United States
Environmental Protection
Agency

Industrial Environmental Research
Laboratory
Research Triangle Park NC 27711

Research and Development

EPA-600/S2-83-070 Jan. 1984

Project Summary

Evaluation of the Efficiency of Industrial Flares: Background—Experimental Design—Facility

D. Joseph, J. Lee, C. McKinnon, R. Payne, and J. Pohl

The U.S. EPA has contracted with Energy and Environmental Research Corporation to conduct a research program which will result in the quantification of emissions from and efficiencies of industrial flares. The study is being conducted in four phases: I—Experimental Design, II—Design of Test Facilities, III—Development of Test Facilities, and IV—Data Collection and Analysis. This report summarizes results of Phases I and II.

The report discusses the technical literature on the use of flares and reviews available emission estimates. Technical critiques of past flare efficiency studies are provided. The parameters affecting flare efficiency are evaluated and a detailed experimental test plan is developed. The design of a flare test facility is discussed, including flare tips, fuel and steam supply/flow control and measurement, emissions sampling and analysis, and data acquisition and processing.

Results of the testing program (Phases III and IV) will be provided in a later report.

This Project Summary was developed by EPA's Industrial Environmental Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

A flare is a device that allows the economic safe disposal of waste gases by combusting them. The waste gases are injected into the open air through a tip, designed to promote entrainment of the ambient air and provide a stable flame with a wide range of throughputs in high crosswinds. To reduce flame radiation at ground level, the flare tip must be elevated (its height will depend on flame size). If the heating value of the waste gas is too low to sustain a flame, auxiliary fuel may be added. Small flares may utilize fans to provide some air premixing before injection, but most large flares are natural draft with optional steam injection to promote fuel/air mixing. Flares are used extensively to burn purged and waste products from refineries, excess production from oil wells, vented gas from blast furnaces, unused gas from coke ovens, and gaseous wastes from the chemical industry.

An estimated 16 million tons/year of gas may be flared in the U.S. The amount is difficult to estimate because throughputs fluctuate widely with time and are seldom measured. The normal, time-averaged throughput ranges from zero to 5 percent of design capacity, which is exceeded only during emergencies or upsets. The flared gases fall into three categories:

- Low heating value gas produced in blast furnaces which account for 60 percent of the weight and 19 percent of the heating value of the estimated annual flared gases.
- Medium heating value gases produced in coke ovens and in the petrochemical industry.

- High heating value gases flared in refineries which account for 18 percent of the weight and 32 percent of the heating value of the estimated annual flared gases.

Pollutant emissions from flares result from a failure to completely combust the flared gases. The pollutant species are normally carbon monoxide, hydrocarbon, and soot; total emissions are assessed based on an estimate of flare efficiency. The efficiency of combustion of a flare, which is a measure of its ability to destroy the flared gas, is difficult to measure; consequently, estimates of pollutant emission indices vary. Estimates of flare efficiencies vary widely: some are very high, in excess of 99 percent; whereas, others are as low as 70 percent. This leads to the conclusion that emission factors necessary for accurate quantification of mass emissions are unknown. If flares were 90 percent efficient, then emissions of carbon monoxide and hydrocarbons would be approximately 12 percent of those emitted by all stationary sources. More important are the contributions of flares as localized sources because of their concentration in refineries and steel plants where they could be among the most significant sources of pollutants if the efficiencies are relatively low.

It can only be concluded that pollutant emissions from flares are unknown. This is due to a combination of uncertainties in the quantity of gases being flared and their composition, together with the uncertainties in flare efficiency. Before a decision can be made whether pollutant emissions from flares are of concern, an accurate assessment of flare efficiency must be made. Theoretical estimates of flare efficiency cannot be made, emission measurements from operating flares are difficult, and previous pilot scale studies are contradictory or incomplete. Thus, there is a need for a study to accurately assess flare efficiency as a function of: flared gas composition; throughput; flare design and operation (steam injection, etc.); ambient conditions; and scale. Data from this study can be used to provide an accurate assessment of pollutant emissions from flares.

Deficiencies in Previous Flare Emission Studies

Relatively few investigations, concerned with pollutant emission or efficiency of flares, have been reported in the open literature.

Table 1 summarizes the most recent, known studies, each of which addressed one or more of the following topics:

- The emissions of incompletely burned material.
- The distance required to burn the flared gases.
- The impact of steam injection on pollutant emissions.
- The effect of ambient conditions on pollutant emissions.

Although these studies have made valuable contributions to the knowledge of flare performance, they neither allow accurate determination of pollutant emissions nor provide adequate information on the effects of scale or flared gas composition.

A review of the previous studies indicates that data acquisition and manipulation are common problems that prevent accurate assessment of flare efficiency. These problems are discussed below in four main areas:

- Inability to close a material balance.
- Measurement of soot concentration.
- Difficulties caused by flare "intermittency."
- Lack of scaling methodology.

Closure of Material Balance

The global (overall) efficiency of a flare flame can be calculated if the inlet fuel composition and mass flux are known, together with the mass flux of all hydrogen- and carbon-containing species of flared material at a height above the flame where all reaction has ceased. There is more interest in that fraction of the fuel flux that becomes air polluting species rather than harmless CO_2 and H_2O. It is usual to concentrate on the carbon in the fuel because all of the ultimate air polluting species contain it (i.e., CO, H_xC_y, soot). If the carbon fraction of all product gas flux species is summed, the result should equal the carbon fraction of fuel mass flux. This is the usual mass balance concept and is an accounting check on the pollutant species measurements. It is easy to state but rather difficult to implement. Of the studies in Table 1, only Siegel attempted to close the mass balance. Generally he was able to account for only about half of the fuel carbon in the off-gas flux. Siegel stated that the largest errors were associated with the velocity measurements needed to determine the mass flux. Siegel circumvented the need for

Table 1. Previous Flare Emission Studies

Investigator	*Flare Tip Design*	*Flared Gas*	*Throughput 10^6 Btu/hr*	*Flare Efficiency %*
Palmer[a]	*0.5 in. dia.*	*Ethylene*	*0.4 - 2.1*	*>97.8*
Lee & Whipple[b]	*Discrete Holes in 2 in. dia. cap.*	*Propane*	*0.3*	*96 - 100*
Siegel[c]	*Commercial Design (27.6 in. dia. steam)*	*≈50% H_2 plus light hydrocarbons*	*49 - 178*	*97 - >99*
Howes et al.[d]	*Commercial Design (6 in. dia. air assist)*	*Propane*	*44*	*91 - 100*
	Commercial Design H.P. (3 tips @ 4 in. dia.)	*Natural Gas*	*28 (per tip)*	*>99*

[a] *Palmer, P.A. "A Tracer Technique for Determining Efficiency of an Elevated Flare," E.I. du Pont de Nemours and Co., Wilmington, DE (1972).*
[b] *Lee, K.C. and G.M. Whipple. "Waste Gas Hydrocarbon Combustion in a Flare," Union Carbide Corporation, South Charleston, WV (1981).*
[c] *Siegel, K.D. "Degree of Conversion of Flare Gas in Refinery High Flares," Ph.D. Dissertation, University of Karlsruhe (German), February (1980).*
[d] *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 68-02-2686, Task 118 (1981).*

further mass balance by using "local burnout" efficiency, and showing that errors in the resulting global efficiency values are minor.

A material balance requires time-averaged concentration, velocity, and temperature measurements at some plane normal to the mean direction of flow. These measurements are made above the flame when total emissions are being assessed, requiring integration of the species flux across the total jet. Major errors which prevent adequate material balance closure are:

- Material escapes undetected, because at the flame extremities dilution lowers its concentration below the detectability limit of the analytical equipment.
- All the species are not measured.
- The time-averaged velocity is difficult to measure in and near turbulent flames.

A tracer in the fuel can be used to aid in obtaining a mass balance by yielding a double check on the dilution factor in the product gases. However, the use of a tracer does not eliminate the need for velocity measurements in determining mass flux.

Measurement of Soot Concentration

Soot represents uncombusted fuel carbon which should be included in flare flame efficiency calculations. Siegel measured soot concentrations between 20 and 80 mg/m^3 in an intentionally smoking flame, estimating that those dilution conditions reduced flare efficiency by 3 to 4 percent. More recently, Howes measured soot in a smoking propane flame. Using a dilution factor obtained from the CO_2 concentration, the 18 mg/m^3 of soot measured represented a decrease in combustion efficiency of 0.4 percent. Note that these local efficiencies are not equivalent to global efficiency, since they were samples collected at one sampling point.

Flare Intermittency

"Intermittency" essentially means that, at one fixed point above the flare, the flame is not present all of the time. Even in calm winds, the turbulence induced by the combustion process causes the flame to undulate and appear unsteady. This usually causes corresponding fluctuations in measured quantities at fixed points above the flame. Using sufficient sampling times is one way to time-average data to avoid this intermittency. An objective of the proposed experimental plan is to determine sampling times so that characteristics of the flame are measured, unmasked by intermittency.

Scaling Methodology

The studies listed in Table 1 did not provide a methodology whereby the data from these pilot-scale or small plant-scale flares could be used to assess emissions from the total population of flares. A methodology is required which will allow data to be obtained economically at pilot-scale and used to determine performance of full-scale systems. The current state-of-the-art of turbulent flame structure precludes the use of predictive models. Thus the experimental plan must provide data which will allow both the effects of scale to be determined and, in conjunction with developing theories of turbulent flame structure, extrapolation to full scale.

Technical Approach

Current information on flare combustion is fragmentary and inconclusive. This program attempts to answer several questions:

- What are the combustion efficiencies of small flare flames?
- How are these efficiencies influenced by operational parameters, flare design, fuel composition, and scale?
- What are the mechanisms of these influences?
- How can the efficiencies of large industrial flares be estimated?

A research program with emphasis on experimental measurements on a pilot-scale flare is the most cost-effective way to approach answering these questions. It must fulfill these requirements:

- Representativeness - The hardware and operational conditions must relate to full-scale practice.
- Data Accuracy - The measurement methods must be developed and verified satisfactorily to eliminate the uncertainties that plagued previous experiments.
- Basic Understanding - Experiments must be designed to develop an understanding of the underlying controlling processes that take place in flare flames.
- Extrapolation - Information must be generated to extend the applicability of the small-scale data to full-scale flares.

The design of valid experiments involving flares must consider the fact that flare flames are different from other combustion processes (e.g., enclosed boiler flames) in that they are buoyancy dominated, are affected by ambient air movements, and lose heat to a much colder environment. It is commonly accepted that, if sufficient air is mixed with the fuel and if the resultant mixture is kept above the reaction temperature, combustion will go to near 100 percent completion. However, these two conditions are not necessarily maintained in flare combustion systems, particularly for the fuel eddies that are separated from the main flame body. Because of the geometry of the eddies, they tend to be quenched at a higher rate than the main flame body and hence are more likely to be extinguished before all the fuel is burned.

The presence of oxygen next to the fuel is essential for continuation of combustion. In a flare flame, air may be entrained into the fuel jet by natural convection and exhausted by forced convection through air- or steam-assist. The effectiveness of these mixing processes directly affects the combustion reaction. If the mixing is not completed before the burning fuel elements are quenched below the reaction temperature, the flame will be extinguished. Therefore, the research program must develop the basic understanding of the mixing and eddy behavior of flare flames. This may be aided by modeling.

The main emphasis of the research program, therefore, will be the measurement and characterization of emissions and flame structures. The program includes studies of:

- Four flare sizes (1½, 3, 6, and 12 in. in diameter), linearly scaled replicas of each other, including features of commercial flares.
- Detailed measurements throughout and beyond the visible flame envelope to determine profiles of temperature and species concentration.
- Tracers injected and measured to assess air entrainment.
- Photographically recorded flame structures.

The experiments will start with the smaller flares to develop and verify the measurement methods. Once the baseline flare behavior is defined, the effects of operational parameters and scale will be studied.

The experimental test program is divided into four tasks.

Task 1 involves generation of a data base of gross flame parameters as a function of the complete range of all input parameters. This will be a rapid screening process on all flare sizes to assess the major effects of fuel rate, wind level, steam rate, and gas composition. The output measurements will be limited to visual and photographic observations of flame length, form and structure, and sooting tendency. Video recordings can supplement the photographic technique. The utility of this task lies in its identification of those regimes of the original test plan that need greater emphasis in the succeeding tasks.

Task 2 relates to the development and verification of all measurement techniques. This can most effectively be done using the smaller flare sizes. The measurements will consist of species concentration measurements in and near the flame, including a tracer. Development of an integrating hood will be included. A major objective of this task is verification of an adequate carbon mass balance to provide confidence in the succeeding task.

Task 3 concerns detailed measurements according to the test plan revised by Task 1. The major effort will be on the smaller sizes, with the knowledge gained indicating the most important test conditions to be used for the limited number of large-size tests.

Task 4 relates to continuous evaluation of test data, development of modeling and scaling parameters, and documentation. Information on the range of experimental parameters to be evaluated during the testing is provided in Table 2.

Test Facility Design

The test facility will simulate the important features of the flare process. The objective of the design is not to build an optimized flare tip in terms of combustion efficiency and steam utilization, but to include sufficient flexibility to simulate the flaring process so that the measurements can describe flare flame characteristics. The experimental flare system discussed here is based on flare heads which retain all the important features but are scaled down in size. An array of different size flare heads provide information on the effects and parameters of scale.

The parameters that are fundamental to the design are: flare size, flare gas properties, nozzle gas exit velocity, wind condition, air entrainment, and measurements.

The full report provides details of the designs of the various subsystems: flare stack and tips; fuel supply and handling (propane, methane, nitrogen, and/or CO_2); tracer supply and handling (SO_2); steam supply; flow controls and metering; ambient conditions measurement and control; extractive species sampling; photography; and control, data acquisition, and processing.

Table 2. *Experimental Parameters and Fuel Costs for Pilot-scale Flare Tests*

Dia. in.	Case	Velocity ft/sec	Flow Rate ft^3/hr	$\tau = \frac{d_o}{V_o}$	Reynolds Number[a]	$g\frac{d}{u_o^2}$ Richardson Number	Propane Flow Rate lb/hr[b]	Propane Cost $/hr	Methane Flow Rate lb/hr[c]	Methane Cost $/hr	Nitrogen Flow Rate lb/hr[d]	Nitrogen Cost $/hr
	1	0.25	11	$500x10^{-3}$	83	6 4	0.7	0 12	0 45	0.07	0.7	0.15
1.5	2	1.41	62	$89x10^{-3}$	471	2.013	4.0	0.7	2.56	0.4	4.1	0.86
	3	10.0	442	$13x10^{-3}$	3343	0 0403	28	5.0	18.3	3.0	29.3	6.15
	4	0 5	88	$500x10^{-3}$	334	32 20	5 6	1.0	3 64	0.6	5.8	1.2
3.0	5	2.0	353	$125x10^{-3}$	1337	2.013	23	4 1	14 6	2 4	23.4	4.9
	6	10.0	1767	$25x10^{-3}$	6687	0.081	113	20.0	73.0	12 0	117.2	24.6
	7	1.0	707	$500x10^{-3}$	1337	16 1	45	8 0	29 2	4.8	46 9	9.8
6.0	8	2.83	2000	$177x10^{-3}$	3785	2.013	128	22.6	82.6	13.5	132.6	27.8
	9	10.0	7069	$50x10^{-3}$	13373	0.161	451	79 8	292 1	47.9	468.7	98.3
	10	2 0	5655	$500x10^{-3}$	5349	8.05	361	63 8	233 7	38 8	375	78.6
12.0	11	4.0	11310	$250x10^{-3}$	10699	2.013	722	127.7	467 7	76 6	750	157.3
	12	10.0	28274	$100x10^{-3}$	26747	0.322	1806	319 4	1168.0	191.4	1875	393

(a) *Reynolds number based on 56% propane, 44% nitrogen mixture*
(b) *Propane diluted to 1350 Btu/ft^3(56 volume %)*
(c) *Methane fired without dilution.*
(d) *Nitrogen used to dilute propane to 175 Btu/ft^3 (92 7 volume %).*

D. Joseph, J. Lee, C. McKinnon, R. Payne, and J.Pohl are with Energy and Environmental Research Corp., Irvine, CA 92714.
***Bruce A. Tichenor** is the EPA Project Officer (see below).*

The complete report, entitled "Evaluation of the Efficiency of Industrial Flares: Background—Experimental Design—Facility," (Order No. PB 83-263 723; Cost: $23.50, subject to change) will be available only from:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: 703-487-4650

The EPA Project Officer can be contacted at:

Industrial Environmental Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

United States
Environmental Protection
Agency

Center for Environmental Research
Information
Cincinnati OH 45268

Official Business
Penalty for Private Use $300

PS 0000329
U S ENVIR PROTECTION AGENCY
REGION 5 LIBRARY
230 S DEARBORN STREET
CHICAGO IL 60604

☆ U.S. GOVERNMENT PRINTING OFFICE: 1984-759-102/835