## 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 (CO_2) 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.

$$C_3H_8 + 5\ O_2\ \rightarrow\ 3\ CO_2 + 4\ H_2O$$
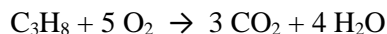
During a combustion reaction, several intermediate products are formed, and eventually, most are converted to CO_2 and water. Some quantities of stable intermediate products such as carbon monoxide, hydrogen, and hydrocarbons will escape as emissions.

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 and is almost always unassisted. Ground flares vary in complexity, and they may consist either of conventional flare burners with no enclosures or of multiple burners in refractory-lined steel enclosures. Ground flares may also be known as shielded flares.[a] Ground flares should not be mistaken for thermal oxidizers or incinerators. Ground flares operate under the same principals as elevated flares and combustion is achieved through the natural draft of combustion air. Thermal oxidizers and incinerators have combustion air blowers and can be tuned to control combustion chamber temperature, thereby allowing for more effective combustion control.

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

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[a] For the purposes of 40 CFR part 60 subparts OOOO and OOOOa and 40 CFR part 63 subparts HH and HHH, these units are not considered flares. The definition of flare in these subparts specifically exclude these units. In these subparts, a flare is defined as a thermal oxidation system using an open flame (without enclosure). Under these subparts, these units are considered combustion devices that must be field-tested. Alternatively, a unit tested by a manufacturer may be installed.

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.

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 can fall below the flammability region, and reduced combustion efficiencies can 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, reduced 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).
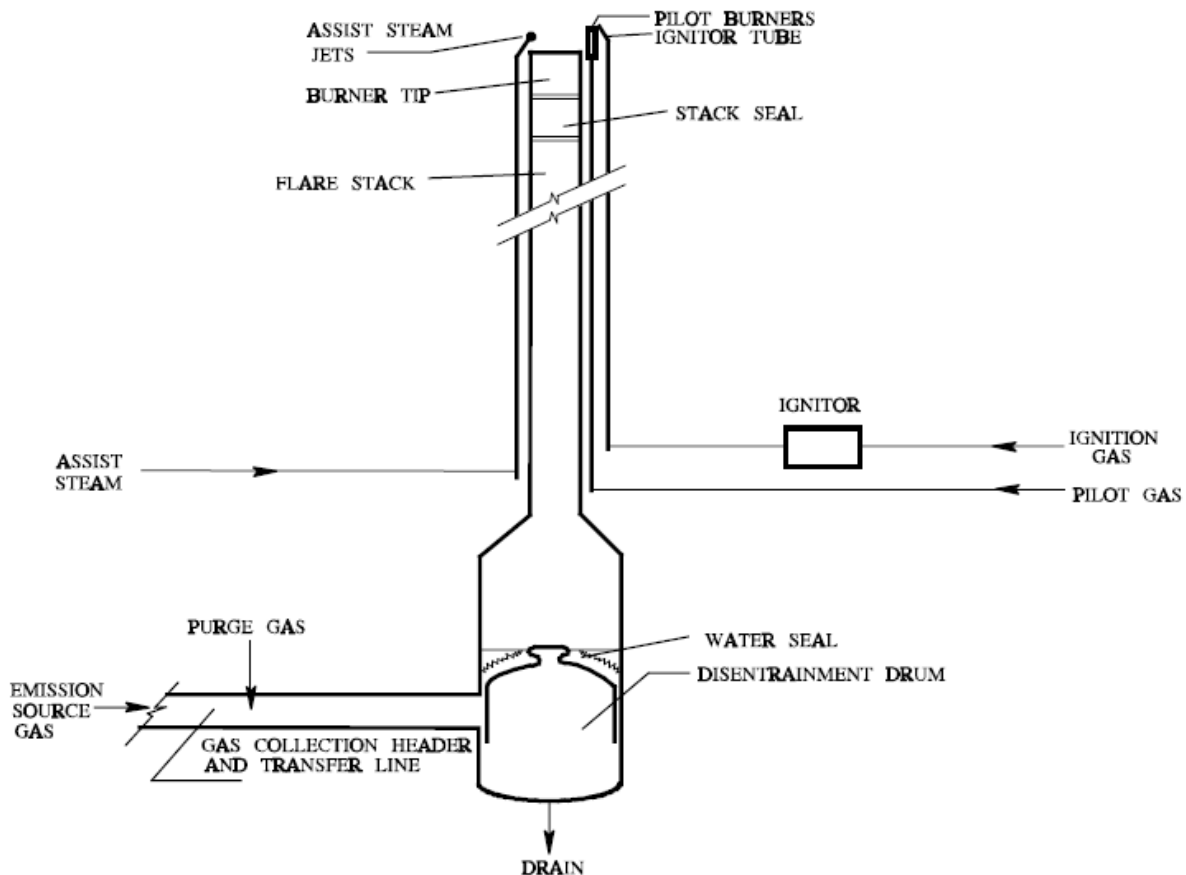

Figure 13.5-1. Diagram of a typical steam-assisted smokeless elevated flare.

Combustion efficiency is the percentage of hydrocarbon in the flare vent gas that is completely converted to CO_2 and water vapor. Destruction efficiency is the percentage of a specific pollutant in the flare vent gas that is converted to a different compound (such as CO_2, 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, have a higher tendency to 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.

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.

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 45 to 90 kilograms per hour (kg/hr) (100 - 200 pounds per hour [lb/hr]) 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). Thus, the required flare turndown ratio can be over 15,000 to 1.

Many 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 is intended to handle regular gas volumes and the other flare is generally intended to handle excess gas flows from emergencies.

13.5.2 Emissions

Noise, heat, and 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. Because the flame in a ground flare is generally not visible, and they reduce noise and thermal radiation to the surrounding area, these flares are common in populated areas. Emissions from flaring may include carbon particles (soot), unburned hydrocarbons, CO, and 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 (SO_2). 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 destruction efficiency in the flare plume, meaning that hydrocarbon emissions 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 elevated flares do not lend themselves to conventional emission testing techniques, until recently only a few attempts have been made to characterize elevated flare emissions. 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/m^3 (300 Btu/ft^3).[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 studies cover a number of flares at refineries, chemical plants and flare test facilities with varying waste gas compositions. The pFTIR studies support the conclusion that the combustion 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 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] For flares operated at petroleum refineries, EPA has determined that the net heating value of the gas in the combustion zone of the flare should be greater than or equal to 270 Btu/ft^3 to obtain a destruction efficiency of at least 98%.[b]

Table 13.5-1 presents flare emissions factors from the EPA tests[1]; Table 13.5-2 presents 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

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[b] See Petroleum Refinery Sector Risk and Technology Review and New Source Performance Standards Final Rule, December 1, 2015 (80 FR 75183). Net heating value of the combustion zone is determined on a 15-minute average, and refinery owners and operators may use a corrected heat content for hydrogen when determining the combustion zone heat value.

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 SO_2 when burned. The amount of SO_2 emitted depends directly on the quantity of sulfur in the flared gases.

With the promulgation of the New Source Performance Standards for Crude Oil and Natural Gas Production, Transmission, and Distribution, EPA developed a manufacturer testing program for combustion control devices. These units are generally equivalent to enclosed ground flares, although they are explicitly excluded from the definition of flare in those subpart (see footnote a to this section). The manufacturer testing program requires performance testing be conducted using pure propylene under four different test conditions. Emissions data from these manufacturer tests have been used to develop emissions factors for enclosed ground flares. Because the factors are representative of enclosed ground flares burning propylene, the factors are included in Table 13.5-1, which are the flare factors developed from the EPA testing of elevated flares using crude propylene. Two factors are representative of enclosed ground flares operating at a low percent load, and two factors are representative of enclosed ground flares operating at a normal to high percent load.[c]

Additionally, the Oil and Gas sector rules, as well as some state programs, are requiring more testing for these types of units in the field. As a result, emissions data are available from enclosed ground flares burning field gas. Table 13.5-3 presents two enclosed ground flare emissions factors for total hydrocarbons (THC) applicable to natural gas production.

Table 13.5-4 presents the description of the source classification codes (SCCs) to which the emissions factors in Tables 13.5-1 through 13.5-3 are applicable.

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[c] Because it is possible to test enclosed ground flares, the EPA recommends testing sources and using site-specific data in lieu of emissions factors whenever possible.

Table 13.5-1 (English Units). THC, NOx AND SOOT EMISSIONS FACTORS FOR FLARE OPERATIONS FOR CERTAIN CHEMICAL MANUFACTURING PROCESSES[a]

Pollutant	SCC[e]	Emissions Factor Value	Emissions Factor Units	Grade or Representativeness
THC, elevated flares[c]	30190099; 30119701; 30119705; 30119709; 30119741	0.14[b,f]	lb/10^6 Btu	B
THC, enclosed ground flares[g,h] Low Percent Load[i]		8.37[j] or 3.88e-3[f]	lb/10^6 scf gas burned lb/10^6 Btu heat input	Moderately
THC, enclosed ground flares[g,h] Normal to High Percent Load[i]		2.56[j] or 1.20e-3[f]	lb/10^6 scf gas burned lb/10^6 Btu heat input	Moderately
Nitrogen oxides, elevated flares[d]		0.068[b,k]	lb/10^6 Btu	B
Soot, elevated flares[d]		0 – 274[b]	μg/L	B

[a] All of the emissions factors in this table represent the emissions exiting the flare. Since the flare is not the originating source of the THC emissions, but rather the device controlling these pollutants routed from a process at the facility, the emissions factors are representative of controlled emissions rates for THC. These values are not representative of the uncontrolled THC routed to the flare from the associated process, and as such, they may not be appropriate for estimating the uncontrolled THC emissions or potential to emit from the associated process.

[b] Reference 1. Based on tests using crude propylene containing 80% propylene and 20% propane.

[c] Measured as methane equivalent. The THC emissions factor may not be appropriate for reporting volatile organic compounds (VOC) emissions when a VOC emissions factor exists.

[d] 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.

[e] See Table 13.5-4 for a description of these SCCs.

[f] Factor developed using the lower (net) heating value of the vent gas.

[g] THC measured as propane by US EPA Method 25A.

[h] These factors apply to well operated ground flares achieving at least 98% destruction efficiency and operating in compliance with the current General Provisions requirements of 40 CFR Part 60, i.e. >200 btu/scf net heating value in the vent gas and less than the specified maximum exit velocity. The emissions factor data set had an average destruction efficiency of 99.99%. Based on tests using pure propylene fuel. References 12 through 33 and 39 through 45.

[i] The dataset for these tests were broken into four different test conditions: ramping back and forth between 0 and 30% of load; ramping back and forth between 30% and 70% of load; ramping back and forth between 70% and 100% of load; and a fixed rate maximum load condition. Analyses determined that only the first condition was statistically different. Low percent load is represented by a unit operating at approximately less than 30% of maximum load.

[j] Heat input is an appropriate basis for combustion emissions factor. However, based on available data, heat input data is not always known, but gas flowrate is generally available. Therefore, the emissions factor is presented in two different forms.

[k] Factor developed using the higher (gross) heating value of the vent gas.

Table 13.5-2 (English Units). VOC and CO EMISSIONS FACTORS FOR ELEVATED FLARE
OPERATIONS FOR CERTAIN REFINERY AND CHEMICAL MANUFACTURING PROCESSES[a,b]

Pollutant	SCC[e]	Emissions Factor (lb/10^6 Btu)[f]	Representativeness
Volatile organic compounds[c]	30190099; 30600904; 30119701; 30119705; 30119709; 30119741; 30119799; 30130115; 30600201; 30600401; 30600508; 30600903; 30600999; 30601701; 30601801; 30688801; 40600240	0.66	Poorly
Carbon monoxide[d]		0.31	Poorly

[a] The emissions factors in this table represent the emissions exiting the flare. Since the flare is not the originating source of the VOC emissions, but rather the device controlling these pollutants routed from a process at the facility, the emissions factor is representative of controlled emissions rates for VOC. This values is not representative of the uncontrolled VOC routed to the flare from the associated process, and as such, it may not be appropriate for estimating the uncontrolled VOC emissions or potential to emit from the associated process.

[b] These factors apply to well operated flares achieving at least 98% destruction efficiency and operating in compliance with the current General Provisions requirements of 40 CFR Part 60, i.e. >300 btu/scf net heating value in the vent gas and less than the specified maximum flare tip velocity. The VOC emissions factor data set had an average destruction efficiency of 98.9%, and the CO emissions factor data set had an average destruction efficiency of 99.1% (based on test reports where destruction efficiency was provided). These factors are based on steam-assisted and air-assisted flares burning a variety of vent gases.

[c] References 4 through 9 and 11.

[d] References 1, 4 through 8, and 11.

[e] See Table 13.5-4 for a description of these SCCs.

[f] Factor developed using the lower (net) heating value of the vent gas.

Table 13.5-3 (English Units). THC EMISSIONS FACTOR FOR ENCLOSED GROUND FLARES AT NATURAL GAS PRODUCTION SITES[a]

Pollutant	SCC[e]	Emissions Factor[f]	Representativeness
THC[b,c,d]	31000205 31000212 31000227	332 lb/10^6 scf gas burned or 0.335 lb/10^6 Btu heat input[g]	Poorly

[a] The emissions factor in this table represents the emissions exiting the flare. Since the flare is not the originating source of the THC emissions, but rather the device controlling these pollutants routed from a process at the facility, the emissions factor is representative of controlled emissions rates for THC. This value is not representative of the uncontrolled THC routed to the flare from the associated process, and as such, it may not be appropriate for estimating the uncontrolled THC emissions or potential to emit from the associated process.

[b] THC measured as propane by US EPA Method 25A.

[c] These factors apply to well operated flares achieving at least 95% destruction efficiency, as required by the Oil and Gas sector rules in 40 CFR parts 60 and 63. Although the Oil and Gas sector rules in parts 60 and 63 do not require ground flares to operate in compliance with the current General Provisions requirements of 40 CFR Part 60 or 63, i.e. >200 btu/scf net heating value in the vent gas and less than the specified maximum exit velocity, the reference flares do meet these requirements. The emissions factor data set had an average destruction efficiency of 99.33% for the gas volume basis and an average destruction efficiency of 99.23% for the heat input basis. Based on tests using natural gas production field gas, e.g. tank vents, dehydrator vents. References 32 through 38.

[d] For enclosed ground flares with the SCCs specified in this table, the EPA recommends the use of this THC emissions factor instead of the VOC emissions factor in WebFIRE, as background documentation for this new emissions factor is available and the factor is based on field data from similar units.

[e] See Table 13.5-4 for a description of these SCCs. For the purposes of 40 CFR part 60 subparts OOOO and OOOOa and 40 CFR part 63 subparts HH and HHH, these units are not considered flares. The definition of flare in these subparts specifically exclude these units. In these subparts, a flare is defined as a thermal oxidation system using an open flame (without enclosure).

[f] Heat input is an appropriate basis for combustion emissions factor. However, based on available data, heat input data is not always known, but gas flowrate is generally available. Additionally, based on the available reports, there was a more robust dataset to develop an emissions factor on a gas volume basis. Therefore, the emissions factor is presented in two different forms.

[g] Factor developed using the lower (net) heating value of the vent gas.

Table 13.5-4. SCC Descriptions

SCC	Level 1 Description	Level 2 Description	Level 3 Description	Level 4 Description
30600903	Industrial Processes	Petroleum Industry	Flares	Natural Gas
30600904	Industrial Processes	Petroleum Industry	Flares	Process Gas
30190099	Industrial Processes	Chemical Manufacturing	Fuel Fired Equipment	User Specified
30600999	Industrial Processes	Petroleum Industry	Flares	Not Classified
30600201	Industrial Processes	Petroleum Industry	Catalytic Cracking Units	Fluid Catalytic Cracking Unit
30130115	Industrial Processes	Chemical Manufacturing	Chlorobenzene	Atmospheric Distillation Vents
30688801	Industrial Processes	Petroleum Industry	Fugitive Emissions	User Specified
30600401	Industrial Processes	Petroleum Industry	Blowdown Systems	Blowdown System with Vapor Recovery System with Flaring
30601801	Industrial Processes	Petroleum Industry	Hydrogen Generation Unit	General
30601701	Industrial Processes	Petroleum Industry	Catalytic Hydrotreating Unit	General
30600508	Industrial Processes	Petroleum Industry	Wastewater Treatment	Oil/Water Separator
40600240	Petroleum and Solvent Evaporation	Transportation and Marketing of Petroleum Products	Marine Vessels	Gasoline: Barge Loading - Average Tank Condition
30119701	Industrial Processes	Chemical Manufacturing	Butylene, Ethylene, Propylene, Olefin Production	Ethylene: General
30119741	Industrial Processes	Chemical Manufacturing	Butylene, Ethylene, Propylene, Olefin Production	Ethylene: Flue Gas Vent
30119705	Industrial Processes	Chemical Manufacturing	Butylene, Ethylene, Propylene, Olefin Production	Propylene: General
30119709	Industrial Processes	Chemical Manufacturing	Butylene, Ethylene, Propylene, Olefin Production	Propylene: Fugitive Emissions
30119799	Industrial Processes	Chemical Manufacturing	Butylene, Ethylene, Propylene, Olefin Production	Other Not Classified
31000205	Industrial Processes	Oil and Gas Production	Natural Gas Production	Flares
31000212	Industrial Processes	Oil and Gas Production	Natural Gas Production	Condensate Storage Tank
31000227	Industrial Processes	Oil and Gas Production	Natural Gas Production	Glycol Dehydrator Reboiler Still Stack

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