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Project Summary

Evaluation of the Efficiency of Industrial Flares: Flare Head Design and Gas Composition

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This report documents a continuation of Phase 4 of a research program to quantify emissions from, and efficiencies of, industrial flares. Phases 1 (Experimental Design) and 2 (Design of Test Facilities) were reported in EPA-600/2-83-070 (NTIS No. PB83-263723). Phase 3 (Development of Test Facilities) and initial work in Phase 4 (Data Collection) were reported in EPA-600/2-84-095 (NTIS No. PB84-199371). Further data collection during Phase 4 is reported here.

Initial results were limited to tests conducted burning propane/nitrogen mixtures in pipe flares without pilot light stabilization. The work reported here extends the previous results to other flare head designs and other gases and includes a limited investigation of the influence of pilot flames on flare performance. The following results were obtained:

- **Flare head design influences the flame stability curve.**
- **Combustion efficiency can be correlated with flame stability for pressure heads and coanda steam injection heads.**
- **For the limited conditions tested, flame stability and combustion efficiency of air-assisted heads correlated with the momentum ratio of air to fuel; the heating value of the gas had only minor influence.**
- **Limited data on an air-assisted flare show that a pilot light improves flame stability.**
- **The destruction efficiency of compounds depends on the structure of the compounds.**
- **For the compounds tested in this program, the destruction efficiency of different compounds could be correlated with the flame stability curve for each.**

This Project Summary was developed by EPA's Air and Energy Engineering 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

Industrial flares are commonly used to safely and economically destroy large amounts of industrial waste gases. Since most of the gas flared in the U.S. is from leaks, purges, and emergency vents, the amounts and compositions of flared gases vary widely and are difficult to measure. Flare emissions are also difficult to measure. Most flares are elevated to decrease noise and radiation hazards and to increase dispersion of combustion products. Probe collection of plume material in such situations is impractical. Remote sensing of flare emissions is an alternative to direct sampling, but instrumentation and techniques for this purpose are still undeveloped.

To evaluate and control industrial flare emissions, pilot-scale research is necessary to obtain direct sampling of flare emissions. Flare research has been conducted at Energy and Environmental Research Corporation (EER) since 1980. A pilot-scale flare test facility was constructed for the U.S. EPA in 1982.

Previous results (reported in EPA-600/2-83-070 and -84-095) showed that flare combustion efficiencies are generally high (i.e., exceeding 98%), but under some operating conditions (e.g., excess steam injection) efficiencies can be low. The results also showed that, when a flare flame is stable (i.e., not near blow-off conditions), combustion is efficient. However, flares operating with unstable flames tend to be inefficient. Data on flare gas exit velocity were correlated with the gas heating value to describe the region of flame instability. Thus, for the conditions tested, the operating range required for efficient flare performance can be defined.

Caution should be used, however, in applying these results to situations not tested. Flare flame stability and combustion efficiency may vary, depending on the flare head type, gas composition, and operating conditions. Thus, the research was extended to evaluate the effects of: (1) flare head type on flare combustion efficiency, and (2) relief gas composition on flare combustion and destruction efficiency.

Approach

The program was divided into four major tasks:

- Task 1—Evaluation of combustion efficiency for different flare head types.
- Task 2—Identification of representative, potentially difficult-to-destroy compounds.
- Task 3—Evaluation of combustion and destruction efficiency of selected relief gas mixtures.
- Task 4—Data analysis and reporting.

For Task 1, four commercial flare heads were evaluated: an air-assisted head, two pressure heads, and a coanda steam injection head.

Each head was tested on the EER pilot-scale Flare Test Facility (FTF). Flame stability and combustion efficiency were measured as functions of: (1) relief gas and exit velocity, (2) relief gas heating value, (3) steam assist flow rate (for the coanda head), (4) air assist velocity (for the air-assisted head), (5) relief gas pressure (for the pressure head), and (6) with and without pilot flame (for the air-assisted head).

The relief gas for these tests was propane, mixed with nitrogen to vary the heating value. Natural gas was used for the pilot flame.

Tasks 2 and 3 were designed to measure effects of flare gas composition on flame pollutant emissions. A wide variety of industrial compounds are frequently flared in the U.S. Most often, they are flared in mixtures containing several different compounds. Each different mixture may exhibit somewhat different flaring characteristics. Pilot or large-scale testing of every conceivable relief gas mixture would be expensive and unending.

Task 2 involved the testing of compounds in a laboratory facility. Although laboratory-scale flare flames are aerodynamically unlike pilot or large-scale flare flames, laboratory-scale tests can be used to economically and swiftly screen compounds to determine comparative potential for destruction in flares. Compounds which demonstrate flaring difficulties in the laboratory-scale Flare Screening Facility (FSF) are candidates for testing on the FTF.

Twenty-one compounds were selected for laboratory-scale testing in the FSF, representing the following classes: sulfur compounds, nitrogen compounds, chlorinated compounds, oxygenated compounds, aliphatic hydrocarbons, aromatic hydrocarbons, and compounds with low heating value. Of the 21 compounds screened, 6 were selected as candidates for testing on the FTF. Selection criteria included low destruction efficiency, poor ignitability, and high soot production.

Three of the six compounds, along with hydrogen sulfide, were tested on the FTF.

Hydrogen sulfide and ammonia were tested in mixtures with propane and nitrogen. Ethylene oxide and 1, 3-butadiene were tested diluted with nitrogen to vary the heating value. Flame stability, combustion and destruction efficiency, soot production, and byproduct formation from incomplete combustion were measured for each compound. All tests were conducted using the 3-in.* open pipe flame, without pilot flame stabilization.

For Tasks 1 and 3 (conducted on the FTF), samples were taken at five radial positions above the flame. These local samples were analyzed for O_2, CO, CO_2, hydrocarbon, NO_X, and soot concentration. Where applicable, the samples were also analyzed for H_2S, SO_2, and NH_3 concentration.

Sampling in the FSF (Task 2) was easier. In this facility, the flare nozzle was enclosed in a reaction chamber, which isolated the flame from the external environment. Sampling of the well-mixed products at the reactor outlet required only one probe.

Samples were analyzed during tests on both the FSF and FTF to evaluate air dilution, mass balances, combustion efficiency, and destruction efficiency. SO_2, injected during some of the pilot tests, was used as a tracer for mass balances. Mass balances on the FTF were more difficult because of product loss, air dilution in the large exposed flame, and plume concentration gradients. Local mass balances were used to accurately evaluate local mass fluxes, local combustion efficiency, and destruction efficiency. Local mass fluxes were radially integrated to calculate overall combustion and destruction efficiencies.

(*) To convert to metric units, please use the equivalents at the end of this Summary.

Results

Flare Head Design

The data show that flare head design influences the flame stability curve (as a function of gas heating value) as shown in Figure 1 for the coanda steam injection head and the pressure heads. The flame stability of the air-assisted head was controlled by the ratio of air to fuel momentum as shown in Figure 2. The heating value of the gas had little influence on flame stability for the air-assisted flare. The combustion efficiency of the pressure and coanda steam injection heads correlated with the gas heating value needed to maintain flame stability, as shown in Figure 3. For the air-assisted flare, the air to fuel momentum ratio was used to develop a correlation with combustion efficiency. Figure 4 shows this relationship, but caution should be used in applying these data due to the limited number of observations.

Gas Composition

The relative destruction efficiency of different gases was determined in the FSF. Table 1 gives results of these tests. Six compounds were identified as potentially difficult to destroy:

- 1, 3-butadiene yielded large amounts of soot.
- Carbon monoxide was difficult to ignite when pure.
- Ethylene oxide yielded low destruction efficiency.
- Vinyl chloride yielded low destruction efficiency.
- Hydrogen cyanide yielded low destruction efficiency.

- Ammonia was difficult to ignite when pure.

The destruction efficiency (DE) of three of these compounds and H_2S was measured on the FTF. The flame stability curve depended on the compound as shown in Figure 5. (H_2S and NH_3 were tested as minor constituents in propane/nitrogen mixtures.) The DE of the individual compounds depended on compound type but correlated with the stability curve for each compound as shown in Figure 6.

Conclusions

- Flare head design influences the flame stability curve.
- Combustion efficiency can be correlated with flame stability for pressure heads and coanda steam injection heads.
- For the limited conditions tested, flame stability and combustion efficiency of air-assisted heads correlated with the momentum ratio of air to fuel; the heating value of the gas had only minor influence.
- Limited data on an air-assisted flare show that a pilot light improves flame stability.
- The destruction efficiency of compounds depends on the structure of the compounds.
- For the compounds tested in this program, the destruction efficiency of different compounds could be correlated with the flame stability curve for each.

Conversion Factors

To convert nonmetric units used in this Summary to their metric equivalents, please use the following factors:

Nonmetric	*Multiplied by*	*Yields metric*
Btu	1.055	kJ
ft	0.305	m
ft^3	0.028	m^3
in.	2.54	cm

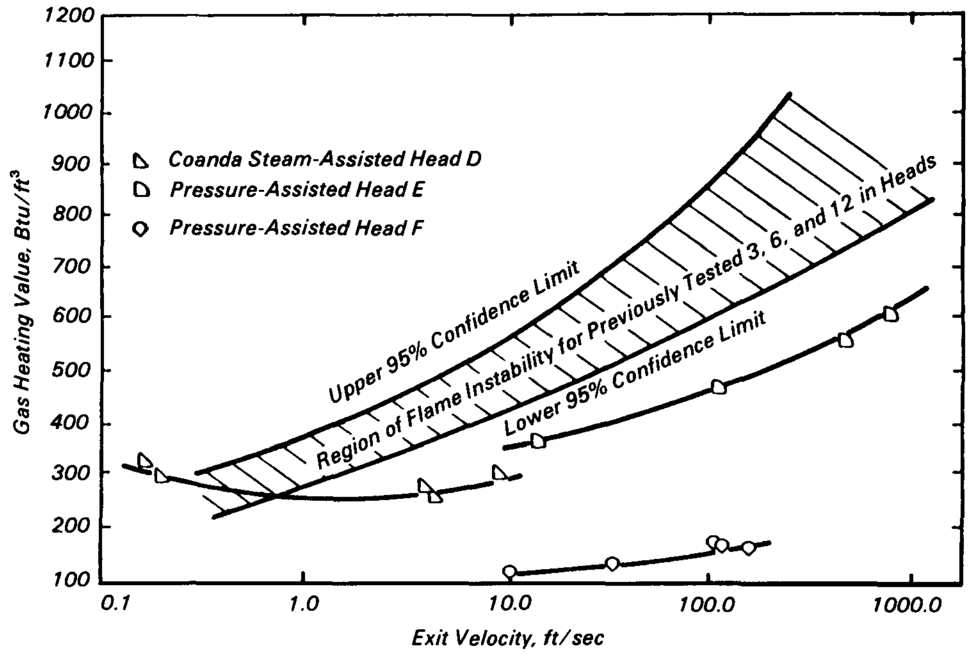

Figure 1. *Region of flame stability for steam-injected and pressure-assisted heads D, E, and F.*

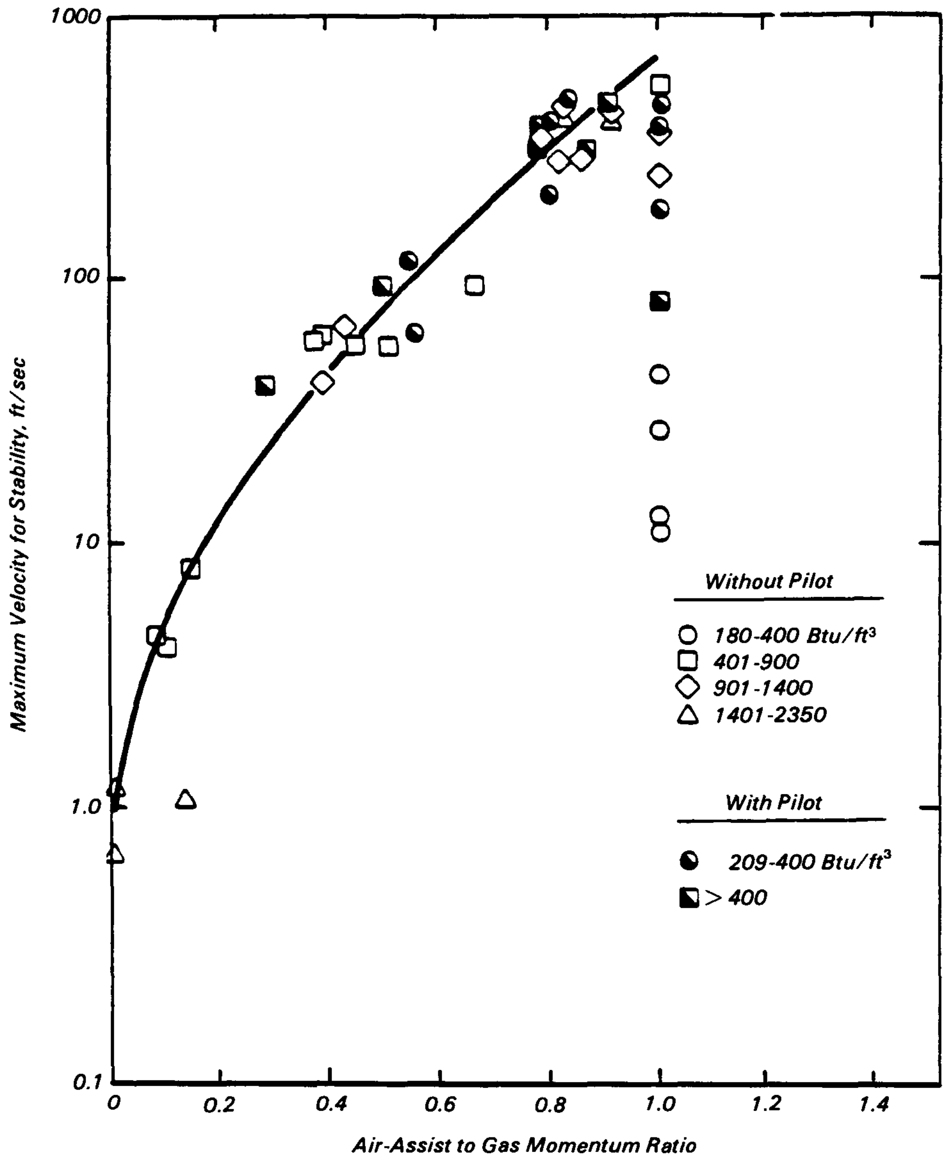

Figure 2. *Maximum gas exit velocity for stability versus air-assist to gas momentum ratio for the air-assisted head G, with and without pilot.*

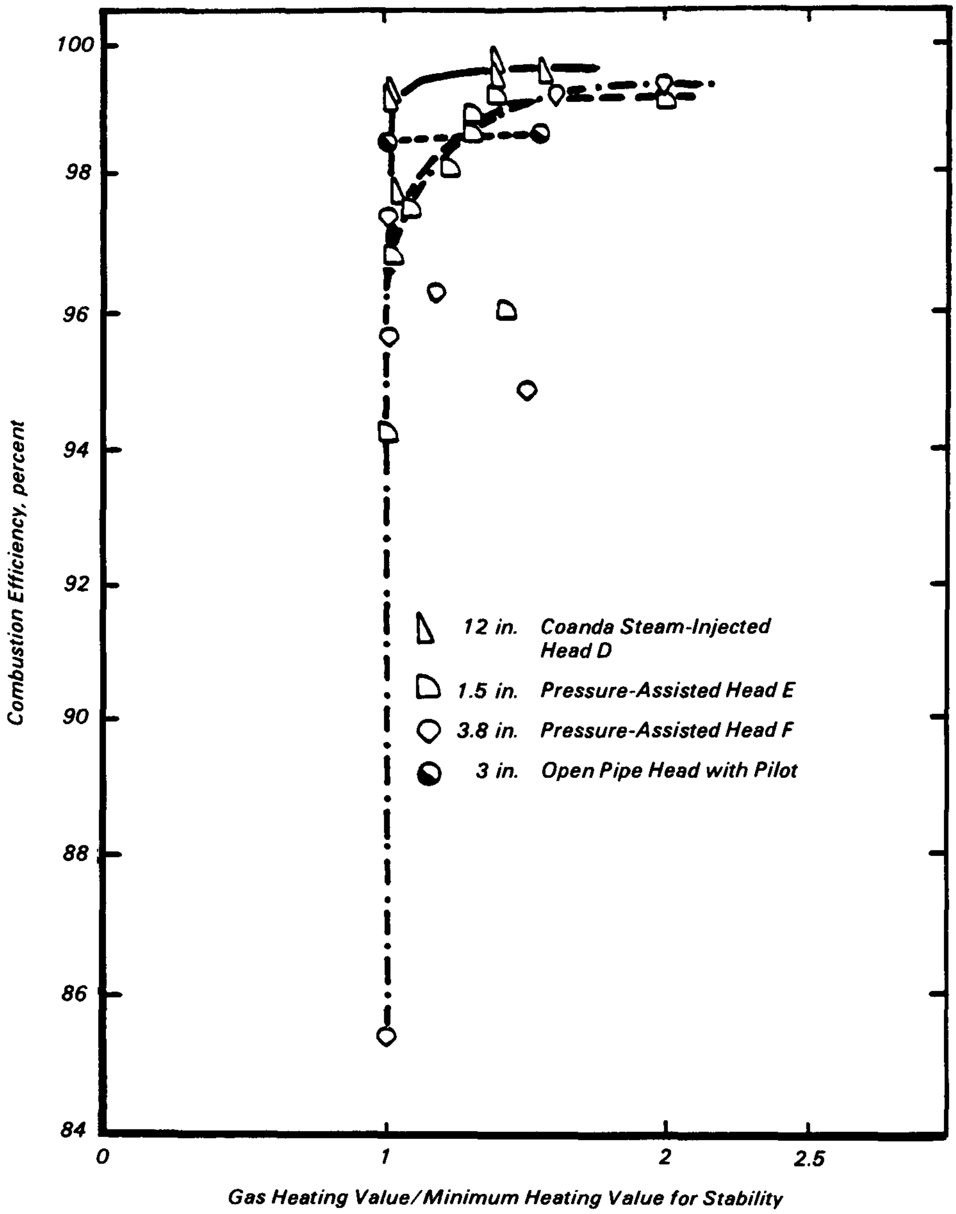

Figure 3. *Combustion efficiency vs. flame stability for steam-injected and pressure-assisted flare heads.*

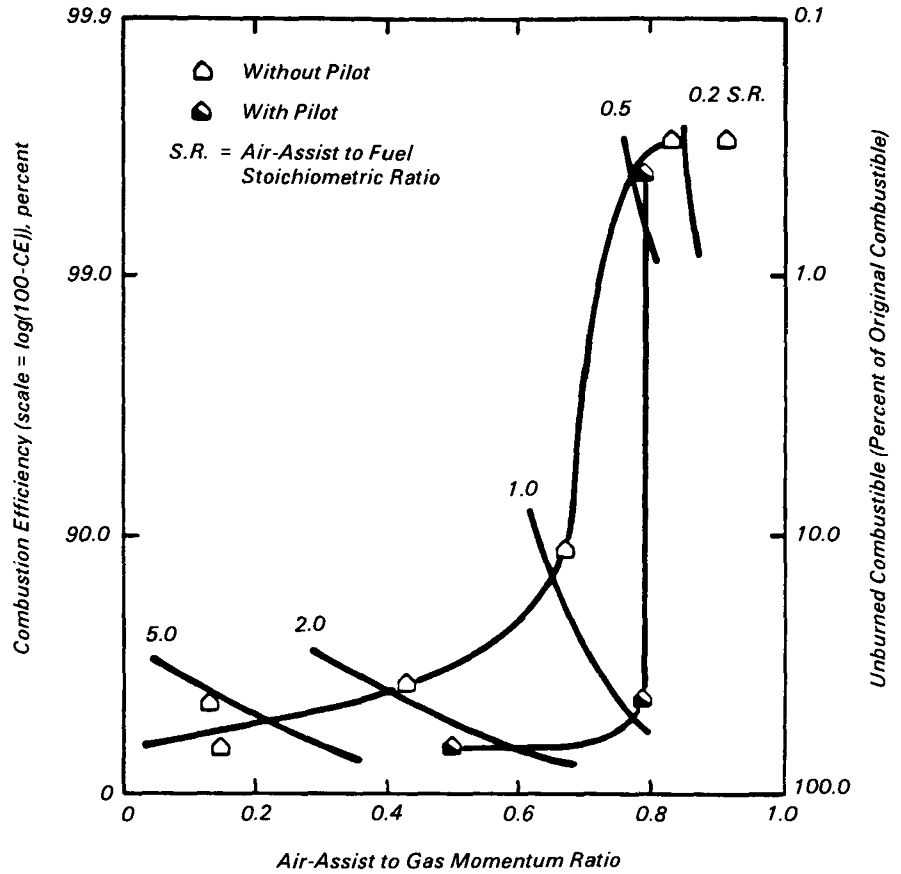

Figure 4. *Combustion efficiency vs. air-assist to gas momentum ratio for commercial air-assisted head G.*

Table 1. *Results of Compound Screening Tests (Gases in Propane/Nitrogen Mixtures)*

Compound	% Compound in Gas	% Nitrogen in Gas	Heating Value Btu/ft³	DE[a] %	CE[b] %	Soot mg/m³
Acetylene	100	0	1475	99.99	99.97	<1.5
Ethylene	100	0	1580	99.91	99.92	<1.5
Propylene	100	0	2300	99.98	99.93	<1.5
1, 3-Butadiene	100	0	2780	99.93	99.93	75[c]
Butane	100	0	3321	99.99	99.96	<1.5
Propane	100	0	2350	99.98	98.18	<1.5
Propane	25	75	1763	99.97	NA[d]	NA
Benzene	1.50	43	2370	99.59	99.95	<1.0
Toluene	1.50	43	2381	99.99	99.90	<1.0
Chlorobenzene	1.15	43	2350	99.49	99.95	<1.0
Carbon Monoxide	100	0	Could Not Ignite			
Carbon Monoxide	30	44	1760	99.60	99.88	<1.0
Carbon Monoxide	NA	NA	1111	NA	99.42	<1.0
Acetone	1.43	43	2347	99.80	99.96	<1.0
Acetaldehyde	2.07	43	2331	99.99	99.97	<1.5
Ethylene Oxide	1.42	43	2337	96.92	99.95	<1.0
Carbon Dioxide	7.58	43	2171	NA	99.93	<1.0
Methyl Chloride	9.17	42	2212	99.94	99.96	<1.0
Ethylene Dichloride	1.43	43	2335	99.70	99.95	<1.0
Vinyl Chloride	0.11	44	2350	96.79	NA	<1.0
Methyl Mercaptan	10.7	40	2218	99.39	99.82	<1.0
Acrylonitrile	1.47	43	2350	99.99	99.96	<1.0
Hydrogen Cyanide	0.013	44	2350	85.00	NA	<1.0
Ammonia	20	37	1967	99.90	NA	<1.0
Ammonia	100	0	Could Not Ignite			

[a]DE = Destruction Efficiency.
[b]CE = Combustion Efficiency.
[c]Boxes indicate compounds with potential problems.
[d]NA = Not Available.

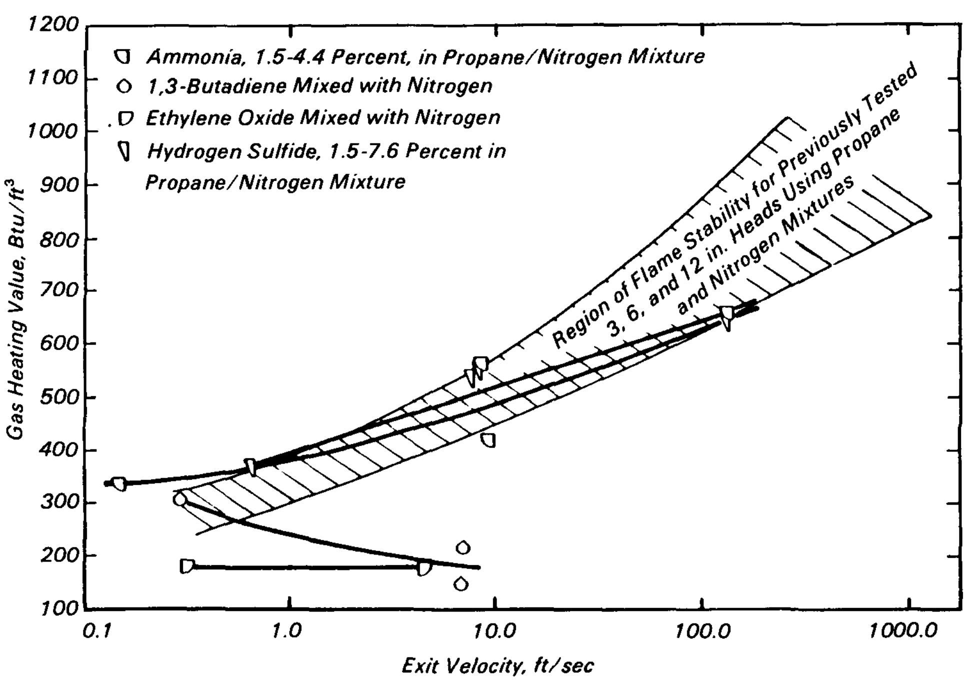

Figure 5. *Region of flame stability for the 3-in. open-pipe flare head burning selected relief gas mixtures.*

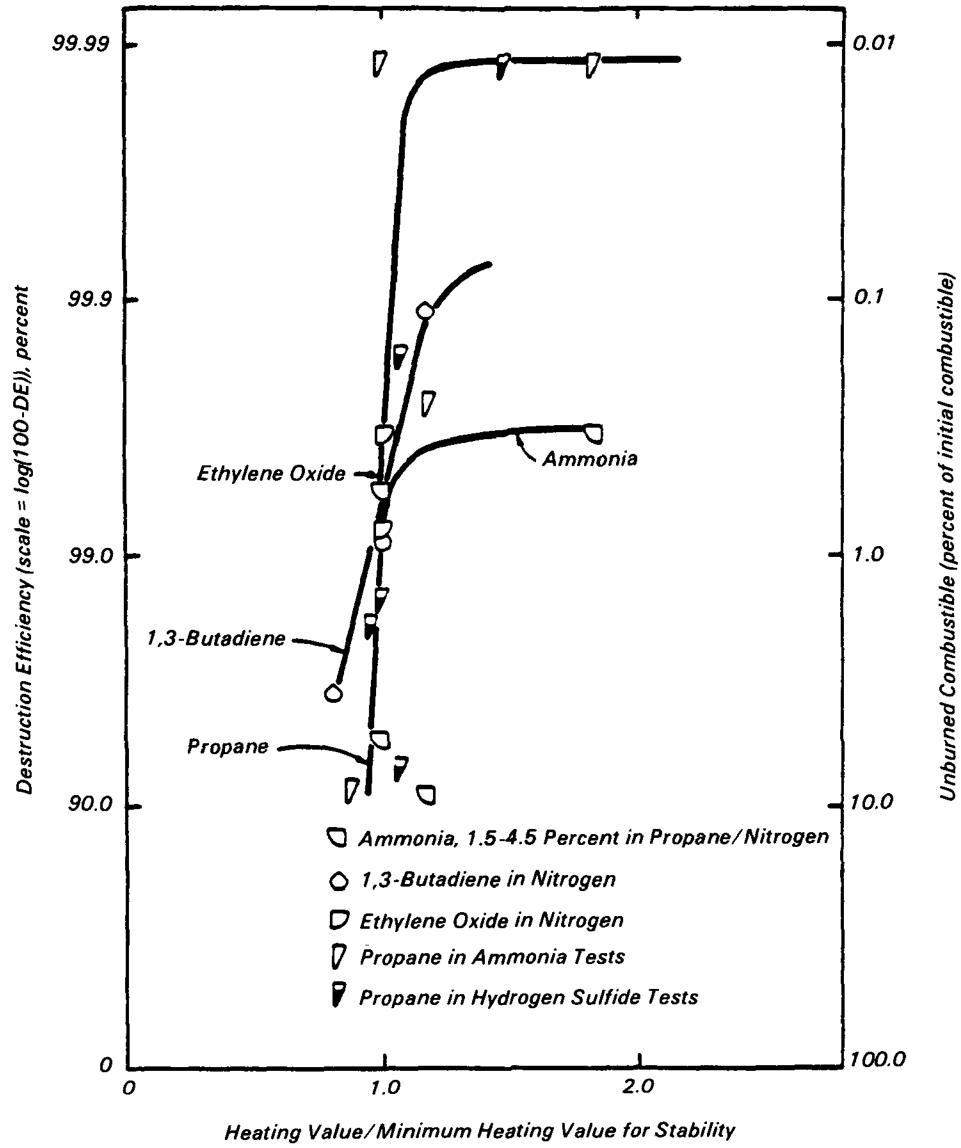

Figure 6. *Destruction efficiency of different gases.*

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***Bruce A. Tichenor** is the EPA Project Officer (see below).*

The complete report, entitled "Evaluation of the Efficiency of Industrial Flares: Flare Head Design and Gas Composition," (Order No. PB 86-100 559/AS; Cost: $16.95, subject to change) will be available only from:

National Technical Information Service
5285 Port Royal Road
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