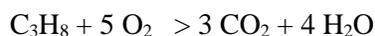


13.5 Industrial Flares

13.5.1 General

Flaring is a high-temperature oxidation process used to burn combustible components, mostly hydrocarbons, of waste gases from industrial operations. Natural gas, propane, ethylene, propylene, butadiene and butane constitute over 95 percent of the waste gases flared. In combustion, gaseous hydrocarbons react with atmospheric oxygen to form carbon dioxide (CO₂) and water. In some waste gases, carbon monoxide (CO) is the major combustible component. Presented below, as an example, is the combustion reaction of propane.



During a combustion reaction, several intermediate products are formed, and eventually, most are converted to CO₂ and water. Some quantities of stable intermediate products such as carbon monoxide, hydrogen, and hydrocarbons will escape as emissions.

Flares are used extensively to dispose of (1) purged and wasted products from refineries, (2) unrecoverable gases emerging with oil from oil wells, (3) vented gases from blast furnaces, (4) unused gases from coke ovens, and (5) gaseous wastes from chemical industries. Gases flared from refineries, petroleum production, chemical industries, and to some extent, from coke ovens, are composed largely of low molecular weight hydrocarbons with high heating value. Blast furnace flare gases are largely of inert species and CO, with low heating value. Flares are also used for burning waste gases generated by sewage digesters, coal gasification, rocket engine testing, nuclear power plants with sodium/water heat exchangers, heavy water plants, and ammonia fertilizer plants.

There are two types of flares, elevated and ground flares. Elevated flares, the more common type, have larger capacities than ground flares. In elevated flares, a waste gas stream is fed through a stack anywhere from 10 to over 100 meters tall and is combusted at the tip of the stack. The flame is exposed to atmospheric disturbances such as wind and precipitation. In ground flares, combustion takes place at ground level. Ground flares vary in complexity, and they may consist either of conventional flare burners discharging horizontally with no enclosures or of multiple burners in refractory-lined steel enclosures.

The typical flare system consists of (1) a gas collection header and piping for collecting gases from processing units, (2) a knockout drum (disentrainment drum) to remove and store condensables and entrained liquids, (3) a proprietary seal, water seal, or purge gas supply to prevent flash-back, (4) a single- or multiple-burner unit and a flare stack, (5) gas pilots and an ignitor to ignite the mixture of waste gas and air, and, if required, (6) a provision for external momentum force (steam injection or forced air) for smokeless flaring. Natural gas, fuel gas, inert gas, or nitrogen can be used as purge gas. Figure 13.5-1 is a diagram of a typical steam-assisted elevated smokeless flare system.

~~Complete combustion requires sufficient combustion air and proper mixing of air and waste gas. Combustion requires three ingredients: fuel, an oxidizing agent (typically oxygen in air), and heat (or ignition source). Flares typically operate with pilot flames to provide the ignition source, and they use ambient air as the oxidizing agent. The waste gases to be flared typically provide the fuel necessary for combustion. Combustible gases generally have an upper and lower flammability limit. The upper flammability limit (UFL) is the highest concentration of a gas in air that is capable of burning. Above this flammability limit, the fuel is too rich to burn. The lower flammability limit (LFL) is the lowest~~

concentration of the gas in air that is capable of burning. Below the LFL, the fuel is too lean to burn. Between the upper and lower flammability limits, combustion can occur. Flare waste gases with concentrations above the UFL will become more dilute as the waste gas mixes with ambient air above the flare tip. As this dilution occurs, the air-waste gas mixture will pass through the flammability region, and combustion will occur. However, if flare waste gas concentrations are near the LFL prior to mixing with air, the air-waste gas mixture will quickly fall below the flammability region, and poor combustion efficiencies will occur. If steam is added to the flare waste gas at or prior to the flare tip (i.e., prior to the “combustion zone” where the mixing with air occurs), the steam will act to dilute the waste gas. Thus, even if there are adequate concentrations of combustibles in the waste gas, if too much steam is added to the waste gas so that the combustibles concentration becomes diluted to near the LFL as the steam-waste gas mixture enters the combustion zone, poor combustion efficiencies will result. Consequently, critical considerations of flare combustion include the net heating value and the combustibles concentration in the flare gas and in the combustion zone (e.g., accounting for the amount of dilution by steam or other assist gas that occurs to the waste gas prior to the combustion zone).

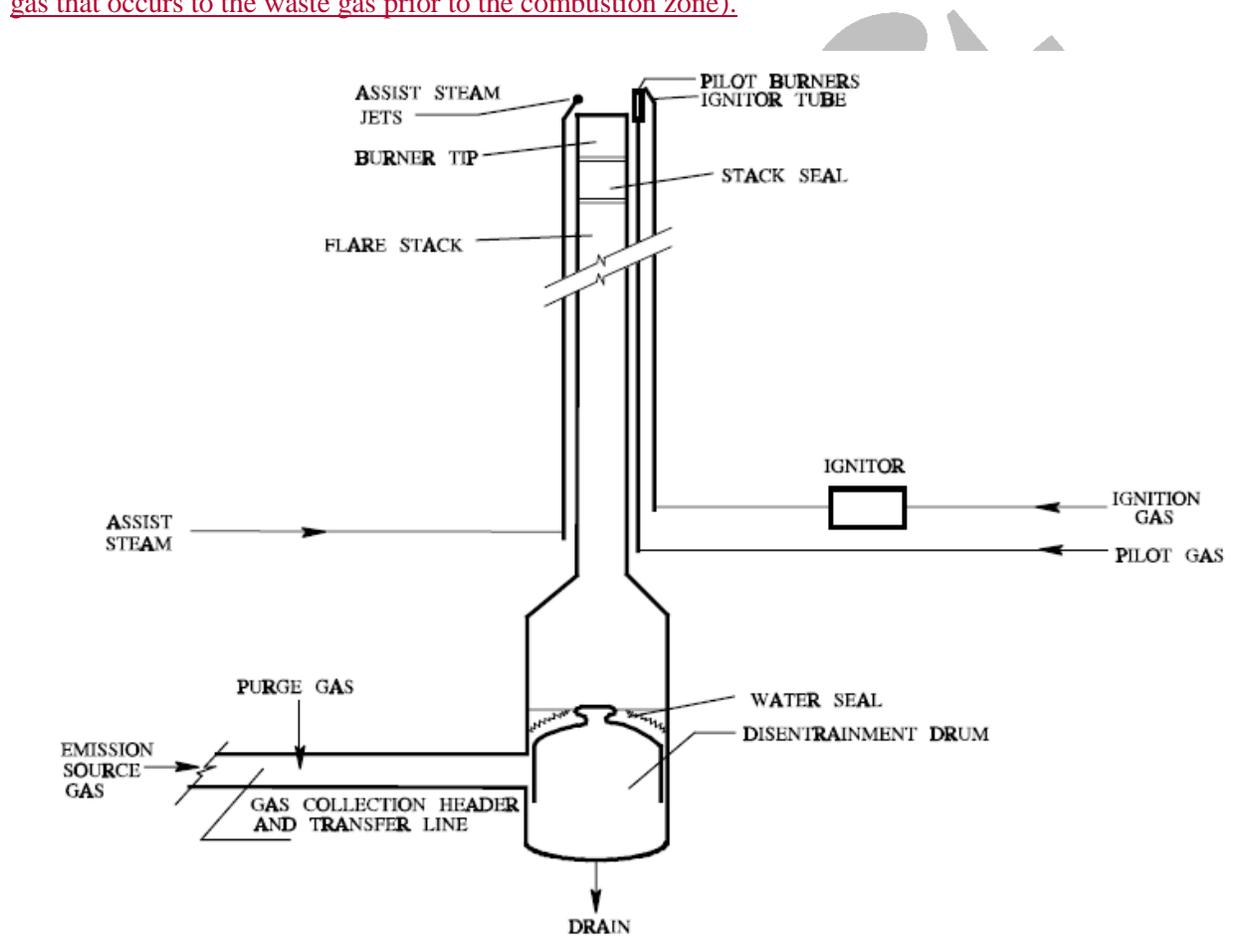


Figure 13.5-1. Diagram of a typical steam-assisted smokeless elevated flare.

Combustion efficiency is the percentage of carbon in the flare vent gas that is completely converted to CO₂. Destruction efficiency is the percentage of a specific pollutant in the flare vent gas that is converted to a different compound (such as CO₂, CO or other hydrocarbon intermediate). The destruction efficiency of a flare will always be greater than the combustion efficiency of a flare. It is

generally estimated that a combustion efficiency of 96.5 percent is equivalent to a destruction efficiency of 98 percent.¹⁰

Smoking may result from combustion, depending upon waste gas components and the quantity and distribution of combustion air. Waste gases containing methane, hydrogen, CO, and ammonia usually burn without smoke. Waste gases containing heavy hydrocarbons such as paraffins above methane, olefins, and aromatics, cause usually burn with smoke. An external momentum force, such as steam injection or blowing air, is used for efficient air/waste gas mixing and turbulence, which promotes smokeless flaring of heavy hydrocarbon waste gas. Other external forces may be used for this purpose, including water spray, high velocity vortex action, or natural gas. External momentum force is rarely required in ground flares.

~~Figure 13.5-1. Diagram of a typical steam-assisted smokeless elevated flare.~~

Steam injection is accomplished either by nozzles on an external ring around the top of the flare tip or by a single nozzle located concentrically within the tip. At installations where waste gas flow varies, both are used. The internal nozzle provides steam at low waste gas flow rates, and the external jets are used with large waste gas flow rates. Several other special-purpose flare tips are commercially available, one of which is for injecting both steam and air. ~~Typical steam usage ratio varies from 7:1 to 2:1, by weight.~~

~~Waste gases to be flared must have a fuel value of at least 7500 to 9300 kilojoules per cubic meter kJ/m^3 (200 to 250 British thermal units per cubic foot $[\text{Btu/ft}^3]$) for complete combustion; otherwise fuel must be added. Flares providing supplemental fuel to waste gas are known as fired, or endothermic, flares. In some cases, even flaring waste gases having the necessary heat content will also require supplemental heat. If fuel-bound nitrogen is present, flaring ammonia with a heating value of $13,600 \text{ kJ/m}^3$ (365 Btu/ft^3) will require higher heat to minimize nitrogen oxides (NO_x) formation.~~

~~At many locations, flares normally used to dispose of low-volume continuous emissions are~~
Flares are generally designed to handle large quantities of waste gases that may be intermittently generated during plant emergencies, although they may also be used routinely to dispose of low-volume continuous or intermittent emissions from various sources at the plant. Flare gas volumes can vary from a few cubic meters per hour during regular operations up to several thousand cubic meters per hour during major upsets. Flow rates at a refinery could be ~~from~~ 45 to 90 kilograms per hour (kg/hr) (100 - 200 pounds per hour [lb/hr]) for relief valve leakage during regular operation but could reach a full plant emergency rate of 700 megagrams per hour (Mg/hr) (750 tons/hr). Normal process blowdowns may release 450 to 900 kg/hr (1000 - 2000 lb/hr), and unit maintenance or minor failures may release 25 to 35 Mg/hr (27 - 39 tons/hr). ~~A 40 molecular weight gas typically of 0.012 cubic nanometers per second (nm^3/s) (25 standard cubic feet per minute [scfm]) may rise to as high as 115 nm^3/s (241,000 scfm). The required flare turndown ratio for this typical case is~~ Thus, the required flare turndown ratio can be over 15,000 to 1.

Many ~~flare systems~~ plants have 2 or more flares, in parallel or in series. In the former, 1 flare can be shut down for maintenance while the other serves the system. In systems of flares in series, 1 flare, usually a low-level ground flare, is intended to handle regular gas volumes, and the other, an elevated flare, to handle excess gas flows from emergencies.

13.5.2 Emissions

Noise, heat, and heat/visible flame and/or smoke are the most apparent undesirable effects of flare operation. Flares are usually located away from populated areas or are sufficiently isolated, thus minimizing their effects on populations.

Emissions from flaring include carbon particles (soot), unburned hydrocarbons, CO, and other partially burned and altered hydrocarbons. Also emitted are nitrogen oxides (NO_x) and, if sulfur-containing material such as hydrogen sulfide or mercaptans is flared, sulfur dioxide (SO₂). The quantities of hydrocarbon emissions generated relate to the degree of combustion. The degree of combustion depends largely on the rate and extent of fuel-air mixing and on the flame temperatures achieved and maintained. Properly operated flares achieve at least 98 percent combustion/destruction efficiency in the flare plume, meaning that hydrocarbon and CO-emissionsemissions amount to less than 2 percent of the hydrocarbons in the gas stream.

The tendency of a fuel to smoke or make soot is influenced by fuel characteristics and by the amount and distribution of oxygen in the combustion zone. For complete combustion, at least the stoichiometric amount of oxygen must be provided in the combustion zone. The theoretical amount of oxygen required increases with the molecular weight of the gas burned. The oxygen supplied as air ranges from 9.6 units of air per unit of methane to 38.3 units of air per unit of pentane, by volume. Air is supplied to the flame as primary air and secondary air. Primary air is mixed with the gas before combustion, whereas secondary air is drawn into the flame. For smokeless combustion, sufficient primary air must be supplied, this varying from about 20 percent of stoichiometric air for a paraffin to about 30 percent for an olefin. If the amount of primary air is insufficient, the gases entering the base of the flame are preheated by the combustion zone, and larger hydrocarbon molecules crack to form hydrogen, unsaturated hydrocarbons, and carbon. The carbon particles may escape further combustion and cool down to form soot or smoke. Olefins and other unsaturated hydrocarbons may polymerize to form larger molecules which crack, in turn forming more carbon.

The fuel characteristics influencing soot formation include the carbon-to-hydrogen (C-to-H) ratio and the molecular structure of the gases to be burned. All hydrocarbons above methane, i. e., those with a C-to-H ratio of greater than 0.33, tend to soot. Branched chain paraffins smoke more readily than corresponding normal isomers. The more highly branched the paraffin, the greater the tendency to smoke. Unsaturated hydrocarbons tend more toward soot formation than do saturated ones. Soot is eliminated by adding steam or air; hence, most industrial flares are steam-assisted and some are air-assisted. Flare gas composition is a critical factor in determining the amount of steam necessary.

Since flares do not lend themselves to conventional emission testing techniques, until recently only a few attempts have been made to characterize flare emissions. Recent/Early EPA tests using propylene as flare gas indicated that efficiencies of 98 percent can be achieved when burning an offgas with at least 11,200 kJ/m³ (300 Btu/ft³).¹ However, recent studies on flare performance using passive Fourier Transform Infrared (pFTIR) spectroscopy have been performed on a number of different flares.⁴⁻⁸ The tests conducted on steam-assisted studies cover a number of flares at velocities as low as 39.6 meters per minute (m/min) (130 ft/min) to 1140 m/min (3750 ft/min), and on air-assisted flares at velocities of 180 m/min (617 ft/min) to 3960 m/min (13,087 ft/min) indicated different industrial sources with different waste gas compositions. The pFTIR studies support the conclusion that variations in incoming gas flow rates have no effect on the combustion efficiency. Flare gases with less than 16,770 kJ/m³ (450 Btu/ft³) zone properties of the steam-waste gas mixture are predictive of proper flare combustion.¹⁰ There have also been recent studies on sources, including flares, using differential infrared absorption LIDAR [light detection and ranging] (DIAL). To date, many of these studies do not smoke-provide the data necessary to isolate the emissions from a particular flare. But enough data existed in one study that the emissions measured by DIAL could be attributed to the flare.⁹

Table 13.5-1 presents flare ~~emission~~emissions factors, ~~and from the EPA tests~~¹; Table 13.5-2 presents ~~emission composition data obtained from the EPA tests~~¹ flare emissions factors from pFTIR and DIAL studies.⁴⁻⁹ Crude propylene was used as flare gas during the early EPA tests. Methane was a major fraction of hydrocarbons in the flare emissions, and acetylene was the dominant intermediate hydrocarbon species. Many other reports on flares indicate that acetylene is always formed as a stable intermediate product. The acetylene formed in the combustion reactions may react further with hydrocarbon radicals to form polyacetylenes followed by polycyclic hydrocarbons.² Typical refinery waste gas feeds were used as flare gas during the pFTIR and DIAL studies.

In flaring waste gases containing no nitrogen compounds, NO is formed either by the fixation of atmospheric nitrogen (N) with oxygen (O) or by the reaction between the hydrocarbon radicals present in the combustion products and atmospheric nitrogen, by way of the intermediate stages, HCN, CN, and OCN.² Sulfur compounds contained in a flare gas stream are converted to SO₂ when burned. The amount of SO₂ emitted depends directly on the quantity of sulfur in the flared gases.

Table 13.5-1 (English Units). THC AND SOOT EMISSIONS FACTORS FOR FLARE OPERATIONS^a

EMISSIONS FACTOR RATING: B

<u>Component</u> <u>Pollutant</u>	<u>Emissions</u> <u>Factor</u> <u>Value</u> (lb/10 ⁶ <u>Btu</u>)	<u>Emissions</u> <u>Factor</u> <u>Units</u>
Total hydrocarbons ^b	0.14	lb/10 ⁶ Btu
Carbon monoxide	0.37	
Nitrogen oxides	0.068	
Soot ^c	0 - 274	µg/L

^a Reference 1. Based on tests using crude propylene containing 80% propylene and 20% propane.

^b Measured as methane equivalent.

^c Soot in concentration values: nonsmoking flares, 0 micrograms per liter (µg/L); lightly smoking flares, 40 µg/L; average smoking flares, 177 µg/L; and heavily smoking flares, 274 µg/L.

~~Table 13.5-2. HYDROCARBON COMPOSITION OF FLARE EMISSION^a~~

<u>Composition</u>	<u>Volume %</u>	
	<u>Average</u>	<u>Range</u>
<u>Methane</u>	55	14—83
<u>Ethane/Ethylene</u>	8	1—14
<u>Acetylene</u>	5	0.3—23
<u>Propane</u>	7	0—16
<u>Propylene</u>	25	1—65

~~^a—Reference 1. The composition presented is an average of a number of test results obtained under the following sets of test conditions: steam-assisted flare using high-Btu content feed; steam-assisted~~

using low Btu content feed; air-assisted flare using high Btu content feed; and air-assisted flare using low Btu content feed. In all tests, "waste" gas was a synthetic gas consisting of a mixture of propylene and propane.

Table 13.5-2 (English Units). VOC, CO, AND NO_x EMISSIONS FACTORS FOR FLARE OPERATIONS

<u>Pollutant</u>	<u>Emissions Factor (lb/10⁶ Btu)</u>	<u>Representativeness</u>
<u>Volatile organic carbon^a</u>	<u>0.55</u>	<u>Moderately</u>
<u>Carbon monoxide^b</u>	<u>0.34</u>	<u>Moderately</u>
<u>Nitrogen oxides^c</u>	<u>2.9</u>	<u>Moderately</u>

^a References 4-9.

^b References 1 and 4-8.

^c References 1, 4-6, and 8.

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