

Technical Guidance Document: Flaring

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Technical Guidance Document: Flaring

Version 2.0

1 Definitions

A number of terms related to specific aspects of gas flaring are used throughout this document. Following is a list of terms and definition.

Assisted flare	Flare where air or steam is intentionally introduced into the flame. It is typically used with the intention of improving mixing, to favor efficient combustion and reduce smoke, or for protection of the flare tip. Hybrid systems in which an assisted tip is adjacent to an unassisted flare are considered assisted flares. Endothermic flares are excluded.
Batch flaring	As a subset of non-routine flaring, batch flaring involves the intermittent or periodic combustion of fixed gas volumes. This practice is typically employed during specific midstream and downstream operations, using portable flares.
Combustion efficiency (CE)	Fraction of carbon in the fuel stream that is converted to CO ₂ . See Box 1 for more detailed definition.
Destruction removal efficiency (DRE)	Fraction of a given species that is destroyed or converted in the combustion system. See Box 1 for a more detailed definition.
Enclosed flare	Gas combustion system situated within an enclosed structure, which shields the flame from wind interference, improving combustion stability and efficiency.
Flare	A combustion system used to safely dispose of gas via controlled burning. Types of flares considered in this document include open flares (single or multiple tip), multiple point ground flares, enclosed flares, combustors for gas management, and portable flares.
Flaring	Process or intent to combust gas sent to the flare tip.
Flare pilot	System used to keep the flare ignited. It typically consists of a small volume of gas fed continuously to a dedicated pilot tip, burning adjacent to the main flare, to ensure the gas sent to flare is ignited as it reaches the flare tip.
Flare under ignition surveillance	Flares equipped with a continuous or regular ignition surveillance system (e.g. camera filming flare tip connected to an alert system, thermo-couple monitoring system of the pilot flame connected to an alert system, auto-ignition system), or operator checking the flare is continuously lit while in operation (gas flowing to the flare, with the intention of combusting the gas). The chosen surveillance system should be effective and appropriate for the specific flare type and operating conditions. Predictive monitoring of combustion performance (CE/DRE), upstream of the flare tip and without flame-out detection, does not qualify as ignition surveillance under this TGD.
Lit flare	A flare actively combusting gas at the flare tip. Depending on the destruction removal efficiency, a share of the gas (methane slip) remains unburned, leading to methane emissions in the exhaust gases released to the atmosphere.
Measurement	Physical detection of a quantity (e.g., concentration, flow, DRE or emissions) by an instrument.
Quantification	Determination of an emission rate or amount (e.g., combination of measurement data with a method such as atmospheric dispersion modelling).
Unassisted flare	Flare where no auxiliary air or steam is intentionally introduced into the flame to assist combustion. Oxygen needed for combustion exclusively comes from ambient air. This excludes routine operational gases such as purge gas and pilot fuel.
Unlit flare	Flare stack where no ignition occurs, and thus the gas sent to the flare stack is emitted uncombusted.

Unsurveilled flare	Flares not equipped with a continuous or regular ignition surveillance system (e.g. camera filming flare tip connected to an alert system, thermo-couple monitoring system of the pilot flame, auto-ignition system), or no operator checking the flare is continuously lit while in operation.
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2 Brief description of the source

The typical flare system consists of (1) a gas collection header and piping for collecting gases, (2) a knockout drum (dis-entrainment drum) to remove and store condensable and entrained liquids, (3) a seal or a water seal, and purge gas supply to prevent flash-back, (4) a single- or multiple-burner unit and a flare stack, (5) gas pilots and an ignitor to ignite the mixture of waste gas and air, and, if required, (6) assist systems (steam or air) for smokeless flaring. Other types of flares exist, such as multiple point ground flares, enclosed ground flares, combustors for gas management and portable flares, which have different configurations but serve the same purpose of combusting waste gases.

The flare system, together with the pressure relief system forms a critical part of the safety system and is designed to prevent escalation of accidents and dangerous situations, as well as reduce vented methane emissions to the atmosphere, through combustion. It is also used for the elimination of waste gas (i.e. gas from the process which is not recovered, such as flash gases from low pressure systems or compressor seal gas) and reduce exposure of personnel to harmful or toxic components.

Flaring, aside from portable flaring, is rarely used in gas transmission and distribution systems.

Methane emissions from flares can arise for different reasons:

- Unlit flare: when a flare is unlit, all gas sent to the flare is emitted uncombusted (see definition above). Typical causes may include, but not be limited to, malfunction of the flare pilot, wind conditions, fuel mixtures outside the flammability limits (snuffing), failure of an auto-ignition system, delay/failure in operating the manual ignition system, and malfunction in the flame front generator system.
- Lit flare: even when a flare is lit, a portion of the methane in the fuel is not combusted (i.e., incomplete combustion/methane slip), resulting in the presence of methane in exhaust gases released to the atmosphere.

3 Scope boundaries

This TGD applies to all sources of methane emissions related to the incomplete combustion of waste gas as it is combusted in either a flare, enclosed flare, thermal oxidizer or combustor, where there is an intention to combust the gas, whether the device is **lit¹** or **unlit²**.

Emissions within the scope of this TGD should be reported as follows:

- In the **mid/downstream** reporting template:
 - o 'Incomplete combustion' > 'Flaring' for both lit and unlit flares.
- In the **upstream** reporting template³:
 - o 'Flaring (Incomplete Combustion)' for lit flares.

¹ Share of methane in waste gas which is not combusted through flaring.

² The full gas stream remains unintentionally unlit and thus is emitted to the atmosphere.

³ Note – Companies should provide justification on the methodology used to report flaring emissions (both in lit and unlit states) in their implementation plan.

- 'Unlit Flaring' for unlit flares.

The following emissions sources are **outside** the scope of this TGD:

- Incomplete combustion emission sources not associated with flaring: emissions from incomplete combustion in devices whose purpose is to generate heat, power, or mechanical work.
 - > These sources are covered in the *Incomplete combustion TGD*, and should be reported accordingly.
- Venting emission sources: emissions that are released through the flare stack without the intention of combusting the gas (intentional vent through the flare stack).
 - > These sources are covered in the *Purging and venting, starts and stops and other process and maintenance vents TGD*, and should be reported accordingly.

Guidance on materiality is presented in the *General Principles TGD*.

4 Level 3 Quantification Methodologies

The following equation and parameters provide a recommended approach for Level 3 quantification (if the data is available, one or two of the parameters can be quantified using Level 4 quantification methodologies, however, to qualify as Level 4 estimate, all three parameters should comply with Level 4 requirements – see section below):

$$CH_4 \text{ emissions} = \text{Gas flow to the flare}_{\text{measured or calculated}} \times CH_4 \text{ content}_{\text{measured or calculated}} \times (1 - CH_4 \text{ Destruction Removal Efficiency}_{\text{generic}})$$

Parameter	Description
Gas flow to the flare	Measured or indirectly determined using a mass balance or engineering calculations.
Gas composition/methane content	Measured or indirectly determined using a mass balance or engineering calculations.
Methane destruction removal efficiency ⁴	Default methane Destruction Removal Efficiency (DRE) values. Combustion Efficiency (CE) can also be used in place of the DRE⁵. Practitioners should select methane destruction removal efficiency (DRE) values that are representative of the flare type, operating conditions, and monitoring practices, and are supported by an appropriate reference source (e.g., regulatory guidance, literature, manufacturer specifications, engineering estimates, or other defensible basis). In the absence of facility-specific data or a more representative reference, practitioners may apply conservative reference values derived from widely recognized industry practices and literature. These values are intended to support consistency in reporting while maintaining flexibility for operators to apply more representative assumptions where justified.

⁴ Companies are advised to practice caution when searching for methane destruction efficiencies in the literature and/or manufacturer specifications as annual and instantaneous values are often, mistakenly, used interchangeably. This can lead to omitting emissions from unlit states. For example, if the instantaneous methane destruction efficiency of a lit flare is 98% and 6% of the annual amount of flared gas escaped when it was unlit, the effective annual destruction efficiency is roughly 92%, leading to a factor of four difference in the reported emissions.

⁵ Note that CE does not account for partial combustion and therefore may overestimate methane emissions compared to using the DRE.

	For example: - For flares where ignition assurance and monitoring practices provide confidence that the flare is operating as intended for the majority of the reporting period, methane DRE values of 98% have been widely applied in industry and regulatory frameworks. - For flares where continuous or systematic assurance of ignition is not available, lower effective annual DRE values on the order of 92% may be appropriate to account for the potential occurrence of unlit or suboptimal combustion events that may not be fully detected. Where such reference values are applied, no additional justification is required beyond documenting the selected value and its basis within the operator's methodology. Operators may apply alternative DRE values where these are supported by: - regulatory requirements, - manufacturer specifications, or - relevant literature (e.g., API compendium, government programs, or peer-reviewed studies), provided that the selected value is appropriately justified and documented. For any periods of confirmed unlit flaring, a DRE of 0% shall be applied.
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Accepted emissions quantification methodologies, as detailed in the *General Principles TGD*, or those prescribed by local regulation are considered as providing Level 3 estimates, provided they are specific for the source type and consider gas flow, gas composition and methane DRE. Practitioners should use quantification methodologies that best represent conditions and practices at their facilities and adjust the estimation methods, where warranted, to more accurately estimate emissions given differences between the reference system on which the methodology is based, and their systems.

Box 1 - Combustion efficiency vs. destruction removal efficiency⁶

The performance of a flare can be evaluated through the determination of the combustion efficiency or the destruction removal efficiency of a specific combustible species (for example, methane) in the fuel stream.

The **combustion efficiency** (η) – or carbon conversion efficiency, - is usually defined as the fraction of carbon mass in the hydrocarbon fuel stream that is fully reacted and converted to carbon dioxide. The combustion efficiency is not directly related to methane emissions.

$$\eta = \frac{\text{mass of carbon in produced } CO_2}{\text{mass of carbon in hydrocarbon fuel stream}}$$

The **destruction removal efficiency** – or destruction efficiency - of a species i (DRE_i) is defined as the fraction of species i molecules that are destroyed or converted in a combustion system relative to the number of molecules of species i that entered the system.

$$DRE_i = \left(1 - \frac{\text{emission rate of species } i}{\text{flow rate of species } i \text{ in the fuel stream}} \right)$$

⁶ The equations are intended to clarify the definitions. They do not need to be directly used by Companies to calculate methane emissions from flaring.

For Level 3 and Level 4 reporting, CH₄ emissions can be calculated using **either combustion efficiency or methane destruction removal efficiency**, with the latter being preferable.

5 Level 4 Quantification Methodologies

This section presents the quantification methods considered for Level 4. Flaring emissions can be quantified through measurements and/or engineering calculations/process simulation.

Annual methane emissions can be quantified with direct measurements technologies, which allow methane emissions to be measured at the source, or by combining measurement and/or process simulation of the three key parameters: gas flow to flare, gas composition and methane Destruction Removal Efficiency (DRE).

Irrespective of the quantification approach used, all unlit flaring periods must be identified and quantified, either using direct measurement of methane emissions from unlit flares or applying a DRE of 0% , regardless of flare type.

Direct measurement of methane emissions from flares (including continuous or periodic monitoring) or emission factors derived from representative measured emissions are considered Level 4 emissions quantification.

If the chosen approach is determining the three key parameters (gas flow to flare, gas composition and methane DRE), flares are classified (during lit operations) as either **low-risk** or **high-risk**. This classification determines whether a default DRE value may be applied, or whether DRE must be established through direct measurement or engineering calculations. Both are described in detail in the DRE section below.

The methodology and associated details for each approach are described in the sections that follow.

Level 4 emissions quantification can be based on measurements conducted on **a representative sample** of flare systems, considering the flare configuration (flare type, flare size, gas composition, flow rate) and the range of operating and environmental conditions these flares can be subject to in order to determine 'like' systems. Each system that is not 'like' will require determination of a separate parameter value for that system based on appropriate measurement or modelling studies. Section 5.3 also highlights the importance of considering environmental and operational parameters for representativeness. For general guidelines on the methodology to develop a statistically representative sample of emission sources, companies can refer to the current guidance on sampling and extrapolation.

5.1 Quantification methods

5.1.1 Direct methane measurement technologies

A range of **technologies** can be used to obtain **measurements** of methane concentrations around a flare, including aerial platforms, ground-based systems (e.g., tracer-release setups), and other instruments equipped with specialised **sensors**. These technologies support different **methods** for interpreting the measured data and, where applicable, for **quantifying** methane emissions.

Two broad sensor types can be used:

- **Single-component sensor:** These sensors measure **only methane concentration**; coupled with wind data, a method is then used to quantify the emission rate from sources, including flares. When using

a single-component sensor, it is important to recognise that observed methane may originate from multiple sources at the site (e.g., other equipment, wellheads). The associated method must therefore include steps to distinguish flare-related methane from other potential sources.

- **Multi-component sensor:** These sensors measure **both methane and carbon dioxide concentrations**. This enables methods that analyse the correlation between methane and CO₂ originating from combustion processes. Such correlation analysis can support quantification of methane emissions from flaring and may also be used to infer DRE. However, the method must also account for the fact that correlation alone does not guarantee that methane and CO₂ originate from the same source.

Certain technologies are capable of directly resolving flare-specific emissions at source level can serve as a standalone quantification method, provided the operator has accounted for flare type, configuration, and operating status. These may include but are not limited to:

- Differential Absorption Lidar (DIAL)⁷
- LiDAR (aerial or ground-based)
- Tunable Diode Laser Absorption Spectroscopy (TDLAS)

These measurement technologies can also be used to inform or validate DRE assumptions. For example, where a dual sensor drone is deployed alongside known feed information such as flow rate and gas composition.

When members deploy such technologies for **site-level measurement** and reconciliation, the same technology may also be used for **flare-specific methane quantification** at Level 4, provided the two datasets are **independent**.

To accurately measure methane emissions at the source level from flares, it is important to isolate the flare's plume from other emission source plumes. This typically requires conducting measurements close to the flare to ensure the measurement captures only the emissions from that flare source. However, flares are often situated away from main facility operations or key processes, which naturally aids in isolating methane emissions from the flare.

Where a single equipment combines multiple flare tips (e.g. low- and high-pressure flare tips), measurements of the combined emissions from the comingled plumes can be taken, as current measurement equipment do not allow distinguishing between the individual plumes. The distance between the flare and the measurement equipment must be carefully considered to ensure that the entire plume is adequately captured. Additional consideration should be given to variations in operational configurations when multiple flare tips are combined within a single piece of equipment. However, when using calculation-based tools, models or CFD to determine methane emissions from flaring, these should be applied to the flare tips individually even when these are combined within a single piece of equipment.

5.1.2 Quantification based on determination of relevant parameters (flow rate, gas composition and DRE)

Measurements may be taken that represent the feed to the flare (total flow, associated methane content) and the methane DRE of each considered flare. It is recommended that measurements are based on representative flare systems and operating/environmental conditions described in Section 5.3.

⁷ Few, J. Review of Differential Absorption Lidar Flare Emission and Performance Data. Chief Scientist's Group report October 2019 Version: SC150026/R (HOEV151612 Task 1), Environment Agency: London UK, ISBN: 978-1-84911-434-9.

Engineering model simulations based on measured parameters (e.g. GOR, gas composition), representative of current operating conditions, that capture one or more of the aspects necessary to quantify methane emissions from flaring (such as gas flow and/or methane DRE) are considered Level 4 emissions quantification. Measured parameters can be continuous or based on representative sampling.

Measurements and engineering model simulations can be used to determine methane emissions using the following equation and parameters, considered as providing Level 4 estimates.

$$CH_4 \text{ emissions} = \text{Gas flow to flare} \times CH_4 \text{ content} \times (1 - CH_4 \text{ Destruction Removal Efficiency})$$

Several methods can be considered to determine each of the parameters in the equation aligned with Level 4 principles. These methods are summarized in the table below, additional details on the different methods are presented below.

Parameter	Description
Gas flow to the flare	Continuous measurement, detailed engineering calculation or advanced process simulation based on measured parameters. For batch flaring (fixed volumes of gas sent to flare), engineering calculations taking into consideration pressure, volume and temperature.
Gas composition/ Methane content	Continuous measurement, advanced process simulation, or sample measurement/gas analysis. In cases where the methane content can be assumed to meet a regulated specification (e.g. underground gas storage, gas transmission, gas distribution and LNG terminals), the gas specification compositions may be applied ⁸ .
Methane destruction removal efficiency (DRE)	The following describes an acceptable step-by-step approach to quantifying the DRE of flares. 1. Unlit flaring consideration For all periods of unlit flaring, a DRE of 0% should be applied. If the flare is not under surveillance, operators are required to document their approach to identifying and accounting for unlit flaring periods in their implementation plan. 2. Risk classification during lit operations Flares are classified as low-risk or high-risk, which determines the quantification approach during lit operations. Justification and supporting documentation for the chosen approach should be included in the operator's implementation plan. <u>Low-risk flares</u> A flare is considered <i>low-risk</i> if it falls into one of the following categories: ○ The flare is enclosed⁹ ○ The flare is a portable unit used for batch flaring events (as described in Section 0)

⁸ For example, within the EU, regulated specifications and quality standards may be applied.

⁹ By design, enclosed flares are generally expected to achieve high combustion efficiency under normal operating conditions.

	○ The flare is a standard unassisted¹⁰ flare (fixed or portable) that is under ignition surveillance <u>and</u> where the lower heating value (LHV) of the gas sent to flare does not typically fall below 300 BTU/scf (11.18 MJ/scm)¹¹. Where the flare meets any of the above criteria, the following options can be applied for lit operations: ○ default DRE of 98% ○ manufacturer-specified DRE (where applicable and operating conditions are within design specifications) ○ DRE values required to be attained by regulation ○ DRE values derived from measurement or engineering or modelling approaches, such as described below, if available. If the flare does not meet any of the above criteria, it is classified as high-risk. <u>High-risk flares</u> For high-risk flares, methane DRE can be determined through either: ○ direct measurements ○ engineering calculations and modelling using parameters representative of the environmental and operational conditions experienced by the flare Where an asset has a combination of low-risk and high-risk flares, members are encouraged to prioritize measurement of high-risk flares.
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5.1.2.1 Quantification of gas flow to the flare

Gas flow to flare can be quantified through **direct measurements**, using widely accepted metering equipment¹², such as ultrasonic flow meters, thermal mass flow meters, or Pitot tube flow meters. If appropriate for the specific operating conditions, **engineering calculations** and **process simulation** based on measured parameters can also be used, with the chosen approach justified in the operator's implementation plan. Level 4 reporting approaches recognize that flares may accept gas from several sources within a facility, all at different flow rates, particularly during upset or emergency conditions. To account for this, a **mass balance approach** is deemed appropriate provided it is measurement based with the primary sources of gas to flare measured.

For batch flaring events (as described in Section 0), where a fixed volume of gas is sent to flare, a simple engineering calculation is appropriate to determine the volume of gas released from the equipment and then convert it to a mass. As a simple example of depressurizing a fully isolated system, the following calculation can be used to determine the volume of gas sent to flare:

$$V_r = V_i - V_f = V_i - \frac{P_i V_i T_f}{P_f T_i}$$

¹⁰ No air- or steam- assistance. Over-assisting can lead to a drop in methane destruction efficiency. (<https://pubs.acs.org/doi/full/10.1021/ie202675f>). Current studies and industry knowledge provide insufficient data and evidence to conclude that air- and steam-assisted flares present a sufficiently low risk of poor destruction efficiency. This could be revisited at a later stage as more data and industry knowledge is made available.

¹¹ Fluctuations in gas composition (LHV < 300 BTU/scf) could lead to reductions in methane destruction efficiency (<https://www.mdpi.com/2073-4433/15/7/800>).

¹² Additional information available from E. Estrada, *Flare measurement according to API 14.10*, no date, available at <https://asgmt.com/paper/flare-measurement-according-to-api-14-10-3/>

Where:

- V_r = the volume of gas released (i.e. sent to flare) as a result of equipment/system depressurization
- V_i = Volume of gas within the equipment/system prior to depressurization
- V_f = Volume remaining in the equipment/system following depressurization
- P_i = Initial pressure of the gas in the equipment/system to be depressurized
- P_f = Remaining pressure of the equipment/system (atmospheric pressure if fully depressurized)
- T_i = Initial gas temperature prior to depressurization
- T_f = Gas temperature in the equipment/system following depressurization

5.1.2.2 Determination of gas composition

Gas composition should be determined through direct measurements, using accepted sampling equipment and techniques. Following is a non-exhaustive list of such measurement solutions:

- Online analysis methods: gas chromatograph, Wobbe Index Analyzer (Calorimeter), Specific Gravity Analyzer (Relative Density)
- Gas sampling at regular interval
- Portable gas chromatography
- Dräger tubes
- Standard/regulatory gas composition
- Spectrometry (GC-MS, optical)
- Infer Molecular Weight (MW) from Speed of Sound (SoS)

In cases where the methane content can be assumed to meet a regulated specification (e.g. underground gas storage, gas transmission, gas distribution and LNG terminals), the gas specification compositions may be applied. For example, if direct measurement on the flare system is not feasible to install, measured **export gas composition** can be used as a proxy.

Where direct measurements is not feasible or where the composition of specific streams cannot easily be measured directly (e.g. tank vapors sent to flare from flash, working, and breathing losses), validated **process simulation** models (e.g. ProMax, HYSYS or equivalent) that are representative of actual operating conditions are acceptable, provided the approach is justified and documented in the operator's implementation plan.

5.1.2.3 Quantification of Methane Destruction Efficiency (DRE)

As defined in Section 5.1.2, for high-risk flares (or low-risk flares where the member has elected not to use a default value), DRE may be determined through direct measurements, engineering calculations, or process modelling. Modelling (parametric model, CFD) can also be used to assess the impact of adverse environmental conditions such as high winds on destruction removal efficiency. The sections below describe each of these approaches in more detail. Measured combustion efficiency factors may also be used, recognizing they will provide a conservative reported value compared to methane destruction removal efficiency. For general guidelines on the methodology to develop a statistically representative sample of emission sources, companies can refer to the current guidance on sampling and extrapolation.

5.1.2.3.1 Direct measurements

Following is a non-exhaustive list of emerging measurement techniques:

- Passive optical gas measurement systems:

- Optical infrared flare monitoring systems (including Video Imaging Spectral Radiometry (VISR) and dual-band infrared technologies)
Real time measurement of the flare combustion efficiency through the measurement of carbon dioxide and unburnt hydrocarbons concentrations of the flare. Such systems may also offer pilot flame monitoring.
- Passive Fourier Transform Infrared (PFTIR)
Measurement of the amount of carbon dioxide, hydrocarbons, and carbon monoxide. Specialist operators required: not suitable for long-term deployment.
- Active optical gas measurement systems:
 - Open-Path OP-FTIR

5.1.2.3.2 Calculation-based tools

Sensors measuring different types of parameters, such as temperature, can also provide useful data points for the quantification of methane DRE. However, to determine methane DRE, these parameters need to be processed using calculation-based tools.

Currently, several calculation tools are being developed based on ultrasonic flow meters, spectrometers, infrared cameras, or other existing measurements and provide combustion efficiency, methane DRE and/or gases (CH₄, CO₂) emissions.

Inputs required by such tools can be measured and include parameters such as gas concentrations, meteorological data (wind speed, wind direction, humidity, temperature...), information on the flare and flare gas metering system design (tip design, process conditions such as flow rate, pressure, temperature, gas density). Calculations can be conducted using input data representative of the different environmental and operating conditions a flare can be subject to. For guidelines on the methodology to develop a statistically representative sample of emission sources, companies can refer to the current guidance on sampling and extrapolation.

5.1.2.3.3 Process simulation models: numerical modelling

Process simulation models based on representative flare systems and operating/environmental conditions, validated by direct measurements and engineering calculations based on studies relevant to the flare condition can also be used to determine the methane DRE of the flare. Following are some examples of academic studies having conducted experiments, using wind tunnels, which have shown that waste-gas velocity at flare tip and external environmental factors (such as wind speed, atmospheric pressure, and relative humidity) have an impact on methane destruction removal efficiency. For example, the following **parametric model**¹³ can be used to estimate combustion efficiency in flares and CH₄ emission rates.

$$\eta = 1 - \frac{A * \exp\left(B * \frac{U_{\infty}}{(gV_j d_o)^{\frac{1}{3}}}\right)}{(LHV_{mass})^3}$$

Where:

η = carbon combustion efficiency

LHV_{mass} = lower heating value (MJ/kg) – can be calculated based on gas composition (as defined for Level 4 quantification).

A = fuel-dependent coefficient (for natural gas: 156.4 (MJ/kg)³, for propane- or ethane-based flare streams 32.06 (MJ/kg)³)

B = fuel-dependent coefficient (for natural gas: 0.318, for propane- or ethane-based flare streams 0.272)

¹³ Johnson, M.R. and Kostiuk, L.W., *A Parametric Model for the Efficiency of Flares in a Crosswind*, Proceedings of the Combustion Institute, 2002, *Experimentation carried out on flares from 0.5 to 2-inch burner diameters*.

U_{∞} = wind speed (m/s) – for batch flaring, average wind speed over the duration of the event from nearest meteorological historical reporting or forecast can be used

g = gravitational constant ($6.674 \times 10^{-11} \text{ m}^3/(\text{kg} \cdot \text{s}^2)$)

V_j = flare tip exit velocity (m/s) – Can be calculated based on measured gas flow to flare. For batch flaring, the average flare tip exit velocity can be calculated.

d_o = stack outside diameter (mm)

U_{∞} = wind speed (m/s) – for batch flaring, average wind speed over the duration of the event from nearest meteorological historical reporting or forecast can be used. For other types of flares, a statistically weighted average of efficiency taking into account widely varying wind conditions can be calculated using the following parametric dataset and model (e.g. weighted average of destruction efficiency based on historical meteorological data of wind speed)¹⁴

$$\bar{\eta} = \int_0^{\infty} P(U_{\infty}) \eta(U_{\infty}, V_j, D, HV) dU_{\infty}$$

Where

$P(U_{\infty})$ = probability distribution function of wind speed, U_{∞}

$\eta(U_{\infty}, V_j, D, HV)$ = efficiency of the flare as function of wind speed and operating parameters

This empirical model is derived from data for flares burning methane and propane with a diameter between 12.2 mm and 49.8 mm, flow velocity between 0.5 m/s and 4 m/s and wind speed between 2 m/s and 17 m/s, with fuel dilutions using CO_2 or N_2 up to 80% (by volume). There are currently no published studies demonstrating the applicability of these equations for flares which operate under different conditions. Results of extrapolating these equations to flares operating outside of empirical test boundaries will increase uncertainty of this source as part of the reconciliation exercise (Level 5).

5.1.2.3.4 Modelling: Computational Fluid Dynamics (CFD)

Quantitative analysis and verification of CFD models represents a valuable addition to physical measurements of emissions. CFD models need to be validated against relevant field data and the range of environmental conditions encountered at the facility.

CFD models are typically used for research purpose or to address a specific flare design challenge and are not used routinely by operators. Following is a non-exhaustive list of CFD models which can be used to complement measurements:

- Reduced combustion mechanism for C1–C4 hydrocarbons and its application in computational fluid dynamics flare modeling¹⁵
- Computational fluid dynamics modeling of laboratory flames and an industrial flare¹⁶
- Detailed Expressions and Methodologies for Measuring Flare Combustion Efficiency, Species Emission Rates, and Associated Uncertainties¹⁷

As with measurement, modelling may be performed for a representative sample of like systems and then applied to the larger population.

¹⁴ Johnson, M.R, Flare efficiency and emissions: Past and current research, Carleton University, 2008, https://globalmethane.org/documents/events_oilgas_20081203_oilgas-5Dec08_johnson.pdf

¹⁵ <https://www.tandfonline.com/doi/full/10.1080/10962247.2016.1268546>

¹⁶ <https://www.tandfonline.com/doi/full/10.1080/10962247.2014.948229>

¹⁷ <https://pubs.acs.org/doi/pdf/10.1021/ie502914k>

5.2 Duration of unlit flaring events

The duration of each unlit flaring event should be measured (Level 4) or estimated based on best available data (Level 3).

The time from the start of the event to its repair and verification should be considered to determine the duration. If the start of the event is unknown, to allow for an estimation of emissions, the previous inspection, when the equipment was functioning properly, can be considered as the start of the unlit flaring event.

If the start of the event can be clearly identified (e.g., triggers an alert at the facility, notification sent), a more precise estimate of when the unlit flaring event started can be used. For that purpose, predictive feedback and control systems can be installed. A continuous ignition surveillance linked to an alarm system can be implemented with for example an optical camera, a thermal imaging camera, a thermocouple – identifying low temperatures announcing a potential unlit flare or a flame ionization detection.

The methane plume of an unlit flare can also be detected with visual inspections. For example, an optical gas imaging camera such as the ones used for leak detection and repair (LDAR) activities can be used to detect uncombusted methane emitted through the flare tip.

5.3 Environmental or operational parameters that can influence flare performance

To assess the performance of the flare over time, and ensure annual emissions estimates remain conservative, members should be aware of potential environmental and operational parameters which can impact the methane destruction removal efficiency of the flare, irrespective of flare risk classification as defined in Section 5.1.2.

Environmental conditions and **operational parameters**, such as variation in the gas composition, flow, pressure, or flare tip condition (i.e. damage) can vary over time and play a significant role in the variation of methane DRE of a flare.

For example, wind speed and direction at the location of the flare and the exit velocity of the flare should be taken into consideration as these have an impact on the methane DRE of a flare. Flares that may be deemed more vulnerable to wind impacts include those located in areas with persistent high winds and where the exit velocity of the flare may be lower (e.g. low pressure flares, high pressure flares at pilot/purge flow rates). In such cases, engineering judgement and/or modelling can be used to consider the potential impact of high wind/low exit velocity scenarios on flare DRE and ensure any applied DRE remains conservative to assess annual emissions.

The parametric model in Section 5.1.2.3.3. above may facilitate investigation of the potential impact of wind speed and exit velocity on flare performance. However, as noted above, this model was derived from experiments on a limited sample of flare configurations and there are currently no published studies demonstrating the applicability of these equations for flares which operate under different conditions. Results of extrapolating these equations to flares operating outside of empirical test boundaries will increase uncertainty of this source as part of the reconciliation exercise (Level 5). It is anticipated that this guidance will be updated as further research is undertaken to understand the impacts of wind and exit velocity on flare DRE in wider upstream applications.

In addition, operational parameters such as variation in the gas composition, flow, pressure, or flare tip condition (i.e. damage) should be considered to ensure the DRE applied, and annual estimate of emissions, remains conservative for the full range of operating conditions for the flare. Gas composition variations due to presence of inert gases could lower the net heating value in the combustion zone (NHVcz), reducing the DRE; variations in assist flow relative to vent gas flow could lead to over-assist in assisted flares which could lower the NHVcz and the DRE; and environmental conditions could damage the flare tip leading to lower DRE. Engineering judgement and/or measurements, engineering calculations (using parametric models) or CFD simulations at the boundary operating conditions can be used to assess the impact of such parameters on flare DRE.

These considerations may be particularly important if reconciliation indicates a discrepancy in flare emissions.