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BACKGROUND INFORMATION DOCUMENTATION  
FOR EMISSION RATE INFORMATION IN  
AP-42 SECTION 11.5 - INDUSTRIAL FLARES

May 1985

Background Information Documentation for  
Flare Emission Estimates

Note Only one reference with actual test measurement was available for use in this study. This reference identified as Reference 1 in AP-42 Section 11.5 - Industrial Flares, is as follows:

Engineering Science, Inc. Flare Efficiency Study.  
Industrial Environmental Research Laboratory  
Report No. EPA-600/2-83-052. July 1983.

Data Presented in Table 11.5.1 Emission Factors for Flare Operation

The hydrocarbon emission data presented in Table 11.5.1 were obtained as follows: (The emission rate data were presented in ppm because the test data available in Reference 1 were in ppm.

- o Soot emissions data are taken from page 46. Reference 1.
- o THC emission data are taken from Tables 7 and 8 (pages 41 and 42). Reference 1.

The following modifications were made to the THC emission test data: Reference 1 contained data on total of 22 steam-assisted flare tests and 10 air-assisted flare tests. The report discarded six steam-assisted test runs (Nos. 61, 55, 54, 23, 52, and 53) and three air-assisted test runs (66/29, 33, and 32) for the following reasons:

- Tests 61 and 55 were conducted at usually high steam-to-gas ratio (i.e., at ratios of 6.67 and 6.86, respectively), resulting in lower combustion efficiencies.
- Tests 54, 23, 52, and 53 were conducted burning mostly natural gas and purge gas.
- Tests 66 and 29 burned the relief gas with the lowest contents (146 to 158 Btu/scf).
- Tests 33 and 32 evaluated the performance of the air-assisted flare in burning purge rate flows of low Btu content gases.

Data presented in Table 11.5.2. Flare Emission Hydrocarbon Composition

The hydrocarbon emission analysis data presented in Table 11.5.2 were obtained as follows:

- o The data were taken from Tables 7 and 8 of Reference 1, with the following modifications:
  - The composition data reported as methane equivalent were converted to individual component basis. Tables 1 and 2 present hydrocarbon data on individual component basis.

Table 1. HYDROCARBON ANALYSIS SUMMARY<sup>a</sup>

Test No.	Instantaneous samples, Average values							Comments
	C <sub>1</sub> <sup>b</sup>	C <sub>2</sub> /C <sub>2</sub> <sup>=</sup>	C <sub>2</sub> <sup>=</sup>	C <sub>3</sub>	C <sub>3</sub> <sup>=</sup>	C <sub>4</sub>	THC	
1								Discarded because the GC electrometer attenuation was set to a less sensitive scale.
2								Discarded for the same reason as above.
3								Discarded for the same reason as above.
4	4.73	0.62	2.04	0.23	2.33	---	9.95	
8	5.70	0.57	2.44	0.14	1.6	---	10.45	
7	1.79	0.18	0.24	0.11	0.31	---	2.63	
5								Discarded for the same reason as in Test 1.
17	2.59	0.23	---	0.08	---	---	2.9	
50	3.59	0.98	0.4	1.23	4.94	---	11.14	
56	4.06	0.11	0.08	0.17	1.33	---	5.75	
61								Discarded because of high steam-to-flare gas ratio.
55								Same as above.
57	6.72	0.34	0.02	0.27	0.44	---	7.79	
11	4.29	0.22	0.42	0.28	0.62	---	5.83	
59	4.0	2.68	0.85	3.03	8.43	---	18.99	
60	3.75	1.16	0.45	1.35	5.44	---	12.15	
51	5.82	0.51	0.43	0.46	1.56	---	8.78	
16	6.06	0.44	0.15	0.59	1.89	---	9.13	
54								Data from tests 54, 23, 52 and 53 were discarded because during the tests the pilot contributed greater than 95 percent of the total combustible gas to the flare.

Table 1. HYDROCARBON ANALYSIS SUMMARY  
(Concluded)

Test No.	Instantaneous samples, Average values							Comments
	C <sub>1</sub>	C <sub>2</sub> /C <sub>2</sub> =	C <sub>2</sub> =	C <sub>3</sub>	C <sub>3</sub> =	C <sub>4</sub>	THC	
23								
52								
53								
26	3.36	0.78	0.12	0.61	1.77	---	6.64	
65	4.63	0.06	0.15	0.06	0.05	---	4.95	
28	4.15	0.07	0.02	0.17	0.47	---	4.98	
31	4.85	4.47	0.98	3.32	25.38	---	39	
66/29								Discarded because heat content of the relief gas was about 160 Btu/scf.
64	7.59	0.49	0.05	0.33	0.72		9.18	
62								Discarded because of low Btu content of relief gas at 150 Btu/scf.
63	5.97	1.42	0.63	1.53	5.64	0.03	15.22	
33								Discarded because mostly natural gas was burned during the test.
34								Same as above.

<sup>a</sup> Reference 1. Engineering Science, Inc. Flare Efficiency Study, Industrial Environmental Research Laboratories, Report No. EPA-600/2-83-052, July 1983. All values are ppm by volume.

<sup>b</sup> Key: C<sub>1</sub> = methane, C<sub>2</sub> = ethane, C<sub>2</sub> = ethylene, C<sub>2</sub> = acetylene, C<sub>3</sub> = propane, C<sub>3</sub> = propylene, C = butane, and THC = total hydrocarbon.

Table 2. STATISTICAL AVERAGES OF MEASURED HYDROCARBON COMPOSITION<sup>a</sup>

Compound	Average %	Standard of duration n-1
Methane	59.35	24.6
Ethane/ethylene	6.78	3.5
Acetylene	5.14	6.6
Propane	5.98	4.1
Propylene	22.73	17.9
Butane	0.01	

<sup>a</sup> Total number of test points with valid readings was 18, (i.e.,  $n = 18$ ).

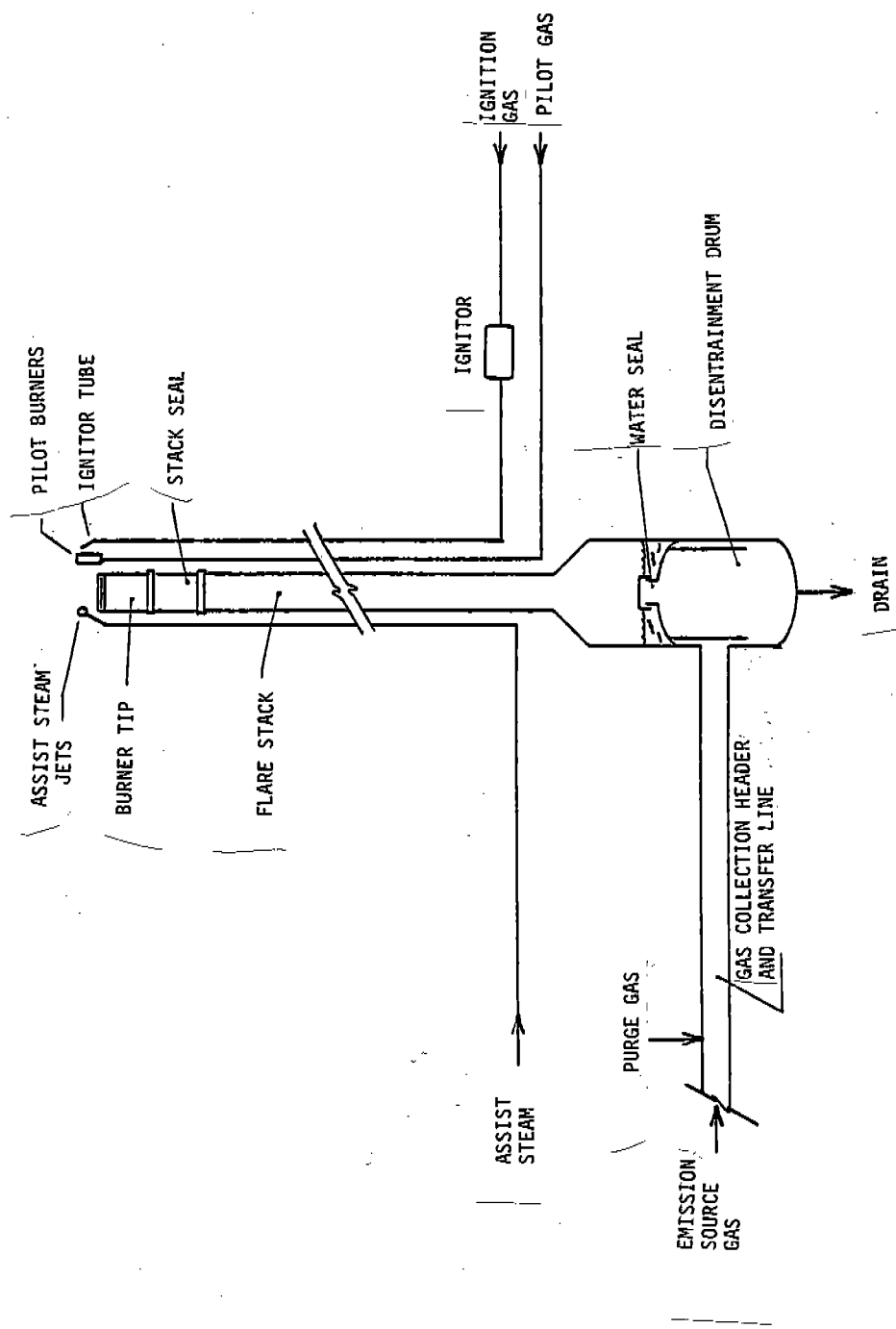


Figure 11.5.1.1. Diagram of steam-assisted smokeless elevated-flare system.

Table 1 HYDROCARBON ANALYSIS SUMMARY<sup>a</sup>

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Test no	Instantaneous samples, Average values						Comments
	C <sub>1</sub>	C <sub>2</sub> /C <sub>2</sub> <sup>≡</sup>	C <sub>2</sub> <sup>≡</sup>	C <sub>3</sub>	C <sub>3</sub> <sup>≡</sup>	C <sub>4</sub>	
1							Discarded because the GC electrometer attenuation was set to a less sensitive scale
2							Discarded for the same reason as above
3							Discarded for the same reason as above
4	4.73	0.62	2.04	0.23	2.33	-	9.95
8	5.70	0.57	2.44	0.14	1.6	-	10.45
7	1.79	0.18	0.24	0.11	0.31	-	2.63
5							Discarded for the same reason as in Test 1.
17	2.59	0.23	-	0.08	-	-	2.9
50	3.59	0.98	0.4	1.23	4.94	-	11.14
56	4.06	0.11	0.08	0.17	1.33	-	5.75
61							Discarded because of very high steam-to-flare gas ratio
55							Same as above
57	6.72	0.34	0.02	0.27	0.44	-	7.79
11	4.29	0.22	0.42	0.28	0.62	-	5.83

## Table | HYDROCARBON ANALYSIS SUMMARY

Test no	Instantaneous samples, Average values						Comments
	C <sub>1</sub>	C <sub>2</sub> /C <sub>2</sub> <sup>≡</sup>	C <sub>2</sub> <sup>≡</sup>	C <sub>3</sub> <sup>≡</sup>	C <sub>4</sub>	THC	
59	4.0	2.68	0.85	3.03	8.43	-	18.99
60	3.75	1.46	0.45	1.35	5.44	-	12.15
51	5.82	0.51	0.43	0.46	1.56	-	8.78
16	6.06	0.44	0.15	0.59	1.89	-	9.13
54							
23							
52							
53							
26	3.36	0.78	0.12	0.61	1.77	-	6.64
65	4.63	0.06	0.15	0.06	0.05	-	4.95
28	4.15	0.17	0.02	0.17	0.47	-	4.98
31	4.85	4.47	0.98	3.32	25.38	-	3.9
66/29							
64	7.59	0.49	0.05	0.33	0.72		<del>9.18</del> 9.18
62							
68							

Test data from tests 54, 23, 52 and 53 were discarded because during the tests the pilot contributed greater than 95% of the total combustible gas to the flame

Discarded because the BTU content of the relief gas was about 160 BTU/SCF

Discarded because of low BTU content of relief gas at 150 BTU/SCF



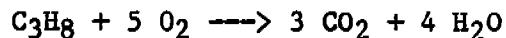
Table 1 HYDROCARBON ANALYSIS SUMMARY

Est. no	Instantaneous samples, Average values						Comments
	C <sub>1</sub>	C <sub>2</sub> /C <sub>2</sub> <sup>+</sup>	C <sub>2</sub> <sup>+</sup>	C <sub>3</sub>	C <sub>4</sub>	THC	
63	5.97	1.42	0.63	1.53	5.64	0.03	15.22 <del>13.8</del>
33							Discarded mostly natural gas was burned during test
34							Same as above.
a) <del>All values of and</del>							
a) Reference. Engineering Science Inc. Flow Effluent study, Industrial Environment Research Laboratories, Report No. EPA-600/2-83-052, July 1983. All values are ppm by volume.							

## 11.5 INDUSTRIAL FLARES

### 11.5.1 Process Description

Flaring is a high temperature oxidation process used to burn combustible components of waste gases from industrial operations. Hydrocarbons are the major combustibles in most waste gases flared. In some waste gases, carbon monoxide (CO) is the major combustible component. Waste gases composed of natural gas, propane, ethylene, propylene, butadiene and butane constitute over 95 percent of the material flared. In combustion, gaseous hydrocarbons react with atmospheric oxygen to form carbon dioxide (CO<sub>2</sub>) and water. Presented below as an example is the combustion reaction of propane.



During a combustion reaction, several intermediate products are formed and eventually, most of them are converted to CO<sub>2</sub> and water. Some quantities of stable intermediate products such as carbon monoxide, hydrogen and hydrocarbons escape as emissions.

Flares are used extensively to burn purged and waste products from refineries, unrecoverable gases emerging with oil from oil wells, vented gases from blast furnaces, unused gases from coke ovens, and gaseous wastes from chemical industries. Gases flared from refineries, petroleum production, chemical industries and, to some extent, those flared from coke ovens are composed largely of low molecular weight hydrocarbons with high heating value. The gases flared from blast furnaces are composed largely of inert species and CO and have 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 most common type, have larger capacities than ground flares. In elevated flares a waste gas stream is fed through a stack 10 to over 100 meters tall and 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 may consist either of conventional flare burners discharging horizontally with no enclosures or multiple burners in refractory-lined steel enclosures.

The flare system typically consists of 1) a gas collection header and piping for collecting gases from process units, 2) a knockout drum (disentrainment drum) to remove and store condensables and entrained liquids, 3) 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 11.5-1 is a diagram of steam-assisted elevated smokeless flare systems with typical components.

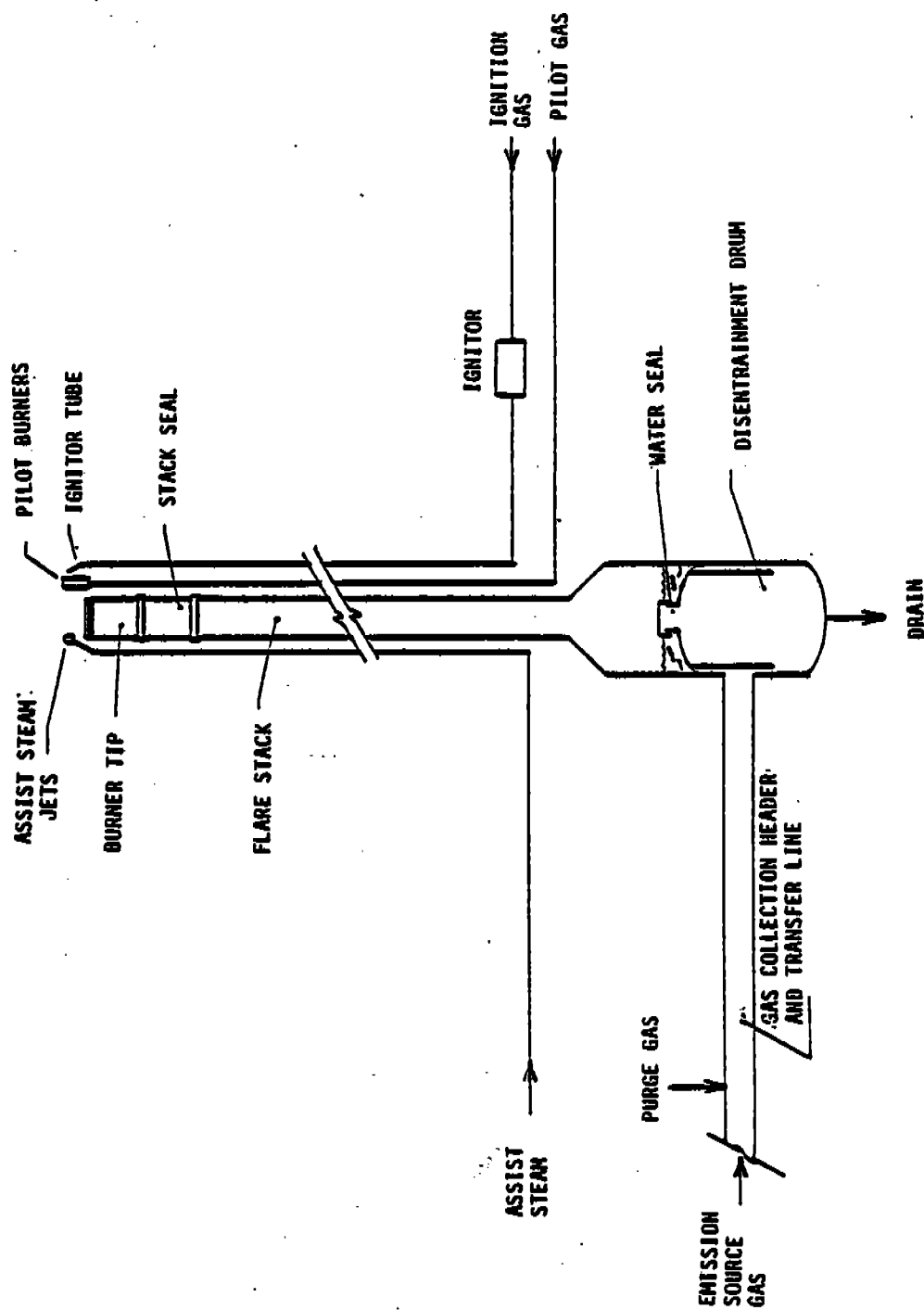


Figure 11.5.1. Diagram of steam-assisted smokeless elevated-flare system.

Sufficient combustion air and proper mixing of air and waste gas are required for complete combustion. Smoking may result from combustion depending upon the 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 smoke. External momentum force such as steam injection, the most common method, or blowing air is used for efficient air/waste gas mixing and turbulence for smokeless flaring of heavy hydrocarbon waste gas. Other external forces used for this purpose include 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 some flare installations, these two methods are combined for use with varied waste gas flow conditions. The internal nozzle provides steam at low waste gas flow rates while the external jets are used for large waste gas flow rates. There are several other special purpose flare tips commercially available. One of these is for injecting both steam and air. Typical steam usage ratio varies from 7:1 to 2:1 on a weight basis.

Waste gases to be burned in flares must have a fuel value of at least 7,500 to 9,300 kJ/m<sup>3</sup> (200 to 250 Btu/ft<sup>3</sup>) for complete combustion. If lacking such fuel value they must be supplemented with additional fuel. Flares providing supplemental fuel to waste gas are known as fired or endothermic flares. Some cases of waste gases having higher than minimum heat contents also require supplemental heat. One such case is ammonia flaring with a heating value of 13,600 kJ/m<sup>3</sup> (365 Btu/ft<sup>3</sup>) and the presence of fuel-bound nitrogen which has a quenching effect on the flare. A higher heat content is required to minimize nitrogen oxide (NO<sub>x</sub>) formation.

At many locations, flares are intended and designed to handle large quantities of intermittent waste gases generated during plant emergencies. These flares usually dispose of low volume continuous emissions during normal operations. Typical flare gas volumes vary from a few cubic meters per hour during regular flaring to several thousand cubic meters per hour during major upsets. For example, flow rates at a typical refinery could range from 45-90 kg/hr (100-200 lb/hr) for relief valve leakage to full plant emergency rate of 700 Mg/hr (750 tons/hr). Normal process blowdowns may release 450-900 kg/hr (1,000-2,000 lb/hr) and unit maintenance or minor failures may release 25-35 Mg/hr (27-39 tons/hr). At these typical flow rates, a waste gas of 40 molecular weight represents a minimum of 0.012 Nm<sup>3</sup>/sec (25 scfm) to as high as 115 Nm<sup>3</sup>/sec (241,000 scfm). The required flare turndown ratio for this typical case is over 15,000 to 1.

Many flare systems have two flares connected in parallel or in series. Parallel flares have the advantage that one flare can be shut down for maintenance while the other serves the system. In systems of flares in series, one flare, usually a low-level ground flare, is intended to handle regular low gas volumes and the other, an elevated flare, handles excess gas flows resulting from emergencies.

### 11.5.2 Emissions

Noise and heat are the most apparent undesirable effects of flare operation. Usually flares are located away from populated areas or sufficiently isolated, thus minimizing noise and heat effects on populations.

Emissions from flaring include carbon particles (soot), unburned hydrocarbons, and CO and other partially burned and altered hydrocarbons. Also released from the flares are emissions of nitrogen oxides ( $\text{NO}_x$ ) and, if sulfur-containing material such as hydrogen sulfide or mercaptans is flared, sulfur dioxide ( $\text{SO}_2$ ). The quantities of hydrocarbon emissions generated are related to the degree of combustion. The degree of combustion depends largely on the rate and extent of fuel-air mixing and the flame temperatures achieved and maintained. Properly operated flares achieve at least 98 percent combustion efficiency in the flare plume, meaning that the emissions of hydrocarbons and CO amount to less than 2 percent of input hydrocarbons.

The tendency of a fuel to smoke or soot is influenced by fuel characteristics as well as 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 on a volume basis. Air is supplied to the flame as primary air and secondary air. Primary air is premixed with the gas prior to combustion, whereas secondary air is that drawn into the flame. For smokeless combustion, sufficient amount of air must be supplied as primary air. The amount of primary air required varies 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 heat from the combustion zone. As a result, 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 that influence soot formation include the carbon-to-hydrogen 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 saturated ones. The addition of steam or air eliminates soot; for this reason most industrial flares are steam-assisted and some are air-assisted. The 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, only a few attempts have been made to characterize flare emissions. Recent 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<sup>3</sup> (300 Btu/ft<sup>3</sup>). The tests conducted on steam-assisted flares at velocities as low as 0.66 m/sec (130 ft/min) to 19 m/sec (3,750 ft/min), and on air-assisted flares at velocities of 3 m/sec (617 ft/min) to 66 m/sec (13,087 ft/min) indicated that variations in incoming gas flow rates have no effect on the combustion efficiency. Flare gases with less than 16,770 kJ/m<sup>3</sup> (450 Btu/ft<sup>3</sup>) do not smoke.

Table 11.5-1 presents flare emission factors and Table 11.5-2 presents emission composition data obtained from the EPA tests.<sup>1</sup> Crude propylene was used as flare gas during the tests. Methane was a major fraction of hydrocarbons present in the flare emissions, and acetylene was a predominant 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 further react with hydrocarbon radicals to form polyacetylenes followed by polycyclic hydrocarbons.<sup>2</sup>

Reference 2 reported that in the case of flaring waste gases containing no nitrogen compounds, NO is formed by either the fixation of atmospheric nitrogen with oxygen or the reaction between the hydrocarbon radicals present in the reaction products with atmospheric nitrogen by way of the intermediate stages HCN, CN, and OCN.

Table 11.5-1. EMISSION FACTORS FOR FLARE OPERATIONS<sup>a</sup>

*This is not the factor table in the published version*

Component	Emission factor, average (range), ppm
Soot	0 to 274 <sup>b</sup>
THC <sup>c</sup>	63 (2 to 315)
CO	19
NO <sub>x</sub>	2 (0.5 to 8.2)

*published version, factors: pounds/10<sup>6</sup> Btu*

- Reference 1. Based on tests using crude propylene containing 80 percent propylene and, of the remaining, up to 20 percent propane and 2 percent ethane and ethylene.
- Zero for nonsmoking flares, 40 µg/l for lightly smoking flares, 177 µg/l for average smoking flares, and 274 µg/l for heavily smoking flares.
- Measured as methane equivalent.

Table 11.5-2. FLARE EMISSION HYDROCARBON COMPOSITION<sup>a</sup>

Composition <sup>b</sup>	Average (range), %	
Methane	59	(12-94)
Ethane/Etylene	7	(1-14)
Acetylene	5	(0.3-23)
Propane	6	(0-16)
Propylene	23	(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 flare 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 propane and propylene.

b) NO<sub>2</sub> occurs for the most part only in the atmosphere. Water is sometimes added to reduce the formation of nitrogen and for soot-free combustion. Sulfur compounds contained in a flare gas stream are converted to SO<sub>2</sub> upon burning. The amount of SO<sub>2</sub> emitted may vary from a trace to very large amounts depending upon the flaring, if regular or irregular, such as during upsets.

#### References for Section 11.5

1. Engineering Science, Inc. Flare Efficiency Study, Industrial Environmental Research Laboratory, Report No. EPA-600/2-83-052, July 1983.
2. Siegel, K.D. Degree of Conversion of Flare Gas in Refinery High Flares, Ph.D. Dissertation, University of Karlsruhe, (Germany), February 1980.
3. Manual on Disposal of Refinery Wastes, Volume on Atmospheric Emissions, Chapter 15-Flares, API Publication 931, American Petroleum Institute Refining Department, Washington, D.C., June 1977.