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UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711

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LBE--4/29/83

MEMORANDUM

SUBJECT: Flare Efficiency Position

FROM: James F. Durham, Acting Chief
Chemicals and Petroleum Branch

TO: See Below

Our current position on flare efficiency is presented in the attached material. The material includes sections for inclusion in the BID, the Preamble, and the Regulation. A list of references is included and copies of the references are available for the docket.

If you have questions or comments, please contact Leslie Evans at telephone number 541-5671.

Attachment

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BID EXAMPLE

4.2.1 Flares

4.2.1.1 Flare process description. Flaring is an open combustion process in which the oxygen required for combustion is provided by the air around the flame. Good combustion in a flare is governed by flame temperature, residence time of components in the combustion zone, turbulent mixing of the components to complete the oxidation reaction, and oxygen for free radical formation.

Kalcevic (1980)(Reference 6) presents a detailed discussion of different types of flares, flare design and operating considerations, and a method for estimating capital and operating costs for flares. Elevated steam and air assisted flares are most common in the ____________ industry. The basic elements of an elevated steam flare system are shown in Figures 1 and 2. Process off-gases are sent to the flare through the collection header. The off-gases entering the header can vary widely in volumetric flowrate, moisture content, VOC concentration, and heat value. The knock-out drum removes water or hydrocarbon droplets that could create problems in the flare combustion zone. Off-gases are usually passed through a water seal before going to the flare. This prevents possible flame flashbacks, caused when the off-gas flow to the flare is too low and the flame front pulls down into the stack.

Purge gas (N_2, CO_2, or natural gas) also helps to prevent flashback in the flare stack caused by low off-gas flow. The total volumetric flow to the flame must be carefully controlled to prevent low flow flashback problems and to avoid a detached flame (a space between the stack and flame with incomplete combustion) caused by an excessively high flowrate. A gas barrier or a stack seal is sometimes used just below the flare head to impede the flow of air into the flare gas network.

The VOC stream enters at the base of the flame where it is heated by already burning fuel and pilot burners at the flare tip. Fuel flows into the combustion zone where the exterior of the microscopic gas pockets is oxidized. The rate of reaction is limited by the mixing of the fuel and oxygen from the air. If the gas pocket has sufficient oxygen and residence time in the flame zone it can be completely burned. A diffusion flame receives its combustion oxygen by diffusion of air into the flame from the surrounding atmosphere. The high volume of fuel flow in a flare requires more combustion

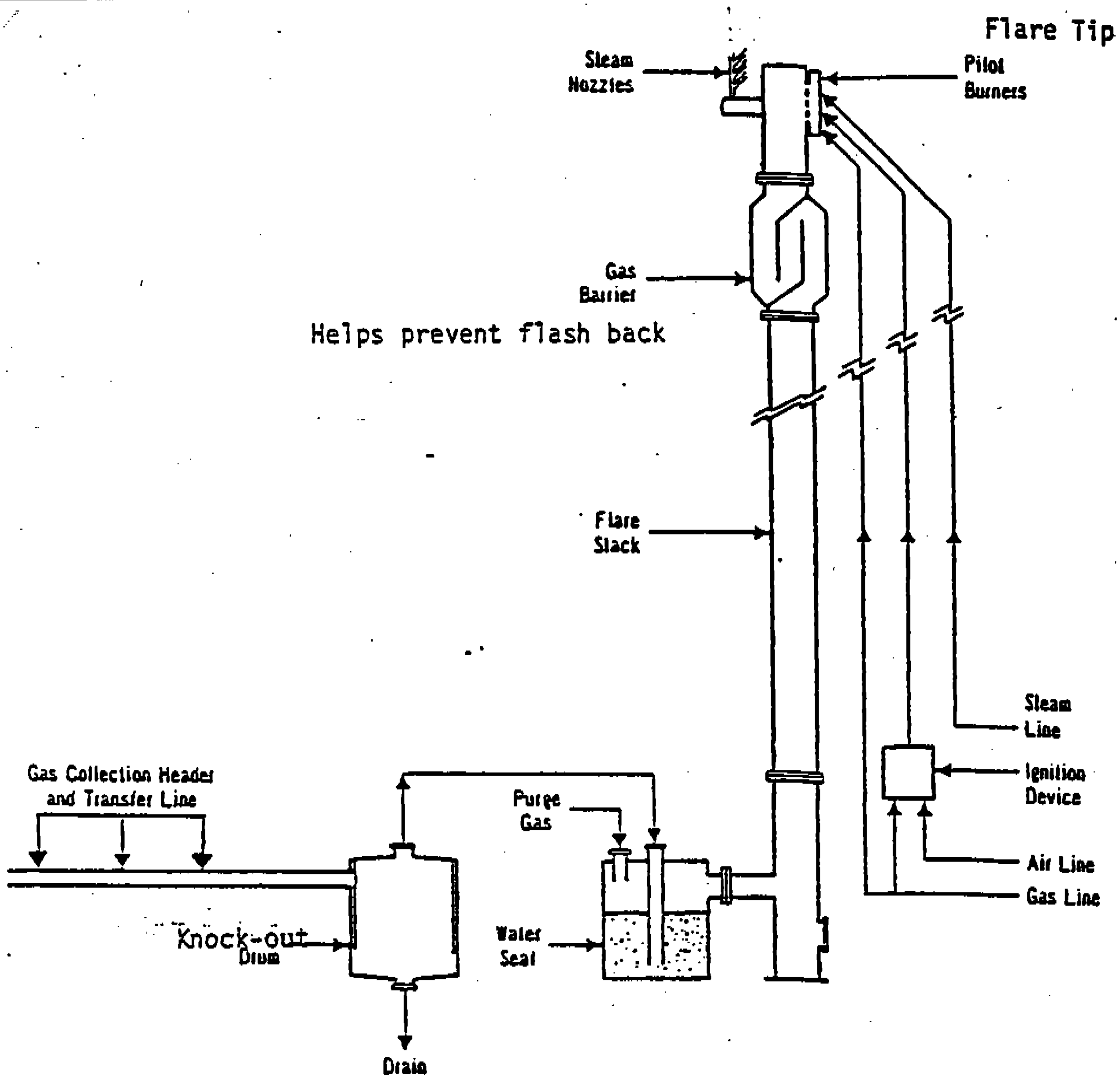

Figure 1. Steam assisted elevated flare system.

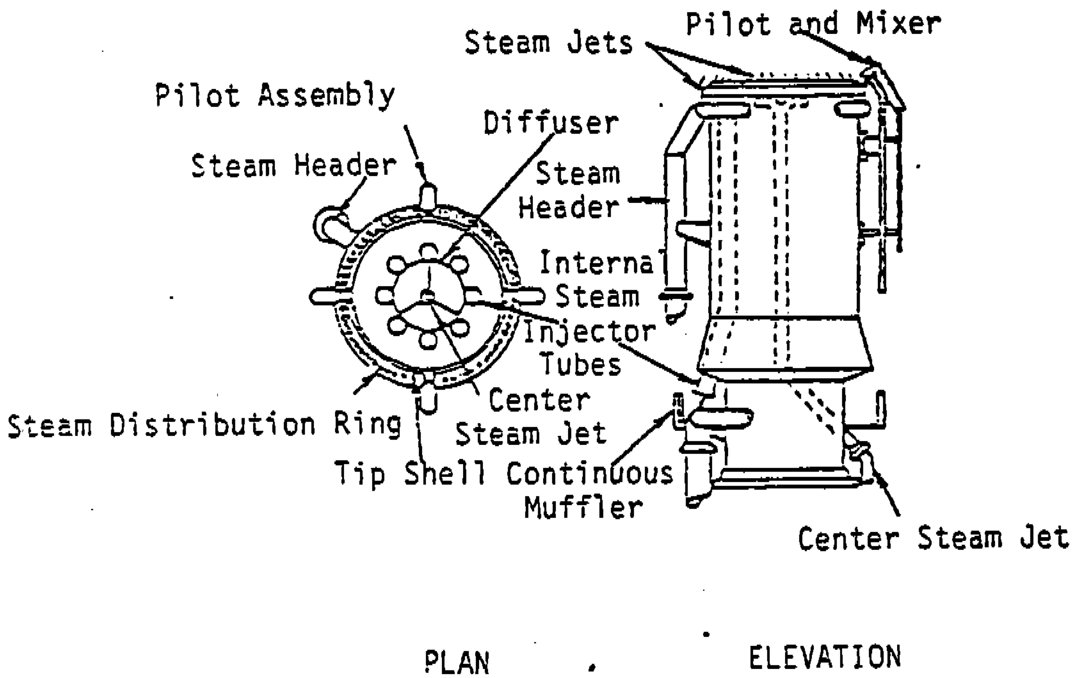

Figure 2. Steam injection flare tip

air at a faster rate than simple gas diffusion can supply so flare designers may add steam injection nozzles to increase gas turbulence in the flame boundary zones, drawing in more combustion air and improving combustion efficiency. This steam injection promotes smokeless flare operation by minimizing the cracking reactions that form carbon. Significant disadvantages of steam usage are the increased noise and cost. The steam requirement depends on the composition of the gas flared, the steam velocity from the injection nozzle, and the tip diameter. Although some gases can be flared smokelessly without any assist, typically 0.15 to 0.5 kg of steam per kg of flare gas is required.

Steam injection is usually controlled manually with the operator observing the flare (either directly or on a television monitor) and adding steam as required to maintain smokeless operation. Several flare manufacturers offer devices which sense flare flame characteristics and adjust the steam flowrate automatically to maintain smokeless operation.

Some elevated flares use forced air instead of steam to provide the combustion air and the mixing required for smokeless operation. These flares consist of two coaxial flow channels. The combustible gases flow in the center channel and the combustion air (provided by a fan in the bottom of the flare stack) flows in the annulus. The principal advantage of air assisted flares is that expensive steam is not required. Air assist is rarely used on large flares because air flow is difficult to control when the gas flow is intermittent. About 0.8 hp of blower capacity is required for each 100 lb/hr of gas flared (Klett and Galeski, 1976) (Reference 7).

Ground flares are usually enclosed and have multiple burner heads that are staged to operate based on the quantity of gas released to the flare. The energy of the gas itself (because of the high nozzle pressure drop) is usually adequate to provide the mixing necessary for smokeless operation and air or steam assist is not required. The fence or other enclosure reduces noise and light from the flare and provides some wind protection.

Ground flares are less numerous and have less capacity than elevated flares. Typically they are used to burn gas "continuously" while steam assisted elevated flares are used to dispose of large amounts of gas released in emergencies (Payne, 1982) (Reference 1).

4.2.1.2 Flare combustion efficiency

4.2.1.2.1 Factors affecting flare efficiency. The flammability limits of the gases flared influence ignition stability and flame extinction (gases must be within their flammability limits to burn). When flammability limits are narrow, the interior of the flame may have insufficient air for the mixture to burn. Outside the flame, so much air may be induced that the flame is extinguished. Fuels with wide limits of flammability are therefore usually easier to burn (for instance, H_2 and acetylene). However, in spite of wide flammability limits, CO is difficult to burn because it has a low heating value and slow combustion kinetics.

The auto-ignition temperature of a fuel affects combustion because gas mixtures must be at a high enough temperature and at the proper mixture strength to burn. A gas with low auto-ignition temperature will ignite and burn more easily than a gas with a high auto-ignition temperature. Hydrogen and acetylene have low auto-ignition temperatures while CO has a high one.

The heating value of the fuel also affects the flame stability, emissions, and structure. A lower heating value fuel produces a cooler flame which does not favor combustion kinetics and also is more easily extinguished. The lower flame temperature will also reduce buoyant forces, which reduces mixing (especially for large flares on the verge of smoking). For these reasons, VOC emissions from flares burning gases with low Btu content may be higher than those from flares which burn high Btu gases.

Some fuels, also, have chemical differences (slow combustion kinetics) sufficient to affect the VOC emissions from flares. For instance, CO is difficult to ignite and burn and consequently flares burning fuels with large amounts of CO may have greater VOC emissions than flares burning pure VOC.

The density of the gas flared also affects the structure and stability of the flame through the effect on buoyancy and mixing. The velocity in many flares is very low, and therefore most of the flame structure is developed through buoyant forces on the burning gas. Lighter gases therefore tend to burn better, all else being equal. The density of the fuel also affects the minimum purge gas required to prevent flashback and the design of the burner tip.

Poor mixing at the flare tip or poor flare maintenance can cause smoking (particulate) Fuels with high carbon to hydrogen ratios (greater than 0.35) have a greater tendency to smoke and require better mixing if they are to be burned smokelessly.

4.2.1.2.2 Flare efficiency test data. This section presents a review of the flares and operating conditions used in five studies of flare combustion efficiency. Each study can be found in complete form in the docket.

Palmer (1972) (Reference 2) experimented with a 1/2-inch ID flare head, the tip of which was located 4 feet from the ground. Ethylene was flared at 50 to 250 ft/sec at the exit, (0.4×10^6 to 2.1×10^6 Btu/hr). Helium was added to the ethylene as a tracer at 1 to 3 volume percent and the effect of steam injection was investigated in some experiments. Four sets of operating conditions were investigated; destruction efficiency was measured as greater than 99.9 percent for three sets and 97.8 percent for the fourth. The author questioned the validity of the 97.8 percent result due to possible sampling and analytical errors. He recommended further sampling and analytical techniques development before conducting further flare evaluations.

Siegel (1980) (Reference 4) made the first comprehensive study of a commercial flare system. He studied burning of refinery gas on a commercial flare head manufactured by Flaregas Company. The flare gases used consisted primarily of hydrogen (45.4 to 69.3 percent by volume) and light paraffins (methane to butane). Traces of H_2S were also present in some runs. The flare was operated from 0.03 to 2.9 megagrams of fuel/hr (287 to 6,393 lb/hr), and the maximum heat release rate was approximately 235×10^6 Btu/hr. Combustion efficiency and local burnout was determined for a total of 1,298 measurement points. Combustion efficiency was greater than 99 percent for 1,294 points and greater than 98 percent for all points except one which had a 97 percent efficiency. The author attributed the 97 percent result to excessive steam addition.

Lee and Whipple (1981) (Reference 3) studied a bench-scale propane flare. The flare head was 2 inches in diameter with one 13/16-inch center hole surrounded by two rings of 16 1/8-inch holes, and two rings of 16 3/16-inch holes. This configuration had an open area of 57.1 percent. The velocity through the head was approximately 3 ft/sec and the heating rate was 0.3 M Btu/hr. The effects of steam and crosswind were not investigated in this study. Destruction efficiencies were greater than 99 percent for three of four tests. A 97.8 percent result was obtained in the only test where the probe was located off the center line of the flame. The author did not believe that this probe location provided a valid gas sample for analysis.

Howes, et al. (1981) (Reference 5) studied two commercial flare heads at John Zink's flare test facility. The primary purpose of this test (which was sponsored by the EPA) was to develop a flare testing procedure. The commercial flare heads were an LH air assisted head and an LRGO (Linear Relief Gas Oxidizer) head manufactured by John Zink Company. The LH flare burned 2,300 lb/hr of commercial propane. The exit gas velocity based on the pipe diameter was 27 ft/sec and the firing rate was 44 x 10^6 Btu/hr. The LRGO flare consisted of 3 burner heads 3 feet apart. The 3 burners combined fired 4,200 lbs/hr of natural gas. This corresponds to a firing rate of 83.7 x 10^6 Btu/hr. Steam was not used for either flare, but the LH flare head was in some trials assisted by a forced draft fan. In four of five tests, combustion efficiency was determined to be greater than 99 percent when sampling height was sufficient to insure the combustion process was complete. One test resulted in combustion efficiency as low as 92.6 percent when the flare was operated under smoking conditions.

An excellent detailed review of the above four studies was done by Payne, et al. (Reference 1), in January 1982, and a summary of the studies is given in Table 1. A fifth study by McDaniel, et al. (1982) (Reference 8) determined the influence on flare performance of mixing, Btu content, and gas flow velocity. Steam assisted and air assisted flares were tested at the John Zink facility using the procedures developed by Howes. The test was sponsored by the Chemical Manufacturers Association (CMA) with the cooperation and support of the EPA. All of the tests were with an 80 percent propylene, 20 percent propane mixture diluted as required with nitrogen to give different Btu/scf values. This was the first work which determined flare efficiencies at a variety of "nonideal" conditions where lower efficiencies had been predicted. All previous tests were of flares which burned gases which were very easily combustible and did not tend to soot. This was also the first test which used the sampling and chemical analysis methods developed for the EPA by Howes.

The steam assisted flare was tested with exit flow velocities up to 62.5 ft/sec, with Btu contents from 294 to 2,183 Btu/scf and with steam to gas (weight) ratios varying from 0 (no steam) to 6.86/1. Flares without assist were tested down to 192 Btu/scf. All of these tests, except for those with very high steam to gas ratios, showed combustion efficiencies of over 98 percent. Flares with high steam to gas ratios (about 10 times more steam than that required for smokeless operation) had lower efficiencies (69 to 82 percent) when combusting 2,183 Btu/scf gas.

The air assisted flare was tested with flow velocities up to 218 ft/sec and with Btu contents from 83 to 2,183 Btu/scf. Tests at 282 Btu/scf (and above) gave over 98 percent efficiency. Tests at 168 Btu/scf gave 55 percent efficiency.

After consideration of the results of these five tests, the EPA has concluded that 98 percent combustion efficiency can be achieved by steam assisted flares if these flares are operated with combustion gas heat co and exit flow velocities within ranges determined by the tests. Steam f obtain 98 percent combustion efficiency combusting gases with heat conte over 300 Btu/scf at velocities of less than 60 ft/sec. Steam flares are normally operated at the very high steam to gas ratios that resulted in efficiency in some tests because steam is expensive and operators make e effort to keep steam consumption low. Flares with high steam rates are noisy and may be a neighborhood nuisance. Non assisted pipe flares obta 98 percent efficiency with heat contents over 200 Btu/scf at velocities of less than 60 ft/sec. Air assisted flares obtain 98 percent efficienc with heat contents over 300 Btu/scf and at velocities not exceeding that determined by the following formula.

$$v \text{ ft/sec} = 28.75 + 0.0867 \text{ HG}$$

v = maximum gas velocity in ft/sec, standard conditions

HC = heat content of the combusted gas in Btu/scf

The EPA has a program under way to determine more exactly the effic of flares used in the petroleum/SOCMI industry and a flare test facility been constructed. The combustion efficiency of four flares (1 1/2 inche 12 inches D) will be determined and the effect on efficiency of flare operating parameters, weather factors, and fuel composition will be esta The efficiency of larger flares will be estimated by scaling. A final r of this work should be available in the spring of 1984.

PREAMBLE EXAMPLE

As described in the background information document, test data show that some flares meeting certain conditions achieve 98 percent emission reduction. Consequently, the Agency concluded that the format for ~~distillation~~ vent streams using flares should be an equipment standard with the stated specifications. The proposed standards require, therefore, the use of a smokeless flare for those streams using a flare to comply with the standards. Only flares that are steam-assisted, air-assisted, or nonassisted may be used. Furthermore, the net heating value of the flared gas must not be less than 11.2 MJ/scm (300 Btu/scf) for steam-assisted and air-assisted flares or less than 7.45 MJ/scm (200 Btu/scf) for a nonassisted flare. In addition, the exit velocity of the flare gas at the flare tip must not exceed 18 m/sec (60 ft/sec) for steam-assisted and nonassisted flares. Air-assisted flares must also operate below a maximum exit velocity, which is dependent upon the net heating value of the flared stream. The maximum exit velocity is determined using the equation found in Section ~~60.664~~ of the regulation. These are the only conditions for which EPA has data supporting that flares achieve 98 percent emission reduction.

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Another consideration in developing the equipment standard for streams using flares is the potential for process variations such as flow surges that can cause a flare to smoke for short periods of time until the flare can be adjusted. Five minutes is a reasonable period of time for alleviating the smoking condition by making the needed adjustment to the steam or air to the flare. Flow surges occur infrequently and generally do not occur more than once in a 2-hour period. Therefore, operational requirements have been included as part of the proposed standards. A smokeless flare is defined as a flare which produces visible emissions (smoke) for no more than 5 minutes within any 2-hour period. This requirement is consistent with the flare requirement in Texas where many of these plants are located.

In summary, under the proposed standards, sources for which the costs of further control are reasonable would be subject to the following requirements: (1) a 98 percent weight reduction of the total organic compounds (minus methane and ethane) etc., etc.____________________; or (2) when a flare is used to comply with the standards, the flare must be smokeless and minimum heat content and maximum exit velocity requirements for the flared gas must be met.

As explained under selection of the format of the standard, an equipment standard was selected for cases where a flare is used to meet the standards. Therefore, a performance test measuring percent reduction is not required for streams equipped with flares. However, part of the standards requires that the flare be smokeless. Reference Method 22, as reviewed, has been selected to determine whether a flare is smokeless. Furthermore, certain other criteria must be met in order for flares to be used. The net heating value of the flared stream must be determined for compliance with the heat content criterion set for the different flare types; the velocity of the gas at the flare tip must be measured to ensure compliance with the maximum exit gas velocity allowed for flares. The methods for determining these values are given in Section ______ of the regulation.

EXAMPLE STANDARD

On or before the date on which the performance test is required by Section ________, each owner or operator subject to the provisions of this subpart shall comply with one of the following for each vent stream.

(b) Combust the emissions in a flare:

(1) That is designed for and operated with no visible emissions as determined by the methods specified in Section ___________ , except for periods not to exceed a total of 5 minutes during any 2 consecutive hours.

(2) That is operated with a flame present at all times, as determined by the methods specified in Section __________.

(3) That is used only with the net heating value of the gas being combusted being 11.2 MJ/scm (300 Btu/scf) or greater if the flare is steam-assisted or air-assisted; or with the net heating value of the gas being combusted being 7.45 MJ/scm (200 Btu/scf) or greater if the flare is nonassisted. The net heating value of the gas being combusted shall be determined by the methods specified in Section ______________.

(4) That is designed for and operated with an exit velocity, as determined by the methods specified in Section ________, less than 18 m/sec (60 ft/sec) if steam-assisted or nonassisted.

(5) That is steam-assisted, air-assisted, or nonassisted.

(6) That is designed and operated with an exit velocity less than the velocity, V_{max}, as determined by the methods specified in Section ___________ if air-assisted.

EXAMPLE MONITORING REQUIREMENT

(b) The owner or operator of an affected facility that uses a smokeless flare to comply with (d)(1) and (2) shall install, calibrate, maintain and operate according to manufacturer's specifications a heat-sensing device at the pilot light to indicate the continuous presence of a flame.

EXAMPLE RECORDKEEPING REQUIREMENT

(d) Each owner or operator subject to the provisions of this subpart shall keep up-to-date, readily accessible, continuous records of the flare pilot light flame heat-sensing monitoring specified under (b), as well as up-to-date, readily-accessible records of all periods of operations in which the pilot flame is absent.

EXAMPLE TESTING REQUIREMENT

(b) When a flare is used to comply with (d), a performance test according to Reference Method 22 shall be performed to determine visible emissions. The observation period shall be at least 2 hours except as otherwise specified in Reference Method 22.

(c) When a flare is used to comply with (e) the net heating value of the gas combusted shall be determined using the following procedure.

(1) The molar composition of the process vent stream shall be determined as follows:

(i) Reference Method 18 and ASTM D2504-67 (reapproved 1977) to measure VOC concentration and concentration of all other compounds present except water vapor and carbon monoxide.

(ii) Reference Method 4 to measure the content of water vapor.

(iii) Reference Method 10 to measure carbon monoxide concentration.

The process vent stream carbon monoxide concentration shall be calculated on a wet basis using the following equation:

$$C_{wco} = C_{co}\,(1 - B_w)$$

where:

C_{wco} = Concentration of carbon monoxide, wet basis, ppm

C_{co} = Concentration of carrbon monoxide as determined using the recommended test method, ppm, dry.

B_w = Water vapor in the gas sample, proportion by volume.

(2) The net heating value of the process vent stream shall be calculated using the following equation:

$$H_T = K\left(\sum_{i=1}^{n} C_i H_i + C_{wco}\, H_{co}\right)$$

where:

H_T = Net heating value of the sample, MJ/scm, where the net enthalapy per mole of offgas is based on combustion at 25/C and 760 mm Hg, but the standard temperature for determining the volume corresponding to one mole is 20/C, as in the definition of Q_S (offgas flowrate).

K = Constant, 1.740×10^{-7}

where standard temperature for

C_i = Concentration of sample component i, ppm.

H_i = Net heat of combustion of sample component i, kcal/g-mole. The heats of combustion of process vent stream components would be required to be determined using ASTM D2382-76 if published values are not available or cannot be calculated.

C_{wco} = Concentration of carbon monoxide, wet basis, ppm.

H_{co} = Net heat of combustion of carbon monoxide, kcal/g-mole.

(d) When a flare is used to comply with (f) the tip exit velocity shall be determined as follows:

(1) The gas volume flowrate in the line to the flare shall be found by Reference Method 2A.

(2) The gas exit velocity shall be calculated by correcting the volume flowrate determined in (1) to the temperature of the gas at the flame exit and to atmospheric pressure and dividing the resulting corrected volume flowrate by the free cross sectional area at the flare tip.

REFERENCES

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3. Lee, K. C., and G. M. Whipple, Waste Gas Hydrocarbon Combustion in a Flare, Union Carbide Corporation, South Charleston, WV (1981).

4. Siegel, K. D., Degree of Conversion of Flare Gas in Refinery High Flares, Ph.D. Dissertation, University of Karlsruhe (German), February (1980).

5. Howes, J. E., T. E. Hill, R. N. Smith, G. R. Ward, W. F. Herget, Development of Flare Emission Measurement Methodology, DRAFT Report, EPA Contract No. 68-02-2682 (1981).

6. Kalcevic, V., Control Device Evaluation, Flares and Use of Emissions as Fuels, EPA-450/3-80-026, December (1980).

7. Klett, M. G., and J. B. Galeski, Flare Systems Study, NTIS Report PB-251664, EPA-600/2-76-079, (1976).

8. McDaniel, M., Flare Efficiency Study, Volume I, undated but received March 1983.

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Table 1

FLARE EMISSION STUDIES COMPLETE

JUNE 1983

Investigator	Sponsor	Flare Tip Design	References	Flared Gas	Throughput 10^6 Btu/hr	Flare Efficiency %
Palmer (1972)	E. I. du Pont	0.5" dia.	2	Ethylene	0.4 - 2.1	> 97.8
Lee & Whipple (1981)	Union Carbide	Discrete Holes in 2" dia. cap.	3	Propane	0.3	96 - 100
Siegel (1980)	Ph.D. Dissertation University of Karlsruhe	Commercial Design (27.6" dia. steam)	4	≈ 50% H_2 plus light hydrocarbons	49 - 178	97 - > 99
Howes et al. (1981)	EPA	Commercial Design (6" dia. air assist)	5	Propane	44	92.6- 100
		Commercial Design H.P. (3 tips @ 4" dia.)		Natural Gas	28 (per tip)	> 99
Source: Reference 1						
~~Source: Reference~~ McDaniel et al. (1982)	CMA - EPA	Commercial Design ([illegible] dia. air assist) 18"	8	Propylene	0.063 - 58	~~59.6 - 99.9~~ 61.9 to 100.0
		Commercial Design ([illegible] dia. steam assist) 8"			0.009 - 57	~~[illegible] - 99.9~~ 68.9 - 100.0