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Flare Efficiency Estimator and Case Studies

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FLARE EFFICIENCY ESTIMATOR AND CASE STUDIES

by:

John Willis
Brown and Caldwell

David Checkel
Checkel Engineering Inc.

Dan Handford
University of Alberta

Anup Shah
Brown and Caldwell

Matt Joiner
Brown and Caldwell

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For more information, contact:
Water Environment Research Foundation
635 Slaters Lane, Suite G-110
Alexandria, VA 22314-1177
Tel: (571) 384-2100
Fax: (703) 299-0742
www.werf.org
werf@werf.org

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Brown and Caldwell

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Research Team

Principal Investigator:
John Willis, P.E., BCEE
Brown and Caldwell

Project Team:
David Checkel, P.Eng., Ph.D.
Checkel Engineering Inc., Alberta, Canada

Dan Handford
University of Alberta, Canada

Matt Joiner
Anup Shah, P.E., LEED® AP
Brown and Caldwell

WERF Project Subcommittee

Eliza Jane Whitman, P.E.
GEI Consultants

Patrick Wootton, P.E.
Nixon Energy Solutions

Liaison
Bob Bastian
United States Environmental Protection Agency

Water Environment Research Foundation Staff

Director of Research: Daniel M. Woltering, Ph.D.
Senior Program Director: Lauren Fillmore, M.S.

ABSTRACT AND BENEFITS

Abstract:

A flare efficiency estimator (FEE) tool is part of Water Environment Research Foundation (WERF) project U2R08 entitled *Methane Evolution from Wastewater Treatment and Conveyance* under WERF's Climate Change Program and funding from the New York State Energy Development Authority (NYSERDA). The FEE is based on the work of the Flare Research Group at the University of Alberta (UoA) and it will help estimate the fugitive greenhouse gas (CH_4) emissions from the unprotected 'candlestick' flares for digester gas and landfill gas flares. FEE is available online for free and can be obtained from this NYSERDA webpage: http://www.nyserda.ny.gov/Commercial-and-Industrial/Sectors/Municipal-Water-and-Wastewater-Facilities/Final-Reports-for-Water-and-Wastewater-Technology-and-Demonstration-Projects.aspx.

Benefits:

- FEE helps accurately estimate flaring efficiencies for unprotected 'candlestick' flares.
- FEE helps estimate fugitive GHG emissions from the unprotected 'candlestick' flares.
- FEE can be used to evaluate the ambient conditions for flaring operations such that combustion efficiencies are maximized and GHG emissions are minimized.

Keywords: Fugitive greenhouse gas emission, flares, flaring efficiency, methane.

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LIST OF ACRONYMS

ARC	Alberta Research Council
BC	Brown and Caldwell
BTU	British Thermal Unit
CH_4	Methane
CO_2	Carbon Dioxide.
DO	Dissolved Oxygen
FEE	Flare Efficiency Estimator
GHG	Greenhouse Gas
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
H_2O	Water
HHV	Higher Heating Value
LHV	Lower Heating Value
NOx	Nitrogen Oxides
NYSERDA	New York State Energy Research and Development Authority
UoA	University of Alberta
U.S. EPA	United States Environmental Protection Agency
WERF	Water Environment Research Foundation
WRRF	Water Resource Recovery Facility

EXECUTIVE SUMMARY

Anaerobic digestion of sludge at water resource recovery facilities and biological decay of organic matter in landfills primarily generates methane (CH_4) and carbon dioxide (CO_2) along with other secondary by-products. Although, CH_4 evolved from such processes is routinely captured for beneficial use (combined heat and power generation), the unused CH_4 generated from these processes is routinely flared for safe and less environmentally harmful disposal. Due to high inert gas and moisture content, these gases have a low heating value and lower flaring efficiency at the flares. Furthermore, environmental factors such as wind velocity, atmospheric pressure, and relative humidity also play a significant role in affecting the combustion efficiency, especially at the unconfined and unassisted ‘candlestick’ flares.

However, the prevalent understanding is that flaring provides nearly complete combustion of CH_4 contained within the digester or landfill gas and converts it to CO_2. Moreover, flue gases contain insignificant amounts of CH_4 or GHG emissions. The most widely accepted reference to estimate flaring efficiency, EPA’s Emissions Factors and AP-42 (1998), recommends using a value between 98-100% (99% as a default) as flaring efficiency for the candlestick flares operating on landfill or digester gas. However, simply assuming 99% combustion efficiency can significantly underestimate the GHG emissions.

Leveraging the past research work done at the University of Alberta’s (UoA’s) Flare Research Group, an emissions calculation method has been developed as part of this research project. This method has been converted into a stand-alone tool, the Flare Efficiency Estimator (FEE). FEE has flare gas composition and flaring conditions such as flare gas throughput, flare size, wind speed, gas temperature, ambient temperature, and atmospheric pressure input parameters. FEE can help estimate the combustion efficiency, as well as fugitive GHG emissions from the digester gas and landfill gas flares.

FEE was originally developed under this project (U2R08) and expanded further under WERF’s OWSO11C10 project to include the NOx emissions. The most current version of FEE uses the 100-year global warming potential (GWP) of CH_4 as 25 CO2e (IPCC, 2007).

To demonstrate the use of the FEE to estimate fugitive GHG emissions, data from two water resource recovery facilities (WRRF), one from Georgia and another from Tennessee are presented as case studies. These case studies were developed using the first version of FEE and did not include NOx emissions estimate.

For the Tennessee case study, gas flaring data for a 100-mgd capacity WRRF were analyzed. With an average digester gas flaring volume of nearly 203,000 ft^3/day and 70% CH_4 fraction, FEE estimated a flaring efficiency of 95.5%. Which meant an estimated 834 MT CO_2e/yr were emitted in the atmosphere due to flaring inefficiency. Using the 99% flaring efficiency assumption per EPA AP-42, these estimates would have been underreported by approximately 649 MT CO_2e/yr.

Similarly, for the Georgia case study, gas flaring data and prevalent flaring conditions for an 80-mgd capacity plant were evaluated. With an average digester gas flaring volume of nearly 133,000 ft^3/day and 65% CH_4 fraction, FEE estimated a flaring efficiency of 94.5% which meant an estimated 759 MT CO_2e/yr were emitted in the atmosphere due to flaring inefficiency. Using the 99% flaring efficiency assumption per EPA AP-42, these estimates would have been only 138 MT CO_2e/yr, an underestimating of GHG emissions by approximately 621 MT CO_2e/yr.

FEE is available online from this NYSERDA webpage: http://www.nyserda.ny.gov/Commercial-and-Industrial/Sectors/Municipal-Water-and-Wastewater-Facilities/Final-Reports-for-Water-and-Wastewater-Technology-and-Demonstration-Projects.aspx.

CHAPTER 1.0

RESEARCH OBJECTIVES AND REPORT OUTLINE

The goal of a flare is to consume gases safely, reliably, and efficiently through oxidation and to produce a more desirable emission in the form of CO_2 than simply venting the gases that are combustible and odorous. The environmental issues of gas flaring are generally described in terms of efficiency and emissions. The flare efficiency is a measure of the effectiveness of the combustion process to fully oxidize the fuel. When inefficiencies occur, unburned fuel, carbon monoxide, and other products of incomplete combustion (e.g., soot, volatile organic compounds, etc.) are emitted into the atmosphere. In the context of this report, the unburned fuel represents an increase in GHG emissions in the form of CH_4.

The prevalent belief in the wastewater industry is to assume a combustion-efficiency between 98-100% for the waste gas burner or flares including the open and unassisted 'candlestick' type flares. This is based on EPA's guidance on emissions factors (U.S. EPA, 1995). However, due to high inert gas and moisture content, these gases have a low heating value (LHV) and this can reduce the flaring efficiency. Assuming a default flaring efficiency of 98% or greater also leads to general understanding that any CH_4 sent to the waste gas burners is completely combusted and converted to CO_2.

The primary objective of this research was to increase awareness about the combustion efficiency of candlestick flares and to gain an understanding of the fugitive emissions from gas flaring operations. While this research helps document fugitive GHG emissions from candlestick flares, it also shows that simply replacing the candlestick flares with enclosed flares would help utilities reduce their overall carbon footprint. Alternatively, utilities may also be able to optimize the flaring operation by carefully addressing the parameters most adversely affecting the combustion efficiency of the flares.

As part of this work, WERF also wanted to create the Flare Efficiency Estimator (FEE), a stand-alone tool that users can use to input the local operating conditions and parameters and estimate the flare efficiency. Another objective was to help utilities incorporate a more realistic estimate of the fugitive emissions in their baseline carbon footprint calculations.

This report provides the details of the FEE including a brief overview of prior research on flares, the researcher's approach for this research study, the calculation methodology, and a description of the user interface for the estimator tool.

At the end of the report, two case studies are presented where the FEE was used to estimate fugitive GHG emissions for two separate sites using actual site data and conditions.

CHAPTER 2.0

RESEARCH APPROACH

For this research, previous research conducted on the flares by the Flare Research Group (FRG) at the UoA for the petroleum industry was leveraged. Models created as part of the previous research were simplified and expanded to a calculation method that can be applied to the waste gas burners used by the environmental industry.

To leverage the findings from the UoA research and further apply them to the wastewater industry, the project team collaborated with Dr. Checkel from UoA's Flare Research Group. As part of this collaboration, Dr. Checkel simplified the flare combustion model developed for the "solution gas flares" of the petroleum industry and expanded it for use with low BTU, moist waste gases from anaerobic digesters and landfills. To estimate the flaring efficiency, this calculation method uses the flare gas composition (CH_4, CO_2, O_2, N_2, and moisture) along with the flaring conditions (flare jet velocity, wind speed, gas temperature, ambient temperature, and atmospheric pressure).

Using a MATLAB® routine, this calculation method was further converted into a stand-alone tool, FEE, available online from this NYSERDA webpage:

http://www.nyserda.ny.gov/Commercial-and-Industrial/Sectors/Municipal-Water-and-Wastewater-Facilities/Final-Reports-for-Water-and-Wastewater-Technology-and-Demonstration-Projects.aspx.

Details of the modeling and the estimator tools are provided in the following sections.

CHAPTER 3.0

BACKGROUND AND OVERVIEW OF PAST RESEARCH

Over the last 50 years, many different flare designs and strategies have been developed to meet the widely different purposes and operating conditions for waste gas flaring. Flares are typically designed to handle the peak generation or handle emergency situations such as plant upsets or scheduled facility shutdowns for maintenance. Waste gas flares used at water resource recovery facilities with anaerobic digesters, but without the cogeneration or gas storage facilities, are important examples of such continuous gas flares. This leads to installation of large diameter flare sizes to handle very high flow rates of flare gas at very high exit velocities. However, during routine operation, flares deal with continuous but relatively low combustible gas flows and consequently low exit velocities. At such low exit velocities, the candlestick flares tend to be more susceptible to inefficient flaring due to ambient conditions. Estimating the fugitive GHG emissions from such inefficient flaring at the water resource recovery facilities and the bulk of the landfill sites with continuous flares is the main interest of this study.

Figure 3-1. Typical Unconfined "Candlestick" Waste Gas Burner.

While many new installations of waste gas burners at water resource recovery facilities and landfills have used enclosed, high-efficiency, low-NOx waste gas burners, there are numerous existing and new waste gas burner installations that are candlestick type. There is no official documentation on how many candlestick flares are in service within the U.S. or around the world but researchers believe that candlestick flares represent a considerable fraction of the waste gas burners in service. Several large facilities still have candlestick flares.

Most previous research on flares has supported the general observation that flare efficiencies were high (>95%) as long as the flames were stable. One such study was sponsored by the United States Environmental Protection Agency (U.S. EPA) and involved the testing of flares ranging in nominal size from 3.8 to 30 cm burning bottled gases over a range of flow rates. The tests were conducted in such a manner that the wind speed impinging on the flare was low (<3 mph) and a collection hood placed above the flame collected all the products of combustion. The products of combustion were then sampled and the overall combustion efficiency was calculated. The main conclusion of the U.S. EPA study was that flares had efficiencies greater than 98% for the gas mixtures tested as long as the flame remained stable. Consequently, the problem of maintaining high-efficiency combustion from flares was shifted to understanding the set of operating parameters (e.g., flare gas exit velocity, energy density of the fuel, etc.) that would ensure stable combustion. The results of this U.S. EPA study (U.S. EPA, 1995) are the foundations of current U.S. federal regulations on flaring as well as the prevalent belief that flares provide near-complete combustion of CH_4.

Figure 3-2. Typical Enclosed Low-NOx Flare with a Candlestick Flare Burning in the Background.

However, a multi-year experimentally based study by the Alberta Research Council (ARC) on solution gas flares found results that were in stark contrast with the previous findings from U.S. EPA. The ARC study found that at normal operating conditions and prevailing wind conditions, the measured efficiencies of the unconfined gas flares were as low as 62% (Kostiuk et al., 2004)

The contrast between the ARC and EPA studies was essentially the starting point for the UoA Flare Research Project. Given the differences in the test conditions, developing a better understanding of how flares could produce such varied outcomes was considered crucial. Therefore, rather than focus on specific local conditions, research at UoA focused on the fundamental physical phenomena affecting flaring performance. The research utilized flare stacks modeled as simple vertical pipes that were tested within the confines of a wind tunnel. This experimental setup allowed for the scientific exploration of flaring performance as a set of physical parameters contained within a well-controlled environment. Consequently, the fluid mechanics and the combustion associated with flares were studied in near-uniform and steady crosswinds with total collection of combustion products. These simplifications to the testing environment allowed the research to be generalized to cover a wide range of conditions rather than limited to site-to-site variations that exist in the field.

3.1 Previous Research Work at University of Alberta

The approach taken in the UoA research was to experimentally study sub-scale pipe flares in the well-controlled conditions that exist within wind tunnels. Within these wind tunnel environments, the defining parameters of a flaring operation (i.e., wind speed, wind direction, flare stream flow rate, stack size, flare stream composition, etc.) were specified and varied independently to elucidate the important physical processes occurring around the flare that impact emissions. The exhaust from the wind tunnels could be tested and characterized, providing reliable data on performance at controlled conditions.

The UoA Flare Research Facility was developed to study the emissions, the efficiency, and the related fluid mechanics of flares in a crosswind. The centerpiece of the facility was a closed-loop wind tunnel that was capable of testing flares up to 49.8 mm in outside diameter (more typically 24.7 mm) at wind speeds up to 35 m/s. The flares were supplied with mixtures of natural gas, propane, ethane, carbon dioxide, nitrogen, and liquid droplets.

This research used the carbon conversion efficiency as the measure of combustion efficiency. This combustion efficiency was defined as the fraction of carbon mass in the fuel (excluding carbon dioxide) of the flare stream that becomes carbon dioxide.

The measured efficiencies of natural gas, ethane, and propane flares (i.e., gases with relatively high energy densities) at calm and low winds were found to be very high (<99.5%). UoA research noted that with increased wind speed, the efficiency fell slowly but that at high wind speeds there was a dramatic decline in efficiency. The wind speed where the efficiency rapidly drops depended on the exit velocity of the flare stream, the size of flare stack, and the composition of the flare gases. In all cases, the dependency of efficiency on wind speed was found to be exponential. Reduced energy density gas streams produced very similar results, except that the efficiency in calm conditions did not approach 100%.

UoA research created a model based on the combustion efficiency data collected and focusing on the origins of the inefficiencies. The key to this modeling was that the dominant fluid-mechanic forces associated with gas flares are the momentum flux of the crosswind and the buoyancy of the combustion products. The inefficiencies result from the emissions of either carbon monoxide (i.e., the partial oxidation of the hydrocarbon fuel) or the raw fuel (CH_4). In the case of raw fuel, the fuel is stripped from the flare stream without any participation in the combustion. At low crosswinds these two sources of inefficiency were of the same order of magnitude, but as the wind speed increased the fraction of raw fuel being stripped rapidly increased and was the dominant cause. The pathway that allowed the raw fuel to be stripped away from the flame was determined to be driven by a standing vortex on the leeward side of the flare stack. The interaction of this standing vortex with the ring vortices emerging from the stack affected the flame such that packets or bursts of raw fuel were drawn beneath the flame. Once under the flame, these packets of raw fuel were dispersed into the atmosphere and then measured as the main source of inefficiencies.

One implication of this fuel-stripping mechanism for inefficiency is that the composition of the emitted hydrocarbon depends on the composition of the flare stream. For example, if the fuel in the flare stream is natural gas, then CH_4 is the dominant emitted hydrocarbon. This raises issues regarding greenhouse gas emissions since CH_4 has a greater greenhouse effect than carbon dioxide.

The most important flare gas property is energy content. This is typically described in terms of the LHV and depends on gas composition and moisture content. Other important factors include physical geometry surrounding the flare including the flare stack size, wind speed and flare gas exit velocity.

The general conclusion of this research was that the combustion efficiency of candlestick gas flares could be very high as long as a few important conditions were maintained. These operating conditions are as follows:

- The flare stream must have a relatively high energy density (approximately 20MJ/m^3 or higher).
- The flare stack size should be designed appropriately for the flow rate of flare gas to maintain a reasonable minimum exit velocity in the order of 1 m/s.
- The composition of the flare stream must have a low propensity to form and emit soot.
- The flare stream must not contain materials that form other toxic compounds (e.g., chlorine in saltwater).

Other important parameters affecting flaring efficiency include the volumetric flow rate and the velocity of the solution gas exiting from the flare stack. The gas flow fluctuations due to the process variations or selective redirection of gas flow (e.g., intermittent use of the waste gas for heating purposes) coupled with variations in the mean wind speed at the site continually alter the flaring conditions.

Further research on setting an appropriate lower limit for energy density is required. Since the efficiency is highly dependent on the wind velocity, it is suggested that that the limit be based on a yearly average efficiency which also takes into consideration the annual wind patterns.

CHAPTER 4.0

CALCULATION METHODOLOGY FOR FEE

A brief overview of the calculation methods used in the FEE are provided below. Detailed calculation methodology and the tool interface are described in a separate report by Dr. David Checkel and Mr. Dan Handford provided in Appendix A.

The heating value or energy value of a fuel is the amount of heat released during the combustion. It is measured in units of energy per unit of the substance, usually mass, such as: kJ/kg, kJ/mol, kcal/kg, Btu/lb. The heat of combustion for fuels is typically expressed as the HHV or LHV.

The HHV is determined by bringing all the products of combustion back to the original precombustion temperature, and in particular condensing any vapor produced. It takes into account the latent heat of vaporization of water in the combustion products or in other words, HHV assumes all the water component is in liquid state at the end of combustion (in product of combustion). The LHV on the other hand is a measure of the energy content of a gas; it treats any water formed at the end of combustion as a vapor. The LHV assumes that the latent heat of vaporization of water in the fuel and the reaction products is not recovered. Thus, LHV is determined by subtracting the heat of vaporization of the water vapor from the HHV.

Typically, the waste gas generated from digesters or landfills is saturated with water. A small portion of the moisture drops off in the piping as condensation; however, the digester or the landfill gas remains close to saturated (with relative humidity close to 100%). In order for the flaring efficiency to be accurately calculated, it is important to take the moisture content into account and focus on the LHV. This is typically the case in comparing fuels where condensation of the combustion products is impractical such in case of the gas flaring.

In the FEE calculations, the dry concentrations of the waste gas were first converted to wet concentrations to account for the water vapor entering the flare. Effluent water vapor concentrations were calculated using Raoult's Law below:

$$Water\ Vapor\ (\%\ by\ volume) = \frac{Vapor\ Pressure\ (kPa)}{Barometric\ Pressure\ (kPa)} \times \frac{\%\ Humidity}{100} \qquad \text{(Equation 4.1)}$$

Where vapor pressure is calculated using a variation of Antoine's Equation (Smith, et al., 2000).

$$Vapor\ Pressure\ (kPa) = e^{\left(16.262 - \frac{-3799.89}{Temperature\ (℃) + 226.36}\right)} \qquad \text{(Equation 4.2)}$$

Once the water vapor concentration in the waste gas is determined, it is subtracted proportionally from each of the dry effluent constituents (CH_4, CO_2, etc.) to calculate their wet gas concentrations. The wet waste gas concentrations could then be used to determine the molar mass of the effluent gas mixture, followed by a calculation of a LHV for the waste gas. A higher LHV indicates a higher tendency of a gas to burn. The LHV of 100% CH_4 is documented as:

$$LHV_{Methane} = 50.009\frac{MJ}{kg}$$

Using this value and fraction of CH_4 in the gas, the LHV of the waste gas is calculated.

$$LHV_{gas}\left(\frac{MJ}{kg}\right) = \frac{\frac{\%\,Methane}{100}\times Molar\ Mass_{Methane}\left(\frac{g}{mol}\right)\times LHV_{Methane}\left(\frac{MJ}{kg}\right)}{Molar\ Mass_{gas}\left(\frac{g}{mol}\right)} \qquad \text{(Equation 4.3)}$$

Using the flare diameter and the gas flow, jet velocity leaving the flare is calculated in meters per second. Using the flare jet velocity and the prevailing wind speed, the overall flare efficiency can be calculated based on the following equation derived from the model developed by UoA Flare Research Group.

$$X_1 = \frac{Windspeed\ (\frac{m}{s})}{(Flare\ Gas\ Velocity\left(\frac{m}{s}\right)\times g\left(\frac{m}{s^2}\right)\times Flare\ Diameter\ (m))^{1/3}} \qquad \text{(Equation 4.4)}$$

Finally, the flare efficiency is calculated as

$$Flare\ Efficiency = 1 - (0.00166 \times e^{(0.387\times X_1)} \times \frac{LHV_{CH_4}\ (\frac{MJ}{kg})}{LHV_{flare}\ (\frac{MJ}{kg})}) \qquad \text{(Equation 4.5)}$$

The FEE uses a physics-based algorithm which can be extended confidently to larger flare diameters and with less confidence to a wider range of wind and jet speeds.

The model created by the Flare Research Group is developed and validated for the flares that are operating in wind speeds of less than 25 miles per hour and a flare jet velocity of lower than 14 feet per second with flare stacks of 0.25 inch to 4.5 inches in diameter. The background experimental work involved CH_4-based flares of with LHV as low as 4,300 BTU/lb. Within these ranges, this model can reliably predict the flare-efficiency. The model can be utilized for data beyond the specified ranges; however, the results may not accurately predict the flaring efficiency.

CHAPTER 5.0

FLARE EFFICIENCY ESTIMATOR

The FEE is developed and compiled in MATLAB®, and requires the installation of the MATLAB® Compiler Runtime (MCR) libraries (MCRInstaller.exe) prior to running the flare efficiency calculator. Following the successful installation of the runtime libraries, the computer will be able to run compiled MATLAB® executable programs such as Flare.exe. The MCR Installer program is available from Mathworks and a detailed description of MCR installation and use is available on the Mathworks website at http://www.mathworks.com/access/helpdesk/help/toolbox/compiler/br2jauc-1.html or search www.mathworks.com for MCR Installer help. The Flare.exe executable file was compiled with MATLAB® compiler version 7.10 and the MCRInstaller program should be the same version. The FEE is also distributed as a set of MATLAB® ".m" files which should be placed in a single directory and can be run directly in the MATLAB® command window on computers running that software.

5.1 Using the Tool

Running the executable Flare.exe launches a Windows COMMAND window and then, a moment later, the FEE interface window opens, as shown on Figure 5-1. If the window opens with only part of the interface panel showing, try expanding or maximizing the window to see the entire interface panel. The upper part of the panel contains input zones for flare gas composition, flow rate, flare diameter and ambient conditions. The lower part of the panel presents the calculated results. There is also a "help" information window which can be activated by clicking the help button at the top of the panel. The interface panel is continuously updated –

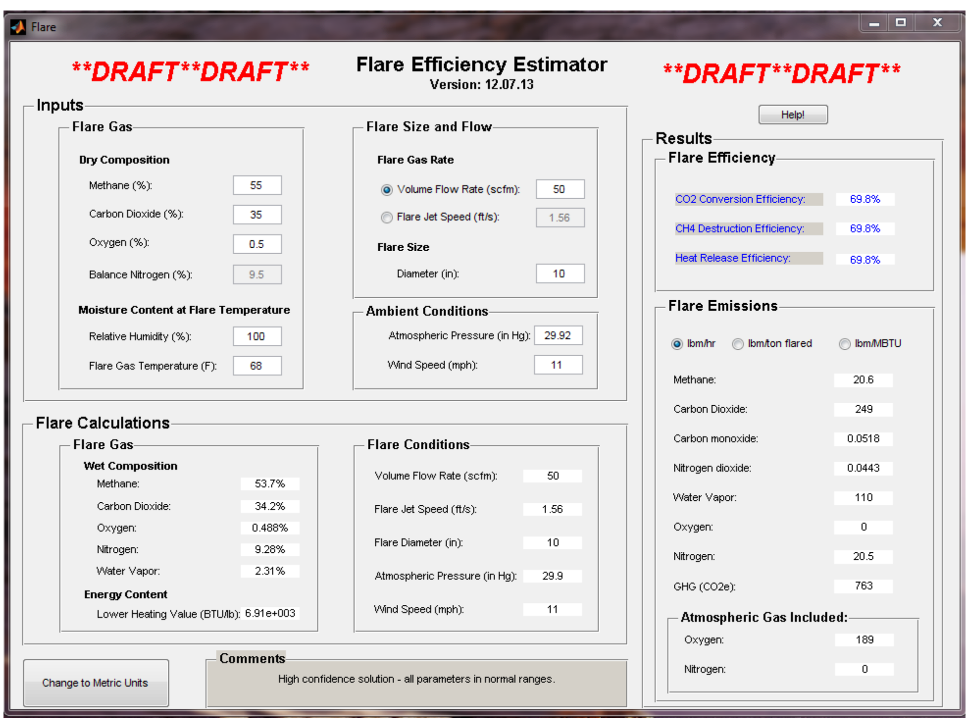


Figure 5-1. Interface of the Flare Efficiency Estimator (FEE).

every time an input is changed and the user enters that value by pressing 'enter' or 'tab' or by clicking elsewhere in the panel, the results are updated to reflect the changed inputs. The inputs must be entered as numeric values only (i.e., type “35” for 35%, rather than typing “35%” or using decimal notation, “0.35”).

By default, the FEE launches in standard American units and can be changed to metric units using the ‘Change to Metric Units’ button below the results.

5.2 Key Parameters

There are nine key parameters that influence the flare efficiency as indicated by the modeling equations presented in the Chapter 4.0. These include: CH_4 content, CO_2 content, O_2 content, relative humidity, gas temperature, flare diameter, flare jet velocity, wind velocity, and atmospheric pressure. The FEE interface provides for user input of these parameters. If the flare jet velocity is not directly available then the user can input the flare diameter and gas flow and the FEE will calculate the flare jet velocity.

The parameter values must be entered using the appropriate units as specified by the panel (and as shown in Table 5-1).

Table 5-1. Units and Limits for the Flare Efficiency Estimator Parameters.

Parameter	Units	Normal Parameter Range	Extended Parameter Range
CH_4 composition	%	40 – 100	40 – 100
CO_2 composition	%	0 – 60	0 – 60
O_2 composition	%	0 – 60	0 – 60
Relative humidity	%	0 – 100	0 – 100
Flare gas temperature	degrees F	-40 – 158	-40 – 158
Gas flow rate	Ft^3/min	Calculated based on jet velocity and flare diameter	Calculated based on jet velocity and flare diameter
Flare diameter	inches	0.25 – 4.5	0.25 – 18
Flare jet speed	ft/s	0.82 – 14	0.82 – 14
Atmospheric pressure	In. Hg. abs.	22 – 37	22 – 37
Wind speed	mph	0 – 12	0 – 25
Lower heating value (LHV)	BTU/lbm	4,299 – 21,500	4,299 – 21,500

Table 5-1 also shows the parameter value limits for which the flare efficiency model has been directly validated or is inherently considered valid. Use of parameters shown in the Normal Range column, provides validated results; use of parameters in the Extended Range is less certain but results are more accurate than other known tools or references. Use of parameters values outside of the extended range is cautioned.

As a rule, flares are highly efficient (99+ %) for high-CH_4-content (high BTU) flare gas, high gas jet velocity, low cross wind speed, and large flare pipe diameter. In this region, the model predictions are very stable and can be confidently extended to situations which increase the efficiency, such as larger flare diameter.

On the other hand, for situations which decrease the efficiency, such as lower BTU gas or higher wind speeds, the model shows a sharp efficiency drop as the limits in Table 5-1 are passed. The experimental work at the UoA showed that, as flare combustion efficiency dropped below about 75%, the flame became unstable and a complete blow-out (0% efficiency) was likely. To provide a useful tool, the FEE does not limit inputs to the fully validated ranges shown in Table 5-1. Instead, it allows the user to set inputs, attempts a calculation, and then adds a comment below the calculated flare efficiency.

Of the nine parameters, CH_4 content, wind velocity, and flare jet velocity are the three key parameters that impact the flaring efficiency the most. Figures 5-2 and 5-3 illustrate the importance of each key parameter and how it impacts the flare efficiency.

The figure below illustrates the effect a change of CH_4 gas composition can have on flare efficiency. Flaring efficiency falls sharply once the waste gas CH_4 content drops below 50% and the LHV of the waste gas consequently also drops.

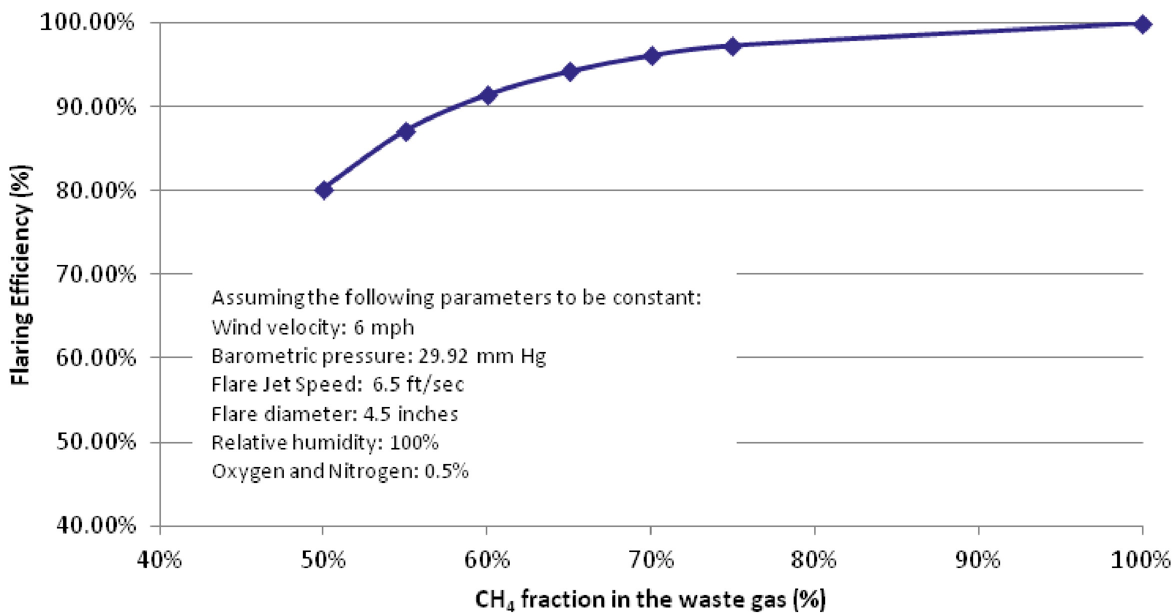


Figure 5-2. Flaring Efficiency as a Function of CH_4 Content in the Flare Gas.

Similarly, Figure 5-3 shows the impact of wind speed and flare jet velocity on the flaring efficiency. At low flare jet velocities, the wind starts impacting the flaring efficiency even at low speeds. In 10 mph winds with all other parameters being same, the flaring efficiency ranges between 93% and 69% for the flare jet velocities of 14 ft/sec and 1 ft/sec, respectively. As indicated in the chart, the flaring efficiency drops sharply with an increase in the wind speeds at low flare jet velocities. Under such conditions, a complete blowout of the flare is very likely.

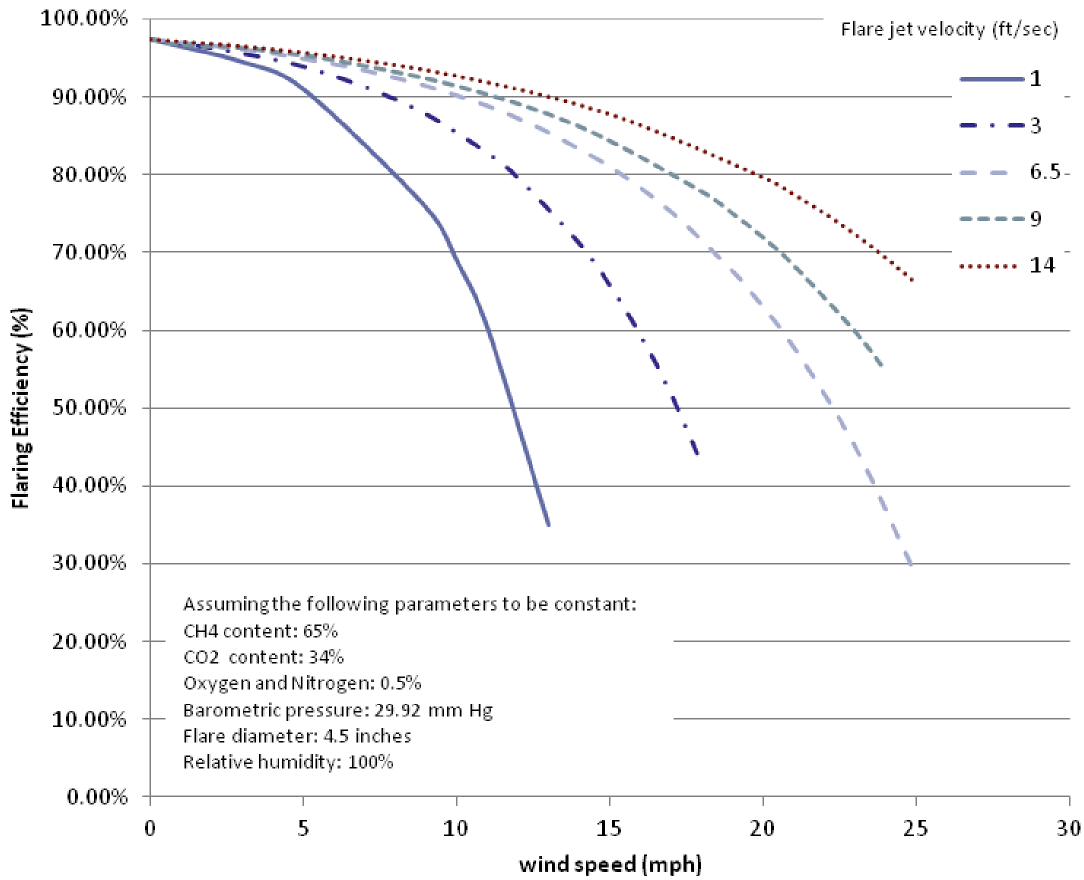


Figure 5-3. Flaring Efficiency as a Function of Wind Speed and Flare Jet Velocity.

CHAPTER 6.0

CASE STUDIES

These case studies are provided to demonstrate the use of the FEE, as well as to provide a firsthand estimate of fugitive GHG emissions from candlestick flares.

Two water resource recovery facilities were selected, one from Georgia and the other from Tennessee, both with candlestick waste gas burners. Utilities operating the plants chose to remain anonymous in this report; however, they provided the historical data for the analysis. Projects are currently underway at both of these plants to install CHP equipment or more beneficial use of the digester gas. Results from these case studies can also be used as benchmarks in the future to estimate reduction in the overall GHG emissions with the CHP equipment installation.

Sludge and waste gas flaring data from year 2007, prior to CHP installation, were evaluated. Along with the gas data, site wind velocity, barometric pressure and ambient temperatures were used for the analysis. Historical average daily values for wind velocity, barometric pressure and ambient temperatures were obtained from online sources (weather.com and weatherunderground.com).

Where historical data were not available, a few simplifying assumptions were made which are listed below.

- Plants did not record daily CH_4 and CO_2 fractions in the digester gas. Therefore, diurnal and daily variations in the CH_4 concentrations were ignored and CH_4 concentration was assumed constant for the entire 12-month duration.
- In order to understand the effect of CH_4 concentration on flare efficiency, analysis was carried out at different CH_4 concentrations within the typical range from 50-70% CH_4 in the gas stream.
- N_2 and O_2 levels were assumed constant for the analysis at 0.5% each. CO_2 fraction was calculated to balance the gas composition at 100%.
- The digester gas coming from the digesters was assumed fully saturated. As such some of the moisture does drop out as condensation upon cooling of the gas; however, the falling gas temperature also keeps the relative humidity near saturation. Due to lack of data, a constant relative humidity level of 95% was assumed for the case studies.
- Average daily values for gas flow, wind velocity, and other ambient parameters were used for the calculation as the plant data did not include diurnal variations for these parameters.

6.1 Case Study 1 – Large Capacity WRRF in Tennessee

The WRRF in Tennessee treats in excess of 100 mgd flow on an average daily basis and has a total of six anaerobic digesters in operation. At this WRRF, the anaerobic digesters operate in two parallel process trains; each with one thermophilic digester is followed by two mesophilic digesters. Since the majority of the gas evolves from the first-stage thermophilic temperature digester, the gas temperature was assumed as 130 °F for the calculations. This plant has two 6-inch-diameter 'candlestick' flares to dispose excess gas. Below is a summary of the year 2007 data for the Tennessee plant used for the case study:

- Waste gas flared per day, average 203,000 ft^3/day with a peak day of 744,000 ft^3/day.
- Gas temperature, 130 °F.
- Two flares at 6 inches in diameter each.
- Flare jet velocity, average 6 ft/sec with a peak of 28 ft/sec.
- Daily average wind speed of 4.5 mph with a range of 0-15 mph.
- Average yearly barometric pressure of 30.09 in. Hg

Figure 6-1 shows the general impact of the wind velocity and the flare jet velocity on the flaring efficiency at this facility while assuming the CH_4 fraction in the digester gas to be constant at 65% in FEE.

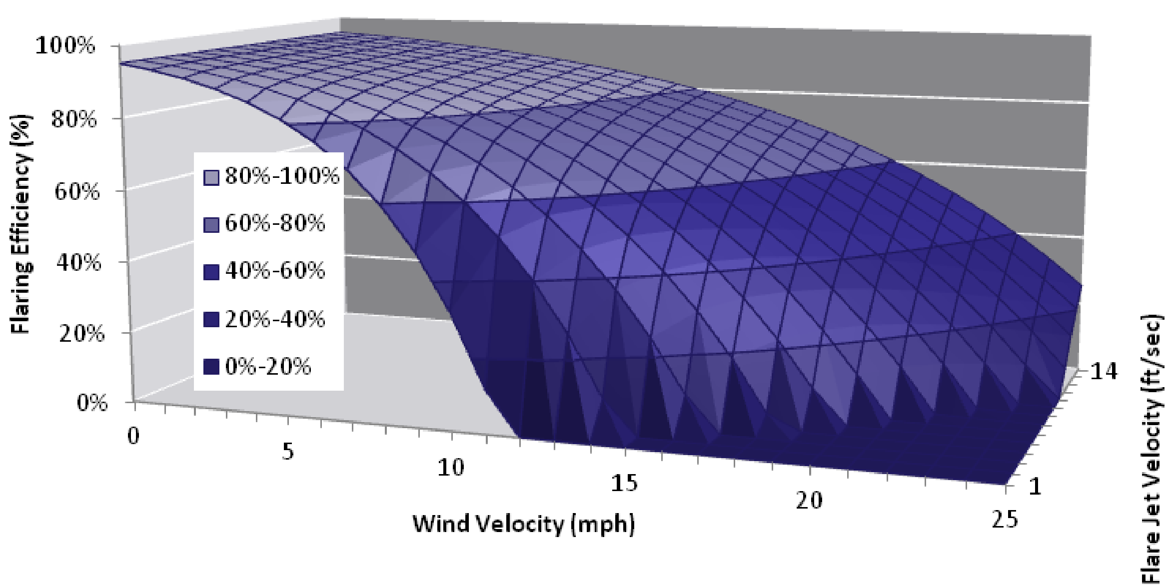


Figure 6-1. Combined Effects of Wind Velocity and Flare Jet Velocity on the Flaring Efficiency at the WRRF Studied in Tennessee (location name withheld).

Flaring efficiency was calculated individually for each flare for each day. The majority of the data was within the 'normal' range of parameters tested for the model. However, there were a few instances where the input data were beyond the model's calibrated range.

At high wind velocity conditions, the model calculated flaring efficiencies less than 50% indicating a blowout. For such conditions, the flaring efficiencies were manually adjusted to be 50% to provide a more conservative GHG emissions estimate. Similarly, where the flare jet velocities were greater than 50 feet per second (representing average gas productions in excess of 745,000 ft^3/day) such data points were considered erroneous and ignored. Overall, there were 42 days of data that were ignored. In order to estimate the annual emissions, results from the remainder of the data were extrapolated to 365 days.

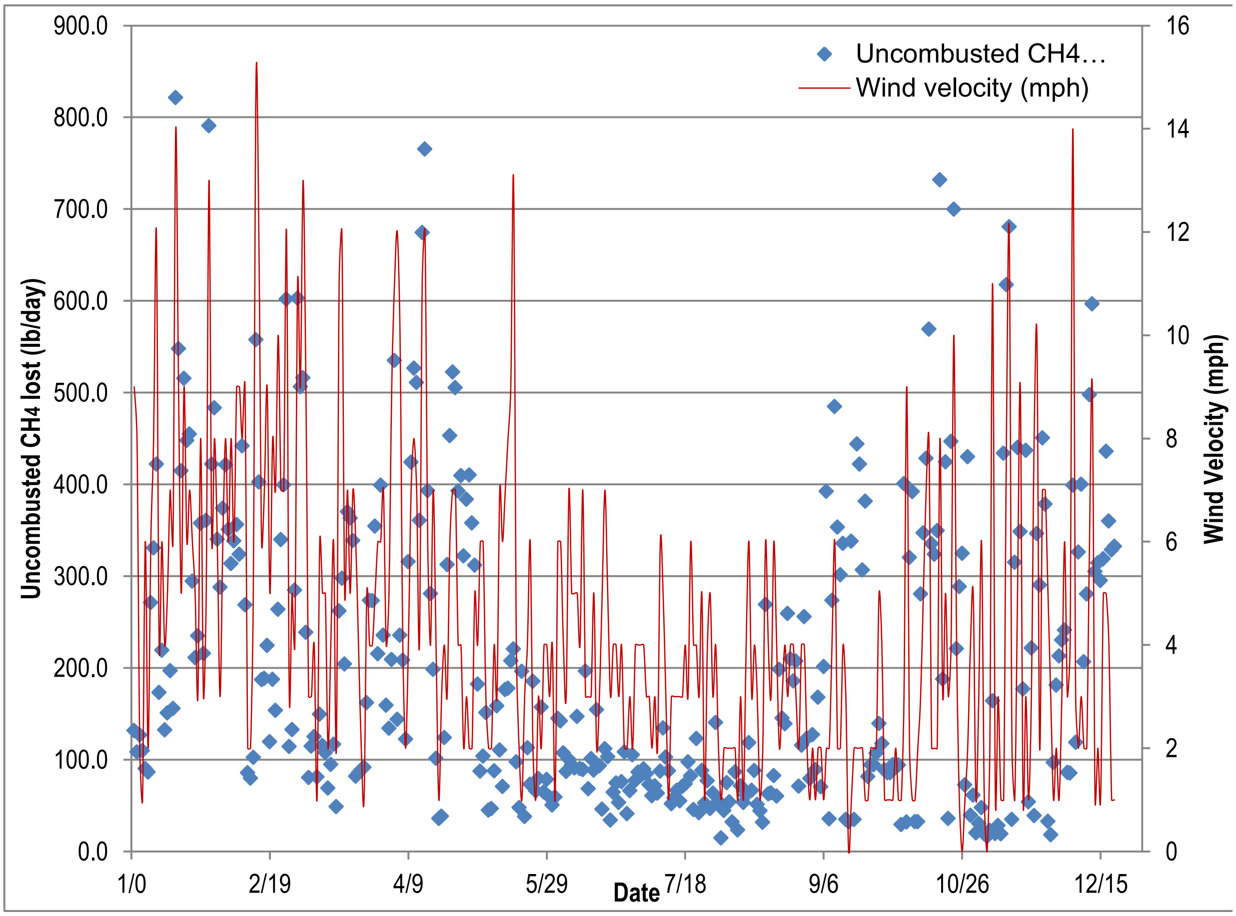


Figure 6-2. Flaring Efficiency and Uncombusted CH_4 Emissions and Wind Velocity at the WRRF Studied in Tennessee (location name withheld).

Figure 6-2 shows the combined plots of the uncombusted CH_4 emissions, plotted on left Y-axis, and the wind velocity, plotted on the Y-axis on the right. The following table provides the summary of the analyzed data. Table 6-1 assumes gas temperature of 13°F and 95% relative humidity.

Table 6-1. Flare Combustion Efficiency and Estimated CH_4 Emissions as a Function of CH_4 Content in Waste Gas for the WRRF Studied in Tennessee.

CH_4 fraction in the waste gas (%)	Flare combustion efficiency (%)	Estimated CH_4 emissions (lb / year)	Estimated GHG emissions (CO_2eq tons / year)
55	86.7	170,798	1,941
60	90.9	127,192	1,445
65	93.7	96,009	1,091
70	95.5	73,413	834

Note: Assumed gas temperature of 130 °F.

Based on the analysis of the gas data using the FEE, the average efficiency of the flares operating at this plant for the year of 2007 was 95.5% assuming CH_4 and CO_2 fractions of 70% and 29%, respectively. At this efficiency, nearly 2.38 million cubic feet or 89,000 lb of uncombusted CH_4 escaped into the atmosphere from the candlestick flares at this site. Using the EPA AR-42 method (99% efficiency assumption), the total emissions were estimated to be only 16,300 lb/yr which underreports the GHG by nearly 649 MT CO_2e per year.

6.2 Case Study 2 – WRRF in Georgia

This facility, located in West Central Georgia, treats 80 mgd flow on an average daily basis. In 2007, the facility was operating three anaerobic digesters in parallel.

Sludge production data from the year 2007 were used to estimate the digester gas production and waste gas to the flares. The temperature of the digester gas coming off the digesters was assumed as 95°F for this case study. The facility operated two candlestick flares, each with 4.5-inch-diameter burners. Data analysis assumed that a single gas flare was operated up to 20 ft/sec before the second flare was brought online for parallel operation.

Below is a summary of the year 2007 data used for the case study:

- Average waste gas flared per day, 143,700 ft^3.
- Two flares at 4.5 inches in diameter each.
- Daily average wind speed of 5.5 mph.
- Average yearly barometric pressure of 30.08 in Hg.
- Gas temperature of 95°F.

For operating conditions at this facility, Figure 6-3 shows the general impact of the wind velocity and the flare jet velocity on the flaring efficiency.

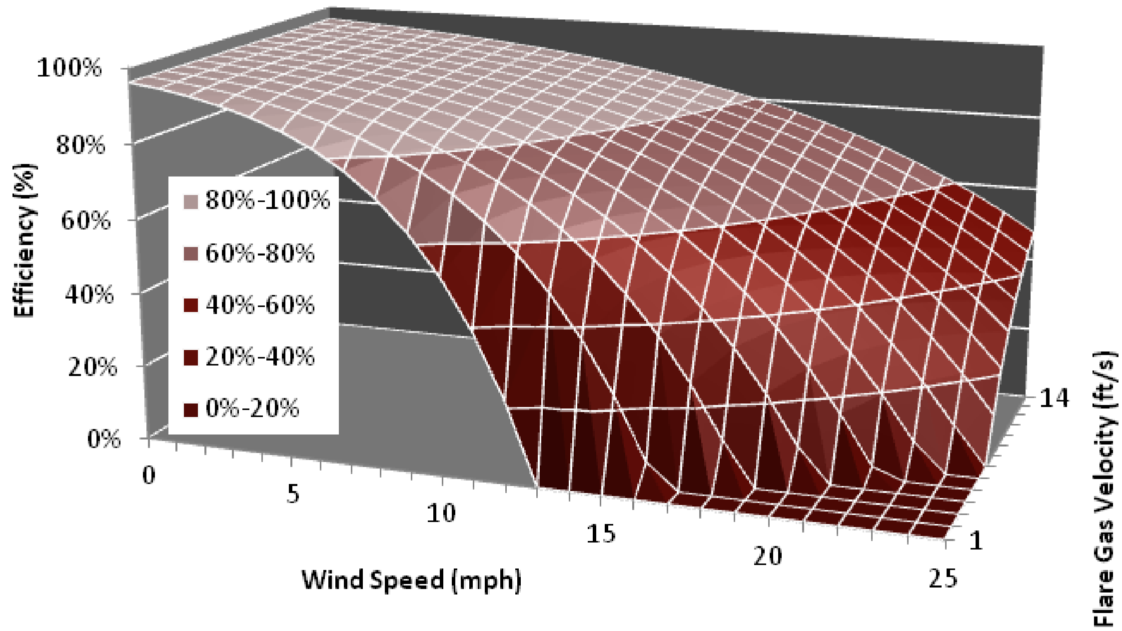


Figure 6-3. Combined Effects of Wind Velocity and Flare Jet Velocity on the Flaring Efficiency at the WRRF Studied in Georgia.

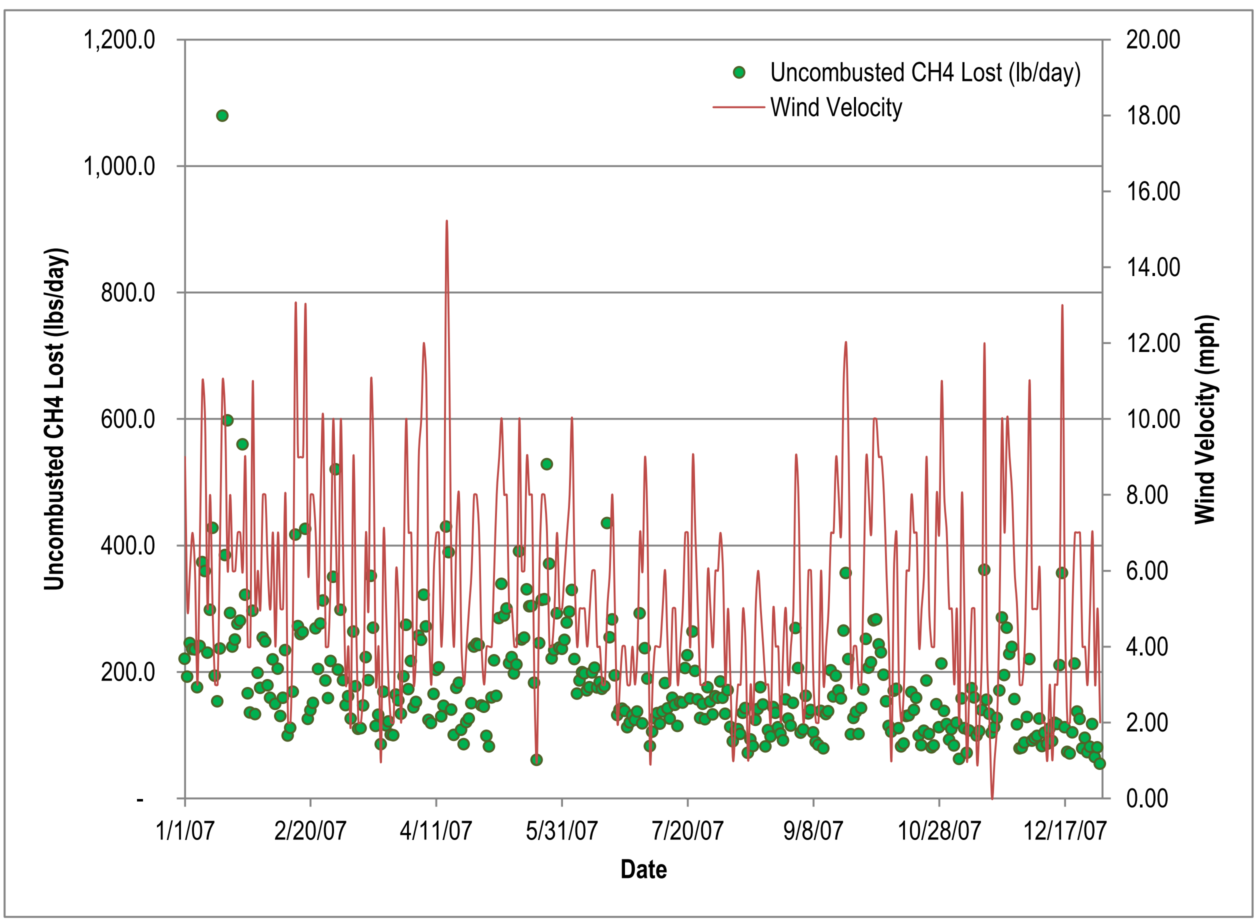


Figure 6-4. Flaring Efficiency and Uncombusted CH_4 Emissions and Wind Velocity at the WRRF Studied in Georgia (location name withheld).

For the two flares operating at the WRRF in Georgia, the flare efficiencies were calculated for each flare for each day of operation. Waste gas CH_4 concentration was assumed in the range of 55-70% and flare efficiency was assumed with prevailing wind conditions and flare jet velocity. Similar to the previous case study, the relative humidity of the digester gas was assumed as 95%.

Table 6-2. Flare Combustion Efficiency and Estimated CH_4 Emissions as a Function of CH_4 Content in Waste Gas for the WRRF Studied in Georgia.

CH_4 fraction in the waste gas (%)	Flare combustion efficiency (%)	Estimated CH_4 emissions (lb/year)	Estimated GHG emissions (CO2eq tons / year)
55	87.73%	125,790	1,429
60	91.83%	91,367	1,038
65	94.49%	66,796	759
70	96.24%	49,011	557

Note: Assumed gas temperature of 95 °F.

Based on the analyses of 2007 gas data using the FEE, the average efficiency of the flares operating at this plant was 94.5% assuming CH_4 and CO_2 fractions of 65% and 34%, respectively. At this efficiency, nearly 1.7 million cubic feet or 66,800 lbs. of uncombusted CH_4 escaped in the atmosphere from the candlestick flares at this site. Using the EPA AR-42 method (99% efficiency assumption), the total emissions were estimated to be only 12,000 lb/yr which underreports the GHG by nearly 621 MT CO_2e per year.

CHAPTER 7.0

CONCLUSIONS

The flaring efficiency depends primarily on three key parameters: the CH_4 fraction in the waste gas, the flare jet velocity, and the wind speed. Simply assuming a near-complete combustion under all operating conditions or 99% flaring efficiency per EPA AP-42 can lead to considerable underreporting of the GHG.

As indicated in the two case studies, a significant mass of CH_4 can escape into the atmosphere due to inefficient combustion at candlestick flares. Results from the two case studies are summarized in Table 7-1. Furthermore, the differences between the calculated flaring efficiency using the FEE and the assumed 99% flaring efficiency per EPA AP-42 were approximately 649 MT CO_2e/year and 621 MT CO_2e/year for the Tennessee and the Georgia case studies, respectively.

Table 7-1. Summary of Estimated GHG Emissions from Flares Using the Flare Efficiency Estimator from the Case Studies.

	Average gas flared	CH_4 fraction	Overall flaring efficiency	Estimated total fugitive GHG emissions from flares	
Case Study	(ft^3/day)	%	%	as lb of CH_4 emitted / year	as MT CO2e/yr
WRRF Studied in Tennessee	203,675	70%	95.5%	72,597	837
WRRF Studied in Georgia	132,679	65%	94.5%	66,796	759

The FEE helps estimate the flaring efficiency and provides an opportunity to optimize the flaring operation based on the prevailing ambient conditions as well as to estimate the fugitive GHG emissions in the form of uncombusted CH_4.

Flaring efficiency could be greatly improved if one or more of the critical operational parameters for the flaring operation can be managed. FEE provides an opportunity to evaluate each parameter independently and predict its impact on the flaring efficiency. For example, if the flares are enclosed at the Tennessee WRRF to prevent the wind from impacting the flaring operation, the flaring efficiency improves to 97.2%. This minor change could reduce the GHG emissions by 320 MT CO_2e/yr in the form of uncombusted CH_4 reaching the atmosphere.

Appendix A

THE FLARE EFFICIENCY AND EMISSIONS ESTIMATOR

FLAREVersion12.07.13 created by: M.D. Checkel and D.I. Handford

Link to download FEE tool.

http://www.nyserda.ny.gov/Commercial-and-Industrial/Sectors/Municipal-Water-and-Wastewater-Facilities/Final-Reports-for-Water-and-Wastewater-Technology-and-Demonstration-Projects.aspx.

FLARE VERSION 12.07.13

THE FLARE EFFICIENCY AND EMISSIONS ESTIMATOR

D.I. Handford and M.D. Checkel, July 13, 2012

FLARE MODEL MOTIVATION

Landfill and digester gases produced by organic decomposition are traditionally flared to avoid explosive buildups and reduce health/odor concerns and greenhouse gas impact. Past practice was to assume flare efficiencies of 98% or greater [1] based on testing under ideal conditions. More recent research [2,3] links flare efficiency to flame stability which depends on flare gas energy content, flare stack diameter, exit speed and ambient wind speed. The *Flare* software model estimates the efficiency and emissions of flares based on both flaring and ambient conditions.

FLARE INPUTS

Three types of inputs that must be specified: the flare gas composition, the flare conditions, and the ambient conditions. The *FLARE* model accepts the following parameters:

1. For flare gas composition, (ie. the gas composition on a dry gas analysis basis):
    a. Methane (CH_4) content,
    b. Carbon dioxide (CO_2) content,
    c. Oxygen (O_2) content;
    Nitrogen (N_2) content is automatically adjusted to balance the composition,
    d. Flare gas humidity, (usually assumed saturated, ie 100%)
    e. Flare gas temperature.
2. For flaring conditions:
    a. EITHER flare jet speed OR volume flow rate,
    b. Flare stack internal diameter.
3. For ambient conditions:
    a. Barometric pressure,
    b. Wind speed.

The input parameters must combine to produce a reasonable range where the flare could hold a stable flame. When input parameters would give an unstable flame, the *FLARE* program issues warnings and then resets input values to the default values. The input limits are shown in Table 1.

Some flare gas compositions that satisfy limits for each component would still give a heating value too low to burn with a stable flame. If the flare gas heating value is too low, the model issues a warning and resets the composition to default values.

If you specify flare volume flow rate, the flare gas jet speed calculated using the flare stack diameter must satisfy the limitations in Table 1. To prevent resets due to too-high jet speed, you might need to set the flare diameter first before setting flare gas flow rate.

Table 1: Parameter units and limits for the Flare model.

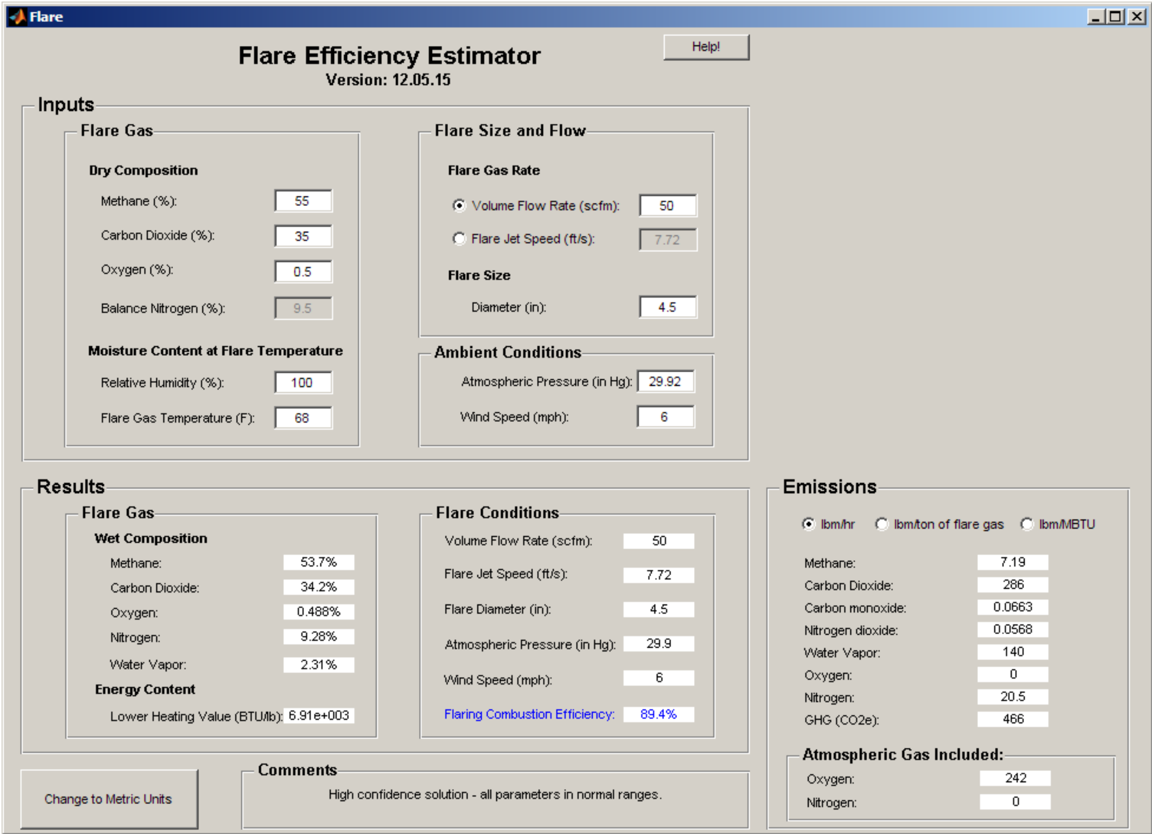
Parameter	SI Units		Standard Units	
	Lower Limit	**Upper Limit**	**Lower Limit**	**Upper Limit**
Flare gas CH_4 Content	40%	100%	40%	100%
Flare gas CO_2 Content	0%	60%	0%	60%
Flare gas O_2 Content	0%	60%	0%	60%
Relative Humidity	0%	100%	0%	100%
Flare Gas Temperature	-40 ˚C	70 ˚C	-40 ˚F	158 ˚F
Volume flow rate	*Limited by jet speed and flare size*			
Flare jet speed	0.25 m/s	4.25 m/s	0.82 ft/s	14 ft/s
Flare diameter	0.006 m	0.115 m	0.25 inches	4.5 inches
Barometric Pressure	75 kPa	125 kPa	22 inches Hg	37 inches Hg
Wind Speed	0 kph	18 kph	0 mph	12 mph
Lower Heating Value	10,000 kJ/kg	----------	4299 BTU/lb	----------

FLARE OUTPUTS

The *Flare* model opens with default values and immediately calculates and posts results. The results are updated anytime an input parameter is changed and the Enter or Tab key is pressed. Calculated results include the flare gas composition on a wet basis, a summary of the flaring conditions, and the estimated flare efficiency and emissions rates. The *Flare* model returns emissions in three user-selectable unit systems: a mass flow rate basis (lbm/hr or kg/hr), a flare gas basis ($lbm_{pollutant}$/short $ton_{flare\ gas}$ or $g_{pollutant}/kg_{flare\ gas}$), and an energy basis ($lbm_{pollutant}/MBTU_{flare\ gas}$ or $g_{pollutant}/MJ_{flare\ gas}$). A sample screenshot is shown in Figure 1.

FLARE MODEL BACKGROUND

Flaring efficiency is estimated based on the flare gas composition, flare gas velocity, cross-wind velocity, and flare diameter. Flaring emissions are then calculated assuming that flaring inefficiency is a result of fuel stripping, and that flared gases which are not stripped are oxidized to the same degree as high efficiency zero-crosswind flares. The efficiency calculation and the fuel stripping mechanism are based on the work of Kostiuk et al. [4]. The emission factors used for carbon monoxide and oxides of nitrogen are based on a report recommending an update to the US EPA's current emission factors [5]. Greenhouse gas emissions are calculated on an equivalent carbon dioxide basis using the UN IPCC's global warming potentials [6]. It is assumed that all oxides of Nitrogen emitted will ultimately react with atmospheric oxygen to form Nitrogen Dioxide (NO_2), and can therefore be reported as NO_2.



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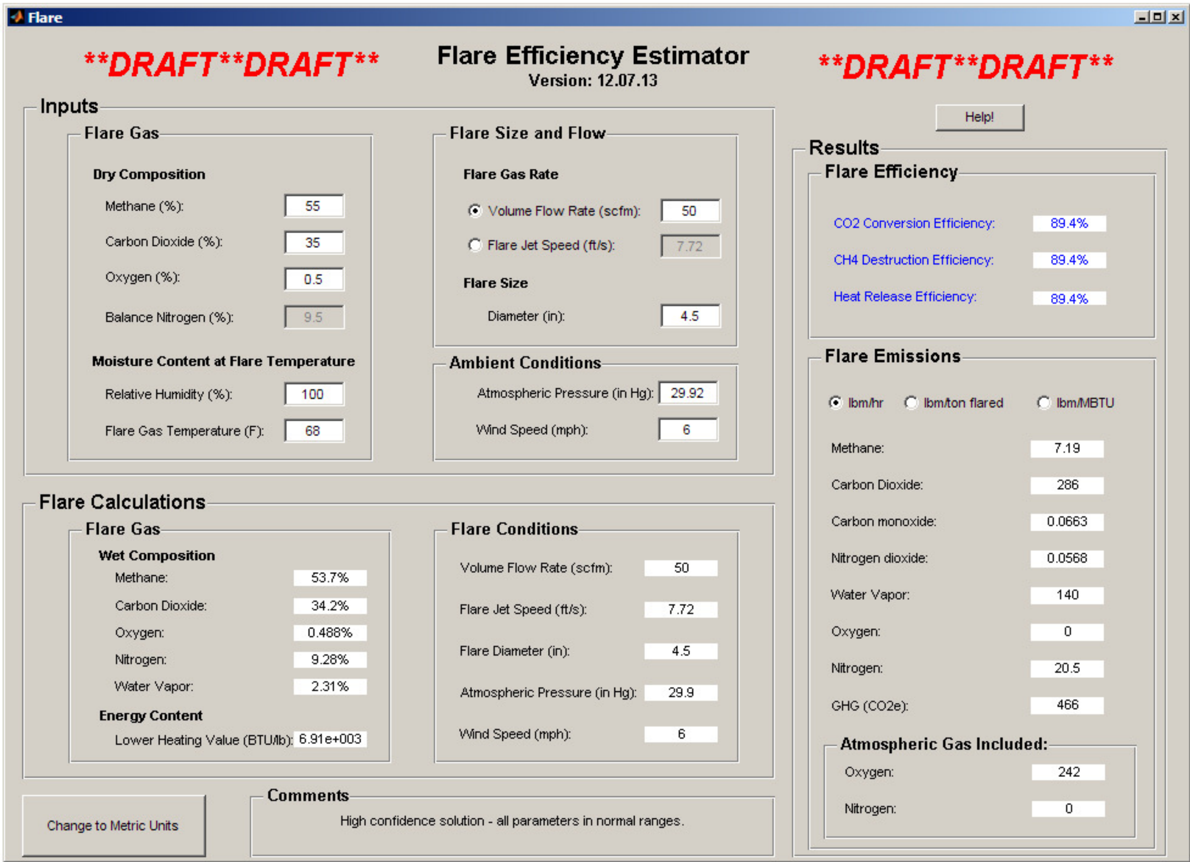
3. Bourguignon, E., Johnson, M. R., and Kostiuk, L. W. 1999. *The Use of a Closed-Loop Wind Tunnel for Measuring the Combustion Efficiency of Flames in a Cross Flow*.
4. Kostiuk, L., Johnson, M., and Thomas, G. 2004. *University of Alberta Flare Research Project: Final Report November 1996 – September 2004*. University of Alberta, Department of Mechanical Engineering, September 2004, 254 pages. Available online, last accessed March 27, 2012: http://www.mece.ualberta.ca/groups/combustion/flare/papers/Final%20Report2004.pdf
5. Eastern Research Group. 2008. *Background Information Document for Updating AP42 Section 2.4 for Estimating Emissions from Municipal Solid Waste Landfills.* Prepared by Eastern Research Group, Inc. for the United States Environmental Protection Agency Air Pollution Prevention and Control Division. Also known as EPA report number EPA/600/R-08-116.
6. 2007. *IPCC Fourth Assessment Report: Climate Change 2007 (AR4).* United Nations Intergovernmental Panel for Climate Change.


Flare
DRAFTDRAFT**
Flare Efficiency Estimator
Version: 12.07.13
DRAFTDRAFT**
Inputs
Flare Gas
Dry Composition
Methane (%): 55
Carbon Dioxide (%): 35
Oxygen (%): 0.5
Balance Nitrogen (%): 9.5
Moisture Content at Flare Temperature
Relative Humidity (%): 100
Flare Gas Temperature (F): 68
Flare Size and Flow
Flare Gas Rate
Volume Flow Rate (scfm): 50
Flare Jet Speed (ft/s): 7.72
Flare Size
Diameter (in): 4.5
Ambient Conditions
Atmospheric Pressure (in Hg): 29.92
Wind Speed (mph): 6
Help!
Results
Flare Efficiency
CO2 Conversion Efficiency: 89.4%
CH4 Destruction Efficiency: 89.4%
Heat Release Efficiency: 89.4%
Flare Emissions
lbm/hr lbm/ton flared lbm/MBTU
Methane: 7.19
Carbon Dioxide: 286
Carbon monoxide: 0.0663
Nitrogen dioxide: 0.0568
Water Vapor: 140
Oxygen: 0
Nitrogen: 20.5
GHG (CO2e): 466
Atmospheric Gas Included:
Oxygen: 242
Nitrogen: 0
Flare Calculations
Flare Gas
Wet Composition
Methane: 53.7%
Carbon Dioxide: 34.2%
Oxygen: 0.488%
Nitrogen: 9.28%
Water Vapor: 2.31%
Energy Content
Lower Heating Value (BTU/lb): 6.91e+003
Flare Conditions
Volume Flow Rate (scfm): 50
Flare Jet Speed (ft/s): 7.72
Flare Diameter (in): 4.5
Atmospheric Pressure (in Hg): 29.9
Wind Speed (mph): 6
Change to Metric Units
Comments
High confidence solution - all parameters in normal ranges.


FlareSI
DRAFTDRAFT**
Flare Efficiency Estimator
Version: 12.07.13
DRAFTDRAFT**
Inputs
Flare Gas
Dry Composition
Methane (%): 55
Carbon Dioxide (%): 35
Oxygen (%): 0.5
Balance Nitrogen (%): 9.5
Moisture Content at Flare Temperature
Relative Humidity (%): 100
Flare Gas Temperature (C): 20
Flare Size and Flow
Flare Gas Rate
Volume Flow Rate (scm/s): 0.025
Flare Jet Speed (m/s): 2.507
Flare Size
Diameter (m): 0.114
Ambient Conditions
Atmospheric Pressure (kPa): 101.3
Wind Speed (kph): 10
Help!
Results
Flare Efficiency
CO2 Conversion Efficiency: 89.3%
CH4 Destruction Efficiency: 89.3%
Heat Release Efficiency: 89.3%
Flare Emissions
kg/hr g/kg flared g/MJ
Methane: 3.5
Carbon Dioxide: 137
Carbon monoxide: 0.0318
Nitrogen dioxide: 0.0272
Water Vapor: 67.3
Oxygen: 0
Nitrogen: 9.87
GHG (CO2e): 225
Atmospheric Gas Included:
Oxygen: 116
Nitrogen: 0
Flare Calculations
Flare Gas
Wet Composition
Methane: 53.7%
Carbon Dioxide: 34.2%
Oxygen: 0.488%
Nitrogen: 9.28%
Water Vapor: 2.31%
Energy Content
Lower Heating Value (kJ/kg): 1.61e+004
Flare Conditions
Volume Flow Rate (scm/s): 0.025
Flare Jet Speed (m/s): 2.51
Flare Diameter (m): 0.114
Atmospheric Pressure (kPa): 101
Wind Speed (kph): 10
Change to Standard Units
Comments
High confidence solution - all parameters in normal ranges.

Flare Estimator Help - Standard Units

Flare Efficiency Estimator Help

Version: 12.07.13

The Flare Efficiency Estimator calculates the flaring efficiency of diluted methane flares based on correlations from an extensive flare research project [1]. Flaring emissions are calculated using the fuel stripping mechanism proposed by Kostiuk et al. [1], and with the emission factors described by Eastern Research Group [2]. The flaring conditions must fall within the following limits:

Parameter	Lower Limit	Upper Limit	Units
CH4 Composition:	40%	100%	
CO2 Composition:	0%	60%	
O2 Composition:	0%	60%	
Relative Humidity:	0%	100%	
Flare Gas Temperature:	-40	158	Fahrenheit
Volume Flow Rate:	Dependent on Jet Speed**		
Flare Jet Speed:	0.82	14	ft/s
Flare Diameter:	0.25	18***	inches
Atmospheric Pressure:	22	37	inches Hg
Wind Speed:	0	25****	mph
Lower Heating Value:	4299	--	BTU/lb

** The standard volume flow rate varies with jet speed, flare diameter, atmospheric pressure, relative humidity, and flare gas temperature. The limiting parameter is the jet speed - so the volume flow rate must produce a jet speed within the above limits at the given conditions.

*** The flare diameter upper limit is set at 18 inches. Experiments have only verified these results up to flare diameters of 4.5 inches.

**** The wind speed upper limit is set at 25 mph. The efficiency of flares in high crosswinds depends on flame stability and crosswinds higher than 12 mph may produce low-confidence solutions.

1. Kostiuk, L., Johnson, M., and Thomas, G. 2004. University of Alberta Flare Research Project Final Report. University of Alberta, Department of Mechanical Engineering. Available online, last accessed March 27, 2012: http://www.mece.ualberta.ca/groups/combustion/flare/papers/Final%20Report2004.pdf

2. Eastern Research Group. 2008. Background Information Document for Updating AP42 Section 2.4 for Estimating Emissions from Municipal Solid Waste Landfills. Prepared by Eastern Research Group, Inc. for the United States Environmental Protection Agency Air Pollution Prevention and Control Division. Also known as EPA report number EPA/600/R-08-116.

Exit

Flare Estimator Help - SI Units

Flare Efficiency Estimator Help

Version: 12.07.13

The Flare Efficiency Estimator calculates the flaring efficiency of diluted methane flares based on correlations from an extensive flare research project [1]. Flaring emissions are calculated using the fuel stripping mechanism proposed by Kostiuk et al. [1], and with the emission factors described by Eastern Research Group [2]. The flaring conditions must fall within the following limits:

Parameter	Lower Limit	Upper Limit	Units
CH_4 Composition:	40%	100%	
CO_2 Composition:	0%	60%	
O_2 Composition:	0%	60%	
Relative Humidity:	0%	100%	
Flare Gas Temperature:	-40	70	Celsius
Volume Flow Rate:	Dependent on Jet Speed**		
Flare Jet Speed:	0.25	4.25	m/s
Flare Diameter:	0.006	0.46***	meters
Atmospheric Pressure:	75	125	kPa
Wind Speed:	0	40****	kph
Lower Heating Value:	10,000	--	kJ/kg

** The standard volume flow rate varies with jet speed, flare diameter, atmospheric pressure, relative humidity, and flare gas temperature. The limiting parameter is the jet speed - so the volume flow rate must produce a jet speed within the above limits at the given conditions.

*** The flare diameter upper limit is set at 0.46 m. Experiments have only verified these results up to flare diameters of 0.114 m.

**** The wind speed upper limit is set at 40 kph. The efficiency of flares in high crosswinds depends on flame stability and crosswinds higher than 18 kph may produce low-confidence solutions.

1. Kostiuk, L., Johnson, M., and Thomas, G. 2004. University of Alberta Flare Research Project Final Report. University of Alberta, Department of Mechanical Engineering. Available online, last accessed March 27, 2012: http://www.mece.ualberta.ca/groups/combustion/flare/papers/Final%20Report2004.pdf

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Exit

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WERF Subscribers

WASTEWATER UTILITY

Alabama
Montgomery Water Works & Sanitary Sewer Board

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Glendale, City of
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Phoenix Water Services Department
Pima County Wastewater Reclamation Department
Tempe, City of

Arkansas
Little Rock Wastewater

California
Central Contra Costa Sanitary District
Corona, City of
Crestline Sanitation District
Delta Diablo Sanitation District
Dublin San Ramon Services District
East Bay Dischargers Authority
East Bay Municipal Utility District
Fairfield-Suisun Sewer District
Fresno Department of Public Utilities
Inland Empire Utilities Agency
Irvine Ranch Water District
Las Gallinas Valley Sanitary District
Las Virgenes Municipal Water District
Livermore, City of
Los Angeles, City of
Montecito Sanitation District
Napa Sanitation District
Novato Sanitary District
Orange County Sanitation District
Palo Alto, City of
Riverside, City of
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San Diego, City of
San Francisco Public Utilities, City and County of
San Jose, City of
Sanitation Districts of Los Angeles County
Santa Barbara, City of
Santa Cruz, City of
Santa Rosa, City of
South Bayside System Authority
South Coast Water District
South Orange County Wastewater Authority
Stege Sanitary District
Sunnyvale, City of
Union Sanitary District
West Valley Sanitation District

Colorado
Aurora, City of
Boulder, City of
Greeley, City of
Littleton/Englewood Wastewater Treatment Plant
Metro Wastewater Reclamation District
Platte Canyon Water & Sanitation District

Connecticut
Greater New Haven WPCA

District of Columbia
DC Water

Florida
Fort Lauderdale, City of
JEA
Loxahatchee River District
Miami-Dade County
Orange County Utilities Department
Pinellas County Utilities
Reedy Creek Improvement District
St. Petersburg, City of
Tallahassee, City of
Toho Water Authority

Georgia
Atlanta Department of Watershed Management
Augusta, City of
Clayton County Water Authority
Cobb County Water System
Columbus Water Works
Gwinnett County Department of Public Utilities
Savannah, City of

Hawaii
Honolulu, City & County of

Idaho
Boise, City of

Illinois
Greater Peoria Sanitary District
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Sanitary District of Decatur
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Unified Government of Wyandotte, County & City of

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Oregon
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Sullivan's Island, Town of

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Murfreesboro Water & Sewer Department
Nashville Metro Water Services

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Dallas Water Utilities
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Houston, City of
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Colorado

Aurora, City of
Boulder, City of

Florida

Orlando, City of

Iowa

Cedar Rapids Water Pollution Control Facilities
Des Moines, City of

Kansas

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Washington

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