Gas Flare Technology Assessment and R&D Recommendations

NETL Natural Gas Infrastructure
Field Work Proposal 1022424
Task 8: Emissions Mitigation in Industrial Gas Flares

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Executive Summary

The purpose of developing this report is to provide an assessment of gas flare technologies, with the intent of informing future high-impact R&D investments that can be used to realize significant reductions in methane and other greenhouse gas (GHG) emissions from U.S. oil and natural gas (ONG) operations.

Flares are devices used to dispose of gases not processed and sold as part of normal operations. Flaring occurs in a variety of industries, including ONG (up/mid/down-stream), landfills, and chemical plants. Gas flares represent a more attractive alternative to simply venting the gas, which contains a number of constituents with high global warming potential (GWP). The two primary causes for flaring are intermittent operational needs, such as pressure relief, blow-down, or bleed off, and economic reasons, such as a lack of gathering, compression, and sales infrastructure. The former is considered *non-routine* flaring, while the latter is *routine* flaring. Routine flaring is particularly problematic, as it generally includes greater volumes of gas and longer duration, representing a significant waste of resources in addition to contributing negatively to climate change through the release of GHGs.

Routine flaring continues to be a problem, with U.S. and global initiatives to ban it by 2025 and 2030, respectively. In comparing trends in flaring between the U.S. and globally, the most significant difference is in the distribution of flares. Globally, the main source of emissions tends to be large, continuous flares, while in the U.S., many flares are located within unconventional basins, consisting of smaller volumes of gas but a larger number of individual sources. This poses a challenge to monitoring and regulation in the U.S., as smaller flares tend to have diverse, varied compositions and flows, and operations lack economies of scale needed to implement advanced technologies for emissions mitigation.

Flare gas generally has a similar compositional makeup to natural gas, consisting of mostly methane, along with heavier C2-C5 hydrocarbons, and can also include sour gas compounds and inert gases. Its composition can vary considerably over time and by geographical location/basin. Associated petroleum gas (APG) is one type of natural gas which is often routinely flared due to its reduced quality compared to pipeline natural gas and abundance alongside high value oil deposits. In the U.S., the largest amount of flaring (natural gas and APG) occurs within the Permian, Bakken, and Eagle Ford basins.

Flaring is regulated at both the state and federal level, however regulations differ considerably depending on geography, industry, and estimated gas volumes. Federal regulations for gas flares in ONG operations are covered in CFR Title 40, Part 60 (e.g., OOOOa/b/c). In general, state and federal regulations require reporting for flare gas volumes above a certain threshold, including provisions for measuring and/or estimating various process parameters such as volume, composition, heating value, and destruction efficiency. In the absence of an independent measurement or manufacturer specified flare destruction efficiency, a value of 98% is assumed. Furthermore, there are provisions in many existing regulations to substitute engineering estimates for direct measurements, making the reliability of reported values questionable.

The U.S. Department of Energy (DOE) Energy Information Administration (EIA) and U.S. Environmental Protection Agency (EPA) collect and publish information on flared and vented gas volumes, which are considered process emissions rather than being aggregated with other fossil fuel combustion devices such as power plants and engines. In ONG operations, the largest flaring contributors tend to be on-shore production, gathering/boosting, and natural gas processing. On a process-source-specific basis, the largest flare-related contributors include acid gas removal units, *other* flare stacks, associated gas venting and flaring, and atmospheric storage tanks.

Recently, a number of studies noted significant discrepancies between EPA/EIA reported flare gas volumes and those measured through satellite, aerial, or ground-based techniques. A further consequence of these studies was identification of so-called "super emitters," consisting of unlit or poorly performing flares emitting large amounts of methane. The net result of these studies demonstrated an average flare destruction efficiency of ~91% with unlit flares and ~95% without, far below the EPA assumed value of 98%.

The good news is that at the end of 2023, the EPA adopted new federal regulations regarding methane and volatile organic compounds (VOCs) from ONG sources, 40 CFR 60 Subpart OOOOb and OOOOc. The OOOOb standards apply to new sites constructed after December 2, 2023, while OOOOc impacts existing installations. Both standards will limit routine flaring and require a demonstrated 95% methane and VOC reduction in flares. Finally, additional monitoring requirements are imposed to deal with unlit and poorly performing flares. Proposed regulations call out new sensor options and specificity, however the current OOOOb/c language does not mandate additional instrumentation.

Technology Assessment

A typical flare system generally includes a knockout drum, one or more flashback mitigation devices, the flare stack/body, a flare tip/burner, a pilot/ignition system, and a number of monitoring and measurement devices. The two main types of flares are elevated and ground level, with a third non-flare designation for the enclosed combustor. Elevated flares are most prevalent and are low cost, the primary benefits being a reduced footprint and isolation of the noise, heat, and visible flame emission from process and personnel. Elevated flares tend to implement the widest array of tip designs. These are generally separated by high and low pressure, with a loose delineation being ~14 psig. Low-pressure designs include mainly utility flares, which are the lowest cost and may or may not be considered smokeless. The biggest challenge in low-pressure flares is entraining sufficient amounts of air, since most flares are self-aspirated. The availability of increased gas pressures affords the use of more complex designs, including sonic, multipoint, staged, and Coanda. Ground flares are generally low-pressure offerings, consisting of an array of burner tips within a fenced region. Ground flares are most often staged, such that the number of active burner tips depends on gas volume. Falling under the same category are enclosed ground flares, which add a structure to shield the surrounding region from visible radiation, while also promoting natural draft by the rising buoyant post-flame gases. In cases where smokeless operation is required with low gas pressure, supplementary air, steam, or gas is used to increase air entrainment and mixing. Steam injection is most prevalent, as the additional momentum vs. air increases turbulence and entrainment. Basic designs include direct in-flame injection, while low-noise approaches inject far upstream to mitigate acoustics. Several novel approaches are beginning to emerge, including retrofittable high-pressure air injection. Enclosed combustors are generally more complex and implement technologies more similar to furnaces or industrial burners. Some are natural draft, while others may incorporate blowers. Extremely high destruction efficiencies can be realized in excess of 99.9%. For this reason, enclosed combustors are often used to dispose of VOCs and hazardous air pollutants (HAPs); however, this comes at significantly greater expense compared to traditional flares.

The technology behind knockout drums and flashback mitigation devices is primarily aimed at reducing system pressure drops. Knockout drums are generally simple devices, relying on gravitational dropout of undesired liquids and condensates. While simple, knockout drums do represent a sizeable capital and maintenance expense. Flashback mitigation can include both water/molecular seals and/or the use of narrow passages to impede flame propagation. Pilots and ignition are an important component to combatting unlit flares. Typically, a number of pilots are prescribed depending on the flare tip diameter, and continuous pilot operation is required through monitoring. Direct and flame-front ignition (initiated from the bottom of the stack) are implemented. While some include automatic re-light, many require manual intervention in the event of a pilot flame-out.

The technology surrounding monitoring and measurement varies widely. In some cases, for low volumes below EPA/DOE reporting thresholds, few or no direct measurements of volume, composition, heating value, and destruction efficiency might be made. Volume measurements are most prevalent, and currently the most cost-effective approach is the use of a thermal mass flow meter. The most sophisticated and high-cost method is ultrasonic, with main advantages being reduced pressure drop and less dependence on gas composition. Pressure-based methods or mechanical devices are less popular due to fouling and flow impedance. When composition is measured, it is most often done using a gas chromatograph (GC). Generally, this is not a continuous measurement, but rather is done once when gas begins to flow and is assumed to be constant thereafter (or done on a semi-regular, but not continuous basis). Calorimeters are sometimes used to directly infer heating value as opposed to a GC, though complete speciation by GC or similar provides the information needed to compute heating value. Spectroscopic means are less prevalent, but can also be used, including Fourier transform infrared (FTIR) or laser-based absorptive techniques. Destruction efficiency is rarely measured directly, though technologies are beginning to emerge that make this possible. Typically, a manufacturer's specified destruction efficiency for a given flare is used in conjunction with measured or estimated gas composition and volume to determine GHG volumes released. Recent developments in IR cameras and open-path FTIR have enabled direct quantification of GHG emissions and destruction efficiency, though these techniques remain challenging due to the open nature of most flares.

DOE has reported on the need for R&D for flaring alternatives. Many alternatives exist but may not currently be economically viable. These options may include practical alternatives such as compression and transport as compressed natural gas (CNG), conversion to electric power either through conventional internal combustion engines and generators or more novel solid oxide fuel cells, or expansion of gathering infrastructure within limited distances. Other, more novel alternatives requiring more R&D include small-scale conversion to value added products such as gas-to-methanal or gas-to-liquids plants. Such approaches require multifunctional catalysts and modular conversion equipment necessary to enable economic and efficient deployment. A number of ongoing DOE-funded research projects focus on technology such as advanced catalysts and microwave enhancements. It is noted that many of these new technologies are also impacted by variables impacting flare efficiency such as changes in flow rates and changes in gas composition.

R&D Recommendations

The following recommendations are made for high-impact follow-on research, and a more complete R&D roadmap is provided. Because of the unique distribution of flaring in the U.S., low-cost technology solutions should be prioritized to solve the problems outlined in the report below. A major finding has been that in many cases, technologies likely exist that could realize significant reductions in methane and other GHG emissions from flares, but they are not being implemented due to economic reasons and lack of regulatory requirements. The recommendations made in this report are consistent with prior DOE reports, showing a major need to improve the efficiency of existing flare technologies and reduce or eliminate routine flaring done for economic reasons.

A major driver for the specific R&D recommendations made is the recently adopted EPA OOOOb and OOOOc standards. Recommendations are broadly divided into information gathering, gas flare technology, and flaring alternatives. Information gathering includes the development of this whitepaper, conducting a flare technology operator survey or request for information (RFI), and development of a tool to navigate the complexities of the new EPA OOOOb and OOOOc regulations.

Flare technology development focuses in the near term on monitoring and re-light to address unlit and poorly performing flares, as well as measurement and reporting technologies. Combined with a reduction in routine flaring, these activities will result in a significant increase to the net destruction efficiency of flares in the field, as well as provide increased data that can be used to assess further improvement to flare performance. Two follow-on activities include development of low-cost retrofit technologies to ensure a field-verified >98% destruction efficiency compliance. Further increases to 99.5%+ would likely require more significant system-level developments, including the use of blowers and/or enclosed combustor designs. A cross-cutting component in the R&D recommendations is identification, development, and demonstration of flaring alternatives, primarily aimed at eliminating routine flaring and providing technology solutions to support the EPA OOOOb and OOOOc language.

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Nomenclature

ONG	Oil and natural gas
GHG	Greenhouse gas
GWP	Global warming potential
APG	Associated petroleum gas
CFR	Code of federal regulation
DOE	Department of Energy
EIA	Energy Information Administration
EPA	Environmental Protection Agency
VOC	Volatile organic compound
HAP	Hazardous air pollutant
GC	Gas chromatograph
FTIR	Fourier transform infrared
CNG	Compressed natural gas
DE	Destruction efficiency
DRE	Destruction removal efficiency
CE	Combustion efficiency
IEA	International Energy Agency
ZRF	Zero routine flaring
Bcm	Billion cubic meters
Mcf	Million cubic feet
GHGRP	Greenhouse gas reporting program
LNG	Liquified natural gas
UT	Uita (basin)
DJ	Denver-Julesburg (basin)
TOC	Total organics
GHGI	Greenhouse gas inventory
NOAA	National Oceanic and Atmospheric Administration
VIIRS	Visible infrared imaging radiometer suite
EDF	Environmental Defense Fund
TRRC	Texas Railroad Commission
LHV	Lower heating value
HHV	Higher heating value
NHV	Net heating value
LFL	Lower flammability limit
UFL	Upper flammability limit
GOR	Gas to oil ratio
CEMS	Continuous emissions monitoring system

BTEX	Benzene, toluene, ethylbenzene and xylene
ECD	Enclosed combustion device
HIS	Hyper-spectral imager
CFD	Computational fluid dynamics
API	American Petroleum Institute
ISO	International Organization for Standardization
NFPA	National Fire Protection Association
NEC	National Electric Code
UL	Underwriters Laboratories
CSA	Canadian Standards Association
BTU	British thermal unit
SCF	Standard cubic feet
CFM	Cubic feet per minute
FPM	Feet per minute
TDLAS	Tunable diode laser absorption spectroscopy
IR	Infrared
UV	Ultraviolet
MWIR	Mid-wavelength infrared
MS	Multi-spectral
IFTS	Imaging Fourier transform spectrometer
TCMR	Thermochemical manifold reduction
TRL	Technology readiness level
OAS	Oxidative aromatization system
MTM	Methane to methanol
NETL	National Energy Technology Laboratory
CRADA	Cooperative research and development agreement
EOR	Enhanced oil recovery
SOFC	Solid oxide fuel cell
GTL	Gas to liquids
NGL	Natural gas liquids
ARPA-E	Advanced Research Projects Administration – Energy
REMEDY	Reducing Methane Emissions Every Day of the Year
SABRE	Systems of Advanced Burners for Reduction of Emissions

Introduction

Flares are devices used by the oil and natural gas (ONG) industry (among others) to dispose of gases that are not processed and sold as part of normal operations. Flaring generally occurs either due to intermittent operational needs (such as pressure relief, blow-down, or bleed-off) or a lack of gathering, compression, and sales infrastructure [1]. Gas flares represent a more attractive alternative to simply venting the gas, which contains a number of constituents with high global warming potential (GWP). This most notably includes methane (GWP~27-30 [2]), but NO2, (GWP~273 [2]), CO2, and heavier hydrocarbons may also be present in significant quantities [3]. Flaring and venting are estimated to waste ~8% of global natural gas production annually, and contribute ~6% of global greenhouse gas (GHG) emissions [4]. Importantly, the gas composition can vary considerably between industries, individual sites/operations, and can, over time, present a major challenge both to regulators and industry in terms of mitigation strategies and technologies.

In the U.S., flaring is primarily regulated at the state level, with limited federal law surrounding gas flare monitoring and measurement practices as defined in the various titles, parts, and subparts of the Code of Federal Regulation (CFR) Part 40 [5–10]. Federal regulations vary depending on the industry type and estimated emissions level. State regulations also vary dramatically, even with specific focus on oil-and-gas-related flaring. While venting or flaring is restricted by state law, various exemptions exist that enable both short-term and long-term use of flares.

The practice of flaring spans numerous industries, scales, and geographic localities around the globe. According to the World Bank [11], as of 2021, the largest flaring volumes (in order) were emitted by Russia, Iraq, Iran, the U.S., Algeria, Venezuela, and Nigeria. While the U.S. ranks as one of the top emitters, the distribution of flaring operations differs from its international counterparts. In Russia, Iraq, Iran, Algeria, Venezuela, and Algeria, the main source of emissions tends to be large, continuous flares, while in the U.S., many flares are located within unconventional basins (shale or tight formations), consisting of small volumes of gas, but a large number of individual wells [12]. This presents a particular challenge in the U.S., as these smaller flares tend to have highly variable flows and compositions and lack the economies of scale benefiting larger operations. Critically, the technologies implemented are driven by regulations, reporting requirements, and oversight.

The primary focus of this report is an analysis of the technologies surrounding gas flares. Specifically, an examination of the systems, components, and instruments in-use within the U.S. and how these devices and approaches are driven by regulatory framework and economics. In 2019, a comprehensive report was written by the U.S. Department of Energy (DOE) [1], which provided an overview of regulations and policies surrounding gas flares. As such, only a cursory overview of those topics will be provided here, including updates to pending legislation in [1].

This report is organized into sections outlining flaring and venting practices in the U.S. oil and gas industry, a detailed examination of gas compositions and their potential environmental impacts, an overview of U.S. regulatory policy surrounding flared and vented gases, and a detailed look at gas flare technology. The report concludes with an overview of flaring alternatives, followed by technology needs and R&D recommendations.

Flaring and Venting in U.S. ONG Operations: Trends and Background Information

Flaring and venting occurs as a normal part of oil and gas extraction in the U.S. and worldwide (see **Figure 1** through **Figure 3**). In general, this occurs due to operational/safety reasons or as a result of economic factors. Operational/safety reasons for flaring include diversion and disposal of gas influx (kick) during drilling, gas production during well testing, and flow-back gas during well completion [1]. Additionally, flaring can occur during maintenance operations, as gases must be diverged from compression/processing equipment, or during routine operation of equipment at an oil or gas processing facility (including gas required to maintain the flare system in a safe and ready condition – purge/make-up/fuel gas [13]).

Flaring for economic reasons tends to have a greater overall impact due to the volumes of gas involved and the duration of flaring operations. The principal driver here, is a lack of gathering, compression, and sales infrastructure [1], or suitable capacity in existing infrastructure [13]. This may be due to economics requiring early production in advance of completion of such infrastructure, or the gas may have a ready market, but the construction, installation, or expansion of such infrastructure is not economic [1]. The latter has the potential to be the most impactful, as it could mean sale-able gas is flared over the lifetime of the well. It should also be noted that this can include transient events during which time gas volumes exceed the capacity of the take-away infrastructure, requiring it to be flared [13].

Figure 1. Flare burning natural gas from a well in the Permian Basin, from [15].

Figure 2. Flare burning natural gas from a well in the Permian Basin, from [15].

Figure 3. A flare for burning excess methane from crude oil production is seen at a well pad east of New Town, North Dakota in 2021 (Matthew Brown / Associated Press), from [17].

From an environmental perspective, venting is always considered less favorable compared to flaring due to the presence of gas compounds with greater GHG potential (e.g., CH_4 vs. CO_2 ~25-80x worse [14]). However, intentional and unintentional venting still occurs. These are primarily intermittent, component-level release events or emergency situations. In the case of the former, this constitutes small gas volumes that are difficult to capture and route to dedicated flares or capture systems, including [1] blowdown from gas processing equipment, pipelines or compressors prior to repairs, bleed-off during routine operation of valves and level controllers, routine emission from pneumatic pumps, leakage from compressor seals, fugitive emissions from equipment leaks, and gas loss during loading/unloading operations (see **Figure 4**). In the case of the latter, these release events are primarily due to system upset or pressure relief emergency [1].

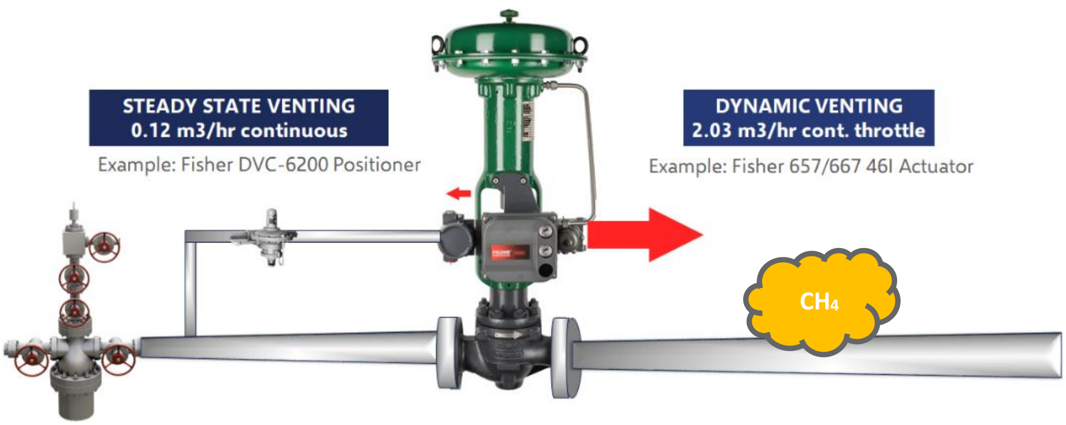


Figure 4. Example of CH4 venting from a gas-driven pneumatic device, modified from [18].

A second designation of non-safety flaring activities is routine vs. non-routine, which are terms used by global organizations such as World Bank and the International Energy Agency (IEA). Non-routine flaring includes intermittent and short-duration processes such as temporary failure of system components, startup/maintenance/construction activities, and exploration, appraisal, and well testing [13]. Routine flaring includes oil/gas separators, process units, and instances of production exceeding infrastructure capacity [13].

There is a global push to ban or eliminate routine flaring — supported by the Zero Routine Flaring (ZRF) initiative, which seeks commitments by governments and oil companies to eliminate routine flaring practices by the year 2030 [14]. In 2019, the IEA estimates around 150 billion cubic meters (bcm) of natural gas was flared globally, representing ~25% of gas extracted [12]. Of the total gas flared globally, ~⅔ constitutes routine flaring [12]. In the U.S., Colorado, New Mexico, and Alaska currently have bans on routine flaring, and an accelerated timeline is proposed for the remainder of the country (ZRF25 Permian [19]), eliminating routine flaring as soon as 2025. Both initiatives have significant support by governments and oil and gas companies.

The economics of flaring vs. capture and sale are complex and require consideration of expected gas volumes and composition, as well as the expense of gathering/compression equipment and infrastructure developments. Secondary considerations also include proximity of pipelines and capacities, gas prices and risk, additional operation costs associated with gas production/processing, land acquisitions/right-of-ways, and current/future regulations [1].

The Energy Information Administration (EIA) projects U.S. oil and gas production and exports to continue to increase through 2050 [20]. As discussed above, gas flaring goes hand in hand with oil and gas operations.

In the U.S., large volumes of associated petroleum gas (APG), a form of natural gas found alongside oil deposits, are extracted [21]. While much of the APG produced in the U.S. is processed and sold into natural gas distribution networks, significant volumes are flared. Flaring of APG can be driven by the economics of storage and transport relative to the volumetric energy density of the product (i.e., liquid oil/petroleum vs. wellhead gas) [21], as well as availability of required infrastructure. According to the IEA [12], the U.S. marketed 251 bcm of APG in 2019, while 41 bcm was reinjected or used on-site, 23 bcm was flared, and 7 bcm was vented (or fugitive). As shown in **Figure 5**, a majority of APG production occurs in the Permian, Bakken, Eagle Ford, Niobrara, and Anadarko basins [22,23]. Of specific concern are the Permian and Bakken basins, where flaring has increased in recent years due to a lack of sufficient gas gathering and transportation infrastructure [22,23].

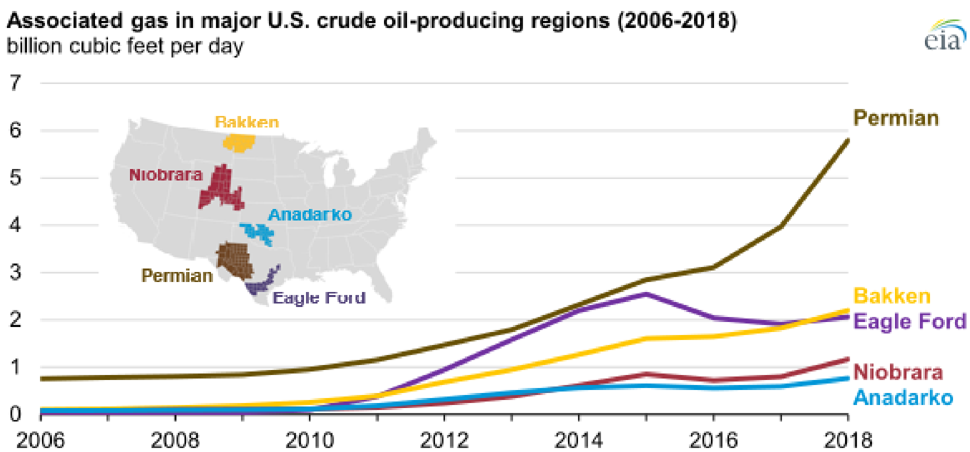


Figure 5. Volumes of associated gas produced, by region, from [23].

Other forms of natural gas are also flared, typically in smaller operations relative to APG flares. Examples include contributions from storage and transport of oil and gas, natural gas production and processing, and, although outside of the scope of this article, biogas from digesters and landfills.

In the U.S. the DOE EIA and Environmental Protection Agency (EPA) collect and publish information on flared and vented gas volumes. The EIA collects data from state agencies, before aggregating and publishing on a (delayed) annual basis [1]. A major note with this data is that it relies completely on self-reporting by producers, and that reporting requirements and standards differ widely between states — with some states not participating in EIA reporting at all. Additionally, a second major caveat is that the EIA data represents both flared and vented gas volumes, without distinction.

Figure 6 shows the vented or flared gas volumes between 2016 and 2021 (2022 data not available as of writing), for any states with non-zero reported volumes during this time period. Note that the non-zero values for California, Idaho, and Utah are extremely small relative to others. The data generally mirrors the locations in **Figure 5** with the highest amounts of APG production. However, interestingly, many of the largest producing states (e.g., North Dakota, Texas) show a considerable drop in 2021. This may have been partly influenced by the COVID-19 pandemic, which was shown to cause reductions in consumer demand, production, and flaring activity in the ~2020 time frame [24,25]. As will be discussed below, the reported volumes shown in **Figure 6** may not be an accurate representation of flaring activity.

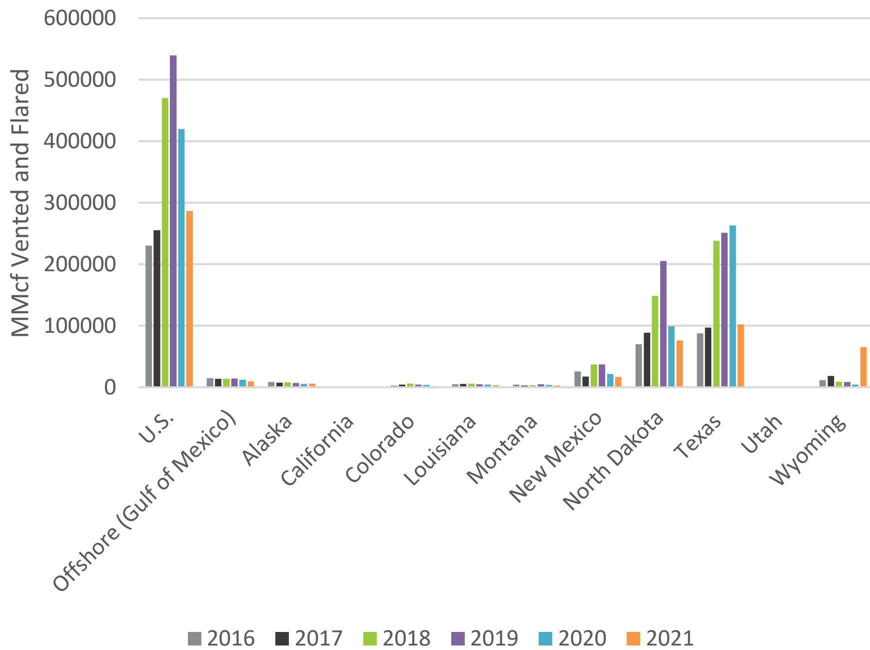


Figure 6. Volume of gas vented and flared reported to the EIA, data from [26].

The EPA collects data on flaring and venting through the Greenhouse Gas Inventory and Greenhouse Gas Reporting Program (GHGRP) [27]. The most recent 2023 publication presents data through 2021. In the Petroleum and Natural Gas Systems source category, Subpart W of the EPA GHGRP requires reporting in 10 industry segments. The total number of facilities and reported emissions (million metric tons of carbon dioxide equivalents, CO_{2e}) are shown in **Table 1**, reproduced from [28]. Here, combustion emissions are due to the combustion of fossil fuels (e.g., engine combustion for power), while process emissions are due to vented emissions, equipment leaks, and flaring [28]. Note that reporting to the GHGRP is only required for facilities that emit more than 25,000 metric tons of CO_{2e} emissions annually (where a facility is not a single location but a reporting operator, which represents all its facilities or physical locations).

Table 1. 2021 EPA Reported Emissions by Industry Segment, data from [28]

Industry Segment	Process Emissions (MMT CO_{2e})	Combustion Emissions (MMT CO_{2e})
Onshore Production	53	37
Offshore Production	2	5
Gathering and Boosting	22	64
Natural Gas Processing	21	39
Natural Gas Transmission Compression	3	29
Natural Gas Transmission Pipeline	3	<1
Underground Natural Gas Storage	<1	1
LNG Import/Export	1	13
LNG Storage	<1	<1
Natural Gas Distribution	12	<1
Other Oil and Gas Combustion	<1	7
Total	117	195

The EPA further delineates process emissions by source, as shown in **Figure 7**. The data in this figure represent a total of all industry segments, including both CO2 and CH4 emissions, in million metric tons of

CO_{2e}. A majority of CH_4 emissions are due to component leaks and/or intentional venting of gases, the largest contributor being due to pneumatic devices, including components such as liquid level controllers, pressure regulators, and valve controllers [29]. The largest flaring contributors include acid gas removal units, APG venting and flaring, atmospheric storage tanks, and other flare stacks. Acid gas removal units are devices that eliminate acidic compounds such as H2S from wellhead gases via absorption/adsorption processes and vent or flare the resulting product stream [30]. Atmospheric storage tanks (tank batteries) are vessels that store produced water, natural gas liquids/condensates, and crude oil. These devices may use flares, vapor recovery units, or vents to handle the release and/or destruction of tank vapor [27]. As discussed above, APG flaring can occur for economic or safety/operational reasons, consisting of the thermal oxidation of gases contained alongside oil deposits. The other flaring category consists of all other process related flares in the oil and gas industry, for example flare stacks at gathering stations and miscellaneous production flaring and liquefied natural gas (LNG) terminal flaring.

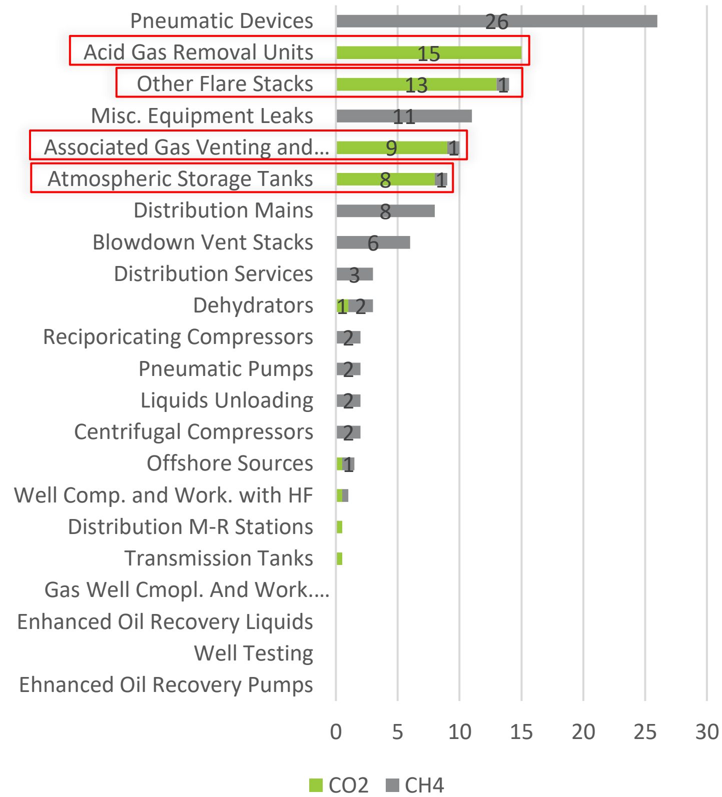


Figure 7. 2021 EPA reported emissions by process source, flaring contributions highlighted, data from [28].

In 2021, APG venting and flaring, atmospheric storage tanks, and other flare stacks represented 97% of production CO_2 emissions for petroleum systems [31]. Flaring accounts for much smaller contributions within the exploration and transportation segments, however under refining, flaring accounts for 52% of CH_4 emissions and >99% of CO_2 emissions. The EPA notes that the highest N_2O emissions from petroleum systems are due to flaring [31], however relative to CH_4 and CO_2 emissions, their contributions are lower (even when converted to CO_{2e}). For natural gas systems, flaring falls under fugitive emissions making up a majority of CO_2 emissions in the exploration, production, and processing (includes acid gas removal units) segments [31]. Under exploration, well completion flaring accounted for most CO_2 emissions. Under production, most CO_2 emissions were from flare stacks at gathering stations, miscellaneous onshore production flaring, and tank flaring.

The data reported to the EIA and EPA show the significance of flaring in a variety of oil and gas applications. However, these data may not tell the whole story. For one, operators are not required to report GHG emissions under a certain threshold [32]. Much of this reporting is self-regulated and inconsistent between operators and states/localities. Furthermore, in many instances un-permitted gas flaring occurs under the pretext of intermittent safety/operational reasons, allowable for up to 24 hours before requiring a permit under Rule 32. A recent report in Texas showed that 69-84% of observed flares were unpermitted [33]. Even in the case of permitted flaring, no volume limitations are imposed and the technology and reporting requirements are limited.

Flare gas composition depends on the application (process and location in the supply chain) but can vary in time and geographical location. For example, flares may be used at oil production sites where APG is produced without market or infrastructure for sales. The Permian and Bakken shale plays produce significant APGs. These APGs will include methane but also higher alkanes such as ethane, propane, butane, isobutane, natural gasoline, and others. Pipeline quality natural gas will typically be 75% or more methane with ethane and propane at less than 10 and 5%, respectively. Associated gas (also known as casinghead gas) typically has a lower methane content with a typical composition of 65% [34], with ethane above 10%, and propane just below 10%. A recent assessment of Bakken gas compositions showed an average methane content of 58% followed by ethane at 20% and propane at 11% [35]; however, the composition varied throughout the basin. In addition, the study examined the change in composition over production life from available data and predicted future compositions based on initial compositions and reservoir characteristics. The study found that methane composition tended to increase during the first five years and then decrease over the life of the well. Propane and ethane tended to remain constant during the first few years and then increased over time. Historical composition data showed variation of C1-C5 alkanes also varied throughout a given year by a few percent.

Beyond APG, flares or enclosed combustors and natural gas fuel equipment exist across the supply chain. Ismail and Umuokoro utilized various compositions from around the world as model inputs to predict emissions from flares [3]. **Table 2** summarizes the varying field gas compositions from around the world along with added heating values, density, and statistics. Lower heating value is based on normalized compositions while density is based on ISO 6976:2016 (20 °C and 101.325 kPa).

Table 2. Example of Gas Composition Variation from Field Data Around the World — by Volume, from [3]

	C1	C2	C3	C4	C5+	N_2	CO_2	H_2S	LHV (kJ/kg)	Density (kg/m3)
1	92.5	2.78	1.66	0.78	0.3	0.11	0.22	–	49211	–
2	81.3	2.9	0.4	0.1	0.1	14.3	0.9	–	38023	0.776
3	69	3	0.9	0.5	0.5	1.5	9.3	15.3	29498	0.949
4	95.7	3.6	–	–	–	0.4	0.3	–	49139	0.695
5	83.7	6.8	2.1	0.8	0.4	5.8	0.2	–	44859	–
6	85.3	5.8	5.3	2.1	0.2	0.9	0.4	–	47969	0.815
7	45.6	5.8	2.9	1.1	0.8	–	43.8	–	18278	1.287
8	82	10	3.7	1.9	0.7	1.5	0.2	–	47716	0.830
9	55.5	18	9.8	4.5	1.6	0.2	8.9	1.5	39891	1.124
10	74.3	14	5.8	2	0.9	2.9	–	0.1	46718	0.890
11	56.9	21.2	6	3.7	1.6	–	7.1	3.5	39889	1.077
12	90.12	6.94	2.09	0.771	0.079	–	–	–	49430	0.749
Min.	45.6	2.8	0.4	0.1	0.1	0.1	0.2	0.1	18278	0.695
Max.	95.7	21.2	9.8	4.5	1.6	14.3	43.8	15.3	49430	1.287
Ave.	76.0	8.4	3.7	1.7	0.7	3.1	7.1	5.1	41719	0.919
Std. Dev.	15.4	5.9	2.7	1.3	0.5	4.3	12.8	6.0	9127	0.180

In addition to flaring of APG and field gases, flares of the enclosed combustor type are often used as emission control devices to combust various gases and volatile organic compound (VOC)-rich streams at well sites, compression facilities, and other locations. In all the cases so far, the plurality of the gas composition was methane. Thoma et al. have reported on the enclosed combustor efficiency and gas compositions of condensate tank vapors in various upstream gas production locations in the Uinta (UT) and Denver-Julesburg (DJ) basins [36].
presents some key components by composition for condensate tanks.

Table 3. Variation in Condensate Tank Gas Composition that may Feed Enclosed Combustors — by Volume, from [36]

	UT	DJ
Methane	20.76	10.44
Benzene	0.148	0.780
Ethane	16.50	14.16
Xylene	0.084	0.234
Toluene	0.170	0.570
n-Butane	13.20	14.53
Ethylbenzene	0.004	0.023
Isopentane	5.034	6.650
n-Pentane	3.908	7.380

Johnson et al. reported on the composition of emissions from production tanks [37]. Fifteen sites were surveyed for leaks and losses, including tanks. All tanks surveyed utilized enclosed combustors as an emissions control device to reduce VOC emissions. Vapor spaces of both produced water tanks and condensate tanks were combined and sent to the combustor. The composition and flow rate of the common streams sent to the enclosed combustors were not monitored. Canister samples from tank associated leaks showed that head space composition varied from tank to tank and from site to site. ***Error! Reference source not found.*****Table 4**. presents the ratio of methane to total organics (TOC) for sites with available data. Further, measured ratios were compared to GHGRP data for some sites. Operators utilized tank modeling software to predict tank emissions sent to the flares. The county average produced gas was 73% methane by volume, while the flash gas estimates varied from 10.7 to 70.6%. Note, that for the greenhouse gas inventory (GHGI) reporting, the default efficiency of 98% was used pursuant to Subpart W [28].

Table 4. Variations in the Ratio of Methane (by Volume) to TOC for Produced Water and Condensate Tanks Utilizing Enclosed Combustors to Reduce Emissions, from [37]

Recently, advanced satellite imaging and drone/aircraft flyover techniques have been implemented to more accurately characterize the impacts of flaring. Satellite imaging has been conducted by the National Oceanic and Atmospheric Administration (NOAA) using the VIIRS instrument on board the Suomi NPP satellite [38,39]. Nighttime images are collected in several IR bands, which can be fit to a blackbody curve to estimate the temperature of luminous sources. These sources are correlated with Google Earth images to construct labels and derive statistics. **Figure 8.** shows an example of flare identification and location mapping. A five-year survey was conducted between 2012 and 2016 [38], which showed substantial discrepancies with EIA flare volumes [1]. Daily flaring maps are available through the SkyTruth website [40], as part of the Earth Observation Group of the Colorado School of Mines. Additionally, annual flaring volumes are published. The total VIIRS gas volumes published on SkyTruth for the year 2021 were plotted alongside the EIA gas volumes from **Figure 6** for the states with the most flares identified.

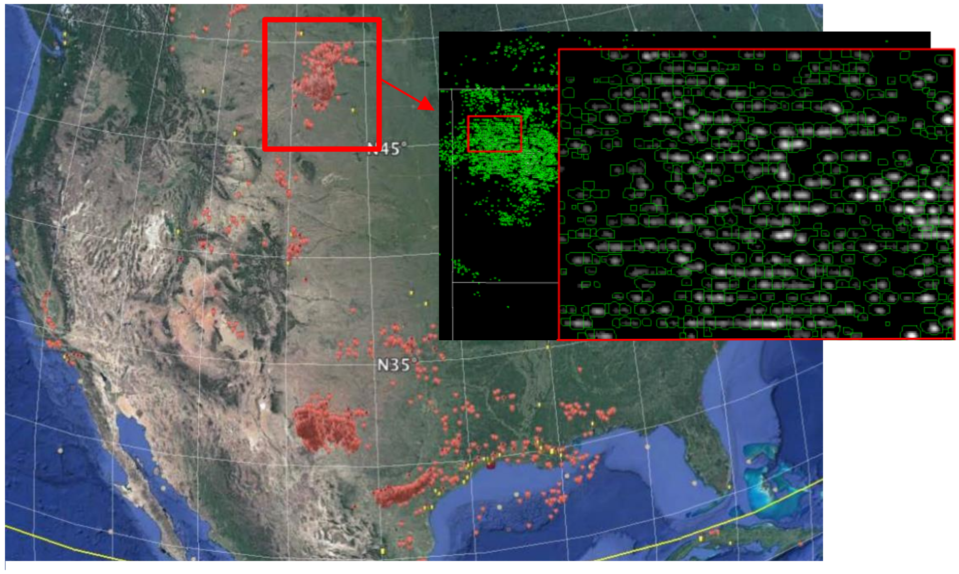


Figure 8. Example of satellite imaging of gas flares using NOAA VIIRS, from [38] (modified to highlight location).

As shown in **Figure** , there are large discrepancies between reported and satellite-identified volumes, both above and below, most notably for Texas and North Dakota. Prior to 2021, similar trends are observed, with varying levels of discrepancy.

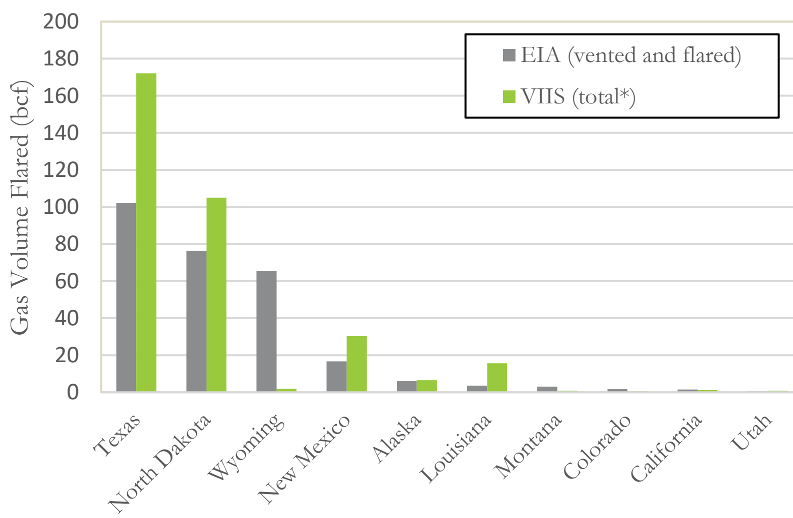


Figure 9. Flared gas volumes published by EIA (Fig. 6 [26]), derived from VIIRS [40] (*total includes upstream flaring plus refineries, downstream oil, downstream gas, midstream flaring, and LNG).

In Texas, flares in the Permian Basin are of such concern that a number of dedicated studies have been conducted to more accurately quantify the activity. In 2017, the Environmental Defense Fund (EDF) examined the NOAA data in the Permian Basin, noting only about half of

Figure 10: Unlit flare detected by aircraft emitting large amounts of methane, from [24].

the gas flared was reported to the Texas Railroad Commission (TRRC), and suggesting regulatory action to limit flaring, treat wasted gas as a valuable resource, improve record keeping and reporting, and critically, require best flaring technologies [1,41]. In 2019 the EDF undertook the Permian Methane Analysis Project (PermianMAP) [42], which collected data on methane plumes using aircraft, cell tower sensors, mobiles laboratories, and satellite imaging (TROPOMI satellite project). Researchers found that 362 of 1320 emissions sources detected were due to flares, 50% of super emitters were from midstream operations (gathering/boosting, transmission/storage, pipelines/compressors), and low-producing "marginal wells" were responsible for half of Permian well pad emissions. Of the flares identified, ~10% were malfunctioning and half (5%) were completely unlit [42,43]. An example of an unlit flare identified by aircraft to be emitting large amounts of methane is shown in **Figure** .
Building on the results of the PermianMAP survey [42] and a Canadian airborne survey [44], which found ~13% of CH_4 emissions were due to unlit flares, a comprehensive survey [45] was performed across the Permian, Eagle Ford, and Bakken basins in 2020 and 2021 (F^3UEL project [46]).

A major interest in this work was uncovering the impacts of unlit flares vs. poorly performing, inefficient flares. An aircraft-based sampling approach was utilized, which measured CH_4, CO_2, NO, and NO_2. The surveyed regions represent ~80-90% of flared gas volumes in the US. Here, destruction removal efficiency (DRE) was the metric employed, which constitutes the amount of CH_4 converted to CO_2 and differs from combustion efficiency. Unlit flare fractions were found to be 4.9% for the Permian basin, 3.2% for the Bakken, and 4.1% for Eagle Ford [45]. Including unlit flares, the average DRE was 91.1% and 95.2% without, significantly below the 98% [47] assumed by regulatory bodies.

In general, GHG emissions are falling in recent years, but in many instances these emissions are up relative to prior decades due to increased oil and gas production. Additionally, as shown in the discussions above, it is unclear whether the data reported to organizations such as the EIA and EPA are representative. As shown in **Figure 6**, EIA estimates peak at 539 bcf in 2019 [26], with ~20-30% reduction per year since. The EPA showed that total CO_2 emissions from petroleum systems in 2021 were 1.8 times higher than 2010 levels, but 15% lower than 2020 levels; in this same sector CH_4 emissions decreased by 8% since 2010 levels, and were 8% lower than in 2020 [31]. For natural gas systems, total GHG emissions were largely driven by CH_4, constituting 83% of CO_{2e} [31]. In 2021, CH_4 emissions were reduced by 16% compared to 1990 levels and 2% compared to 2020 [31]. For non-combustion CO_2 emissions, 2021 saw a 12% increase over 1990 levels and a 1% increase over 2020 [31]. In both oil and gas applications, flaring continues to play a major role in both CO_2 and CH_4 emissions, as well as N_2O, which shows a more minor contribution despite exhibiting a large GWP. However, most advances in recent years are due to regulatory reform, increased enforcement of existing regulations, and public pressure to reduce flaring [48]. Technological advances have been slower, mainly due to economics.

As outlined by initiatives such as the ZRF30 and ZRF25 (U.S.), eliminating routine flaring will further reduce emissions, as will maximizing on-site gas capture opportunities and implementing alternative processes to flaring. However, some amount of flaring will undoubtedly still occur, and as suggested by an EDF report, requiring best available flaring technologies should be paramount [41]. This includes exceeding a flare destruction efficiency of 98%, favoring automatic ignition of piloted flares [41], and critically, requiring implementation of measurement and reporting technologies that provide an accurate representation of the flared gas volumes and concentration of GHGs. In many cases, technologies exist that could be implemented in flaring applications but are perhaps not economical. In the U.S., inexpensive technologies that can be deployed in low-producing wells and small/midstream operations are critical, especially since such operations have been shown to contribute significantly to overall GHG volumes when added together. In other cases, new technology solutions may be required.

Combustion Fundamentals

This section is intended to provide the reader with a general understanding of combustion fundamentals, including relevant parameters and terminology, as pertains to the gas flare technologies presented in subsequent sections. This includes canonical and non-gas flare examples to illustrate various phenomena of consequence. Gas flare performance is governed by the same combustion fundamentals as typical heating or energy conversion devices (engines, boilers, turbines, furnaces, etc.). The major differences being 1) the open nature of most gas flare systems, 2) the complex and varied fuel composition and flow rates, and 3) often times — low gas supply pressure. These key differences present a number of technical challenges with respect to achieving high combustion efficiency and low emissions.

Combustion Chemistry and Emissions

As discussed above, flare gas compositions can vary considerably, including large amounts of methane, but also significant quantities of other hydrocarbons, inert species, and even sour gas components. These compositions are explored in detail in the next subsection. The primary products for a generic hydrocarbon fuel are CO_2 and H_2O, the ratio of which depends on the C:H ratio of the fuel. The fuel-to-air ratio (FAR) will dictate the completeness of combustion, as well as affect the formation of other pollutant species. This is typically characterized by the equivalence ratio (Φ). Using this formulation, $\Phi=1$ implies complete combustion, $\Phi<1$ is a lean condition (excess oxygen), and $\Phi>1$ is a rich condition (excess fuel). In some industries, excess air (EA) is used instead of equivalence ratio, where $EA = 1/\Phi$.

Under lean conditions, CO formation can occur as a result of increased oxygen availability, often used as an indicator of incomplete combustion. For rich conditions, a lack of oxygen will result in some amount of unburnt fuel being released to the environment and can result in fuel cracking (thermally driven breakdown of fuel compounds without oxidation), resulting in the formation of hydrogen, unsaturated hydrocarbons, and carbon [47]. Similarly, olefins and other unsaturated hydrocarbons can polymerize to form larger molecules which crack, forming additional carbon [47]. The release of un-combusted carbon particulate matter is often termed "smoke" by the gas flare community. Note that in addition to causing negative health effects, black carbon has been shown to have direct climate implications [49].

For smokeless operation, fuel characteristics play a significant role, along with the amount and distribution of oxygen in the combustion zone. The amount of air required for complete combustion increases with fuel molecular weight, ranging from 9.6 units of air per unit of methane to 38.3 units of air per unit of pentane, by volume [47]. Depending on flare design, air staging may be utilized, with primary air supplied ahead of the combustion zone and secondary air drawn into the flame through buoyantly driven expansion of the hot gases into the atmosphere. Hydrocarbons above methane (C:H ratio > 0.33) tend to soot, while branched-chain paraffins smoke more readily than corresponding normal isomers (the more highly branched, the more likely to form carbon particulate) [47]. Saturated hydrocarbons (single C-C bonds) are more likely to smoke than unsaturated (double/triple C-C bonds). Flare gases containing methane, hydrogen, CO, and ammonia usually burn without smoke formation, while heavy hydrocarbons including paraffins (above methane), olefins, and aromatics, have a higher tendency for smoking [47]. The amount of primary air needed for smokeless combustion varies from ~20% of stoichiometric for a paraffin to ~30% for an olefin [47].

Nitrogen oxides (NO_x – NO/NO_2 and N_2O) can be formed due to high combustion temperatures (thermal/Zeldovich pathway) or fuel-N/intermediate-N (e.g., HCN, CN) compounds. Sulfur dioxide (SO_2)

formation occurs for sulfur-containing flare gas compounds such as hydrogen sulfide or mercaptans [47]. Gases containing high concentrations of halogenated or sulfur-containing compounds are typically not flared due to flare tip corrosion, formation of secondary pollutants (e.g., SO_2), or EPA regulations. Some of these compounds can be removed from the gas stream prior to flaring using a halogen or amine scrubber. Otherwise, thermal incineration followed by acid gas removal is preferred [50].

In addition to smoke formation, the biggest consideration in gas flare performance is maximizing destruction efficiency. In the context of oil and gas operations, the principal consideration here is methane destruction, however other industries or applications could require destruction of other compounds, such as VOCs or toxic compounds such as hazardous air pollutants (HAPs) [36,50]. While similar, a distinction can be made between combustion efficiency and destruction efficiency. The default value of 98% is for overall destruction efficiency (DE), where destruction efficiency is defined as the percentage of a flare gas pollutant that is converted to a different compound, see Eq. 1 [50].

$$DE = \left(1 - \frac{Pollutant_{exhaust}}{Pollutant_{flare\ feed\ gas}}\right) \times 100 \qquad \text{Eq. (1)}$$

Combustion efficiency (CE) typically refers to the percentage of the complete combustion of a hydrocarbon (products of CO_2 and H_2O alone). However, the early EPA studies (1982/1983) defined combustion efficiency using Eq. 2 [51].

$$CE = \frac{CO_2}{CO_2 + CO + THC + Soot} \times 100 \qquad \text{Eq. (2)}$$

Combustion Properties

A major concern in gas flares is ensuring a stable, lit flame. As discussed above, unlit flares contribute significantly to methane emissions within the U.S oil and gas industry and represent a problem that can be solved by technology (monitoring and automatic re-light). While flare tip technology can be used to address this, optimized designs that achieve high destruction efficiencies and low emissions will inherently depend on the combustion properties of gas stream and resulting flame structure. Properties include heating value, flammability, ignition temperature, and density, which are all a function of the gas stream's chemical composition [50].

Gas density is important to combustion as it relates volumetric and mass-based quantities, for example, energy density or heating value. Additionally, it allows conversion of measured volumetric flow rates to mass flows or species concentrations (molar, volume), to a mass basis. In terms of gas flares specifically, density directly impacts the velocity that will be created at the flare tip from the available upstream pressure as well as buoyancy, mixing, and air entrainment in self-aspirating systems (i.e., air is drawn into the flame by the flow of fuel).

To accurately compute flare gas density, compositional knowledge is required to compute the mixture's mean molecular weight. Estimates of gas composition can be made, however variations in very light (e.g., H_2) or very heavy (e.g., C5+ hydrocarbons) species concentrations can result in significant changes to the bulk gas density.

Heating value represents a substance's energy content or calorific content. In the context of fuels, heating value is the amount of heat released during combustion, directly related to the enthalpy of combustion (ΔHC°), or the enthalpy change when 1 mol of a substance combines with oxygen under standard conditions [52]. The heat of combustion can be determined by the difference in heats of formation between products and reactants, or directly measured using a calorimeter. The two primary conventions used in combustion are the gross (or higher heating value, HHV) and net (or lower heating value, LHV) of a given fuel. The HHV is the upper limit of the available thermal energy produced by complete combustion — it includes the energy produced by bringing all products back to the original pre-combustion temperature, including vapor condensation. This is particularly impactful for water vapor in hydrocarbon combustion. Lower heating value neglects the latent heat of water vaporization, representing a more conservative measure of energy extraction from the fuel in absence of waste heat extraction or bottoming cycles. As an example, the HHV and LHV of methane are 55 and 50 MJ/kg, respectively [53].

The heating value of a mixture of gases with known component heating values can by computed on a corresponding mass or molar basis (depending on units of heating value, energy/mol or energy/mass). An example of computing the net heating value on a molar basis is shown in Eq.3 (per EPA 2015 for steam-assisted flares), where NHVi is the net heating value of component I, xi is the mole fraction, and NHVvg is the net heating value of the vent gas.

$$NHV_{vg} = \sum_{i=1}^{n}(x_i \cdot NHV_i) \qquad \text{Eq. (3)}$$

Related to the concept of heating value, is adiabatic flame temperature. This is the product gas temperature attained under a product species' thermodynamic equilibrium. Adiabatic flame temperature can be derived using constant pressure or constant volume equilibrium, and it represents the upper bound of combustion gas temperature expected for the fuel/oxidizer combination. As an example, the constant pressure adiabatic flame temperature of methane is 2236 K [54].

Flammability is a parameter that dictates whether a flame will propagate through a fuel and oxidizer mixture without additional heat input. In this context, upper and lower flammability limits (LFL and UFL, respectively) can be established, corresponding to the leanest and richest burnable mixtures. These limits depend on the specific fuel and oxidizer combination used, as well as temperature and pressure. Higher temperature and pressure generally extend the flammability limits, as does increasing the oxygen fraction in the oxidizer (e.g., 21% for air, by volume, 100% for pure oxygen as an oxidizer). While ignition energy can play a role in whether a mixture can be ignited, from the perspective of ideal flammability limits ignition energy is typically not considered. For example, methane burning in air has a LFL and UFL of 4.4% and 16.4% by volume in air at 20 °C and 1 atm [55]. Because flare gas is not typically a pure gas, but rather composed of many different species, a volume or mole-fraction weighted sum can be used to determine the mixture's flammability limits. This is shown in Eq. 4, which can be applied to the LFL or UFL and summed over N gas components, where x_i and LFL_i (or UFL_i) correspond to component i.

$$LFL_{mix} = \frac{1}{\sum_N \frac{x_i}{LFL_i}} \qquad \text{Eq. (4)}$$

A gas mixture's flammability can be related to its laminar flame speed (S_L), though not by first principles. Laminar flame speed is a measure of the 1D rate of expansion of an unstretched flame front through a quiescent, perfectly mixed fuel and oxidizer combination. It represents a measure of the mixture's reactivity, diffusivity, and exothermicity [52]. In a gas flare system, laminar flame speed is a critical parameter when considering tip velocity and flame anchoring. If the tip velocity approaches or exceeds this value, the flame will blow off and extinguish. For this reason, geometric features are often added to combustion systems and burners to create low-velocity regions capable of anchoring the flame.

Similar to flammability, laminar flame speed depends on temperature, pressure, and the fuel and oxidizer concentrations (as well as oxidizer type – air, oxygen, etc.). Laminar flame speed only exists within the flammability limits. Flammability limits and laminar flame speed can be determined on a concentration basis or equivalence ratio. For example, the LFL and UFL of methane shown above correspond to equivalence ratios of 0.43 and 1.86, respectively. Often times, a Mach number designation may be utilized when considering gas velocity at or near the flare tip. One reason for this is the use of sonic nozzles to promote increased air entrainment (see flare tip section below).

Mixing

In general, flames can be categorized as premixed or non-premixed. In an ideal sense, premixed flames exhibit a homogeneous fuel and oxidizer mixture. The reaction rate in premixed flames is primarily controlled by the chemistry, though species diffusion can also play a role. Non-premixed flames include separate fuel and oxidizer streams, which must mix prior to burning. In non-premixed systems, the reaction rate is strongly influenced by reactant mixing. Non-premixed flames are often termed diffusion flames, as diffusion and convection control the mixing rate in the absence of turbulence (laminar diffusion flame). In most practical combustion applications, turbulent mixing is the primary mechanism for combining the fuel and oxidizer to create a combustible mixture. Effective mixing strategies often include geometries that cause the reactants to intersect at an angle, thereby enhancing turbulence. Examples include the use of air swirlers to impose a bulk angular motion relative to an axial fuel injector or the so-called "jet-in-crossflow" configuration where fuel injection occurs orthogonally to the air flow.

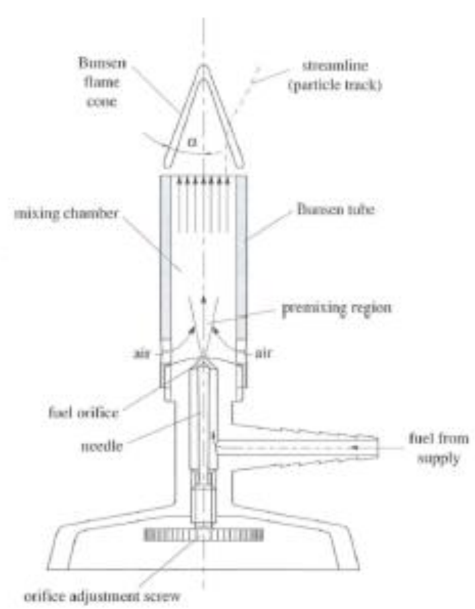


Figure 11. Bunsen burner, from [56].

Mixing can have a significant effect on emissions performance. This is because high levels of un-mixedness will result in large variations in equivalence ratio (i.e., rich and lean zones), which can have very different emissions characteristics (discussed above). Creating a uniform air-fuel mixture within a short distance generally requires substantial flow turbulence, which is primarily created by the fuel and oxidizer flows. In gas flares, this is a major challenge because 1) they are most often self-aspirating and 2) the fuel pressure is often low relative to other combustion applications. For this reason, mixing strategies effective in applications such as gas turbine combustors or industrial burners are not always applicable to gas flares. In gas flares, diffusion may be the dominant mixing mechanism, such that maximizing the air-fuel contact area is the preferred strategy.

In self-aspirating burners, simply entraining sufficient amounts of air is often the biggest challenge — in particular for low fuel gas pressures. The simplest example of a self-aspirating burner is the Bunsen burner, shown in **Figure 11**. Here, pressurized fuel enters the burner body, controlled by an orifice adjustment screw. The fuel exits the orifice and travels upward, drawing air with it by flow momentum. Mixing occurs primarily by diffusion. It is often considered a partially premixed burner design because mixing occurs within the burner tube. Additionally, the upward expansion and buoyancy of hot combustion products aids with the intake of fresh air. This configuration is sometimes called a natural draft burner.

Novel self-aspirating technologies have also been proposed, such as the self-aspirating porous media burner (SPMB), which offers the potential to exhibit positive stability and emissions characteristics [57], and low velocity natural draft burners for even heating and ultralow pollutant emissions [58].

Flashback and Lean Blowoff

Related to flammability, laminar flame speed, and flare tip velocity, is the phenomena of flashback. Flashback occurs when a mixture's flammability and/or laminar flame speed are sufficiently high that the flame front is able to propagate upstream, ahead of where it is designed to anchor. This is a particularly dangerous phenomenon in premixed combustion systems, as sufficient flammability may be maintained far upstream of the burner or combustor, leading to significant hardware damage and/or detonation. Non-premixed systems mitigate flashback by keeping the fuel and oxidizer separated, such that the flammability of either stream is essentially zero (assuming no oxygen within the fuel — not true for alcohol fuels, etc.).

While nearly all gas flares are non-premixed (air is entrained by the flow of the flare gas — see discussion below), there can be air in-leakage and/or oxidizing compounds can be found within the flare gas composition. This makes for a potentially dangerous situation unless appropriate flashback mitigation devices are located near the flare tip. The simplest approach to mitigating flashback is through the use of narrow flow passages that have a `width less than the quenching distance of the combustible mixture. Quenching distance represents the narrowest distance between two parallel plates that a flame can propagate [52]. For reference, the quenching distance of a stoichiometric methane-air flame at ambient conditions is between ~2 and 3.2 mm [59]. In gas flares, the feasibility of this approach may be limited by acceptable pressure drop, requiring novel solutions. A dedicated discussion of the technologies associated with gas flare flashback devices is included in a subsequent section.

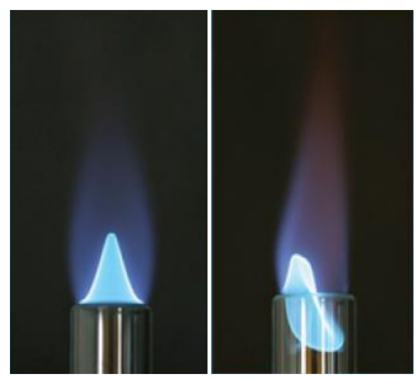


Figure 12. Example of flashback due to increased flammability from H2 addition to CH4, from [61].

Even within the flare tip, flashback can occur. Generally, a flare tip will be designed in conjunction with a range of expected gas compositions and flow rates, such that a suitable operating envelope can be established. However, if exceeding the bounds of this envelope, two primary situations can occur that may result in flashback. First, the mixture flammability (or flame speed) increases due to a change in composition. One example is the presence of even small quantities of hydrogen, which exhibits a flame speed orders of magnitudes above most other hydrocarbon species [60]. The other situation is a drop in flow rate, such that the flame speed of the mixture approaches or exceeds the gas velocity at the flare tip. One example is operating with large amounts of turn-down. Here a potential solution may be operating multiple parallel flare tips that can be activated or deactivated depending on gas flow, while maintaining desired tip velocities. **Figure 12.** shows an example of burner flashback due to increased flammability (or flame speed) as a result of adding hydrogen to a methane flame [61].

Similarly, exceeding the upper bounds of this operating envelope (increasing flow rate or decreasing flammability/flame speed) can result in blowoff. It is important to note that reductions in flammability/flame speed can result from too lean or too rich of a mixture — termed lean and rich blowout limits [52]. An example of blowoff can be seen in **Figure** . Note that here, air flow alone is increasing, which both increases the total reactant flow into the flame and reduces the equivalence ratio, reducing flame speed/flammability. The combined effect more quickly results in blowoff.

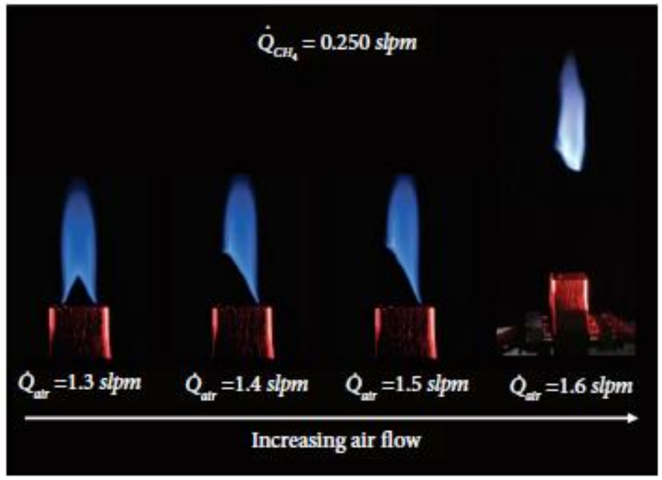


Figure 13. Methane-air flame blowoff due to increasing air flow rate, from [62].

In practice, blowoff limits are not necessarily hard stops that can be predetermined for a given fuel-oxidizer combination. Instead, they depend greatly on the specific burner geometry, mixing strategy, etc. Importantly, prior to reaching these limits, regions of unstable operation can be encountered where the flame may lift and re-attach intermittently.

The above concepts will be directly relevant to the technology assessments presented below. In gas flares, the overwhelming technical challenge from a combustion perspective is entraining sufficient air given a (generally) low-pressure fuel supply. Without sufficient air, both emissions and stability will suffer. Second to this, is mixing the air and fuel to ensure no overly rich pockets exist, which are likely to result in smoke formation and unburnt fuel gas emissions (methane). Knowledge of flare gas composition is critical to optimizing these processes, predicting flame speed, and sizing/designing the flare tip for expected flow rates.

Regulations and Oversight

Flaring regulations vary widely between states and countries. The U.S. DOE published an overview of state and federal regulations in 2019 [1]. The review primarily focused on venting and flaring from oil and gas production, specifically APG due to the high volumes of gas. It highlighted that for the 32 oil and gas producing states:

- Vented and flared gas volumes may or may not be reported.
- Volumes may be estimated instead of quantified — even for states requiring reporting.
- Most states do not require measurement or estimation of volumes.
- Regulations vary significantly between states and a wide variety of state offices set different requirements or provide oversight.
- While many regulations aim to reduce flaring, many exemptions are available that enable short- and long-term use of flares.

Independent studies may highlight underreported volumes being sent to flares in reporting states (e.g., estimates of volumes flared for only five states exceed the volumes reported as vented or flared gas for all reporting states for multiple years). Due to administrative changes and an increased focus on methane reduction, many regulations have changed. As part of their review, the DOE created state-specific fact sheets, which have been updated over time and are listed as current as of 2022 [63]. From a review of fact sheets, there is a general need to better understand, through accurate measurement, the volume of gas being flared.

Oil and gas flaring activities have been primarily regulated under the CFR Title 40, Part 60, Subpart OOOO [9] or OOOOa [7]. It is important to note that in the 40 CFR part 60 subparts OOOO [9] and OOOOa [7] and 40 CFR part 63 subparts HH [64] and HHH [65], a flare is defined as a thermal oxidation system that includes an open flame, thereby excluding enclosed or shielded units. This classification is made with regard to the "open" nature of the flame; an enclosed ground-level flare consists of a stand-alone burner system surrounded by an enclosing structure, while the enclosure is intrinsic to the design and operation of an enclosed combustion device.

OOOOa regulations relied on visual inspections to establish performance, mainly to eliminate visible smoke emissions. Technical specifications on flare or combustion device performance focused on a VOC reduction or destruction efficiency of 95% or limitations of VOC exhaust gas concentration of 275 part per million (ppm). Regulations also required the use of pilot flames and target a minimum combustion temperature of 760 °C as an indicator of destruction efficiency. Periodic performance tests are required but can be avoided if temperature is continuously monitored. These regulations did not require additional sensors or instrumentation, such as those for flow or composition monitoring.

The U.S. EPA finalized new rules regarding methane and VOCs from the oil and gas industry in 40 CFR 60 Subpart OOOOb and OOOOc on December 2, 2023[66]. These new OOOOb standards will impact any sites constructed on or after December 6, 2022. OOOOb aims to eliminate routine flaring from oil wells. Flaring will be prohibited after a phase-in period (dependent upon construction date — up to two years), with exemptions for safety and malfunctions. OOOOc targets pre-existing sites. For those sites where methane emissions do not exceed 40 tons per year, flaring will be permitted so long as a 95% reduction in methane is achieved. For those existing wells with 40 tons or greater, flaring is only permissible when all other options (useful purposes) are not technically feasible. Temporary flaring is allowed for safety, maintenance, service interruptions, or if associated gas does not meet pipeline specifications. The maximum duration for temporary flare operations are 24 hours, 24 hours, 30 days, and 72 hours, respectively.

These new regulations (OOOOb and OOOOc) focus on TOCs, which would eliminate ethane and methane exclusions. For example, flares allowed under OOOOb and OOOOc must demonstrate 95% reduction in both GHGs (methane) and VOCs. In addition, they specify that temperature monitoring must occur at five-minute intervals and that other methods such as ultraviolet beam sensors or infrared sensors can be used. Exhaust gas concentrations would be TOC-based with limitations of less than or equal to 10 ppm (as propane). While proposed regulations do provide additional sensor options and specificity, they do not require additional sensors, instrumentation, flow, or composition monitoring.

CFR Title 40, Part 98 provides details on mandatory GHG reporting, including those from flares [10]. In addition, there are device-specific requirements for reporting vented emissions, which will not be discussed in detail here. In general, the reporting requirements for vented emissions are far more prescriptive than for flares. Reporting is required for facilities that emit 25,000 metric tons of CO_2 equivalent (CO_{2e}) per year. Emissions to be reported include CO_2, CH_4, and N_2O. A majority of reporting requirements for gas flares are covered in § 98.233, paragraph (n) [32]. Associated gas flaring is specifically covered in paragraph (m), which considers the gas-to-oil-ratio (GOR) in determining volume, before computing CO_2 and CH_4 emissions.

When flare gas volumes and/or compositions are measured, their values must be used. When data are not measured, they may be calculated or estimated using good engineering judgment. Subsection (n)(3) allows for the facility to use a default destruction efficiency of 98% if the manufacturer flare efficiency is not available. After computing GHG volumetric emissions according to paragraph (n), they are converted to standard conditions according to paragraph (u) and converted to mass basis according to paragraph (v). Additionally, if a continuous emissions monitoring system (CEMS) is used that has both CO_2 concentration and volumetric flow rate, only report CO_2 must be reported. However, the Tier 4 calculation method must be followed, as well as all associated calculation, quality assurance, reporting, and recordkeeping requirements for Tier 4 in Subpart C [67] of this part (General Stationary Fuel Combustion Sources). N_2O emissions are calculated as outlined in § 98.233 paragraph (z), specifically (2), which applies to field/vent gas with heating value less than 950 Btu per standard cubic feet.

Note that if the fuel heating value is less than 5 MMBtu/hr, reporting is not required.

The CFR also regulates flaring for other industry segments including but not limited to the following:

- CFR Title 40, Part 63, Subpart CC (63.670 and 63.671) covers requirements for flare monitoring systems at petroleum refineries [5].
- CFR Title 30 contains regulations on U.S. mineral resources from public lands [8].
- CFR Title 40, Part 60, Subpart Cf includes regulations for flares at landfills [6].

Refinery Specific Regulations

Beyond emissions and monitoring (pilot flame presence), refinery regulations also focus on other operating limits including the net heating value (NHV) of the combustion zone, the NHV of the dilution, and flare tip exit velocity. Regulations vary depending on the flare type (e.g., steam or air assisted). Pursuant to 63.671 (d), the flare tip velocity must be less than 60 ft/sec based on volumetric monitoring or less than 400 ft/sec and the maximum calculated tip velocity. The second method relies on determination of the gas NHV in BTU/SCF. The operator can determine the NHV in a variety of ways. They may install a compositional monitoring device and use the volume fraction along with component-specific heat values to determine the mixture heating value. Alternatively, operators may also use an installed calorimeter. In either case, data are analyzed on 15-minute intervals. Other methods include periodic grab/canister samples or no monitoring if the gas stream composition does not vary. Use of pipeline-quality gas does not require continuous analysis. If streams contain hydrogen, additional calculations are required.

Pursuant to 63.671 (i), the operator must continuously monitor the volume of vent gas, volume of steam if steam assisted, and volume of air if air assisted or pre-mixed with air. These can include mass flow monitors with correction factors for volume determination. Continuous volume or mass measurements are not required if temperature and pressure are monitored and used along with engineering calculations. Alternatively, for air-assist systems, fan speed can be measured and used in conjunction with performance curves to estimate air assist flow rates. The volumetric flow rates are used with two different methods to determine the NHV for the combustion zone and dilution parameters. All flares covered by these regulations are to demonstrate a flare destruction efficiency of at least 98% or a flare combustion efficiency of at least 96.5% at all times. Further, additional requirements are applicable to the record keeping, process documentation, calibrations, and other specifications for flare operation and compliance. Many refinery flare specifications from the 2014-2015 rulemaking were used in the development and in defense of the new OOOOb and OOOOc standards (e.g., determination of the NHV).

Gas Flare Technology Review

As discussed above, gas flares are devices that attempt to dispose of waste gases through thermal oxidation, thereby reducing the affluent stream's GHG potential. Typically, the practice of flaring has little/no economic benefit to the operation, such that the technology implemented is only that required to maintain regulatory compliance. Furthermore, because gas flare applications span a wide range of scales, the same technology implemented in larger operations may not be economically feasible in smaller ones. This section will examine in detail, the various components and technologies currently implemented in gas flares.

Gas Flare System Overview

Gas flares can be divided into two main categories: elevated and ground flares [47]. As the name suggests, elevated flares consist of a burner mounted high above the operation at the top of a stack, while ground flares are at ground level. Within the ground flare designation, there are open and enclosed systems. Open ground flares can be oriented vertically or horizontally, often consisting of numerous burner heads/manifolds and (typically) surrounded by a radiation fence [68]. Enclosed ground flares include a metal structure surrounding the flame, which may be refractory lined. **Figure** shows an example of an elevated flare, an open ground flare, and an enclosed ground [69,70].

Figure 14. Flare types, elevated flare (left, from [69]), ground flare (upper right, from [70]), enclosed ground flare (bottom right, from [70]).

A final designation can be made between enclosed ground-level flares, and enclosed combustion devices, which are not considered flares according to CFR and EPA definitions [7,9,64,65]. As a result, enclosed combustors are capable of achieving greater than 99% efficiency (destruction or combustion) [51]. Examples of enclosed combustion devices include thermal oxidizers and incinerators [47,50]. An example of an enclosed combustor is shown in **Figure 15**.

A typical flare system consists of a knockout drum, which removes liquids and condensates from the gas stream, a seal and purge gas supply to prevent flashback, a single or multi-Tburner tip (mounted atop a stack for elevated flares), a gas pilot and ignition system, and if required forced air and/or steam injection. In some cases, a secondary flashback arrestor (stack seal) may be included near the burner tip to prevent flame propagation into the stack. Sweep or purge gases are introduced to prevent air/oxygen backflow or accumulation within the flare header, stack, and tip (maintain positive throughput). Sweep and purge gases could include natural gas, fuel gas, N_2, or CO_2 [50]. For cases in which oxygen is present in the flare manifold, sweep and purge gases also serve to reduce the FAR below the explosive limits. An example gas flare system layout can be seen in **Figure 16**, also showing the flare header piping, which transports process gas to be flared into the system, as well as an alternate gas recovery section. When operated in conjunction with a gas recovery system, the flare may be used as backup capacity or for emergency releases. Often, multiple flares are used in series or parallel. Parallel flares enable one to be taken offline for maintenance or due to malfunction without impacting upstream processes, while flares can be arranged in series to handle both low and high gas volumes [47].

Figure 15. Example of enclosed combustor, from [71].

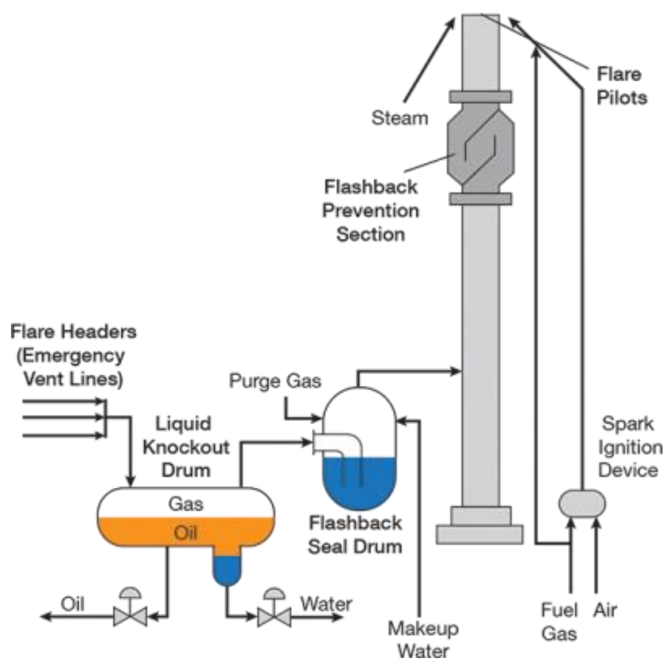


Figure 16. Typical gas flare system layout, from [72].

Separate from the physical system layout, are the monitoring and measurement devices and the flare control system. The sophistication of these components varies widely between industries, applications, and scales, with larger operations including real-time monitoring and control, including automatic flame detection and re-light procedures [73]. In the following sections, the technology associated with each flare type and system component category will be analyzed in detail.

Elevated Flares

Elevated flares are most prevalent and by design attempt to isolate the undesirable noise, heat, and visible flame emission from process and personnel. Because an elevated flare can distance the flame from the operation and personnel, they generally exhibit higher flow capacities relative to ground flares. Elevated flares are used in a variety of applications, including upstream and midstream oil and gas, petroleum refining, chemical processing, and bio-gas [47,68,74].

The defining feature of an elevated flare is the stack, which locates the flare tip anywhere from 10 to 100 meters above the process [47]. Illustrated in **Figure** , elevated flares can be self-supported (left), guyed (middle), or structurally supported by a derrick (right) [50]. An additional elevated designation used in offshore operations is flare tip placement at the end of a flare boom. For a given height, guy-supported flares are the simplest and cheapest to build, followed by self-supported flares (costs increase rapidly with height); derrick-supported flares are most expensive [50].

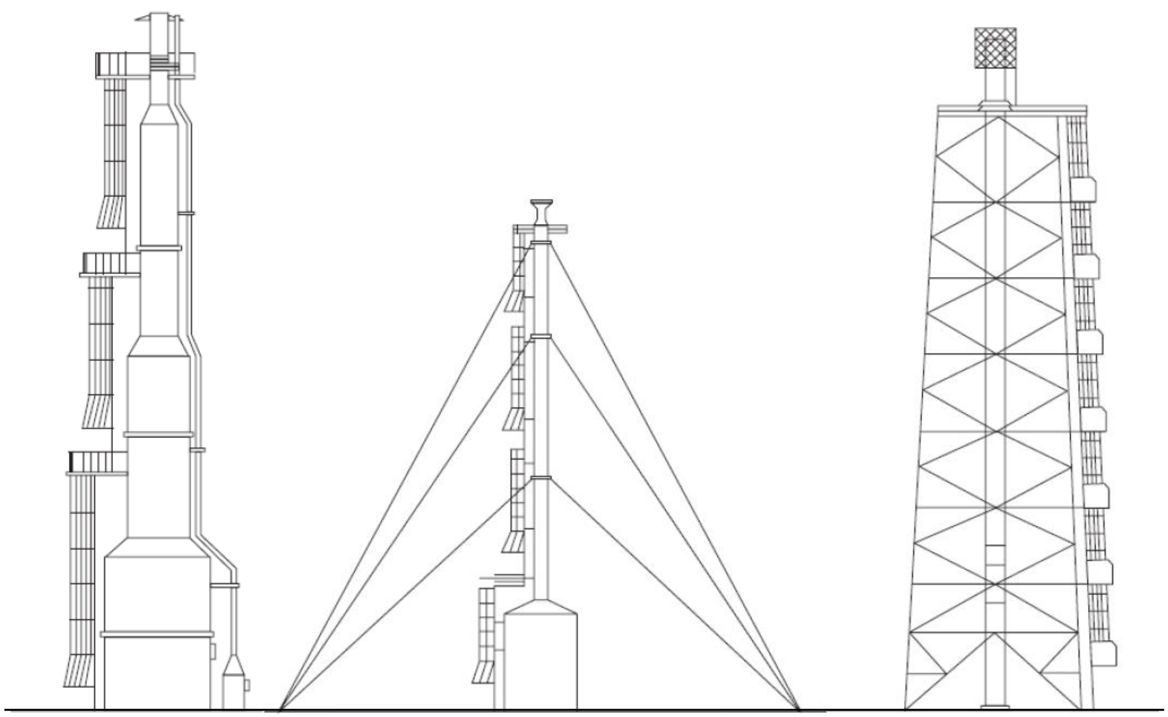


Figure 17. Elevated gas flare structures, self-supported (left), guyed (middle), derrick-supported (right), modified from [50].

Flare height is determined based on the ground level limitations of thermal radiation intensity, luminosity, noise, height of surrounding structures, and the dispersion of exhaust gases [50]. Considerations are also given for plume dispersion in the event of ignition failure, the requirements of which may be determined through plume modeling in a particular installation. Industrial flares are normally sized for a maximum heat intensity of 1500-2000 Btu/hr-ft2 [50]. At these intensity levels, personnel can only be near the flare for a limited time. To remain in the unit area continually, the recommended design radiation level drops to 500 Btu/hr-ft^2, neglecting solar radiation [50]. The minimum elevated flare height is approximately 30 feet, with the exact value determined by considering radiation emitted, lost to atmospheric absorption, and the maximum allowable radiation at a particular distance. The fraction of radiated heat can vary by flare gas composition, with a conservative estimate being ~0.3 (results in a conservatively tall flare stack) [50]. Similarly, neglecting atmospheric absorption (τ=1) allows for a conservative estimate. The net heat release is determined by multiplying the flare gas stream's expected heat content (including any auxiliary fuel or purge gas), by the total volumetric flow rate.

In almost all cases, elevated gas flares are diffusion flames, such that the flare gas must be mixed with air prior to burning. Good air/fuel mixing along with a stable, anchored flame are essential to achieving high combustion and destruction efficiencies and smokeless operation. The flare tip is largely responsible for this and may implement specialized design features specific to the application. A dedicated examination of flare tip technologies is included in a subsequent section.

A major factor affecting elevated flares is wind and other environmental disturbances. For this reason, elevated flares often include wind deflectors or other geometric features designed to minimize flame disturbance and the likelihood of extinction. The wind deflector features surrounding the flare tip in **Figure 18** are said to eliminate the low-pressure zone on the down-wind side of the flare to prevent flame impingement [75]. That is — wind deflectors such as this are not only designed to shield the flame from the wind, but also to minimize entrained air disturbances that can adversely affect the flame's ability to anchor at the appropriate location. Flame-holding structures may also be integrated into the tip design to mitigate the effects of wind and promote stable operation over a wide range of gas velocities [75]. Flare tip designs will be covered in detail in a section below.

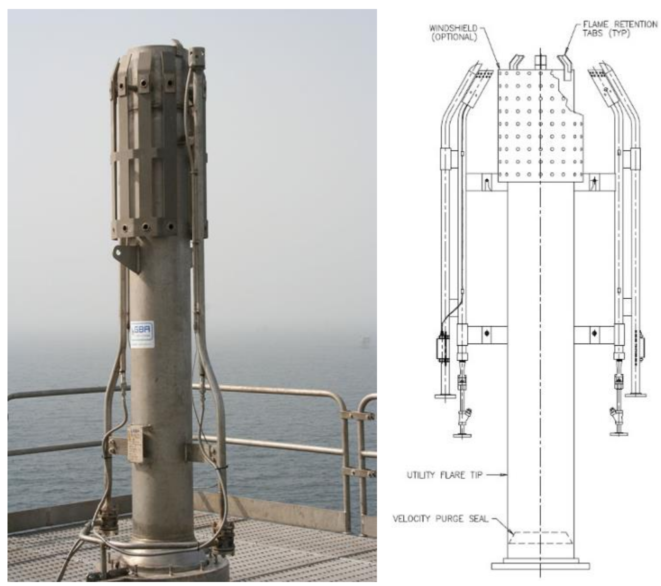


Figure 18. Utility flares manufactured by GBA (left, from [75]) and Encore Combustion (right, from [69]), showing wind deflection and flame holding structures.

Measurement and testing are major challenges in elevated flares due to their remote nature. Typically, thermocouples and/or flame rods (electrostatic probe) are used to detect the presence of a lit flare and the presence of a pilot flame [69,76]. Throughout the flare system piping, pressure measurement devices are used to ensure positive pressure is maintained and component pressure drops are within design specifications. To ensure flare tip velocity compliance, flare gas volumetric flow should also be measured. The technologies surrounding these measurement devices are covered below.

Ground Flares

Ground flares are flaring systems mounted at ground level, typically to hide the flame and reduce thermal radiation and noise as compared to elevated flares [77]. Ground flares are primarily used in locations where it is highly desirable to have a flare that is not visible to the public, such as industries in cities or near residential areas [78]. Two primary types of ground flares are used, open (multi-point) and enclosed ground flares (EGF). **Figure 1** below shows open and enclosed ground flare systems, respectively.

Figure 19. Open ground flare (left) [79] and enclosed ground flare (right) [77].

Ground flare systems are often chosen due to their efficiency under a range of operating parameters, including large variations in flow rates, the capability for nearly 100% smokeless operation and the ability to conceal the flames. Operating noise of ground flares is much lower than elevated flares. All ground flare equipment, including pilots and pilot thermocouples (to detect the presence of a flame), are located at grade. Thermocouples may be retractable for convenient and safe maintenance.

Ground flares are normally designed with staging of flare tips to allow efficient combustion at low and continuous flows and may have up to six stages with the flow rate of successive stages increasing up to a factor of three times the flow rate of the previous stage. As an example, a four-stage system with a first-stage flow rate of 1500 kg/h would have a total capacity of 60,000 kg/h across all four stages [77]. Ground flares generally operate without the need for assist air or steam since the waste gas pressure exiting the burner tips induces efficient air for smokeless combustion. However, the lower pressure first stage may have steam or air assist for combustion. One downside to ground flares is that the combustion products are poorly dispersed due to their proximity to the ground, which may result in local pollution issues in the event of flameout. Another disadvantage is that ground flares typically require more real estate than elevated flares. If ground flaring is required, the ground-level, staged, multi-tip flares will require less area.

Open (Multi-point) Ground Flares

Open ground flares are operated at ground level with the area surrounded by radiation fences and typically have a header to distribute gas to the burner tips located either in a refractory-lined enclosure or in an open pit. Multi-point ground flares are used wherever the flare gas flow is relatively high, 100% smokeless operation is required, higher DRE is desired and noise and light pollution must be minimized [80]. Open pit ground flares utilize either a series of standpipe-mounted burners on underground pipe manifolds or one large burner installed horizontally on one side of the pit. Open ground flares can generally combust larger quantities of gas than enclosed flares. The burners are divided into groups, which are activated via control valves in stages, with additional stages opening as header pressure increases with increased gas flow. Only the first stage of burners is operated continuously; purge requirements for enclosed ground flares are based on maintaining a required flow through those burners only. All staging valves and controls are located outside the radiation fence and are accessible for maintenance even when the flare is online. When a major upset occurs, pressure rises in the header and flow passes to an emergency elevated flare sized to handle the worst-case flaring contingency [78].

Enclosed Ground Flares

Enclosed (or concealed) ground flare (EGF) systems are designed with an enclosure-lined with refractory material to hide the flare flame from view, and combustion exhaust gases are discharged to the atmosphere through an opening at the top of the refractory-lined enclosure. The enclosure also serves to reduce ambient noise, radiation and smoke from the flare. The flare burners themselves are often constructed in arrays of flares with multiple tips [77]. Enclosed ground flares have stages like multi-point ground flares and use flare gas pressure to operate as 100% smokeless. Instead of a fence surrounding the ground flare (like in an open ground flare), waste gases are burned inside the refractory-lined enclosure. EGF systems are typically installed in plant areas that are populated or in close proximity to other equipment, or on plants with a small footprint [77,81].

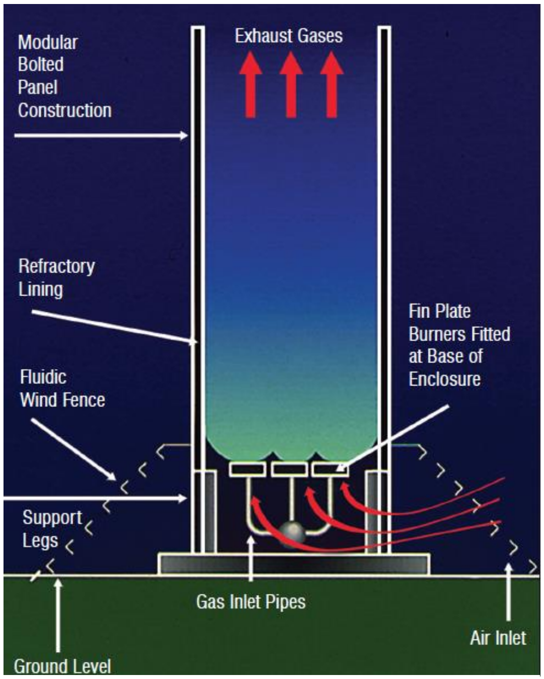


Figure 20. Enclosed ground flare showing air induction [74].

EGFs may be designed in rectangular or cylindrical enclosures. The circular enclosure is the most compact and can be constructed to higher elevations than rectangular enclosures [Argo]. Critical aspects of EGF design are the wind-smoothing fence located around the flare base and internal wind baffles located beneath the burners (see **Figure 20**). This arrangement smooths the air flow throughout the ground flare enclosure to enable greater combustion efficiency. Enclosed flare systems come in both natural and forced-draft types. Most units are temperature-controlled with sample ports available for measurements. Enclosed ground flares combust gases with a high DRE and emit no noise or light pollution. Because combustion occurs inside an enclosure, there is a limit to the flow rate of gas that can be flared. In emergency cases of high gas flow, vapors can be piped to an elevated or multipoint ground flare for emergency release. Common applications for totally enclosed ground flares include marine vapor combustors, truck loading terminals, and tank vent combustors [80].

EGFs are suitable for managing low and medium gas flow rates and are developed as per specific residence time allowing for a very high combustion efficiency under any atmospheric conditions.
Combustion chamber insulation materials are selected according to the flue gas velocity and operating conditions [82]:

- Ceramic fiber with different density, for medium flue gas exit velocity.
- Refractory cement, for high flue gas exit velocity.
- Refractory bricks, for high flue gas exit velocity and certain corrosive conditions.

Enclosed Combustors

Enclosed combustors are categorized separately from gas flares and include their own regulations per the CFR (combustion sources, Tier 4 [67]). Compared to a flare, the main defining characteristic of an enclosed combustor is the inclusion of a direct method to control the volume of air introduced beyond the fixed stack height [50]. Similarly, the enclosure is intrinsic to these devices and does not only serve as a shield. As a broad category, enclosed combustion systems or enclosed combustion devices (ECDs) may include enclosed combustors, thermal oxidizers, gas incinerators, vapor combustion units, regenerative thermal oxidizers, catalytic oxidizers, and others. These technologies enclose the flare or flame thus reducing issues associated with wind and other operating variables that may reduce the efficiency of open flares. ECDs most similar to open flares are enclosed combustors or vapor combustion units. These can be used to combust excess gas from oil and natural gas operations or to reduce VOC streams associated with oil and gas production processes. Both methods reduce wind impacts while reducing light and radiation. Incinerators and oxidizers can also be employed at industrial and chemical facilities to reduce VOCs and HAPS such as BTEX (benzene, toluene, ethylbenzene and xylene). Many of these systems are advertised as having efficiencies of 99.9% or higher. A recent study on hydrocarbon production in Mexico estimated that enclosed flares may represent a 23% cost savings compared to open flares (30-year case study) even though capital costs with enclosed flares is typically higher [83]. Their analysis included an assumption on general improved efficiency of enclosed units compared to open counterparts.

Incinerators may operate at higher temperatures to ensure pollutant reduction and in some cases have installation limitations (just as flares) due to exterior operating temperatures and heat radiation. Enclosed combustors may include insulative materials on the stack to enable their installation closer to other site components and operations. ECDs can operate as natural draft or mechanical draft (relying on air supplied from a blower) and are available from numerous companies (e.g., Cimmaron [84], Encore Combustion [85], MRW Technologies, Inc. [86], GBA [75], Hero Flare [87], TSI [88], Catalytic Combustion [89], and various other manufacturers). In some cases, flares may be cheaper than ECDs, but this depends on the equivalent complexity of both systems. In addition, regulations may limit open flares in some locations such as production sites [90].

ECDs are typically categorized based on their maximum allowable combustion rate in BTU/hr, and this includes the impact of gas composition (heating value) and available flowrate. ECD selection is also impacted by operating pressure. ECDs that are applied to systems such as tank batteries may have limited pressures (< 1 psig) available to transport the fuel from the source to the combustor. This may further create issues for any flow or composition analysis equipment, which may further add to the feed line pressure losses.

Figure shows a basic schematic of an enclosed combustor (natural draft) but designs may vary [91]. The feed gas is fed toward the combustor through a flame arrestor. Just as with open flares, systems utilize a pilot gas and ignitor (may be multiple). These pilots can be monitored with temperature devices, flame ionization detectors, or UV sensors to ensure the pilot remains lit. The main gas is fed to one or more main burners (contra type shown). Air enters through the bottom of the combustor through various inlets and dampers. For natural draft systems, the stack effect provides the motive force for air. Then the flames and combustion products move vertically through the main body and exit via an open top. As discussed above, ECDs can use insulation or refractory materials to ensure decreased exterior temperatures. Unlike open flares, ECDs can include various test ports on the exhaust to enable emissions composition and flow analysis. This simplifies quantification protocols for determining efficiency based on emissions measurements. ECDs may also include a stack temperature monitor to ensure that combustion temperatures remain at or above any regulated temperatures (e.g., above the minimum ignition temperature of methane). For example, Hy-bon recommends minimum operating temperatures of 1400 °F and maximum temperatures of 2100 °F [71].

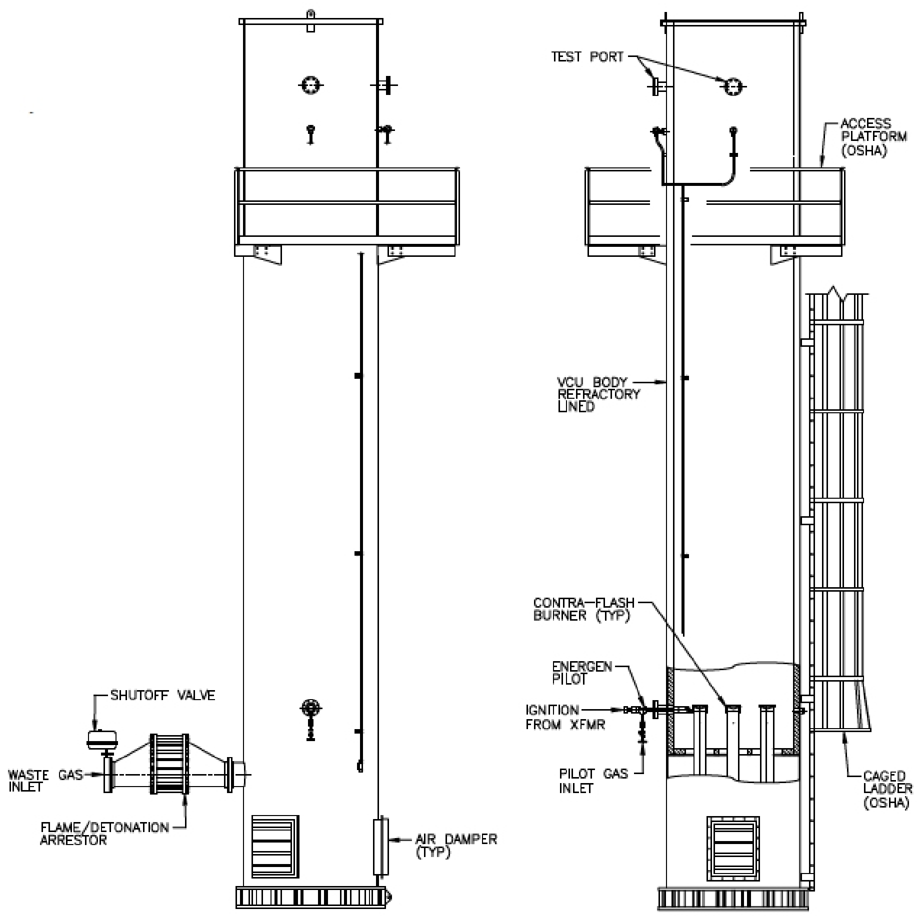


Figure 21. Example of natural draft ECD with key components labeled, from [91].

As with flares, ECDs are intended to be operated as smoke-free devices. Common issues that can impede performance or induce smoking include restrictions in lines — both the fuel and air, clogger burner orifices or tips, which may lead to mixing issues, or possible hydrocarbon liquid carryover beyond the knockout.

Various manufacturers advertise ECDs with destruction efficiencies of greater than 99.9%; in fact, some claim destruction efficiency of up to 99.9999% [51]. However, just as with other combustion or flare systems, these destruction efficiencies are based on tests conducted under controlled conditions. One manufacturer that claims 99.9% destruction efficiencies warns of using default values for emissions reporting purposes because of these testing conditions [92]. They identified the following issues that may yield lower combustion efficiency in real world applications: 1) for OOOOa testing, propene is typically used to assess flare and ECD efficiency as opposed to natural gas or other feed gas compositions; 2) during testing, ECD extensions can be installed for sample port requirements, whereas field applications may have shorter combustion zones; 3) though impacts are reduced using ECDs, wind may still affect operation; 4) variations in ambient air temperature; 5) variations in gas flow rates; and 6) variations in ambient pressures. In a review of various permits, it appears that the use of the default efficiency of 98% is common [37,93].

Thoma et al. reported field measurements of ECD performance [94] for ECDs deployed at 10 production sites as an emissions control for condensate tanks. The study team used passive Fourier transform infrared radiometer (FTIR) or mid-wave infrared hyper-spectral imager (HIS) for inspection at distances just beyond 50 m from the ECD/stack. When working properly, combustion efficiency could be greater than 95%, although combustion efficiency varied throughout the day and in some cases was as low as 60%. Another study examined ECDs at six facilities in Wyoming (state has thousands of ECDs) [95]. They found ECD combustion efficiency ranged from below 20% to above 99%. Their approach used portable emissions analyzers, anticipating that their findings would lead to EPA approving this technique to test ECDs. The study team also identified that best management practices should include combustion zone temperature monitoring and maintaining minimum gas stream inlet pressures. They also found that restricted air intakes typically achieved higher efficiencies. Recent research has utilized computational fluid dynamics (CFD) modeling to improve burner operation inside enclosed flares. Smith et al. examined enclosed combustors that used high and low flow burners [96]. They found that relative velocity through the burner throat was crucial for flame stability and that burner placement within the stack impacted internal flow during normal operations. **Figure** presents an example of the four-burner configuration compared to the total size of the combustion chamber and stack.

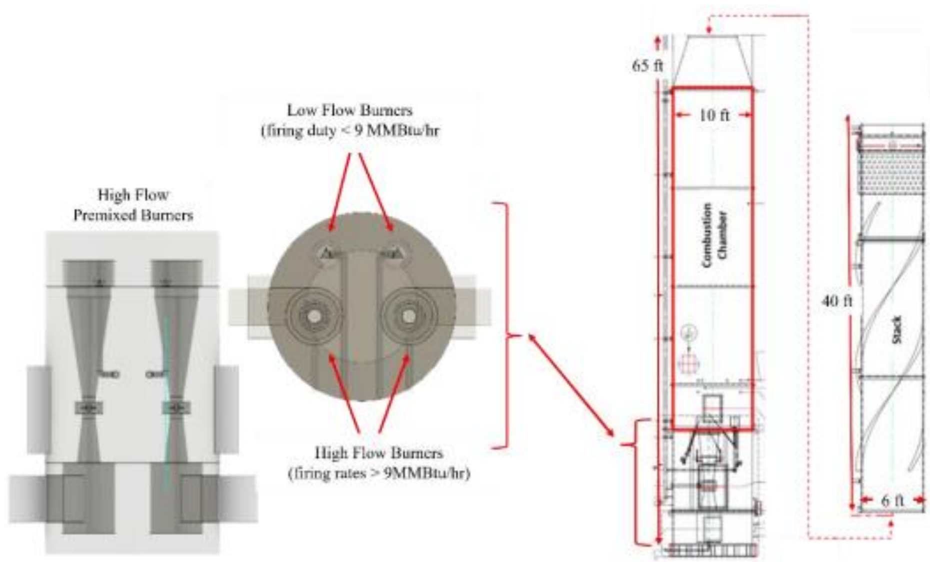


Figure 22. Enclosed flare configuration used for CFD studies to examine design, from [96].

Flare Tip Designs

Among the components comprising a gas flare system, the flare tip design has the greatest impact on flame stability and emissions performance. CFR and EPA regulations largely dictate emissions, monitoring/reporting requirements, and a few operational aspects (e.g., tip velocity) for flares, however they often do not include design guidance. For flares in the petroleum, petrochemical, and natural gas industries used for pressure relief purposes, the API 521 [97] and ISO 23251 [98] provide this type of information for sizing, selection and other technical details relating to the design of gas flare tips and piping systems. This information is primarily provided from a safety perspective. In general, promotion of fuel-air mixing is the most critical aspect of the flare tip design. Flare tip designs can be largely designated by gas pressure (high/low) and whether they are assisted (air/steam) or non-assisted. Non-assisted flares are systems in which the flow of flare gas entrains air to support the combustion process (*self-aspirating* type). This approach is typically limited to gas streams with low heat content and a low C:H ratio, which require less air and burn easily without smoke formation [50].

Most low-pressure flares are considered utility flares, which are the most basic and inexpensive flare type. Utility flare tips often consist of a simple pipe that entrains surrounding air in a co-flow arrangement. This approach generally results in low turbulence levels, making it challenging to achieve specific equivalence ratios and mixedness. For this reason, many utility flares are not considered smokeless, largely driven by rich local-equivalence ratios due to low air penetration into the flame core and/or generally poor mixing. Utility flares are typically designed to maintain Mach<0.2 for continuous flaring and Mach<0.5 for intermittent flaring [99]. While lower gas velocities can help in minimizing the potential for blowoff, low pressure utility flares are more susceptible to wind. Utility flares tend to be most prevalent in small operations where a low-cost option is required, and smokeless operation may not be mandated. In particular, this includes unconventional oil and gas plays and APG applications, which are expected to utilize utility flares due to low gas pressure and an often dispersed nature (i.e., a large number of small wells) requiring low capital expense. No information was available to confirm the distribution of flare technologies in the field. Almost all flare manufacturers have utility offerings within their product line.

High-pressure gas streams (above ~14 psig) are often able to be burnt unassisted due to their ability to entrain sufficient amounts of air and the use of advanced tip designs with increased turbulent mixing. Note that some manufacturers designate "pressure" as an assist medium when describing flare technologies. One common high-pressure design is the sonic tip. While utility flares operate subsonically (i.e., the gas Mach number is maintained below 1), higher gas pressures can enable the use of sonic flares to promote increased air entrainment, lowering smoke and flame radiation, and shortening flame length [100]. These designs operate on the principal of utilizing a converting flow path to create a choke point (Mach=1) at the flare tip exit. As the flare gas passes through this exit restriction and expands into the atmosphere, it rapidly expands, resulting in a drop in local pressure and a corresponding increase in gas velocity. This promotes entrainment of the surrounding air at a rate above that of a subsonic flare and increases turbulent mixing.

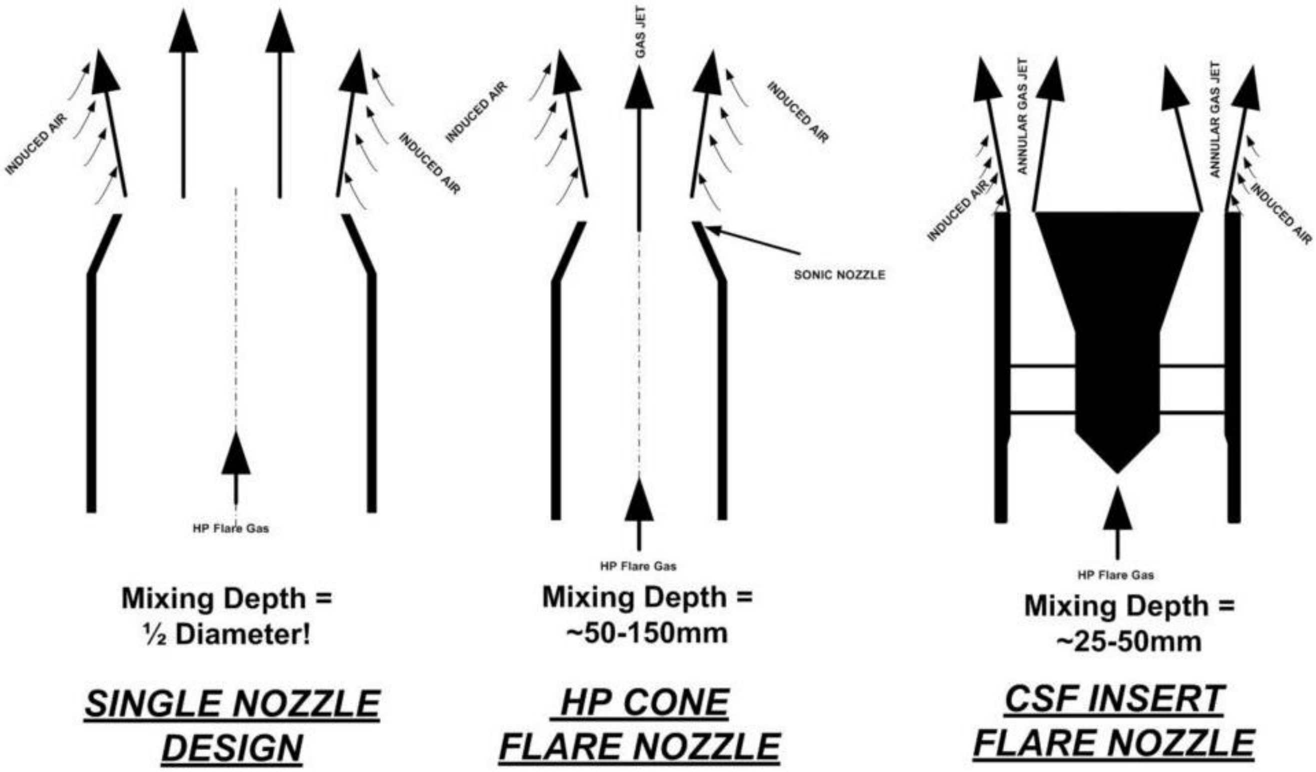


Figure 23. Subsonic vs. HP Sonic nozzle designs, from [105].

Figure 23 illustrates the mixing improvements achieved using sonic flare tips. An annular passage can help to increase the air/gas contact area and/or act as a bluff-body to aid anchoring and stabilization (**Figure 23**, right). In some designs, the exit area is variable via a pressure-driven, spring-loaded centerbody, enabling automatic flow rate adjustment for improved turndown performance. The variable-slot sonic flare tip design is one of the more advanced technologies currently implemented in flares but is only applicable for high-pressure gas streams. Larger manufacturers such as John Zink Hamworthy [76], GBA [75], Cimarron/Aeron [101], and ZeeCo [102] produce variable-area sonic flares. More conventional fixed-area sonic flares are produced by numerous manufacturers including Mission Flares [103], Flaroman [104], Hero Flare [100], and others.

Figure 24. Multipoint sonic flare tip, from [105].

Sonic tips are often used in conjunction with a multipoint flare design, as shown in **Figure 24**. The goal of the multi-point approach is to control the exit gas velocity and flame length for high flare gas flow rates, as well as to maximize the contact area between the flare gas and surrounding air.

A further extension of the multipoint flare is the inclusion of burner staging, such that depending on current flow rates, part or all of the flare tips may be utilized. This serves to further enhance turndown performance for multipoint flares. Some designs utilize staging valves to control gas delivery to first and second stage manifolds (e.g., Zeeco [102]). Others implement multiple setpoints on the exit area adjustment mechanism, enabling automatic transition from first to second stage operation (e.g., John Zink [74]). An example of this transition is shown in **Figure 25** for a John Zink KMI flare system.

The KMI Indair flare tip from John Zink is an example of a more sophisticated flare tip design — the Coanda. Coanda flare tips are a high-pressure design consisting of an annular slot and a tulip-shaped contoured profile that uses the Coanda effect to entrain large volumes of air into the gas stream [77]. An example of a Coanda flare tip can be seen in **Figure 26** (left), with the inset illustrating flame structure. The principle behind the Coanda effect is illustrated in **Figure 27**.

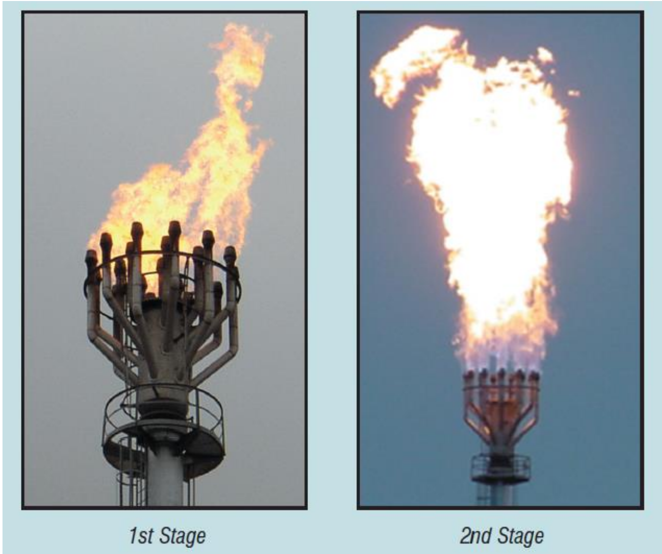


Figure 25. Two-stage flare operation with increasing gas flow, from [74].

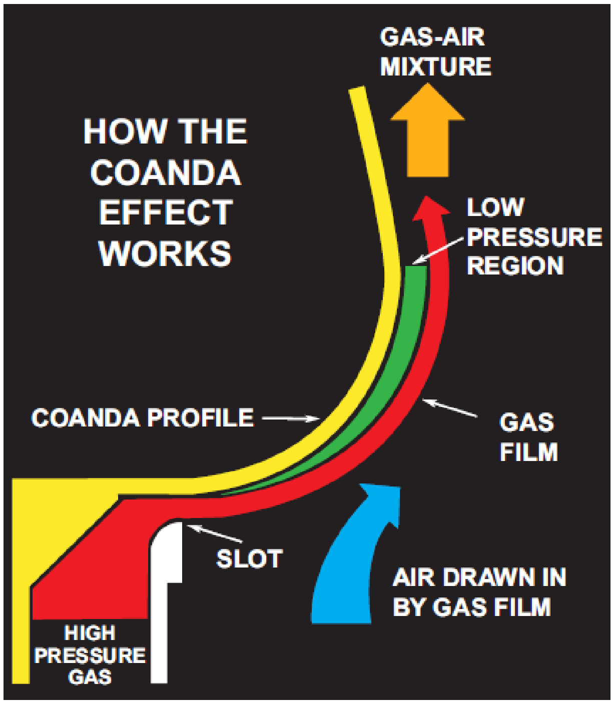


Figure 27. Coanda effect principal, from [77].

Figure 26. Coanda flare tip, from [100].

Coanda flares exhibit good turndown and smokeless capability when combined with a variable orifice (similar to sonic flares). Because gas clings to the Coanda profile, they exhibit good wind performance. It is also noted that low-pressure gas may be fed into the central part of the Coanda tip and flared smoke-free within the main high-pressure flame [77]. However this approach can also be utilized in conventional annular sonic tips [75], and is not unique to Coanda flares. A similar concept has been employed for ground flares, using a fin plate burner [74]. Shown in **Figure 28**, gas impinges on a plate forming a thin film, which entrains air as it travels upward. A curved end causes the flow to separate and create a flame stabilization region.

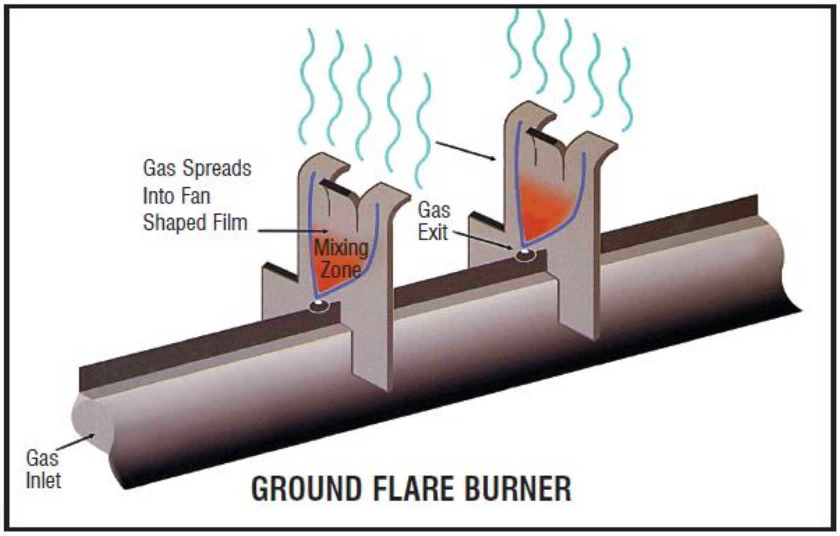


Figure 28. Fin plate ground flare burner, from [74].

Steam and air assist are generally used as needed to control smoke formation. A major driver for this is the presence of heavier hydrocarbons [77,102]. Because high-pressure flare technologies are generally able to achieve smokeless combustion with advanced tip designs, air and steam assist are most prevalent in low-pressure applications. Supplemental air or steam help to achieve smokeless combustion by promoting enhanced air entrainment and mixing. Here, the overall goal is to reduce the formation of rich pockets of reactants that tend to produce soot and/or result in incomplete combustion. In steam-assisted flares, high-pressure steam is used as a source of momentum, thereby entraining additional air for combustion and simultaneously enhancing turbulent mixing. This approach differs from other uses of steam injection in combustion systems, which may be for flame temperature control to reduce nitrogen oxide emissions [106]. That said, it has been suggested that steam injection imparts kinetic effects by promoting oxidation of carbon particles and reducing cracking and polymerization through temperature reduction [50]. A majority of assisted flares implement steam injection, which is often favored over supplemental air due to increased flow momentum [50]. Air assisted flares operate on the same principle, supplying additional air to the combustion process through a fan or blower. Tradeoffs exist between air and steam injection, requiring either on-site high-pressure steam generation or electricity to run a fan or blower. The technology used is typically dependent on the availability of steam/water vs. electricity. **Figure** and **Figure** illustrate the clear impacts of steam and air assist, respectively.

Figure 29. Impact of steam injection on smoke formation, without (left), with (right), from [76].

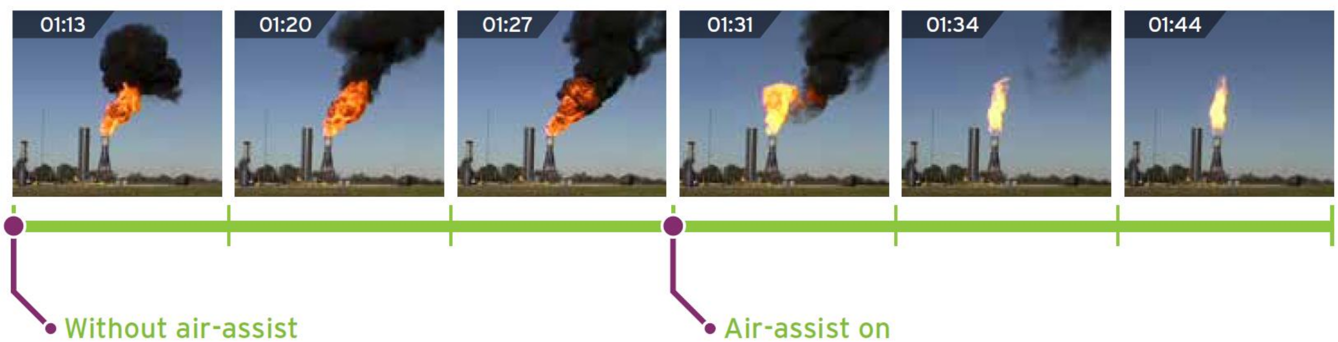


Figure 30. Impact of air assist, from [107].

Steam-assisted flares require large quantities of steam at or above ~4 bar [77]. The quantity of steam required is proportional to the maximum smokeless flow rate and the C:H ratio of the flare gas stream. This is designated to cover known planned flaring situations and unknown process upsets, generally ~15% of total flare capacity [77]. In the simplest systems, steam nozzles are distributed circumferentially around the perimeter of the flare and aimed inward. The momentum of the high-pressure steam discharge promotes increased air entrainment and turbulence, in particular helping to penetrate the core flow. Additionally, steam injection helps to control flame shape in high wind, and reduce radiation levels [102]. **Figure** shows an example of steam injection added to a utility flare. Here, the nozzles are located outside the flare gas pipe, but inside the wind shield. Also shown are several flame holding tabs designed to create a low-velocity region that can be easily ignited by the pilot flame.

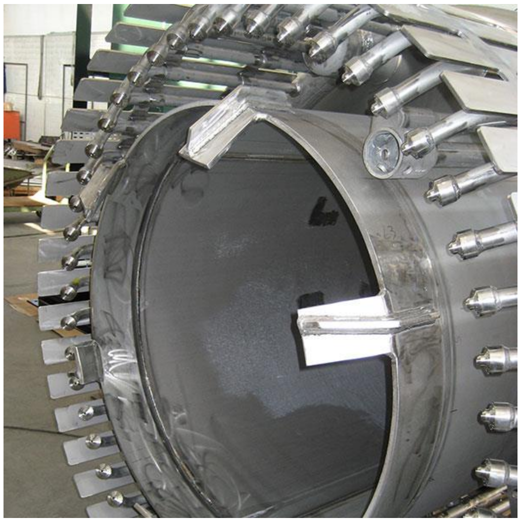


Figure 31. GCT steam assisted flare tip, from [75].

A byproduct of the use of steam injection in gas flares is increased noise. This is driven by the rapid expansion of high-pressure steam through narrow nozzle orifices, rather than interaction with the flame itself. If the flare is located near a populated area with strict noise ordinances, this can pose a problem. Many manufacturers have developed low-noise flare tips, which attempt to muffle and re-direct pressure waves created by the steam nozzles. Zeeco suggests their low-noise HCL series flare tip reduces the noise level by 10-12 dB [102]. As shown in **Figure** , this is generally accomplished through the use of internal steam injection, where a tube system routes a steam/air mixture into the interior of the flare gas column [108]. Within the tube interior, baffles or other structures are incorporated to reduce the acoustic signature of the steam injection. An added benefit of this approach is reduced steam requirements. Most manufacturers include steam injected flare products, including ZeeCo [108], GBA [75], John Zink [76], Aeron [101], Flaroman [104], and more. A slightly smaller subset of these companies include low-noise offerings, including Zeeco [108], GBA [75], and John Zink [76], to name a few.

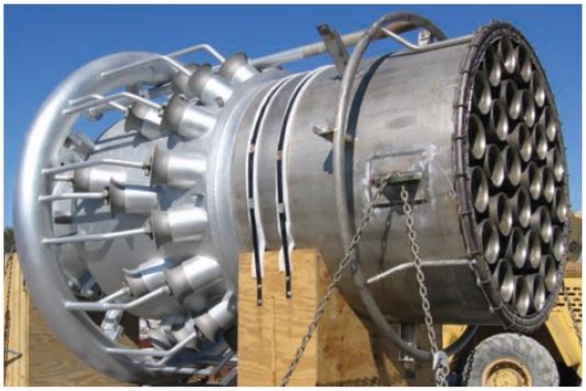


Figure 32. Low-noise steam-assisted flare, from [108].

Other novel steam injection strategies have also been incorporated into some offerings, with the goal of further reducing steam requirements, which can represent direct cost savings to an operation. One example of this is shown in **Figure**, which incorporates a venturi section along with a supersonic steam injection nozzle to enhance air entrainment.

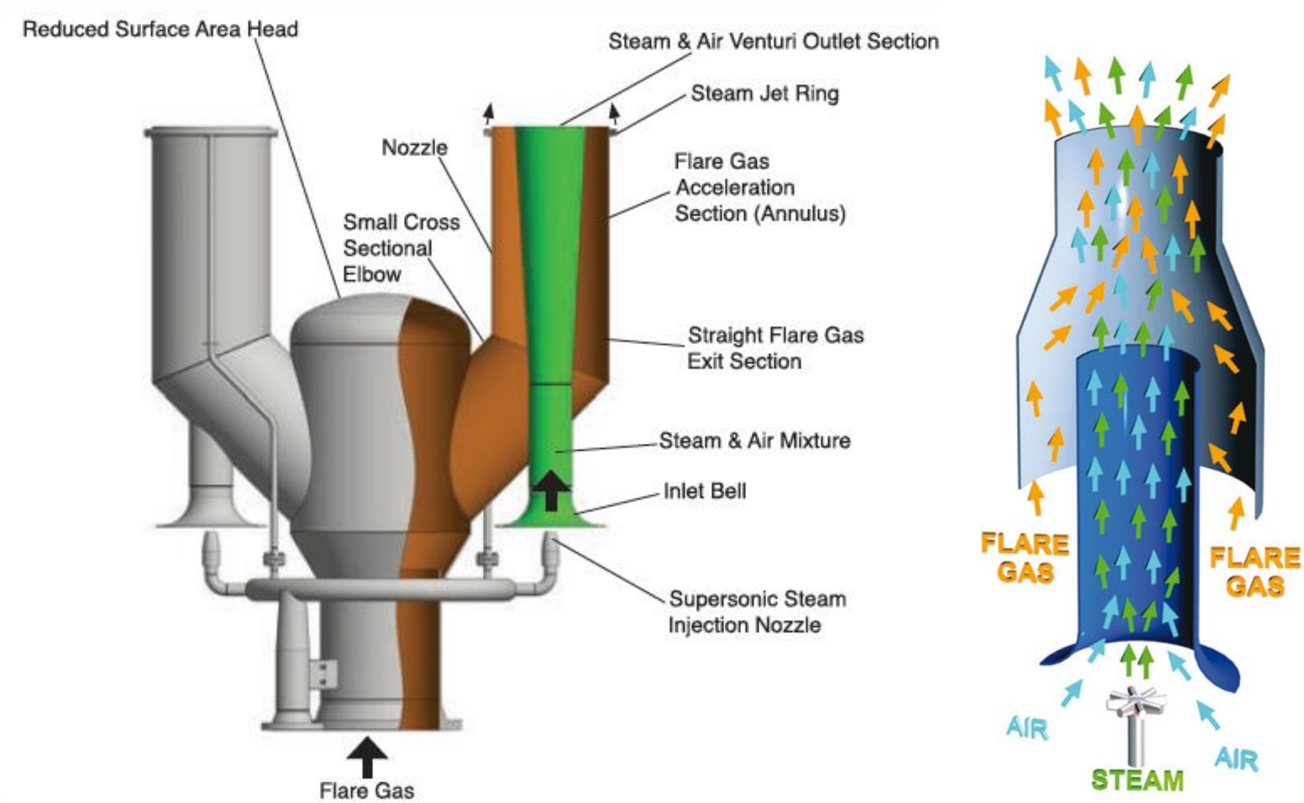


Figure 33. Venturi-style steam assisted flare, (left) from [109], (right) from [110].

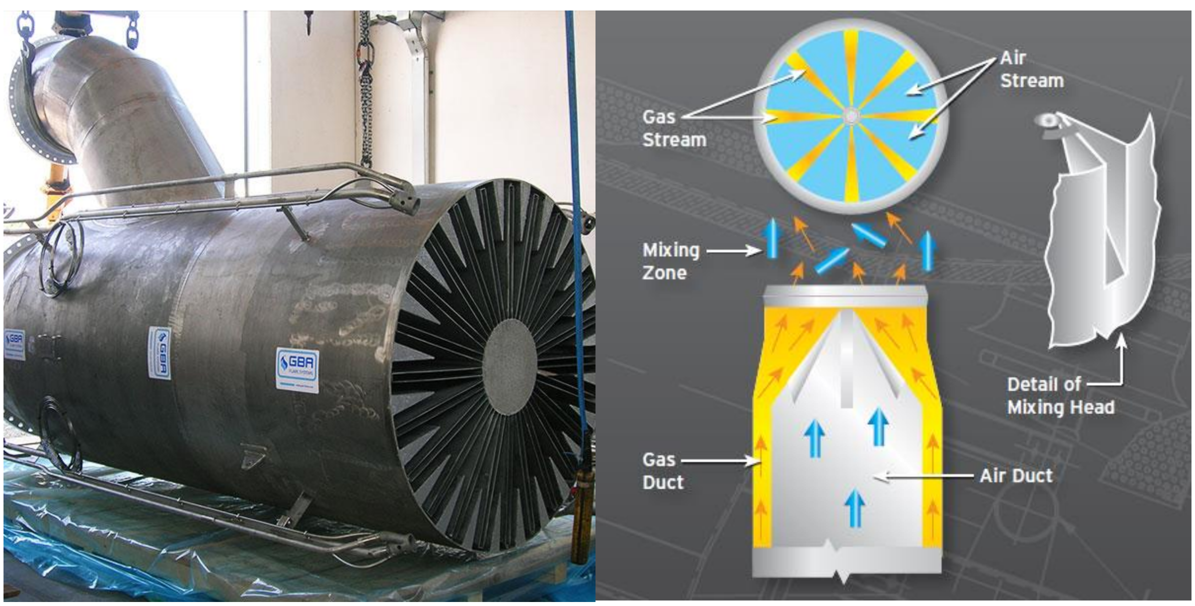
It is noted that two common factors causing flare incidents are ineffective condensate removal (via knockout drums, see next section) or poor quality/wet steam [111]. This can result in tip and ring erosion, improper steam control, flare-outs, tip damage, smoke formation, water backflow, ring fracture, or falling ice (caused by condensate being discharged and freezing). All this to say, the steam generation and delivery systems represent a critical component in steam-assisted gas flares.

Air assist is another approach used to achieve smokeless performance. In general, air-assisted gas flares are less prevalent compared to those that are steam assisted. These systems differ from self-inspirated or steam-injected flares in that they do not rely on entrainment, but rather introduce pressurized air via a blower or fan system. This enables more complex turbulent mixing approaches to be implemented, and perhaps equally important, can offer airflow tuning through the use of dampers or variable speed fan/blower motors [77]. This gives air-assisted flares good turndown performance. Similar to steam injection, forced air is typically used for low-pressure applications where smokeless operation cannot be achieved without assist. It is noted that a properly operated air-assisted flare can achieve well over 98% destruction efficiency, but the equivalence ratio must be within a certain range to avoid lean blow out [112]. The use of air assist has the added benefit of shortening flame length and reducing radiation [113].
As illustrated in
Figure, air-assisted gas flares generally locate a blower at the base of the flare stack/riser and maintain separate air and flare gas streams until reaching the tip. This minimizes the likelihood of flashback compared to premixing. Most air-assisted flares implement a co-annular configuration, with the flare gas traveling down

a central flow path, and air being fed into the outer annular region (or vice-versa). These systems are generally designed for low air velocities, minimizing pressure drops within the system, and conserving the blower capital cost by minimizing its power requirements [114].

Figure 34. Air-assisted flare blowers, from [113].

Most air-assisted flares implement tip designs that aim to maximize the contact area between the flare gas and air. Some also implement swirl vanes to increase turbulent mixing. The flare tip in **`Figure**, left, implements slotted flow paths that extend radially through a duct. A number of wedged geometric features are included to further enhance mixing and/or flame holding. In **`Figure**, right, a similar design is illustrated using a recessed, cone-shaped air duct, again with the intention of maximizing the contact area between flare gas and air, as well as introducing features designed to promote turbulent mixing. Of note, these designs are only feasible due to the use of forced air.



**`Figure 35.** Air-assisted flare tips, from [75] (left), [107] (right). `

Other air-assisted designs mimic the approach of low-noise steam-assisted flare tips, as shown in **Figure 36**. Again, the design goal is to maximize the flare gas/air contact area and to ensure core flow penetration. Air-assisted gas flares utilizing blower technologies are sold by most of the major manufacturers, including Zeeco [113], GBA [75], Aereon [101], Hero Flare [112], John Zink [107], and more.

Figure 36. Air-assisted flare tip similar to steam assisted designs, from [107].

A slightly more novel approach to air-assisted flares is the use of high-pressure air, supplied by a compressor (either as part of the larger operation or stand-alone). This technology is primarily targeted at retrofit applications where water/steam is not available. Because traditional air-assisted flares incorporate large blowers and annular air paths, adoption of these technologies generally requires complete replacement of the flare and stack. The high-pressure air approach mimics that of steam injection, by introducing air through a number of supersonic injectors [114]. In this approach, smaller quantities of air (~10% that of low-pressure blower systems) at much higher pressure are utilized to entrain additional air into the flame zone. This is contrary to low-pressure blower-based air-assisted flares, in which the blown air is the primary oxidizer source. A major benefit suggested for these systems is the use of a single small-diameter air tube, which is easily retrofittable onto the existing flare stack exterior. Zeeco [115] and Hero Flare [116] offer high-pressure air-assisted flares, and this technology is prevalent in Saudi Arabian operations (originally licensed by Aramaco). **Figure 37** shows an example high-pressure air-assisted gas flare tip by Zeeco, accompanying what otherwise appears to be a utility design.

Figure 37. Zeeco HPAAS gas flare tip, from [115].

A final type of assist used in some gas flare operations is gas assist. In gas-assisted flares, a supplementary fuel gas is supplied to enhance the combustion characteristics of the waste gas and/or promote additional air entrainment/mixing, similar to steam or high-pressure air assist. Specific application areas include operations where using steam or air-assist isn't possible, where there is an abundance of high-pressure fuel gas, or for specific low-flammability gas mixtures [77]. In terms of the latter, this may include low-BTU gases involving acid gas, ammonia, or a large inert content. Gas-assisted flares generally utilize a design similar or identical to steam or high-pressure air-assisted flares. In fact, offerings by Hero Flare [116] and Flaroman [104] advertise dual-use air/gas and steam/gas, respectively. Most often, gas-assisted flares utilize natural gas as the fuel, though there are instances of propane usage. Compared to air-assisted flares, gas-assist generally has a lower initial cost but higher operating cost due to high-pressure fuel gas consumption [117].

A separate flare tip designation is sometimes used for systems that specifically target the destruction of liquids/condensates. These tips generally implement one of two strategies, either the inherent pressure of the incoming liquid is used to atomize and evaporate the liquid droplets, facilitating efficient burning, or supplementary air, steam, or fuel gas is used to induce breakup and mixing with air and combustion. These systems attempt to achieve smokeless combustion (if required) and to minimize liquid fallout, which can be particularly hazardous for elevated flares. For this reason, many liquid burners are ground-based and/or pit flares. John Zink [76], Aereon [101], Zeeco [102], and Cimarron [118] produce flare tips designed for liquids destruction.

Knockout Drums

Knockout drums are used to separate liquid hydrocarbons/condensates from the waste gas stream prior to flaring. Most flares not designed specifically for liquids are still capable of efficiently burning small droplets below ~100-300 μm or so [119]. As such, knockout drums are generally designed to remove larger droplets using a gravity-driven approach. The goal of the knockout drum is to slow the gas stream velocity sufficiently that the mass of the droplets causes them to fall downward rather than being conveyed by drag along the gas streamline. This occurs when the residence time of the vapor or gas is greater than the time required for a droplet to travel the available vertical height within the drum [119]. In addition to removing droplets above a given size, knockout drums attempt to minimize pressure drop, particularly critical for low-pressure gas streams.

Figure 38. Horizontal knockout drum, from [120].

Horizontal and vertical knockout drum designs can be utilized. An example of a horizontal drum can be seen in **Figure**. For a horizontal drum, vapor enters at one end of the vessel and exits near the top of the other end. Along its length, particles fall and pool at the bottom of the vessel, and/or drop out through impaction on the far wall. Vertical drums include an inlet nozzle directed downward toward the liquid accumulation pool, and an exit near the top. Baffles may be incorporated within the upper portion of the drum to enhance dropout via impaction, without causing significant pressure drop. Knock-out drum sizing includes consideration of expected gas/vapor flows, droplet drag coefficient, and geometric parameters/orientation of the vessel.

Flashback Mitigation Devices

Both open and enclosed flares include a flashback mitigation device to ensure safe operation. Flares may have multiple flashback mitigation devices including those incorporated on the stack, those on the feed fuel, and those on pilot systems [121]. **Figure 16** shows an example open flare that includes a flashback mitigation device both on the stack (flashback prevention section) and on the feed gas (flashback seal drum). A flashback seal drum avoids air entry into the flare fuel header through use of a hydrodynamic sealing fluid, which in many cases is water. Further, if an explosion or other failure occurs within the flare stack, the seal drum prevents flames from communicating with the upstream fuel. These may be external or included within the flare stack [121]. There are various manufacturers of liquid seal drums. Encore Combustion presents a schematic for their systems, which is shown in **Figure** [122]. This system uses water and a submersed cone gas diffuser where the flare fuel gas flows downward into the liquid seal and then bubbles upward to feed the flare. This method also creates a positive pressure on the feed gas, which may not be applicable to low-feed pressure systems. Such systems can also remove any liquids that may be in the gas stream or any that have slipped past liquid knockout systems. In addition, flashback seal drums require liquid level monitoring and make-up water to ensure proper operation.

It should be noted that, as gas flow increases through the liquid seal system, direct communication might occur between the exit and inlet streams if there is an uninterrupted flow path through the water [123]. In addition, improper design or operation of a flashback seal drum system can lead to pulsating flows whereby the main flare may be extinguished as flare fuel gas pressure builds up behind the seal. Once the pressure is overcome, feed gas "slugs" are exhausted, which reignite the flare due to the pilot/ignition systems.

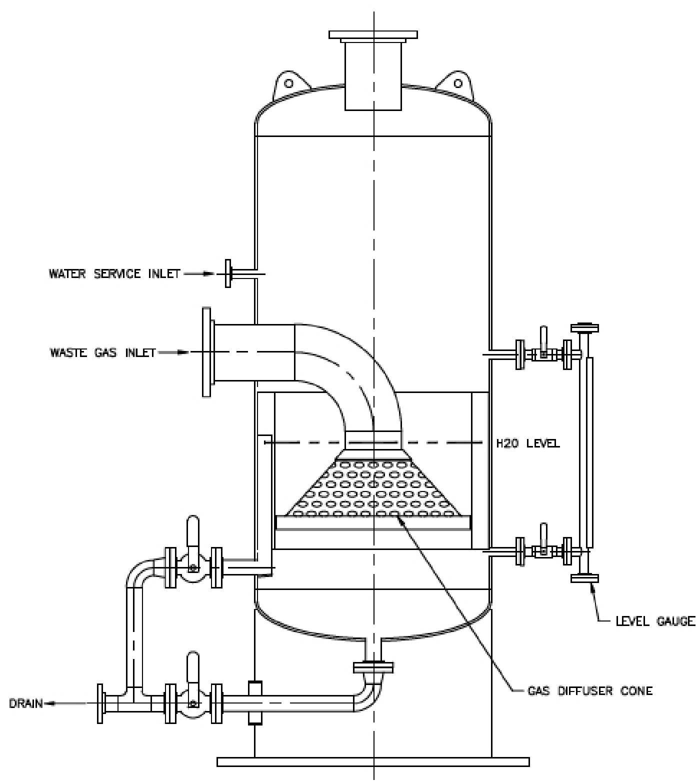


Figure 39. Example of external liquid seal drum to prevent flashback on flare gas feed fuel, from [124].

There are a variety of options for flashback mitigation within the flare stack itself. One method uses a purge gas to prevent air from entering the flare stack, creating a combustible mixture with the stack itself. However, purge gas may require additional blowers or compressors, a source of oxygen-free gas, or it may add to flare emissions. One flare manufacturer (John Zink) recommends purge gas velocities of 0.25 to 50 ft/second [76]. To reduce the demand of purge gases, flares can include either velocity or molecular seals within the stack. **Figure 40** presents example schematics of both types [124]. Velocity seals increase the purge gas velocity through an area reduction, which entrains any entering air and expels it through the flare tip. John Zink's velocity seal system advertises a reduction in required purge gas velocity to only 0.04 ft/sec. They provide an example for a 20-inch diameter flare where normal purge gas flow rates were 2500 standard cubic feet per hour (SCFH) but the velocity seal reduced the required purge rate to 300 SCFH [123]. The molecular seal system uses one or more baffles to change the purge gas flow direction to ensure air backflow does not occur. Molecular seals tend to require slower purge gas consumption than velocity seals, however, case studies have examined issues that can impact flare operation including the need to ensure proper drainage of liquids from the bottom of molecular seals [125]. Liquids can include water condensate from air or steam systems. John Zink also presented an example of purge gas reduction using their molecular seal. The purge gas required would be further reduced to only 75 SCFH [123]. Other case studies of deflagration incidents recommend that hot gases should not be supplied to flares as the elevated temperatures can increase flame speed, enabling downward flame propagation even with active upward purge flows [126].

In addition to flashback mitigation devices on the flares and fuel systems, flame arresting devices can also be employed on the device air inlets. For example, Canadian regulations for enclosed combustors require that, "All intakes must be equipped with a flame arresting device." [127]

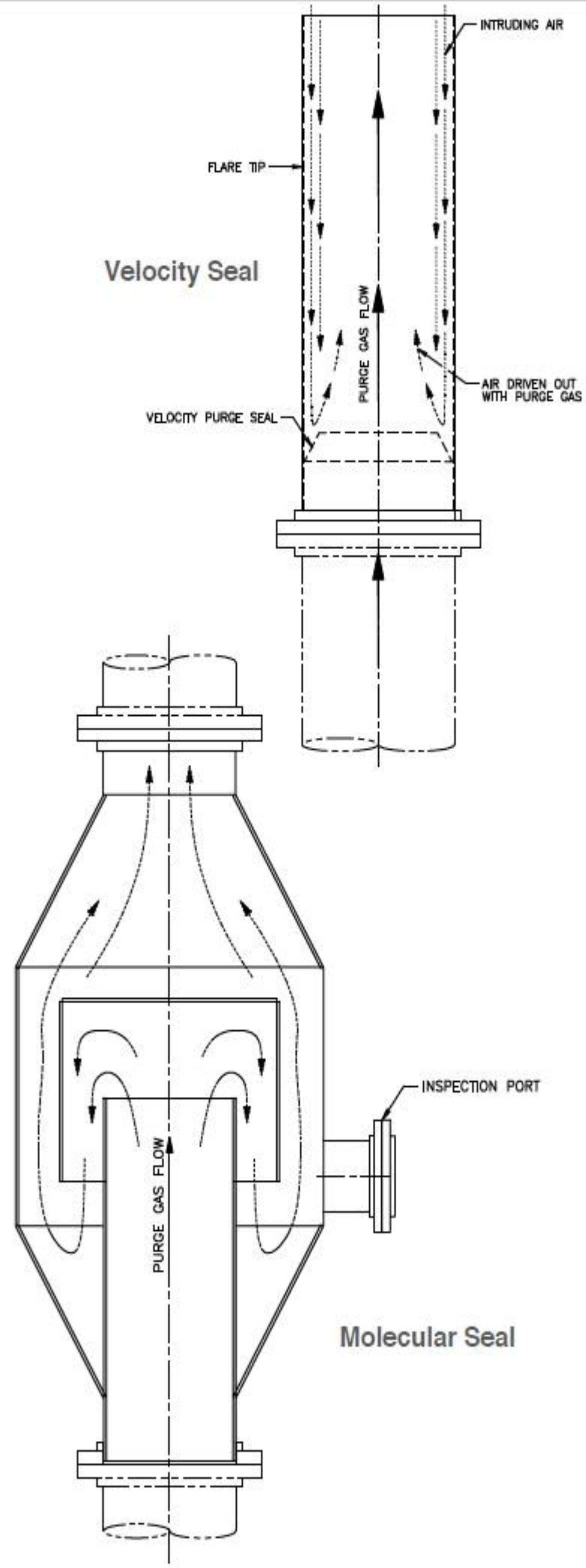


Figure 40. Velocity and molecular seals used to prevent flashback, from [124].

Flame arrestors can be installed on flare systems' fuel or air lines and are available from multiple manufacturers. For example, Tornado provides three different flame arrestor systems. Such technologies may utilize either a stainless steel or aluminum crimped ribbon element that is applicable to low pressure systems [128]. The ribbon elements act to dissipate heat to quench the flame front. Similar approaches can be used for pilots using flame front ignition. **Figure 41** presents an example of a wound crimped ribbon flame arrestor commonly used on various natural gas systems including flares.

Figure 41. Example of wound crimped ribbon style flame arrestor that can be used in various natural gas system components including flares, from [128].

Pilot and Ignition Systems

Pursuant to various current state and federal regulations, flares and combustors are required to have continuous pilots. Systems may have one or more pilot burners around the flare type depending on type and conditions. Pilots may utilize feed gas or an auxiliary gas system to ensure continuous operation (e.g., propane cylinders). The pilot flames can be ignited locally at the system using an electronic ignition system or remotely using a flame front ignition line [129]. For remote systems using flame front ignition lines, air and fuel are mixed remotely and an ignition transformer or spark plug is used to ignite the air-fuel mixture which is transported to the pilot tip where the main pilot gas stream is ignited. Local pilot ignition systems will utilize high-energy spark igniters at the flare with direct use of the pilot gas itself and often a venturi method (pilot gas inspirator, see **Figure**) to introduce air within the pilot fuel line [130]. Some manufacturers include solar-powered flare ignition systems and controls [69], which offer a major advantage for remote and/or distributed installations without electrical service.

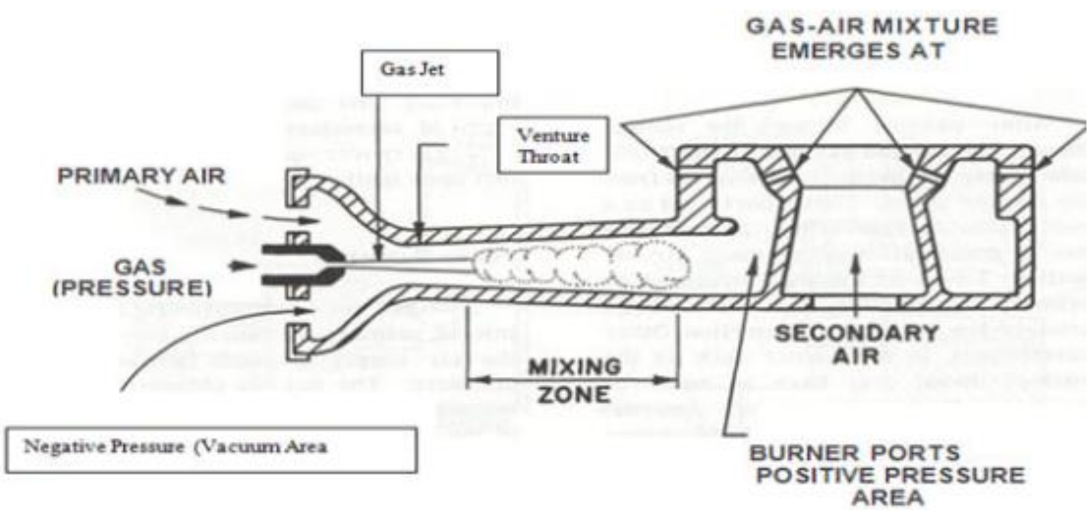


Figure 42. Example of pilot gas inspirator, from [130].

Figure 43 provides pilot example that includes both a local high-energy spark ignition system along with a secondary flame from an ignition tube that serves as back up. The pilot flame and ignition system can include rain and wind shields along with rain hoods for the pilot air intake (inspirator inlet) [131]. The use of rain and wind shields can ensure pilot operation at wind speeds of up to 250 MPH (400 km/hr). API Standard 537 addresses many requirements for flare pilot systems [132]. From this standard, pilots should burn and ignite flares for wind speeds of up to 100 MPH during dry conditions and 85 MPH during rain (up to 2 inches per hour). The standard also recommends a minimum heat release rate of 45,000 BTU/hr when flaring gases with a lower heating value of 300 BTU/scf or greater. The average service life of pilots is about 7 years, but some can last for 30 years.

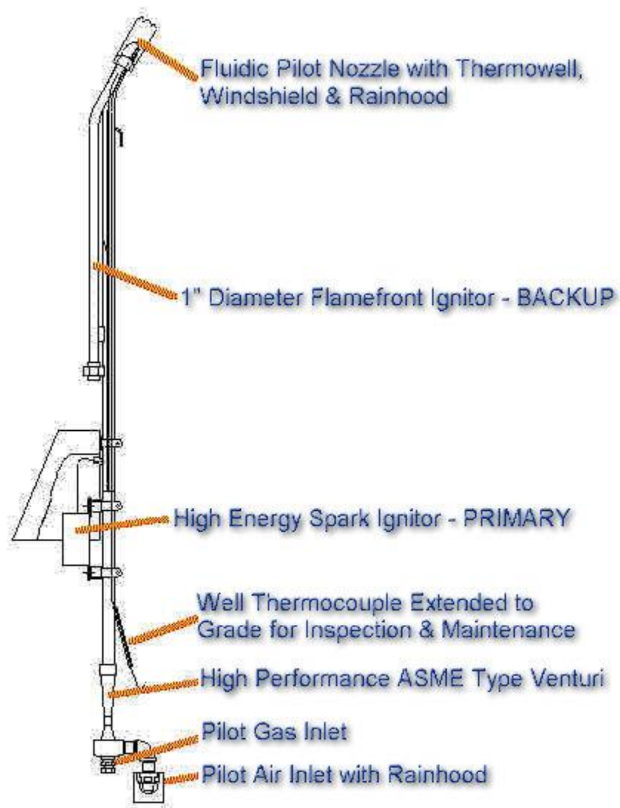


Figure 43. Example of dual ignition pilot system, from [131].

Pilots may be ignited automatically or manually. However, the natural gas STAR program highlighted that sparking pilots present cost savings by reducing continuously burning flares and saving on operator trips to manually light or relight flares [133]. They noted that their cost scenario did not account for any economic or cost benefits from reduction in methane emissions. There are a variety of manufacturers of pilot and ignition systems. For example, Zeeco provides both conventional pilots and various ignition systems. These include handheld sparking and flame-based ignitors for manual systems, and high energy ignition systems but also less conventional ballistic pellet ignition systems [102]. Their high-energy ignition system proves spark at a rate of 3 to 6 sparks per second (SPS) up to 9 to 12 SPS. The system provides a DC voltage of 2000 V and uses a capacitor (i.e., capacitive discharge). The energy rate ranges from 12 to 24 Joules per second (J/s) up to 108 to 144 J/s for harder to ignite atomized fuel oils (4 J per spark event).

The use of pilots can increase emissions from flares and some research has focused on reducing or eliminating pilot gas consumption. The EPA excluded pilot gas and emissions in their reviews of properly designing and operating flares. They examined 312 flare tests and for 304 (>97%) flares, the pilot gas was less than 3% of the total vent gas flow rate. Further, in 224 of these tests (>71%) the pilot gas consumption was less than 1% [134]. The EPA has summarized early findings that recommend the number of pilots for open flares based on the flare tip diameter as shown in **Table 5** [50]. They also present that a default value of pilot gas consumption should be 70 cubic feet per hour for an efficient flare. This value along with the total number of pilots and operating time can be used to calculate annual pilot gas consumption. Additional guidance on pilot design was presented Mendoza et al in 1996 at the American Flame Research Committee [135].

Table 4. Suggested Number of Pilot Burners Based on Flare Tip Diameter, from [50]

Flare Tip Diameter (in)	Number of Pilot Burners (N)
1-10	1
12-24	2
30-60	3
>60	4

Pilots are monitored to ensure continuous operation. Pilots can be monitored with thermocouples, flame ionization detectors, IR sensors, or acoustic sensors. Each method as strengths and weaknesses. For example, IR sensors may not be able to distinguish between the pilot and main flare. Flame ionization and acoustic methods are typically impervious to weather (precipitation and sun) while thermocouples and IR sensors may be impacted. Bellovich et al., provide an overview of the strengths and weaknesses for these four common monitoring systems [132].

Monitoring and Measurement Technology

The technology surrounding gas flare monitoring and measurement is a crucial part of ensuring the device is operating as intended, as well as providing required information to regulatory bodies. In heat and power applications, this type of diagnostic information is also used for active control to ensure optimal operation. This is uncommon in flares, which tend to be (largely) passive systems. Measurement types can be separated into process measurement and monitoring categories. Process parameters include flow rate, composition, heating value, and density. Monitoring parameters might include temperature, ion, or UV light sensors that detect the presence of a flare or pilot flame. Both categories are examined below.

Any device or instrumentation used in flares must be certified based on various safety requirements. Device classification is primarily based on National Fire Protection Association Standard 70 (NFPA 70) — National Electrical Code (NEC) [136] or by the American Petroleum Institute's (API) Recommended Practice (RP) 500 and 505 [137]. Per NFPA 70, Class I locations are those where gases or vapors are present and in sufficient quantity to form explosive or flammable mixtures. Class I is further subdivided into various divisions, primarily Division 1 and 2. Division 1 is a location where an explosive atmosphere could be present during normal operations. Division 2 is a location where the liquids or gases that could lead to an explosive atmosphere are present but are enclosed in various process equipment and would only escape in the case of abnormal operations or accidents. API RP 500 has the same definitions for Division 1 and 2, but API RP 505 includes designation of three Zones (0, 1 and 2). These zones are based on the time duration of the possible explosive environment. Both NEC and API standards have been incorporated into various sections of the CFR.

Devices certified as safe for these locations are likely to be certified by the Underwriters Laboratories (UL) in the U.S. [138] (or under ATEX directives for the European Union or Canadian Standards Association (CSA) in Canada). Devices that are safety certified will utilize one or more methods that include containment, energy limitation, or isolation [139]. Containment methods utilize enclosures with proper sealing that are explosion-proof. In this case, if an explosion occurs within the enclosure it is prevented from failing and extending to the surrounding environment. Energy limitation methods ensure that electrical components do not possess enough thermal or electrical energy to cause ignition. Such items are often referred to as intrinsically safe. Generally, an intrinsically safe device will have limited power below 1.3 W (or less than 29V and 300 mA) [140]. Isolation methods vary and could include purging a device with an inert gas that creates a positive pressure environment. Alternatively, for electrical devices, isolation barriers or circuits may be used to "break" electrical circuits (wires) entering into Class 1, Division 1 or 2 areas (e.g., Zener diodes).

Flow Rate Measurement

Flow rate is the most important process parameter measured in gas flares. The main reason for this is the EPA greenhouse gas reporting requirement, outlined in a previous section. To reiterate, this rule requires operators to determine the volumes of CO_2, CH_4, and N_2O emitted, using volumetric flare gas flow rate and a number of assumptions and calculation methodologies. Major caveats to the EPA requirement is that it only applies to facilities that emit 25,000 tons (CO_{2e}) per year, and in many instances engineering estimates can be used in place of measurements [32]. Along these same lines, many states limit the volume of gas that can be flared per year, requiring volumetric reporting to state regulatory bodies [63]. Flare tip velocity limits may be imposed (see discussion above), which are based on volumetric flow rate.

Flow rate is typically measured in gas flares using three main technologies: ultrasonic, thermal, and pressure-based (differential and pitot tube). Mechanical measurement devices such as turbine meters, positive displacement meters, variable area flowmeters and others are less common due to the potential for fouling and large pressure drops the devices create. Other flow measurement technologies include vortex meters, laminar flow elements, Coriolis flow meters, orifice- or venturi-based meters, among other unique approaches. A key issue with flow measurement is an acceptable turndown ratio of the flow measurement device [141]. Turndown ratio is a measure of a device's maximum measurable flow rate divided by its minimum measurable flow rate. Example turndown ratios are 10:1, 100:1, and 1000:1. Turndown ratios of 1000:1 or more may be required for flaring applications. Such high turndown ratios often increase the complexity or cost of devices when accuracy is to be retained. An additional issue may be the overall low pressure of the flare gas.

Ultrasonic

Ultrasonic flow meters operate using the principle of the speed of sound through a medium. Two primary types include doppler based devices, which measure frequency, or time of flight devices, which measure the transit time between upstream and downstream transducers. **Figure** presents examples of both ultrasonic approaches. Typical oil and gas applications utilize time of flight devices. A benefit of ultrasonic technologies is that they do not impart a pressure drop on the flow, which is beneficial for low-pressure streams. However, low-pressure flows also challenge low-flow measurements and may require the use of multiple sets of transducers. Turndown ratios are therefore typically limited to around 100:1. Primary measurements report the volumetric flow rate, but density can be inferred.

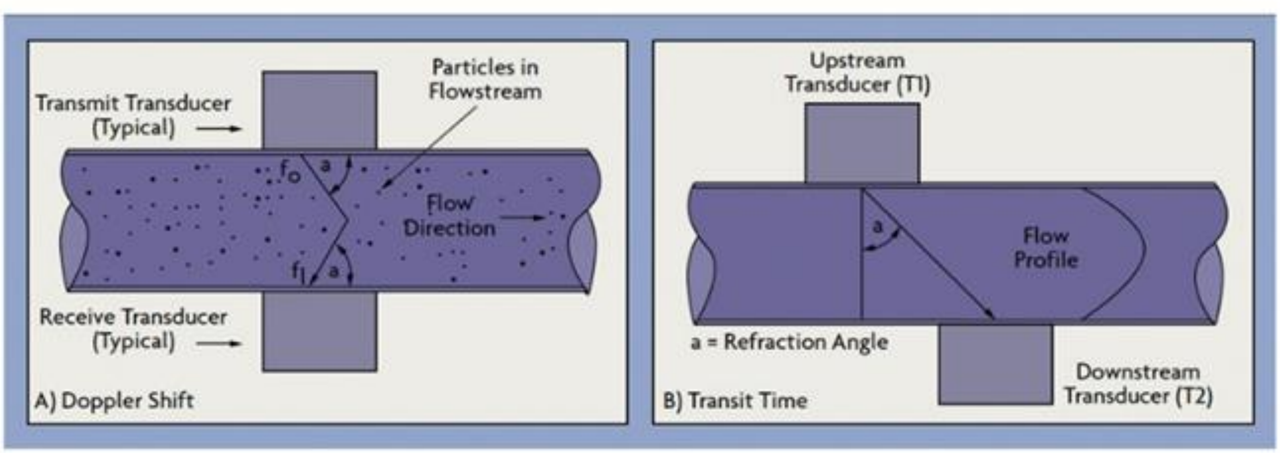


Figure 44. Example of doppler shift and transit time ultrasonic approaches, from [142].

	Standard Accuracy (Turndown ~30:1)		High Accuracy (Turndown ~100:1)	
Diameter (in)	**Min Flow (CFM)**	**Max Flow (CFM)**	**Min Flow (CFM)**	**Max Flow (CFM)**
2	5.27	158	1.58	158
3	12	360	3.6	360
4	20.3	607	6.1	607
6	44.9	1348	13.4	1348
8	77	2310	22.8	2310

Table 5. Example of Flow Ranges and Turndown Ratio for Ultrasonic Flow Meters, from [144]

Ultrasonic flow meters used in the broader gas industry are available from multiple manufacturers, including Flexim [143], Endress+Hauser [144], Rosemount [145], Panametrics [146], and others. Endress+Hauser offers an extensive line of Proline Prosonic flow meters including as an example the Flow B 200. This series is available in diameters of 2, 3, 4, 6, and 8". The standard units have a turndown ratio of around 30:1 while an increased accuracy version has a turndown ratio of 100:1. Even with these broad turndown ratios, minimum detection limits range from 1 to 77 SCFM, see **Table 5**. Such unit prices vary based on size and accuracy but start around $8000. Other manufacturers' units with multiple flow paths may have costs nearly double this (~$15,000). **Figure 45** presents an example of an Endress+Hauser ultrasonic flow meter for natural gas measurement.`

Figure 45. Example of an ultrasonic flow meter for natural gas applications, from [144].

Thermal

Thermal mass flow meters rely on the conservation of energy principle and the measurement of temperatures or currents required to maintain constant temperatures. As flow passes the meter probe, convection heat transfer carries energy from the measurement device [147]. As with ultrasonic methods, thermal mass flow meters can be categorized based on two methods. The "hot-wire" method measures the electrical power required to maintain the hot-wire temperature and this is correlated to a mass flow rate. The calorimetric method holds power constant and utilizes the corresponding temperature drop to determine flow. In both cases the thermodynamic properties of the flow must be known. If the compositions are known, some thermal flow meters allow for these data to be programmed into the device. **Figure** presents an example of an in-line thermal mass flow meter, which uses a heater thermal sensor and a temperature sensor.

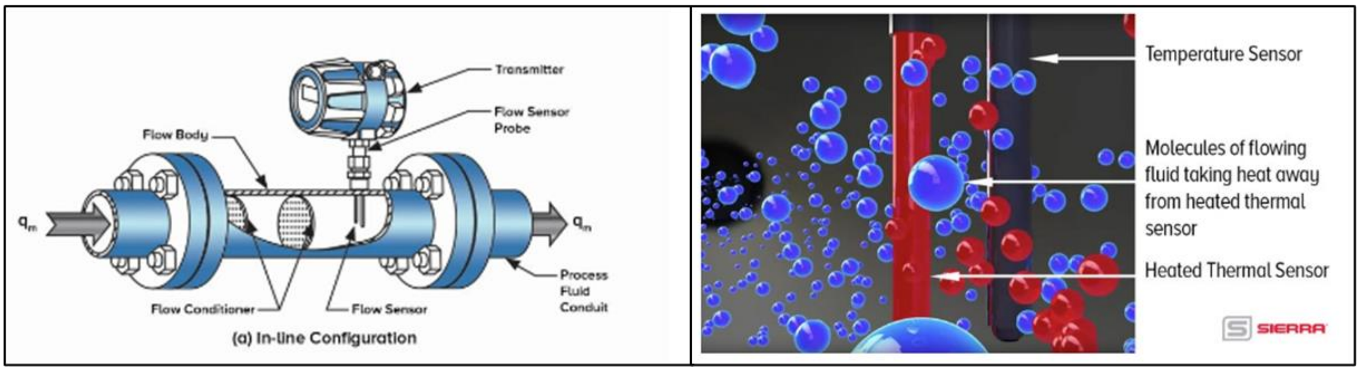


Figure 46. Example of thermal mass flow meter measurement method, from [147].

Thermal mass flow meters used in the broader gas industry are available from multiple manufacturers as inline or as insertion options. Some manufacturers include Cook Compression [148], Fox Thermal [149], CECO [150], Magnetrol [151], SAGE Metering [152], Sierra [141], and others. Thermal mass flow meters can have turndown ratios of 1000:1 or greater. As with any flow measurement method, caution should be used when examining lower flow limitations as flow measurement ranges may be advertised to start at "0" CFM. Thermal based devices all have a minimum detectable velocity which is often given in feet per minute (FPM). This minimum detectable velocity must be combined with the installed pipe size to determine the minimum detectable flow rate. For example, a review of four technologies from SAGE Metering, Magnetrol, Fox Thermal, and Ceco, found their minimum detection velocities as 5, 10, 15, and 60 FPM, respectively. Prices generally range from $4000 to $6000, however, it is noted that Sierra advertises a thermal mass sensor applicable to flares for $3000. **Figure** shows an example of both inline and insertion style thermal mass flow meters from SAGE Metering and Magnetrol.

Figure 47. Examples of inline and insertion style thermal mass flow meters for natural gas flow measurement, from [151,152].

Pressure-Based

Pressure base methods rely on Bernoulli's principle to measure a differential pressure that is correlated to a flow velocity. This differential pressure (stagnation – static) can be created by the measurement probe itself in the case of a conventional J-style pitot tube or in an average pitot tube. Alternatively, the differential pressure can be created by the piping network (lengths of pipe and associated friction factors) or by installation of an obstructive device (e.g., venturi, laminar flow element, orifice). The latter method would likely be unacceptable for low-pressure flow streams. When conventional or averaging style pitot tubes are used, minimal pressure drops are imparted on the flow. An area of possible concern lies in the potential clogging of the stagnation pressure ports. This point has been raised in prior discussion with industry members.

Figure 48 shows basic schematics of both types. In both types, the turndown ratio issue may necessitate the need for multiple differential pressure sensors, each of which measures a smaller pressure range. Such an approach is used in the measurement of exhaust flow (wide dynamic range) for automotive applications. In these applications, systems may use up to five differential pressure sensors to enable turndown ratio of 100:1 or more. The resulting differential pressures are relatively small and often measured in units of inches of water. Common ranges include 0-0.1, 0-1, 0-10, and 0-28 inches of water.

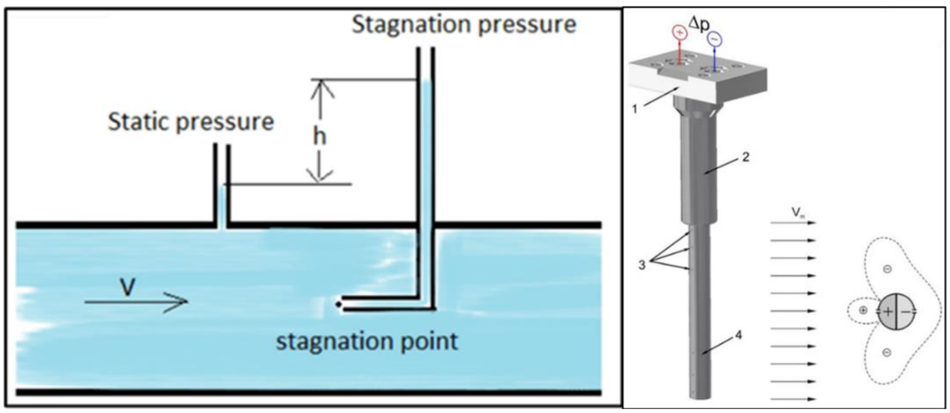


Figure 48. Example of conventional J-style pitot tube (left) and an average pitot tube (right), from [153,154]

Typically, an averaging style method is used in the broader gas industry and is available from multiple manufacturers, including Emerson/Rosemount [155], Krohne [156], ABB/Torbar [157], and others. To alleviate the port fouling issues, some manufacturers (Torbar from ABB) include a back flow option to periodically purge the pressure ports. **Figure 49** shows an example of the Rosemount ProBar flow meter. Prices for this particular flow meter range from around $5000 to well over $10,000 depending on size and overall meter configuration.

Figure 49. Example of differential pressure flow meter from Rosemount, from [157].

Composition

As noted, some flaring applications will require analysis of the flow stream to determine its composition. In cases where the composition is determined to be constant over time, off-line measurements can be used. However, some cases will require the continuous monitoring of the composition if it varies in time. The flow composition enables mixture properties to be determined, which could be used in flow corrections but also for determining the heating value. Alternatively, the mixture heating value can also be directly measured. If composition is to be measured, the natural gas industry often uses inline continuous gas chromatographs (GCs). If the heating value is to be determined directly, a calorimeter is often used.

Gas Chromatographs

Inline GCs are available from various manufacturers including Siemens [158], ABB [159], Ametek [160], Agilent [161], and others. Based on brief discussions with industry and a review of literature, a common inline GC used in the gas industry is the ABB NGC8 series. Such inline GCs can provide high-resolution measurement of C1 to C5 compounds and C6+ measurements. They can also determine inert gas concentrations including carbon dioxide and nitrogen. Measurement detection limits are typically either 0.001% or 0.005% (10 or 50 parts per million). In addition to providing the composition analysis, the GCs can report the heating value using various American Gas Association methods. A potential downfall of deploying GCs for continuous measurements is high capital cost and the required use of carrier gases. In addition, while "continuous" GCs may operate continuously, they still require minimum sampling and elution times. Complete analysis reporting time is typically limited to around 5-15 minutes, but these reporting times would meet regulatory requirements. **Figure** shows three different GC applications for composition analysis at natural gas sites. The left image shows an ABB 8100 series with its carrier gas cylinder, the middle shows an Emerson/Rosemount GC, and the right shows an ABB 8200 series deployed in a weatherproof enclosure. Prices vary but a recent quote for an ABB 8200 series was around $19,000 for the GC alone. For all accessories and enclosures, the price was around $40,000.

Figure 50. Examples of inline GCs for natural gas compositional analysis, from [159].

Calorimeters

Calorimeters are devices that provide fuel heating value or Wobbe index without compositional analysis. Calorimeters utilize controlled combustion of a small fuel sample. Various calorimeters will measure the resulting temperature or examine the residual oxygen concentration using zirconia oxide sensors, while others utilize additional sensors. Control Instruments Corporation offers the CalorVal BTU Calorific analyzer to determine heating value for flare stack fuels [162]. Their method focuses on the temperature measurement of the controlled combustion. It can be used to detect heating value up to 1300 to 2500 BTU/SCF with a response time of only 3.5 seconds. Their method does require the use of hydrogen fuel along with nitrogen and oxygen. COSA Xentaur offers the 9800 Calorimeter, which can measure heating values up to 3000 BTU/SCF [163]. Their approach passes a metered fuel air mixture through a heated (1000 °C furnace) and measures the residual oxygen with a zirconia oxide sensor (i.e., flameless). Their method appears to require pressurized air for operation. The overall response time is 5 to 30 seconds. Riken Keiki Co., Ltd., offers a unique OHC-800 calorimeter [164]. Their technology combines an optical sensor and a sound velocity sensor to determine heat content, with an advertised calorific range of 25 to 50 MJ/m3 (671 BTU/SCF to 1342 BTU/SCF).

Spectroscopic

Another approach that can be used to determine gas composition and/or heating value is spectroscopic techniques, such as FTIR spectrometry. FTIR spectrometers are capable of measuring over a wide spectral range, generally in the near-mid IR (~1-20 μm). They utilize a broadband light source and typically implement an absorptive approach, such that the relative attenuation of light at various wavelengths can be attributed to a particular compound. FTIR spectrometers have also been used in a so-called "passive" or "open-path" configuration to quantify gas flare destruction efficiencies using an emissive or absorptive approach in combination with background sunlight emission [165]. FTIR spectrometers can measure a variety of gas compounds including C1-C5 alkanes, CO/CO_2, H_2O, H_2S, NH_3, NO_x, and more. A particular advantage of FTIR spectrometers is high signal-to-noise and their ability to detect trace compounds. Furthermore, they offer increased acquisition speed (~seconds) compared to GCs, potentially allowing real-time flare tuning in response to compositional changes. As shown in
Figur, FTIR spectrometers differ greatly in their form factor, including benchtop laboratory units, rack-mounted analyzers, and portable units. The cost for a laboratory-grade Thermo Fisher Nicolet iS50 FTIR (
Figur, left) in 2021 was approximately $60,000, while a GasMet GT6000 Mobilis portable FTIR multi-gas monitoring system (
Figur, right) in 2024 is approximately $110,000. At the time of writing, few, if any, manufacturers sell a ruggedized product suitable for hazardous locations and/or specific to oil and gas applications. FTIRs are generally not suitable for measuring homonuclear diatomic molecules such as H_2, O_2, and N_2. However it has been suggested [166] that FTIR can be combined with RAMAN spectroscopy, which utilizes a laser to excite molecules of a gas mixture, and measuring the inelastic scattered light spectra for complete speciation.

Figure 51. FTIR spectrometer form factors, lab-grade (left, from [174]), rack-mount (middle, from [175]), portable (right, from [176]).

A similar technique involves the use of discrete narrow-band laser sources, each targeting one or more species, to measure the corresponding absorption spectra. Known as tunable-diode-laser-absorption-spectroscopy (TDLAS), the analysis is similar to that of FTIR spectroscopy, however, this technique offers the advantage of a much more compact, low-cost, and rugged instrument. This is fueled in particular by recent development of low-cost telecom-grade laser diodes, which have been repurposed for gas sensing in a variety of applications [167,168]. TDLAS sensors have been implemented in commercial products to quantify H_2O, H_2S, CO, CO_2, NH_3, NOx and C_2H_2 in process [169] and flue gas [170] streams. This can include a sample pump and folded-gas-path optical cavity (**Figure 52**, left) used to maintain an optimal temperature and pressure, or in-situ probes that implement a single-ended or cross-pipe approach (**Figure 52**, middle, right) [171,172]. Currently, no manufacturer produces a TDLAS-based analyzer specifically targeting flare gas composition. However, these approaches are beginning to be used to quantify natural gas purity levels and identify contaminants, with +/-1 ppm accuracy [173].

Figure 52. TDLAS gas analyzers, sample-based (left, from [169]), single-ended (middle), cross-pipe (right), from [171].

Destruction Efficiency

Flares can be monitored using infrared (IR) optical technologies or open path spectral methods to assess operation and destruction efficiency. These methods have tended to replace or supplement older opacity-based methods to monitor flares and flare smoke plumes [177]. Thermal imaging cameras have seen a significant increase in use for leak detection and quantification activities in the oil and gas sector and are allowed under OOOOa/b/c for these tasks. Various companies offer an IR camera system for flare stack monitoring. Many of these technologies are based on conventional thermal imaging. Viper Imaging offers monitoring systems to assess optimal flame height, liquid carry over, flame out, and pilot operation [178]. Zeeco, a flare manufacturer, also offers conventional long-wave IR monitoring with the FlareGuardian and IdentifEye systems [179]. They advertise their technology for meeting EPA requirements, especially for refinery applications under 40 CFR 63.670. Similar handheld and fixed-mount IR technologies are available from Teledyne FLIR [180], LIMAB [181], and others. Some IR technologies also enable combustion efficiency (CE) monitoring through multi-spectral IR imagers. These technologies target the measurement of relative concentrations of unburned hydrocarbons, CO_2 and CO by focusing on specific wavelengths of IR absorption for these gases (e.g., 3.2 to 4.6 μm). Providence Photonics offers their MANTIS system for flare monitoring that includes real time CE monitoring and claim an accuracy of 1% [182]. They also highlight this technology can be used to enable closed-loop flare control. This technology was originally developed in part from SBIR funding from the EPA [183]. Results of validation tests were published in 2015 showing CE quantification from around 60-100% with a determination coefficient over the range of 0.9856 [184]. Over 28 validation tests, the average difference compared to a conventional extractive emissions measurement approach was 0.5%. It is noted that the flares used included those fueled by natural gas but also propane and propylene. **Figure** presents an example of the IR images taken during extractive flare tests.

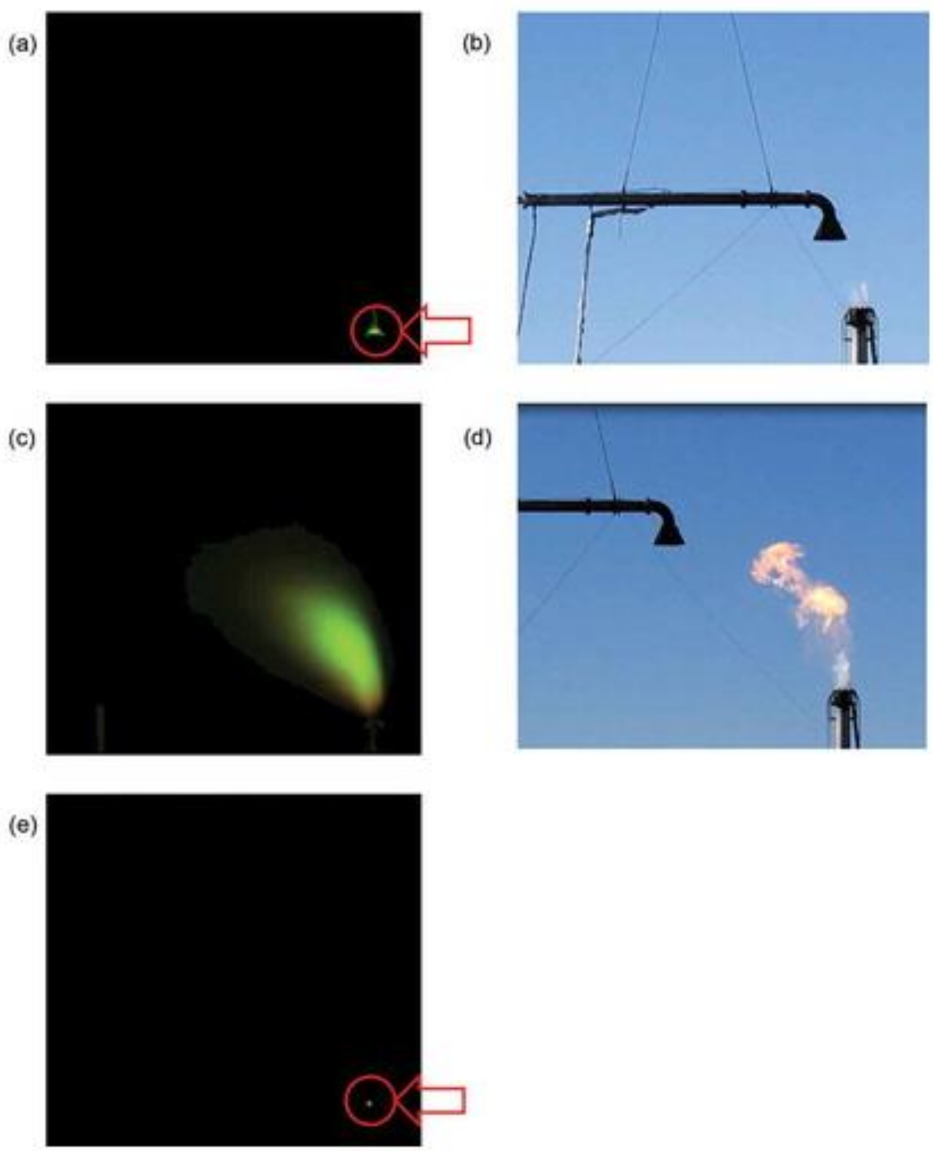


Figure 53. Example of IR images and extractive flare sampling during examination of CE measurements (from [184]).

Other companies such as Sensi also offer systems capable of estimating DRE using their Agni system that utilizes AI analytics [185]. Recent research on assessing CE has examined the use of mid-wavelength infrared (MWIR) multi-spectral (MS) spectroscopy and imaging Fourier transform spectrometers (IFTS) [186,187]. IFTS showed good agreement with laboratory and CFD data. MWIR MS showed inferior results, but it was noted that optimal filters were not used and that it would be more economically viable than IFTS.

As discussed in the earlier ECD section, researchers at EPA utilized passive FTIR and MWIR hyper-spectral imagers (his) to examine CE of ECDs from standoff distances of 50 to 300 m. **Figure** presents an example of the TELOPS Hyper-Cam (left) and chemical mapping sequence results (right) for various species. Recent advancements and preliminary field trial findings from Canadian studies are presented in an online webinar, which includes issues associated with deconvolution for both the HS and MS cameras and a thermochemical manifold reduction (TCMR) method [188]. The TCMR method has been shown to improve CO_2 measurements but did not significantly improve the estimates for unburned hydrocarbons [189].

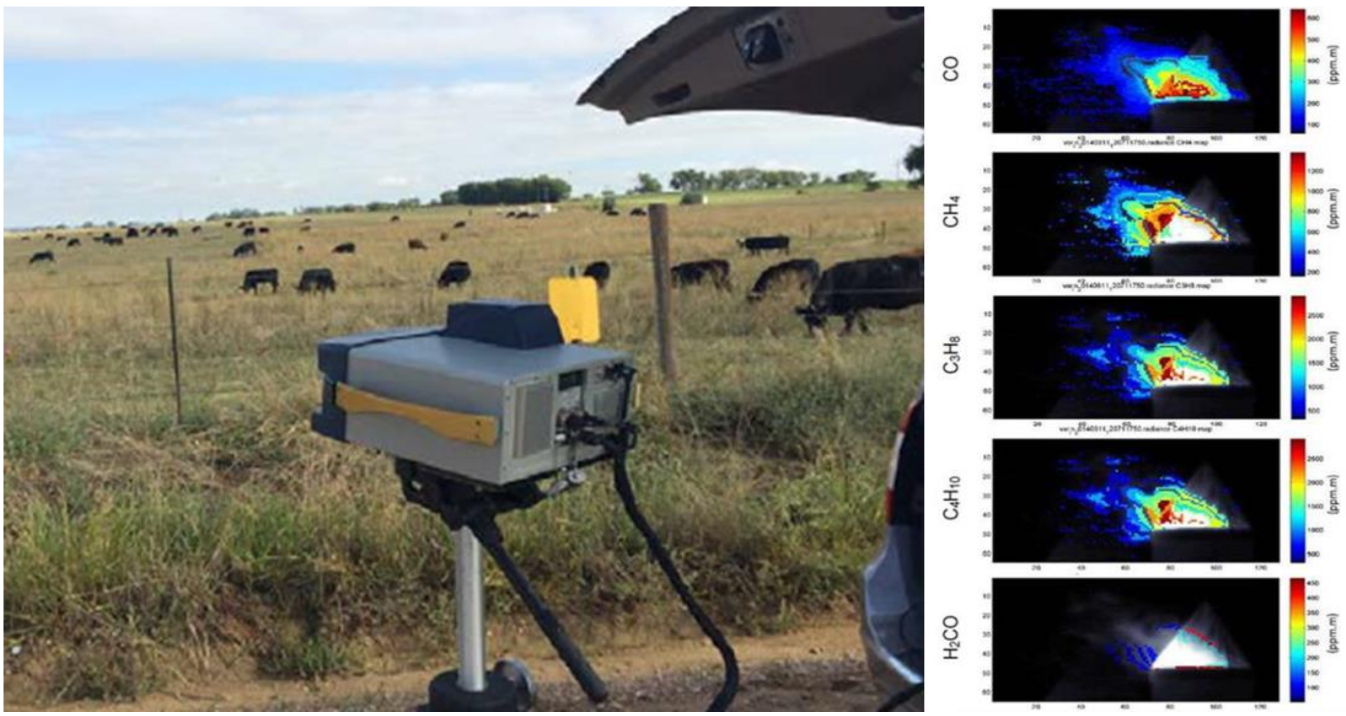


Figure 54. Example hisHSI and resulting plume images of various species (from [94]).

Flaring Alternatives

Flaring natural gas is more favorable than venting natural gas for various reasons. Key benefits include reducing the carbon footprint of vented gas due to the higher global warming potential of methane with respect to CO_2 and the reduction of VOCs or HAPs that may result from various natural gas processes. A variety of research projects discussed below are actively seeking to improve the overall combustion or destruction efficiency of flaring technologies to provide further benefits over venting. However, research is also ongoing to examine flaring alternatives. The U.S. Department of Energy reported to congress on the need for R&D in this field in 2021 [20]. The report identified currently available alternatives including the following: compressing the natural gas and trucking it short distances for use as a fuel for oil field activities; extracting natural gas liquids from the flare gas stream to reduce the flared volume (a partial solution); converting the gas-to-electric power using small-scale generators, and small-scale gas-to-methanol or gas-to-liquids conversion plants. They identified two key R&D opportunities that include multifunctional catalysts for methane conversion and modular conversion equipment designs. A key contributor to the modular focus was due to the findings on the statistics of flare sizes from three basins, which are presented in **Table 6**.

Table 6. 2018 Associated Natural Gas Flaring Statistics for the Permian, Eagle Ford, and Bakken Shale Plays, data from [20]

Flare Size (Mcf/d)	Flare Units	Total Volume (Mcf/d)	Flare Size (Mcf/d)	Flare Units	Total Volume (Mcf/d)	Flare Size (Mcf/d)	Flare Units	Total Volume (Mcf/d)
<=100	44,252	601,057	**<=100**	21,825	253,474	**<=100**	3,781	99,761
100-200	2,401	339,660	**100-200**	659	91,092	**100-200**	753	109,036
200-300	1,105	269,029	**200-300**	210	51,644	**200-300**	442	109,508
300-400	596	205,937	**300-400**	96	33,560	**300-400**	280	96,755
400-500	366	163,629	**400-500**	58	26,053	**400-500**	206	92,716
500-600	240	131,329	**500-600**	35	19,108	**500-600**	149	81,686
600-700	203	131,534	**600-700**	26	16,528	**600-700**	140	91,261
700-800	146	108,801	**700-800**	16	11,903	**700-800**	98	73,091
800-900	99	84,003	**800-900**	19	16,139	**800-900**	83	70,739
900-1,000	73	68,990	**900-1,000**	11	10,125	**900-1,000**	58	54,669

They identified that, by count, smaller flares (lower volumes on a daily basis) represented the largest population and in some cases the highest gas volumes. Such smaller flares deployed for combustion of APG may only be at particular locations for shorter durations and move from site to site as needed. Subsequent to this reporting, the DOE Office of Fossil Energy and Carbon Management announced a funding opportunity in September 2023 [190]. The goal of these research projects is to examine "innovative technologies for capturing associated gas at the well site to reduce or eliminate the need for flaring and venting, as well as novel methods for converting the captured natural gas into value-added products, essentially creating a new product stream from a waste stream." These research projects will be in addition to eight projects currently funded through the DOE's Methane Mitigation Technologies program [191]. Currently funded projects are primarily at the laboratory- or reactor-scale and focus on advancement in catalyst materials and use of microwaves to improve catalyst activity. Most technologies have relatively low technology readiness level (TRL~3) and will require continued R&D before scaled deployments. The projects are summarized below [192].

1) Microwave Catalysis for Process Intensified Modular Production of Carbon Nanomaterials from Natural gas [193]

- This project is led by researchers from West Virginia University along with Pacific Northwest National Laboratory, North Caroline State University, and industry members. The overall goal is the process intensification of modular systems for the one-step conversion of methane to carbon nano tubes or fibers and the co-production of hydrogen. Such an approach eliminates methane and CO_2 emissions. They have identified the need to deal with various gas compositions and high turndown ratios — both issues that also affect flaring performance. The technology is based on a microwave-enhanced, multifunctional catalytic system. We note that such a technology will still require electrical power at small, stranded, or remote sites and the program seeks to demonstrate a pilot system using a 6-kW microwave plasma reactor.

2) Oxidative Aromatization Catalysts for Single Step Liquefaction of Distributed Shale Gas [194]

- This project is led by researchers from North Carolina State University along with West Virginia University, Lehigh University, and industry members. The overall goal is to develop and demonstrate multifunctional catalysts to convert light shale gas into liquid aromatic compounds and water using an oxidative aromatization system (OAS). The approach focuses on new zeolite catalysts (perovskite oxide-based selective hydrogen combustion) developed using a CEM microwave synthesizer. Catalysis reactions appear to occur from 600 to 800 °C. Therefore, they present a base case energy demand of 88.3 MJ/kg of aromatics produced but the OAS system could offer a 78% reduction in required energy. An economic analysis targeted a production of 50 bbl/day. We note that production of benzene and toluene would require additional precautions to ensure that VOC and HAP emissions do not occur.

3) Electrocatalytically Upgrading Methane to Benzene in a Highly Compacted Microchannel Protonic Ceramic Membrane Reactor [195]

- This project is led by researchers from Clemson University. The overall goal to develop highly compacted microchannel protonic ceramic membrane reactors (HCM-PCMRs) for efficient and cost-effective methane dehydrogenation to aromatics (MDA) (e.g., benzene). Their new mesoporous Rh SiO_2 catalyst showed benzene production at 250-300 °C, which is lower than that of Mo/zeolite and Fe SiO_2 catalysts. The research is primarily focused on laboratory-scale results using 2D/3D printing and laser cutting to achieve high-surface-area micro channels.

4) One-Step Non-oxidative Upgrading to Hydrogen and Value-Added Hydrocarbons [196]

- This project is led by researchers at the University of Maryland along with those from the University of Delaware. This project focuses on methane upgrading via one-step non-oxidative methane decoupling as opposed to the conventional multiple step syngas approach. This process is achieved using a single atom M/SiO_2 catalysts. The approach has shown high selectivity conversion to ethylene or benzene. This project is also more laboratory focused on various single atom metals and use of advanced chemical modeling and CFD studies.

5) Methane Partial Oxidation Over Multifunctional 2-D Materials [197]

- This project is led by researchers at the University of South Carolina. It focuses on development of highly selective, active, and stable catalysts for the low temperature partial oxidation of methane to methanol (MTM). The approach would still utilize oxygen but not require pure oxygen as is required for syngas approaches. The project is also more laboratory focused as they seek to investigate single atom catalysts (2-D) such as graphene for bench-scale reactors. Initially they have observed methanol production over Pt-GR/Ni catalysts.

6) Production of Hydrogen and Carbon from Catalytic Flare Gas Pyrolysis [198]

- This project is led by researchers at National Energy Technology Laboratory (NETL). The project focuses on catalytic methane pyrolysis to produce carbon and hydrogen in a single step (without CO_2 production). Such an approach would be advantageous compared to conventional steam methane reforming. The key enabling technology is a novel NETL developed catalyst that has high (>80%) methane conversion. As with other catalyst solutions, this approach requires energy input but they have identified that 20% of the hydrogen produced can serve as the required thermal energy without production of CO_2 emissions. Their fluidized-bed method was also applied to a mixture of ethane and methane (more representative of natural gas in some locations) and showed 100% conversion of ethane to hydrogen while still maintaining around 50-60% conversion of methane. They are working with industrial partner Birla Carbon USA as they have interest in the carbon byproduct.

7) Commercialization Study of NETL Technology for Flare Gas to Olefins and Liquids [199]

- This project is led by researchers at NETL. This project also focuses on use of a patent-pending NETL catalyst building on research on nanostructured FE on a carbon low-temperature catalysis. The research is conducted under a cooperative research and development agreement (CRADA) with Susteon, LLC. Susteon has developed a catalytic plasma reactor to produce syngas from natural gas. This syngas is then converted to olefins using the NETL FE/C catalyst. The Susteon reactor is focused on dry methane reforming as opposed to steam methane reforming.

8) Microwave Enhanced Flare Gas Conversion to Value-Added Chemicals [200]

- This project is also led by researchers from NETL. The goal of the project is to develop a modular microwave catalytic conversion system to produce benzene (and ethylene) from associated gas. The project aims to develop a system for field testing, but early work has focused on reactor-scale laboratory testing. The catalyst is Mo-ZSM-5, which is undergoing bench-scale and chemical modeling. Pilot-scale demonstrations are not expected until 2028.

In addition to ongoing R&D, there are other alternatives to flaring. Such approaches include gas combustion in engines (for gas compression or power generation), reinjection into wells to improve oil production, compression or liquefaction for transport, conversion to methanol or dimethyl ether, power production using solid oxide fuel cells, recompression of vented/flared gas for sales in non-stranded locations, and others. Various economic studies have examined flaring alternatives for higher flaring regions around the world [201–203]. According to IEA, flaring alternatives of electrical power generation or transport to market via pipelines was economically feasible if sites produced more than 10,000 m^3 (343 MCF) per day and were within 2000 km (~1250 miles) of a viable market [204]. However, as noted in Table 7, most flaring sites have much lower flaring volumes. Still, a study in the Intermountain West region found that in some locations (70%) these smaller flaring locations were located within 1 mile of a pipeline and nearly all (99.8%) were within only 4 miles of a pipeline [205]. Recompression of vent or flash gases is an alternative to sending gas to an enclosed combustion device or flare. For example, flash gas from tanks, mercaptan removal units, or other on-site treatment units that would otherwise be vented or flared could be recovered using a vapor recovery unit (VRU). Recompression will require mechanical energy to return low-pressure products into pipelines and the recompressed stream must be permissible based on gas quality standards at the location. A Canadian study found that recompression would be economically feasible so long as the gas were within 1 km of existing infrastructure [206]. Another study examined the reduction in flash gas flaring at a gas processing facility. Flash gas compression on mercaptan removal units reduced flare gas rates from 13,000 Nm^3/hr to 3000 Nm^3/hr resulting in CO_2 and methane reductions of around 75% [207]. For this particular application, electric motors were used to power the compressors, which may be feasible at larger centralized facilities such as compressor stations, refineries, or gas processing facilities. For remote applications where electricity is not available, small natural gas fueled engines can be used to power the vapor recovery units. In either case, the net reductions in GHGs should account for the energy and emissions associated with the recovery energy. A modeling study suggests such an approach would be techno-economically feasible and may provide for net-negative hydrogen production [208].

An alternative to flaring associated gas in remote locations lacking infrastructure is reinjection within the oil reservoirs to increase production, also known as a form of enhanced oil recovery (EOR). Aoun et al. examined this alternative as a method to reduce flaring in the Bakken shale play [209]. They used modeling to assess the technical and economic feasibility of this approach. They estimated that associated gas reinjection could increase oil recovery by 34%, which would minimize flaring while being economically feasible. Their model utilized a 3MW gas turbine along either three stage compressors or dehydration units to achieve appropriate injection pressures. Even with the CO_2 and methane emissions associated with these additional processes, the reinjection strategy could reduce CO_{2e} emissions from nearly 120,000 mtons per year to around 45,000 mtons per year. The estimated capital and operating cost would be around $4.6M but EOR could represent a value of nearly $120,000 per day. A prior NETL research project (DE-FE00024233) examined EOR using rich associated gas in the Bakken [210]. Their study included modeling and pilot EOR wells. Incremental oil production increases from 8.95 to 15.2% could be possible, depending on the gas composition, for injection pressures of 6000 psi [211]. An alternative to EOR using flare gas itself would be a combination of alternatives such as combining steam methane reforming and carbon capture. Flare gas would be used to produce hydrogen ("gray") and CO_2. To avoid release of CO_2 to the atmosphere, the CO_2 could then be used for EOR.

Instead of flaring gas, it could be used to fuel internal combustion engines to produce compression energy, electrical power generation (also known as gas to wire, or GTW), or in combined heat and power systems. However, issues may arise due to fuel quality and low methane number (MN) for fuel streams containing higher hydrocarbons. Low MN fuels may require addition of pre-chambers and modification of engine ignition systems and other control settings. Researchers at Siemens Energy Engines identified these issues and suggested that current natural gas engine combustion chambers may not be suited for using associated gas as a fuel to reduce flaring [212]. However, this study is only applicable to a particular engine type and multiple commercial engines are available that can run on lower MN number fuels. For example, Cummins produced a white paper focusing on use of flare gas in gensets powered by their lean-burn internal combustion engines [213]. In all cases, both flares and internal combustion engines would benefit from continuous fuel quality monitoring to ensure maximum efficiency and minimal emissions. Internal combustion engines will still produce CO_2 and some methane emissions but a variety of ongoing research projects discussed below aim to decrease methane emissions from natural gas engines. Alternatively, flare gas could also be used to fuel gas turbines for power generation. Proper operation still relies on knowledge of fuel composition but some turbine packages can accept a broader range of gas fuel qualities. GE Verona has used this turbine power generation approach at various ONG sites around the world (e.g., Yemen, Nigeria, Brazil, Oman)[214]. While these projects have typically focused on power generation for local/regional consumption, some oil and gas companies (ExxonMobil, Conoco Phillips) in the U.S. are selling gas that would otherwise be flared to third party operators to power crypto mining operations [215]. An alternative approach has been deployed by Crusoe Energy Systems Inc., which uses stranded gas for local power generation to remotely located, energy-intensive computing centers [216].

Another alternative would be the use of flare gas in solid oxide fuel cells (SOFCs) for power generation. Researchers in Qatar examined the potential use of SOFCs at gas processing to reduce flaring. They examined applications to both on-shore and off-shore facilities [217]. Their analysis suggested that both on-shore and off-shore plants would experience reductions in CO_2e emissions and that a reduction in up to 70% of flare gas could be achieved. Others have also examined the potential use of SOFC to produce electricity at gas plants while significantly reducing GHG emissions [218]. A cursory review found no data regarding real-world application of SOFCs. However, SOFC systems are available from Bloom Energy [219] and FuelCell Energy [220]. Bloom advertises with a specific focus on the oil and gas sector and references the use of associated gas to power their Bloom Servers and electrolyzers [221].

Various vent and flare gas streams may also be liquefied or compressed instead of being flared. Any of these methods will vary in cost and feasibility based on the gas production rate and composition. Creating compressed natural gas (CNG) can reduce volume storage requirements by a factor of about 200 depending on final storage pressure. CNG is commonly stored in special tanks at pressures up to 3600 psig. The CNG can be transported via heavy-duty vehicle in fuel trailers. However, the gas stream will require onsite processing for water removal and fuel quality limitations. The CNG can be trucked to regional natural gas infrastructure for sales or used in CNG vehicles. Both methods would require infrastructure developments for deployment. A 2020 article reviewed these various technologies including CNG [222]. It is noted that CNG and associated processing technologies are available but have not matured to a commercial market. Liquefaction can occur in various methods including processing the stream to be predominately methane to produce LNG, the conversion of gas to liquids (GTLs), or the production of natural gas liquids (NGLs) (e.g., liquefied petroleum gas, or LPG). Improved GTL technologies are currently being investigated as discussed above. All the liquefication methods will require significant energy, resource footprints, and infrastructure for deployment. Macaw Energies has announced a flare to LNG pilot project in the Permian basin [223]. This pilot project would be in collaboration with GTUIT, LLC. GTUIT also advertises services to convert tank vapors (often flared) to NGLs for sales [224].

Ongoing, Federally Funded Research Projects

The Advanced Research Projects Administration – Energy (ARPA-E) is currently funding four research and development projects under the Reducing Methane Emissions Every Day of the Year (REMEDY) program [225]. The program's goal is to improve flares to enable a methane conversion efficiency of 99.5%. Researchers at Advanced Cooling Technologies (ACT) are developing the "Swiss-roll Flare Gas Incinerator" that recovers heat from combustion products to extend the flammability range to enable complete combustion of flare gases including methane over a wide range of flow rates and concentrations. The technology has already been demonstrated to reduce the lean limit for propane combustion by nearly an order of magnitude (0.058 versus 0.5) [226]. **Figure** provides an overview 2-D and 3-D schematic of the technology approach and its application to flare gases [227].

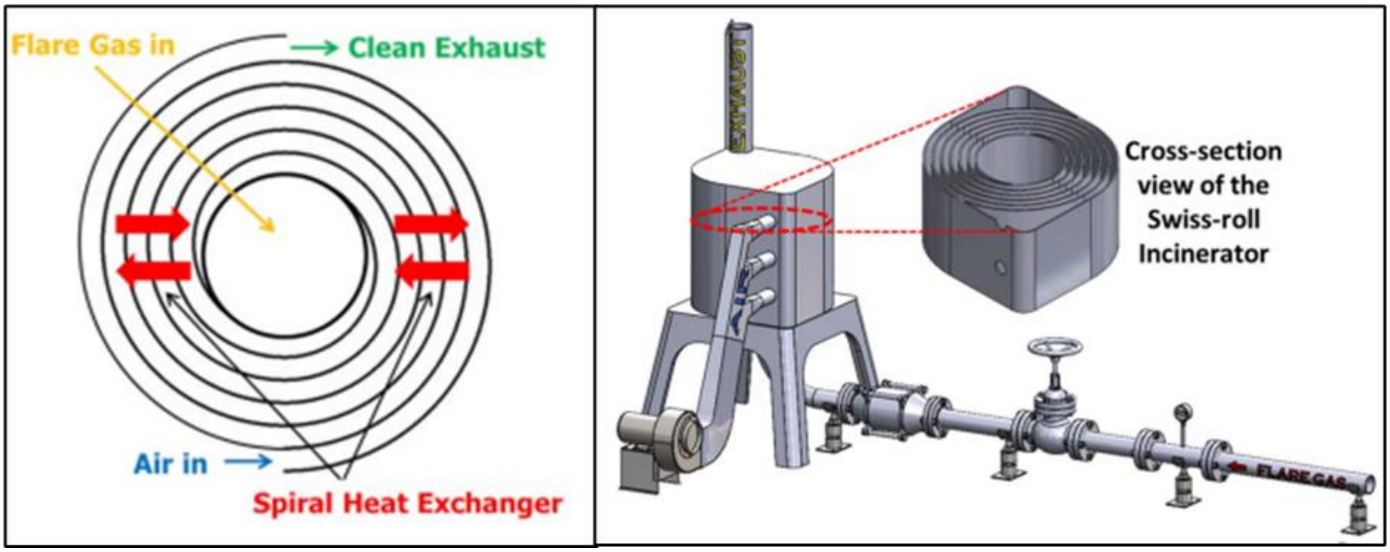


Figure 55. Swiss-roll flare technology to extend flammability limits of flare gases, from [227].

Researchers at Cimmaron are developing a novel flare apparatus to improve methane destruction and removal efficiency [228]. Their approach includes deployment of a microprocessor controller, an image-based, closed-loop feedback system along with flow meters for both high- and low-pressure flare systems. The technology will be applicable to streams of variable methane composition include high-concentration streams of produced gas along with lower methane concentrations from flare gases associated with tanks and other systems. The inclusion of the microprocessor and feedback control enables control of assist-air flow rates via a variable frequency drive to optimize combustion and mitigate cross wind effects. The approach is unique in that it is being developed similar to a retrofit system that would enable its application to flares currently deployed across the oil and gas industry. **Figure** shows their current controller, CFD thermal modeling, and dream duo flare system in a field application [229].

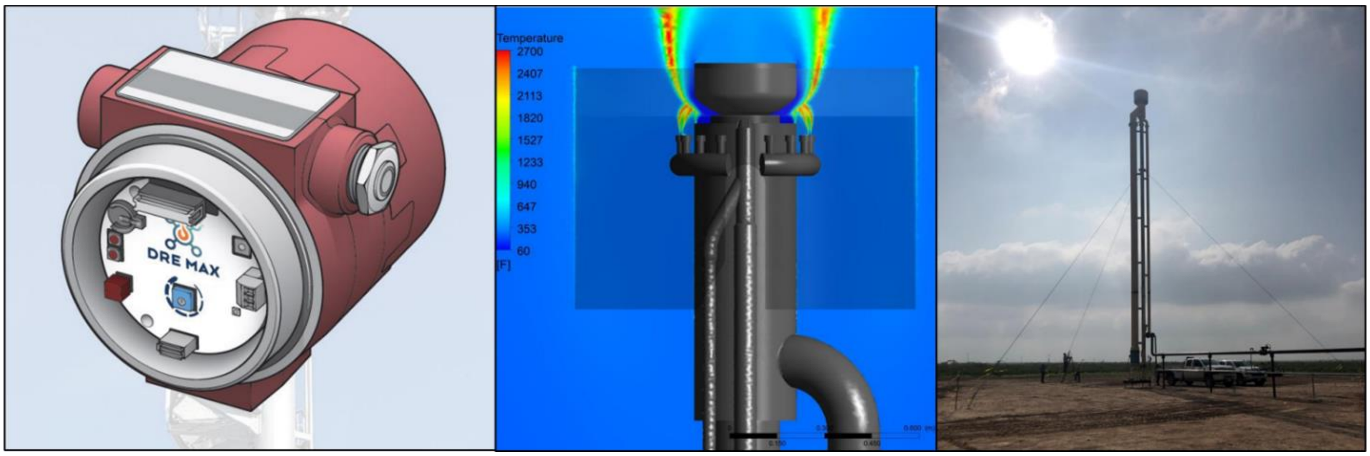


Figure 56. Examples of Cimmaron technologies and research aimed at improving flare efficiency, from [228].

Researchers at the University of Michigan are conducting research under their Systems of Advanced Burners for Reduction of Emissions (SABRE) project [230]. Their goal is to use machine learning and CFD modeling, along with additive manufacturing to develop systems for both high- and low-pressure and high- and low-flow flare gas streams. They have identified the need for their technologies to accommodate variable wind speeds.

Researchers at the University of Minnesota are developing a flare system that uses non-thermal, low-temperature plasma for in-situ gas reforming, ignition, and flame stabilization [231]. Their technology targets smaller unmanned flares including those at remote sites. The low-energy plasma system would be powered by solar and could be used as an on-demand ignition that would eliminate the use of continuous pilots. However, it is noted that some regulations currently require continuous pilot monitoring to ensure flares are lit. The in-situ reforming will produce acetylene, ethene, and hydrogen to improve reactivity and extend flammability. Their custom plasma electrode will be designed as a retrofit option for installation on existing flares [232].

Technology Needs and R&D Recommendations

The preceding technology assessments and general research findings surrounding flaring and venting in U.S. oil and gas operations have led to a number of conclusions and recommendations for follow-on research. The aim of this section is to identify specific areas where additional research investments might best be made to realize rapid reductions in GHG emissions from gas flares, while maintaining a clear understanding of the potential economic hardships that could be placed on operators.

Conclusions

Prior to making recommendations, a number of conclusions can be drawn from our research. First, is that while the U.S. ranks as one of the top emitters globally, the distribution of flaring differs from that of other countries. Specifically, U.S. flaring generally consists of a greater number of small flares, spatially distributed across multiple unconventional basins. As a result, the economic impact of implementing high-cost technologies to each flare is likely to be more significant compared to that of larger, single-source emitters. This can be directly observed when examining technologies implemented in (for example) large offshore oil and gas operations compared to a small well-pad flare in the Permian basin. In the case of the former, advanced flare tips with steam injection and instrumentation can be used to ensure smokeless operation and consistent ignition, while the latter may be a simple utility flare with little/no measurement or control capability. This is to say — in many cases technologies exist today that could solve the emissions problems in flaring but are not implemented for economic reasons. While this is not unique to flaring, it is exacerbated by the fact that flare gas is often considered a waste product with little perceived monetary value.

Next, is reporting. Independent measurement campaigns have shown that the EPA and DOE/EIA reported flaring volumes significantly under-estimate the GHG impacts. This can be likely attributed to three major aspects. First, many smaller operations fall under the GHGRP limit of 25,000 tons CO_{2e} emitted annually. Because the distribution of flaring in the U.S. consists of many smaller emitters, the impact of *not* requiring reporting for these operations is likely significant. Second, a significant number of assumptions are used in reporting requirements, including gas compositions, destruction efficiencies, and even volumes. And third, is accurate quantification of unlit or poorly performing flares.

While the U.S. outperforms many other countries at bringing gas to market vs. flaring for economic reasons (i.e., routine flaring), it still does occur. In particular, flaring continues to occur in many of the unconventional basins due to lack of sufficient gas gathering and transport infrastructure. In many other cases, variations of enclosed combustors are used, which are different than a typical elevated flare but such approaches are still impacted by the same variables that can contribute to poor flare operation. From a technology needs perspective, a delineation can be drawn between routine and non-routine flaring. The ZRF initiatives aim to eliminate routine flaring by 2025 (U.S., Permian) or 2030 (globally). Novel technologies that can provide operators with an alternative to routine flaring will help accelerate these efforts. This was echoed by two recent DOE reports.

- In 2019, as part of a regulatory overview, technology solutions were presented to reduce APG flaring and venting, primarily related to offtake and conversion to electricity or other fuels or chemicals. One suggestion was to improve the efficiency of existing flare reduction technologies to reduce emitted GHG volumes. Here, it was specifically noted that widespread adoption of such technologies is largely stymied by economics, rather than technology readiness.

- In a 2021 report to congress, it was noted that flaring and venting represents a more than $2B loss of revenue, but that economic challenges are largely responsible for not bringing the gas to market. The main R&D recommendations focused on economic alternatives to flaring, specifically technologies to convert flare gas into high(er) value products.

This report concurs with the findings of the 2019 and 2021 DOE reports. Specifically, with the rapidly approaching ZRF initiatives, economic alternatives to routine flaring are needed. However, because flaring cannot be eliminated completely, both considering non-routine applications and potential phase-in periods of ZRF or other state/federal regulations, immediate technology needs should be supported by R&D investments. Below are the most pressing/significant R&D recommendations for gas flares, not including flaring alternatives, which are discussed at the end of this section.

R&D Actions Supporting Emissions Mitigation in Industrial Gas Flares

Similar to the 2019 DOE report, our over-whelming finding is that economics are the largest inhibitor to adoption of advanced gas flare technologies. As mentioned above, this is particularly critical in small/distributed unconventional oil and gas operations within the U.S. In December 2023, new EPA regulations took affect (OOOOb, OOOOc), which will significantly impact flaring operations. All the primary R&D recommendations below focus on the technology needs influenced by these new regulations, including primarily measurement, reporting, and verification requirements; pending DE/emissions verification, additional R&D may be suggested (e.g.., advanced flare tips, air/steam injection, cost-effective retrofit applications and others).

Finally, related to the above two points, is an emphasis on cost-effective retrofittable (and/or modular) technologies. This primarily supports the need for low-cost solutions to meeting OOOOb/c requirements other than replacing the flare system as a whole. Similarly, depending on specific operational configurations, a single modular measurement or verification system could be deployed on a flare-by-flare basis rather than requiring multiple individual systems. In many cases, technologies exist that could address emissions/DE or meet OOOOb/c requirements; however, their implementation is not economically viable. As such, the R&D efforts below are not expected to require significant scientific breakthroughs, but rather are focused on robust and low-cost application of existing solutions. This could include leveraging technologies from other industries (ex. industrial heating, power, etc.).

An overview of the proposed R&D roadmap can be seen in **Figure**. The roadmap focuses on three main areas: information gathering, gas flare technology R&D, and flaring alternatives R&D. Information gathering includes this report, as well as a proposed follow-on task of performing an operator survey or request-for-information (RFI) to provide a clear picture of the technology distribution in the field and specific operator needs with regard to technology developments. This task is expected to inform all subsequent R&D. Considering the recent adoption of the EPA OOOOb/c regulations, a third task is proposed to provide operators with an easy-to-navigate tool or web-interface that can be used to help identify technologies or approaches that can be used to achieve compliance. This was identified as potential need due to the new EPA regulations' complexity, length, and specificity.

As this whitepaper was mostly focused on gas flare technologies, most R&D recommendations fall under gas flare technology R&D. Here, four main categories were identified corresponding to monitoring and re-light, measurement/reporting/verification, retrofits, and new full-replacement technologies. The first two categories are primarily focused on near-term efforts for OOOOb/c compliance. Retrofit technologies are aimed at achieving field-verified 98% or greater DE while minimizing economic impact to the operation, while new/full-replacement technologies are aimed at achieving unprecedented improvements in DE, up to 99.5%+. This goal is in-line with current ARPA-E REMEDY program goals. Importantly, for both the retrofit and new, full-replacement technologies, R&D should be informed by real-world gathered by novel measurement/reporting/verification technologies and mandated under EPA OOOOb/c regulations (and beyond). This type of comprehensive "bottom-up" assessment will help to supplement recent "top-down" data using satellite/aerial/ground-based measurements, providing improved data confidence.

A final cross-cutting area is noted for flaring alternatives. In light of recent ZRF initiatives and specific language in the EPA OOOOb/c regulations, elimination of routine flaring will be paramount in the coming years. Part of this will certainly be driven by technology developments, some of which are highlighted below. However, an equal part of this is likely to be incentivizing capture and use, developing/subsidizing infrastructure developments, and imposing strict regulations against flaring purely for economic reasons.

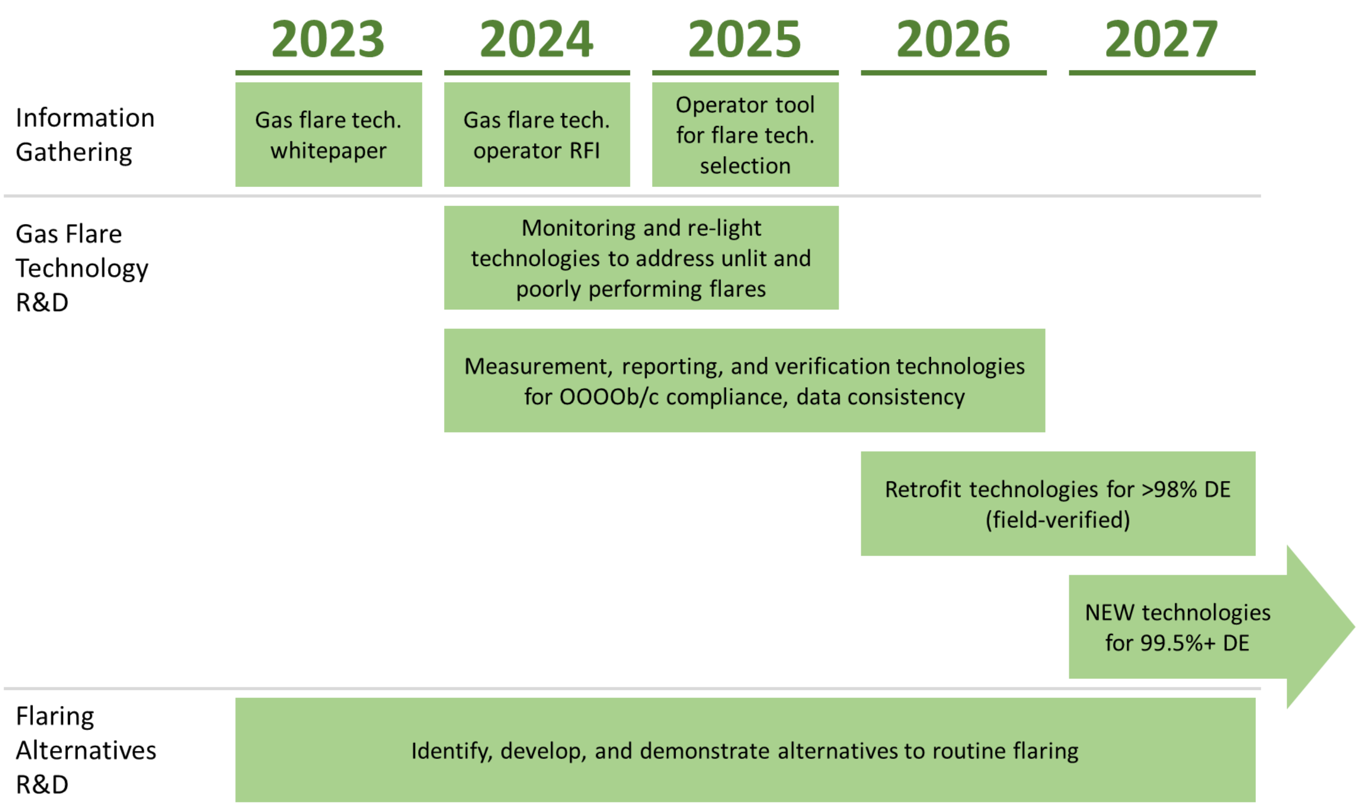


Figure 57. Overview of proposed R&D roadmap for gas flare technologies, 2023-2027.

The table below expands on the roadmap overview with specific R&D actions in the near-, mid-, and long-term time frame. In general, near-term actions focus on information gathering such as this report and an operator RFI, as well as addressing unlit flares. Mid-term primarily focuses on flare technologies needed for OOOOb/c compliance and ZRF initiatives, as well as low-cost retrofittable technologies. Long-term looks toward future elimination of non-routine flaring and/or implementation of advanced high-DE designs such as enclosed combustors.

Roadmap actions with near, mid, long-term R&D plans

	Near-Term 2023-2024	Mid-Term 2025-2026	Long-term 2027+
Information Gathering	• Develop a whitepaper on gas flare technologies (this report). • Conduct an operator survey via RFI to identify the distribution of technologies currently employed in up/mid/down-stream oil and gas operations. • Of specific interest — increase knowledge of technology distribution with respect to size/revenue/volume of operation, and solicit input on technologies needed for impending OOOOb/c compliance. **IMPACT:** Improved understanding of where R&D investments will be most beneficial.	• Develop a tool, software, or clearinghouse that can be used by oil and gas operators to help navigate the complexities of EPA regulations and identify technologies and approaches to achieve compliance (e.g., build upon programs such as EPA Natural Gas STAR Program). **IMPACT:** Accelerated adoption of technologies needed to achieve EPA compliance while minimizing economic impact to operators.	

Gas Flare Technology R&D			
Gas Flare Technology R&D	• Develop and implement retrofittable monitoring and re-light technologies to address unlit and poorly performing flares. • Could include technologies to eliminate continuous pilots in favor of automated high-energy ignition sources for further emissions reductions but would require regulatory changes for adoption. **IMPACT:** Eliminate GHG emissions created by unlit or poorly performing flares, increasing average DRE by as much as 4% [45].	• Develop low-cost, ruggedized instrumentation to support measurement, reporting, and verification needs under EPA OOOOb/c and beyond. • Include gas volume and flow rates, composition, heating value, as well as field-verification of DE and other (currently unregulated) emissions. • Technology development should include mechanisms to support automated collection and reporting, as well as consideration of data consistency and security. • Should consider power requirements and/or the use of stand-alone systems for remote sites without grid connection (ex. solar or other). • Develop retrofittable technologies for existing gas flare systems/designs to enable a field-verified 98% destruction efficiency or greater and 100% smokeless operation. • This is expected to be driven by the information gathered from the above measurement/ reporting/verification action such that R&D efforts are aligned with demonstrable needs for improvements in DE. • Technologies are expected to be focused around improving air entrainment and mixing while considering the economic impact to the operator and	• Develop technologies to achieve 99.5%+ DE in gas flares, improve currently unregulated emissions performance. • DE goal aligned with ARPA-e REMEDY program. • Could include measurement technologies for currently un-regulated pollutants (ex. NOx). • Expected to be non-retrofittable, new/novel approaches and may include the use of enclosed combustors, blowers, or other advanced combustion technologies. • Similar to mid-term retrofits, should be driven by measurement/ reporting/verification actions such that R&D efforts are best aligned to technical needs. **IMPACT:** Realize unprecedented reductions in methane emissions from gas flares, while providing knowledge to inform future regulatory actions.

		availability of supplement medium (or lack thereof). • Should also consider improvements in turndown performance and handling more non-routine, intermittent flaring events. **IMPACT:** Accelerate EPA OOOOb/c compliance while simultaneously providing an improved understanding of real-world gas flare performance (volumes, compositions, DE).	
Flaring Alternatives R&D	• Examine interim results for ongoing studies targeted at creating high-value products from flare gas to determine cost-effective and feasible technologies for continued R&D on a pathway towards commercial deployment. • Synthesize all private and government funded (U.S. and international) research projects including basic and applied research projects to enable detailed techno-economic analyses. **IMPACT:** Support near-term ZRF and OOOOb/c pushes to reduce routine flaring, resource waste.	• Leverage AI, IoT, and additive manufacturing to further decrease cost and increase market penetration of recent advancements and new technologies. **IMPACT:** Support complete elimination of routine flaring through cost-effective technology solutions at varying scales.	• Expand on lessons learned in the reduction or elimination of routine flaring to enable application to non-routine flaring applications. • R&D in conjunction with advanced 99.5%+ DE flare solutions. **IMPACT:** Eliminate non-routine flaring in certain applications, further reducing emissions, waste of resources.

The following are additional, detailed R&D suggestions specific to various flare components and technologies.

1. Processing Systems
    a. Continue to develop new technologies and reduce costs associated with the transition to zero-leak equipment for gas processing operations (e.g., low-emission valves, improved seals, zero loss transfer equipment, etc.) or captured/piped equipment (rather than released to environment). Some of this is currently in development or being federally funded – see [22].
    b. Improve facility design and standard operating procedures with respect to safety flaring/venting (e.g., methods to capture, store, and reuse gas that would otherwise be vented or flared during upset conditions or for required repair and maintenance.
    c. Improve energy and cost for vapor recovery units to reduce storage tank emissions.
    d. Change acid gas treatment process to eliminate/reduce CO_2.
2. Flare Systems
    a. Perform a rigorous, third-party laboratory-scale experimental campaign of various flare designs. Could implement scaled-down burners, simulated wind, integrate advanced diagnostics to understand and optimize these systems in the open literature.
    b. Improve burner/combustor technology to increase CH_4 destruction efficiency to 99.5%+
        i. Ultra-high efficiency blowers/fans.
        ii. Retrofittable high-pressure air injection systems (and air sources – e.g., cheap/efficient compressors).
        iii. Premixed/partially premixed approaches (include low loss flashback technologies).
        iv. 3D printed geometries.
        v. Novel flow physics such as Coanda effect, buoyancy, etc. in lower cost options.
        vi. Ultra-low pressure drop burner designs.
    c. Advance steam and air minimization technologies (direct capital impact, must continue enabling smokeless/high-efficiency).
    d. Improve DE of enclosed combustors through advanced control that could enable use of catalysts for enhanced CH_4 and VOC reductions.
    e. Apply technologies for waste heat extraction from flares (use to power compressors/blowers/etc.).
        i. Improved, low-cost, high efficiency thermoelectric generators (TEGs) to enable remote power generation that may be required to deploy advanced measurement and monitoring technologies.
        ii. Preheating or reforming gas.
        iii. Raising steam from waste heat.
3. Measurement
    a. Reduce costs while maintaining safety and accuracy of flow measurement technologies (composition agnostic, low-cost adaptation of existing technologies).
    b. Develop low-cost composition measurement sensors (e.g., miniaturization of GC, FTIR, or calorimeter based, tunable diode lasers, RF/microwave, SAW sensors, conductive polymers).
    c. Apply IoT/ML/AI approaches for measurement, monitoring, and reporting.

d. Develop low-cost in-situ emissions concentration measurement devices for DE, emissions (e.g., GHG, N_2O, CO_2); continuous monitoring or periodic evaluation (ex. TDL/FTIR/IR imaging, etc.).

4. Control
    a. Real-time flare detection and re-light controls.
    b. Passive or low-cost active controls to handle temporal variability in turndown and composition (e.g., flow splitting to parallel/series flares, air dampers, variable blowers, steam/air injection, etc.).
        i. Active controls could include closed-loop in conjunction with DE, smoke, other emissions detection.

While incremental improvements may seem to lack significant justification or impact, it is important to understand real implications. For example, if current flaring data were deemed accurate and incremental improvements were made to improve DE to 99.5% (ARPA-E goal), this would represent a 75% reduction in flaring related methane emissions. When accounting for GWP of methane, this would represent a substantial reduction in CO2 equivalent emissions for flares that may be unavoidable. Similarly, routine flaring accounts for ~2/3% of flaring globally [12]. However, as of writing, no good source could be found for routine flaring distribution within the United States. While it is likely that routine flaring represents a smaller fraction of flaring in the U.S., its elimination will represent a significant reduction in methane emissions. Additionally, increased measurement and reporting requirements will help better define the significance of routine flaring domestically.

In closing, the practice of flaring remains as a significant source of methane and other GHG emissions in oil and natural gas operations. Additionally, it often represents a significant waste of a limited natural resource. The newly adopted EPA regulations attempt to address many of these issues but are likely to place a significant economic strain on operators. The development of economic technology-driven solutions is going to be critical in supporting this transition, backed by strategic federal investments. The R&D recommendations above directly support the goal of NETL's Natural Gas Infrastructure field work proposal to develop tools and materials to quantify and mitigate emissions from natural gas infrastructure, as well as broader DOE program goals to invest in technologies to reduce methane emissions from the ONG industry.

Acknowledgements

This work was performed in support of the U.S. Department of Energy's Fossil Energy and Carbon Management's Methane Mitigation Program and executed through the National Energy Technology Laboratory (NETL) Research & Innovation Center's Natural Gas Infrastructure Field Work Proposal (DE FE 1022424).

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