and for reducing pressure or for restricting flow (in the latter two cases it is often called a restriction plate). Either a volumetric or mass flow rate may be determined, depending on the calculation associated with the orifice plate. It uses the same principle as a Venturi nozzle, namely Bernoulli's principle which states that there is a relationship between the pressure of the fluid and the velocity of the fluid. When the velocity increases, the pressure decreases and vice versa. The GEM 2000 has the ability to store initial and adjusted flow.

GEM 2000: is a portable instrument designed for analyzing Landfill Gas (LFG) composition and calculating flow. The GEM 2000 is designed for monitoring gas migration probes and for monitoring gas extraction system. The GEM 2000 is certified intrinsically safe and offers improved speed and accuracy. It also measures and displays Btu content, temperature (with optional Temperature Probe) relative and atmospheric pressures as well as CH_4 LEL (Lower Explosive Limit).

Global Warming Potential (GWP): is a relative measure of how much heat a greenhouse gas traps in the atmosphere. It compares the amount of heat trapped by a certain mass of the gas in question to the amount of heat trapped by a similar mass of carbon dioxide. A GWP is calculated over a specific time interval, commonly 20, 100 or 500 years. GWP is expressed as a factor of carbon dioxide (with the GWP of CO_2 standardized to 1).

Greenhouse Gases (GHGs): These are gases which individually act to trap solar energy near the earth. GHGs for which emission levels have been estimated are: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF_6), carbon tetrafluoride (CF_4), carbon hexafluoride (C_2F_6) and hydrofluorocarbons (HFCs). Those gases, that are transparent to solar (short-wave) radiation but opaque to long-wave (infrared) radiation, thus preventing long-wave radiant energy from leaving Earth's atmosphere. The net effect is a trapping of absorbed radiation and a tendency to warm the planet's surface.

HDPE: High Density Polyethylene is a polyethylene thermoplastic made from petroleum. Known for its positive strength-to-density ratio, HDPE is commonly used in the production of plastic bottles, corrosion-resistant piping, geomembranes, and plastic equivalent for lumber. HDPE is commonly recycled, and has the number "2" as its resin identification code (formerly known as recycling symbol).

Landfill: The most common form of disposal of household, commercial, and industrial refuse; it appears that 80 to 90% of the world's refuse will be disposed of by this method for several years to come. The type of sites used for such disposal include: mineral excavations, abandoned quarries, low-lying land, valleys, areas involving the reclamation of land from water, or flat land altered to build up a feature. Generally, in a landfill scheme, refuse is tipped in trenches or cells prepared to such a width that the daily input of refuse can be effectively covered, presenting a clean face each day. The refuse can be tipped either at the bottom of the face and bulldozed into the face, or tipped on top of the previous fill and bulldozed over the face. It is essential that the refuse be adequately covered and compacted to allow traffic over the fill. This landfill method is known in the UK as 'controlled tipping' and in the USA by the title of 'sanitary landfill'; the former emphasizes the system by which the waste is deposited, while the latter emphasizes hygienic aspects. The landfill technique is often used constructively to provide facilities for sport. Its use in urban development involves many years of settlement. Landfills must be carefully located and managed to avoid such negative effects as: leachates reaching streams, the breeding of vectors and rodents, odor, windblown litter, and an appearance of desolation. The method is sometimes used for the disposal of hazardous wastes, necessitating impervious cells and rigorous control methods.

Landfill gas: Gas that is generated by decomposition of organic material at landfill disposal sites. The average composition of landfill gas is approximately 50 percent methane and 50 percent carbon dioxide and water vapor by volume. The methane percentage, however, can vary from 40 to 60 percent, depending on several factors including waste composition (e.g. carbohydrate and cellulose content). The methane in landfill gas may be vented, flared, combusted to generate electricity or useful thermal energy on-site, or injected into a pipeline for combustion off-site.

Landfill Methane Outreach Program: The U.S. Environmental Protection Agency's Landfill Methane Outreach Program (LMOP) is a voluntary assistance outreach that helps to reduce methane emissions from landfills by encouraging the recovery and beneficial use of landfill gas (LFG) as an energy resource. LFG contains methane, a potent greenhouse gas that can be captured and used to fuel power plants, manufacturing facilities, vehicles, homes, and more. By joining LMOP, companies, state agencies, organizations, landfills, and communities gain access to a vast network of industry experts and practitioners, as well as to various technical and marketing resources that can help with LFG energy project development.

Leachate: Water that collects contaminants as it trickles through wastes, pesticides or fertilizers. Leaching may occur in farming areas, feedlots, and landfills, and may result in hazardous substances entering surface water, ground water, or soil.

Marginal Producing Extraction Well: Non-optimal Extraction Well, an extraction well that exhibits an average flow of less than or equal to 2 (scfm) or a methane percentage is less than 50.

Methane Extraction Well: Landfill gas is gathered from landfills through extraction wells placed depending on the size of the landfill. Roughly one well per acre is typical.

Methane Generation Rates: For every one million tons of municipal solid waste approximately 432,000 standard cubic feet per day gas is generated. This equates to approximately 0.78 megawatts (MW) of electricity.

Methane (CH_4): This hydrocarbon is a greenhouse gas with a global warming potential most recently estimated at 21. Methane is produced through anaerobic (without oxygen) decomposition of waste in landfills, animal digestion, decomposition of animal wastes, production and distribution of natural gas and petroleum, coal production, and incomplete fossil fuel combustion. The atmospheric concentration of methane has been shown to be increasing at a rate of about 0.6 percent per year, and the concentration of about 1.7 part per million by volume (ppmv) is more than twice its pre-industrial value. However, the rate of increase of methane in the atmosphere may be stabilizing.

Methaneogensis: methaneogensis or biomethanation is the formation of methane by microbes known as methanogens. Organisms capable of producing methane have been identified only from the domain Archaea, a group phylogenetically distinct from both eukaryotes and bacteria, although many live in close association with anaerobic bacteria. The production of methane is an important and widespread form of microbial metabolism. In most environments, it is the final step in the decomposition of biomass.

MMTCO2e: Million metric tons of carbon dioxide equivalent. This measure can aggregate different greenhouse gases into a single measure, using global warming potentials. One unit of carbon is equivalent to 3.664 units of carbon dioxide.

Municipal Solid Waste: Non-hazardous common garbage or trash generated by industries, businesses, institutions, and homes. It is defined by local governments, and in general does not include automobile oil, tires, lead-acid batteries, hazardous or infectious wastes, demolition debris, etc.

National Emissions Standards for Hazardous Air Pollutants (NESHAP): Also using the acronym NESHAP, are emissions standards set by the United States Environmental Protection Agency—EPA. The standards are for air pollutants not covered by National Ambient Air Quality Standards—NAAQS, that may cause an increase in fatalities or in serious, irreversible, or incapacitating illness.

New Source Performance Standards (NSPS): Section 111 of the Clean Air Act authorized the EPA to develop technology-based standards which apply to specific categories of stationary sources. These standards are referred to as New Source Performance Standards (NSPS) and are found in 40 CFR Part 60. The NSPS apply to new, modified and reconstructed affected facilities in specific source categories such as manufacturers of glass, cement, rubber tires and wool fiberglass. As of 2005, there were approximately 75 NSPS.

Nitrogen (N): This is the chemical element with symbol N and atomic number 7. It is the lightest pnictogen. At room temperature, it is a colorless and odorless diatomic gas. Nitrogen is a common element in the universe, estimated at about seventh in total abundance in our galaxy and the Solar System. On Earth, the element forms about 78% of Earth's atmosphere and as such is the most abundant pure element.

Non-Methane Volatile Organic Compounds (NMVOCs): Organic compounds, other than methane, which participate in atmospheric photochemical reactions. It is a generic term for a large variety of chemically different compounds, for example: benzene, ethanol, formaldehyde, cyclohexane, 1,1,1-trichloroethane or acetone. Essentially, NMVOCs are identical to VOCs, but with methane excluded.

Oxygen (O_2): It is a colorless, odorless and tasteless gas that has a very low solubility in water. Oxygen is the second largest component of the Earth's atmosphere, it occurs as O_2 as well as the allotrope O_3 called Ozone. Oxygen represents 89% of mass in water molecules, so that the Earth's water supplies are largely Oxygen.

Ozone precursors: These are chemical compounds such as carbon monoxide, methane, non-methane hydrocarbons, and nitrogen oxides, which in the presence of solar radiation react with other chemical compounds to form ozone, mainly in the troposphere.

Ozone: Ozone, the triatomic form of oxygen (O_3), is a gaseous atmospheric constituent. In the troposphere, it is created by photochemical reactions involving gases resulting both from natural sources and from human activities (photochemical smog). In high concentrations, tropospheric ozone can be harmful to a wide range of living organisms. Tropospheric ozone acts as a greenhouse gas. In the stratosphere, ozone is created by the interaction between solar ultraviolet radiation and molecular oxygen (O2). Stratospheric ozone plays a decisive role in the stratospheric radiative balance. Depletion of stratospheric ozone, due to chemical reactions that may be enhanced by climate change, results in an increased ground-level flux of ultraviolet (UV- B) radiation.

Ozone layer (ozonosphere): A layer or stratum of the atmosphere about 20 km and 50 km above the surface of the Earth. In this layer, oxygen molecules are split by the sun's ultraviolet radiation, the resulting atomic oxygen recombining with unaffected molecules to produce ozone. The concentration of ozone around the globe in this layer varies throughout the year. A thinning may occur, for example, over the Antarctic. This phenomenon is often referred to as a ‘hole’ in the ozone layer. The preservation of the ozone layer is most important for the survival of humanity, as it is a protective belt moderating the effect of incoming ultraviolet radiation from the sun. Its impairment will undoubtedly promote an increase in the incidence of skin cancer throughout the world. The ozone layer is thought to be threatened by the use of chlorofluorocarbons (CFCs), thus efforts are being made to restrict the production and use of these substances.

Post-perforation: A new technology developed to rehabilitate methane extraction wells at municipal solid waste facilities: a process of creating apertures (perforations) in HDPE or PVC methane extraction wells.

Radiative forcing: A measure of the influence of a particular factor (e.g. greenhouse gas (GHG), aerosol, or land use change) on the net change in the Earth’s energy balance.

Renewable energy: Energy obtained from sources that are essentially inexhaustible. A contrast is fossil fuels, of which there is a finite supply. Renewable sources of energy include wood and other plant material waste, geothermal, wind, photovoltaic, and solar thermal energy.

Resource Conservation and Recovery Act (RCRA): Enacted in 1976, this was the first law mandating a federal regulatory role, to deal with existing and future sites.

Resource Recovery Act: An Act enacted in 1970, focused on recycling and reclamation of waste. Its main focus was diversion from landfilling.

Sink: In air pollution, a reception area for the absorption of material from the atmosphere; for example, the absorption of carbon dioxide by the oceans, or the absorption of carbon dioxide by photosynthetic plants. In water pollution, the assimilative capacity of bodies of water for thermal pollution and other pollutants.

Solid Waste Disposal Act (SWDA): The first solid waste management act, enacted in 1965.

Static pressure: A pressure can be identified for every point in a body of fluid, regardless of whether the fluid is in motion or not. Pressure can be measured using an aneroid, Bourdon tube, mercury column, or by various other methods. The GEM 200 gas meter can record initial and adjusted static pressure.

Subtitle “D”: RCRA, Subtitle D regulates the management of nonhazardous solid waste. It establishes minimum federal technical standards and guidelines for state solid waste plans in order to promote an environmentally sound management of solid waste.

System Pressure/Vacuum: A prime mover that creates a vacuum to operate the gas collection and control system at a landfill. The GEM 2000 gas meter can measure the value, record, and upload the value into a database.

Waste: Any matter, whether liquid, solid, gaseous, or radioactive, which is discharged, emitted, or deposited in the environment in such volume, concentration, constituency, or manner as to cause a significant alteration of the environment. The concept of waste embraces all unwanted and economically unusable byproducts or residuals at any given place and time, and any other matter that may be discharge, accidentally or otherwise, into the environment.

Waste Generation Rates: Solid waste generation rates estimate the amount of waste created by residences or businesses over a certain amount of time (day, year, etc.). Waste generation includes all materials discarded, whether or not they are later recycled or disposed in a landfill. Waste generation rates for residential and commercial activities can be used to estimate the impact of new developments on the local waste stream.

Waste management: A comprehensive, integrated, and rational systems approach aimed towards the achievement and maintenance of acceptable environmental quality and the support of sustainable development. It involves preparing policies; determining environmental standards; fixing emission rates; enforcing regulations; monitoring air, water, and soil quality; dealing with noise emissions; and offering advice to government, industry, land developers, planners, and the public.

Acronyms

ATSDR	Agency for Toxic Substances and Disease Registry
BFI	Browning-Ferris Industries, presently operating as Republic Services Inc.
CAA	Clean Air Act
CERCLA	Comprehensive Environmental Response Compensation and Liability Act
CFC_S	Chlorofluorocarbons
CFR	Code of Federal Register
CH_3	Methyl Group
CH_4	Methane
CL	Chlorine
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
EPA	Environmental Protection Agency
Ft BGS	Feet Below Ground Surface
GCCS	Gas Collection and Control System
GHG	Greenhouse Gas
GWP	Global Warming Potential
H/ET	Hydrogeologic / Environmental Testing
H_2O	Water
HCL	Hydrochloric Acid
HDPE	High-density Polyethylene
HSWA	Hazardous and Solid Waste Amendments
IPCC	Intergovernmental Panel on Climate Change

LFG	Landfill Gas
LMOP	Landfill Methane Outreach Program
LNG	Liquefied Natural Gas
MMSCFD	Million Metric Standard Cubic Feet per Day
$MMTCO_2eq$	Million Metric Tons Carbon Dioxide Equivalent
MSW	Municipal Solid Waste
MSWF	Municipal Solid Waste Facilities
$MTCO_2$ eq	Metric Tonnes Carbon Dioxide Equivalent
MW	Mega Watts
N	Nitrogen
N_2O	Nitrogen Oxide
NESHAP	National Emissions Standards for Hazardous Air Pollutants
NSPS	New Source Performance Standards
NSWMA	National Solid Waste Management Authority
O	Oxygen
O_3	Tropospheric Ozone
OECD	Organization for Economic Co-operation and Development
OH	Hydroxyl Radical
OLS	Ordinary Least Squares
ppbv	Part per Billion by Volume
ppm	Parts per Million
PVC	Polyvinyl Chloride
RCRA	Resource Conservation and Recovery Act

SCFM	Standard Cubic Feet per Minute
SWDA	Solid Waste Disposal Act
SWICS	Solid Waste Industry for Climate Solutions
TBI	Traumatic Brain Injury
$TgCO_2eq$	Carbon Dioxide Equivalent
TLC	Transitional Learning Center
USDOC	United States Department of Census
USPTO	United States Patent and Trademark Office
Δ (delta)	Incremental change in a variable

Chapter I

Introduction

All municipal solid waste landfills emit methane. The release of methane is a problem because this gas is one of the most potent contributors to the greenhouse effect. Methane from the landfilling of municipal solid waste is the third largest anthropogenic factor in climate change (Kabir & Halim, 2011).

Present methane gas collection and control systems at municipal solid waste facilities are sub-optimal. Such deficiency can cause an increase in the volume of methane released into the atmosphere and decease the capture of a gas that can be utilized as a renewable energy source. Any methodology that successfully increases the capture of methane will help protect the environment and add a supply of domestic energy otherwise lost.

In the United States, regulations mandate control of municipal solid waste facilities producing methane. Facilities must capture this recoverable gas and prevent its release into the atmosphere. Many facilities have installed systems to use the captured gas for beneficial purposes. As of 2014, approximately 3,091 Municipal Solid Waste Facilities (MSWF's) operate to dispose of the two hundred and fifty million tons of waste generated annually (U.S EPA, 2015). All are required to collect and control landfill gas, preventing its off-site migration. Currently, 636 facilities enhance methane capture with a beneficial use component (U.S EPA, 2015). The landfill gas (LFG) can be indirectly used for electricity generation, or directly used as compressed natural gas (CNG) or liquefied natural gas (LNG). For electricity generation, the detailed data is tracked closely (U.S.EPA, 2015). According to the Environmental Protection Agency's Landfill Methane Outreach Program (LMOP), these facilities generate 2,032 Mega Watts (MW) annually, from approximately 317 million metric standard cubic feet per day (mmscfd) of landfill gas. An additional 440 candidate landfills exist, with a projected annual capacity of approximately 830 MW (U.S.EPA, 2015). However 2000-plus open facilities simply flare or burn-off the gas they collect.

Typically, a nuclear power plant produces 1,000 MW, a geothermal power plant produces 750 MW, coal, and natural gas plants produce 100 MW, a wind power plant produces 15 MW, and solar power panel produces 7.5 MW annually. Therefore the energy produced from landfill gas-to-energy plants is equivalent to more than two nuclear power plants. The environmental benefits outweigh costs and are much less detrimental than allowing emissions. For example, the reduction of one scfm methane emitted directly from a landfill can prevent the atmospheric accumulation of six tons CH_4/yr.

Whether, a facility captures and flares, captures for direct use or captures for electricity generation, many situations result in methane emissions. For example, as the landfill is being developed, gas is emitted into the atmosphere because a collection system is not yet in place. After all systems are installed, if an extraction well fails, becomes clogged, becomes silted or becomes watered-in or flooded, that location is rendered ineffective for the collection of methane. Historically, when vertical extension of extraction wells becomes necessary, as the level of fill mounts, methane from the upper layers of decomposing waste cannot be captured. In all cases, if the collection and control cannot be achieved, then fugitive emissions rise and accumulate in the atmosphere as greenhouse gasses (GHGs). All these scenarios contribute to an overall low capture of methane over the life of the site. If the capture system has not been installed, the prevention of emissions cannot be controlled at all. While all existing systems for capture are vulnerable to deterioration, if a methane extraction well can be rehabilitated, the system can capture gas and reduce emissions, thereby increasing the overall effectiveness and efficiency of the entire system. Until recently, the industry has seen very little success with rehabilitation technology of vertical extraction or inoperable wells. The only option available was total methane extraction well replacement. In fact, the industry has not been able to solve the problem and has resorted to replacing wells, time, and time again.

There are two main reasons why this problem of well rehabilitation has not been addressed. First, the municipal solid waste sector of the waste industry is subjected to federal and state regulatory intervention. The Environmental Protection Agency and each state agency can impose considerable burden of compliance with mandated operational procedures and reporting requirements. These restrictions or permit conditions place the industry in a restrictive product market and limit or restrict innovation. Moreover, the industry is controlled by a few large players that compete on commodity pricing. Competition is fierce. The dissemination of proprietary information among competitors is minimal. Because of these two factors, motivation for research geared to innovation is scant.

Recently, a technique of post-perforation was developed and field-tested as a new technology to rehabilitate methane extraction wells (Stamoulis, 2011). The benefits of post-perforation technology include: extending the operational life of an extraction well, increasing capture and flow of methane, minimizing methane emissions and increasing energy generation.

Vertical extensions, unsuccessful rehabilitation, and the replacement cost of extraction wells were factors that prompted the idea of post-perforation for methane extraction wells. My preliminary testing of such technology indicated it works (Barber et al., 2011). However, it has not been determined whether the technology provides statistically significant results or if the apparent results are due to random error.

This thesis evaluates the effectiveness of this technology for the first time. I hypothesized that post-perforation methodology can assist in rehabilitating impaired methane extraction wells that it can increase the capture of methane from a landfill facility. These two attributes can reduce fugitive emissions of GHG's while increasing the production of a valuable domestic energy source. The overall objective of my thesis research is to test whether post-perforations methodology is effective in capturing more LFG.

The specific research objective for this study is to determine if extraction wells that had undergone post-perforation can increase capture of methane gas. The objective can be addressed by comparing extraction wells that have undergone post-perforation to extraction wells that have not been post-perforated within the same facility during the same period of time. This requires evaluation of the % methane (CH_4), initial flow (scfm) and adjusted flow (scfm) for all extraction wells prior to post-perforation and after post-perforation. The statistical analysis tests for differences between the mean values of these variables in the treatment post-perforated extraction wells and the control non-treatment extraction wells.

The research question this thesis seeks to answer is: does post-perforation increase methane flow rate in marginally producing methane extraction wells? The research hypothesis is that post-perforation will rehabilitate marginally producing or non-optimal extraction wells by increasing methane flow rate. Marginally producing extraction wells are defined as wells with a methane flow of less than two standard cubic feet per minute and a methane percentage of less than 50%. The research methods will include the utilization of post-perforation technology on these marginally producing and non-optimal extraction wells.

There is a foreseeable social and corporate benefit in that the capture of fugitive landfill gas has the potential to become a significant portion of the renewable energy generated nationwide, contributing to the larger energy grid with minimum integration costs, especially because capture requirements already exist. The cost of electricity generated from landfill gas is competitive with other renewable resources (Wiltsee, 2009). Capturing more methane and reducing fugitive emissions has an environmentally positive effect as well: a lower volume of GHG's will accumulate in the atmosphere. Economically, by generating and increasing LFG-to-energy opportunities, a landfill can generate new revenue streams from a process previously thought an economic drain. The regulatory requirement of LFG capture makes it logical to collect, convert, and sell the gas to make up for maintenance and regulation costs. The ultimate capture of more methane (CH_4) and the resulting increase in gas available to a gas-to-energy facility should contribute to any waste company's social, environmental and financial triple bottom line (Savitz, 2006).

Background

One anthropogenic source of methane emissions has led to the development and evolution of the waste management industry-- the decay and decomposition of landfilled organic material. An industry was created to capture and utilize this by-product as a renewable energy source.

U.S. Waste History Overview

The disposal of waste as a utility function started long ago. Since 400, B.C. when the Athenians first recorded the existence of a municipal dump, landfilling and waste disposal has used the same basic techniques (ASTC, 1998, Rathje & Murphy, 2001). The early disposal method for waste consisted of digging a hole in the earth. Sometimes this hole had been originally excavated for mining purposes, although there were also excavations for the sole purpose of disposal of waste. Excavations were unlined earthen pits where waste was deposited in direct contact with the soil, leaving it free to impact groundwater and the environment. For most of civilizational time, waste was not segregated as it is in the controlled municipal solid waste landfill facility of today. Often all types of refuse lay commingled in the same excavation. As the development of landfilling evolved, the typical focus was not to devise a new means of the disposal of waste but to modify and enhance the age-old concept.

In the United States, regulations refined landfilling practice by instituting protective instruments, collection systems, and monitoring systems. These developments and implementations were reactions to observed problems. The first protective techniques were of three sorts: lining the bottom and sidewalls of the excavation with compacted clay, segregating different waste types, and recycling reusable items prior to final disposal. In 1996, Federal Regulations under Subtitle "D," (U.S. CFR, 2006) required that all existing sites upgrade to the new standards or cease accepting waste. Many sites that were old, small or filled almost to capacity closed under the pressure of these rules rather than upgrade. Protective measures under Subtitle "D" mandated stricter standards than before. These environmental controls included: monitoring of groundwater, implementation of a polymeric liner in the bottom and sidewalls of the excavation, installation of leachate collection systems, and the installation of landfill gas collection and control systems. Additionally, a financial assurance provision was implemented that tended to eliminate many marginal producers. Dumps in small communities and municipalities were either closed or pushed towards outsourcing to larger, more remote sites.

Anthropogenic methane derived from the decay and decomposition of municipal waste is a crucial externality. Released unchecked, the gas will degrade the environment. Captured for use as energy, it has great ecological and economic value. The regulations and the infrastructure mechanisms exist, and the benefits of capture are evident. Emphasis on continually increasing capture or improving capture efficiency makes social, economic and environmental sense.

U.S. waste regulatory framework. The Solid Waste Disposal Act (SWDA) of 1965 represented the first federal solid waste management law. Its provisions dealt mainly with observation and understanding of the disposal of waste. The 1970 Resource Conservation Recovery Act (RCRA) focused on early recycling and reclamation of the salvageable fraction of wastes. Both these measures were designed to assist state and local authorities with technical assistance on the disposal of waste and the recovery of resources from the waste stream. (Bell et.al, 2013)

In 1976, came the passage of the Resource Conservation and Recovery Act (RCRA), the first time the federal government took a hands-on role pertaining to existing waste sites and the future permitting of sites that dealt with the management of waste. In 1980, with the passage of the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) - (Bell et.al, 2013), the federal government established a platform to address historic and abandoned facilities. Also, in 1980 Congress passed the Solid Waste Disposal Act (SWDA), (Bell et.al, 2013). These amendments were designed to prevent hazardous wastes from entering municipal solid waste landfills. In 1984, the U.S. Congress attempted to strengthen RCRA, through the Hazardous and Solid Waste Amendments (HSWA). RCRA was amended further in 1992 and 1996. Those two amendments strengthened the enforcement and regulatory flexibility for the disposal of certain types of wastes. Within RCRA, the current regulations under subtitle "D" define rules of permitting and operational procedures for municipal solid waste. Subtitle "D" was instrumental in the early developmental stage of gas collection and control systems at municipal landfill sites.

Global waste generation rates. Current global municipal solid waste generation (MSW) volumes are approximately 1.3 billion tons per year (Hoornweg & Bhada-Tata, 2012). By 2025, they are expected to increase to approximately 2.2 billion tons per year (Hoornweg & Bhada-Tata, 2012). So huge an increase represents an enormously challenging and unsustainable financial burden. The projected cost to manage this amount of waste in 2025 will be approximately $375.5 billion U.S. dollars (Hoornweg & Bhada-Tata, 2012).

Waste generation relates to economic development. In simple terms, waste generation is a function of the production of goods and their consumption. For this reason, on average, the higher its population and gross domestic product, the higher a country's waste generation rate. Intuitively we can see that, as countries move up the development class scale, they will produce more waste. A notable increase in the standard of living will create a vast amount of waste with environmental and social consequences.

The fundamental problem with the increase in waste generation is in less developed countries. In such societies waste disposal cannot be managed in an economical way. The developing and developed countries ultimately begin spending more money dealing with the problem as a social rather than an environmental issue (Coase, 2013). Waste disposal may be thought of as an allocation inefficiency because the equilibrium of the disposal service is not Pareto optimal (Lind & Granqvist, 2010). The social burden or inefficiency is created by the externality. Subsequently, the generation of global environmental impact from the disposal by-products, including methane gas, becomes more pronounced. The "global" reduction of emissions is more important than any "regional" approach, as the reduction in one country has little effect globally (Fiore et al., 2002). From a global perspective, the waste generated in the Organization for Economic Cooperation and Development (OECD) countries comprises 44% or 572 million tons annually (Wiggin, 2008). However, 22% of those countries do not have methane emissions controls in place. In addition, few of the remaining countries, comprising the majority 56% or 718 million tons annually, have any environmental controls (Wiggin, 2008). For this reason, approximately 78% of the waste generated annually (over one billion tons) is produced in countries with few mechanisms to control environmental degradation, including methane emissions.

United States waste generation rates. In the United States, 250 million tons of waste were generated in 2012 (U.S. EPA, 2014). There was a steady climb since 1960, but, then leveled off after 2000, along with the per capita generation rate (Figure 1).

Figure 1. U.S. waste per capita generation (1960-2012) (U.S. EPA, 2014).

Although economic development and growth produce waste as an unwanted but unavoidable consequence, the basic problem, however, is not waste generation but waste disposal and its environmental effects.

In the U.S., the organic and paper fraction of waste generated that requires disposition (either disposal or recycling) is estimated to be about 63% (U.S.EPA, 2014). The remaining 37% constitutes less biodegradable recyclables and re-useable material. The organic fraction of waste in a landfill decomposes to generate methane gas CH_4. By landfilling, we are entombing resources and creating an unwanted by-product that contributes to changes in the atmosphere. Capture of methane gas minimizes negative impact on the environment and on climate change, while providing a renewable fuel source.

Generation of Anthropogenic Methane from Waste

In order to understand and devise methods to reduce or minimize the effects of methane gas on the environment, it is important to understand the mechanisms behind the generation of anthropogenic methane from municipal waste. The generation of waste and methane has an enormous impact on the local and global environment (Hoornweg & Bhada-Tata, 2012, Wiggin, 2008, Reinhart et al., 2012, Amini et al., 2012). Demographers estimate the world's population in July of 2006 at 6.53 billion (Wiggin, 2008). As of July 2014 the likely figure was 7.22 billion (US DOC, 2014). This rate of growth is rapid, yet the rate of waste generation is growing even faster. In the last ten years, the municipal solid waste generation rate was estimated at 1.4 lb per person per day (Hoornweg & Bhada-Tata, 2012). Today the global generation rate has increased to an estimated 2.6 lb per person per day (Hoornweg & Bhada-Tata, 2012). The roughly doubling in ten years illustrates the interrelation between population and municipal solid waste generation.

In 2000, GHG emissions from the waste management sector consisted of 1,255 metric tons carbon dioxide equivalent (MtCO_2eq) representing approximately 3% of the global total GHG's (McKinsey & Company, 2007, Spokas et. al., 2006, Scharff and Jacobs, 2006). In 2010, it was estimated that greenhouse gases from the waste management sector were 1,236 ($MtCO_2eq$), with 1,078($MtCO_2$ eq) or approximately 80% directly derived from methane (U.S. EPA, 2011).

Atmospheric gas composition. Greenhouse gases comprise two groups; CO_2 in one and non-CO_2 in the other. The non-CO_2 group consists of water vapor (H_2O), methane (CH_4), nitrous oxide (N_2O) and chlorofluorocarbons (CFCs). The non-CO_2 greenhouse gases are more potent (per unit weight) than CO_2 at trapping heat within the atmosphere.

Since 1750, global average atmospheric concentrations of methane have increased 150 percent, from approximately 700 to 1745 parts per billion by volume (ppbv) (Griggs & Noguer, 2002, Field, et al, 2014). As waste generation increases in our globalized economy, so will the methane emissions. The methane in the atmosphere can be removed only by diversion to another molecular state. The balance between CH_4 emissions and CH_4 removal determines atmospheric concentration and the duration of time CH_4 remains in the atmosphere (U.S. EPA, 2006).

Atmospheric chemical processes and methane. Methane is an important trace gas in the composition of the atmosphere. Because it functions to regulate the earth's temperature, it is considered a naturally occurring greenhouse gas. Without these naturally occurring GHG's the earth would be uninhabitable. Like the well-known compound carbon dioxide (CO_2), methane (CH_4) derived from anthropogenic sources heightens the greenhouse effect and has assisted in increasing the earth's temperature

Methane along with all other non-CO_2 greenhouse gas traps more heat in the atmosphere than CO_2 on a per unit weight basis (U.S.EPA, 2006, Ewall, n.d.). Globally, the average surface temperature would be 1.3˚C higher than without methane (Ewall, n.d.). Methane is a known major source or precursor in the creation of tropospheric ozone

(O_3). It assists the production of this background ozone because of its long life (8-9 years) (Fiore et al., 2002, Frankel, 1999).

In the last 250 years, the atmospheric concentration of methane has increased by approximately 150% (U.S. EPA, 2006). Since the start of the industrial era, methane has contributed to a net radiative forcing which has increased by 0.5-2.5 W/m^2 (Watts per meter squared) (Foster et al., 2007). For this reason, reducing methane emissions would create a powerful lever for diminishing climate forcing and improving air quality via decreases in tropospheric ozone O_3 (Fiore et al., 2002).

Earth's atmospheric composition equates to 79% nitrogen (N), 20% oxygen (O) and 1% of other gases. Of the one percent designated as "other", methane (CH_4) comprises approximately 2 ppm or 0.0002% (Berger & Mann, 2002). The anthropogenic gases CH_4, CO_2 and other GHG's generated but not captured will rise into the atmosphere. In a landfill, if the methanogenesis process is active without a collection and control system, atmospheric release is imminent.

The growth rate of atmospheric methane is estimated by tracking the balance between surface emissions and photochemical destruction by the hydroxyl radical (OH), a major atmospheric oxidant (Bousquet et al., 2006).

$$CH_4 + OH \text{ --------->} CH_3 + H_2O$$

If CH_4 is not oxidized, it persists with ozone (O_3) and acts as a barrier preventing outgoing infrared radiation from its transit back into space. This process skews the greenhouse balance and enhances the warming of the earth's temperature. Increasing anthropogenic methane leads to a net ozone production in the lower elevation of the troposphere and to net ozone destruction and lessening of water vapor in the stratosphere

(Bousquet et al., 2006). It also plays a role in the conversion of chlorine (Cl) to hydrochloric acid (HCL) in the stratosphere (Wahlen, 1993). The current climate forcing by CH_4 (excluding indirect chemical effects) is 26 times that of CO_2 (calculated on a Mole CO_2/ Mole CH_4) basis.

Landfill gas emissions. Fugitive emissions of landfill gas (LFG) composed of methane, carbon dioxide and non-CO_2 components have potentially long-lasting effects that can be lessened by capture and treatment prior to release from the facility (Table 1).

Table 1.Typical landfill gas components (Berger & Mann, 2001).

Typical Landfill Gas Components		
Component	**Percent by Volume**	**Characteristics**
methane	45–60	Methane is a naturally occurring gas. It is colorless and odorless. Landfills are the single largest source of U.S. man-made methane emissions
carbon dioxide	40–60	Carbon dioxide is naturally found at small concentrations in the atmosphere (0.03%). It is colorless, odorless, and slightly acidic.
nitrogen	2–5	Nitrogen comprises approximately 79% of the atmosphere. It is odorless, tasteless, and colorless.
oxygen	0.1–1	Oxygen comprises approximately 21% of the atmosphere. It is odorless, tasteless, and colorless.
ammonia	0.1–1	Ammonia is a colorless gas with a pungent odor.
NMOCs (non-methane organic compounds)	0.01–0.6	NMOCs are organic compounds (i.e., compounds that contain carbon). (Methane is an organic compound but is not considered an NMOC.) NMOCs may occur naturally or be formed by synthetic chemical processes. NMOCs most commonly found in landfills include acrylonitrile, benzene, 1,1-dichloroethane, 1,2-cis dichloroethylene, dichloromethane, carbonyl sulfide, ethyl-benzene, hexane, methyl ethyl ketone, tetrachloroethylene, toluene, trichloroethylene, vinyl chloride, and xylenes.
sulfides	0–1	Sulfides (e.g., hydrogen sulfide, dimethyl sulfide, mercaptans) are naturally occurring gases that give the landfill gas mixture its rotten-egg smell. Sulfides can cause unpleasant odors even at very low concentrations.
hydrogen	0–0.2	Hydrogen is an odorless, colorless gas.
carbon monoxide	0–0.2	Carbon monoxide is an odorless, colorless gas.

Control of the migration off-site of landfill gas is very important because of the explosive nature of methane, especially at uncontrolled dumps where gases are continually emitted. Methane is generated in phases, first in aerobic and then in anaerobic environments as depicted below in Figure 2.

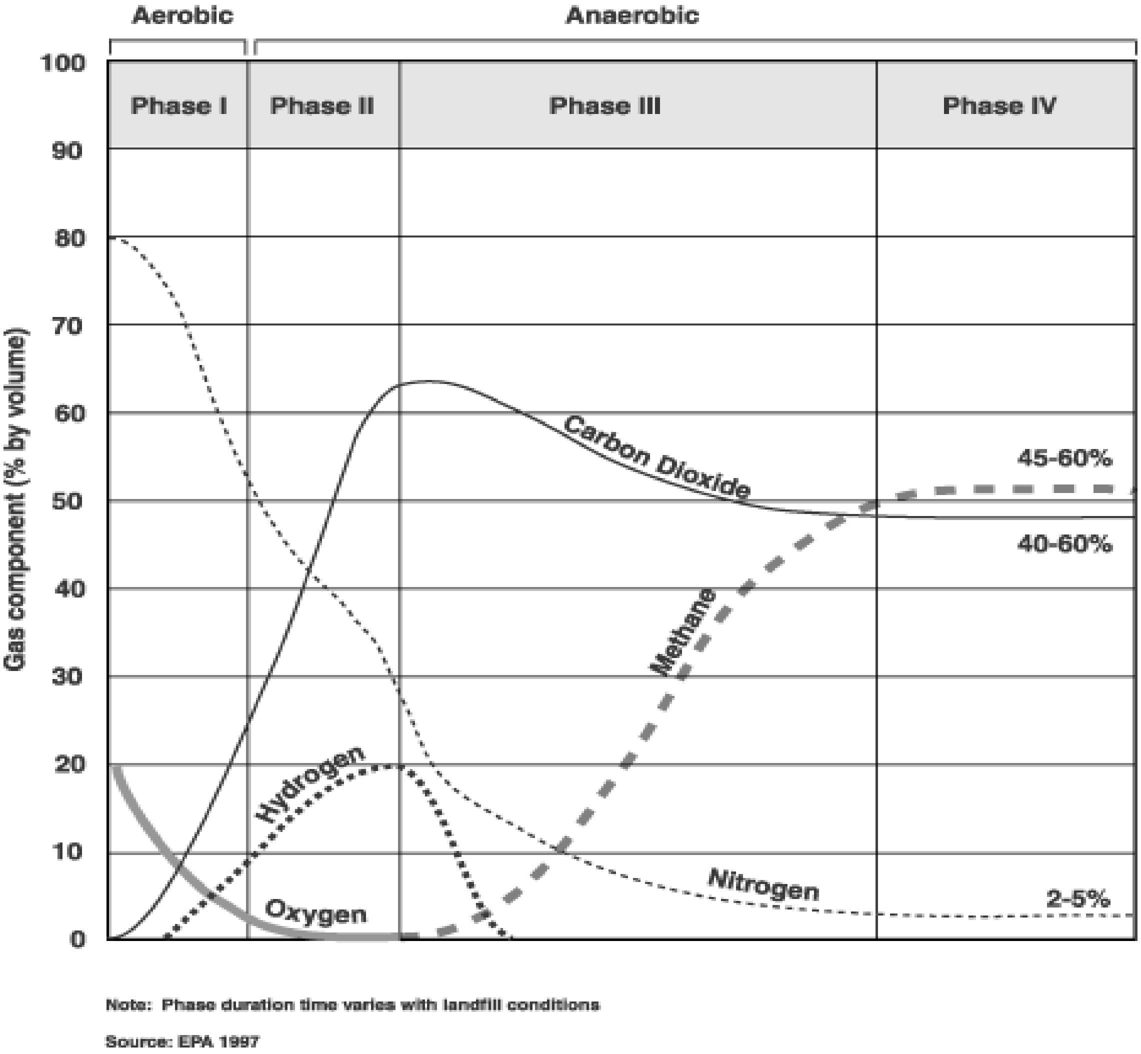


Figure 2. Landfill gas composition and production phases (Berger & Mann, 2001).

Typically the peak output of gas production occurs approximately 5 to 7 years after waste has been buried (U.S.EPA, 1996). Landfill gas production can continue for 10 to 60 years or longer (Berger & Mann, 2001). Methane, like most other gas, tries to find the path of the least resistance. If not captured by a landfill gas collection and control system, it will either migrate laterally or emit through the landfill's cap. The capture of gas is essential as carbon dioxide and methane are powerful GHGs (Gómez et al., 2007).

History of Landfill Methane Regulations

Landfill gas migration was first noticed sometime between 1953 and 1961 (Hickman, 2003), during the national transition and progression from open burning dumps to the municipal solid waste landfill facilities (MSWLF's) of today.

Sometime during the late 1950's, lateral movement of landfill gas from a waste cell into nearby structures was observed (Hickman, 2003). Because of this, the first engineered solution to lateral movement of landfill gas was designed and implemented in Arlington, MA: a gravel-filled interceptor trench was put in place to passively vent landfill gas moving laterally and away from the landfill and a number of monitoring probes were installed between the trench and buildings to monitor the success of the passive control measure (Hickman, 2003).

The first legislation to enact both air and sub-sequential landfill gas compliance and monitoring guidelines was achieved under the Clean Air Act (CAA) of 1970. However, no standards were implemented at that time. The EPA issued the "Guidelines for the Land Disposal of Solid Wastes" in 1974 to help facilitate the design and monitoring of landfills. However the guidelines were not recognized as standards and, for this reason, were unenforceable. It was not until the CAA Amendments were legislated by Congress in 1990 that two regulatory programs, now integral to the solid waste industry, were established: the New Source Performance Standards (NSPS) and National Emissions Standards for Hazardous Pollutants (NESHAP). This new regulatory framework set standards by which all emissions must be monitored.

The New Source Performance Standards (NSPS) have impacted the way in which the solid waste industry operates (U.S. EPA, 1998). The NSPS are intended to promote effective mechanisms for the collection of landfill gas. Mandating new compliance criteria, including regular and frequent monitoring, capture of landfill gas, and timely installation of landfill gas collection devices got results. The amount of landfill gas emitted into the atmosphere as greenhouse gas since New Source Performance Standards inception has declined (U.S. EPA, 2009).

Hazardous air pollutants were also considered in the CAA Amendments of 1990, but enforcement was not practical in the form of National Emissions Standards for Hazardous Air Pollutants (NESHAP) until 2003 (Sullivan, 2007). NESHAP increased reporting requirements from annual events to semi-annual events and attempted to bring a proactive approach for site and self-regulation to the industry.

The industry finds greenhouse gas regulations becoming stricter as the sizes of landfills grow. Since December 29, 2009, the larger MSWLF sites, those with the potential for emitting 25,000 metric tons or more of carbon dioxide equivalents per year, have faced stricter reporting standards (U.S. EPA, 2009). Stricter standards are sure to continue. Compliance will increase expenses as new technology is installed and precise record-keeping takes up staff time. Yet increased recovery of gas formerly wasted can provide a revenue stream as methane increasingly becomes a recognized marketable commodity.

By installing and maintaining LFG extraction wells and LFG-to-energy infrastructures, facilities can better manage landfill gas and reduce greenhouse gas emissions. The generation, efficient capture, and conversion of landfill gas to energy form a coherent process with the potential to create income from a source once lost via flaring as other forms of emission.

Agency and industry development of a renewable market. In December of 1994, the Environmental Protection Agency established the Landfill Methane Outreach Program (LMOP). This program was established to “reduce methane emissions by lowering barriers and promoting the development of cost-effective and environmentally beneficial LFG energy projects” (U.S. EPA, 2015). The program is voluntary and brings together members of the regulatory community, consultants, vendors, and industry. The program has been instrumental in assisting in the development and capture of landfill gas at facilities across the country and internationally.

The Landfill Methane Outreach Program provides technical assistance and technology transfer to partners and industry. LMOP’s sole focus is the capture and beneficial use of methane. It has successfully demonstrated that methane recovery has a positive social and economic potential. I am a partner in this organization and have presented a paper and lecture at its annual conference. Thanks to LMOP, new technology and policy suggestions have a direct pipeline path to the Environmental Protection Agency.

Landfill Gas Collection and Control System

The primary purpose of a landfill gas extraction system is to prevent landfill gas (LFG) from exiting the facility via subsurface migration and fugitive surface emissions. The secondary purpose of landfill gas extraction wells is to generate revenue from the gas-to-energy production. Given the abundance and environmental hazards of greenhouses gases involved, an extraction system is crucial so that LFG is captured before it is emitted into the atmosphere. The landfill gas extraction system is one component of the Gas Control and Collection System (GCCS) of a Municipal Solid Waste Landfill Facility (MSWLF).

Gas control and collection systems at municipal solid waste landfill facilities are continually being upgraded, repaired or modified. Gas extraction wells are installed in stages over the life of the site. These wells are subject to modification, being raised, vacuum tuning, re-drilling, and monitoring. Many factors contribute to the diminished efficiency or effectiveness of the individual well or the gas control and collection system. The nature of the environment at a municipal solid waste landfill facility creates an unpredictable life expectancy for any gas extraction well. Entrained fluids can water-in the screen section. Improper installation can result in clogging or silting-in of a well. Heavy equipment like a bulldozer or compactor can damage or totally destroy an extraction well. Wells installed in relatively dry sectors yield no gas or low-gas generation and production cycles. Extraction wells, once vertically extended, can become unable to capture gas from upper zones.

An extraction well operates under the basic principle that LFG generated within a landfill is drawn towards the well by the pressure gradient created by the vacuum applied to the well (Dillah et al., 2005, Hartz & Ham, 1982). LFG extraction wells are installed throughout a facility to capture the LFG. A typical ratio is one such well per acre. For a 600-acre facility, it is not uncommon to have at least 600 LFG extraction wells at the time of the MSWLF reaches final closure. After installation, and throughout the site's life cycle, the operational efficiency of the GCCS, particularly its extraction wells, becomes degraded over time.

Factors that reduce operational efficiency of an individual landfill gas extraction well and its capture of methane gas include: the well screen becoming clogged or flooded, and vertical extensions of well casings by outmoded methods as site expansion occurs. Examples are graphically illustrated in Figure 3. Clogging of the well screen can be caused by many factors but mainly by trash and other debris reducing the intake area of the well screen. Flooding of the extraction well is typically caused by leachate and condensate accumulation inside the annular space of the well to a point higher than the top of the screen. The continual placement of new waste requires installation of vertical extensions of well casing (risers). Even with such extensions, the GCCS can capture gas only from the original screen located at the bottom of the well. Eventually, any of these scenarios will require total replacement of the LFG extraction well. Replacement of methane wells is costly and time-consuming.

Landfill gas extraction well integrity is essential for an efficient capture of methane. Even utilizing all available efficiency techniques, if the screen interval is clogged, flooded or silted, there is an increased likelihood the Gas Control and Collection System (GCCS) operates at less than the optimal level of performance for which it was designed. This unavoidable situation has few remedies. Ultimately all deficiencies will end with the same fate: a replacement well for the dysfunctional, inoperable well. Before that point is reached, some options exist to enhance or rehabilitate non-optimal wells: the installation of pumps is one option for flooded wells, while solution / pressure-fracturing is an option for clogged well. However, the success rate of these methods is marginal.

The vertical placement of additional waste in a landfill mandates a vertical extension of the methane extraction well to accommodate the increased in height of the amassing refuse (see Figure 3). The methane collection and control system becomes unable to capture gas above the screen zone. Extension of a methane extraction wells requires the addition of blank riser sections to the vertical extension. Screen sections cannot be added as air intrusion causes underground fires.

If flooding occurs, a dedicated pump can be installed as a de-watering option, however this solution increases the operational and maintenance cost of the gas collection and control system. The installation of a pump involves a continuous operational and maintenance cost. In northern climates, operational difficulties of the pump due to freezing conditions require constant attention. The replacement of a methane extraction well will result if pumping cannot correct the problem.

A common practice in the water well industry, solution / pressure-fracturing is beginning to make an entrance into the solid waste industry. When wells become silted in or clogged, solution / pressure-fracturing is an option to attempt to break up the accumulated silt or debris and reopen the screened interval. However, because solution / pressure-fracturing is applied only to the silt or debris directly on the screen, the well will most likely accumulate more silt or debris around the screened interval because the process does not affect the environment and associated conditions surrounding the well screen. The solution / pressure method is a temporary “fix” to a persistent problem.

Ultimately, after application one or more of the above rehabilitation techniques, the well will need to be replaced. It becomes less and less cost effective to rehabilitate the same well and replacement is the only solution, both physically and economically. The installation cost of an extraction well ranges from $70.00 to $100.00 USD per foot. Thus a methane extraction well with a length of 100 feet ranges from $7,000.00 to $10,000.00 USD.

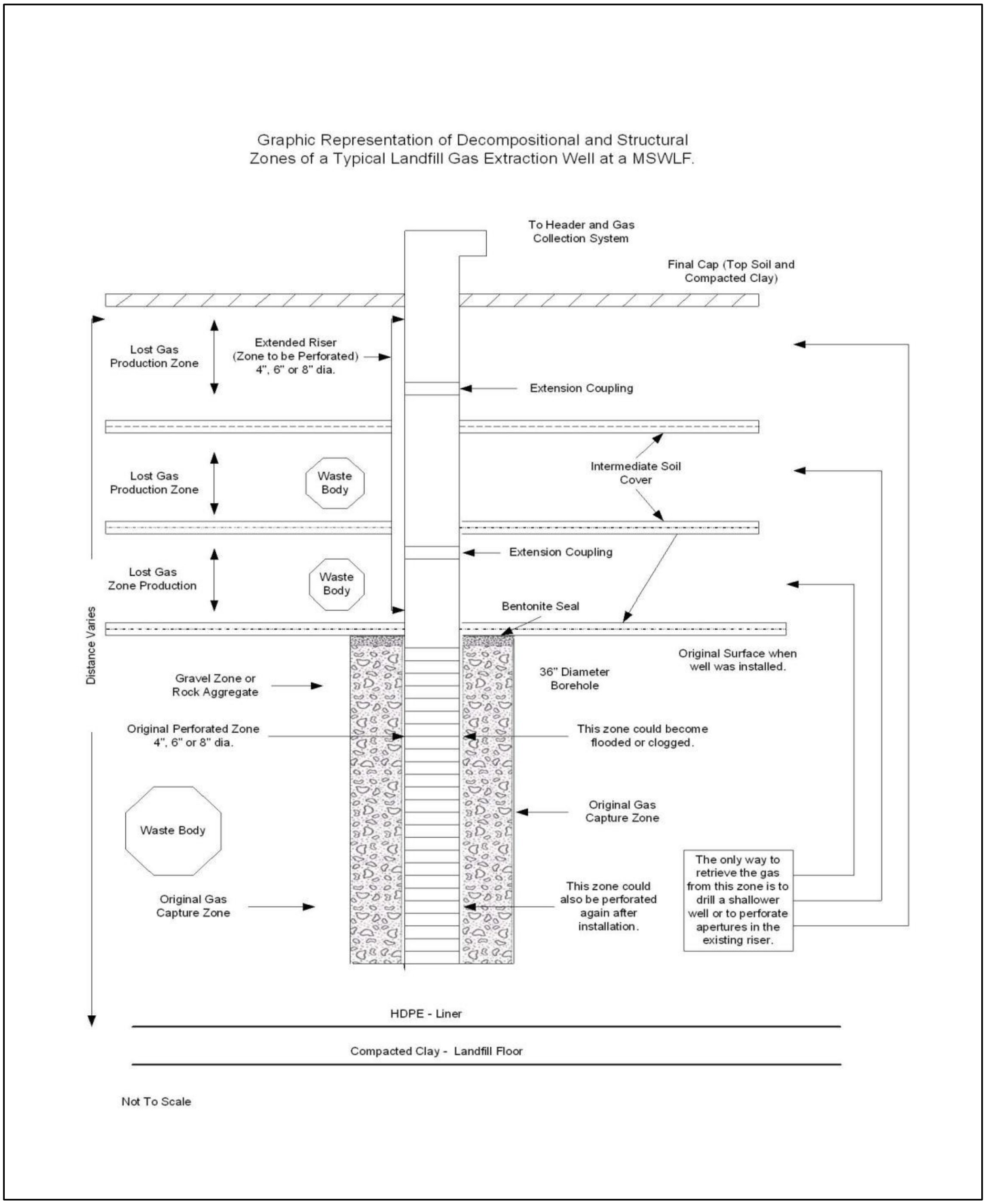


Figure 3. Schematic of a typical LFG-methane extraction well, illustrates the potential for emission (potential for capture) after original installation of the well (Stamoulis, 2011)

Until recently, limited remedies existed for maximizing capture and reducing emissions from MSWLs. Efficiency is highly dependent on the operation's maintenance and design. The higher collection efficiencies are exhibited at facilities that maintain gas control and collection systems (U.S. EPA, 2011). It is worth noting that studies conducted by the Solid Waste Industry for Climate Solutions (SWICS) indicate collection systems meeting the requirements of NSPS are often more capable of achieving higher collection efficiencies than collection systems used solely for energy recovery because it is difficult to optimize gas quality while trying to attain a high level of gas collection (SWICS, 2007).

Development of Post-Perforation Technology

Post-perforation is a new technology (Stamoulis, 2011; Stamoulis, 2011b; Stamoulis, 2013) developed after careful observation of the installation, unsuccessful rehabilitation, and well replacement cycle by people with specific knowledge of the drilling and engineering techniques involved. Post-perforation is achieved by directing a tool into the inner diameter of the LFG extraction well casing down the well to a desired depth. Once at that depth, the tool creates new apertures in the well, essentially creating a new screened interval. The benefit of this technology is that the new screened interval can be achieved at any depth within the well (i.e. the original screened interval or above). Post-perforation is achieved with a tool specifically designed for extraction well. This tool can be navigated effectively through slight bends and deflections in existing well casing/riser and other well deviation. The idea to post-perforate LFG extraction wells from inside the well constitutes a realistic solution to an age-old industry problem – how to extend the operational life of a vertical extraction well. After several years of research, design and development, the post-perforation theory has proven successful at several locations along the U.S. Gulf Coast. Three patents for this technology were recently awarded under the Federal Green Technology program. These awards are recognition of a successful, innovative technology that will help to lower greenhouse gases and overall emissions from MSWFs while increasing capture and flow of Landfill gas. (Stamoulis, 2011)

This new approach can assist in rehabilitating wells once thought destined only for replacement. Post-perforation greatly extends the life of LFG extraction wells and increases capture and flow of LFG almost instantaneously. Post-perforation of LFG extraction wells provides a key additional method to enhance rehabilitation of extraction wells, extending their lives and production of LFG. The positive effects include: maintaining compliance, decreasing operational costs, and increasing the capture of landfill gas over time.

Preliminary Test of Post-Perforation Technology

I conducted post-perforation testing on twenty-two extraction wells at three facilities. The three facilities were located in Texas. Two industry papers were subsequently generated from this testing, (Stamoulis et al., 2011), (Barber et al., 2011). These three examples were the first post-perforation field testing using the new technology. The results obtained were initially presented at waste industry conferences. Data and results are presented here to illustrate the relevance of the technology. The evaluation from each of the three facilities and from the landfill gas extraction wells compare averages for a period of three or four consecutive months prior to post-perforation with results for three or four consecutive months after post-perforation. This initial evaluation was rudimentary and limited to using simple averages. It was clear that an evaluation utilizing more sophisticated methods of statistical analysis was critical to proving the technology significance. This prompted the proposal and execution of this thesis.

Application of post-perforation on facility 1. At Facility (site) 1, five LFG extraction wells were post-perforated, on average, approximately 16.4 feet in length and to depth ranging from approximately 20 feet below ground surface (ft. bgs) to approximately 36.5 ft. bgs. All five wells were post-perforated on the same day. Results from average readings obtained from each well from a period of three consecutive months prior to post-perforation were compared with results for three consecutive months after post-perforation (Table 2 and Figure 4).

Table 2. Site 1 – well designation, measurement and change in flow (Stamoulis et al., 2011).

Well ID	Measured flow pre-perforation (SCFM)	Measured flow post-perforation (SCFM)
Well 1	1.67	19.67
Well 2	0.33	1.00
Well 3	2.33	25
Well 4	4.67	10.67
Well 5	3.33	3.0

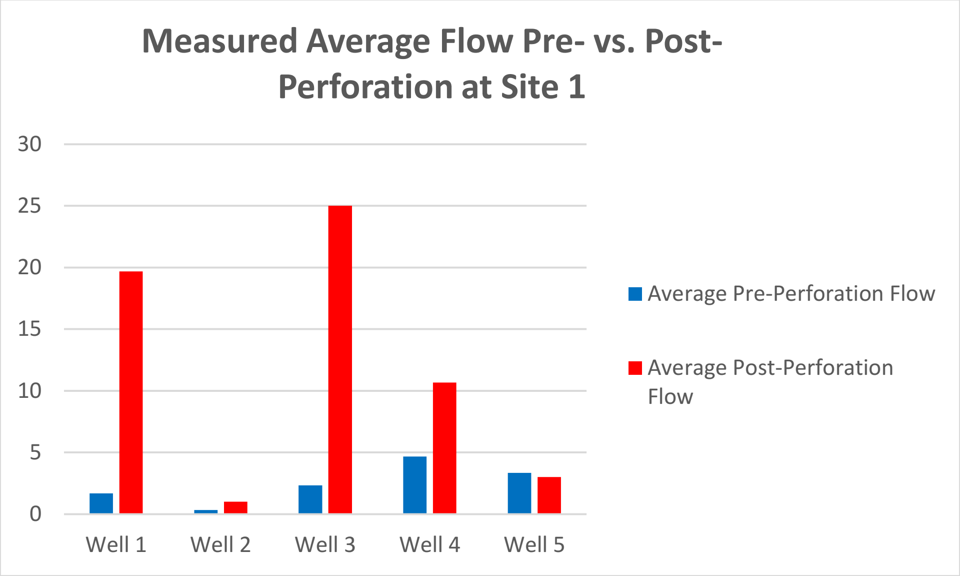


Figure 4. Test site 1 – average flow pre- and post-perforation (Stamoulis et al., 2011).

It is apparent in the Figure above that post-perforation at Facility (site) one successfully increased the volume of flow in (scfm) in four of the five wells treated with post-perforation.

Application of post-perforation on facility 2. At the second facility, twelve locations were selected because they were low producing LFG extraction wells or were experiencing watered-in effects from entrained fluids. The twelve wells, on average, were post perforated approximately 15 feet in length and from a depth of approximately 20 feet below ground surface. All landfill gas extraction wells were post-perforated in the same day.

Here, the readings from each landfill gas extraction well represent a period of four consecutive months prior to post-perforation compared with those for four consecutive months after post-perforation (Table 3). This method was utilized to normalize the data and allow for an evaluation over time rather than focusing on an abrupt or instantaneous change that might later prove atypical.

Table 3. Site 2 – well designation, measurement and change in flow (Stamoulis et al., 2011)

Well ID	Measured flow (pre-perforation) (SCFM)	Measured flow (post-perforation) (SCFM)	Difference in pre- versus post-perforation (SCFM)
Well 1	0.5	28.5	28.0
Well 2	1.5	3.75	2.25
Well 3	2.33	13.75	11.42
Well 4	2.50	7.5	5.0
Well 5	2.33	5	2.67
Well 6	22	45	23
Well 7	33.3	28.75	-4.55
Well 8	2.5	32.25	29.75
Well 9	6.5	37.25	30.75
Well 10	71	85	14
Well 11	3.33	3.75	0.42
Well 12	9.75	6.25	-3.5

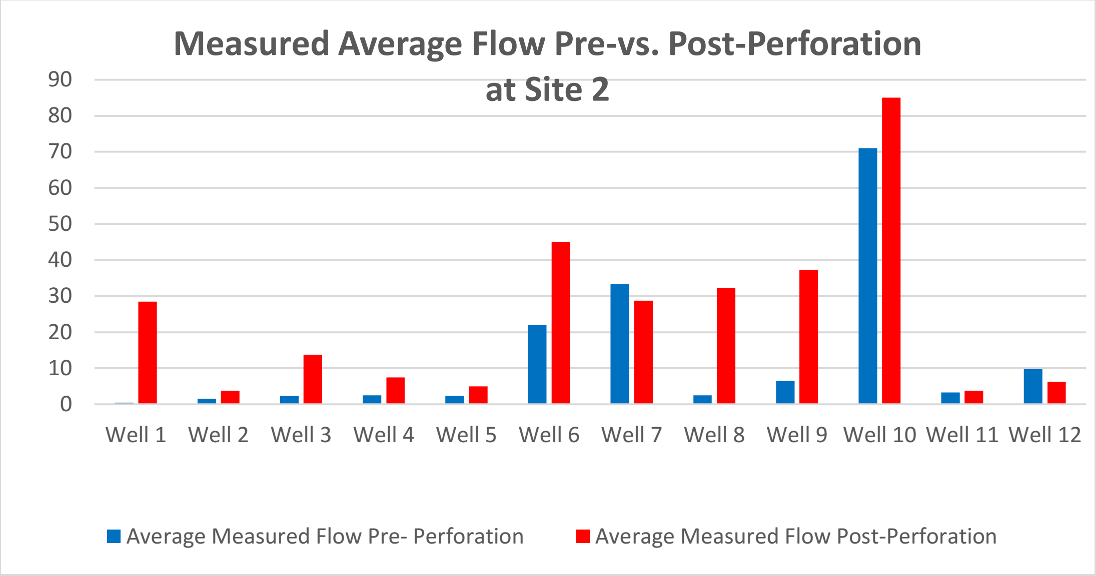


Figure 5. Test site 2 - average flow pre- and post-perforation (Stamoulis et al., 2011)

Testing conducted at Test site 2 shows that the measured flow in (scfm) increased for ten of the twelve wells post-perforated during the application of the post-perforation. Six of the twelve wells showed an increase in measured flow from one to three times the pre-perforation readings. Four of the twelve showed an increase from five to fifty-six times the pre-perforation readings (Figure 5). Two wells showed a decrease in measured flow from pre- to post-perforation readings, Well 7 (33.3 scfm to 28.75 scfm) and Well 12 (9.75 scfm to 6.25 scfm).

Application of post-perforation on facility 3. At the third facility, five locations were selected because the LFG extraction wells had been vertically extended. The five wells, on average, were post perforated approximately ten feet in length and to a depth of approximately 20 feet below the surface. All were post-perforated on the same day.

The readings from each landfill gas extraction well represent a period of three consecutive months prior to post-perforation; averages and differences are shown in Table 4.

Table 4. Site 3 – well designation, measurement and change in flow (Barber et al., 2011).

Well ID	Measured Flow (Pre-Perforation) (SCFM)	Measured Flow (Post-Perforation) (SCFM)	Difference in Pre- versus Post-Perforation (SCFM)
Well 1	52.0	62.67	10.67
Well 2	18.67	56.33	37.66
Well 3	35.00	14.33	-20.67
Well 4	40.67	44.00	3.33
Well 5	29.67	28.67	-1.0

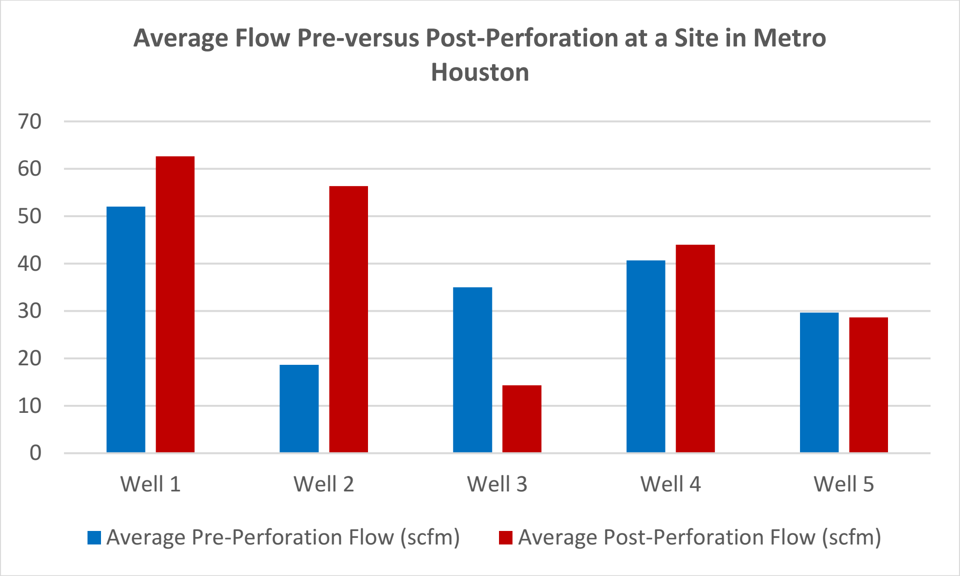


Figure 6. Test site 3 – average flow pre- and post-perforation (Barber et al., 2011).

Figure 6 illustrates that post-perforation at this facility successfully increased the flow in three of the five wells. Extraction Well 2 exhibited the largest increase in flow volume with an increase of approximately 67%. Extraction Well-3 exhibited the least successful results after post-perforation with a flow volume decrease of approximately 59%. Overall, for the five wells post-perforated, the volume of flow increased a net total of 30.0 standard cubic feet per minute (scfm).

Continual improvement of methane gas capture is one of the most crucial issues facing the waste disposal industry. The trajectory of regulations are expected to increase and will stress capture efficiencies and emissions reductions from waste facilities. The preliminary studies at these three sites suggested that a larger sample size and stricter statistical analysis of the data would help the landfill operators to assess the effectiveness of post- perforation technology as a rehabilitation method to extend the life of a well and to increase the capture of landfill gas.

If demonstrated to be effective, the technology creates new methods and opportunities to capture gas before it is emitted into the atmosphere. This research was designed with these goals in mind.

Chapter II

Research Methods and Design

Historical data from Municipal Solid Waste Facilities that had undergone post-perforation treatment were used in this analysis. To control for facility effects and the high variability among facilities and individual wells, it was determined that any facility with less than nine treatment wells would not be included in this analysis. Secondly, a determination was made to minimize variability by analyzing the data using the mean of mean values for the selected facilities and extraction wells. To test the hypothesis this analysis consisted of two components: a statistical and an environmental/energy analysis.

To evaluate the statistical component of the analysis, three variables, methane (CH_4), initial flow (scfm), and adjusted flow (scfm) were selected. The wells at each facility were categorized into three groups: Group 1- marginally producing wells that had undergone treatment or post-perforation: Group 2- marginally producing wells that did not receive treatment: and Group 3- fully functional fully operational wells.

Mean values for all three variables were calculated from the sequence of readings (on a monthly basis) for the six months before treatment (pre-perforation) and the six months after treatment (post-perforation). Because the readings fluctuated erratically over time, these mean values gave better overall estimates of flows for each well before and after post-perforation. Student's T-Test were performed on the difference between pre and post-perforation mean values from all three groups, and standard errors of the grouped mean values were calculated.

Additionally, to determine the environmental and energy benefits component of this study, the EPA Landfill Methane Outreach Program (LMOP) landfill gas equivalent calculator was utilized. The facility mean flow (scfm) value was used to illustrate the possible environmental and energy benefits derived from the additional capture of methane CH_4. Research protocol is presented in Figure 7.

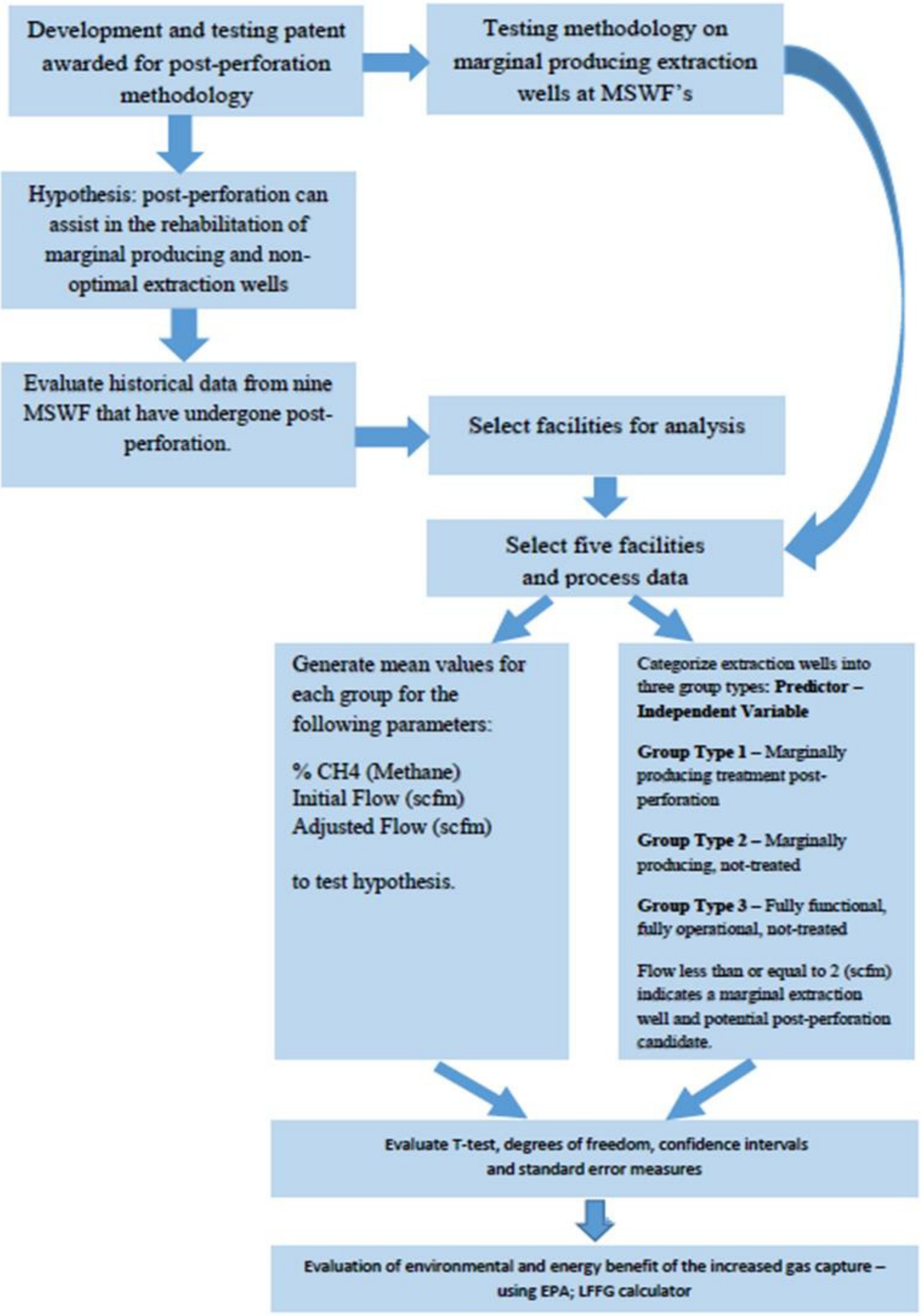


Figure 7. Research protocol for testing the effectiveness of post-perforation on marginally producing and non-optimal extraction wells at Municipal Solid Waste Facilities.

Post-Perforation Technology

Post-perforation, promising technology patented in the United States in 2011 (Stamoulis, 2011), is achieved by lowering a tool into the inner annular space of an extraction well casing to a desired depth (Figure 8). Once at that depth, the tool is hydraulically activated to generate new apertures (perforations) in a polymeric well casing, essentially creating a new screened interval.

Figure 8. Post-perforation tool being lowered into an extraction well (Stamoulis et al., 2011).

The tool is transported to each extraction well using a track carrier unit under radio control. Because the hydraulics operate on biodegradable fluid, the post-perforation process, as designed, is environmentally safe. This post-perforation technology was applied to the marginally producing extraction wells in the present study. The treatment took place at all MSWF's in accordance with Hydrogeologic /Environmental Testing standard operating procedures. The well casing and screen sections were composed of a 6" or 8" diameter PVC or HDPE material. Post-perforated selection consisted of wells: 1) that were non-optimal, or low producing, or 2) that were watered-in or flooded screen sections.

The wells were perforated 180° degrees apart and at one inch spacing. The apertures were either 3/8 or 1/2 inches in diameter. The post-perforation interval varied from facility to facility. The number of extraction wells undergoing post-perforation at each facility varied (Figure 12 and Table 5).

Figure 9. Image of the patented perforation tool (Stamoulis, 2011).

To navigate deflections and deviations commonly experienced in extraction wells, the tool was specifically designed small (Figure 9). The size of perforation tools will vary with different diameter casings.

Figure 10. Example of 8 inch casing after perforation with 3/8 inch apertures (Stamoulis, 2011).

In undergoing post-perforation treatment, the integrity of the casing is maintained since the tool is specifically designed to create an aperture (perforation) but not crack or break the polymeric pipe (Figure 10).

Figure 11. Example of an extended extraction well.

After installation, a well casing often requires vertical extension (Figure 11) as waste is pushed up against it. The vertical extension process can be performed multiple times on an extraction well.

Field Measurements

Field measurements and parameter readings were obtained using a Landtec GEM 2000 gas meter. This meter is considered the gold standard in the industry and is favored by most facilities with gas collection and control systems. It meets all regulatory requirements for compliance reporting. A detailed description of the operation and accuracy of the Landtec GEM 2000 gas meter can be accessed at the Landtec website: www.landtecna.com.

Prior to each measurement event, the meter was calibrated in accordance with each facility's specific site gas plan and the clients' internal standard operating procedures. The manufacturer requires factory calibration twice each year and provides a certification. These semi-annual calibrations are a facility permit and a regulatory compliance requirement. The Landtec GEM 2000 is considered highly reliable, giving accurate measurement. The meter is capable of obtaining the following readings: Device ID, Date/Time, CH_4, CO_2, O_2, Balance Gas, Initial Static Pressure, Adjusted Static Pressure, Initial Temperature, Adjusted Temperature, Initial Flow, Adjusted Flow, Barometric Pressure, and System Pressure/Available Vacuum. The field measurements for the nine facilities, and specifically the five analyzed in this thesis, were obtained either by a third party contractor or by a company representative of the facility owner. The historical data and database queries were conducted by the third party contractor or the company representative respectively. The post-perforations on all extraction wells were conducted by my company, Hydrogeologic/ Environmental Testing and by me each facilities.

Selection of Facilities and Well Group Types

Historical data were collected from nine facilities with extraction wells. These nine facilities are located along the southern Gulf Coast of the United States and contain 849 wells in total. The number of post-perforated wells ranging from one to 19 treated wells. The date of the application of post-perforation technology was known for each facility. Therefore, the data collection period was determined as starting with the date of post-perforation. The post-perforation technology at these facilities was conducted intermittently between February 2009 and April 2014. The historical database at these facilities yielded data from six months prior through six months after the treatment of post-perforation. At the nine facilities, eighty extraction wells had been post-perforated.

All facility-specific data was de-identified and facilities were subsequently numbered as 1 through 9. After facilities selection five were chosen for analyses. Facilities 1, 4, 5, 6, and 9 were used in this thesis. Table 5 summarizes the pertinent data from each facility, and the facilities used are in bold.

Table 5. Facilities and post-perforation information.

Facility Designation	Number of Extraction Wells	Number of Post-perforated Extraction Wells	Date of Post-Perforation	Data Collection Interval
1	**76**	**9**	**2/17/2010**	**9/2009 – 8/2010**
2	75	4	8/19/2009	3/2009 – 2/2010
3	48	1	8/25/2009	3/2009 – 2/2010
4	**135**	**19**	**4/13/2010**	**10/2009 – 9/2010**
5	**138**	**15**	**10/27/2011**	**5/2011 – 4/2012**
6	**95**	**9**	**7/21/2010**	**1/2010 – 12/2011**
7	135	3	8/25/2009	3/2009 – 2/2010
8	98	5	8/31/2010	3/2010 – 2/2011
9	**49**	**15**	**4/11/2014**	**10/2013 – 10/2014**

Selection of Wells and Data to be Analyzed

Data from each facility and at each extraction well were collected on, at minimum, a monthly basis. Each facility is required to maintain a database for the Gas

Control and Collection System. The measurements are collected for facility compliance and reporting.

Data Collection – Well Classification

Prior to post-perforation at each facility, the site database was reviewed and all wells were classified into groups. The classification consisted of identification as either 1) low flow producing wells, or 2) wells with a low concentration, by percentage of methane. If an extraction well had a methane percentage of less than 50% or if the flow (scfm) was less than or equal to 2, the well was classified as marginally producing and a candidate for post-perforation.

At each facility, all wells were evaluated and classified by the client. Additionally, the client selected the extraction wells to receive post-perforation (Group 1). The remaining wells were candidates for post-perforation but did not receive treatment. These extraction wells were classified as Group 2 and serve as control on the perforation treatment. The functional wells were classified as Group 3. From these five facilities, a total of four hundred and ninety-three extraction wells: 67 within Group 1, 165 within Group 2 and 261 within Group 3, were identified. Table 6 summarizes the evaluation criteria, well status, and group type along with function summary.

Table 6. Perforation analysis, group designation and function summary.

Evaluation Criteria	**Extraction Well Status**	**Group Type**	**Option Function**
Flow $\leq$ 2(scfm) $CH_4 < 50\%$	Candidate for rehabilitation	1	Treatment post-perforation
Flow $\leq$ 2(scfm) $CH_4 < 50\%$	Candidate for rehabilitation	2	Treatment no post-perforation
Flow > 3 (scfm)	Fully functional and operational	3	Non-treatment

Removal of Incomplete Data

Prior to facility selection, each database and extraction well data set was evaluated for data completeness. The key criterion here was that each well was in place and functioning during the entire evaluation interval. If any of the following conditions existed, the extraction well was removed from the database.

- An extraction well was not installed prior to post-perforation date.
- A well was damaged and readings could not be obtained during the measurement interval.
- An extraction well yielded no methane or flow readings more than six times during the year of data collection.

A total of 116 extraction wells failed to meet the criterion and were removed from the database. All 67 wells from the five selected facilities undergoing post-perforation survived and were measured during their respective measurement periods.

All collection intervals were examined to ensure that the period was within a year time frame and no overlap of data existed. All data fields were examined to ensure that duplicate data points at well locations did not exist. If two readings at any extraction well location were obtained on the same day, the higher flow value of the day was retained. If readings were taken on two consecutive days, the reading with the higher flow value was retained. If a methane CH_4 reading was obtained and no flow measurements were recorded, a value of zero was inserted.

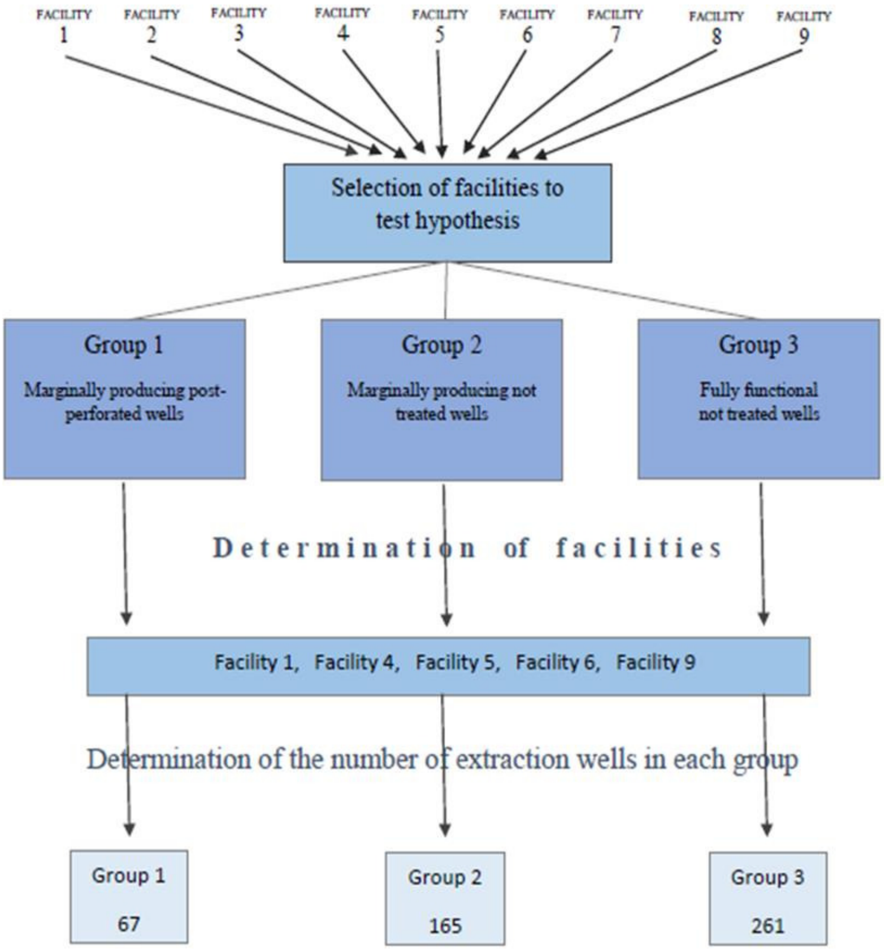


Figure 12. Selection of five municipal solid waste facilities and determination of the number of wells in each group.

From these nine facilities, five were selected for analysis based on the sample size of wells to be analyzed. Any facility with less than nine post-perforated extraction wells was not included in this analysis. As presented in Figure 12, five facilities were selected;

the other four facilities were not included in the analyses due to the facilities containing a low number of post-perforated wells. The low number of treatment wells would not yield a representative sample for analysis. A total of (493) extraction wells were analyzed in this study (Table 7). Each extraction well was categorized into three groups. Group 1 contained 67 extraction wells (13.6% of the total), group 2 contained 165 extraction wells (33.5% of the total) and group 3 contained 261 extraction wells (53.9% of the total). Table 7 depicts the number of wells in each group after facility selection.

Table 7. Number of wells in each group after facility selection.

Facility	**Group 1**	**Group 2**	**Group 3**	**Facility Total**	**Facility %**
1	9	18	49	76	15.40%
4	19	88	28	135	27.40%
5	15	20	103	138	28.00%
6	9	30	56	95	19.30%
9	15	9	25	49	9.90%
Total	**67**	**165**	**261**	**493**	**100%**

To test the hypothesis, the analysis will evaluate if post-perforation methodology can assist in rehabilitating impaired methane extraction wells and if it can increase the capture of methane from a landfill facility.

Statistical Analysis

Pre- and post-perforation mean values of each of the three variables were derived for each of the five selected facilities. For each extraction well, mean values for the variables CH_4, Initial flow and adjusted flow for six months before the treatment period and for six months after were obtained. Once the mean values were calculated for each extraction well, the mean of means for CH_4, initial flow (scfm) and adjusted flow (scfm) for each group were derived for the wells on Groups 1, 2 and 3 at each facility. An example of data from one facility used to calculate the mean values is presented in Appendix 2.

A t-test analysis was conducted on the two population means (pre-perforation vs. post-perforation), for each of the three variables CH_4, initial flow (scfm) and adjusted flow (scfm), for each of the three Groups. The test was used to examine whether the sample means are significantly different between the three types of wells. The on-line version of Vassar stats (www.vassarstats.net) was utilized to run the analysis for the t-test. Along with the t-value, the confidence interval, degrees of freedom, p-value and standard error measures were calculated. Differences among the pre-perforation and the post-perforation mean along with the standard error multiplied by the 95% confidence interval were plotted to illustrate the data.

Environmental and Energy Benefits from Gas Capture

The Environmental Protection Agency (EPA) Landfill Methane Outreach Program (LMOP) has developed a calculator to evaluate the emission reduction and environmental and energy benefits for landfill gas-to-energy projects (U.S EPA, 2015).

The calculator developed by LMOP illustrates estimated environmental and energy benefits from the capture of landfill gas by putting the results in palpable comparisons. The tool calculates the Direct Equivalent Emission Reduced (reduction of methane emitted directly from the landfill) and presents the results in $MMTCO_2E$/year or Tons CH_4/year. It also calculates the Avoided Equivalent Emissions Reduced (offset of carbon dioxide from avoiding the use of fossil fuels) and presents the results in $MMTCO_2E$/year or Tons CO_2 /year, and the Total Equivalent Emissions Reduced in $MMTCO_2E$/year, and presents the results in Tons CH_4 /year, or Tons CO_2/ year.

Introducing any flow (scfm) value into the EPA LMOP calculator, yields a value in tons of methane per year (Tons CH_4/year), or tons of carbon dioxide per year (Tons CO_2/year). The value of LFG and methane captured is then converted into electricity (energy). The data for the five facilities used to generate the mean flow (scfm) values are presented in Appendix 3.

Selection of Data to Illustrate Additional Methane Capture

The data from Group 1, the treatment group from four of the five facilities were selected to demonstrate the environmental and energy benefits from additional methane capture; the mean value of the adjusted flow across all the measured wells was inputted into the EPA calculator. Facility 6 did not produce a positive increase after post-perforation and was not utilized for the demonstration.

Nine extraction wells at Facility 1 underwent post-perforated on 2/17/2010. Nineteen wells at facility 4, received post-perforation treatment on 4/13/2010. Fifteen wells at facility 5 received post-perforation treatment on 10/27/2011. Fifteen wells at facility 9 received post-perforation treatment on 4/11/2014. For all these wells at all four facilities, data on adjusted flow for the six-month period prior to post-perforation and for the period six months after the post-perforation period were collected and averaged over the period.

Once the facilities were selected, the mean difference of the adjusted flow (scfm) values from each facility was inserted into the EPA-LMOP, the gas-calculator. The Environmental Protection Agency, Landfill Methane Outreach Program, landfill gas calculator calculations and references are presented in Appendix 1. A copy of the program can be found at (www.epa.gov/lmop).

Chapter III

Results

Examples of the data for successive measures of the three variables methane (CH_4), initial flow (scfm) and adjusted flow (scfm) are shown in Appendix 2. Statistical analysis was performed after first representing each well by its mean values for these repeated measures before and after the data of post-perforation for Group 1 at each facility. These mean values for each well are shown in Appendix 3.

Mean Statistics

The mean values for methane (CH_4), initial flow (scfm) and adjusted flow (scfm) for each pre- and post- perforated interval across all extraction well of each group at the five facilities are shown in Tables 8 a-e. These tables summarize the means calculated in Appendix 3.

Table 8a. Summary of mean values for pre- vs. post-perforation including all groups at Facility 1.

Facility 1	Group 1					
	pre-perforation			post-perforation		
	CH_4	Initial Flow	Adjusted Flow	CH_4	Initial Flow	Adjusted Flow
Mean	51.9	8.5	8.9	54.9	20.8	22.8
Facility 1	**Group 2**					
	pre-perforation			post-perforation		
	CH_4	Initial Flow	Adjusted Flow	CH_4	Initial Flow	Adjusted Flow
Mean	51.6	10.2	11.3	52.6	18.4	19.2
Facility 1	**Group 3**					
	pre-perforation			post-perforation		
	CH_4	Initial Flow	Adjusted Flow	CH_4	Initial Flow	Adjusted Flow
Mean	51.6	18.8	18.8	52.3	31.5	33.1

(n= 9 for Group 1, n= 18 for Group 2, n= 49 for Group 3). Mean values are % methane (CH_4), and (scfm) for initial and adjusted flow.

Table 8b. Summary of mean values for pre- vs. post-perforation including all groups at Facility 4.

Facility 4	Group 1					
	pre-perforation			post-perforation		
	CH_4	Initial Flow	Adjusted Flow	CH_4	Initial Flow	Adjusted Flow
Mean	48.0	12.3	15.0	51.8	16.9	23.3

Facility 4	Group 2					
	pre-perforation			post-perforation		
	CH_4	Initial Flow	Adjusted Flow	CH_4	Initial Flow	Adjusted Flow
Mean	49.8	3.0	4.2	51.4	10.2	14.8

Facility 4	Group 3					
	pre-perforation			post-perforation		
	CH_4	Initial Flow	Adjusted Flow	CH_4	Initial Flow	Adjusted Flow
Mean	53.1	23.9	28.5	53.1	23.0	31.2

(n= 19 for Group 1, n= 88 for Group 2, n= 28 for Group 3). Mean values are % methane (CH_4), and (scfm) for initial and adjusted flow.

Table 8c. Summary of mean values for pre- vs. post-perforation including all groups at Facility 5.

Facility 5	**Group 1**					
	pre-perforation			**post-perforation**		
	CH_4	**Initial Flow**	**Adjusted Flow**	**CH_4**	**Initial Flow**	**Adjusted Flow**
Mean	52.1	22.5	22.3	52.9	29.1	30.3

Facility 5	**Group 2**					
	pre-perforation			**post-perforation**		
	CH_4	**Initial Flow**	**Adjusted Flow**	**CH_4**	**Initial Flow**	**Adjusted Flow**
Mean	41.6	10.6	11.2	45.7	7.9	8.7

Facility 5	**Group 3**					
	pre-perforation			**post-perforation**		
	CH_4	**Initial Flow**	**Adjusted Flow**	**CH_4**	**Initial Flow**	**Adjusted Flow**
Mean	48.2	22.6	22.2	50.0	18.8	19.3

(n= 15 for Group 1, n= 20 for Group 2, n= 103 for Group 3). Mean values are % methane (CH_4), and (scfm) for initial and adjusted flow.

Table 8d. Summary of mean values for pre- vs. post-perforation including all groups at Facility 6.

Facility 6	Group 1					
	pre-perforation			post-perforation		
	CH_4	Initial Flow	Adjusted Flow	CH_4	Initial Flow	Adjusted Flow
Mean	54.9	3.4	3.6	53.4	3.1	3.1

Facility 6	Group 2					
	pre-perforation			post-perforation		
	CH_4	Initial Flow	Adjusted Flow	CH_4	Initial Flow	Adjusted Flow
Mean	55.0	4.5	4.9	53.2	6.1	5.5

Facility 6	Group 3					
	pre-perforation			post-perforation		
	CH_4	Initial Flow	Adjusted Flow	CH_4	Initial Flow	Adjusted Flow
Mean	55.1	9.6	10.0	55.3	9.1	8.6

(n= 9 for Group 1, n= 30 for Group 2, n= 56 for Group 3). Mean values are % methane (CH_4), and (scfm) for initial and adjusted flow.

Table 8e. Summary of mean values for pre- vs. post-perforation including all groups at Facility 9.

Facility 9	Group 1					
	pre-perforation			post-perforation		
	CH_4	Initial Flow	Adjusted Flow	CH_4	Initial Flow	Adjusted Flow
Mean	54.1	37.7	34.1	51.9	72.4	71.3

Facility 9	Group 2					
	pre-perforation			post-perforation		
	CH_4	Initial Flow	Adjusted Flow	CH_4	Initial Flow	Adjusted Flow
Mean	46.5	36.0	36.4	45.5	64.7	66.9

Facility 9	Group 3					
	pre-perforation			post-perforation		
	CH_4	Initial Flow	Adjusted Flow	CH_4	Initial Flow	Adjusted Flow
Mean	44.6	45.8	44.8	44.7	43.0	46.7

(n= 15 for Group 1, n= 9 for Group 2, n= 25 for Group 3). Mean values are % methane (CH_4), and (scfm) for initial and adjusted flow.

Table 9 summarizes these mean values from Tables 8 a-e by group type, and shows the overall means across the five facilities. The hypothesis examined with these data is that post-perforation increases well performance, so mean values are expected to increase from the pre- to the post-perforation.

The data indicate the mean value for CH_4 did not change in any of the three groups during the post-perforation period. The largest net change exhibited was in group 1, the treatment group, with an increase of (1.01) % methane (52.2% vs 53.0%). However, these values are very close and non-significant as indicated by the variation in repeated measures for each well (Appendix 3) and by noting that mean values at three facilities declined while two increased from the pre- to post-perforation period. Not surprisingly, this result is similar for Group 2 and Group 3 wells. Therefore, the % methane in the gas flow at any well was not altered by perforation of group 1 wells at any of the facilities.

However, the mean values for initial and adjusted flow exhibited a large increase in group 1, from 16.9 to 28.5 and from 16.8 to 30.1 (scfm), respectively, increases of 68.6% and 79.1% respectively (Table 9).

The mean values for all extraction wells in group 2 and group 3 also increased from the pre-to the post perforation period. For group 2, initial and adjusted flow increased from 12.9 to 21.5 and from 13.6 to 23.0 (scfm), respectively, increases of 66.6% and 69.1% respectively. For group 3, initial and adjusted flow increased from 24.1 to 25.1 and from 24.8 to 27.8 (scfm), respectively, increases of 4.1% and 12.0% respectively.

Table 9. Mean values across the five facilities for all well groups. Group 1 data are at the top, Group 2 in the middle and Group 3 the bottom set of data.

All Sites		**Pre-Perforation**			**Post-Perforation**		
		CH_4	**Initial Flow**	**Adjusted Flow**	**CH_4**	**Initial Flow**	**Adjusted Flow**
GROUP 1	**Facility 1**	51.9	8.5	8.9	54.9	20.8	22.8
	Facility 4	48.0	12.3	15.0	51.8	16.9	23.3
	Facility 5	52.1	22.5	22.3	52.9	29.1	30.3
	Facility 6	54.9	3.4	3.6	53.4	3.1	3.1
	Facility 9	54.1	37.7	34.1	51.9	72.4	71.3
Mean		**52.2**	**16.9**	**16.8**	**53.0**	**28.5**	**30.1**
GROUP 2	**Facility 1**	51.6	10.2	11.3	52.6	18.4	19.2
	Facility 4	49.8	3.0	4.2	51.4	10.2	14.8
	Facility 5	41.6	10.6	11.2	45.7	7.9	8.7
	Facility 6	55.0	4.5	4.9	53.2	6.1	5.5
	Facility 9	46.5	36.0	36.4	45.5	64.7	66.9
Mean		**48.9**	**12.9**	**13.6**	**49.7**	**21.5**	**23.0**
GROUP 3	**Facility 1**	51.6	18.8	18.8	52.3	31.5	33.1
	Facility 4	53.1	23.9	28.5	53.1	23.0	31.2
	Facility 5	48.2	22.6	22.2	50.0	18.8	19.3
	Facility 6	55.1	9.6	10.0	55.3	9.1	8.6
	Facility 9	44.6	45.8	44.8	44.7	43.0	46.7
Mean		**50.5**	**24.1**	**24.8**	**51.1**	**25.1**	**27.8**

(n= 67 for Group 1, n= 165 for Group 2, n= 261 for Group 3). Mean values are % methane (CH_4), and (scfm) for initial and adjusted flow.

Statistical Tests of Post-Perforation Effectiveness

T-tests were conducted to assess whether the means of the post versus pre - perforation were statistically different from each other. The means from the post-perforation versus the pre-perforation period for each parameter methane (CH_4), initial flow (scfm) and adjusted flow (scfm) were evaluated for each group within each facility. A two sample t-test for correlated samples was utilized to compensate for the unequal variance between sample sets. This utilized a blocked design whereby the test utilizes the mean difference for each well for the statistical test.

Tables 10a-e present the mean differences in gas flow parameters for the post- versus the pre-perforation period's at all five facilities. Statistically significant p-values are in bold font in the tables for easy identification. Facilities 1 and 4 showed large and significant increases in all three parameters for groups 1 and 2, but not for group 3 (Table 10a and b). Facility 9 (Table 10e) had significant increases in the two flow parameters but not for CH_4. Facility 5 (Table 10c) shows large, but not significant (p=.12 and p=.07) increases in the two flow parameters for group 1, no significant change in mean flow for group 2, and small negative significant changes in flow for group 3 wells. In this case the large sample (n=122) accounted for significance even though the size of the change is relatively small. Facility 6 (Table 10d) was the lone site where Group 1 flow values did not change, similarly for Group 2 and 3.

Table 10a. T-test results for Facility 1 of mean differences in gas parameters in post- vs. pre-perforation periods.

Facility 1		**Mean Post -Mean Pre**	**t**	**df**	**P one-tailed**
Group 1	CH_4	2.9	1.74	8	0.060
	Initial Flow	12.2	2.07	8	**0.036**
	Adjusted Flow	13.8	2.06	8	**0.036**
Group 2	CH_4	0.9	0.55	17	0.294
	Initial Flow	8.2	3.42	17	**0.001**
	Adjusted Flow	7.9	3.41	17	**0.001**
Group 3	CH_4	0.7857	1.93	48	**0.029**
	Initial Flow	12.7571	6.03	48	**<.0001**
	Adjusted Flow	14.2102	6.01	48	**<.0001**

Table 10b. T-test results for Facility 4 of mean differences in gas parameters in post- vs. pre-perforation periods.

Facility 4		Mean Post -Mean Pre	t	df	P one-tailed
Group 1	CH_4	3.8	3.26	18	**0.002**
	Initial Flow	4.6	2.18	18	**0.021**
	Adjusted Flow	8.2	3.76	18	**0.000**
Group 2	CH_4	1.5	2.04	87	**0.022**
	Initial Flow	7.1	7.21	87	**<.0001**
	Adjusted Flow	10.5	9.87	87	**<.0001**
Group3	CH_4	-0.0	-0.03	27	0.488
	Initial Flow	-0.8	-0.36	27	0.360
	Adjusted Flow	2.7	1.02	27	0.158

Table 10c. T-test results for Facility 5 of mean differences in gas parameters in post- vs. pre-perforation periods.

Facility 5		Mean Post -Mean Pre	t	df	P one-tailed
Group 1	CH_4	0.8	0.59	14	0.282
	Initial Flow	6.5	1.24	14	0.117
	Adjusted Flow	8.0	1.58	14	0.068
Group 2	CH_4	4.1	2.72	19	**0.006**
	Initial Flow	-2.7	-1.34	19	0.098
	Adjusted Flow	-2.4	-1.06	19	0.151
Group 3	CH_4	1.8	3.39	102	**0.000**
	Initial Flow	-3.7	-2.88	102	**0.002**
	Adjusted Flow	-2.9	-2.11	102	**0.018**

Table 10d. T-test results for Facility 6 of mean differences in gas parameters in post- vs. pre-perforation periods.

Facility 6		**Mean Post -Mean Pre**	**t**	**df**	**P one-tailed**
Group 1	CH_4	-1.5	-0.59	8	0.285
	Initial Flow	-0.2	-0.19	8	0.427
	Adjusted Flow	-0.5	-0.42	8	0.342
Group 2	CH_4	-1.8	-1.95	29	**0.030**
	Initial Flow	1.6	1.72	29	**0.048**
	Adjusted Flow	0.6	0.61	29	0.273
Group 3	CH_4	0.2	0.44	55	0.330
	Initial Flow	-0.4	-0.89	55	0.188
	Adjusted Flow	-1.3	-2.43	55	**0.009**

Table 10e. T-test results for Facility 9 of mean differences in gas parameters in post- vs. pre-perforation periods.

Facility 9		**Mean Post -Mean Pre**	**t**	**df**	**P one-tailed**
Group 1	CH_4	-2.1	-0.93	14	0.184
	Initial Flow	14.2	1.85	14	**0.042**
	Adjusted Flow	37.2	2.53	14	**0.012**
Group 2	CH_4	-0.9	-0.95	8	0.184
	Initial Flow	28.7	2.11	8	**0.033**
	Adjusted Flow	30.4	2	8	**0.040**
Group 3	CH_4	0.0	0.03	24	0.488
	Initial Flow	-2.8	-0.43	24	0.335
	Adjusted Flow	1.9	0.27	24	0.394

To summarize for group 1, the study treatment group, three facilities exhibited statistical significance ($p < 0.05$) for the initial flow and adjusted flow (and another large, nearly significant increases), whereas only one facility showed significant increases in methane. For group 2, three facilities exhibited significance increases for methane (CH_4), four for initial flow and three for adjusted flow. For group 3, two facilities exhibited statistically significance increases for methane (CH_4), and, initial flow and three for adjusted flow. There were a few negative mean values, but only one statistically significant – a slight decline in adjusted flow for Group 3 wells at facility 6.

In summary, these results support the hypothesis that post-perforation of poorly performing wells, enhances flow rates not only for those wells post-perforated, but for those in the same field that are unperforated. The responses are large and significant across four of the facilities, but post-perforation had no demonstrable effects on Facility 6 wells.

As a final summary of the effects of post-perforation, the data from all facilities were compiled across all the wells in the three groups (Table 11). Note that these samples are not strictly independent given that there is seemingly an effect of facility as discussed above. With that caveat, the results emphasizes the large positive effect of perforation of Group 1 wells on the two flow parameters on both Group 1 and similarly low performing Group 2 wells, but not on the already high performing Group 3 wells.

Table 11. T-test results for all five Facilities of mean differences in gas parameters in post- vs. pre-perforation periods.

All Five Facilities		**Mean Post -Mean Pre**	**t**	**df**	**P one-tailed**
Group 1	CH_4	0.9	1.16	66	0.125
	Initial Flow	12.1	3.05	66	**0.001**
	Adjusted Flow	14.2	3.66	66	**0.000**
Group 2	CH_4	1.0	1.98	164	**0.024**
	Initial Flow	6.2	5.76	164	**<.0001**
	Adjusted Flow	7.9	6.64	164	**<.0001**
Group3	CH_4	0.9	2.95	260	**0.001**
	Initial Flow	0.4	0.46	260	0.322
	Adjusted Flow	1.7	1.58	260	0.057

Standard Errors and Confidence Intervals

The standard error for each mean value (S.E.) was calculated for each variable (CH_4, initial flow and adjusted flow), for each group and each facility separately for the pre-perforation and post-perforation interval (Tables 12a-c). Additionally, a 95% confidence interval was calculated by multiplying the (S.E.) value by 1.96.

Table 12a. Methane (CH_4), initial flow (scfm), adjusted flow (scfm), mean values, standard errors (S.E.) and 95% confidence intervals for Group 1 for all five facilities.

GROUP 1							
Facilities		**Mean PRE**	**S.E.**	**95% C.I.**	**Mean POST**	**S.E.**	**95% C.I.**
CH_4	**Facility 1**	51.9	0.81	1.6	54.9	1.26	2.5
	Facility 4	48.0	1.93	3.8	51.8	1.17	2.3
	Facility 5	52.1	1.17	2.3	52.9	0.80	1.6
	Facility 6	54.9	0.95	1.9	53.4	1.93	3.8
	Facility 9	54.1	1.63	3.2	51.9	1.64	3.2
I-FLOW	**Facility 1**	8.5	3.02	5.9	20.8	8.05	15.8
	Facility 4	12.3	3.47	6.8	16.9	2.84	5.6
	Facility 5	22.5	6.21	12.2	29.1	7.16	14.0
	Facility 6	3.4	1.10	2.2	3.1	0.27	0.5
	Facility 9	37.7	8.14	16.0	72.4	16.80	32.9
ADJUSTED FLOW	**Facility 1**	8.9	3.03	5.9	22.8	8.76	17.2
	Facility 4	15.0	3.48	6.8	23.3	3.47	6.8
	Facility 5	22.3	6.28	12.3	30.3	7.17	14.0
	Facility 6	3.6	1.18	2.3	3.1	0.36	0.7
	Facility 9	34.1	8.27	16.2	71.3	16.53	32.4

Table 12b. Methane (CH_4), initial flow (scfm), adjusted flow (scfm), mean values, standard errors (S.E.) and 95% confidence intervals for Group 2 for all five facilities.

GROUP 2							
Facilities		**Mean PRE**	**S.E.**	**95% C.I.**	**Mean POST**	**S.E.**	**95% C.I.**
CH_4	**Facility 1**	51.6	0.69	1.4	52.6	1.77	3.5
	Facility 4	49.8	0.85	1.7	51.4	0.68	1.3
	Facility 5	41.6	2.60	5.1	45.7	2.07	4.1
	Facility 6	55.0	0.74	1.5	53.2	0.97	1.9
	Facility 9	46.5	6.97	13.7	45.5	7.79	15.3
I-FLOW	**Facility 1**	10.2	1.37	2.7	18.4	2.83	5.6
	Facility 4	3.0	0.60	1.2	10.2	0.93	1.8
	Facility 5	10.6	3.48	6.8	7.9	1.84	3.6
	Facility 6	4.5	0.74	1.4	6.1	0.84	1.6
	Facility 9	36.0	10.22	20.0	64.7	15.77	30.9
ADJUSTED FLOW	**Facility 1**	11.3	1.61	3.2	19.2	2.86	5.6
	Facility 4	4.2	0.80	1.6	14.8	1.13	2.2
	Facility 5	11.2	3.68	7.2	8.7	1.86	3.7
	Facility 6	4.9	0.81	1.6	5.5	0.82	1.6
	Facility 9	36.4	10.29	20.2	66.9	17.68	34.7

Table 12c. Methane (CH_4), initial flow (scfm), adjusted flow (scfm), mean values, standard errors (S.E.) and 95% confidence intervals for Group 3 for all five facilities.

GROUP 3							
Facilities		Mean PRE	S.E.	95% C.I.	Mean POST	S.E.	95% C.I.
CH_4	**Facility 1**	51.6	0.69	1.4	52.6	1.77	3.5
	Facility 4	49.8	0.85	1.7	51.4	0.68	1.3
	Facility 5	41.6	2.60	5.1	45.7	2.07	4.1
	Facility 6	55.0	0.74	1.5	53.2	0.97	1.9
	Facility 9	46.5	6.97	13.7	45.5	7.79	15.3
I-FLOW	**Facility 1**	10.2	1.37	2.7	18.4	2.83	5.6
	Facility 4	3.0	0.60	1.2	10.2	0.93	1.8
	Facility 5	10.6	3.48	6.8	7.9	1.84	3.6
	Facility 6	4.5	0.74	1.4	6.1	0.84	1.6
	Facility 9	36.0	10.22	20.0	64.7	15.77	30.9
ADJUSTED FLOW	**Facility 1**	11.3	1.61	3.2	19.2	2.86	5.6
	Facility 4	4.2	0.80	1.6	14.8	1.13	2.2
	Facility 5	11.2	3.68	7.2	8.7	1.86	3.7
	Facility 6	4.9	0.81	1.6	5.5	0.82	1.6
	Facility 9	36.4	10.29	20.2	66.9	17.68	34.7

Graphic Representation of Post-Perforation Effects

The differences in mean values for the pre-and post-perforation periods for each parameter are shown as histograms in Figures 13a-c, 14 a-c and 15a-c.

For Group 1, three facilities (1, 4 and 5) exhibited an increase in CH_4 (Fig. 13a). Additionally, four facilities (1, 4, 5 and 9) exhibited large mean value increases for initial and adjusted flow (Fig. 13b and 13c).

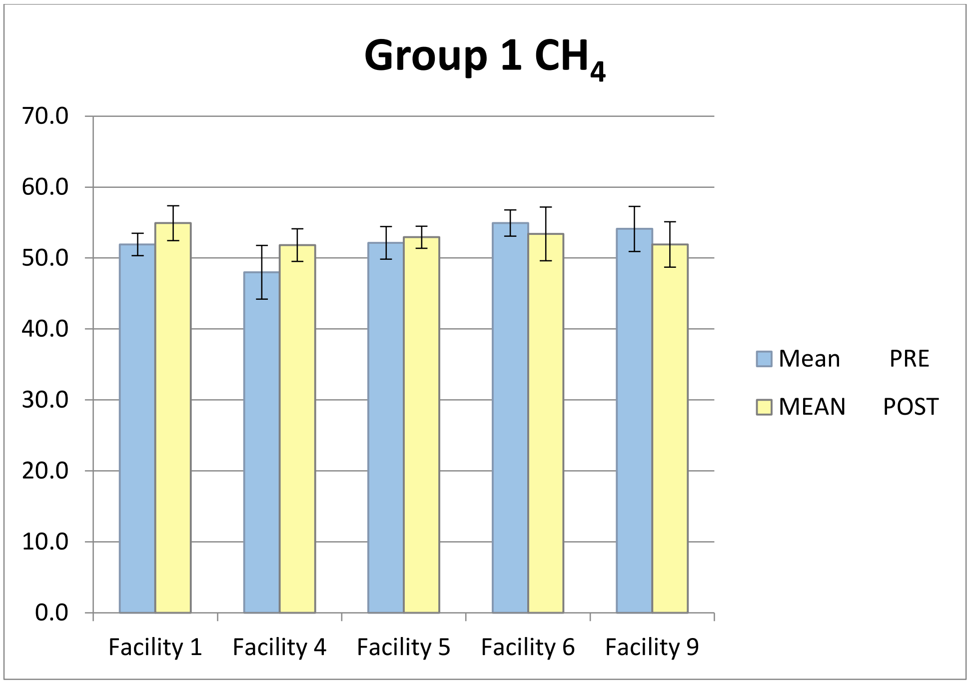


Figure 13a. Group 1 differences in mean values (S.E.) for pre- versus post-perforation for % methane (CH_4).

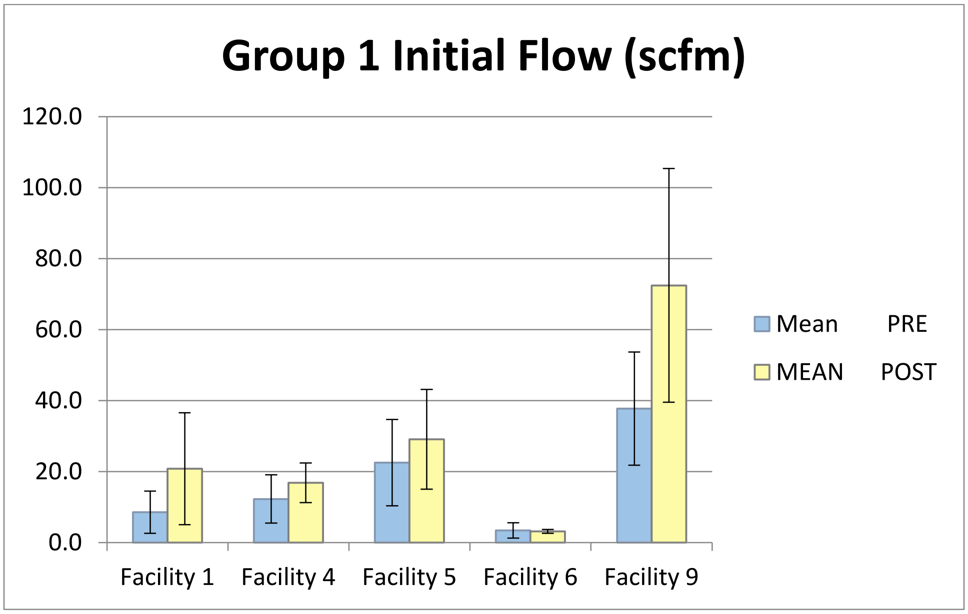


Figure 13b. Group 1 differences in mean values (S.E.) for pre- versus post-perforation for initial flow (scfm).

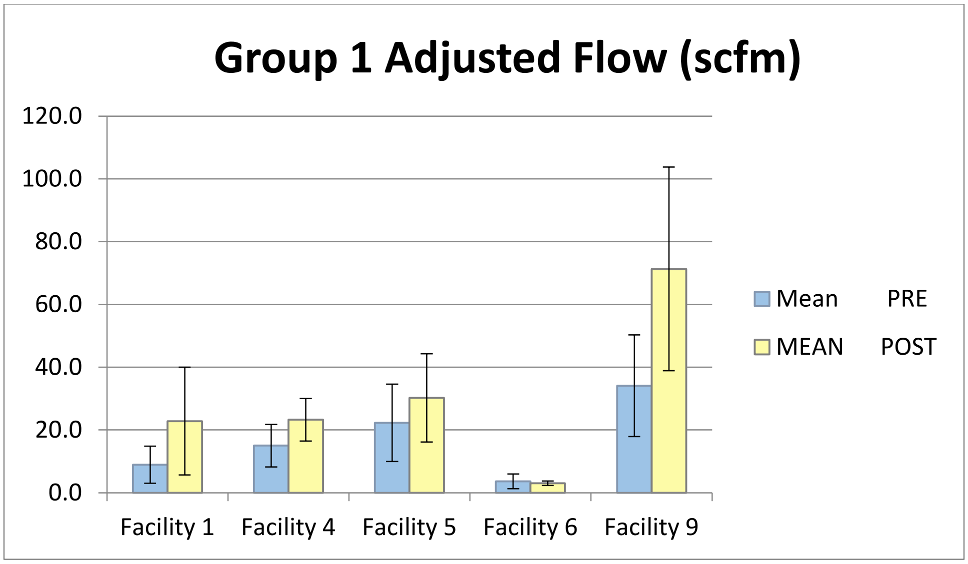


Figure 13c. Group 1 differences in mean values (S.E.) for pre- versus post-perforation for adjusted flow (scfm).

For Group 2, three facilities (1, 4 and 5) exhibited a small mean value increase in CH_4 after the post-perforation period (Fig 14a). Facilities 1, 4, 6 and 9 exhibited a mean value increase in initial and adjusted flow (Fig 14b and 14c).

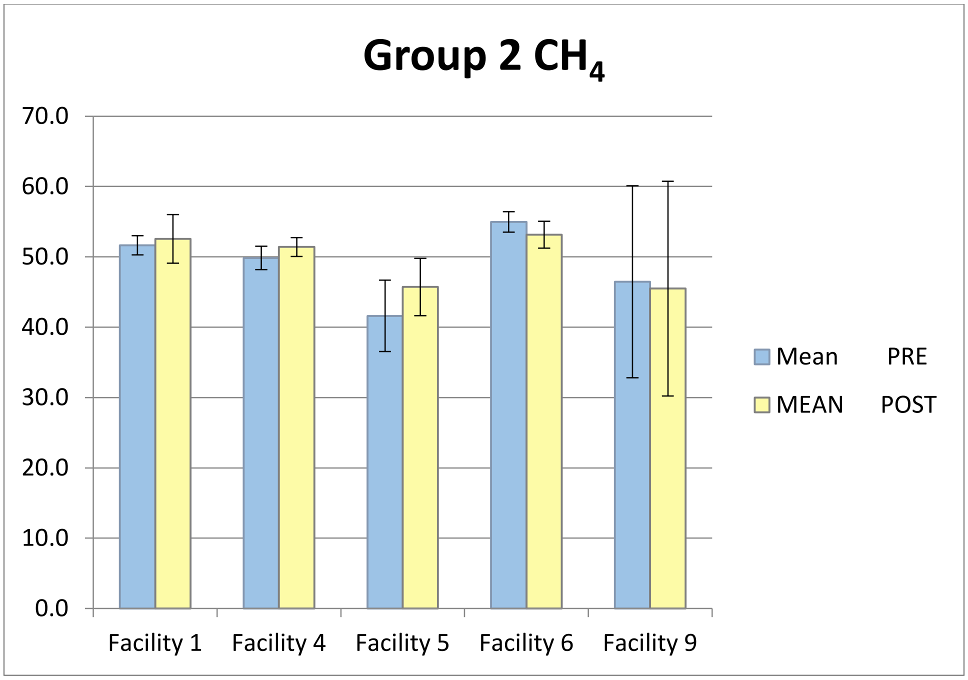


Figure 14a. Group 2 differences in mean values (S.E.) for pre- versus post-perforation for % methane (CH_4).

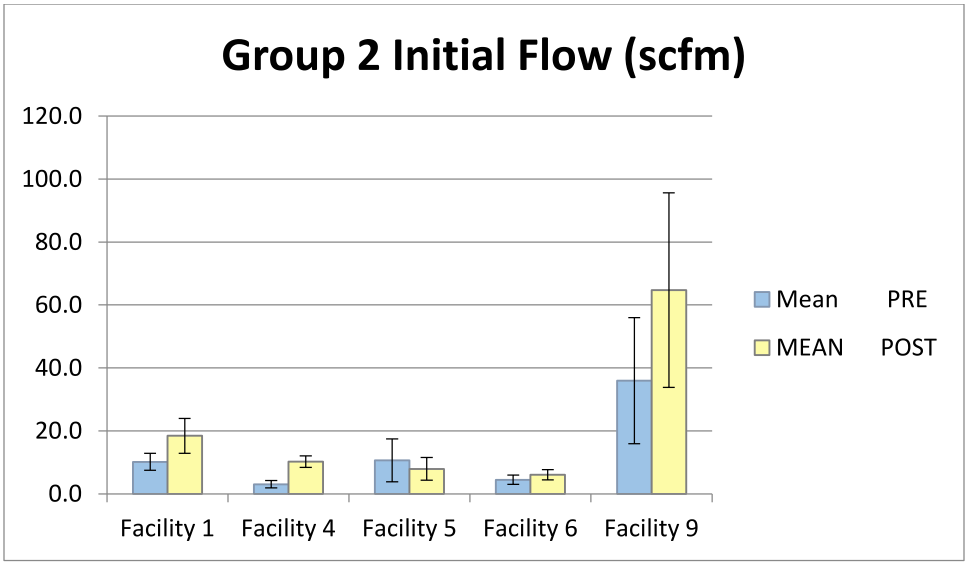


Figure 14b. Group 2 differences in mean values (S.E.) for pre- versus post-perforation for initial flow (scfm).

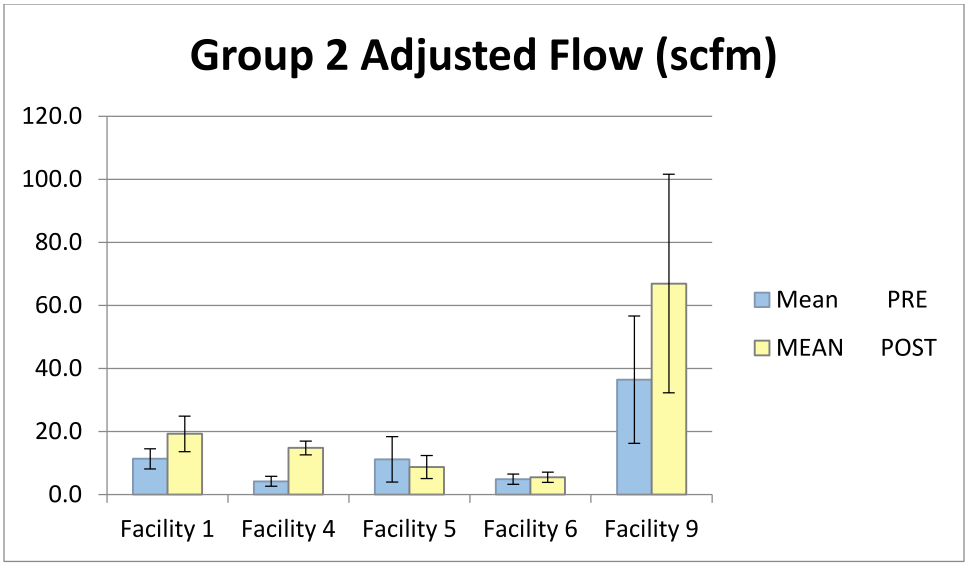


Figure 14c Group 2 differences in mean values (S.E.) for pre- versus post-perforation for adjusted flow (scfm).

For Group 3, three facilities (1, 5 and 6) exhibited a slight increase in CH_4 after the post-perforation period (Fig 15a). Facility 1 exhibited an increase in mean initial flow (Fig. 15b), and two facilities (1 and 4) exhibited increases in mean adjusted flow (Fig. 15c).

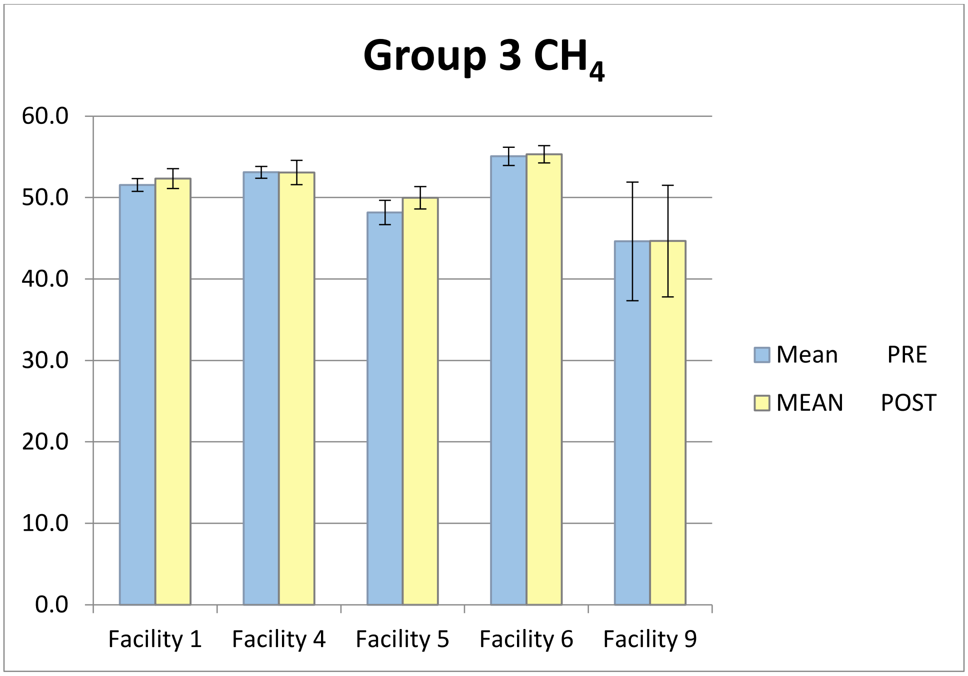


Figure 15a. Group 3 differences in mean values (S.E.) for pre- versus post-perforation for % methane (CH_4).

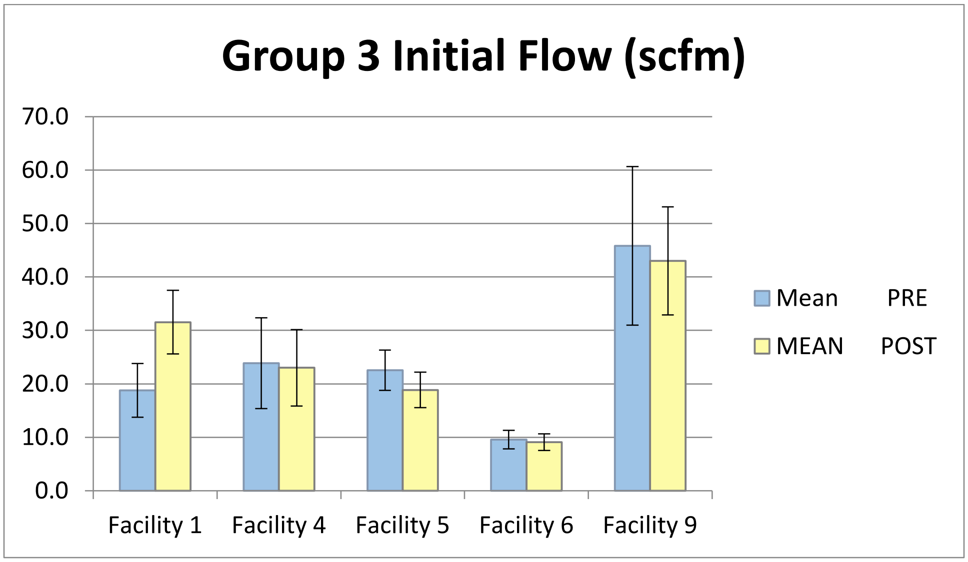


Figure 15b. Group 3 differences in mean values (S.E.) for pre- versus post-perforation for initial flow (scfm).

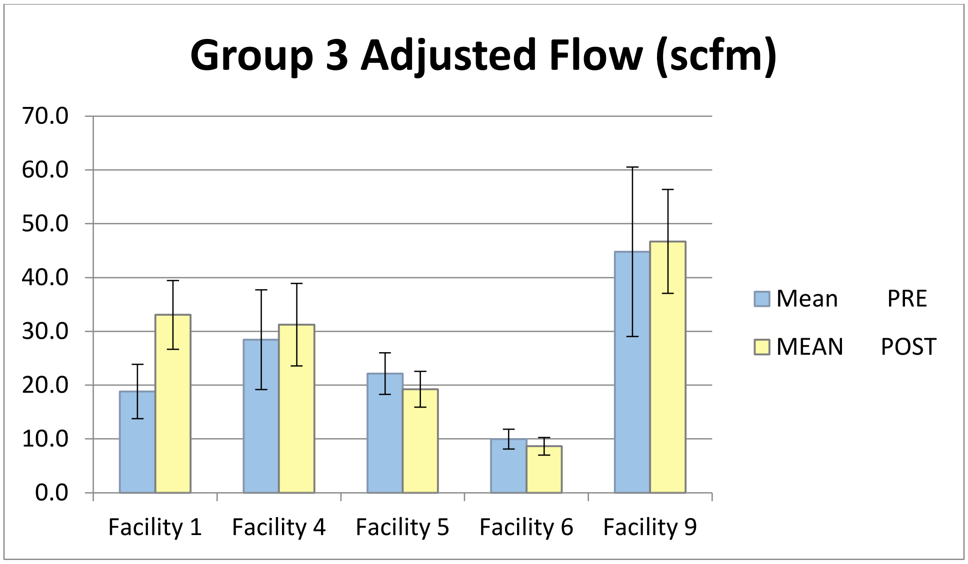


Figure 15c. Group 3 differences in mean values (S.E.) for pre- versus post-perforation for adjusted flow (scfm).

EPA – LMOP-Landfill Gas Calculator

Four of the five facilities were selected to highlight the environmental and energy benefits from increased CH_4 capture after post-perforation treatment. Facilities 1, 4, 5, and 9 were selected for this demonstration of benefits. From these four facilities, 58 treatment wells were able to increase the capture of an additional 960 scfm of methane.

Additional Flow Capture at Facility 1

Facility 1 contained 76 extraction wells. Forty-nine of these wells or (65%) were fully functional and produce large quantities of gas used for gas to energy production. Eighteen or (23%) of the facility’s extraction wells met the criteria for post-perforation, and 9 or (12%) of the overall extraction wells were post- perforated at this facility on February 17, 2010. The post-perforation yielded an increase for 5 of the 9 wells over this study period. Table 13 summarizes the data for the difference in six month’s mean flow (scfm) from extraction wells at Facility 1; Figure 16 displays these changes for each well.

Table 13. Difference in six months average flow (scfm) from extraction wells at Facility 1. Extraction wells were perforated on 2/17/2010. Measurement interval for facility 1 was conducted from 9/2009 through 8/2010.

Facility 1	**Perforation**		**Mean difference**
	Pre	**Post**	
	Adjusted flow (mean)	**Adjusted flow (mean)**	
EW-4	3.80	2.80	-1.00
EW-8	4.70	10.30	5.60
EW-17	3.00	22.80	19.80
EW-20	3.70	3.50	-0.20
EW-24	25.80	41.20	15.40
EW-36	3.80	35.30	31.50
EW-43	23.50	81.20	57.70
EW-45	3.70	2.80	-0.90
EW-47	8.30	5.30	-3.00
Total	**80.30**	**205.20**	**124.90**

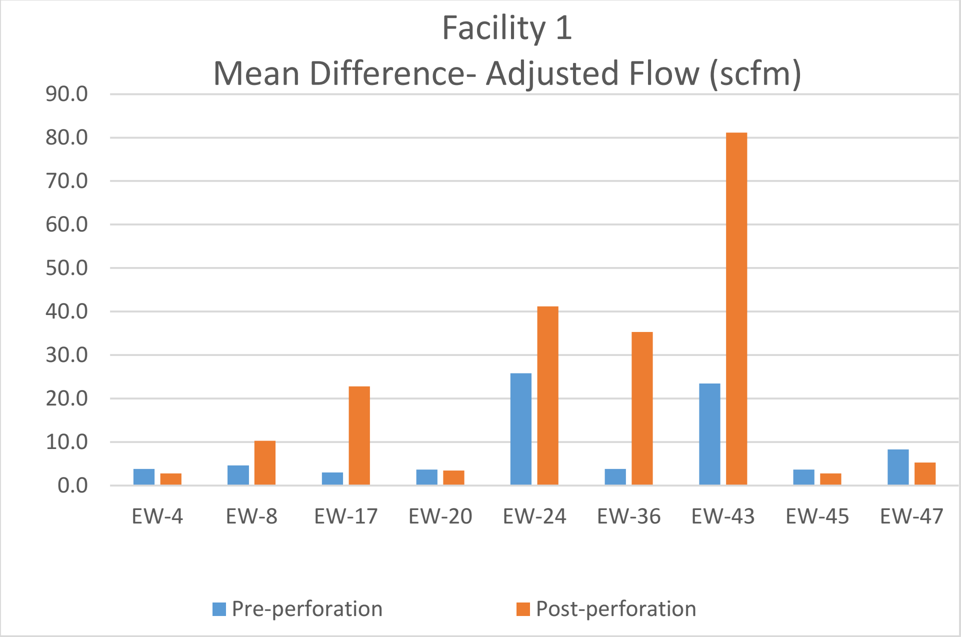
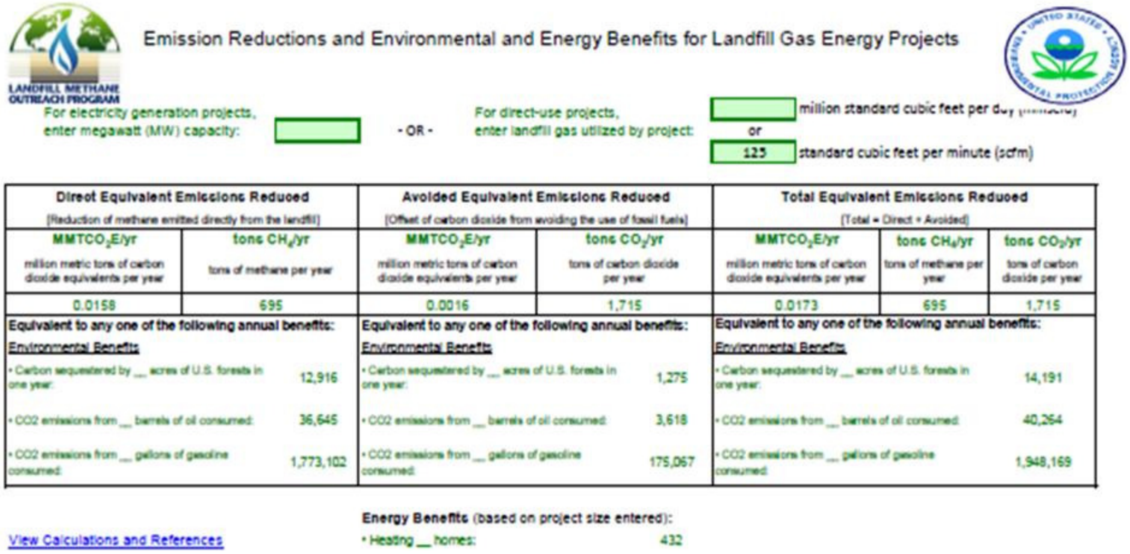


Figure 16. Average flow (scfm) pre- versus post-perforation at Facility 1.

Differences between the two values for each well (Fig. 16) were averaged to yield an overall average increase flow of 125 scfm (Table 13). This additional flow (scfm) was inputted into the Emissions Reduction and Environmental and Energy Benefits, for landfill gas energy projects calculator (U.S. EPA, 2015) below.



Emission Reductions and Environmental and Energy Benefits for Landfill Gas Energy Projects

For electricity generation projects, enter megawatt (MW) capacity: - OR - For direct-use projects, enter landfill gas utilized by project: million standard cubic feet per day or 125 standard cubic feet per minute (scfm)

Direct Equivalent Emissions Reduced [Reduction of methane emitted directly from the landfill]		Avoided Equivalent Emissions Reduced [Offset of carbon dioxide from avoiding the use of fossil fuels]		Total Equivalent Emissions Reduced [Total = Direct + Avoided]		
$MMTCO_2E/yr$ million metric tons of carbon dioxide equivalents per year	tons CH_4/yr tons of methane per year	$MMTCO_2E/yr$ million metric tons of carbon dioxide equivalents per year	tons CO_2/yr tons of carbon dioxide per year	$MMTCO_2E/yr$ million metric tons of carbon dioxide equivalents per year	tons CH_4/yr tons of methane per year	tons CO_2/yr tons of carbon dioxide per year
0.0158	695	0.0016	1,715	0.0173	695	1,715

Equivalent to any one of the following annual benefits:		Equivalent to any one of the following annual benefits:		Equivalent to any one of the following annual benefits:	
Environmental Benefits		Environmental Benefits		Environmental Benefits	
• Carbon sequestered by __ acres of U.S. forests in one year:	12,916	• Carbon sequestered by __ acres of U.S. forests in one year:	1,275	• Carbon sequestered by __ acres of U.S. forests in one year:	14,191
• CO2 emissions from __ barrels of oil consumed:	36,645	• CO2 emissions from __ barrels of oil consumed:	3,618	• CO2 emissions from __ barrels of oil consumed:	40,264
• CO2 emissions from __ gallons of gasoline consumed:	1,773,102	• CO2 emissions from __ gallons of gasoline consumed:	175,067	• CO2 emissions from __ gallons of gasoline consumed:	1,948,169

View Calculations and References

Energy Benefits (based on project size entered):

• Heating __ homes: 432

Figure 17. Landfill gas energy calculator, net CH_4 increase of 125 (scfm) from Facility 1.

Even so small an amount of methane capture as 125 scfm, can create substantial benefits to the environment. Both direct equivalent and avoided equivalent emissions reduce methane emitted from a facility and offset carbon dioxide from avoiding the use of fossil fuels. For this facility, the increase over a one-year period would directly reduce emissions by 0.0158 $MMTCO_2E/yr$ or 695 tons CH_4/yr. Additionally, the offset from avoiding fossil fuels to provide this energy would be 0.0016 $MMTCO_2E/yr$ or 1,715 tons CO_2/yr.

These combined reductions and avoided values mean more when put in tangible comparative examples. The total equivalent emissions reduced would be equivalent to any one of the following:

- Carbon sequestered from 14,191 acres of U.S. forest in one year,
- CO_2 emissions from 40,264 barrels of oil consumed, or
- CO_2 emissions from 1,948,169 gallons of gasoline consumed.

The energy benefit from capturing an additional 125 scfm of methane could heat 432 homes for a year’s period.

Additional Flow Capture at Facility 4

Facility 4 contained 135 extraction wells. Twenty-eight of these wells or (21%) were fully functional and produce large quantities of gas used for gas to energy production. Eighty-eight (65%) of the facility’s extraction wells met the criteria for post-perforation, and 19 (14%) of the overall extraction wells were post- perforated at this facility on April 14, 2010. The post-perforation yielded a change or increase for 16 of the 19 wells over this study period. Table 14 summarizes the data for the differences in the six month’s mean adjusted flow (scfm) from extraction wells at facility 4: Figure 18 displays these changes for each well.

Table 14. Difference in cumulative flow (scfm) for a six months period before/after post-perforation on extraction wells at Facility 4. Extraction wells were perforated on 4/13/2010. Measurement interval for Facility 4 was conducted from 10/2009 through 9/2010.

Facility 4	Perforation		Mean difference
	Pre	Post	
	Adjusted flow (mean)	Adjusted flow (mean)	
EW-251	23.70	46.80	23.10
EW-261	0.70	8.20	7.50
EW-265	0.00	10.80	10.80
EW-270	11.70	15.80	4.10
EW-272	60.50	58.50	-2.00
EW-273	12.50	24.30	11.80
EW-284	18.50	15.50	-3.00
EW-286	0.00	30.80	30.80
EW-297	6.80	17.50	10.70
EW-300	20.80	23.80	3.00
EW-301	8.30	17.80	9.50
EW-302	10.20	20.50	10.30
EW-306	37.00	55.50	18.50
EW-316	15.00	20.00	5.00
EW-318	8.50	24.50	16.00
EW-320	5.20	5.50	0.30
EW-322	5.70	7.00	1.30
EW-331	33.70	24.00	-9.70
EW-341	6.30	15.00	8.70
Total	**285.10**	**441.80**	**156.70**

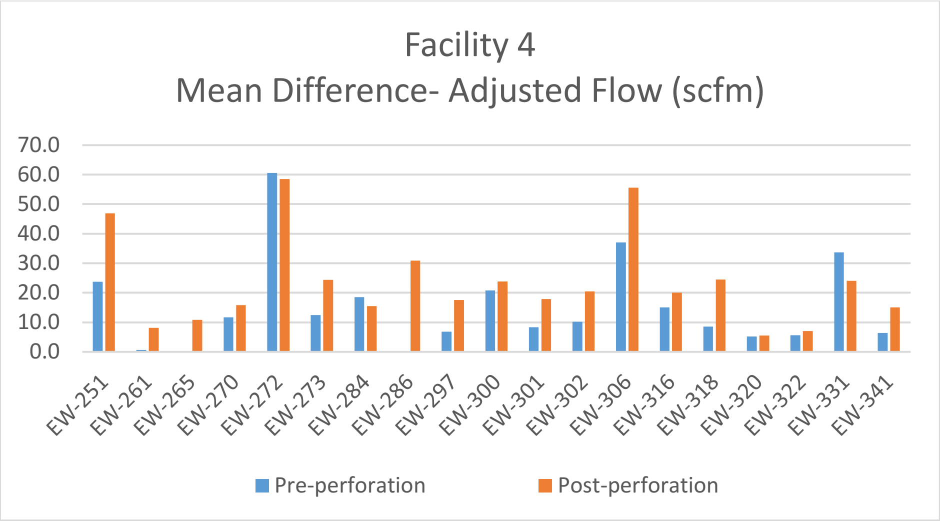
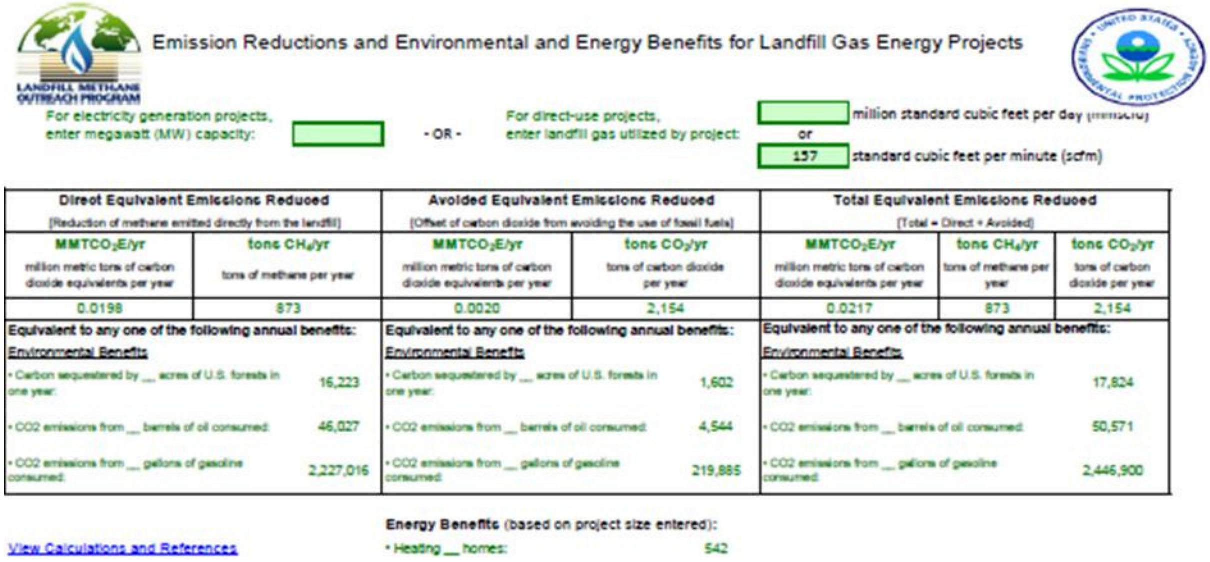


Figure18. Average flow (scfm) pre- versus post-perforation at Facility 4.

Differences between the two values for each well (Fig. 18) were averaged to yield an overall average increase flow of 157 scfm (Table 14). This additional flow was inputted into the Emissions Reduction and Environmental and Energy Benefits, for landfill gas energy projects calculator (U.S. EPA, 2015) below.



Emission Reductions and Environmental and Energy Benefits for Landfill Gas Energy Projects

For electricity generation projects, enter megawatt (MW) capacity: - OR - For direct-use projects, enter landfill gas utilized by project: million standard cubic feet per day (mmscfd) or 157 standard cubic feet per minute (scfm)

Direct Equivalent Emissions Reduced [Reduction of methane emitted directly from the landfill]		Avoided Equivalent Emissions Reduced [Offset of carbon dioxide from avoiding the use of fossil fuels]		Total Equivalent Emissions Reduced [Total = Direct + Avoided]		
$MMTCO_2E/yr$ million metric tons of carbon dioxide equivalents per year	tons CH_4/yr tons of methane per year	$MMTCO_2E/yr$ million metric tons of carbon dioxide equivalents per year	tons CO_2/yr tons of carbon dioxide per year	$MMTCO_2E/yr$ million metric tons of carbon dioxide equivalents per year	tons CH_4/yr tons of methane per year	tons CO_2/yr tons of carbon dioxide per year
0.0198	873	0.0020	2,154	0.0217	873	2,154

Equivalent to any one of the following annual benefits: Environmental Benefits		Equivalent to any one of the following annual benefits: Environmental Benefits		Equivalent to any one of the following annual benefits: Environmental Benefits	
• Carbon sequestered by __ acres of U.S. forests in one year:	16,223	• Carbon sequestered by __ acres of U.S. forests in one year:	1,602	• Carbon sequestered by __ acres of U.S. forests in one year:	17,824
• CO2 emissions from __ barrels of oil consumed:	46,027	• CO2 emissions from __ barrels of oil consumed:	4,544	• CO2 emissions from __ barrels of oil consumed:	50,571
• CO2 emissions from __ gallons of gasoline consumed:	2,227,016	• CO2 emissions from __ gallons of gasoline consumed:	219,885	• CO2 emissions from __ gallons of gasoline consumed:	2,446,900

Energy Benefits (based on project size entered):

• Heating __ homes: 542

View Calculations and References

Figure 19. Landfill gas energy calculator, net CH_4 increase 157 (scfm) from Facility 4.

For this facility, the increase over a one-year period would directly reduce emissions by 0.0198 MMTCO$_2$E/yr or 873 tons CH$_4$/yr. Additionally, the offset from avoiding fossil fuels would be 0.0020 MMTCO$_2$E/yr or 2,154 tons CO$_2$/yr. The total equivalent emissions reduced would be equivalent to any one of the following:

- Carbon sequestered from 17,824 acres of U.S. forest in one year,
- CO$_2$ emissions from 50,571 barrels of oil consumed, or
- CO$_2$ emissions from 2,446,900 gallons of gasoline consumed.

The energy benefit from capturing an additional 157 (scfm) of methane could heat 542 homes for a year's period.

Additional Flow Capture at Facility 5

Facility 5 contained 138 extraction wells. One hundred and three or (75%) were fully functional and produce large quantities of gas used for gas to energy production. Twenty (14%) of the facility's extraction wells met the criteria for post-perforation, and 15 (11%) of the overall extraction wells were post- perforated at this facility on October 27, 2011. The post-perforation yielded a change or increase for 6 of the 15 wells over this study period. Table 15 summarizes the data for the differences in the six month's mean adjusted flow (scfm) from extraction wells at Facility 5; Figure 20 displays these changes for each well.

Table 15. Difference in six- month average flow (scfm) from extracted wells at Facility 5. Extraction wells were perforated on 10/27/2011. Measurement interval for Facility 5 ranged from 5/2011 through 4/2012.

Facility 5	**Perforation**		**Mean difference**
	Pre	**Post**	
	Adjusted flow (mean)	**Adjusted flow (mean)**	
EW-379	18.20	59.50	41.30
EW-380	17.20	47.80	30.60
EW-381	37.50	35.80	-1.70
EW-382	26.00	11.80	-14.20
EW-383	15.00	46.80	31.80
EW-394	8.80	4.70	-4.10
EW-395	8.20	7.20	-1.00
EW-417	104.20	95.70	-8.50
EW-418	22.00	26.20	4.20
EW-456	15.50	8.70	-6.80
EW-457	3.00	2.00	-1.00
EW-513	16.00	63.70	47.70
EW-539	15.30	12.30	-3.00
EW-540	23.70	29.50	5.80
EW-542	3.30	2.20	-1.10
Total	**333.90**	**453.90**	**120.00**

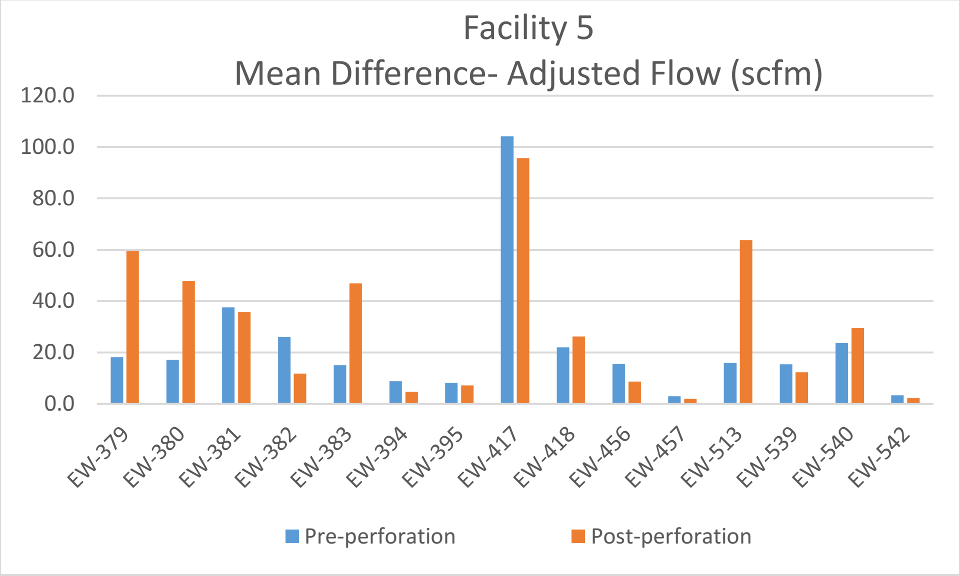
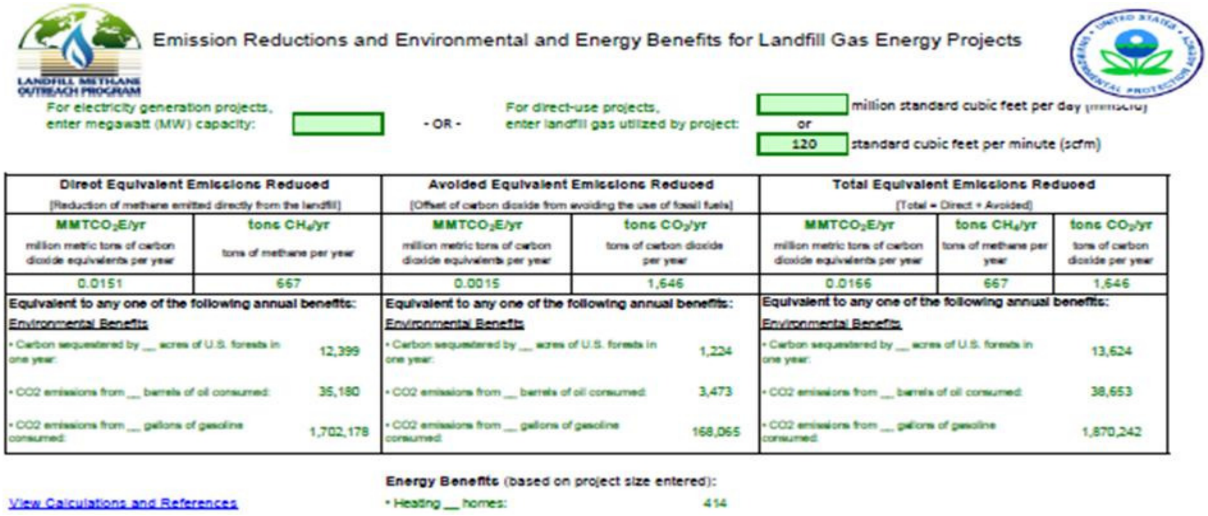


Figure 20. Average flow (scfm) pre- versus post-perforation at Facility 5.

Differences between the two values for each well (Fig.20) were averaged to yield an overall average increase flow of 120 scfm (Table 15). This additional flow was inputted into the Emissions Reduction and Environmental and Energy Benefits, for landfill gas energy projects calculator (U.S. EPA, 2015) below.



Emission Reductions and Environmental and Energy Benefits for Landfill Gas Energy Projects

For electricity generation projects, enter megawatt (MW) capacity: - OR - For direct-use projects, enter landfill gas utilized by project: million standard cubic feet per day (mmscfd) or 120 standard cubic feet per minute (scfm)

Direct Equivalent Emissions Reduced [Reduction of methane emitted directly from the landfill]		Avoided Equivalent Emissions Reduced [Offset of carbon dioxide from avoiding the use of fossil fuels]		Total Equivalent Emissions Reduced [Total = Direct + Avoided]		
$MMTCO_2E/yr$ million metric tons of carbon dioxide equivalents per year	**tons CH_4/yr** tons of methane per year	**$MMTCO_2E/yr$** million metric tons of carbon dioxide equivalents per year	**tons CO_2/yr** tons of carbon dioxide per year	**$MMTCO_2E/yr$** million metric tons of carbon dioxide equivalents per year	**tons CH_4/yr** tons of methane per year	**tons CO_2/yr** tons of carbon dioxide per year
0.0151	667	0.0015	1,646	0.0166	667	1,646
Equivalent to any one of the following annual benefits: Environmental Benefits		**Equivalent to any one of the following annual benefits:** Environmental Benefits		**Equivalent to any one of the following annual benefits:** Environmental Benefits		
• Carbon sequestered by __ acres of U.S. forests in one year:	12,399	• Carbon sequestered by __ acres of U.S. forests in one year:	1,224	• Carbon sequestered by __ acres of U.S. forests in one year:		13,624
• CO2 emissions from __ barrels of oil consumed:	35,180	• CO2 emissions from __ barrels of oil consumed:	3,473	• CO2 emissions from __ barrels of oil consumed:		38,653
• CO2 emissions from __ gallons of gasoline consumed:	1,702,178	• CO2 emissions from __ gallons of gasoline consumed:	168,065	• CO2 emissions from __ gallons of gasoline consumed:		1,870,242

View Calculations and References

Energy Benefits (based on project size entered):

• Heating __ homes: 414

Figure 21. Landfill gas energy calculator, net CH_4 increase of 120 (scfm) from Facility 5.

For this facility, the increase over a one-year period would directly reduce emissions by 0.0151 $MMTCO_2E$/yr or 667 tons CH_4/yr., Additionally, the offset from avoiding fossil fuels to provide this energy would be 0.0015 $MMTCO_2E$/yr or 1,646 tons CO_2/yr. The total equivalent emissions reduced would be equivalent to any one of the following:

- Carbon sequestered from 13,624 acres of U.S. forest in one year,
- CO_2 emissions from 38,653 barrels of oil consumed, or
- CO_2 emissions from 1,870,242 gallons of gasoline consumed.

The energy benefit from capturing an additional 120 scfm of methane could heat 414 homes for a year's period.

Additional Flow Capture at Facility 9

Facility 9 contained 49 extraction wells. Twenty-five of these wells (51%) were fully functional and produce large quantities of gas used for gas to energy production. Nine (18%) of the facility's extraction wells met the criteria for post-perforation, and 15 (30%) of the overall extraction wells were post- perforated at this facility on April 11, 2014. The post-perforation yielded a change or increase for 12 of the 15 wells over this study period. Table 16 summarizes the data for the differences in the six month's mean adjusted flow (scfm) from extraction wells at Facility 9; Figure 22 displays these changes for each well.

Table 16. Difference in six- month average flow (scfm) from extracted wells at Facility 9. Extraction wells were perforated on 4/11/2014. Measurement intervals for facility 9 were conducted from 10/2013 through 9/2014.

Facility 9	**Perforation**		**Mean difference**
	Pre	**Post**	
	Adjusted flow (mean)	**Adjusted flow (mean)**	
EW-898	25.80	79.30	53.50
EW-899	26.70	58.80	32.10
EW-900	29.30	32.80	3.50
EW-906	46.50	103.50	57.00
EW-909	5.80	219.70	213.90
EW-912	35.20	28.00	-7.20
EW-913	36.80	54.70	17.90
EW-914	122.30	218.50	96.20
EW-916	6.70	17.70	11.00
EW-917	5.70	38.80	33.10
EW-918	77.30	61.70	-15.60
EW-919	13.20	24.30	11.10
EW-925	9.30	53.30	44.00
EW-938	13.20	28.80	15.60
EW-939	57.50	49.80	-7.70
Total	**511.30**	**1069.70**	**558.40**

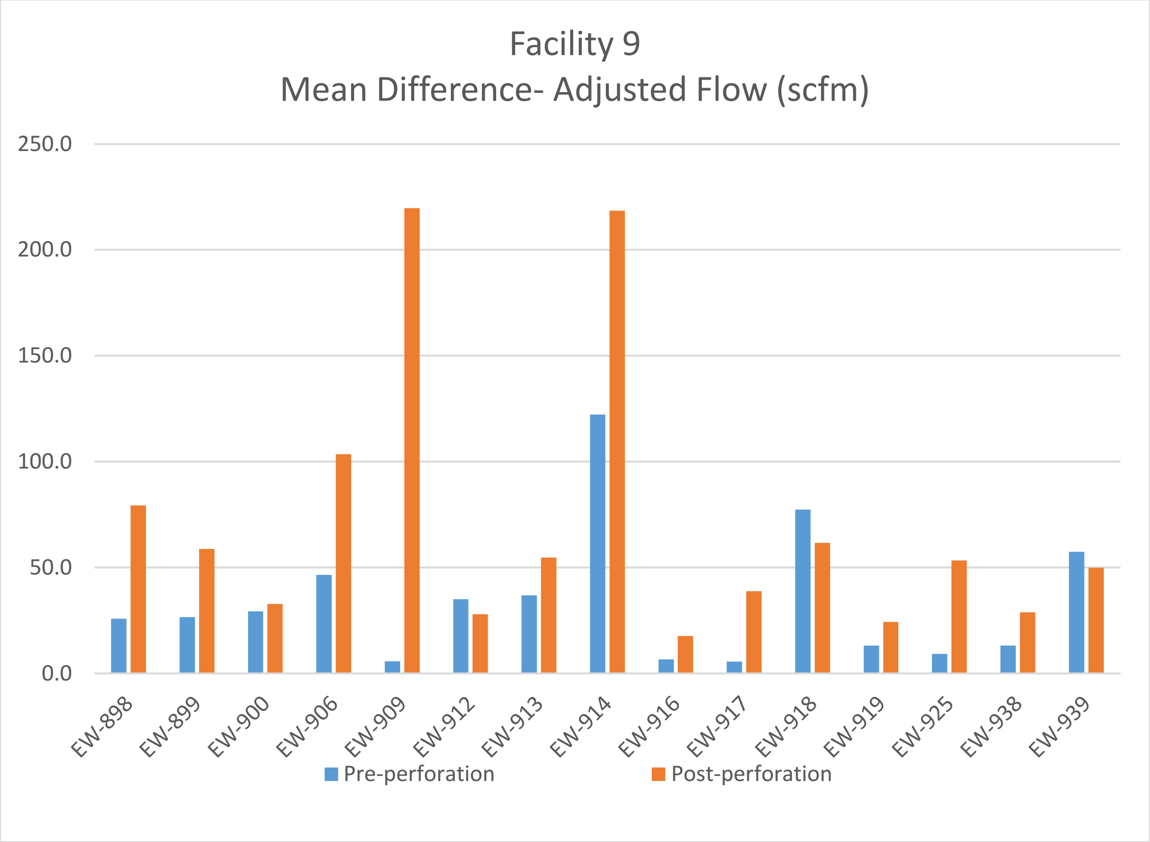
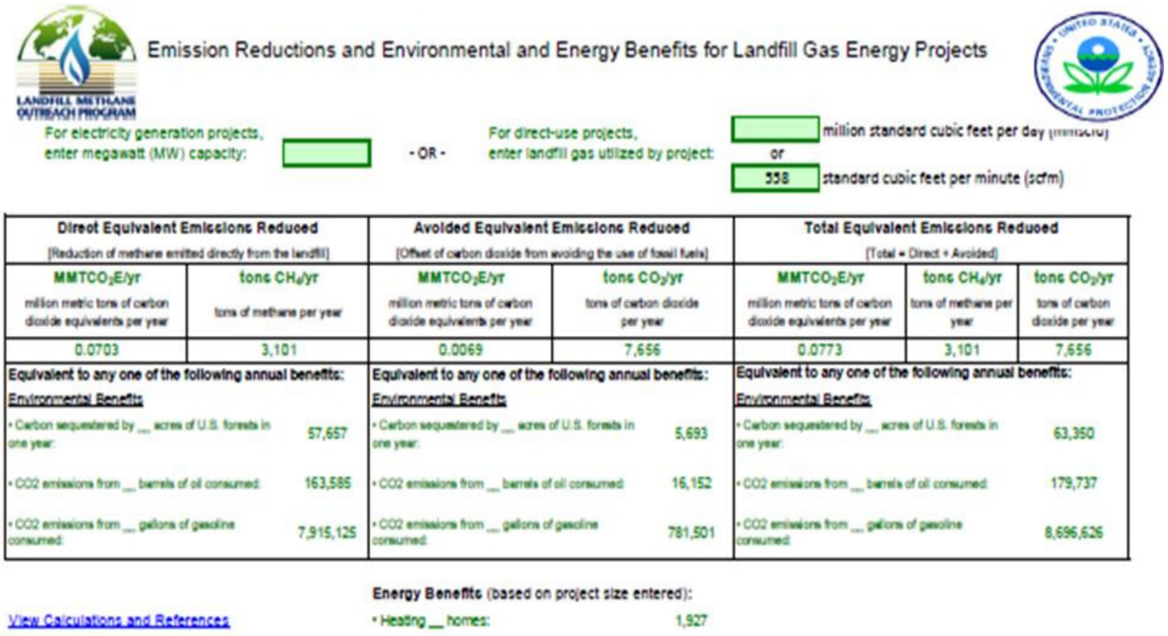


Figure 22. Average flow (scfm) pre- versus post-perforation at Facility 9.

Differences between the two values for each well (Fig. 22) were averaged to yield an overall average increase flow 558 scfm (Table 16). This additional flow was inputted into the Emissions Reduction and Environmental and Energy Benefits, for landfill gas energy projects calculator (U.S.EPA, 2015).



Emission Reductions and Environmental and Energy Benefits for Landfill Gas Energy Projects

For electricity generation projects, enter megawatt (MW) capacity: ☐ - OR - For direct-use projects, enter landfill gas utilized by project: ☐ million standard cubic feet per day

or

558 standard cubic feet per minute (scfm)

Direct Equivalent Emissions Reduced [Reduction of methane emitted directly from the landfill]		Avoided Equivalent Emissions Reduced [Offset of carbon dioxide from avoiding the use of fossil fuels]		Total Equivalent Emissions Reduced [Total = Direct + Avoided]		
$MMTCO_2E/yr$ million metric tons of carbon dioxide equivalents per year	**tons CH_4/yr** tons of methane per year	**$MMTCO_2E/yr$** million metric tons of carbon dioxide equivalents per year	**tons CO_2/yr** tons of carbon dioxide per year	**$MMTCO_2E/yr$** million metric tons of carbon dioxide equivalents per year	**tons CH_4/yr** tons of methane per year	**tons CO_2/yr** tons of carbon dioxide per year
0.0703	3,101	0.0069	7,656	0.0773	3,101	7,656

Equivalent to any one of the following annual benefits:		Equivalent to any one of the following annual benefits:		Equivalent to any one of the following annual benefits:	
Environmental Benefits		Environmental Benefits		Environmental Benefits	
• Carbon sequestered by __ acres of U.S. forests in one year:	57,657	• Carbon sequestered by __ acres of U.S. forests in one year:	5,693	• Carbon sequestered by __ acres of U.S. forests in one year:	63,350
• CO2 emissions from __ barrels of oil consumed:	163,585	• CO2 emissions from __ barrels of oil consumed:	16,152	• CO2 emissions from __ barrels of oil consumed:	179,737
• CO2 emissions from __ gallons of gasoline consumed:	7,915,125	• CO2 emissions from __ gallons of gasoline consumed:	781,501	• CO2 emissions from __ gallons of gasoline consumed:	8,696,626

Energy Benefits (based on project size entered):

• Heating __ homes: 1,927

View Calculations and References

Figure 23. Landfill gas energy calculator, net CH_4 increase of 558 (scfm) from Facility 9.

For this facility, the increase over a one-year period would directly reduce emissions by 0.0703 $MMTCO_2E/yr$ or 3,101 tons CH_4/yr., additionally, the offset from avoiding fossil fuels to provide this energy would be 0.0069 $MMTCO_2E/yr$ or 7,656 tons CO_2/yr. The total equivalent emissions reduced would be equivalent to any one of the following:

- Carbon sequestered from 63,350 acres of U.S. forest in one year,
- CO_2 emissions from 179,737 barrels of oil consumed, or
- CO_2 emissions from 8,696,626 gallons of gasoline consumed.

The energy benefit from capturing an additional 558 scfm of methane could heat 1,927 homes for a year's period.

Table 17 summarizes the total equivalent emissions reduced and the energy benefit from the additional mean capture of 960 scfm, from the four facilities in this study.

Table 17. Environmental and energy benefits from the five study facilities.

Facility	**Mean adjusted flow (scfm)**	**Total equivalent emissions reduced**			**Energy benefit**
		$MMTCO_2$ eq/Yr	**Tons CH_4/Yr**	**Tons CO_2/Yr**	**Home heating**
1	125	0.0173	695	1,715	432
4	157	0.0217	873	2,154	542
5	120	0.0166	667	1,646	414
9	558	0.0773	3,101	7,656	1,927
Total	**960**	**0.1329**	**5,336**	**13,171**	**3,315**

Chapter IV

Discussion

The release of methane from municipal solid waste facilities constitutes both a danger and an opportunity. Methane (CH_4) is a potent greenhouse gas, and the third largest anthropogenic source currently contributing to the degradation of the atmosphere. The long-life and heat-trapping attributes of methane contribute to global warming. Many detrimental chemical processes are directly linked to methane emissions. For example, methane is a precursor of and persists with ozone (O_3). The current climate forcing by CH_4 is 26 times that of CO_2 (calculated on a molar basis).

In the United States, 3,000 municipal solid waste facilities (MSWFs) dispose of approximately 250 million tons of waste per year. On a global scale, 1.3 billion tons of waste requiring disposal are generated annually. Each MSWF produces by-products. One of the main externalities is the production of methane through the decomposition of the organic fraction of the waste. A remarkable fact is that 78% of the countries in the world have few environmental controls at their modern midden heaps.

Much literature indicates that current municipal solid waste gas collection and control systems are often only marginally effective in the capture of methane (Hartwell, 2011, U.S. EPA, 2011). Reports show gas collection efficiencies varying from a low of 36% to a high of 75%, although, some facilities report collections as high as 80 to 85%. In the study population on which the present work is based, at the five facilities examined, fully functional wells were only 20% to 74% efficient. The data collected in this study appear quite consistent with cited collection efficiencies averages.

Few methodologies have contributed much to an additional increase in methane (CH_4) capture. According to the EPA (U.S. EPA, 2011), gas collection efficiencies can be increased by covering waste with highly plastic clay, installing a geomembrane, and by focusing on detection and leak repair. The post-perforation technology described in this study is an additional tool to expand the capture of methane. Capturing methane should be a global priority. Considering all the detrimental effects that anthropogenic methane causes, the need for improved technology is warranted. The reinforcement of research and development methods that enhance methane capture should be encouraged.

This thesis set out to examine whether post-perforation technology was effective in rehabilitating marginally producing, non-optimal vertical extraction wells at typical landfill facilities.

The results of the analyses demonstrated a statistical effect after post-perforation in the treatment group. The difference in mean values after post-perforation for group 1-the treatment group, indicated the largest increase for the initial flow and the adjusted flow. The mean initial flow increased from 16.9 to 28.5 ($t = 3.05$; $p = 0.016$; $n=67$), and the adjusted flow increased from 16.8 to 30.1 ($t = 3.66$; $p = 0.002$; $n=67$) (Table 9). Group 2 and Group 3 mean values also increased after the time of perforation of Group 1 wells, but to a lesser extent in each variable (Table 11).

Facilities 1, 4, 5 and 9 yielded an increase in average flow of 125, 157, 120 and 558 scfm, after post-perforation in the treatment well (Table 17). In a six month period after post-perforation, the 67 wells in this study yielded an average increase of 960 scfm.

This represents an average flow increase of 14.0 scfm methane from each extraction well. The total equivalent emissions reduction from 960 scfm is equivalent to 0.1329 $MMTCO_2E$/year, or 5,336 tons CH_4/year or 13,171 tons CO_2/year. The energy benefits from this methane capture would heat 3,315 homes a year.

This study provided a realistic view of capture, considering the percentage of post-perforated wells, the number of facilities and the rate of methane increase. The blocked research design that included large samples of all three types of wells at multiple facilities gives a clear statistical signal of the effectiveness of post-perforation technology.

As presented in Tables 13 through Table 16, four facilities exhibited an increase of capture, an improvement considering the small percentage (13.6%) of wells post-perforated versus total wells at each facility. This data supports the contention that post-perforation provides a better than average success rate treating marginally-producing extraction wells.

Uncontrollable Facility and System Inconsistencies

The factor that contributed most to high fluctuation in the data fields is believed to be system pressure. Lack of consistent or constant system pressure appears to have caused all the percent methane, initial flow and adjusted flow measures to fluctuate erratically between successive measurements. The inability to control effects from system pressure created a challenging degree of variability.

All the post-perforated treatment wells survived the data collection period free from damage by Gulf Coast wind and rain or the inevitable mishaps attending human effort in a physical world. The extraction wells in all three groups, however, experienced effects from flooded screen zones due to a rise in entrained fluids. Well measurements would indicate that fluid levels rose, in some cases, above the screen zones or the post-perforation intervals in extraction wells at least in some wells at all facilities. Such entrained fluids are most likely the main cause of the poor performance exhibited at Facility 6.

Future Considerations and Research

With more than three thousand active landfills and waste generation at 250 million tons per year, it appears that landfill as a disposal method will long continue in the United States. The EPA has reported that 646 facilities capture and utilize the methane that rises as a by-product, turning it to a renewable energy source. Many more facilities are capable of assisting in the control of this potent greenhouse gas and instead using it to generate renewable energy. Even at landfills with methane capture technology, much methane is lost to fugitive emission, as some extraction wells are not capturing gas at any given time. It is not difficult to conclude that, if capture mechanisms are not working, then methane is escaping.

It would be unrealistic to believe that all wells at all facilities can be repaired. Some wells are not repairable, just as the installation of a new extraction well may not produce gas. Many wells are filled with entrained fluids after installation. Research on the development of methods to prevent entrained fluids from entering the waste body and flooding extraction wells is also a crucial issue. Where rainfall is higher, as on the Gulf

Coast, flooding caused by entrained fluids is a huge enemy of any extraction well and collection and control system.

More research is required to analyze the statistical significance of increased production after post-perforation. Emphasis should fall on evaluating one facility and focus on the control of unexplained variables. New field techniques are required to further demonstrate and increase the effectiveness of the post-perforation technology. The many observations made during the methodology development, field testing and the writing of this thesis have provided useful questions and suggests inquiries into continued development.

This study demonstrates the importance of landfill gas collection and capture efficiencies. The technology has created new opportunities to assist in methane gas capture. Research and development are required to advance further this technology. Rehabilitation in a few wells is still better than allowing unchecked emissions. Continued advance is the only option to increase capture efficiencies and minimize emissions in a world demanding fuel and threatened by climate change.

References

Amini, H. R., Reinhart, D. R., & Mackie, K. R. (2012). Determination of first-order landfill gas modeling parameters and uncertainties. Waste Management, 32(2), 305-316.

Association of Science and Technology Centers Incorporated and the Smithsonian Traveling Exhibition. (1998). A history of garbage collection. Retrieved July 9, 2014 from http://www.astc.org/exhibitions/rotten/rhome.htm

Barber, H. B., Stamoulis, S., Trebus, S., Widner, M. (2011, January). Enhancement of LFG Capture from Landfill Gas Extraction Wells at Municipal Solid Waste Facilities. Paper presented at the EPA Landfill Methane Outreach Program, Baltimore.

Bell, C. L., Brownell, F. W., Case, D. R., Ewing, K. A., King, J. O., Landfair, S. W., . . . & Von Oppenfeld, R.R. (2013). Environmental law handbook: Bernan Press

Berger, S., & Mann, J. (2001). Landfill gas primer: An overview for environmental health professionals. Department of Health and Human Services, Agency for Toxic Substances and Disease Registry (ATSDR), Division of Health Assessment and Consultation.

Bousquet, P., Ciais, P., Miller, J.B., Dlugokencky, E.J., Hauglustaine, D.A., Prigent, C.,… & White, J. (2006). Contribution of anthropogenic and natural sources to atmospheric methane variability. Nature 443(7110), 439-443.

Coase, R H. (2013). The problem of social cost. The Journal of Law & Economics, (56), 837-878.

Dillah, D. D., McCarron, G. P., Panesar, B. S. (2005, March). Vertical landfill gas extraction wells: The SCS model. Retrieved from http://www.scsengineers.com/wp-content/uploads/2015/03/Dillah-McCarron-Balwinder_Vertical_LFG_Wells_The_SCS_Model.pdf

Ewall, M. (n.d.). Primer on landfill gas as green energy. Retrieved July 8, 2014 from http://www.energyjustice.net/lfg

Field, C. B., Barros, V. R., Mastrandrea, M. D., Mach, K. J., Abdrabo, M. K., Adger, N., ... & Porter, J. R. (2014). Summary for policymakers. Climate change 2014: impacts, adaptation, and vulnerability. Part a: global and sectoral aspects. Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change, 1-32.

Fiore, A. M., Jacob, D. J., Field, B. D., Streets, D. G., Fernandes, S. D., & Jang, C. (2002). Linking ozone pollution and climate change: The case for controlling methane. Geophysical Research Letters, 29(19), 25-21-25-24.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D. W…... & Van Dorland, R. (2007). Changes in atmospheric constituents and in radiative forcing. Chapter 2. In Climate Change 2007. The Physical Science Basis.

Frankel, J. A. (1999, June). Greenhouse gas emissions [Brookings policy brief]. Retrieved from http://www.hks.harvard.edu/fs/jfrankel/BrookingsPolicyBrief1999.pdf

Gómez, D. R., Watterson, J. D., Americano, B. B., Ha, C., Marland, G., Matsika, E., ... & Treanton, K. (2006). IPCC guidelines for national greenhouse gas inventories. Institute for Global Environmental Strategies, Kamiyamaguchi Hayama, Japan. http:// www.ipcc-nggip.iges.or.jp/public

Griggs, D. J., & Noguer, M. (2002). Climate change 2001: the scientific basis. Contribution of working group I to the third assessment report of the intergovernmental panel on climate change. Weather, 57(8), 267-269.

Hartwell, J. (2011, March/April). Regarding LFG. MSW Management, the Journal for Municipal Solid Waste Professionals, 8-9. Retrieved from http://digital.mswmanagement.com/publication/index.php?i=61784&m=&l=&p=52&pre=&ver=swf

Hartz, K. E., & Ham, R. K. (1982). Gas generation rates of landfill samples. Conservation & Recycling, 5(2–3), 133-147.

Hickman, H. L. (2003). American alchemy: The history of solid waste management in the United States. ForesterPress: Santa Barbara, California.

Hoornweg, D., & Bhada-Tata, P. (2012). What a waste: A global review of solid waste management. Retrieved from http://siteresources.worldbank.org/INTURBANDEVELOPMENT/Resources/336387-1334852610766/What_a_Waste2012_Final.pdf

Kabir.K.B. and Halim, S.Z. (2011). Anthropogenic methane: Emission sources and mitigation options, ChE Thoughts 2 (1), 16-22

Le Treut, H., Somerville, R., Cubasch, U., Ding, Y., Mauritzen, C., Mokssit, A., ... & Prather, M. (2007). Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Retrieved from https://www.ipcc.ch/publications_and_data/ar4/wg1/en/spm.html

Lelieveld, J., Crutzen, P.J. & Bruhl, C. (1993). Climate effects of atmospheric methane, Chemosphere, 26(1-4), 739-768. Retrieved from http://www.sciencedirect.com/science/article/pii/004565359390458H

Lind, H. & Granqvist, R. (2010). A note on the concept of excess burden. Economic Analysis and Policy, 40:63-73. Retrieved from http://www.sciencedirect.com/science/article/pii/S0313592610500043

McKinsey & Company. (2007, December) Reducing U.S. Greenhouse Gas Emissions: How Much at What Cost? Retrived from http://www.mckinsey.com/client_service/sustainability/latest_thinking/reducing_us_greenhouse_gas_emissions

Rathje, W., Murphy, C. (2001). Rubbish! The archaeology of garbage. Tucson, Arizona: University of Arizona Press.

Reinhart, D.R., Amini, H., & Bolyard, S.C. (2012). The role of landfills in US sustainable waste management. Environmental Engineer: Applied Research and Practice, 15, 1-4. Retrieved from http://www.researchgate.net/publication/235760294_The_Role_of_Landfills_in_US_Sustainable_Waste_Managament?

Savitz, A. (2006). The triple bottom line: How today's best-run companies are achieving economic, social, and environmental success-and how you can too (1st ed.). San Francisco, CA: Jossey-Bass.

Scharff, H., & Jacobs, J. (2006). Applying guidance for methane emission estimation for landfills. Waste Management, 26(4), 417-429.

Solid Waste Industry for Climate Solutions. (2007, June). Current MSW Industry Position and State-of-the -Practice on LFG Collection Efficiency, Methane Oxidation, and Carbon Sequestration in Landfills. Los Angeles, CA: Helget, C & Caponi, F.

Spokas, K., Bogner, J., Chanton, J. P., Morcet, M., Aran, C., Graff, C., . . . Hebe, I. (2006). Methane mass balance at three landfill sites: What is the efficiency of capture by gas collection systems? Waste Management, 26(5), 516-525.

Stamoulis, S. (2011). USA Patent No. 7,866,921. Washington, DC: U.S. Patent and Trademark Office.

Stamoulis, S. (2011b). USA Patent No. 8,047,276. Washington, DC: U.S. Patent and Trademark Office.

Stamoulis, S. (2013). USA Patent No. 8.398,335. Washington, DC: U.S. Patent and Trademark Office.

Stamoulis, S., Meyer, W. & Nichols, K. (2011, March). Methodologies to rehabilitate methane recovery wells that outweigh the cost of well replacement. Paper presented at the Solid Waste Association of North America, San Diego, California

Sullivan, P. (2007, March). Update on Major Air Quality Regulations Affecting Landfills. Proceedings, 30th Annual Landfill Gas Symposium. Symposium conducted at the annual meeting of the Solid Waste Association of North America, Monterey, CA.

U.S. Code of Federal Regulations. (2006). Title 40 Protection of the Environment, 1-End. Retrieved from http:// www.gpoaccess.gov/cfr/index/htmc

U.S. Department of Commerce, Census Department. (2014). Retrieved from Department of Commerce website http:// www.U.S.departmentof commerce/census.gov

U.S. Environmental Protection Agency, Landfill Method Outreach Program (LMOP). (2015). Energy projects and candidate landfills. Retrieved from LMOP website http://www.epa.gov/lmop

U.S. Environmental Protection Agency. (2014). Managing non-hazardous municipal and solid waste (RCRA). Retrieved from EPA website http:// www.epa.gov/waste/nonhaz/municipal

U.S. Environmental Protection Agency. (2011). Draft U.S. greenhouse gas inventory report – Draft inventory of U.S. greenhouse gas emissions and sinks: 1990- 2009. (Executive Summary 2011: ES-9). Retrieved from EPA website http://www.epa.gov/climatechange/emissions/usinventoryreport.html

U.S. Environmental Protection Agency. (2009). Greenhouse gas reporting program. (Federal Register). Retrieved from http://www.epa.gov/climatechange/emissions/ghgrulemaking.html

U.S. Environmental Protection Agency. (2009). Greenhouse gas reporting program. (Federal Register). Retrieved from EPA website http://www.epa.gov/climatechange/emissions/ghgrulemaking.html

U.S. Environmental Protection Agency, Office of Atmospheric Programs. (2006). Global mitigation of non-CO^{2} greenhouse gases. (6207J), EPA-430-R-06-005. Retrieved from EPA website http://www.epa.gov/climatechange/emissions/usinventoryreport.html

U.S. Environmental Protection Agency. (1990). Standards of performance for new stationary sources and guidelines for control of existing sources: Municipal solid waste landfills. (Federal Register) Retrieved from EPA website http://www.law.cornell.edu/uscode/html/uscode42/usc_sec_42_00007411----000-.html

U.S. Environmental Protection Agency. (1990). Title I air pollution prevention and control. (Federal Register). Retrieved from EPA website http://epa.gov/oar/caa/title1.html

U.S. Environmental Protection Agency, Office of Research and Development. (1998). Emerging technologies for the management and utilization of landfill gas. Retrieved from EPA website http://www.epa.gov/ttn/catc/dir1/etech_pd.pdf

U.S. Environmental Protection Agency. (1996). Standards of performance for new stationary sources and guidelines for control of existing sources: Municipal solid waste landfills. (Federal Register: 9905). Retrieved from EPA website http://www.epa.gov/ttn/atw/landfill/fr12mr96.pdf

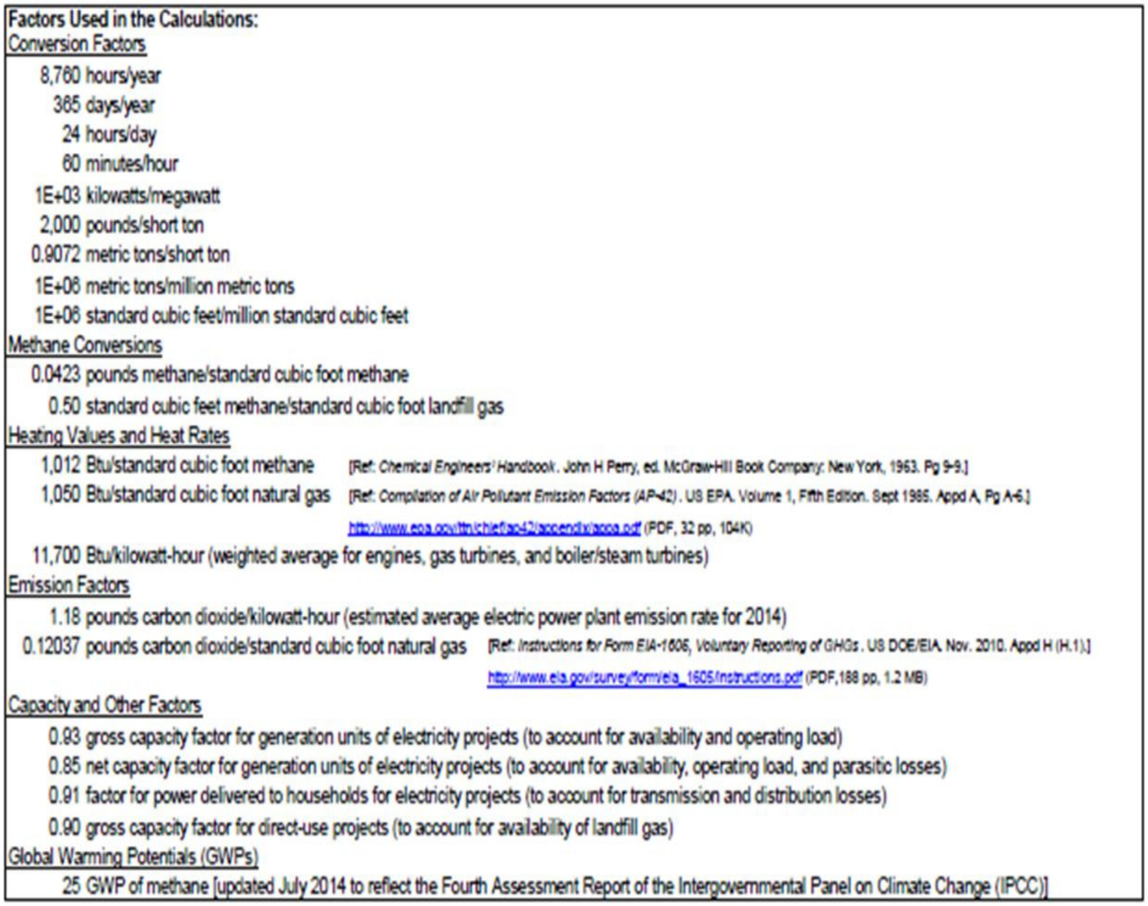
Wahlen, M., (1993). The global methane cycle. Annual review of Earth and Planetary Sciences, 21: 407-426. Retrieved from http://adsabs.harvard.edu/full/1993AREPS.21.407W

Wiggin, E. (2008), Waste management, market assessment 2007. Retrieved from Key Note publications http://r.search.yahoo.com/Key_Global_Waste_Generation.pdf

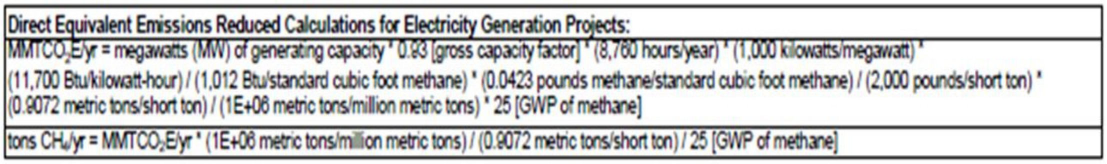
Wiltsee, G. (2009, March). Contracting with a Utility for Sale of Renewable Energy and Green Attributes. Proceedings, 32nd Annual Landfill Gas Symposium. Symposium conducted at the annual meeting of the Solid Waste Association of North America, Atlanta, GA.

Appendix 1

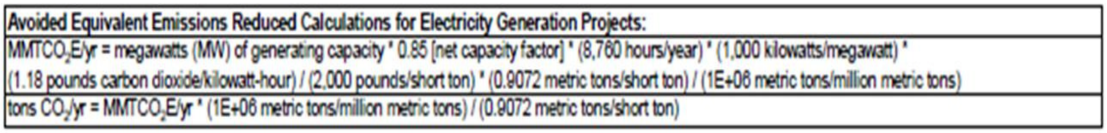
EPA-LMOP, LFGE – Calculations and References



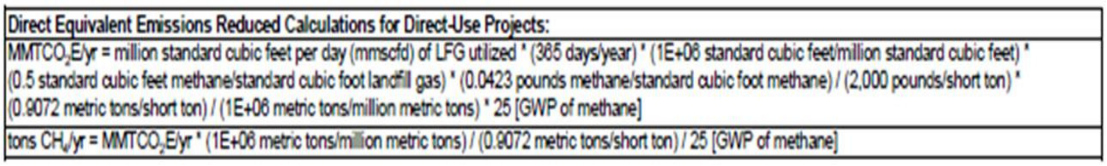
Factors Used in the Calculations:		
Conversion Factors		
8,760	hours/year	
365	days/year	
24	hours/day	
60	minutes/hour	
1E+03	kilowatts/megawatt	
2,000	pounds/short ton	
0.9072	metric tons/short ton	
1E+06	metric tons/million metric tons	
1E+06	standard cubic feet/million standard cubic feet	
Methane Conversions		
0.0423	pounds methane/standard cubic foot methane	
0.50	standard cubic feet methane/standard cubic foot landfill gas	
Heating Values and Heat Rates		
1,012	Btu/standard cubic foot methane	[Ref: *Chemical Engineers' Handbook*. John H Perry, ed. McGraw-Hill Book Company: New York, 1963. Pg 9-9.]
1,050	Btu/standard cubic foot natural gas	[Ref: *Compilation of Air Pollutant Emission Factors (AP-42)*. US EPA. Volume 1, Fifth Edition. Sept 1995. Appd A, Pg A-6.] http://www.epa.gov/ttn/chief/ap42/appendix/appa.pdf (PDF, 32 pp, 104K)
11,700	Btu/kilowatt-hour (weighted average for engines, gas turbines, and boiler/steam turbines)	
Emission Factors		
1.18	pounds carbon dioxide/kilowatt-hour (estimated average electric power plant emission rate for 2014)	
0.12037	pounds carbon dioxide/standard cubic foot natural gas	[Ref: *Instructions for Form EIA-1605, Voluntary Reporting of GHGs*. US DOE/EIA. Nov. 2010. Appd H (H.1).] http://www.eia.gov/survey/form/eia_1605/instructions.pdf (PDF,188 pp, 1.2 MB)
Capacity and Other Factors		
0.93	gross capacity factor for generation units of electricity projects (to account for availability and operating load)	
0.85	net capacity factor for generation units of electricity projects (to account for availability, operating load, and parasitic losses)	
0.91	factor for power delivered to households for electricity projects (to account for transmission and distribution losses)	
0.90	gross capacity factor for direct-use projects (to account for availability of landfill gas)	
Global Warming Potentials (GWPs)		
25	GWP of methane [updated July 2014 to reflect the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)]	



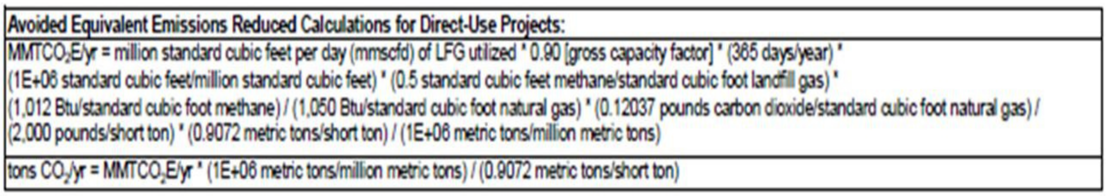
Direct Equivalent Emissions Reduced Calculations for Electricity Generation Projects:
MMTCO$_2$E/yr = megawatts (MW) of generating capacity * 0.93 [gross capacity factor] * (8,760 hours/year) * (1,000 kilowatts/megawatt) * (11,700 Btu/kilowatt-hour) / (1,012 Btu/standard cubic foot methane) * (0.0423 pounds methane/standard cubic foot methane) / (2,000 pounds/short ton) * (0.9072 metric tons/short ton) / (1E+06 metric tons/million metric tons) * 25 [GWP of methane]
tons CH$_4$/yr = MMTCO$_2$E/yr * (1E+06 metric tons/million metric tons) / (0.9072 metric tons/short ton) / 25 [GWP of methane]



Avoided Equivalent Emissions Reduced Calculations for Electricity Generation Projects:
MMTCO$_2$E/yr = megawatts (MW) of generating capacity * 0.85 [net capacity factor] * (8,760 hours/year) * (1,000 kilowatts/megawatt) * (1.18 pounds carbon dioxide/kilowatt-hour) / (2,000 pounds/short ton) * (0.9072 metric tons/short ton) / (1E+06 metric tons/million metric tons)
tons CO$_2$/yr = MMTCO$_2$E/yr * (1E+06 metric tons/million metric tons) / (0.9072 metric tons/short ton)



Direct Equivalent Emissions Reduced Calculations for Direct-Use Projects:
MMTCO$_2$E/yr = million standard cubic feet per day (mmscfd) of LFG utilized * (365 days/year) * (1E+06 standard cubic feet/million standard cubic feet) * (0.5 standard cubic feet methane/standard cubic foot landfill gas) * (0.0423 pounds methane/standard cubic foot methane) / (2,000 pounds/short ton) * (0.9072 metric tons/short ton) / (1E+06 metric tons/million metric tons) * 25 [GWP of methane]
tons CH$_4$/yr = MMTCO$_2$E/yr * (1E+06 metric tons/million metric tons) / (0.9072 metric tons/short ton) / 25 [GWP of methane]



Avoided Equivalent Emissions Reduced Calculations for Direct-Use Projects:
MMTCO$_2$E/yr = million standard cubic feet per day (mmscfd) of LFG utilized * 0.90 [gross capacity factor] * (365 days/year) * (1E+06 standard cubic feet/million standard cubic feet) * (0.5 standard cubic feet methane/standard cubic foot landfill gas) * (1,012 Btu/standard cubic foot methane) / (1,050 Btu/standard cubic foot natural gas) * (0.12037 pounds carbon dioxide/standard cubic foot natural gas) / (2,000 pounds/short ton) * (0.9072 metric tons/short ton) / (1E+06 metric tons/million metric tons)
tons CO$_2$/yr = MMTCO$_2$E/yr * (1E+06 metric tons/million metric tons) / (0.9072 metric tons/short ton)

Appendix 2

Examples Variation in Measurements from Individual Wells

These data from Group 1, 2 and 3 wells from Facility 5 illustrate the temporal variation in data before and after post-perforation of Group 1 wells on 10/27/2011.

FACILITY 5	**GROUP 1**	**GROUP 2**	**GROUP 3**	**TOTAL**
	15	**20**	**103**	**138**

GROUP 1				
Date Time	**Well Number**	**CH4**	**Initial Flow**	**Adjusted Flow**
5/13/2011 9:32	EW-379	49.4	11	13
6/15/2011 10:20		51.5	40	37
7/25/2011 10:34		52.6	21	21
8/2/2011 15:41		50.9	21	21
9/8/2011 12:04		57.8	10	10
10/26/2011 13:24		54.4	7	7
11/2/2011 17:02		54.4	69	68
12/2/2011 10:31		51.6	74	75
1/5/2012 17:13		38.5	87	82
2/3/2012 10:05		45.5	67	46
3/9/2012 11:47		50.1	48	49
4/5/2012 14:21		45.1	39	37
5/12/2011 8:36	EW-380	52.6	22	18
6/15/2011 13:34		54.6	20	18
7/25/2011 10:43		54	14	13
8/3/2011 14:40		56.1	18	15
9/8/2011 12:08		58.1	23	22
10/6/2011 10:08		54.5	17	17
11/1/2011 16:20		54.7	85	88

12/2/2011 11:36		52.7	78	73
1/5/2012 17:08		42.6	72	65
2/3/2012 9:59		44.4	37	23
3/21/2012 10:06		54.7	17	18
4/11/2012 11:37		53.9	7	20
5/12/2011 8:44	EW-381	52.5	51	49
6/15/2011 10:16		53	42	43
7/13/2011 16:42		56.2	38	38
8/3/2011 14:47		55.7	33	34
9/8/2011 12:22		57.8	32	33
10/6/2011 10:10		54.4	27	28
11/1/2011 16:12		51.2	24	32
12/7/2011 8:58		56.6	52	57
1/5/2012 15:58		56.1	25	39
2/2/2012 15:21		54.7	34	38
3/8/2012 14:28		54.3	26	25
4/5/2012 10:29		54.7	24	24
5/25/2011 11:01	EW-382	56.8	48	14
6/20/2011 13:50		53.9	53	65
7/13/2011 16:36		55.2	23	25
8/3/2011 14:45		55.8	19	19
9/8/2011 12:16		58	18	17
10/6/2011 9:54		54.7	15	16
11/1/2011 16:15		54.9	4	2
12/2/2011 11:44		37.5	38	32
1/5/2012 16:58		54.6	7	7
2/3/2012 9:44		54.5	9	12
3/8/2012 15:23		54.8	7	9
4/5/2012 10:32		54	8	9
5/25/2011 11:15	EW-383	58.4	50	12
6/20/2011 14:24		56.2	23	48
7/23/2011 12:14		58.3	0	0
8/3/2011 16:49		55	0	0
9/8/2011 12:13		58.4	15	17
10/6/2011 9:57		56.4	8	13
11/2/2011 17:06		54.7	51	53
12/2/2011 11:38		53.1	83	80
1/5/2012 17:03		42.5	80	36

2/3/2012 9:38		54.8	27	33
3/21/2012 11:19		53.9	42	42
		53	15	37

GROUP 2				
Date Time	**Well Number**	**CH4**	**Initial Flow**	**Adjusted Flow**
5/11/2011 10:42	EW-377	59.9	0	0
6/3/2011 13:36		52.6	0	0
7/16/2011 9:07		43.1	2	2
8/3/2011 9:58		57.5	0	2
9/7/2011 10:00		14	1	1
10/5/2011 9:43		33.7	1	1
11/1/2011 10:56		47.3	2	1
12/21/2011 14:24		58.7	1	2
1/5/2012 12:27		54	0	0
2/1/2012 12:05		52.6	0	0
3/9/2012 14:04		45.3	0	0
4/4/2012 12:10		46.2	0	0
5/13/2011 8:37	EW-414	51.9	2	2
6/15/2011 8:53		49.4	5	5
7/13/2011 10:52		42.1	1	1
8/3/2011 13:24		39.2	0	1
9/7/2011 12:46		28.5	0	2
10/5/2011 12:03		1.4	1	1
11/1/2011 15:39		49	3	3
12/8/2011 11:57		31.2	0	4
1/5/2012 15:36		0	1	1
2/1/2012 13:41		35.9	0	0
3/12/2012 13:17		35.5	0	1
4/5/2012 15:04		18.5	0	0
5/10/2011 14:24	EW-416	48	10	10
6/15/2011 9:02		54.9	18	18
7/11/2011 15:02		12.5	9	2
8/3/2011 13:36		34.2	5	6
9/7/2011 12:39		26.8	5	4
10/5/2011 11:52		26.1	14	14
11/1/2011 15:48		51.9	3	23

12/2/2011 10:18		22.4	37	27
1/5/2012 15:02		22.4	6	5
2/1/2012 13:29		55.3	3	6
3/12/2012 13:32		39.4	5	5
4/4/2012 10:37		53.1	5	19
5/6/2011 9:29	EW-423	38.3	3	4
6/14/2011 10:25		45.1	8	9
7/11/2011 9:32		24.5	9	5
8/3/2011 9:04		24.9	5	5
9/7/2011 8:38		28.1	4	4
10/5/2011 8:39		32.6	2	2
11/1/2011 9:01		36.6	8	8
12/1/2011 9:28		25.9	8	9
1/5/2012 9:22		33.5	10	4
2/1/2012 9:46		46.5	3	5
3/3/2012 11:07		57.3	3	20
4/12/2012 15:04		58.1	10	20
5/13/2011 8:39	EW-426	16.6	4	4
6/14/2011 10:16		14.8	20	24
7/11/2011 8:29		3.6	15	6
8/3/2011 9:29		12.9	7	7
9/7/2011 9:01		15.3	7	7
10/5/2011 9:01		12.5	2	2
11/1/2011 10:09		10.6	2	3
12/21/2011 13:19		15.7	1	8
1/5/2012 10:46		20.4	9	4
2/1/2012 10:22		23.1	4	1
3/3/2012 11:39		28.5	0	4
4/12/2012 14:56		27.3	6	5

GROUP 3				
Date Time	**Well Number**	**CH4**	**Initial Flow**	**Adjusted Flow**
5/11/2011 10:00	EW-361	45	78	77
6/15/2011 14:10		48.5	87	85
7/12/2011 19:34		46.4	87	85
8/4/2011 11:02		54.8	63	63
9/8/2011 14:50		55.9	116	118

10/6/2011 8:47		46.1	115	116
11/2/2011 10:00		50	113	111
12/1/2011 15:10		35.7	110	104
1/6/2012 14:52		25.5	120	99
2/4/2012 8:12		50.2	74	72
3/12/2012 10:31		21.9	74	34
4/10/2012 10:12		57.2	10	21
5/11/2011 9:53	EW-363	32.4	24	22
6/15/2011 14:16		34.9	13	15
7/12/2011 19:11		10.2	60	31
8/4/2011 10:57		34.8	0	7
9/8/2011 14:48		37.1	0	0
10/6/2011 8:44		18.6	6	6
11/3/2011 9:08		19.3	10	10
12/1/2011 15:06		8.4	2	5
1/6/2012 14:48		3.5	5	4
2/4/2012 8:17		26.5	4	3
3/12/2012 10:37		3.2	2	5
4/11/2012 11:54		57.8	15	23
5/11/2011 9:43	EW-364	26.4	49	49
6/15/2011 14:33		35.5	12	15
7/12/2011 19:07		28.8	70	64
8/4/2011 10:53		24.4	54	51
9/8/2011 14:44		17.2	36	13
10/6/2011 8:39		25.1	11	9
11/2/2011 9:50		57.4	7	12
12/1/2011 14:51		22.9	7	7
1/6/2012 14:36		10.1	8	5
2/4/2012 8:23		16.7	7	7
3/12/2012 10:52		14.5	5	8
4/10/2012 10:28		57.8	8	14
5/11/2011 9:37	EW-365	51.1	82	81
6/15/2011 13:52		54.3	89	88
7/12/2011 18:54		54.8	86	85
8/4/2011 10:47		55.9	74	74
9/8/2011 14:38		57.6	96	113
10/6/2011 8:34		58.1	115	120
11/2/2011 9:44		59.5	117	119

12/5/2011 9:33		57.8	91	98
1/6/2012 14:27		45.4	112	97
2/4/2012 8:35		52.8	106	112
3/12/2012 11:01		53.2	110	110
4/10/2012 10:54		57.4	31	10
5/11/2011 10:06	EW-366	53.9	18	18
6/13/2011 8:18		37.5	4	3
7/12/2011 20:08		58.2	16	13
8/4/2011 11:07		55.9	11	8
9/8/2011 14:56		59.1	11	11
10/6/2011 8:54		54.5	10	9
11/2/2011 10:09		55.8	9	11
12/1/2011 15:19		56.9	9	8
1/6/2012 15:40		52.2	10	8
2/4/2012 8:06		55.6	9	9
3/12/2012 11:12		52.3	5	6
4/5/2012 14:28		52.6	6	5

Appendix 3

Mean Values for All Facilities

Facility 1	**Group 1**					
	pre-perforation			**post-perforation**		
	CH4	**Initial Flow**	**Adjusted Flow**	**CH4**	**Initial Flow**	**Adjusted Flow**
EW-4	51.7	2.7	3.8	53.1	2.7	2.8
EW-8	51.9	6.7	4.7	55.2	10.2	10.3
EW-17	47.0	3.2	3.0	56.3	21.0	22.8
EW-20	52.3	3.7	3.7	58.2	3.5	3.5
EW-24	53.5	24.7	25.8	57.9	37.8	41.2
EW-36	54.8	2.8	3.8	46.3	28.0	35.3
EW-43	49.4	23.7	23.5	56.6	75.7	81.2
EW-45	53.0	2.0	3.7	53.0	2.8	2.8
EW-47	53.8	7.5	8.3	57.7	5.2	5.3
Mean	51.9	8.5	8.9	54.9	20.8	22.8

Facility 1	**Group 2**					
	pre-perforation			**post-perforation**		
	CH4	**Initial Flow**	**Adjusted Flow**	**CH4**	**Initial Flow**	**Adjusted Flow**
EW-2	50.9	1.8	1.5	56.7	4.8	4.8
EW-7	53.2	2.5	2.3	48.2	5.0	4.8
EW-15	50.3	9.7	24.5	50.5	18.8	18.0
EW-23	49.5	9.7	6.7	55.5	12.0	12.7
EW-29	53.8	8.2	9.8	54.5	26.7	26.5
EW-30	49.9	18.2	20.5	52.6	43.5	42.8
EW-34	55.3	25.5	25.7	58.5	36.8	42.3
EW-38	47.5	6.2	6.7	53.5	12.2	11.5
EW-41	53.2	3.3	4.5	47.4	33.0	32.7
EW-49	51.1	6.8	7.8	55.8	27.3	24.7
EW-50	54.7	8.0	8.5	57.2	11.0	12.3
EW-58	44.6	12.0	11.8	53.1	15.2	16.2
EW-60	51.0	10.5	11.0	54.3	12.2	12.5
EW-62	53.3	12.3	12.3	58.4	0.7	2.0

EW-64	53.9	10.0	11.2	56.1	11.3	11.3
EW-74	55.5	8.8	9.3	54.7	19.8	20.3
EW-75	48.5	12.2	12.2	25.1	10.7	18.3
EW-79	53.9	17.2	17.5	54.5	30.7	32.3
Mean	51.6	10.2	11.3	52.6	18.4	19.2

Facility 1	**Group 3**					
	pre-perforation			**post-perforation**		
	CH4	**Initial Flow**	**Adjusted Flow**	**CH4**	**Initial Flow**	**Adjusted Flow**
EW-3	52.8	11.5	12.2	54.2	24.3	25.5
EW-5	51.7	11.8	11.7	54.9	12.2	11.5
EW-6	51.5	13.5	13.2	51.5	25.0	25.0
EW-9	51.3	3.7	3.2	48.3	7.5	8.8
EW-10	52.3	24.7	22.8	56.1	27.5	34.7
EW-12	50.5	31.8	29.7	49.9	54.7	55.3
EW-13	49.8	16.0	17.2	54.3	54.8	53.8
EW-14	51.7	5.2	7.3	48.7	49.5	49.7
EW-18	53.8	43.7	42.0	57.2	44.0	48.3
EW-19	51.7	11.7	6.5	56.7	26.2	27.7
EW-21	53.2	15.0	16.3	54.2	23.7	27.8
EW-22	50.8	10.8	10.7	51.7	30.3	36.0
EW-25	54.4	23.7	26.3	55.6	32.7	35.0
EW-26	49.0	5.5	6.3	50.1	27.7	30.5
EW-27	50.5	7.3	8.3	50.6	25.2	26.7
EW-28	41.2	46.7	38.2	42.4	107.8	118.2
EW-31	54.2	22.5	22.5	54.5	19.0	19.7
EW-32	53.2	26.2	27.5	50.5	22.8	25.0
EW-33	54.5	22.2	25.7	56.1	33.5	34.3
EW-35	54.8	6.8	6.8	54.6	23.3	26.7
EW-37	53.5	14.8	15.3	57.6	22.5	23.0
EW-39	50.9	13.8	14.0	46.8	24.3	25.2
EW-40	47.0	4.3	4.0	46.3	5.8	5.8
EW-42	50.2	6.3	7.3	53.9	55.8	57.2
EW-44	53.4	9.8	10.2	55.3	21.0	21.5
EW-48	50.6	10.7	9.5	52.0	27.0	20.3
EW-51	53.2	19.8	16.7	55.4	32.5	33.2
EW-52	48.5	12.2	13.7	50.8	14.3	14.3
EW-53	52.6	25.0	25.7	54.3	28.5	31.8
EW-54	50.0	12.7	12.0	49.6	29.2	29.8

EW-55	51.4	13.7	14.2	44.3	11.5	10.2
EW-56	51.5	27.7	30.0	51.4	41.0	45.0
EW-57	53.6	12.5	14.2	54.8	27.0	26.0
EW-59	53.4	12.0	13.3	57.8	20.8	18.8
EW-61	49.0	10.2	7.0	54.2	12.0	12.8
EW-63	53.2	6.8	7.2	55.4	12.0	12.7
EW-65	54.9	16.2	15.3	56.1	44.2	44.2
EW-66	53.4	36.2	27.5	55.9	83.2	86.3
EW-67	53.6	14.8	15.2	54.5	36.8	38.7
EW-68	54.6	12.3	11.2	57.7	19.5	21.5
EW-69	49.8	39.7	37.0	47.5	38.3	41.5
EW-70	43.7	29.3	33.2	44.8	41.0	35.8
EW-71	53.8	10.8	17.5	54.8	31.8	34.7
EW-73	50.2	9.5	8.8	41.6	17.3	21.5
EW-76	53.0	17.8	18.7	57.3	19.2	19.2
EW-77	45.6	6.7	7.2	42.6	11.5	11.0
EW-78	52.8	2.3	5.7	52.0	12.8	13.0
EW-80	53.4	118.3	122.3	53.2	104.8	113.0
EW-81	52.8	33.0	35.3	55.0	27.3	31.7
Mean	51.6	18.8	18.8	52.3	31.5	33.1

Facility 4	**Group 1**					
	pre-perforation			**post-perforation**		
	CH4	**Initial Flow**	**Adjusted Flow**	**CH4**	**Initial Flow**	**Adjusted Flow**
EW-251	51.0	20.3	23.7	53.3	38.3	46.8
EW-261	34.1	0.0	0.7	39.0	6.3	8.2
EW-265	51.7	0.0	0.0	51.8	5.3	10.8
EW-270	24.7	10.3	11.7	45.2	12.7	15.8
EW-272	52.3	59.0	60.5	48.7	41.2	58.5
EW-273	48.4	8.7	12.5	49.7	15.8	24.3
EW-284	38.7	17.3	18.5	49.2	13.3	15.5
EW-286	48.9	0.0	0.0	55.1	21.7	30.8
EW-297	52.5	2.8	6.8	57.4	10.0	17.5
EW-300	53.9	17.3	20.8	55.5	23.5	23.8
EW-301	54.2	6.8	8.3	54.6	12.3	17.8
EW-302	46.7	7.5	10.2	54.4	14.5	20.5
EW-306	51.1	35.0	37.0	54.6	44.2	55.5
EW-316	52.5	10.5	15.0	55.4	15.5	20.0
EW-318	53.9	3.7	8.5	54.9	18.7	24.5

EW-320	54.4	2.8	5.2	55.6	3.5	5.5
EW-322	54.7	1.0	5.7	54.9	4.2	7.0
EW-331	52.2	28.8	33.7	53.9	16.3	24.0
EW-341	35.7	0.8	6.3	41.5	2.8	15.0
Mean	48.0	12.3	15.0	51.8	16.9	23.3

Facility 4	**Group 2**					
	pre-perforation			**post-perforation**		
	CH4	**Initial Flow**	**Adjusted Flow**	**CH4**	**Initial Flow**	**Adjusted Flow**
EW-211	31.5	9.3	11.2	52.2	15.2	19.0
EW-212	49.7	0.7	1.8	54.9	1.5	2.8
EW-213	53.5	2.5	2.5	55.9	25.0	29.2
EW-214	54.9	0.0	0.8	53.2	8.7	16.3
EW-215	52.5	0.0	0.8	54.6	16.7	25.0
EW-216	54.6	12.2	4.2	55.6	20.2	35.2
EW-217	54.8	0.0	0.2	55.2	13.7	19.8
EW-219	54.6	0.7	0.5	57.0	4.2	7.0
EW-220	54.5	6.8	8.3	56.8	5.2	7.0
EW-221	44.3	0.2	0.0	52.1	7.5	11.0
EW-222	46.4	0.0	0.0	39.1	2.8	3.2
EW-223	52.0	0.0	0.0	50.0	7.7	14.5
EW-224	56.4	0.0	0.3	54.2	13.5	20.8
EW-225	55.2	4.3	1.8	51.7	11.7	9.2
EW-226	50.8	13.3	12.5	39.9	2.0	2.7
EW-228	53.4	0.8	4.8	55.0	8.7	16.0
EW-230	36.9	1.2	1.5	25.8	4.2	4.0
EW-231	51.1	3.0	4.8	50.1	0.0	4.8
EW-232	54.1	0.0	0.0	52.1	2.7	5.0
EW-233	34.3	2.2	1.8	46.1	11.8	16.0
EW-234	54.4	0.0	0.0	50.8	8.7	8.2
EW-235	49.9	0.0	0.0	53.0	10.2	11.0
EW-236	54.4	0.0	0.0	54.1	6.3	10.5
EW-237	52.6	1.0	1.5	53.7	13.2	14.8
EW-238	54.4	0.0	0.0	53.8	2.8	4.2
EW-239	46.5	0.0	0.2	50.4	0.0	1.7
EW-241	53.5	0.2	0.2	52.9	9.2	16.5
EW-242	53.5	0.2	0.0	54.4	14.0	19.2
EW-243	51.2	0.0	1.5	46.3	7.8	14.3
EW-244	54.3	1.3	4.7	51.6	12.5	16.8

EW-246	53.3	0.0	0.0	55.7	33.5	18.7
EW-247	52.5	0.0	0.0	49.7	19.8	24.8
EW-248	53.0	0.0	0.0	49.7	14.7	20.8
EW-249	35.4	0.0	0.0	48.5	8.7	11.3
EW-253	53.7	0.0	0.0	51.9	8.3	22.5
EW-254	52.7	6.0	2.8	36.0	9.0	17.8
EW-255	50.5	0.0	0.0	49.4	1.7	3.2
EW-258	54.1	0.2	0.3	55.8	14.0	16.2
EW-259	53.6	0.0	0.0	52.5	11.7	17.5
EW-260	53.6	0.0	0.0	56.3	7.5	13.8
EW-264	54.7	0.0	0.0	50.4	8.7	9.8
EW-266	52.6	0.0	0.0	54.4	12.8	19.3
EW-267	47.9	18.0	19.7	50.5	8.7	18.2
EW-268	51.8	0.0	0.0	53.6	2.2	9.5
EW-269	35.6	0.0	0.0	53.6	4.8	3.2
EW-274	53.9	8.7	16.8	57.0	1.0	8.3
EW-275	52.8	22.2	35.7	55.7	49.0	68.7
EW-276	34.4	2.8	1.7	33.2	3.3	8.0
EW-277	29.5	0.2	0.3	56.1	8.5	15.7
EW-279	32.1	32.5	38.2	45.4	7.5	22.8
EW-283	53.9	0.0	0.0	53.5	32.0	36.0
EW-285	52.9	2.7	3.3	51.6	19.0	24.5
EW-287	54.1	1.0	0.8	53.6	27.8	34.0
EW-288	53.6	0.0	0.0	55.8	23.0	27.3
EW-289	53.6	1.0	3.7	55.7	15.8	26.2
EW-290	53.8	0.0	0.5	53.4	17.7	22.5
EW-291	52.9	14.5	31.0	47.1	24.0	32.7
EW-293	54.3	4.3	4.2	56.0	14.7	25.5
EW-294	54.2	1.0	1.7	55.8	21.5	35.0
EW-295	51.8	5.3	6.3	56.1	32.5	20.3
EW-296	53.3	0.0	0.2	55.0	2.3	4.3
EW-299	54.9	12.3	15.8	52.8	7.5	25.0
EW-303	51.6	4.3	10.7	54.1	6.8	10.8
EW-304	52.4	2.0	4.3	56.1	7.8	10.8
EW-305	54.4	6.2	6.3	56.1	9.2	13.2
EW-307	48.2	15.2	20.8	51.3	4.2	19.2
EW-309	52.0	0.8	2.5	56.0	12.7	12.0
EW-310	52.9	1.5	1.8	54.3	12.7	15.8
EW-311	53.9	0.2	0.5	49.5	5.0	5.2
EW-315	52.2	0.0	0.0	54.3	0.0	0.0
EW-317	44.7	13.0	18.0	54.6	16.3	26.5

EW-319	54.0	2.3	5.5	56.3	14.0	18.3
EW-321	54.6	10.2	12.3	55.3	8.8	12.2
EW-323	55.1	0.5	0.0	56.9	4.7	6.5
EW-325	54.5	0.0	0.0	56.2	4.0	7.8
EW-326	54.9	1.8	5.0	55.2	5.8	6.8
EW-327	54.2	4.3	8.5	55.8	5.2	11.0
EW-332	42.2	0.0	1.0	47.1	4.3	13.8
EW-333	54.3	0.0	0.0	38.5	0.0	0.0
EW-342	20.3	1.5	6.3	37.6	12.2	11.5
EW-343	55.3	2.3	4.2	51.2	2.2	4.3
EW-345	54.0	0.0	0.0	51.6	5.8	13.2
EW-347	30.6	0.0	0.0	23.3	2.7	8.7
EW-348	45.8	0.0	0.2	52.8	5.0	8.3
EW-349	53.7	0.0	0.7	51.7	0.2	2.2
EW-350	52.3	3.3	3.8	52.7	5.8	7.7
EW-351	49.7	4.0	5.5	53.6	0.5	3.7
EW-354	17.7	0.3	0.7	48.5	0.2	0.8
Mean	49.8	3.0	4.2	51.4	10.2	14.8

Facility 4	**Group 3**					
	pre-perforation			**post-perforation**		
	CH4	**Initial Flow**	**Adjusted Flow**	**CH4**	**Initial Flow**	**Adjusted Flow**
EW-218	52.4	9.8	12.7	54.2	8.0	20.5
EW-240	53.9	13.3	15.8	54.8	8.8	13.0
EW-250	53.0	17.5	23.3	54.4	17.5	34.5
EW-252	47.4	14.5	17.5	51.7	18.0	26.3
EW-256	53.5	7.7	8.3	50.8	8.5	14.7
EW-257	55.0	3.5	3.7	48.6	3.7	7.0
EW-262	53.5	5.7	6.8	50.3	43.7	47.8
EW-263	54.4	23.5	27.5	53.5	17.8	22.8
EW-271	51.5	22.2	15.0	53.0	19.3	29.5
EW-278	54.1	54.3	68.0	49.1	41.7	48.7
EW-281	54.0	56.7	59.8	54.5	50.2	54.0
EW-282	53.9	48.0	51.7	54.5	45.8	51.2
EW-298	54.0	11.8	16.8	54.7	19.5	27.0
EW-308	53.0	12.7	22.2	55.7	34.5	40.7
EW-312	53.6	7.2	13.0	55.1	14.5	28.0
EW-313	54.4	1.8	9.8	56.2	13.3	15.5
EW-314	50.8	5.7	13.2	56.3	7.8	14.7

EW-324	53.7	6.2	7.0	54.7	5.5	9.8
EW-334	54.0	61.8	67.8	54.1	60.3	73.2
EW-335	53.8	8.3	8.7	53.2	9.8	12.5
EW-336	54.5	70.3	73.7	52.4	74.7	83.3
EW-337	47.6	10.8	16.2	53.3	7.3	39.0
EW-339	52.8	23.8	34.3	53.1	7.3	16.2
EW-340	54.4	51.7	64.8	36.6	22.2	35.8
EW-344	52.5	79.7	89.3	54.5	51.2	67.5
EW-346	56.4	4.5	3.3	59.7	1.2	2.0
EW-352	54.1	26.8	33.8	56.0	18.3	21.7
EW-353	50.9	8.7	12.7	51.3	13.7	18.0
Mean	53.1	23.9	28.5	53.1	23.0	31.2

Facility 5	**Group 1**					
	pre-perforation			**post-perforation**		
	CH4	**Initial Flow**	**Adjusted Flow**	**CH4**	**Initial Flow**	**Adjusted Flow**
EW-379	52.8	18.3	18.2	47.5	64.0	59.5
EW-380	55.0	19.0	17.2	50.5	49.3	47.8
EW-381	54.9	37.2	37.5	54.6	30.8	35.8
EW-382	55.7	29.3	26.0	51.7	12.2	11.8
EW-383	57.1	16.0	15.0	52.0	49.7	46.8
EW-394	49.0	9.8	8.8	45.5	1.7	4.7
EW-395	49.3	7.0	8.2	54.9	8.2	7.2
EW-417	48.8	102.7	104.2	55.5	93.5	95.7
EW-418	50.2	23.8	22.0	54.6	20.5	26.2
EW-456	48.6	15.3	15.5	56.0	8.0	8.7
EW-457	39.9	3.2	3.0	52.0	0.8	2.0
EW-513	54.0	15.2	16.0	53.8	57.3	63.7
EW-539	55.7	15.0	15.3	55.4	14.0	12.3
EW-540	55.0	23.2	23.7	54.4	23.7	29.5
EW-542	55.8	2.7	3.3	55.5	2.3	2.2
Mean	52.1	22.5	22.3	52.9	29.1	30.3

Facility 5	**Group 2**					
	pre-perforation			**post-perforation**		

	CH4	Initial Flow	Adjusted Flow	CH4	Initial Flow	Adjusted Flow
EW-377	43.5	0.7	1.0	50.7	0.5	0.5
EW-414	35.4	1.5	2.0	28.4	0.7	1.5
EW-416	33.8	10.2	9.0	40.8	9.8	14.2
EW-423	32.3	5.2	4.8	43.0	7.0	11.0
EW-426	12.6	9.2	8.3	20.9	3.7	4.2
EW-427	25.4	6.5	8.7	34.8	4.8	10.0
EW-447	45.8	1.0	0.8	45.8	2.5	2.3
EW-459	49.7	49.3	51.7	50.1	28.3	27.7
EW-465	52.5	0.7	0.8	48.0	1.0	1.0
EW-479	56.5	4.0	4.0	54.4	1.3	1.2
EW-482	56.1	1.3	1.3	51.0	7.8	8.2
EW-497	39.6	12.5	10.5	51.9	8.3	8.3
EW-499	33.2	19.2	25.7	48.3	14.3	14.0
EW-502	31.6	5.0	4.5	45.4	3.7	2.3
EW-504	51.6	25.7	28.0	55.7	11.8	12.5
EW-506	55.4	54.0	55.7	55.9	26.7	27.3
EW-510	36.9	3.8	2.5	47.5	18.0	18.5
EW-524	53.3	0.3	0.2	57.0	2.2	3.3
EW-525	44.7	0.0	0.2	40.2	1.8	1.7
EW-528	42.4	2.8	3.3	44.9	4.2	3.8
Mean	41.6	10.6	11.2	45.7	7.9	8.7

Facility 5	Group 3					
	pre-perforation			post-perforation		
	CH4	Initial Flow	Adjusted Flow	CH4	Initial Flow	Adjusted Flow
EW-361	49.5	91.0	90.7	40.1	83.5	73.5
EW-363	28.0	17.2	13.5	19.8	6.3	8.3
EW-364	26.2	38.7	33.5	29.9	7.0	8.8
EW-365	55.3	90.3	93.5	54.4	94.5	91.0
EW-366	53.2	11.7	10.3	54.2	8.0	7.8
EW-368	47.3	37.3	35.7	54.7	32.2	33.7
EW-369	53.3	13.3	8.3	45.5	25.2	27.2
EW-370	53.3	15.0	11.0	52.3	6.8	6.8
EW-371	52.3	17.2	18.0	45.3	19.3	16.2
EW-372	54.0	32.5	37.7	53.8	20.7	20.8
EW-373	33.7	15.0	11.5	32.6	5.0	6.3
EW-374	47.2	80.5	86.0	47.6	45.8	46.7

Ew-375	35.7	67.0	55.2	51.9	35.8	42.7
EW-376	36.2	17.0	13.8	51.5	8.2	8.8
EW-378	54.7	5.7	7.7	52.6	4.3	5.2
EW-392	40.2	35.0	31.8	47.8	21.2	19.5
EW-397	52.6	17.2	15.7	56.6	34.8	42.2
EW-399	54.4	2.3	2.5	57.1	2.0	3.5
EW-400	52.1	16.5	16.7	55.6	14.8	14.3
EW-401	53.0	12.5	13.0	56.5	8.5	7.7
EW-404	51.2	51.0	57.8	50.7	18.3	17.8
EW-406	43.5	8.3	4.2	53.9	11.7	13.7
EW-413	52.6	7.7	7.8	57.7	6.8	10.3
EW-415	55.2	39.0	39.8	52.7	55.8	58.2
EW-421	55.7	22.0	23.2	55.3	31.7	32.0
EW-422	49.7	3.5	4.2	52.8	3.2	5.0
EW-424	31.6	6.5	5.8	34.3	8.8	10.0
EW-425	30.7	10.5	9.7	35.9	2.7	4.3
EW-428	47.1	11.3	10.2	55.3	20.7	22.0
EW-430	50.7	3.3	2.3	54.0	3.0	3.3
EW-431	56.7	10.3	9.0	57.4	10.0	9.3
EW-432	57.6	2.5	2.5	58.3	3.8	4.2
EW-433	49.1	3.8	2.8	56.4	3.3	4.7
EW-434	57.3	17.0	17.3	54.7	19.2	15.2
EW-435	51.4	3.3	2.5	58.4	0.3	0.3
EW-436	49.3	12.2	10.8	57.0	3.5	4.3
EW-437	47.5	8.5	5.3	56.6	4.2	7.0
EW-438	53.4	25.2	24.3	57.0	44.2	46.3
EW-441	52.7	29.8	39.3	52.7	18.2	18.0
EW-442	34.5	25.2	26.5	44.6	21.7	9.0
EW-443	50.7	18.0	19.3	50.1	4.3	3.5
EW-444	46.0	9.0	8.8	48.4	17.7	16.8
EW-445	52.8	78.5	87.0	54.5	30.2	29.5
EW-446	52.7	31.3	32.0	54.9	37.5	38.2
EW-449	48.3	62.5	61.7	48.1	50.3	48.0
EW-450	47.1	36.0	34.8	52.3	45.8	46.3
EW-451	55.9	52.2	53.2	55.8	41.8	42.5
EW-452	53.9	17.0	17.0	55.5	14.3	15.5
EW-453	55.4	36.7	38.7	53.7	13.8	17.8
EW-454	43.4	17.8	16.0	35.6	14.5	8.5
EW-458	50.7	19.0	18.8	50.2	15.3	15.0
EW-460	49.6	32.2	31.0	51.2	10.0	10.2
EW-461	46.8	9.7	7.5	50.4	8.0	7.5

EW-462	42.8	43.3	41.0	51.4	11.8	13.8
EW-463	44.6	3.5	4.3	48.5	4.2	3.8
EW-464	52.2	6.0	6.0	54.0	7.5	5.7
EW-466	54.0	34.2	34.2	55.0	39.0	39.0
EW-467	51.6	20.2	22.3	52.9	20.8	21.0
EW-468	42.7	38.8	35.2	45.1	24.5	21.3
EW-469	41.6	39.2	33.0	45.4	24.7	18.8
EW-470	50.1	6.0	7.7	42.1	11.5	13.5
EW-471	39.3	14.7	7.5	43.4	10.5	9.3
EW-472	51.8	18.0	18.2	56.2	38.0	44.2
EW-473	49.8	13.7	12.2	52.9	21.8	24.7
EW-475	41.7	23.5	24.2	55.6	27.0	38.5
EW-476	50.4	52.8	51.2	55.9	43.3	47.2
EW-477	52.6	24.2	18.0	54.1	20.5	19.8
EW-478	55.6	26.0	26.3	54.8	30.3	30.7
EW-480	55.6	26.7	28.5	53.5	22.8	26.7
EW-481	53.9	14.7	14.0	55.1	32.2	31.5
EW-483	53.4	0.8	2.0	46.7	0.5	0.7
EW-484	54.8	5.2	5.2	55.5	3.5	3.3
EW-485	53.9	4.7	4.8	50.0	4.3	5.3
EW-486	55.4	11.8	9.5	56.5	10.7	10.2
EW-488	52.4	2.2	2.7	44.4	1.7	1.7
EW-491	42.2	3.8	2.5	40.9	2.0	3.7
EW-492	43.2	2.8	3.5	44.0	2.0	2.3
Ew-493	55.1	27.3	27.2	53.9	13.7	14.3
EW-494	50.8	6.8	6.0	43.9	6.2	6.2
EW-495	41.3	32.7	32.3	42.0	18.5	14.7
EW-496	53.6	12.0	18.5	42.8	10.5	9.2
EW-498	36.3	15.0	12.2	47.1	15.2	20.5
EW-500	26.6	9.2	9.0	31.3	11.5	12.2
EW-501	32.3	16.3	15.0	47.5	8.3	9.0
EW-503	45.5	22.0	21.0	54.2	19.8	23.5
EW-505	47.6	18.7	16.7	47.6	29.8	27.5
EW-507	44.4	46.2	42.2	48.9	19.5	19.5
EW-508	52.7	33.7	34.5	55.0	16.2	16.7
Ew-509	51.1	10.5	10.7	54.3	54.2	58.5
EW-516	22.1	51.5	47.0	34.0	8.0	11.5
EW-518	53.4	39.3	40.8	55.4	49.8	50.3
EW-521	60.7	3.5	4.2	55.1	4.7	5.0
EW-522	51.9	7.0	7.5	52.7	5.8	6.3
EW-523	50.1	8.2	9.8	47.8	3.0	4.0

EW-526	53.9	6.5	6.8	42.9	9.5	7.2
EW-527	48.9	3.3	3.2	49.4	1.8	2.5
EW-529	46.7	2.0	2.2	47.3	2.0	2.0
EW-530	54.7	13.2	16.0	55.9	12.0	11.8
EW-532	51.6	51.5	49.5	54.8	43.0	45.3
EW-534	43.1	8.8	9.3	51.1	7.3	7.8
EW-535	41.9	18.8	18.5	41.0	8.3	6.2
EW-536	48.6	38.3	39.8	51.0	36.3	36.3
EW-537	49.0	30.3	32.0	52.0	31.8	32.8
Mean	48.2	22.6	22.2	50.0	18.8	19.3

Facility 6	**Group 1**					
	pre-perforation			**post-perforation**		
	CH4	**Initial Flow**	**Adjusted Flow**	**CH4**	**Initial Flow**	**Adjusted Flow**
EW-606	51.1	7.8	9.0	57.0	2.7	2.7
EW-607	57.4	0.5	0.7	56.0	4.0	3.2
EW-608	52.0	7.5	8.0	58.7	2.7	2.3
EW-611	53.1	0.5	0.8	53.0	1.7	2.7
EW-624	56.2	1.0	1.0	48.8	4.2	5.2
Ew-635	56.5	7.8	7.8	56.9	2.7	2.5
EW-649	59.3	1.5	1.5	39.9	3.7	4.3
EW-654	52.4	1.2	1.2	55.1	3.0	3.0
EW-655	56.5	2.8	2.8	55.2	3.8	1.7
Mean	54.9	3.4	3.6	53.4	3.1	3.1

Facility 6	**Group 2**					
	pre-perforation			**post-perforation**		
	CH4	**Initial Flow**	**Adjusted Flow**	**CH4**	**Initial Flow**	**Adjusted Flow**
EW-559	50.5	2.8	3.2	58.1	0.2	0.0
EW-564	58.0	11.7	12.0	62.3	8.8	8.8
EW-583	58.4	2.5	2.5	54.3	3.3	3.2
EW-584	49.0	0.5	0.5	52.2	9.3	8.8
EW-595	50.6	1.0	1.5	51.9	1.0	2.5
EW-598	55.5	8.0	8.3	57.5	6.0	5.2
EW-600	59.0	8.0	8.5	55.9	6.2	3.5
EW-601	51.9	0.7	0.7	46.1	1.0	1.3
EW-603	53.2	8.8	9.5	54.1	9.0	11.5

EW-604	56.0	10.2	9.8	57.7	19.2	18.2
EW-605	53.1	13.0	16.0	57.5	1.5	1.8
EW-609	56.5	1.0	1.0	54.1	2.2	2.5
EW-610	51.2	0.7	1.2	47.3	1.0	1.2
EW-616	56.8	0.0	0.0	56.3	13.2	12.2
EW-617	57.6	7.5	7.7	55.9	8.3	5.3
EW-620	62.2	8.2	8.5	55.0	5.2	4.3
EW-621	61.2	7.3	8.3	56.7	12.8	12.0
EW-626	54.5	7.3	8.3	50.1	8.8	8.2
EW-627	43.4	6.7	7.7	41.5	7.7	7.7
EW-631	56.5	0.0	0.0	36.8	2.0	2.0
EW-633	53.1	0.8	0.8	57.6	13.8	14.5
EW-634	51.9	1.5	1.7	48.7	2.3	2.5
EW-637	52.6	0.8	0.8	52.6	2.3	2.0
EW-639	60.4	0.0	0.0	57.2	4.2	4.2
EW-642	53.4	4.8	6.8	55.8	2.2	2.2
EW-644	58.0	7.2	7.5	55.6	2.5	2.0
EW-646	58.7	0.0	0.0	50.7	4.5	2.7
EW-647	58.0	0.0	0.0	50.2	8.2	4.0
EW-651	52.0	8.0	8.2	48.9	8.5	7.0
EW-652	56.5	4.7	4.8	56.2	7.0	2.8
Mean	55.0	4.5	4.9	53.2	6.1	5.5

Facility 6	**Group 3**					
	pre-perforation			**post-perforation**		
	CH4	**Initial Flow**	**Adjusted Flow**	**CH4**	**Initial Flow**	**Adjusted Flow**
EW-557	51.3	8.8	8.7	52.3	7.2	7.3
EW-558	44.6	6.2	5.8	55.9	5.5	7.7
EW-560	42.8	13.0	13.7	59.4	7.8	7.7
EW-561	43.4	8.3	8.8	56.9	3.5	3.8
EW-562	54.9	12.5	12.5	57.1	10.8	11.0
EW-563	54.4	12.5	12.8	62.4	8.8	8.8
EW-565	50.4	8.5	8.0	51.9	8.0	7.0
EW-566	50.1	10.2	9.7	53.2	8.7	9.0
EW-567	57.6	10.2	10.5	63.4	7.3	7.7
EW-568	51.5	6.7	7.2	54.3	11.0	12.5
EW-569	59.8	23.2	24.7	57.2	18.2	19.2
EW-570	58.0	26.7	27.0	56.5	23.5	24.2
EW-571	52.3	21.3	22.0	54.0	14.8	15.2

EW-572	58.4	24.3	22.0	63.2	22.0	21.3
EW-573	58.8	10.8	10.7	59.8	5.2	2.8
EW-574	60.3	9.7	10.2	58.8	5.2	5.5
EW-575	48.3	7.7	6.7	49.8	9.8	8.5
EW-576	56.6	24.0	25.2	56.9	27.5	28.0
EW-577	56.2	20.2	21.3	56.3	22.7	22.8
EW-578	56.1	8.0	8.3	54.5	1.8	2.2
EW-579	56.0	2.7	1.7	56.8	4.8	3.8
EW-580	57.2	1.0	1.2	54.6	7.2	3.8
EW-581	56.8	19.0	20.3	57.7	11.8	8.7
Ew-582	58.2	14.7	17.0	58.0	17.2	18.0
EW-585	44.8	4.0	4.0	48.9	6.5	5.2
EW-586	50.1	4.5	4.5	41.8	6.2	4.8
EW-587	56.6	5.3	6.5	56.3	8.0	7.3
EW-588	56.3	9.8	10.0	58.0	5.8	4.5
EW-589	58.7	6.8	6.8	55.7	10.0	4.0
EW-590	58.1	1.5	1.2	55.1	4.2	4.2
EW-591	56.4	10.0	9.5	55.8	5.7	4.7
EW-592	60.0	20.5	20.5	55.6	21.8	22.3
EW-593	51.8	7.5	8.3	51.7	5.2	2.2
EW-594	57.9	9.5	9.7	57.9	7.3	7.0
EW-596	55.4	7.8	13.7	54.3	5.5	6.2
EW-597	57.2	8.5	8.8	58.0	4.2	6.0
EW-599	52.3	1.2	0.8	50.1	2.7	2.2
EW-602	55.7	7.3	7.7	56.6	12.3	13.2
EW-612	56.3	2.3	2.7	52.2	5.2	4.5
EW-613	55.9	19.7	21.2	50.5	19.2	16.0
EW-614	55.6	1.5	1.3	51.8	12.5	12.8
EW-615	57.6	9.7	9.7	55.9	4.8	5.0
EW-618	58.1	14.5	15.0	55.2	11.2	12.3
EW-619	58.6	13.7	14.7	59.1	9.7	9.0
EW-622	56.9	4.0	3.7	57.6	8.0	7.2
EW-623	57.3	10.5	13.2	56.9	13.8	13.5
EW-625	58.7	2.2	1.7	57.5	3.2	3.3
EW-629	59.2	8.0	9.0	57.5	5.5	5.7
EW-630	61.6	11.7	11.2	57.6	4.5	4.7
EW-632	58.8	2.3	2.2	56.8	3.7	3.0
EW-636	57.4	2.2	3.7	57.9	7.5	3.5
EW-638	51.8	3.3	3.5	47.6	5.3	5.2
EW-640	56.8	0.8	1.5	56.2	3.7	3.3
EW-643	53.4	9.3	10.5	50.4	7.7	7.2

EW-650	52.3	2.0	1.8	45.3	5.0	3.5
EW-653	52.5	3.7	3.5	56.1	3.5	3.8
Mean	55.1	9.6	10.0	55.3	9.1	8.6

Facility 9	**Group 1**					
	pre-perforation			**post-perforation**		
	CH4	**Initial Flow**	**Adjusted Flow**	**CH4**	**Initial Flow**	**Adjusted Flow**
EW-898	56.7	23.0	25.8	53.3	68.7	79.3
EW-899	57.3	28.0	26.7	37.5	51.3	58.8
EW-900	32.6	37.7	29.3	53.8	24.0	32.8
EW-906	56.6	33.5	46.5	57.3	108.2	103.5
EW-909	54.3	9.0	5.8	57.4	227.0	219.7
EW-912	56.2	30.2	35.2	52.7	40.0	28.0
EW-913	55.9	53.2	36.8	56.3	67.0	54.7
Ew-914	57.0	128.7	122.3	56.4	218.7	218.5
EW-916	54.9	14.0	6.7	50.6	15.7	17.7
Ew-917	51.7	16.3	5.7	40.1	35.8	38.8
Ew-918	54.2	78.7	77.3	56.2	47.3	61.7
EW-919	57.9	19.7	13.2	44.6	37.7	24.3
EW-925	51.9	17.3	9.3	51.0	55.0	53.3
EW-938	59.0	19.0	13.2	55.2	27.7	28.8
EW-939	55.6	57.7	57.5	56.7	62.5	49.8
Mean	54.1	37.7	34.1	51.9	72.4	71.3

Facility 9	**Group 2**					
	pre-perforation			**post-perforation**		
	CH4	**Initial Flow**	**Adjusted Flow**	**CH4**	**Initial Flow**	**Adjusted Flow**
EW-932	11.3	9.5	6.2	8.7	21.5	22.5
EW-933	8.0	8.2	8.8	0.3	29.7	13.5
EW-936	57.0	109.0	106.7	56.8	119.0	128.5
EW-940	58.7	32.3	32.5	58.5	31.3	25.3
EW-941	56.6	21.5	16.8	58.4	49.3	62.2
EW-942	57.7	43.2	51.7	59.3	53.5	56.7
EW-943	55.5	19.8	22.3	57.4	138.2	156.8
EW-954	55.6	48.8	49.7	55.3	119.5	112.7
EW-957	57.9	31.5	33.3	54.8	20.2	23.8
Mean	46.5	36.0	36.4	45.5	64.7	66.9

Facility 9	**Group 3**					
	pre-perforation			**post-perforation**		
	CH4	**Initial Flow**	**Adjusted Flow**	**CH4**	**Initial Flow**	**Adjusted Flow**
EW-892	56.5	57.3	65.0	54.3	63.8	55.7
EW-901	56.5	31.2	28.0	56.1	42.0	46.2
EW-907	4.6	79.7	93.0	9.8	12.7	18.3
EW-910	55.7	55.5	36.7	43.5	59.8	52.8
EW-911	4.4	20.2	19.7	26.5	34.7	38.8
EW-915	56.7	46.8	37.0	57.2	26.5	56.0
EW-920	52.4	27.8	19.0	53.6	29.7	36.2
EW-921	50.7	31.5	28.0	54.4	42.8	53.2
EW-922	47.9	39.2	34.3	56.1	89.8	94.2
EW-923	57.0	48.2	46.7	58.2	39.8	41.3
EW-924	29.6	13.3	11.3	10.7	18.5	20.8
EW-926	53.7	106.8	118.0	52.6	87.3	88.5
EW-927	56.5	36.7	41.7	56.7	29.5	28.0
EW-928	55.8	22.0	18.0	49.5	82.7	79.7
EW-929	55.8	23.8	18.7	57.1	32.0	27.3
EW-930	56.6	44.5	39.8	57.8	62.3	54.2
EW-931	54.4	57.7	55.5	52.5	79.7	80.0
EW-934	56.7	189.5	189.7	56.6	88.2	96.0
EW-935	57.9	11.2	18.2	56.1	14.0	14.3
EW-937	19.2	19.8	21.8	20.3	13.2	16.7
EW-951	59.0	74.3	81.0	51.6	34.2	35.5
EW-955	10.2	21.0	21.8	20.1	19.3	16.5
EW-956	13.6	10.7	6.3	5.3	25.5	37.5
EW-958	44.5	46.7	42.8	53.4	25.5	36.7
EW-959	49.8	30.3	27.8	46.8	21.3	43.3
Mean	44.6	45.8	44.8	44.7	43.0	46.7