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EVALUATION OF THE EFFICIENCY OF INDUSTRIAL FLARES

USED TO DESTROY WASTE GASES

Interim Report

Background - Experimental Design - Facility

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TABLE OF NOMENCLATURE

Variable Symbol	Meaning
A	Cross-sectional area
b	Characteristic jet radius
C_E	Local entrainment coefficient
C_s	Spready coefficient
C_L	Flammability lean limit
c	Concentration
c_p	Specific heat, constant pressure
c_v	Specific heat, constant volume
D	Distance
DE	Local fuel destruction efficiency
DF	Dilution factor
d	Diameter
E	Global emission, E = 1-U
F	Fraction of heat released in a flare that is radiating
FRG	Federal Republic of Germany
FR	Froude number
f	Edyy generation frequency
$\dot{G}$	Jet momentum flux
g	Gravitational acceleration constant
H	Height
HV	Low Heating value of gas
HC	Hydrocarbon (expressed as equivalent methane)
h	Height of stack
ICBF	Incompletely burned fuel
K	Radiation heat flux
K_T	Tracer concentration ratio
L	Length
M	Molecular weight
m	Mass
$\dot{m}$	Mass flow rate
$\dot{m}^*$	Ratio of mass flow rates
N	Number of eddies

TABLE OF NOMENCLATURE (Cont'd)

Variable Symbol	Meaning
$\tilde{N}$	Number of moles
n	Number of atoms per molecule
O	Global efficiency based on oxygen consumption
P	Pressure
Q	Radiation intensity per unit volume of product
R	Gas constant
Re	Reynolds number
Ri	Richardson number
r	Radius or intermediate variable
S	Dimensionless coordinate
SR	Stirred reactor
T	Temperature
t	Time
U	Global efficiency
u	Velocity
V	Volume
$\dot{V}$	Volumetric flow rate
w	Vertical velocity (ref. Brzustowski)
X_L	Dimensionless downwind coordinate
x	Radial distance from centerline
Y	Mass fraction
z	Axial distance from nozzle

TABLE OF NOMENCLATURE (Cont'd)

GREEK SYMBOLS

Symbol	Meaning
α	Local combustion efficiency based on CO_2
α_E	Empirical entrainment coefficient
α_{st}	Empirical factor used to predict the amount of steam required to suppress soot
β	Burning rate parameter
γ	Entrainment coefficient
δ	Thickness of jet
η	Local combustion efficiency based on pollutants
θ	Jet spreading angle
λ	Kolmogorov length scale
μ	viscosity
ξ	Dimensionless streamline coordinate
ρ	Density
$\tilde{\rho}$	Mixing cup density
σ	Standard deviation
$\sigma_{\overline{x}}$	Standard error of $\overline{x}$
ϕ	Stoichiometric coefficient
Ω	Intermittence factor-fraction of the time the flame is present at radial distance X

TABLE OF NOMENCLATURE (Cont'd)

SUBSCRIPTS

Subscript Symbol	Meaning
a	Air
ad	Adiabatic
C	Carbon
c	Centerline values
e	Eddy
F	Flame
f	Fuel
j	Jet
L	Flame length
o	Conditions at nozzle
p	Products
s	Sonic
st	Steam
unhc	Unburned hydrocarbon
w	Wind
∞	Ambient conditions
overbar	Ambient conditions
[ ]	Concentrations

1.0 SUMMARY

This report discusses the problems associated with the determination of combustion efficiencies of elevated industrial flares. Such flares are primarily used to safely dispose of infrequent releases of large quantities of combustible gases during emergency or process upset conditions. In addition, flares are used on a continuous or semi-continuous low flow basis, which is the focus of the present study.

There are numerous practical difficulties associated with making measurements on full scale, operational flares. Consequently, meaningful, cost-effective efficiency measurements must be developed on pilot scale flares. An experimental program has been formulated using several flare sizes and which will evaluate the flare process and the operational parameters controlling pollutant formation in flare flames. The data obtained from this experimental program will be capable of extrapolation to full scale and therefore will allow an accurate estimate of pollutant emissions from industrial flares. An essential factor in the experimental plan is an understanding of combustion system scaling which will allow the extrapolation from pilot to full scale.

1.1 Pollutant Emissions from Flares

A flare is a device which allows the economic safe disposal of waste gases by combusting them. The waste gases are injected into the open air through a tip which is designed to promote entrainment of the ambient air and provide a stable flame with a wide range of throughputs in high cross-winds. In order to reduce flame radiation at ground level, the flare tip must be elevated and its height will be dependent upon flame size (i.e., flare throughput). If the waste gas has too low a heating value 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 16M tons/yr 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-average throughput is in the range of zero to 5 percent of design capacity, which is exceeded only during emergencies or upsets. The flared gases fall into three categories (Klett & Galeski, 1976):

- 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, and total emissions are assessed based upon 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, and consequently estimates of pollutant emission indices vary. Estimates of flare efficiencies vary widely, some are very high, in excess of 99 percent, whereas others range as low as 70 percent (T.A. - Luft 1974) leading to the conclusion that emission factors 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 elevated 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;
- scale.

Data from this study can then be used to provide an accurate assessment of pollutant emissions from flares.

1.2 Deficiencies in Previous Flare Emission Studies

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

Table 1-1 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, none allow an accurate determination of pollutant emissions nor do they 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 the common problems which prevent an accurate assessment of flare efficiency. These problems are discussed below in four main areas, namely:

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

Table 1-1. Previous Flare Emission Studies

Investigator	Flare Tip Design	Flared Gas	Throughput M Btu/hr	Flare Efficiency %
Palmer (1972)	0.5" dia.	Ethylene	0.4 - 2.1	> 97.8
Lee & Whipple (1981)	Discrete Holes in 2" dia. cap.	Propane	0.3	96 - 100
Siegel (1980)	Commercial Design (27.6" dia. steam)	≈ 50% H_2 plus light hydrocarbons	49 - 178	97 - > 99
Howes et al (1981)	Commercial Design (6" dia. air assist)	Propane	44	91 - 100
	Commercial Design H.P. (3 tips @ 4" dia.)	Natural Gas	28 (per tip)	> 99

Closure of Material Balance

The global efficiency of a flare flame can be calculated if the inlet fuel composition and mass flux is known together with mass flux of all hydrogen and carbon containing species of flared material at some 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 1-1, only Siegel attempted to close the mass balance. Generally he was only able to account for approximately 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 circumvents the need for further mass balance by using "local burnout" efficiency, and showing that errors in the resulting global efficiency values are minor. Thus, without mass balance closure, no great confidence can be placed on Siegel's efficiency values.

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 which requires an integration of the species flux across the total jet. The 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 average 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 determination of mass flux. More details on tracers will be discussed in Section 7.7.2.

Measurement of Soot Concentration

Soot represents uncombusted fuel carbon which should be included in flare flame efficiency calculations. Siegel (1980) measured soot concentrations between 20 and 80 mg/m^3 in an intentionally smoking flame, estimating that at those dilution conditions this reduced flare efficiency by 3 to 4 percentage points. More recently, Howes, et al (1981) performed soot measurements 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. It should be noted that these local efficiencies are not equivalent to global efficiency, since they were samples collected at one sampling point.

Flare Intermittency

The term "intermittency" essentially means that at one fixed point above the flare, the flame is not present all of the time. Even in calm wind conditions, the turbulence induced by the combustion process causes the flame to undulate and appear unsteady. This usually causes corresponding fluctuations in measured quantitites at fixed points above the flame. Using sufficient sampling times provides one means of time averaging data to avoid this intermittency effect. As discussed in Sections 1 and 8, one objective of the proposed experimental plan is to determine sampling times so that the characteristics of the flame are measured, unmasked by intermittency.

Scaling Methodology

The studies listed in Table 1-1 did not provide a methodology whereby the data from these pilot scale or small, plant scale flares could be used to assess the 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 the effects of scale to be determined and in conjuction with developing theories of turbulent flame structure will allow extrapolation to full scale.

1.3 Technical Approach

As will be shown in the Background Section, current information on flare combustion is fragmentary and inconclusive. This program attempts to answer these 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 in experimental measurements on a pilot scale flare is the most cost-effective way to approach 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 bring understanding on 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.

Flare flames are different from other combustion processes, such as enclosed boiler flames, in that they are buoyancy dominated, and are affected by the ambient air movements, and that they lose heat to a much colder environment. It is commonly accepted that provided sufficient air is mixed with the fuel and provided the resultant mixture is kept above the reaction temperature, combustion will go to near 100% completion. However, these two conditions are not necessarily true 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 which will be discussed in more detail later on in this report.

The main emphasis of the research program will be the measurements and characterization of emissions and flame structures. It will include these considerations:

- Four flare sizes (1½, 3, 6 and 12 inches in diameter) will be linearly scaled replicas of each other and will include features of commercial flares.
- Detailed measurements will be made throughout and beyond the visible flame envelope to determine profiles of temperature and species concentration.
- Tracers will be injected and measured to assess air entrainment.
- Photography will record 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 can be logically divided into four tasks.

The Task 1 objective is 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 also 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 will be concerned with 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 will be concerned with the detailed measurements according to the test plan as 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 is a general category related to continuous evaluation of test data, development of modeling and scaling parameters and documentation. A more detailed breakdown of these tasks is found in Section 4.

1.4 Report Organization

The report describes the background related to flare design, characteristics and emissions in Section 2. Sections 3 and 4 discuss the need for futher work and a technical approach to carry this work out. Section 5 gives a review of the potential test facilities which may be considered for the experiments. The design objectives, a facility description and the measurement techniques to be used in assessing flare characteristics are described in Sections 6 and 7. Section 8 discusses data analysis and application of the information generated in the experimental program.

2.0 BACKGROUND

The primary use of flares by industry is the safe venting and combustion of process gases during emergency or "upset" conditions. They are also available to dispose of much lower flowrates of waste gas that occur during normal process operation. It is this latter condition that prevails most of the time and is thus of major importance in determination of flare efficiency. Industrial flares encompass a wide variety of conditions; both in terms of the type of installation and operating conditions. Important factors are gas composition, heating value and percent dilution by inert gases, flowrate, ambient conditions and combustion assist features, such as steam or forced draft air. These depend on the type of plant and its location such that flare designs tend to be site specific. Consequently, there is a wealth of hard engineering experience with respect to flare design and adaptation to different conditions, but due to the varied nature of the flaring process, there is a lack of comprehensive information in the open literature with regard to specific operational details as they affect the waste gas combustion process. There is only meager and often contradictory information published on the potentially harmful materials issuing from industrial flares; thus there exists an information gap that must be closed in order to assess the environmental impact of flare systems.

Within this framework, the objective of this present program is to define an experimental plan which will both improve the understanding of flare combustion, and provide a means of estimating emissions from flares of various sizes and characteristics. There is a great deal of background information which is relevant to this task, and the purpose of this section is to review the important available literature in order to define the scope of the required experimental program. Of particular interest is information concerning flare use and the range of gas compositions encountered in the different industries, flare designs and the range of operating conditions, and experimental data and methods available for the modeling and scaling of flare type combustion.

In recent years, a number of surveys of flare use have been carried out, both in the United States and abroad. in an attempt to define the significance of flare emissions. Results from such studies provide a basis for the estimation of total gas quantities flared, the range of gas compositions encountered and, by inference possible emission factors for the different industries. Information is also available concerning flare types and design methods, although the nature of the flare combustion process, and the lack of appropriate measurement methods, has precluded the kind of detailed study that would permit a definition of combustion efficiencies or allow quantification of the effect of different flare design parameters. A number of small and pilot scale studies have, however, been carried out, and these are reviewed to provide insight into the relevance of small scale experiments and the possibilities for data extrapolation. Much of the available data shows, however, that our knowledge of basic combustion phenomena is lacking in certain areas, and that direct transfer of experimental data from small to full scale is usually not possible. To this end, a simple mathematical modeling approach is required to provide a direction for the design of small scale experiments and a means of defining scaling criteria by which the data can be extrapolated. Available modeling approaches and basic information concerning the characteristics of large turbulent diffusion flames are review in this light.

2.1 Use of Industrial Flares

Much of the information on use, design, and operation of flares has been reviewed by Klett and Galeski (1976). More recently the German Society for Petroleum Sciences and Coal Chemistry, DGMK, (Program 135-01) analyzed the results of a questionnaire sent to 31 German refineries. Unpublished results from a questionnaire sent out to California refiners by the California Air Resources Board (Metzger and Vincent, 1980) has also been made available. Most of the information which follows is based on these studies.

Flares are designed for the maximum anticipated gas release caused by process upset or emergency shutdown. These conditions occur infrequently and are of relatively short duration. A lower level continuous or semi-continuous release is caused by leaks in equipment, necessary venting of a process, and purging of gases during start up and shutdown. These flows, while of much reduced magnitude compared to emergency use, occur most of the time. Thus a flare must be a very flexible device, capable of high throughput, and sustained operation at a high turn down ratio. For instance, an instantaneous flow rate of 100 MSCF/hr may be demanded while sustained normal operation occurs at 1/1000 of this value.

This section reviews the industries in which flares are used, characterizes the gases flared, and estimates the amount of gas flared in these industries. Unfortunatly, the use of flares is largely uncontrolled and, hence, the flow rates of gases are infrequently monitored. Flow rates are only occasionally measured so that the amount of steam required to suppress smoking can be regulated. Rough estimates have been made of the amount of gas flared in four major industrial operations: oil refining, blast furnaces, coke ovens, and ethylene manufacturing for 1974. Here we extrapolate this estimate to 1980 and estimate the amount of gas flared in petroleum production and the chemical industry.

2.1.1 Petroleum Refining

The petroleum industry flares large quantities of gas from refinery operations and production wells.

Table 2-1 has been constructed from the data of California Air Resources Board Survey. Although the number of initial questionnaires sent out is unknown, the 63 flares referenced by the 21 respondents show very simlar characteristics. Although "emergency" is the primary use, continuous use is also assumed. Steam is the most universal means of smoke suppression. None of the flares are equipped to measure flow rate of the flared gas, so annual amounts are only estimates. The composition and heating value vary widely.

These results are similar to the results from the German refinery survey (DGMK, 1981) wherein thirty-one West German refineries responded. Figure 2-1 shows the flare gas density variation from one of these refineries during the period in 1978 of Siegel's research there. The flowrate is that of Siegel's side stream and not the main flare.

Generally, the gas flared in refineries is not measured and thus is difficult to estimate. However, gases flared in refineries contribute significantly to the total amount of gas flared in the United States. Therefore, the amount of gas flared in petroleum refining must be estimated, if the total emissions of incompletely burned fuel is to be estimated.

In 1974, a survey (Table 2-2) of 11 of the 288 refineries in the United States showed that from 0.039 to 2.8 percent of the refinery throughput was flared. The average amount flared excluding the highest number was about 0.2 percent. This number is the same as that estimated by Seigel (1980) for German refineries. About 12.3×10^6 BBL/cd of petroleum was refined in 1974. Therefore, petroleum refineries flared approximately 7.4×10^6 lb/cd of gas based on barrels refined. The figures for 1980 are 18×10^6 BBL/cd refined and 10.8×10^6 lb/cd of gas flared.

Table 2-1. Survey of California Oil Refinery Flares (California Air Resource Board, 1980)

Refinery	Flare Type	Flare Diameter (in)	Smoke Suppression	Service	Annual Flowrate scf/yr	Fuel	Steam/Fuel
1	Elevated	30	Steam	Emergency	---	---	~0.35
1	Elevated	24	Steam	Emergency	---	---	~0.35
1	Elevated	24	Steam	Emergency	---	---	~0.35
2	Elevated	---	Steam	Continuous	---	---	---
3	Elevated	30	Steam	Emergency	---	H_2, CO, N_2, C_1-C_3	---
3	Elevated	30	Steam	Emergency	---	---	---
3	Elevated	8	Steam	Emergency	---	---	---
4	Ground	---	Steam	Emergency	---	---	0.40
4	Elevated	30	Steam	Emergency	---	---	0.38
4	Elevated	8	Steam	Emergency	---	C_3, C_4, S	0.30
4	Elevated	10	Steam	Emergency	---	LPG	---
5	Ground	---	Steam	Emergency	180M	---	---
5	Elevated	---	Steam	Emergency	---	---	---
5	Elevated	16	Steam	Emergency	---	---	---
5	Elevated	20	Steam	Emergency	---	---	---
5	Elevated	10	Steam	Emergency	---	---	---
6	Elevated	30	Steam	Emergency	36M	---	---
7	Ground	---	Venturi	Emergency	---	---	---
8	Elevated	8	Steam	Con't & Emer.	---	---	~0.5
9	Elevated	8	Steam	Emergency	50M	H_2, C_1-C_6, H_2O	1.7
9	Elevated	12	Steam	Emergency	3.5M	H_2, C_1-C_6, H_2O	1.7
10	Elevated	---	Steam	Emergency	0.9M	---	0.5
11	Elevated	36	Steam	Emergency	---	---	~0.3
11	Elevated	36	Steam	Emergency	---	---	~0.3
11	Elevated	36	Steam	Emergency	---	---	~0.3
11	Elevated	10	Steam	Emergency	---	---	~0.3
12	Elevated	18	Steam	Emergency	547M	HC, H_2S, RSR	0.3 ->1.
13	Elevated	31	Steam	Emergency	---	HC, H_2S, RSR	0.23
14	Elevated	6	Steam	Con't & Emer.	3.9M	C_1-C_5, H_2	0.43
15	Elevated	48	Steam	Emergency	111	---	0.3-0.4
15	Elevated	48	Steam	Emergency	283	---	0.3-0.4
15	---	30	Forced Draft	Emergency	1.2	---	---
15	Elevated	16	Steam	Emergency	27.6	---	0.2-0.35
16	Elevated	36	Steam	Emergency	---	C_1,C_5, H_2, N_2, H, C, CO_2	~0-2.
16	Elevated	36	Steam	Emergency	---	C_1,C_5, H_2, N_2, H, C, CO_2	~0-2.
16	Ground	---	Steam	Emergency	---	C_1,C_5, H_2, N_2, H, C, CO_2	~0-2.
16	Elevated	36	Steam	Emergency	---	C_1,C_5, H_2, N_2, H, C, CO_2	~0-2.
16	Elevated	36	Steam	Emergency	---	C_1,C_5, H_2, N_2, H, C, CO_2	~0-2.

Table 2-1. Survey of California Oil Refinery Flares (Cont'd) (California Air Resource Board, 1980).

Refinery	Flare Type	Flare Diameter (in)	Smoke Suppression	Service	Annual Flowrate scf/yr	Fuel	Steam / Fuel
16	Elevated	42	Steam	Emergency	---	$C_1, C_2, H_2, N_2, H, O, CO_2$	~0-2.
16	Elevated	42	Steam	Emergency	---	$C_1, C_2, H_2, N_2, H, O, CO_2$	~0-2.
16	Elevated	48	Steam	Emergency	---	$C_1, C_2, H_2, N_2, H, O, CO_2$	~0-2.
16	Elevated	---	Steam	Emergency	---	$C_1, C_2, H_2, N_2, H, O, CO_2$	~0-2.
16	Elevated	70	Steam	Emergency	---	$C_1, C_2, H_2, N_2, H, O, CO_2$	~0-2.
16	Elevated	---	Steam	Emergency	---	$C_1, C_2, H_2, N_2, H, O, CO_2$	~0-2.
16	Elevated	---	Steam	Emergency	---	$C_1, C_2, H_2, N_2, H, O, CO_2$	~0-2.
17	Ground	---	Steam	Emergency	---	$C_1, C_2, H_2, N_2, H, O, CO_2$	~0-2.
17	Elevated	42/100	Steam	Emergency	---	$C_1, C_2, H_2, N_2, H, O, CO_2$	~0-2.
17	Elevated	36	Steam	Emergency	---	$C_1, C_2, H_2, N_2, H, O, CO_2$	~0-2.
17	Elevated	---	Steam	Emergency	---	$C_1, C_2, H_2, N_2, H, O, CO_2$	~0-2.
17	Elevated	48/72	Steam	Emergency	---	$C_1, C_2, H_2, N_2, H, O, CO_2$	~0-2.
17	Elevated	12	Steam	Emergency	---	$C_1, C_2, H_2, N_2, H, O, CO_2$	~0-2.
17	Elevated	12	Steam	Emergency	---	$C_1, C_2, H_2, N_2, H, O, CO_2$	~0-2.
18	Elevated	---	Steam	Emergency	10,740	C_1-C_5, NH_3, CO_2	~0.3
18	Elevated	---	Steam	Emergency		H_2S	0.3
19	Elevated	42	Steam	Emergency	---	---	~0.3
19	Elevated	36	Steam	Emergency	---	---	~0.3
19	Ground	---	---	Emergency	---	---	0
20	Ground	---	Steam	Emergency	---		---
20	Elevated	---	Steam	Emergency	---		---
20	Elevated	---	Steam	Emergency	---		---
20	Elevated	---	Steam	Emergency	---		---
20	Elevated	---	Venturi	Emergency	---		---
21	Ground	---	Self-Inspiration	Emergency	0.25M	C_1-C_3	0

Table 2-2. Gas Flared in U.S. Refineries
(Klett and Galeski, 1976).

Refinery	Refinery Throughput bbl/cd	% Flared	Composition (%)								Total Hydro-carbon lb/cd	Composition			
			C_1	C_2	C_3	C_4	C_5	Aromatic	Olefins	Paraffins		H_2	H_2S	NH_3	Other
1	54,437	0.170	0	1.2	1.8	2.4	0	0	0	5.4	5.4	0	9.4	0	85.1
2	167,650	0.554	49.4	14.5	12.9	9.3	11.1	0	10.3	87.0	97.3	1.9	0.8	0	0
3	213,000	0.143	2.3	5.1	70.5	30.5	40.0	11.5	29.5	57.4	98.4	1.6	0.0	0	0
4	73,700	0.145	47.9	14.9	14.2	12.2	8.9	0	10.3	87.7	98.1	0.6	0.9	0	0
5	106,064	0.059	11.1	26.0	1.8	2.8	2.5	0	12.7	31.4	44.2	1.0	43.8	1.3	9.8
6	255,000	0.039	7.8	32.4	29.2	14.3	6.8	1.2	17.7	75.0	93.8	3.2	2.9	0	0
7	239,400	0.056	8.5	8.4	34.4	41.7	4.5	0	9.7	87.7	97.5	1.4	1.1	0	0
8	369,500	0.210	7.3	9.1	53.6	5.3	8.0	0	10.2	75.1	85.3	0.4	2.1	0	12.2
9	112,652	0.604	20.9	17.8	34.9	11.5	8.6	0	19.7	74.0	93.7	1.6	1.3	0	3.3
10	162,908	0.142	22.9	32.1	18.1	7.2	8.9	0	11.8	77.4	89.1	4.6	6.3	0	0
11	145,060	0.189	24.2	13.2	67.3	7.1	4.2	0	0	94.3	94.3	0.4	0.5	0	4.7
Total	1,899,419	0.19	23.3	14.4	31.6	11.4	11.0	1.0	12.9	76.3	90.2	1.5	2.4	0	5.8
12	306,590	2.78	8.3	6.5	48.4	33.6	3.1	0	0	100.0	100.0	0	0	0	0

The composition of gas flared in refineries varies widely, both within a refinery (Figure 2-1 and Figure 2-2 and Table 2-3) and between refineries. (Table 2-1 and 2-2). The amount of gas flared in a German refinery varied by a factor of 22, the density by a factor of 3.4, and the composition of some species by a factor of 5. However, most of the refinery gases flares are light paraffinic hydrocarbons with large amounts of C_3 and C_4 compounds. An average composition for a refinery gas is shown in Table 2-4.

2.1.2 Petroleum Production

Gas flared during production of petroleum also contributes to the total amount of gas flared in the United States. In the past, large amounts of low molecular weight gases have been flared from oil producing wells. This practice has been reduced recently, since the gas product is now valuable and much of it can be sold.

The amount of gas flared in petroleum production has not been previously estimated, and it is difficult to make such an estimate. In one report approximately 0.7 percent of the oil production was flared (Minkkinen, 1981). Assuming a ratio of 0.5 percent gas flared to all petroleum production in the United States, the 10 MBBL/cd produced in the United States in 1980 resulted in the flaring of approximately 3 M tons/yr of gases from oil production.

The composition of gases flared during production of petroleum is the same as natural gas. These gases are mostly methane with small quantities of other light hydrocarbon gases and inert gases (Table 2-5).

2.1.3 Blast Furnaces

Another major use of flares is to dispose of waste gas from the blast furnaces used in the iron and steel industries. As in refineries, blast furnace gases are flared intermittently to control process pressures. Gases flared from blast furnaces account for approximately 60 percent of the weight and 19 percent of the Btu content of all gases flared.

The flowrate of combustible gas flared divided by blast furnace throughput capacity serves an indicator for this industry. In Table 2-6, it is seen that this figure varies from 0.07 percent to 43.2 percent. On the average 6.7 percent of blast furnace capacity was flared in 1974 when the production of blast furnaces was 145.5 x 10^6 tons/yr. Since steel production has changed little from 1974 to 1980, based on a production of 145.5 x 10^6 ton/yr, 52.6 M/lb/cd of blast furnace gas is assumed to have flared in 1980.