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EVALUATION OF THE
EFFICIENCY OF INDUSTRIAL
FLARES: H_2S GAS MIXTURES AND
PILOT ASSISTED FLARES

Prepared for

Office of Air Quality Planning and Standards

Prepared by

Air and Energy Engineering Research
Laboratory
Research Triangle Park NC 27711

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EVALUATION OF THE EFFICIENCY OF INDUSTRIAL FLARES: H_2S GAS MIXTURES AND PILOT ASSISTED FLARES

Prepared by:
J. H. Pohl and N. R. Soelberg

ENERGY AND ENVIRONMENTAL RESEARCH CORPORATION
18 MASON
IRVINE, CALIFORNIA 92718

EPA Contract No. 68-02-3661

EPA Project Officer: Bruce A. Tichenor
Air and Energy Engineering Research Laboratory
Hazardous Air Technology Branch
Research Triangle Park, North Carolina 27711

Prepared for:
U.S. Environmental Protection Agency
Office of Research and Development
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ABSTRACT

The U.S. EPA has contracted with Energy and Environmental Research Corporation to conduct a research program which will result in quantification of emissions from, and efficiencies of, industrial flares. The program is divided into four phases: Phases I and II (Experimental Design and Design of Test Facilities, respectively) have been reported in report EPA-600/2-83-070; and Phases III and IV (Development of Test Facilities and Data Collection) have been reported in report EPA-600/2-84-095. Further data collection (part of Phase IV) is reported in report EPA-600/2-85-106.

Initial results (EPA-600/2-84-095) were limited to tests conducted burning propane/N_2 mixtures in pipe flares without pilot flare stabilization. Further results (EPA-600/2-85-106) reported the influence of the flared gas and flare head design on destruction and combustion efficiency without stabilization by pilot flares. The current report is the fourth in the series and gives test data on the combustion efficiency and destruction efficiency of (1) gas mixtures containing H_2S, and (2) flare flames with pilot flare stabilization. The tests were conducted on 3- and 6-in. open pipe flares without aerodynamic flame stabilization devices. The following results were obtained from this work:

- Gas mixtures of H_2S/N_2 can be stably flared at much lower volumetric gas heating values than can propane/N_2 mixtures.
- Destruction and combustion efficiencies greater than 98% are obtained for gas mixtures of H_2S/N_2 and H_2S/propane/N_2 when the gas heating value is at least 1.2 times the level required to produce a stable flame.
- For mixtures containing both H_2S and propane, H_2S destruction efficiency was consistently higher than propane combustion efficiency.
- The gas heating value required to maintain a stable flame, including the heating value contribution of the pilot gas, is 3 times lower with pilot assist than without pilot assist on 3- and 6-in. open pipe flares without aerodynamic flame stabilization devices.
- Combustion efficiencies greater than 98% for pilot assisted flares are achieved when the heating value is greater than 1.2 times that required to stabilize the flame.
- Increasing the pilot flow from 2 to 5 scfm, or the number of pilot flames from 1 to 3 (on 3- and 6-in. open pipe flares without other flame stabilization) could decrease the heating value of the gas required for stability by about 10-20%.

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1.0 INTRODUCTION

Large amounts of waste and purge gases are flared annually in the United States and worldwide. Exact figures are uncertain because of the limited measurement and control of flare gas flow. An estimate of the amount of gas flared in the United States in 1974 was 12 million tons[1] (1.1); this estimate was extrapolated to 16 million tons of gas flared in 1980 (1.2). Sources of flared gases include oil refineries, oil and gas production, blast furnaces, coke ovens, and chemical plants. By volume, the largest contributor is from blast furnaces which were estimated to release 9.6 million tons (69×10^{12} Btu) in 1980. By energy released however, the major contributors are oil refineries and oil and gas production wells which were estimated to release 5.0 million tons (219×10^{12} Btu) in 1980. Commonly flared gases include a wide variety of compounds, such as aliphatic hydrocarbons, aromatic hydrocarbons, and chlorinated, oxygenated, nitrogen-bearing, or sulfur-bearing compounds.

Industrial flare operating conditions and emissions are frequently very difficult to measure. Flow control and measurement is often limited or non-existent. Many flares burn mixtures of leaked or purged gases where the gas composition is largely unknown. Generally, flares are elevated to decrease ground level noise and radiation and to enhance dissipation of heat and combustion products. For this reason collection of plume samples from commercial flares is difficult. Various methods to determine plume composition and flare emissions by remote means are still being developed and are not yet available.

The most flexible, economical and accurate method of determining flare emission and combustion efficiency is to use a pilot-scale facility dedicated to accurate flare gas flowrate measurement and control with reliable plume sampling to determine flare emissions. Scaling is then required to apply

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1 English units are generally used throughout this report. Appendix F provides conversion factors from English to Metric units.

pilot-scale results to full-scale flare operations. Several studies have been conducted in which scaling criteria have been evaluated (1.2 - 1.7).

Flare research has been conducted at Energy and Environmental Research Corporation (EER) since 1980 (1.2, 1.4). A pilot-scale flare test facility was constructed for the U.S. EPA in 1982. This research has been sponsored by the U.S. EPA as part of an effort to provide data upon which to base regulations for industrial flaring practices.

1.1 Previous Flare Results

In the past 15 years there has been increased interest in research on flare combustion efficiency, due largely to increased governmental and industrial environmental awareness. Since flare research using full-scale industrial flares is difficult and expensive, most recent research has been conducted on pilot-scale flares 12 inches in diameter or less. Industrial flares are as large as 60 inches in diameter, so application of pilot-scale test results to these large flares requires scaling, using fundamental energy and mass transfer principles. Scaling is difficult, however, because of (1) basic aerodynamic differences, such as incompatible Reynolds number and Richardson number relationships, between small and large flames, (2) non-linear flame envelope and combustion zone characteristics, (3) the effects of the wide variety of industrial flare types and designs on flare performance, and (4) differences in wind and weather conditions. Scaling criteria have been investigated at EER by testing different sized flares (0.042-inch to 12-inch diameter) for comparison of fundamental differences (1.2, 1.3, 1.4, 1.6 1.7). Noble, et al (1.5) have also studied scaling criterial.

Flare combustion efficiency research up to 1983 has been reviewed by Dubnowski and Davis (1.8). Since 1972, flares and nozzles with 0.042-inch to 47-inch diameters have been tested. As Table 1-1 shows, flare combustion efficiency testing after 1983 has been conducted by Pohl, et al. (1.3) and Pohl and Soelberg (1.6). A wide variety of commercial heads have been evaluated, and a data base of results from open pipe flares and nozzles has been accumulated. Gas exit velocities have ranged between 0.15 to 891 ft/

TABLE 1-1. SUMMARY OF PREVIOUS FLARE COMBUSTION EFFICIENCY STUDIES[1]

STUDY	YEAR	FLARE SIZE (in)	DESIGN	GAS EXIT VELOCITY (f/s)	GAS HEATING VALUE (Btu/ft^3)	GAS FLARED	MEASURED COMBUSTION EFFICIENCY %	COMMENTS
Palmer (1.9)	1972	0.5	Steam Assisted experimental nozzle	50 - 250	1448	Ethylene	>97.8	Helium tracer for full size flare evaluation
Herget (1.10)	1977	47	Full size	NA	NA	Carbon black vinyl monomer	2500:1 reduction in CO	EPA ROSE remote sensing system
Straitz (1.11)	1978	2-6	Steam and pilot		1000 - 2350	Natural gas, propane	75 - 99	Results of limited validity due to instrument range sensitivity
Siegel (1.12)	1980	17.	Commercial Flaregas	0.7 - 16	1500	Refinery gas[2]	97 - 99	Multiposition plume extractive sampling
Lee & Whipple (1.13)	1981	2	Holes in 2" cap (1.1 in^2 open area)	1.8	2190 - 2385	Propane	96 - 100	
Howes, et al. (1.14)	1981	6[3]	Commercial air assist. Zink STF-LH	40 - 60	2385	Propane	92 - 100	Both extractive and EPA ROSE plume sampling
	1981	3at4[4]	Commercial H.P.	Near Sonic (estimate)	1000	Natural gas	>99	
McDaniel (1.15, 1.16)	1983	8	Commercial Zink STF-S-8	0.03 - 62	209 - 2183	Propylene/N_2	67 - 100	Both extractive and EPA ROSE plume sampling
	1983	6[3]	Commercial air assist Zink STF-LH-457-5	1.4 - 218	83 - 2183	Propylene/N_2	55 - 100	
Pohl, et al (1.2)	1984	3-12	Open pipe and commercial	0.2 - 420	291 - 2350	Propane/N_2	90 - 99.9	Multiprobe plume extractive sampling

TABLE 1-1. SUMMARY OF PREVIOUS FLARE COMBUSTION EFFICIENCY STUDIES[1] (CONTINUED)

STUDY	YEAR	FLARE SIZE (in)	DESIGN	GAS EXIT VELOCITY (ft/sec)	GAS HEATING VALUE (Btu/scf)	GAS FLARED	MEASURED COMBUSTION EFFICIENCY (%)	COMMENTS
Pohl and Soelberg (1.6)	1985	0.042	Nozzle	31 - 854	923 - 3320	25 different gas mixtures	>98 (80 - 99.99 destruction efficiency)	Comparative screening tests
	1985	1.5-12	Commercial coanda steam injection, pressure assisted, air assisted, open pipe, pilot assisted	0.2 - 591	122 - 2350	Propane/N_2	36 - 99.9	Comparative commercial flare type evaluation
	1985	0.042-2.5	Nozzle	5.6 - 891	588 - 2350	Propane/N_2	NM	Flame aerodynamic tests
	1985	3	Open pipe	0.15 - 139	145 - 877	H_2S/propane/N_2 NH_3/propane/N_2 1,3-butadiene/N_2 Ethylene Oxide/N_2	92 - 99.7 (92 - 99.9 destruction efficiency)	Gas mixture testing

NA = Not Available
NM = Not Measured

1. In part from Dubnowski and Davis (1.8)
2. 50% hydrogen plus light hydrocarbons
3. Supplied through spiders; high Btu gas through area is 5.30 in^2 and low Btu gas through 11.24 in^2
4. Three spiders, each with an open area of 1.3 in^2

sec. Gases and gas mixtures flared in pilot-scale tests include natural gas, ethylene, propane, propylene, refinery gas (50 percent hydrogen plus light hydrocarbons), hydrogen sulfide, ammonia, 1,3-butadiene, and ethylene oxide.

Results of these studies are being used as a data base for the promulgation of industrial flare practices and regulations. The key findings are:

- Flares can be operated with combustion and destruction efficiencies exceeding 98-99 percent.

- Flare efficiency depends on flame stability. A flare operated within the envelope of stable operating conditions will exhibit high efficiency unless too much steam or air assist is used.

- A flare operated outside its stable flame envelope becomes unstable; this can result in combustion and destruction efficiency below 98 percent.

- The stable flame operating envelope is specific to flare head design and gas composition.

- Operating conditions that have the largest influence on flame stability for a given flare head are the gas exit velocity and heating value. Depending on flare type, levels of steam, air, or pilot assist can also affect flame stability and destruction and combustion efficiency. Results also show that flare gases of equivalent heating value but different composition can have different stable flame operating envelopes when flared from the same flare.

Flare efficiency depends on flame stability, which in turn depends on flare head design and flare gas exit velocity, heating value, and composition. There are practically as many different combinations of these variables as there are industrial flares. Therefore further research is

needed on flare flames to improve and extend scaling factors, and to develop methods correlating the influences of gas mixture, flare head type, and operating conditions on the combustion and destruction efficiency for commercial flares.

EER was commissioned by the EPA in 1980 to conduct flare research. For this research, a pilot-scale Flare Test Facility was designed and constructed at EER's test site in El Toro, California (1.2) Flare research at EER is briefly summarized in Table 1-1. A data base has been developed which includes flare performance and efficiency measurements for (1) open pipe nozzles and flares ranging in size from 0.042 to 12 inches in diameter, with and without flame retention rings, (2) seven commercial flare heads ranging in size (based on open area for gas flow) from 1.5 to 12 inches in diameter -- representative of coanda steam injection, pressure, and air assist flare heads, and (3) limited steam and natural gas pilot assisted tests on both open pipe and commercial flare heads. Propane, blended with nitrogen diluent to alter gas heating value, was used as the flare gas for these tests. Scaling parameters investigated include exit velocity, residence time, Reynolds number, and Richardson number. Flare flame aerodynamics, including lift-off and flame length, were also studied. Additional tests have been conducted to generate a data base for flaring different gases and gas mixtures. Combustion and destruction efficiencies of 25 different gases and gas mixtures representing aliphatic, aromatic, chlorinated, oxygenated, sulfur-bearing, nitrogen bearing and low heating value compounds have been tested for comparative performance using a 0.042-inch nozzle. Pilot-scale flare performance of four gases, ammonia, 1,3-butadiene, ethylene oxide, and hydrogen sulfide, has been measured using an unassisted 3-inch open pipe flare.

Throughout the EER flare research program, advice and consultation has been provided by a Technical Advisory Committee. Serving on this committee are representatives from EER, EPA, California Air Resources Board, flare manufacturers (Peabody Engineering, McGill, Inc., John Zink, and Flaregas Corporation) and industrial flare users (Exxon Chemical Company, Exxon R&E, Union Carbide, Getty Refining and Marketing Co., Chevron USA, and Dow

Chemical Company). Among the industrial user representatives are members of the Chemical Manufacturers Association (CMA) and the American Petroleum Institute (API). This committee has provided a review and critique of test plans and results, has ensured relevance of the ongoing study to current regulatory and industrial concerns, and has facilitated efficient information transfer.

1.2 Objectives

Objectives for the research reported herein were:

1) Additional H_2S gas mixture testing to evaluate flame stability and combustion and destruction efficiencies.

2) More extensive pilot assisted flare testing to measure the effects of single and multiple pilots at high and low flowrates on flare performance.

1.3 Approach

Accurate measurement of flare emissions and combustion efficiency is difficult. Experimental difficulties encountered by previous researchers include:

- Inability to close mass balances due to large amounts of plume material lost.

- Inability to measure soot emissions, which may be significant in smoking flare situations.

- Sampling only on the plume centerline, not obtaining measurements representative of the entire plume.

- Flare flame fluctuations due to turbulence and/or wind, causing erroneous data by destabilizing or blowing out the flame, or consistently blowing the plume away from the sample probe.

The Flare Test Facility at EER has been designed and built in order to minimize such problems. The following procedures have been developed to verify the accuracy of combustion efficiency measurements (1.3):

- Material balance closure was verified using a hood to capture the entire flare plume for small flames, and by using SO_2 as a tracer for large flames.

- Soot concentration was measured for all tests.

- The average concentration of completely and incompletely burned combustion species from the flare flame was determined for the entire plume by (1) using a hood to completely capture small flames, and (2) simultaneous sampling using separate probes at five radial positions in the plume for large flames. These local measurements, combined with velocities calculated from jet theory, were integrated to calculate overall combustion efficiency.

- The effects of flare flame fluctuations were limited by using five radially located sample probes and by collecting time-integrated samples over a 20 minute time period. This time span was experimentally determined to be sufficient to time-average flame fluctuations.

Previous EER studies have established accurate flame combustion efficiency test methodology, developed a pilot-scale test facility, and established a data base of combustion efficiency test results for 0.042 through 12 inch diameter flare heads and nozzles burning a variety of gas mixtures. This work has provided the experience necessary to qualitatively estimate flare flame combustion and destruction efficiency and has provided

data for selection of scaling criteria to extrapolate the pilot-scale test results to full-scale operations.

This report is the fourth in a series describing the EPA/EER flare research program, and provides results from the following tasks:

- Task 1. Determine flame stability limits for gas mixtures of increasing H_2S concentration.

- Task 2. Develop an accurate technique for measuring H_2S concentrations in plume samples containing relatively high SO_2 levels.

- Task 3. Measure overall combustion efficiency and H_2S destruction efficiency measurements at and above the limit of flame stability as a function of gas mixture strengths and gas exit velocities.

- Task 4. Determine the flame stability limits for a flare assisted by single, double, and triple pilots at constant pilot gas flowrate, and by a single pilot at different pilot gas flowrates.

- Task 5. Measure overall combustion efficiency at and above the flame stability limits for the flare with each of the pilot assist conditions identified in Task 4.

- Task 6. Reduce, analyze, and report the data.

Open pipe flares were used for these tests, to eliminate any complicating effects from flame holding or stabilization devices and for comparison with the majority of previous EER data. Aerodynamic flame stabilization devices are commonly used industrially, and depending upon design, may be expected to affect the relationship between exit velocity, heat content, and flame stability. A nominal 3-inch (ID = 3.125 inches) head was be used for the H_2S gas mixture tests and for the tests with a single

pilot at a single pilot gas flowrate. For multiple pilot and pilot gas flowrate tests, a nominal 6-inch (ID = 6.065 inches) head was used.

Commercial gases are mixed at the Flare Test Facility prior to delivery to the flare. Holding tanks are available at the facility for commercial liquified propane and nitrogen. Liquified hydrogen sulfide and sulfur dioxide (used as a tracer) are provided in portable cylinders. Natural gas is provided by the local utility company. A flow regulating and measuring system is provided for each gas. The pure flare gas constituents are supplied to a header where they are mixed, and then delivered through a series of baffles for blending, before entering the flare head. Mixtures of various amounts of hydrogen sulfide, propane, and nitrogen were used for the H_2S gas mixture tests. Propane and nitrogen mixtures were used for the pilot assisted tests. Natural gas was used for the pilot flames.

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2.0 SUMMARY AND CONCLUSIONS

The test program "Evaluation of the Efficiency of Industrial Flares" has been funded by the U.S. EPA and conducted at the Energy and Environmental Research Corporation (EER) El Toro Test Site. This program has been conducted in phases. The first phase involved construction of a pilot-scale flare test facility. During the second phase, combustion efficiency tests were conducted on eight different commercial and EER prototype flare heads ranging in size between three and twelve inches in diameter. During the third phase, effects of flare head design and gas composition on flare combustion and destruction efficiencies were studied. Commercial coanda steam assisted heads, pressure heads, and an air-assisted flare head were tested. Also, different gas mixtures containing ammonia, 1,3-butadiene, ethylene oxide, and hydrogen sulfide were tested.

Throughout this test program a Technical Advisory Committee has provided consultation. Committee members included representatives from EER, EPA, California Air Resources Board, flare manufacturers, and industrial flare users. Each phase of this test program has been designed to provide test data relevant to current regulatory and industrial concerns as defined by this committee.

2.1 Summary

This phase of the work had two objectives:

- Evaluation of H_2S destruction efficiency for H_2S-containing flare gases

- Evaluation of the effects of pilot assist on flare combustion efficiency

In order to determine the limits of stable flare operation for these gas mixtures and pilot assisted flares, and key operating conditions that affect flame stability and efficiency, some conditions with poor stability and low

combustion efficiencies were measured. Such results merely indicated flare operating performance at or beyond the edge of the operating envelope, and are not indicative of normal commercial flare operation.

2.1.1 Destruction Efficiency of H_2S

Before H_2S destruction efficiency could be evaluated, it was necessary to develop techniques to accurately and reliably measure H_2S at plume concentration levels of 0-1000 ppm, without interference from SO_2, present in levels between 0-10,000 ppm. Methods successfully adapted for this measurement were the methylene blue method and Draeger tubes. For higher H_2S gas concentrations (25 ppm or greater), gas chromatography was also used.

Tests were conducted with H_2S gas mixtures on the Flare Screening Facility (FSF) shown in Figure 2-1. These tests verified the applicability of H_2S and SO_2 measurement methods and safely and inexpensively determined H_2S destruction efficiency for H_2S gas mixtures flared from a nozzle 0.042 inches in diameter. Results of these tests are shown in Table 2-1. Very high H_2S destruction efficiency (99.7 to >99.99 percent) and propane combustion efficiency (98.6 to 99.99 percent) were measured for tests conducted with gas heating values at and above the flame stability limits as shown in Figure 2-2. This stability limit curve defines the minimum heating value for a given gas exit velocity which will maintain a flame. At heating values below this limit, flame blowout may occur.

Destruction efficiency tests of H_2S were also conducted using a 3-inch diameter open pipe flare at the Flare Test Facility (FTF) shown in Figure 2-3. These tests aerodynamically approximate full-scale industrial operations while those of the laboratory-scale Flare Screening Facility tests do not. Test results are tabulated in Table 2-2. Flame stability limit curves for these tests are shown in Figure 2-4, where gas heating value on a volumetric basis is related to gas exit velocity. Gas heating value on a mass basis may also be correlated to gas exit velocity, but is less effective in correlating flame stability for different gas mixtures. There is good agreement in Figure 2-4 between the current 1985, ~5 percent H_2S gas mixture

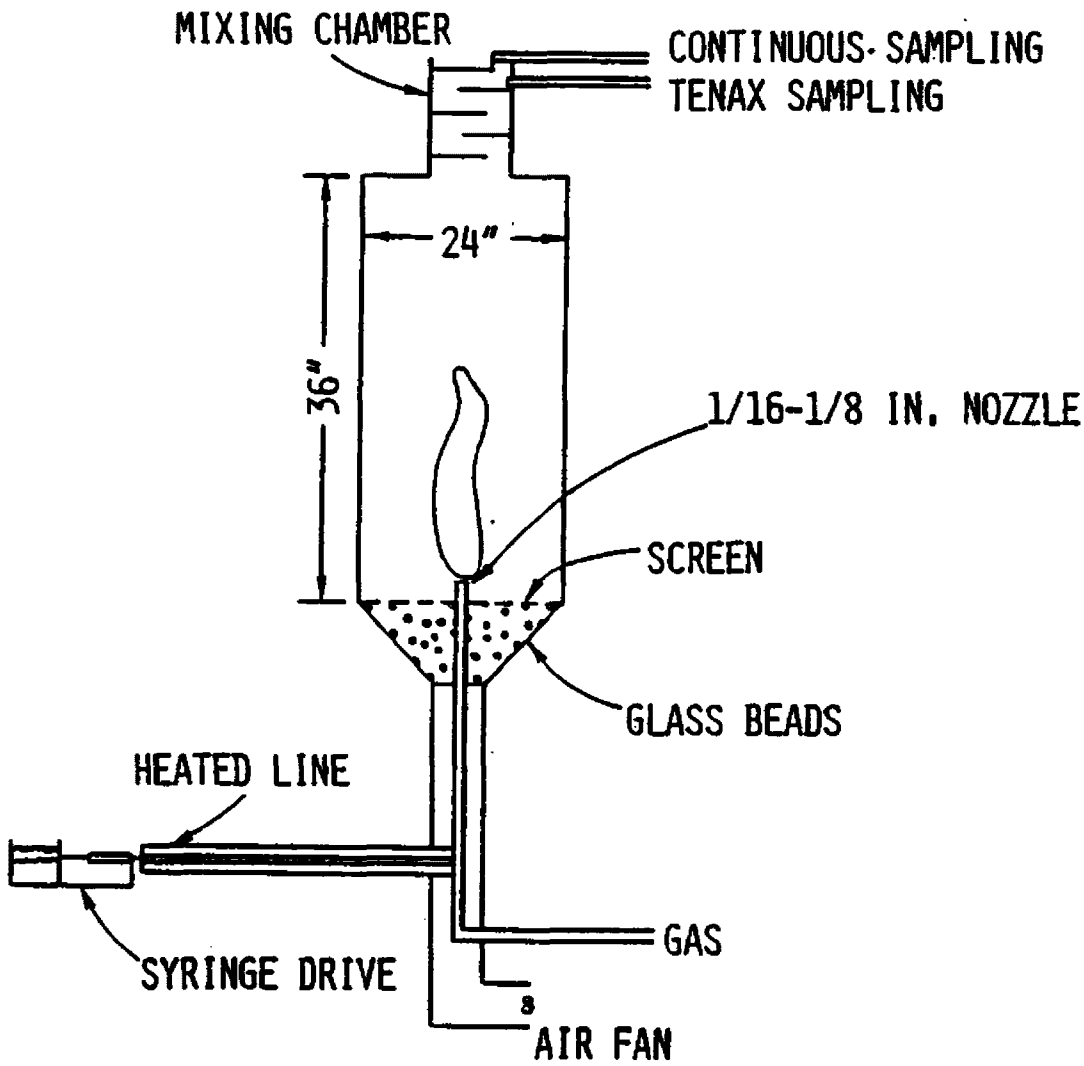


Figure 2-1. Flare Screening Facility (FSF).

TABLE 2-1. FLARE SCREENING FACILITY H_2S GAS MIXTURE TEST RESULTS, NOZZLE ID = 0.042 INCHES

Test No.	Gas Composition (Remainder N_2)		Gas Heating Value (Btu/scf)	Nozzle Exit Velocity (f/s)	Air Stoichiometric Ratio	H_2S Destruction Efficiency (%)	Propane Combustion Efficiency (%)	Mass Balance Closure Mass In/Mass Out		
	H_2S (%)	Propane (%)						C	O	S
1	4.31	45.2	1086	27.5	3.15	>99.99	99.9	0.567	0.944	0.446
2	34.8	52.0	1427	17.4	2.90	>99.99	99.99	0.706	0.939	1.12
3	31.9	55.0	1480	16.5	2.90	>99.99	99.9	0.878	0.852	0.794
4	4.28	45.5	1093	27.0	3.17	>99.7	99.9	0.952	0.918	0.715
5	69.5	30.5	1125	8.52	4.02	>99.99	98.6	0.729	0.891	0.774

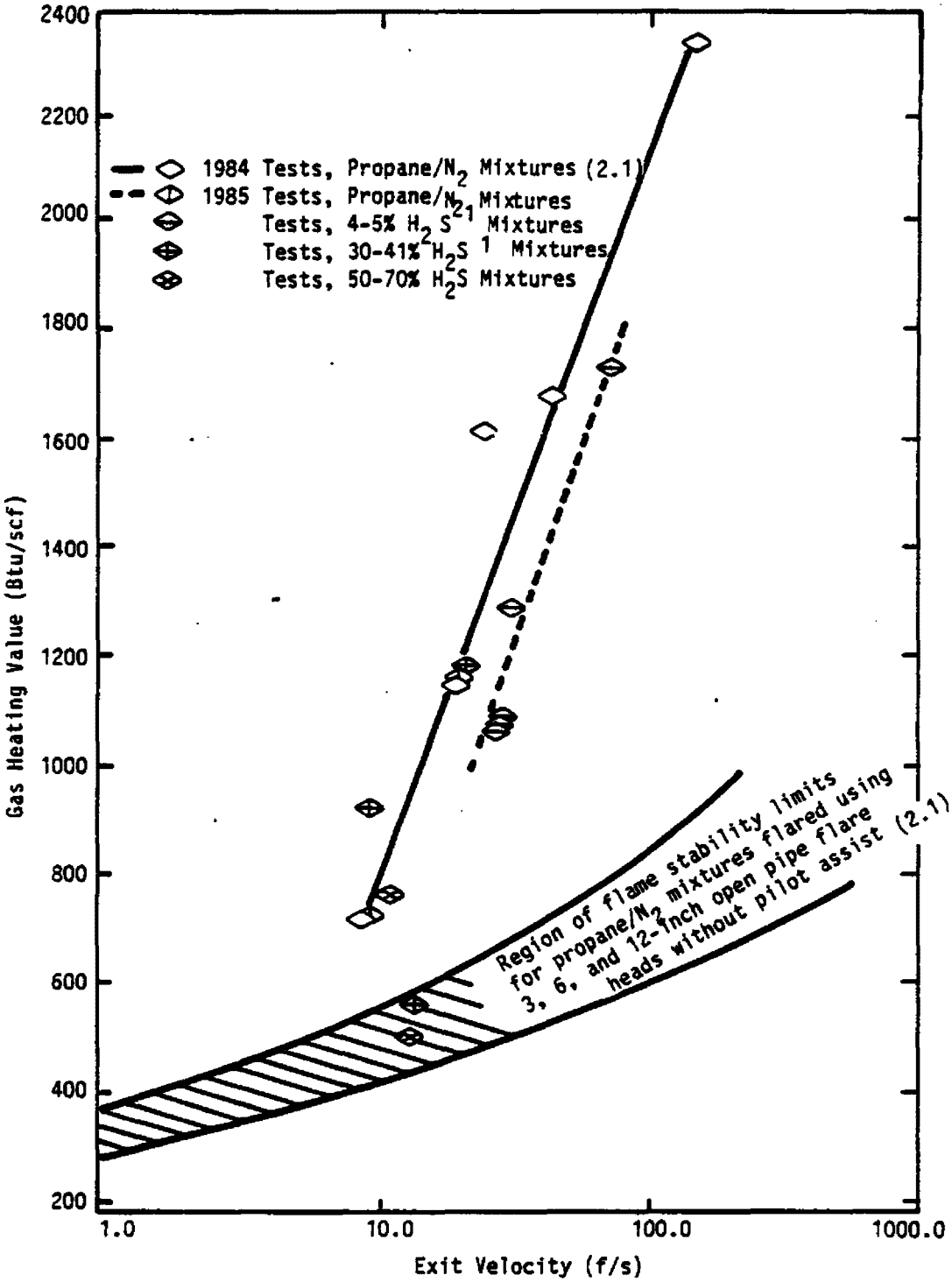


Figure 2-2. Flame stability curves for propane/N_2 and H_2S/propane/N_2 gas mixtures flared using a 0.042 inch ID nozzle.

1. Remainder is propane and N_2

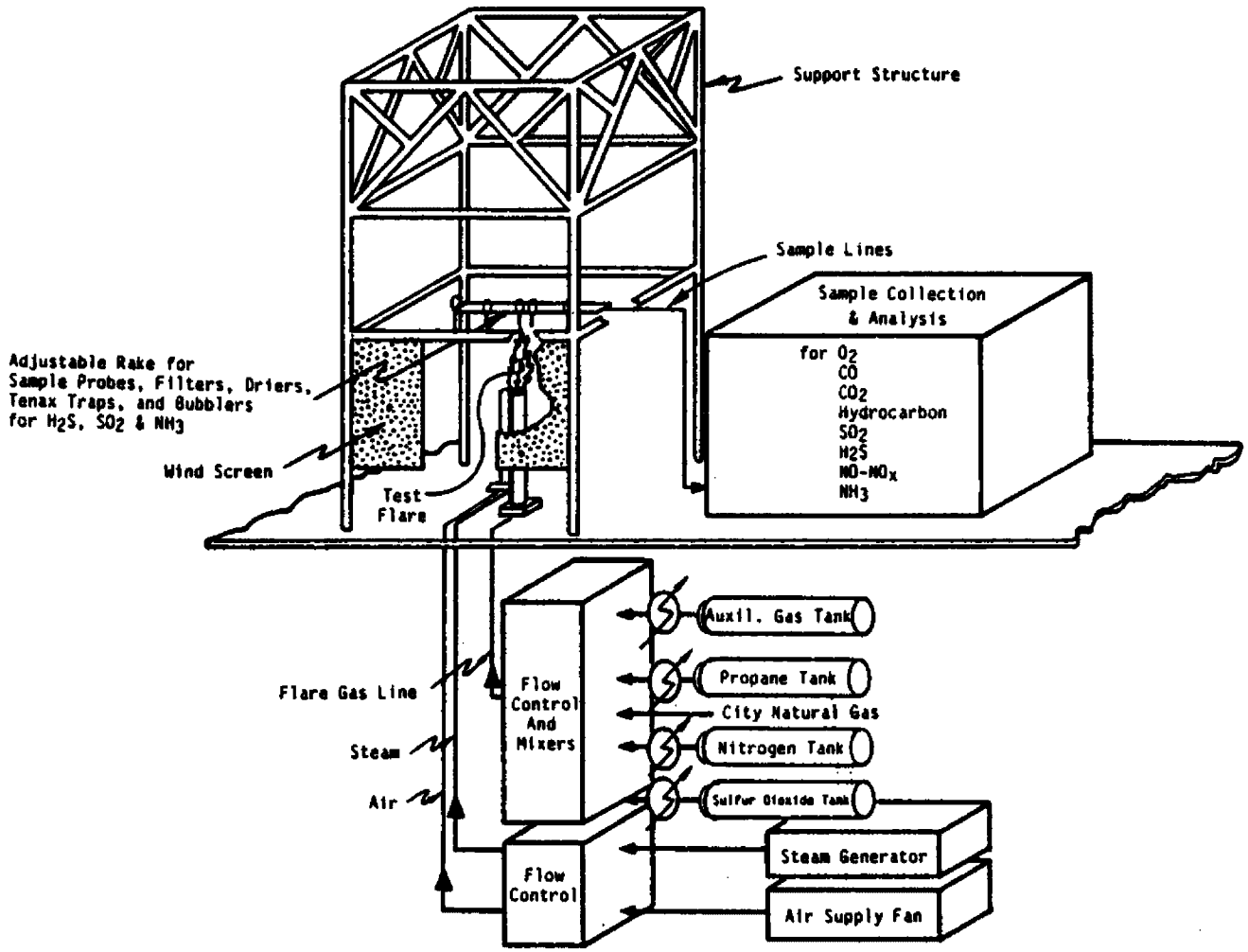


Figure 2-3. EPA Flare Test Facility (FTF) at EER.

TABLE 2-2. H_2S GAS MIXTURE COMBUSTION AND DESTRUCTION EFFICIENCY TEST RESULTS[1]

TEST NO.	EXIT VELOCITY (f/s)	GAS COMPOSITION[2] (%)		GAS HEATING VALUE (Btu/scf)	PROBE HEIGHT[3] (f)	OBSERVATIONS						HYDROCARBON DESTRUCTION EFFICIENCY (%)	H_2S DESTRUCTION EFFICIENCY (%)
		PROPANE	H_2S			WIND SPEED (mph)	FLAME LENGTH (f)	LIFT OFF (in)	COLOR	SMOKE	SOUND		
296	9.15	15.1	3.69	377	11	5	9	3	LIGHT ORANGE	NONE	NONE	94.1	96.2
297	8.88	20.1	5.11	502	12	4	19	2-5	YELLOW ORANGE	SLIGHT	NONE	99.4	99.8
298	0.48	14.4	4.83	366	3	4	1.5	0.5	DIM YELLOW	NONE	NONE	97.9	99.2
299	0.54	4.31	69.5	510	4	4	2.5	0-2	LIGHT PURPLE		NONE	99.7	100
300	32.5	0	42.0	247	15	4	10	6-24	LIGHT PURPLE	PROFUSE GREY BLUE	HISS	NA[4]	98.3
301	9.46	0	49.5	291	8	4	5	0	BLUE YELLOW	GREY BLUE	NONE	NA	99.9
302	9.19	0	56.4	331	8	4	7	0	PURPLE YELLOW GREEN	GREY BLUE	NONE	NA	98.1
303	0.99	0	28.9	170	3	3	1	0	INVISIBLE	GREY BLUE	NONE	NA	99.9

1. 3-INCH PIPE FLARE, NO PILOT
2. REMAINDER IS NITROGEN
3. HEIGHT ABOVE FLARE TIP
4. NOT APPLICABLE

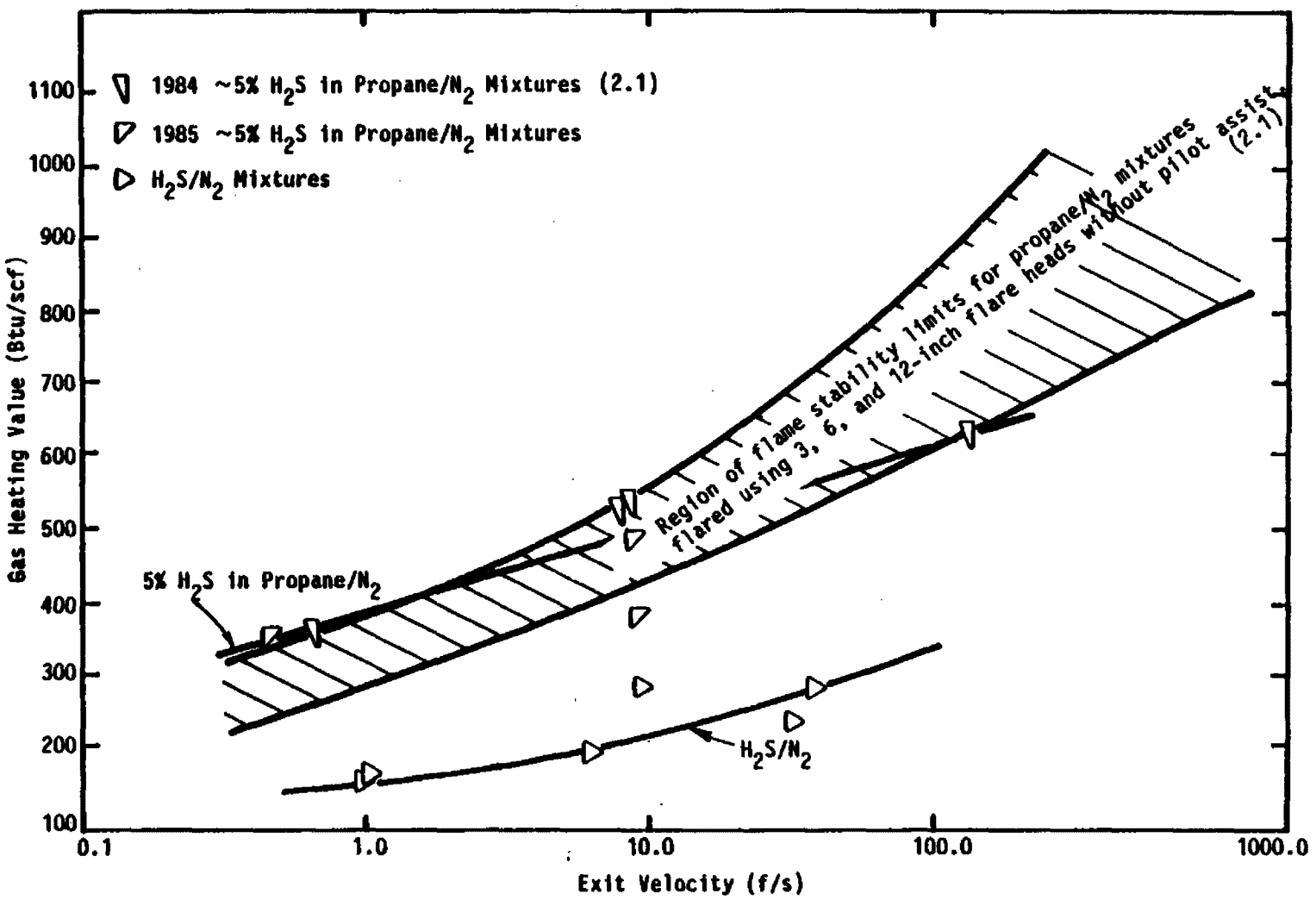


Figure 2-4. Flame stability curves for H_2S gas mixtures flared using a 3-inch diameter open pipe flare.

tests and the 1984, ~5 percent gas mixture tests. The stability limit curve for the H_2S/N_2 gas mixture tests is much lower than that for the tests for the ~5 percent H_2S in propane/N_2 mixture. This shows that gas heating value is not the only contributing factor to flame stability. Other factors may be (1) higher volumetric H_2S concentration in an H_2S/N_2 mixture than propane in a propane/N_2 mixture of equivalent heating value, (2) wider flammable range in air for H_2S than for propane, (3) lower adiabatic flame temperature of H_2S burned in a stoichiometric air mixture, and (4) lower ignition temperature of H_2S. The combination of these factors apparently enhances flame stability of H_2S gas mixtures.

Propane combustion efficiency and H_2S destruction efficiency were correlated to flame stability as shown in Figures 2-5 and 2-6. Destruction efficiencies greater than 98 percent were attained when the gas heating value was at least 1.2 times the minimum gas heating value required for stability. Both propane combustion efficiency and H_2S destruction efficiency can rapidly decrease below 98 percent when the gas heating value ratio decreases below 1.2.

Destruction efficiency of H_2S is compared to propane destruction efficiency in Figure 2-7 for tests of gas mixtures containing both H_2S and propane. H_2S destruction efficiency was consistently higher than propane combustion efficiency.

2.1.2 Influence of Pilot Flares

Tests were also conducted using a pilot assisted 3-inch open pipe flare at the Flare Test Facility. These tests were conducted to measure the effects of pilot assist on combustion efficiency. The flare gas for these tests was propane diluted with nitrogen to reduce the heating value. The pilot gas was utility-supplied natural gas. Test results are shown in Table 2-3. Parameters tested were (1) flare size (3-inch and 6-inch), (2) pilot number from one to three, and (3) pilot gas flowrate, from one to five scfm. For these tests, the flare gas heating value includes the contribution of the pilot gas.

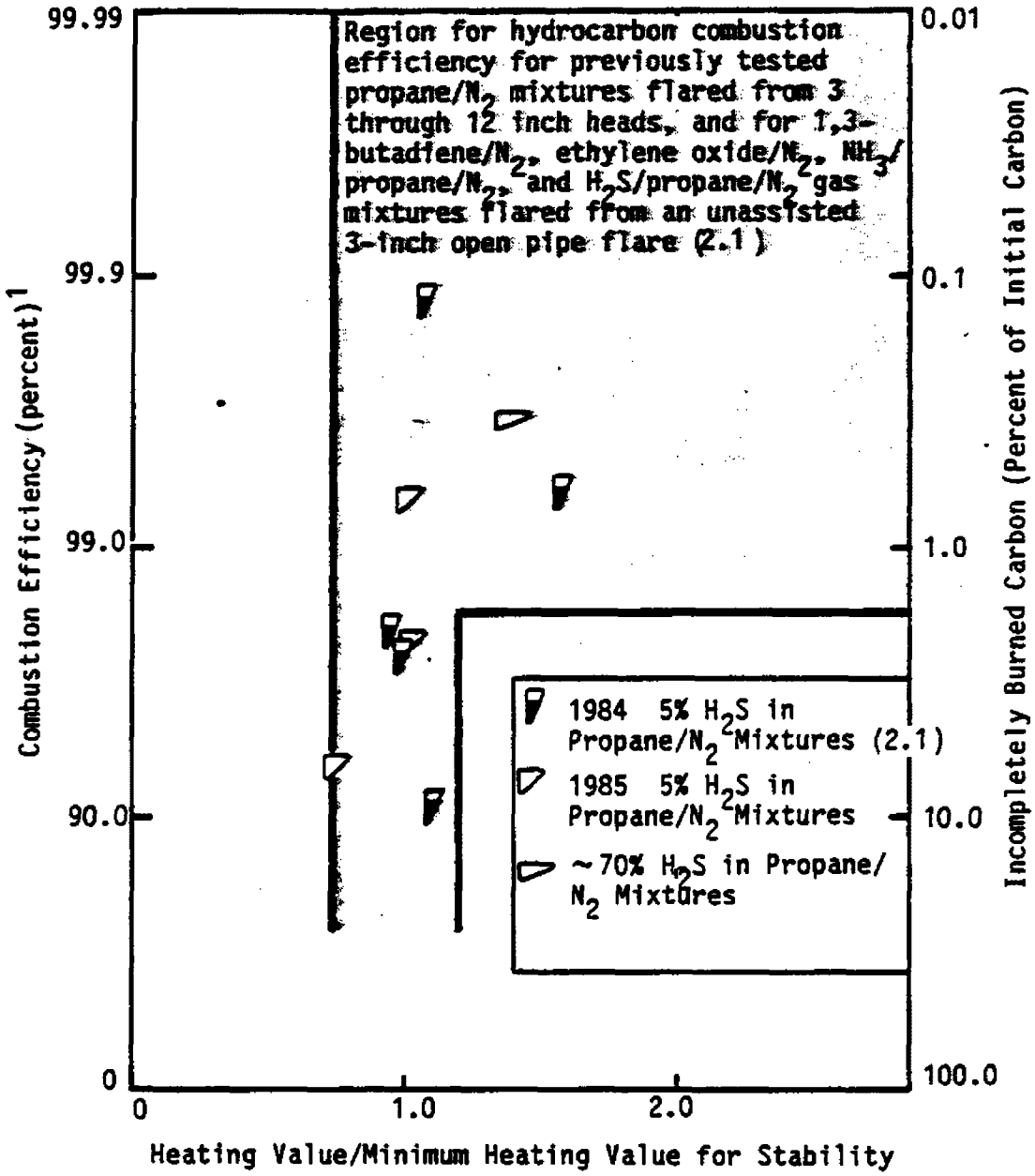


Figure 2-5. Propane combustion efficiency of H_2S/propane/N_2 gas mixtures flared from an unassisted 3-inch open pipe flare.

1. Scale is log (100 - Combustion Efficiency)

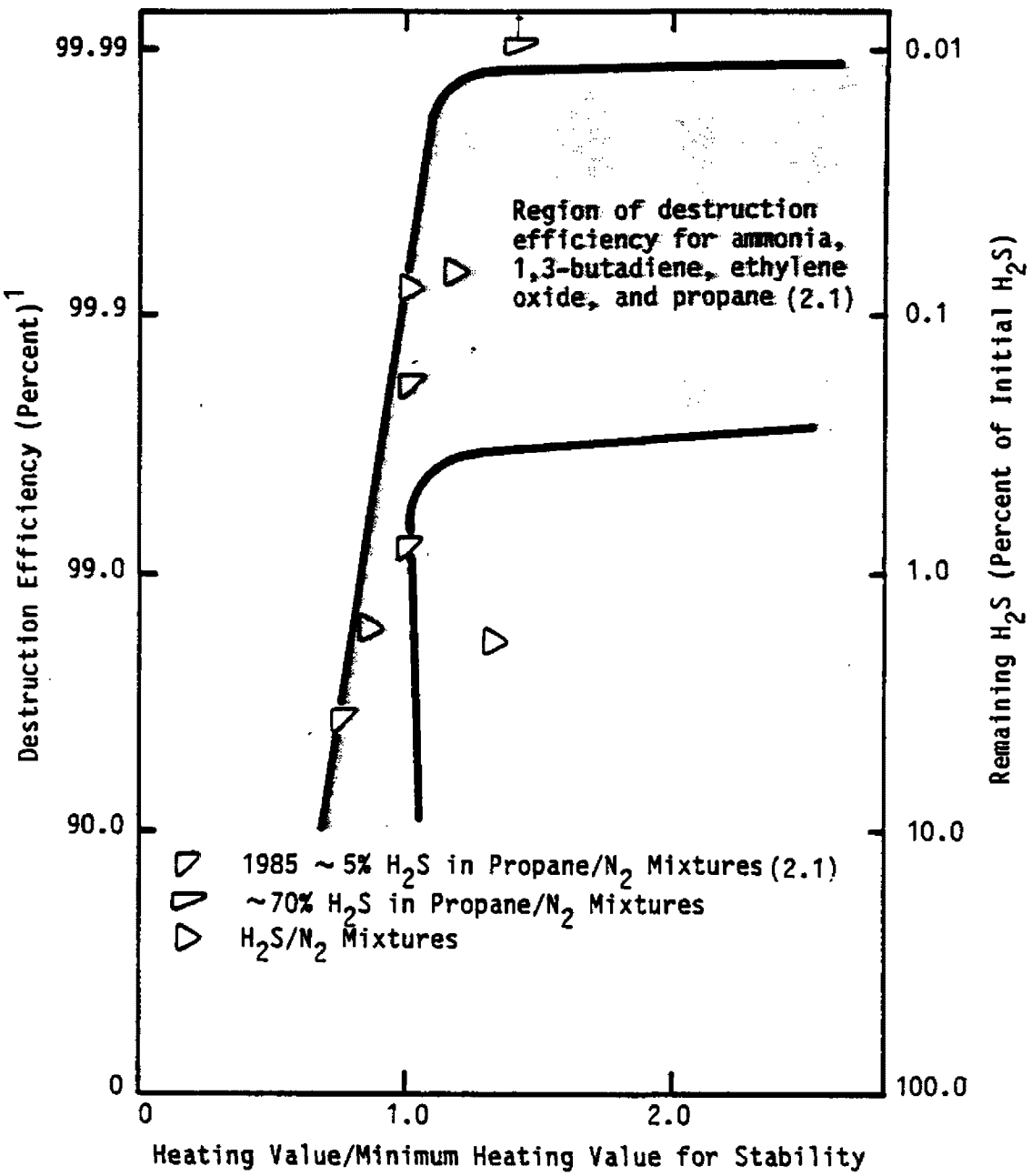


Figure 2-6. Destruction efficiency of H_2S gas mixtures flared from an unassisted 3-inch open pipe flare.

1. Scale is log (100- Destruction Efficiency)

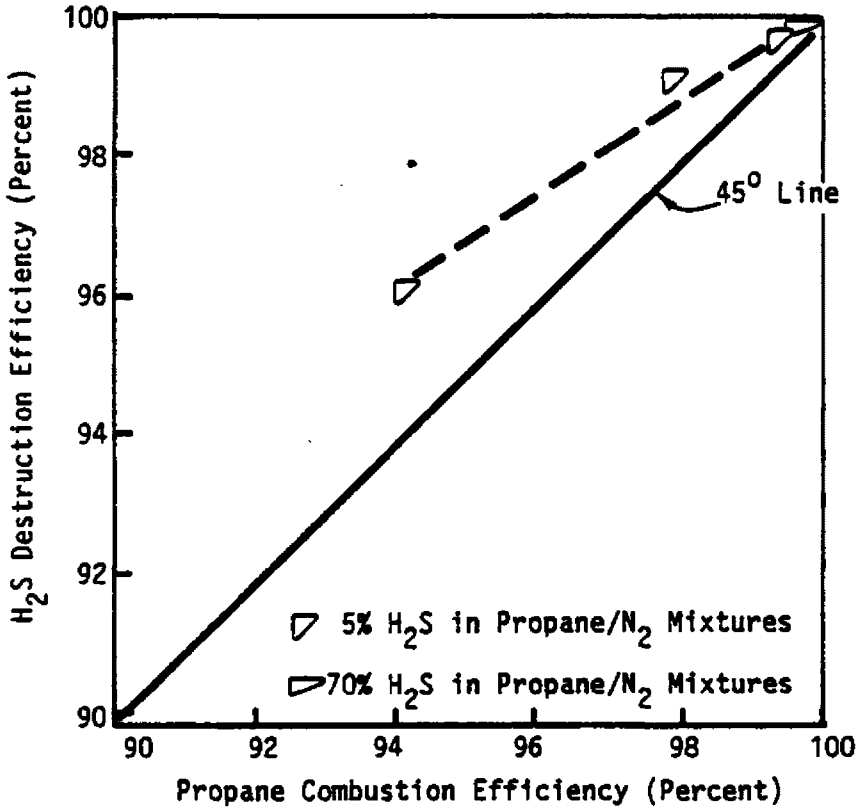


Figure 2-7. Correlation between H_2S destruction efficiency and propane combustion efficiency for H_2S/propane/N_2 mixtures flared from an unassisted 3-inch open pipe flare.

TABLE 2-3. PILOT ASSISTED HEAD TEST RESULTS
(PAGE 1 OF 3)

TEST NO.	FLARE SIZE (in)	NUMBER OF PILOTS	PILOT GAS FLOWRATE (scfm)	FLARE GAS EXIT VELOCITY (f/s)	% PROPANE[1]	GAS HEATING VALUE[2] (Btu/scf)	PROBE HEIGHT[3] (f)	OBSERVATIONS						COMBUSTION EFFICIENCY (%)
								WIND SPEED (mph)	FLAME LENGTH[4] (f)	LIFT OFF (in)	COLOR	SMOKE	SOUND	
304	3.125	1	2.1	19.5	11.0	283					ORANGE FLICKERS			
305	3.125	1	2.1	78.5	15.8	377					ORANGE FLICKERS			
306	3.125	1	2.1	136.	8.60	206					TRANSPARENT			
307	3.125	1	2.1	34.2	13.4	326		STABILITY TESTS			ORANGE FLICKERS			
308	3.125	1	2.1	33.0	10.3	257					ORANGE FLICKERS			
309	3.125	1	2.1	17.2	10.5	275					ORANGE FLICKERS			
310	3.125	1	2.1	18.5	9.53	251					ORANGE FLICKERS			
311	3.125	1	2.1	61.8	6.93	174	15	4	38[5]	3	TRANSPARENT	NONE	LOW ROAR	99.2
312	3.125	1	8.1[6]	63.9	4.77	146	15	6	38[5]	1	TRANSPARENT	NONE	HISS	75.0
313	3.125	1	2.2	130.	8.88	211	25	4	40[5]	0	TRANSPARENT	NONE	ROAR	99.3
314	3.125	1	2.2	121.	8.47	204					TRANSPARENT			
315	3.125	1	2.1	142.	6.99	168					TRANSPARENT			
316	3.125	1	2.1	148.	6.56	158					TRANSPARENT			
317	3.125	1	2.1	33.0	9.08	229					ORANGE FLICKERS			
318	3.125	1	2.1	45.3	6.61	168					TRANSPARENT			
319	3.125	1	2.1	58.9	5.10	130					TRANSPARENT			
320	3.125	1	2.1	77.0	3.89	99		STABILITY TESTS			TRANSPARENT			
321	6.065	1	2.1	19.7	9.25	224					ORANGE FLICKERS			
322	6.065	1	2.1	19.4	7.72	189					ORANGE FLICKERS			
323	6.065	1	2.1	19.1	7.16	176					TRACE ORANGE			
324	6.065	1	2.1	5.61	10.24	264					ORANGE FLICKERS			
325	6.065	1	2.1	6.73	8.44	219					FAINT ORANGE			
326	6.065	1	2.1	7.33	7.76	203					TRANSPARENT			

TABLE 2-3. PILOT ASSISTED HEAD TEST RESULTS
(PAGE 2 OF 3)

TEST NO.	FLARE SIZE (in)	NUMBER OF PILOTS	PILOT GAS FLOWRATE (scfm)	FLARE GAS EXIT VELOCITY (f/s)	% PROPANE[1]	GAS HEATING VALUE[2] (Btu/scf)	PROBE HEIGHT[3] (f)	OBSERVATIONS						COMBUSTION EFFICIENCY (%)
								WIND SPEED (mph)	FLAME LENGTH[4] (f)	LIFT OFF (in)	COLOR	SMOKE	SOUND	
327	6.065	1	2.2	19.6	7.01	172	28	3	15	15	ORANGE FLICKERS	NONE	RUMBLE/HISS	99.3
328	6.065	1	2.4	44.7	5.67	137					TRANSPARENT			
329	6.065	1	2.1	34.8	6.49	157	18	3	17	2	TRANSPARENT	NONE	ROAR	98.2
330	6.065	1	2.1	11.8	4.22	112	7	4	5	12	TRANSPARENT	NONE	RUMBLE/HISS	81.3
331	6.065	1	1.1	36.3	6.97	166					TRACE ORANGE			
332	6.065	1	1.1	39.1	7.96	189					ORANGE FLICKERS			
333	6.065	1	1.1	36.9	5.12	123					TRANSPARENT			
334	6.065	1	1.1	36.7	4.58	110					TRANSPARENT			
335	6.065	1	5.3	36.7	4.58	118					FAINT ORANGE			
336	6.065	1	5.4	36.9	5.23	133					ORANGE FLICKERS			
337	6.065	1	5.3	36.3	3.28	88.3					TRANSPARENT			
338	6.065	1	5.3	36.5	3.67	97.1					TRANSPARENT			
339	6.065	1	1.1	10.3	6.28	155		STABILITY TESTS			TRANSPARENT			
340	6.065	1	1.1	10.1	4.52	114					TRANSPARENT			
341	6.065	1	1.1	10.1	3.72	95.8					TRANSPARENT			
342	6.065	1	1.1	10.5	7.57	185					ORANGE FLICKERS			
343	6.065	1	1.1	10.5	5.66	141					TRANSPARENT			
344	6.065	1	1.1	14.0	4.22	105					TRANSPARENT			
345	6.065	1	1.1	13.9	3.19	40.8					TRANSPARENT			
346	6.065	1	1.1	9.63	6.16	153					TRANSPARENT			
347	6.065	1	5.1	33.1	1.21	40.8					TRANSPARENT			
348	6.065	1	3.9	34.8	1.72	48.9					TRANSPARENT			

TABLE 2-3. PILOT ASSISTED HEAD TEST RESULTS
(PAGE 3 OF 3)

TEST NO.	FLARE SIZE (in)	NUMBER OF PILOTS	PILOT GAS FLOWRATE (scfm)	FLARE GAS EXIT VELOCITY (f/s)	% PROPANE[1]	GAS HEATING VALUE[2] (Btu/scf)	PROBE HEIGHT[3] (f)	OBSERVATIONS						COMBUSTION EFFICIENCY (%)
								WIND SPEED (mph)	FLAME LENGTH[4] (f)	LIFT OFF (f)	COLOR	SMOKE	SOUND	
349	6.065	1	4.1	20.4	3.63	100	9	3	4	18	TRANSPARENT	NONE	ROAR	92.0
350	6.065	1	1.0	20.4	5.15	125	13	3	4	18	TRANSPARENT	NONE	LOW RUMBLE	94.3
351	6.065	1	1.1	20.5	6.96	167	17	3	17	12	ORANGE FLICKERS	NONE	RUMBLE	98.5
352	6.065	1	4.0	20.1	5.21	138	14	4	14	1	TRANSPARENT	NONE	RUMBLE	97.2
353	6.065	2	2.0	20.2	2.44	65.1					TRANSPARENT			
354	6.065	2	2.0	10.2	4.91	130					TRANSPARENT			
355	6.065	2	2.0	28.3	6.81	165					TRANSPARENT			
356	6.065	2	2.0	35.0	4.98	121		STABILITY TESTS			TRANSPARENT			
357	6.065	2	2.0	39.4	6.84	164					TRANSPARENT			
358	6.065	2	2.1	47.6	5.31	128					TRANSPARENT			
359	6.065	2	2.3	20.1	5.22	131	15	3	13	0	TRANSPARENT	NONE	LOW ROAR	95.7
360	6.065	3	2.0	13.3	6.34	160					FAINT ORANGE			
361	6.065	3	2.0	12.9	2.85	79					TRANSPARENT			
362	6.065	3	2.1	30.3	6.39	155		STABILITY TESTS			TRANSPARENT			
363	6,065	3	2.0	34.9	3.88	95					TRANSPARENT			
364	6.065	3	2.0	48.3	6.07	146					TRANSPARENT			
365	6.065	3	2.0	49.6	4.81	116					TRANSPARENT			
366	6.065	3	2.2	20.2	5.21	130	15	3	13	12	TRANSPARENT	NONE	LOW ROAR	96.6

1. REMAINDER OF FLARE GAS IS N_2 AND SO_2 (TRACER)
2. INCLUDING THE HEATING VALUE CONTRIBUTION OF THE PILOT GAS
3. ABOVE FLARE TIP
4. FLAME LENGTH DETERMINED BY LENGTH OF VISIBLE FLAME COLORING AND TRANSPARENT HEAT WAVES (LIGHT DIFFRACTION)
5. INCLUDES HEAT WAVES ABOVE FLAME ENVELOPE
6. USED WRONG ORIFICE METER

The flame stability limit for the pilot assisted tests was difficult to determine, because the presence of a pilot effectively prevented flame blowout, even at very low flare gas heating values. Consequently, the definition and determination of the flame stability limit became more subjective. The gas heating value required for 98 percent combustion efficiency at a given flare gas exit velocity was found to be the operating point where the last faint flickers of orange color disappeared and the flame envelope became transparent. Such flare flames usually had blue-orange cones near the pilot and flare tips. In order to maintain consistency with previous results reported under this program, this operating point was defined as the "stability limit". This stability limit is specific to these tests burning propane/nitrogen mixtures.

Stability curves for the pilot assisted flares are shown in Figures 2-8 through 2-12. Use of pilot assist greatly enhances flame stability. For 3 and 6-inch unassisted open pipe flares, operated with a propane-nitrogen gas exit velocity of 40 f/s, the minimum gas heating value to maintain a flame is about 540 Btu/scf. If a 2 scfm natural gas pilot is used, the total heating value (including pilot contribution) can be reduced to 150 Btu/scf, when the flame envelope becomes transparent and, by definition, the stability limit is reached. For the 6-inch flare, the same heating value reduction can be attained with the pilot at only 1 scfm. Additional pilot assist, however, only marginally increases flame stability. Increasing the pilot gas to 5 scfm only reduces the heating value to 120 Btu/scf for the 6-inch flare. Increasing the number of pilots to two or three while keeping the total pilot gas rate constant at 2 scfm decreases the limiting heating value to 130 Btu/scf for a 6-inch pipe flare.

The quantitative results of these stability tests are limited to open pipe flares in the 3 - 6 inch diameter size range. By scaling the relative number of pilots, the pilot and flare gas flowrates and velocities, Richardson numbers, and Reynolds numbers, these results could also be applied to 12-inch or larger open pipe flares (4.1). The results of improved stability with pilot-assisted flares can be only qualitatively applied to flares that also have aerodynamic or other stability enhancing devices.

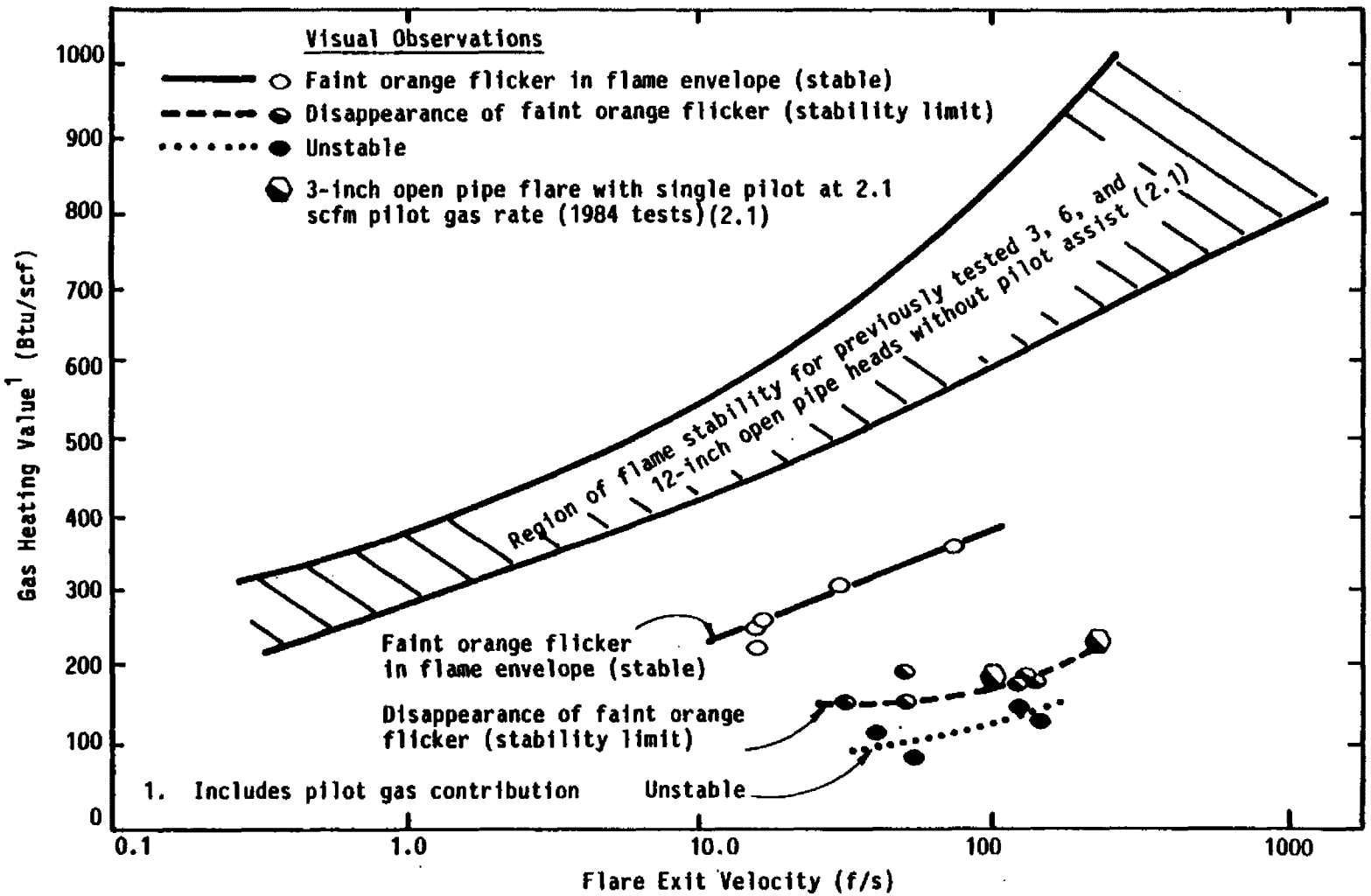


Figure 2-8. Flame stability curve for 3-inch pipe flare with a single pilot at a pilot gas flowrate of 2.1 - 2.2 scfm natural gas.

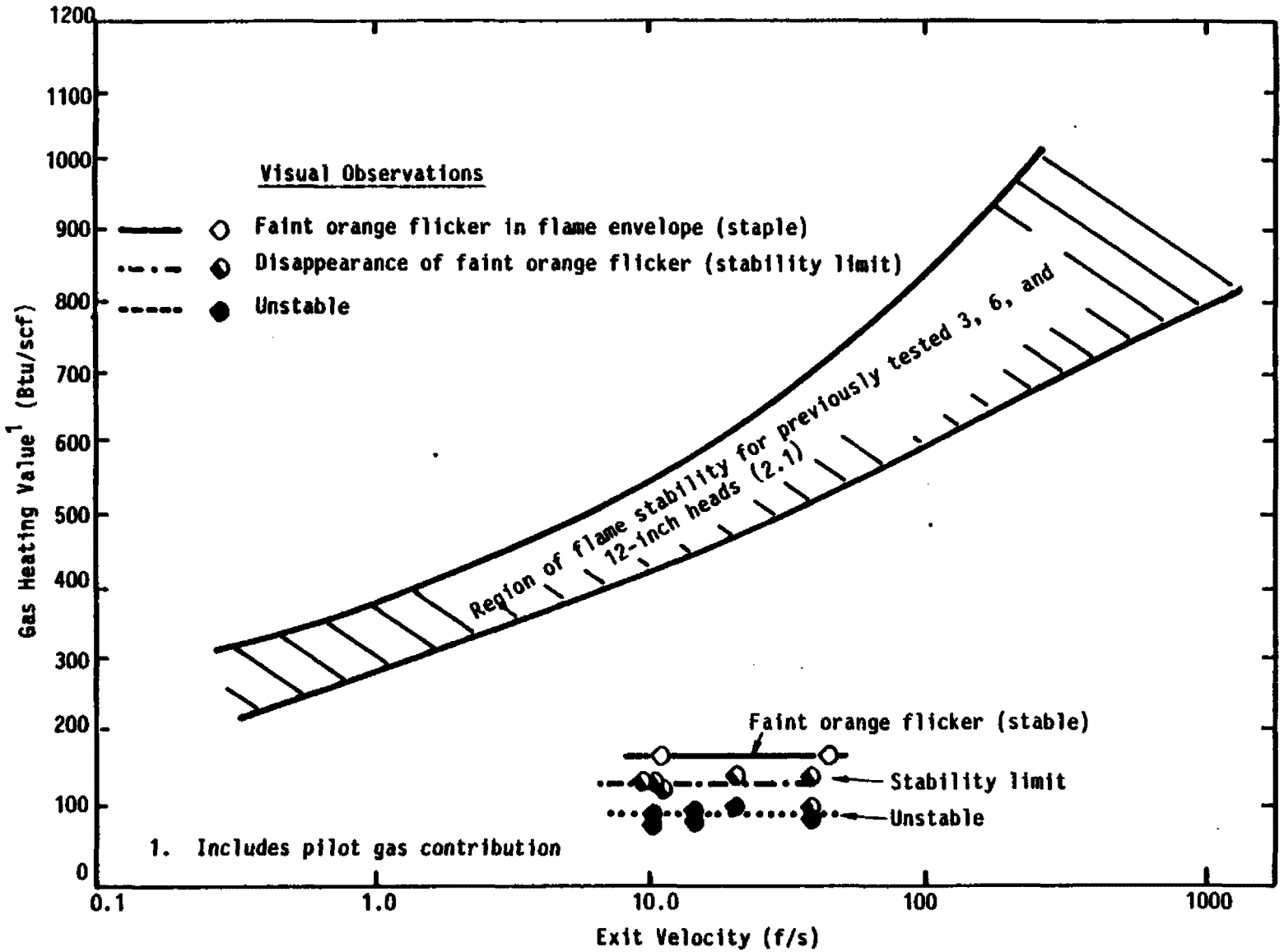


Figure 2-9. Flame stability curves for 6-inch open pipe flare with a single pilot at a pilot gas flowrate of 1.0 - 1.1 scfm natural gas.

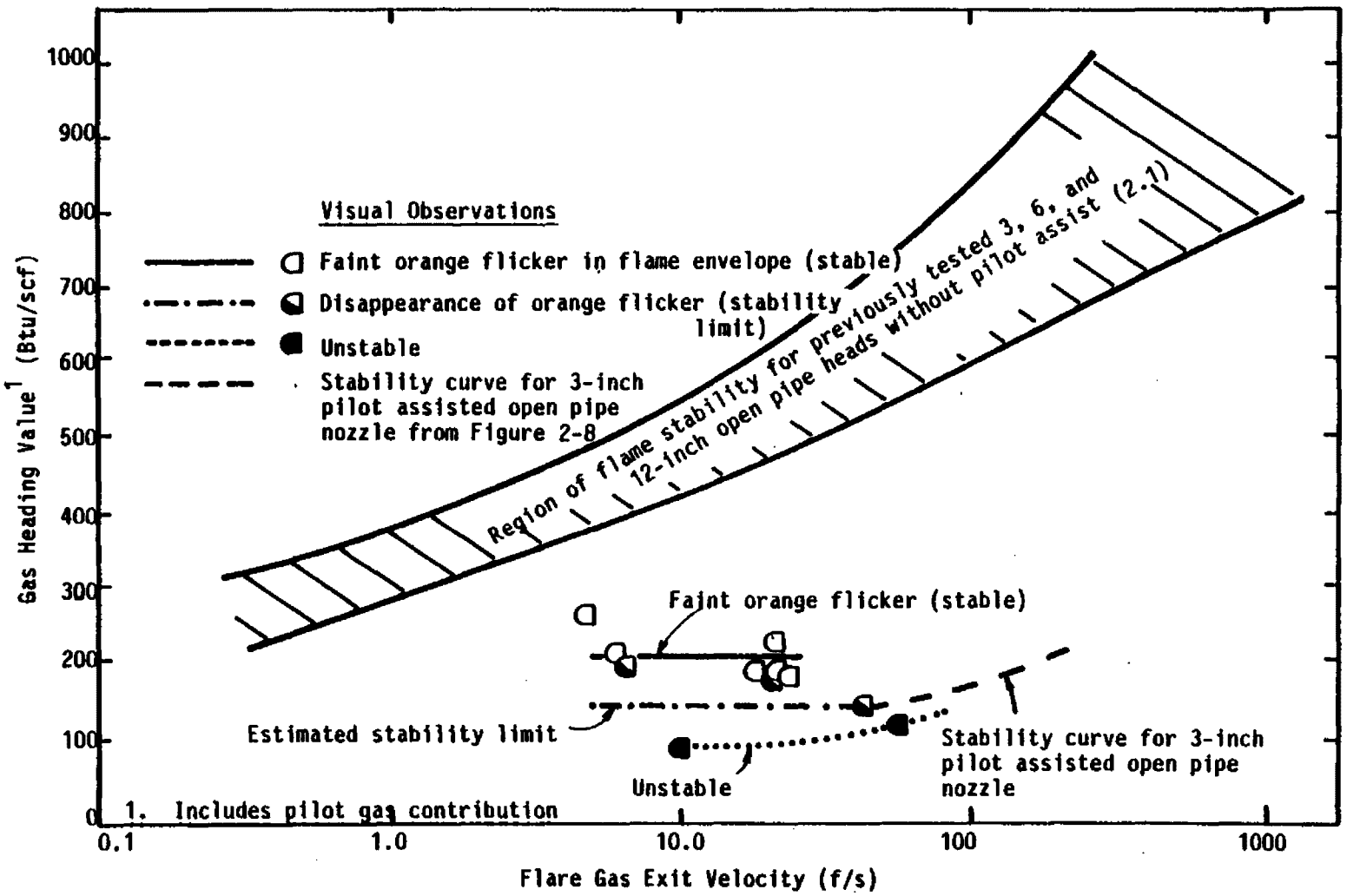


Figure 2-10. Flame stability curves for 6-inch open pipe flare with a single pilot at a pilot gas flowrate of 2.1 - 2.4 scfm natural gas.

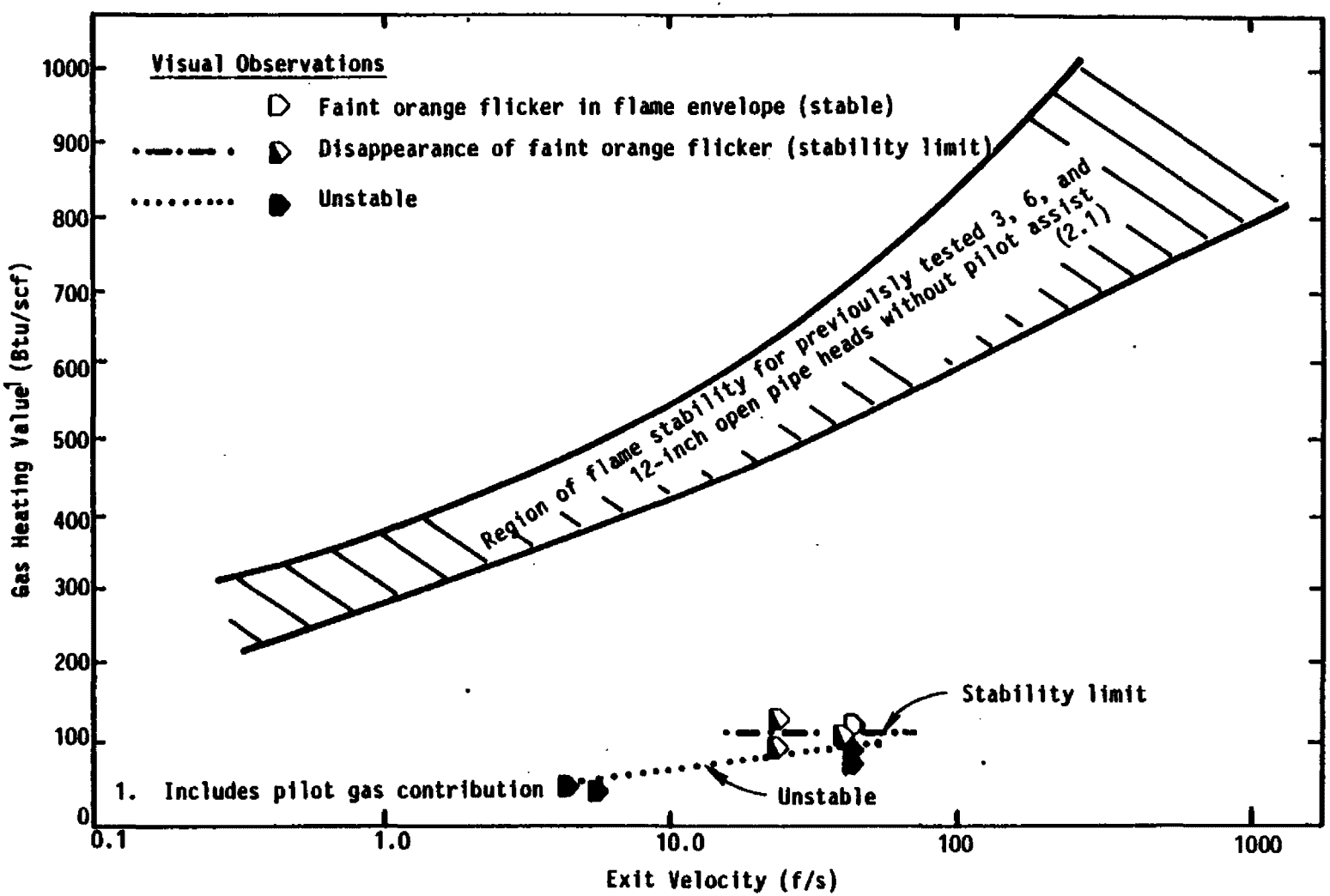


Figure 2-11. Flame stability curves for 6-inch open pipe flare with a single pilot at a pilot gas flowrate of 3.9 - 5.4 scfm natural gas.

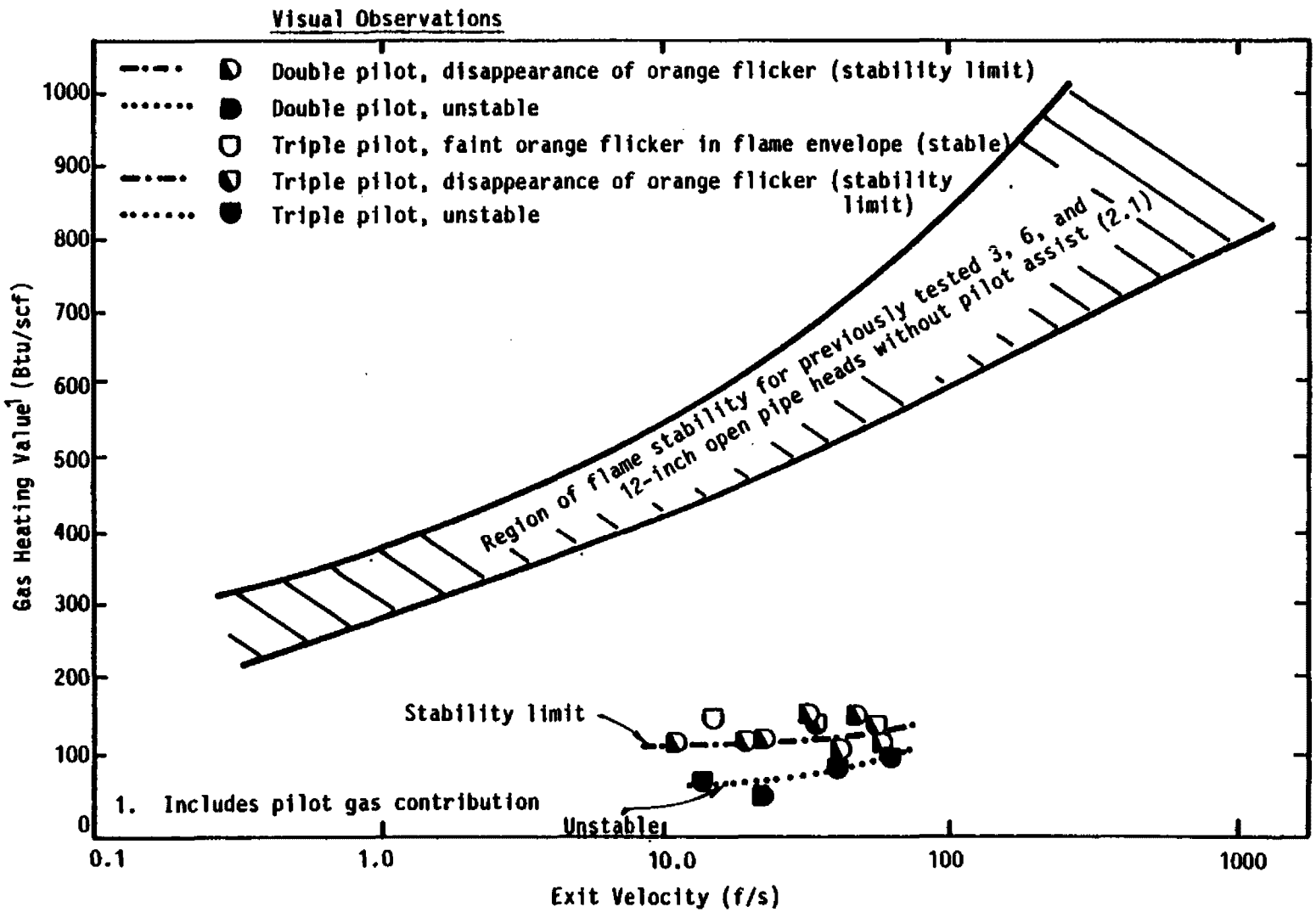


Figure 2-12. Flame stability curve for 6-inch open pipe flare with multiple pilots at a total pilot gas flowrate of 2.0 - 2.3 scfm natural gas.

Adiabatic flame temperature can be used as an indicator of flame stability for specific gases. The flame stability limit is approached when the flame speed approaches the relief gas velocity. Flame speed depends on mixing and flame reaction rates. Flame reaction rates are functions of flame temperature, frequency factors, and activation energies for flame reactions. Figure 2-13 shows that the limiting stable gas exit velocity can be correlated with an estimated adiabatic flame temperature of the gas mixture burned in a stoichiometric air mixture. However, the curves for different gas mixtures and for the pilot assisted flares are different. This indicates that differences in activation energies, frequency factors, mixture strengths, and mixing rates for different compounds may affect flame stability differently for different flare gas mixtures and pilot assisted flares.

Combustion efficiency for the pilot assisted flares is correlated to flame stability in Figure 2-14. Combustion efficiency is greater than 98 percent for heating value stability ratios greater than about 1.2. Combustion efficiency can rapidly decrease when the heating value ratio decreases below about 1.2.

There are some subtle differences in combustion efficiency performance of the pilot assisted flames:

- Combustion efficiency greater than 98 percent is maintained for the 3-inch head down to a heating value stability ratio of 1.0. This could be because the impact of the pilot on the flame for the 3-inch flare is greater than on the flame from the 6-inch flare. Also, tests for the 3-inch head were conducted at slightly higher gas heating values than for the 6-inch head, because the stability limit curve for the 3-inch head requires higher heating value than the curves for the 6-inch head.

- Below a heating value stability ratio of 1.0, however, the decrease in combustion efficiency for the 6-inch head at the high pilot gas rate and for the double and triple pilot is less rapid than for the

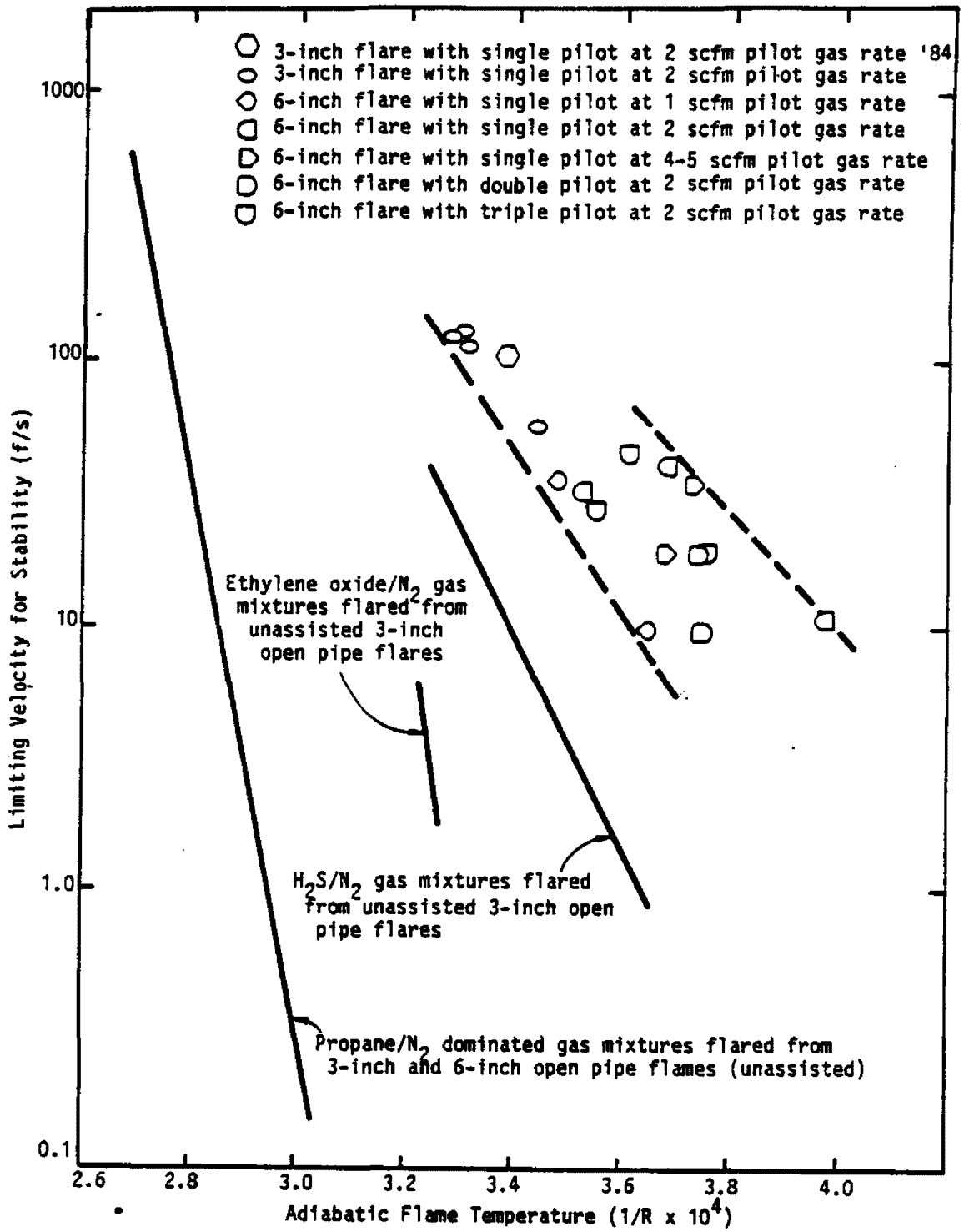


Figure 2-13. Calculated adiabatic flame temperature vs. limiting stable gas exit velocity for propane/N_2 gas mixtures flared using pilot-assisted 3-inch and 6-inch open pipe flares.

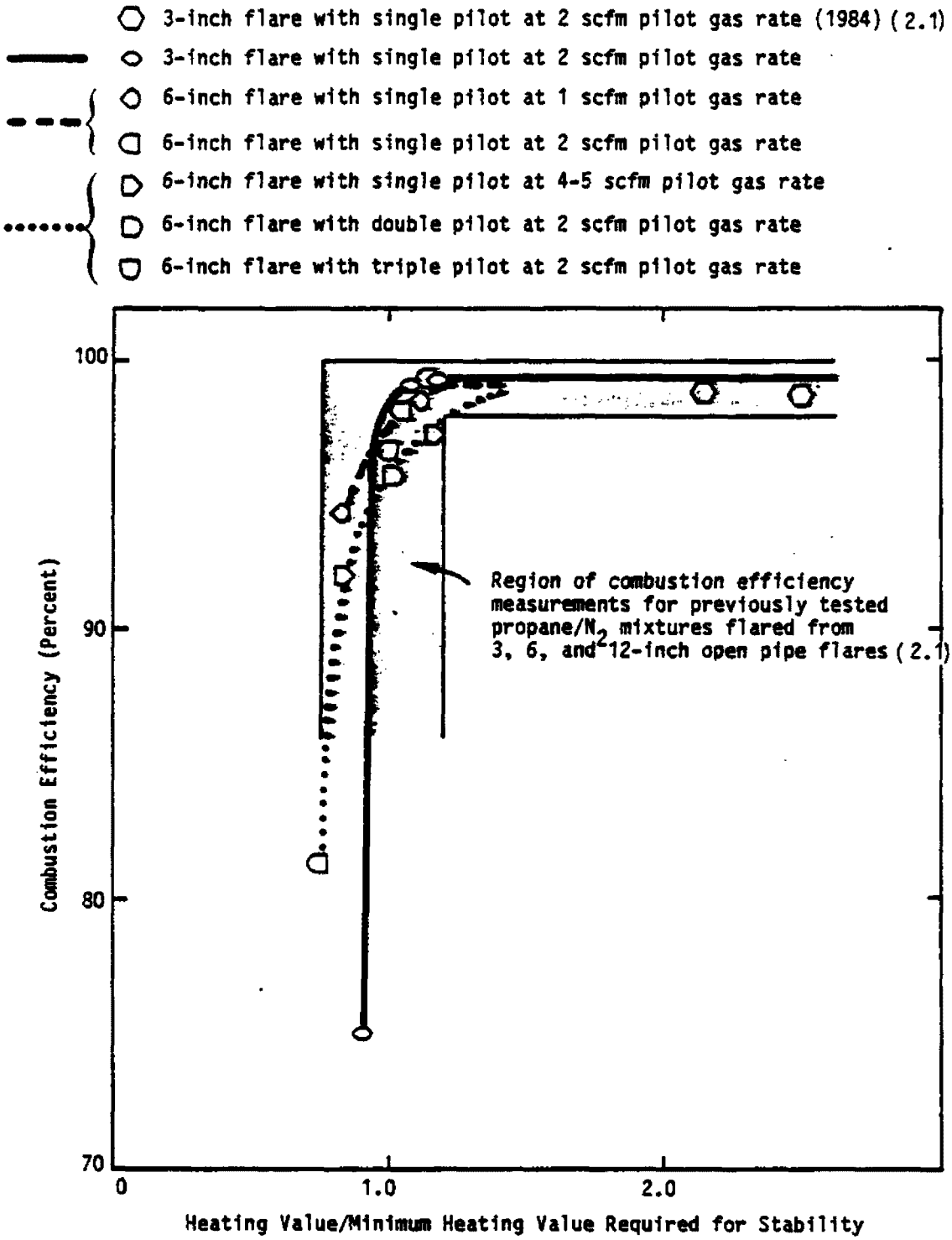


Figure 2-14. Combustion efficiency of pilot-assisted flares.

6-inch head with the single pilot medium and low pilot gas rates, and the 3-inch pilot assisted head. This may be because, even at or below the stability conditions, high relative pilot gas rates or multiple pilots can improve combustion efficiency.

2.2 Conclusions

The following conclusions were made based on the results of this report:

- There are viable methods for accurate and reliable measurement of H_2S and SO_2 in flare plume samples.

- Flame stability depends not only on flare head design and flare gas volumetric heating value, but also on compounds present in the flare gas. Gas mixtures of H_2S/N_2 can be stably flared at much lower volumetric gas heating values than can propane/N_2 or ~5 percent H_2S in propane/N_2 gas mixtures.

- High H_2S destruction efficiency is achieved for H_2S/N_2 and ~5 - 70 percent H_2S in propane/N_2 gas mixtures when the gas heating value is at least 1.2 times the level required for flame stability.

- For gas mixtures containing both H_2S and propane, H_2S destruction efficiency was consistently higher than propane combustion efficiency.

- The total gas heating value required for a stable flame, including pilot contribution, is much lower for pilot assisted 3 and 6-inch open pipe flares than for the same unassisted flares.

- High combustion efficiency is achieved for the pilot assisted tests when the gas heating value is at least 1.2 times the level required for flame stability.

- There are subtle differences in the flare combustion efficiency performance of the different pilot assist configurations tested in this program. Combustion efficiency greater than 98 percent is maintained for the 3-inch head even down to a heating value stability ratio of 1.00. Below a heating value stability ratio of 1.00, however, combustion efficiency decreases more rapidly for the 3-inch and 6-inch head with the single pilot at medium and low pilot gas rates, than for the 6-inch head with the single pilot at the high pilot gas rates and with the double and triple pilots.

2.3 References

2.1 Pohl, J. H. and N. R. Soelberg, "Evaluation of the Efficiency of Industrial Flares: Flare Head Design and Gas Composition," EPA Report No. 600/2-85-106, NTIS No. PB86-100559/AS, 1985.

3.0 GAS MIXTURE TESTS OF H_2S

Unburned hydrogen sulfide emissions from industrial flares are of great concern because of the large amounts of highly poisonous and noxious hydrogen sulfide gases flared in the petroleum industry. Work was conducted during the test program to evaluate the overall combustion efficiency and destruction efficiency of H_2S in gas mixtures. This work repeats limited testing conducted at EER in 1984 (3.1) on gas mixtures containing propane, nitrogen, and 5 percent H_2S. Measurement errors for H_2S prevented evaluation of H_2S destruction efficiency for those tests.

Testing of H_2S gas mixtures proceeded in phases. First, H_2S and SO_2 measurement techniques were evaluated for accuracy and adaptability to measurements of plume samples containing both H_2S and SO_2 at high and low concentrations. After verifying the accuracy of measurement techniques using gas standards, tests were conducted using the laboratory-scale Flare Screening Facility. These tests were conducted to determine at what concentrations H_2S could be burned efficiently. These tests were also used to verify the usefulness of H_2S and SO_2 sampling and analysis.

Although the flames produced on the 0.042 inch ID nozzle of the Flare Screening Facility are not similar to pilot scale and full sized flares, use of this facility has several advantages. Its low capital and operating costs provided an economical way to quickly evaluate if H_2S could be burned efficiently. The nozzle is enclosed in a reactor shell, isolated from the environment which allowed undiluted plume samples to be collected. The small size and reactor shell enclosure increase safety for flaring toxic gases. The isolating enclosure also gives the ability to close inlet and exit mass balances, for verification of sampling techniques.

After the review of measurement techniques and laboratory scale tests were completed, pilot scale H_2S gas tests were conducted using the Flare Test Facility. These tests repeated the incomplete and partially uncertain H_2S gas mixture tests in EER's 1984 test program, and extended those results to

include efficiency measurements for flare gases with higher H_2S concentrations.

3.1 Measurement Techniques

Accurate measurement of H_2S and SO_2 levels in plume samples is essential to estimating H_2S destruction efficiencies. It is important that measurements are made before H_2S and SO_2 levels in the samples can significantly change due to reaction with other sampled species or with the sample apparatus or containers. It is also important that either the H_2S or SO_2 species be physically separated (such as by gas chromatography) before analysis, or that the presence of SO_2 in the sample does not interfere with H_2S measurement, and vice versa. The H_2S destruction efficiency measurements conducted at EER in 1984 were inconclusive because SO_2 in the samples interfered with H_2S measurements.

Prior to H_2S gas mixture testing in this test program, a thorough investigation of H_2S and SO_2 sample techniques was conducted. Analysis methods for H_2S included:

- Concentration of gaseous H_2S gas scrubber bottles containing aqueous cadmium sulfate solution, followed by iodometric titration

- Concentration of gaseous H_2S gas scrubber bottles containing aqueous zinc acetate solution, followed by colorimetric analysis using the methylene blue method

- Reaction of gaseous H_2S with lead acetate, causing darkening of lead acetate impregnated paper tape

- Gas chromatography

- Reaction with color indicators in Draeger tubes

Methods for SO_2 sample analysis that were investigated were:

- Concentration of gaseous SO_2 gas scrubber bottles containing aqueous hydrogen peroxide solutions followed by barium perchlorate titration

- Gas chromatography

- Reaction with color indicators in Draeger tubes

Tests were conducted using standardized gases and gas mixtures. These tests were conducted to verify applicability of the techniques to measure plume gas concentration of H_2S and SO_2 by evaluating accuracy, repeatability, reliability, and measurable ranges. Results of these tests are shown in Table 3-1. The iodometric titration and lead acetate methods for H_2S measurement gave very inaccurate and unreliable results and were not used for further analyses. The methylene blue and Draeger tube methods proved to be most accurate and reliable in the required sample range of 0-100 ppm. Where possible, both methods were used for H_2S sample analysis. Gas chromatography was also used when the H_2S concentration was within the GC detection range of 25 - 1000 ppm.

For SO_2 measurement, the barium perchlorate titration method was most accurate. Occasionally, however, low measurements were obtained, possibly due to sample system leaks or analytical errors. Draeger tubes and gas chromatography were used to verify results from the titration measurements.

3.2 Laboratory Scale Tests

Laboratory scale tests were conducted to determine concentrations at which H_2S could be burned efficiently and to verify the usefulness of H_2S and SO_2 sample procedures. The Flare Screening Facility, equipped with a 0.042 inch ID nozzle, was used for these tests, because it is less expensive and safer to operate than the larger FTF. Complete inlet and outlet mass balance

TABLE 3-1. MEASUREMENT TECHNIQUES FOR H_2S AND SO_2

METHOD	MEASURED SPECIES	REF	RANGE (ppm)	ACCURACY	HOLDING TIME SENSITIVITY	COMMENTS
Iodometric Titration	H_2S	EPA Method 11, 40 CFR Ch. 1 (7-1-85 Ed.)	6 - 520	± 100%	NM[1]	Large errors due to presence of oxidizing or reducing agents, leaks, or H_2S loss
Methylene Blue Method	H_2S	ANSI/ASTM D 2725-70 (Reapproved 1975)	0.5-20	± 50%	0-30% Increase in measured levels in 24 hours	No measurable interference from other species
Lead Acetate Method (Tracor-Atlas H_2S meter)	H_2S	ANSI/ASTM D 2420-66 (Reapproved 1976)	100-2000	± 100%	NM	Considerable interference from SO_2, reducing H_2S measurements
Draeger Tubes	H_2S	Detector Tube Handbook, 4th Ed. Aug. 1979	0.5-2000+	± 20%	Gradual color boundary blurring after 5 minutes to 1 hour	Some interference from SO_2 presence, but this is the best and easiest method for H_2S measurements
	SO_2	Detector Tube Handbook, 4th Ed. Aug. 1979	0.5-5000+	±20%	Good holding time exceeding 48 hours	H_2S also detected in some tube ranges
Gas Chromatography (Perkin-Elmer Sigma 2 Gas Chromatography	H_2S	Supelco Chromatography Supplies	25-1000+	±20%	Slight decrease after 24 hours	No H_2S-SO_2 cross-sensitivity, but not useful at low concentrations
	SO_2	Supelco Chromatography Supplies	10-5000	±20%	Slight decrease after 24 hours	
Barium Perchlorate Titration	SO_2	EPA Method 6 40 CFR Ch.1 (7-1-85 Ed.)	1-2000+	±15%	Good holding time exceeding 48 hours	Occasional low values from leaks in system or analytical errors, but this is the best method for SO_2 measurements.

1. NM = Not Measured

closure could also be determined with this facility to provide verification of sample procedures.

Figure 3-1 compares flame stability limit results for the H_2S gas mixtures to those for propane/N_2 mixtures flared using the 0.042-inch nozzle and 3, 6, and 12-inch flare heads. The flame stability limit is defined as the operating condition where an increase in gas exit velocity or decrease in gas heating value results in flame blowout. The curves in Figure 3-1 were generated by determining the minimum gas heating value attainable before flame blowout for different gas exit velocities. Much higher gas heating values are required to maintain a flame on the 0.042 inch nozzle than for the 3, 6, and 12-inch heads. This is because of the aerodynamic differences between small and large diameter jets. Reynolds number (Re) indicates the degree of turbulence in a fluid stream. For jets from the 0.042 inch nozzle, Re ranged between 10^2 to 10^4, indicating that the flow was in the laminar to turbulent transition regime. Re for jets from the larger flare heads ranged from 10^3 to 10^6, denoting transition to turbulent flow. Richardson number (Ri) indicates relative influence of buoyant forces on aerodynamic flow. Richardson numbers greater than one indicate dominance by buoyant forces. The jets from the 0.042-inch nozzle had Ri ranging from 10^{-6} to 10^{-3}, signifying inertial force dominance over buoyant forces. For the 3 through 12-inch heads, Ri was between 10^{-4} and 10^3. Some of these flames were dominated by inertial forces and some by buoyant forces. Most commercial flare flames are dominated by buoyant forces.

The destruction efficiency of H_2S and mass balances for these tests are shown in Table 3-2. The H_2S gas content was 4.31 to 69.5 percent for these tests and the nozzle exit velocities ranged from 8.52 to 27.5 f/s. Greater than 99 percent H_2S destruction efficiency was measured for all test conditions. Mass balance closure for carbon, oxygen, and sulfur was less than 1.00 for all but one case. The best closure was with oxygen. Carbon and sulfur closure ratios were generally less than the corresponding oxygen closure ratios, but satisfactory for measurement of flare combustion and destruction efficiency.

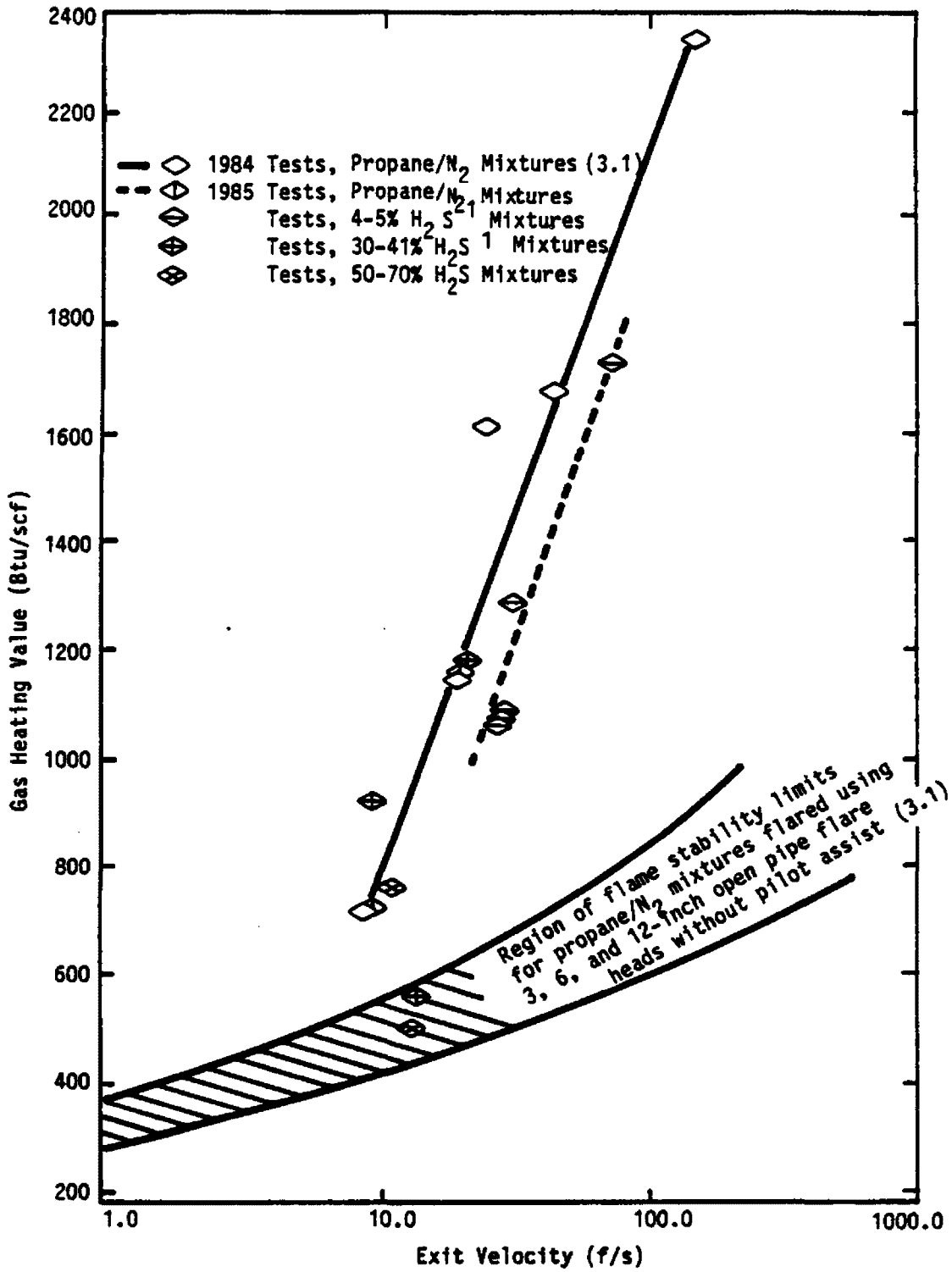


Figure 3-1. Flame stability curves for propane/N_2 and H_2S/propane/N_2 gas mixtures flared using a 0.042 inch ID nozzle.

1. Remainder is propane and N_2

TABLE 3-2. FLARE SCREENING FACILITY H_2S GAS MIXTURE TEST RESULTS, NOZZLE ID = 0.042 INCHES

Test No.	Gas Composition (Remainder N_2)		Gas Heating Value (Btu/scf)	Nozzle Exit Velocity (f/s)	Air Stoichiometric Ratio	H_2S Destruction Efficiency (%)	Propane Combustion Efficiency (%)	Mass Balance Closure Mass In/Mass Out		
	H_2S (%)	Propane (%)						C	O	S
1	4.31	45.2	1086	27.5	3.15	>99.99	99.9	0.567	0.944	0.446
2	34.8	52.0	1427	17.4	2.90	>99.99	99.99	0.706	0.939	1.12
3	31.9	55.0	1480	16.5	2.90	>99.99	99.9	0.878	0.852	0.794
4	4.28	45.5	1093	27.0	3.17	>99.7	99.9	0.952	0.918	0.715
5	69.5	30.5	1125	8.52	4.02	>99.99	98.6	0.729	0.891	0.774

3.3 Pilot Scale Tests

Pilot scale tests of H_2S gas mixtures were conducted using a non-assisted 3-inch open pipe flare head at the Flare Test Facility. These tests were conducted to measure flame stability, combustion efficiency, and destruction efficiency for H_2S gas mixtures. Results were used to verify incomplete results of the EER 1984 test program and to extend the test data to include gas mixtures with higher H_2S concentrations.

Flame stability limit measurements are shown in Figure 3-2. These curves were generated by determining the minimum gas heating value attainable before flame blowout for a range of different gas exit velocities. Good reproducibility was attained between the 1984 and 1985 tests with ~5 percent H_2S in propane/N_2 mixtures. Since the dominant combustible gas in these mixtures is propane (14.4 - 20.1 percent), it is not surprising that the stability curve for these mixtures is within boundaries previously determined for propane/N_2 mixtures flared on the 3, 6, and 12-inch heads.

One other method of depicting the flame stability limit is to correlate the minimum gas heating value on a mass basis to the gas exit velocity. The difference between volumetric heating value and mass heating value for gaseous compounds depends on the compound molecular weight. Compounds with high volumetric heating values (1,3-butadiene, for example, having 2,730 Btu/scf) may have low mass heating values (19,500 Btu/lb for 1,3-butadiene) compared to the heating values of other compounds (hydrogen, for example, having only 275 Btu/scf, but 51,000 Btu/lb). In Figure 3-3, the stability curve shown in Figure 3-2 is presented showing heating value on a mass basis. The correlation with exit velocity for different gases is no better than in Figure 3-2. Since the majority of the flare gas in all these mixtures is nitrogen (50 - 95 percent), the overall molecular weight and density of these gas mixtures only changes slightly from mixture to mixture.

The flame stability limit curve for H_2S/N_2 gas mixtures in either Figure 3-2 or Figure 3-3 is much lower than for the H_2S/propane/N_2 or propane/N_2 mixtures, but the volumetric heating value for H_2S gas (588 Btu/

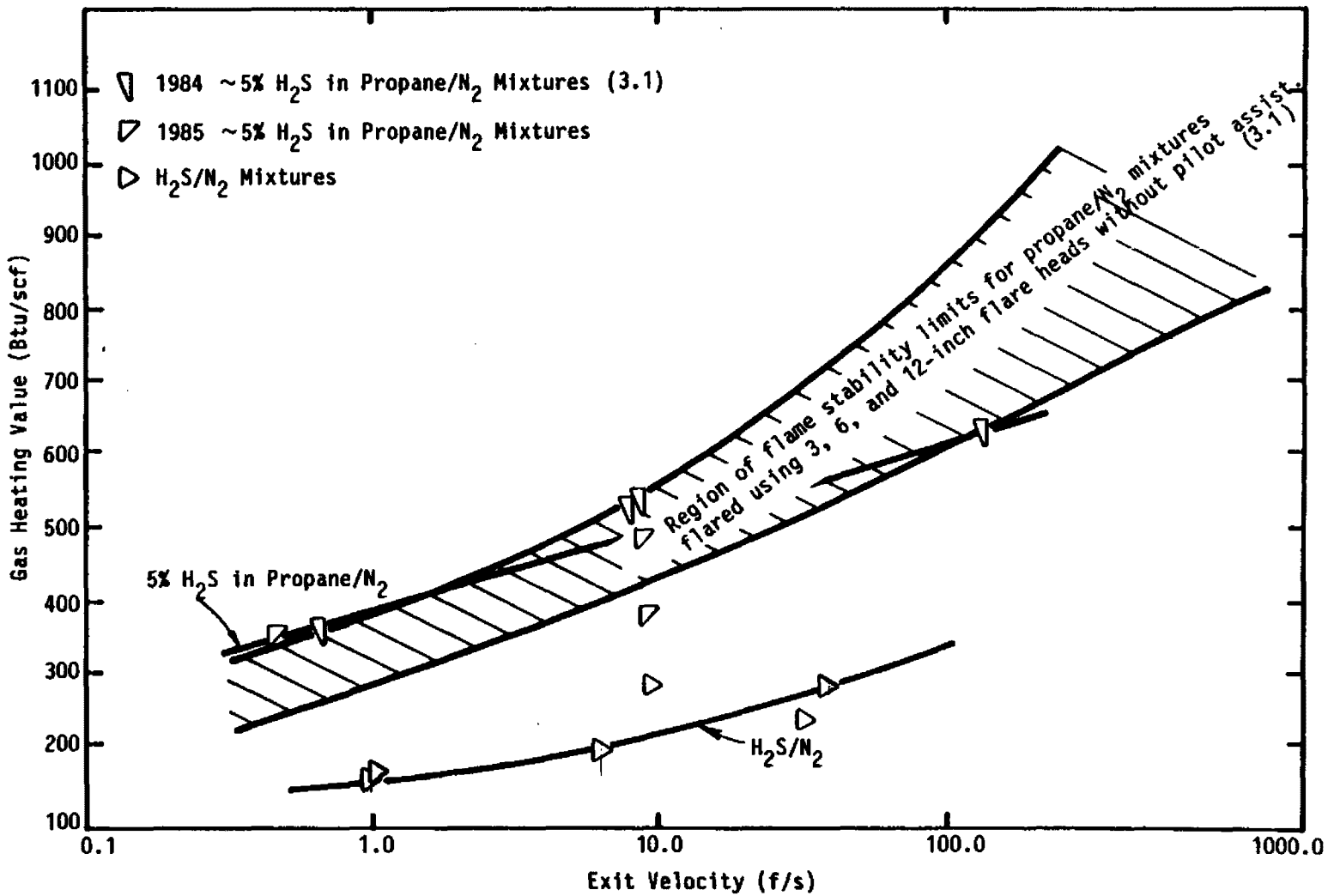


Figure 3-2. Flame stability curves for H_2S gas mixtures flared using a 3-inch diameter open pipe flare.

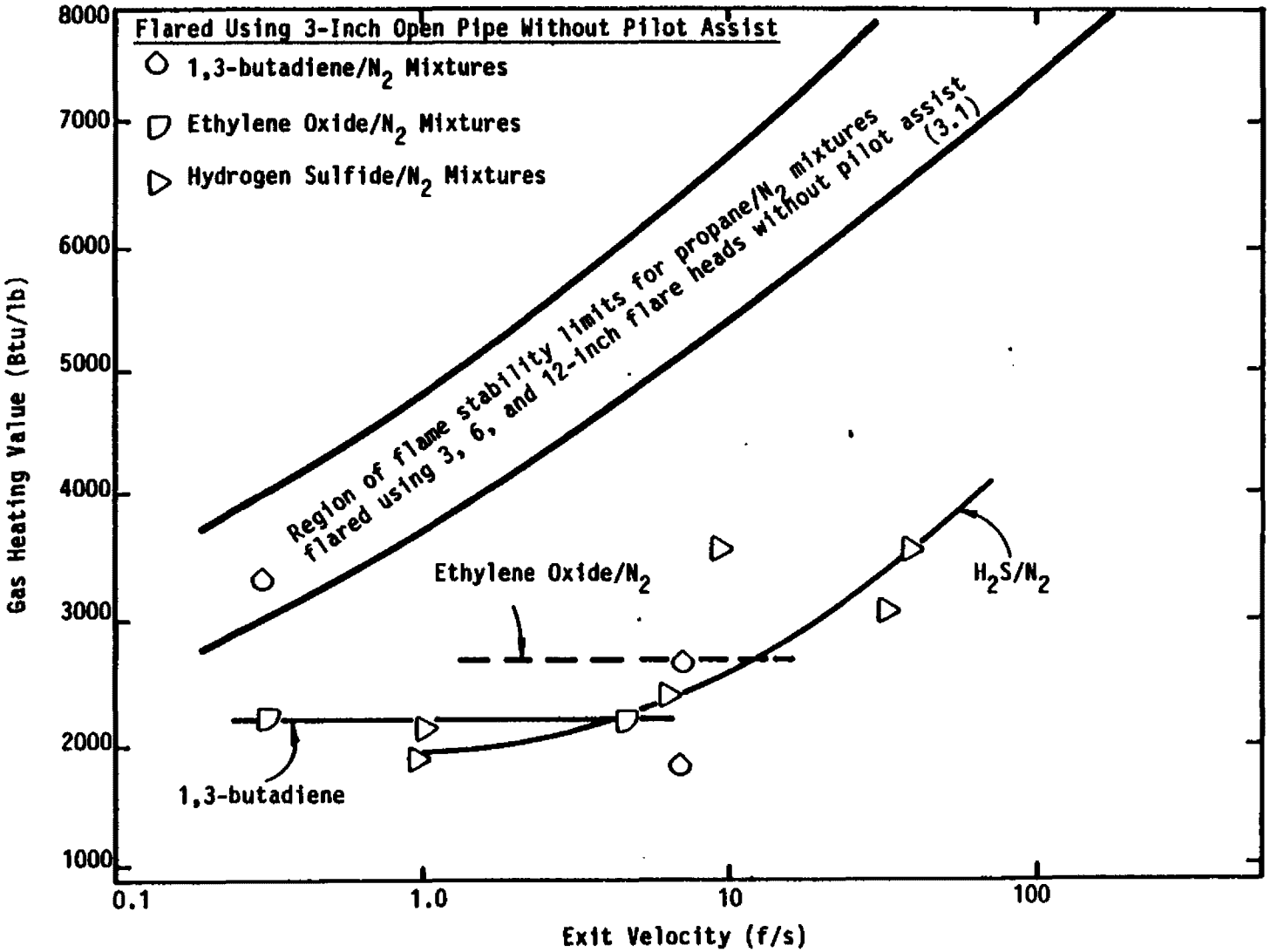


Figure 3-3. Flame stability curves using heating value per mass relationship.

scf) is much lower than that of propane (2350 Btu/scf). There is actually a higher concentration of H_2S (28.9 - 49.5 percent) in the H_2S/N_2 mixtures at the stability limit than the combined propane and H_2S in the 5 percent H_2S mixtures (18.8 - 25.2 percent). The presence of higher H_2S concentrations, and/or better combustion kinetics for H_2S than for propane, may help to maintain a stable flame at lower heat input.

The flame stability limit is approached when the flame propagation speed in the gas approaches the relief gas velocity. The determination of flame speed is very complex, involving reaction kinetics and mixing patterns. The inherent complexities discourage a direct evaluation of flare flame kinetic and mixing rates. However, the higher levels of H_2S concentration in a mixture near the stability limit could increase the flame speed (unless the flame reactions are kinetically limited) by providing a greater number of H_2S - O_2 molecular interactions relative to the total number of molecular interactions.

However, the flame speed may be limited by reaction kinetics, and not affected by mixing. Kinetic rates of flame reactions are dependent on flame temperature and other parameters according to the exponential Arrhenius equation:

$$k = Ae^{-E/RT} \qquad (3\text{-}1)$$

where k is the rate constant for a given reaction, A is the frequency factor, E is the activation energy, R is the ideal gas constant, and T is temperature. If all parameters except temperature in Equation 3-1 are maintained constant as the temperature is increased, the reaction rate constant exponentially increases. If the flame speed is limited by reaction rates, the flame speed (and limiting maximum gas exit velocity) should increase exponentially as the flame temperature increases.

The actual flare flame temperature is however difficult to determine accurately. Since the flame is in the open air, subject to wind and eddy conditions, both in-flame and optical temperature measurement methods are

subject to errors. Also, within the flame envelope, thereis a wide temperature range due to varying degrees of air dilution and reaction completion. As a basis for comparison, a pseudo flame temperature can be used for showing the dependence of flame stability on temperature for different flare gases. This pseudo flame temperature may be calculated assuming (1) adiabatic, complete combustion of the flare gas with a stoichiometric amount of air, or (2) adiabatic, complete combustion of a flare gas-air mixture with stoichiometry between the upper and lower flammability limits of the mixture, or (3) non-adiabatic, complete combustion of a flare gas-air mixture, assuming a certain amount of heat loss. In previous studies (3.1 and 3.2), pseudo adiabatic flame temperatures based on stoichiometric combustion of flare gas with air were compared to flame stability. This pseudo adiabatic flame temperature was also combined with both upper and lower flammability limits and related to flame stability. Within the scope of this report, and in order to make comparisons with previous EER research (3.1), pseudo adiabatic flame temperatures based on stoichiometric combustion were related to flame stability in Figure 3-4.

The limiting maximum stable gas exit velocity is shown to correlate well with adiabatic flame temperature for individual gas mixtures. However, there is poor agreement between the correlations for the different gas mixtures. A much higher flame temperature is required to burn propane mixtures at a given velocity than other gas mixtures. Gas mixtures of H_2S exhibit the lowest flame temperature for a given gas exit velocity. Therefore factors other than flame temperature also affect the flame stability of different gases.

Such differences in flame stability of different gas mixtures shown in Figure 3-4 is expected, considering the structural, physical, and chemical differences of the different compounds. Each of the compounds shown in Figure 3-4 has a different structure and properties distinctive of different classes of materials - alkanes (propane), conjugated dienes (1,3-butadiene), oxygenated compounds (ethylene oxide), and sulfur compounds (hydrogen sulfide). Some comparative physical properties for H_2S and propane are shown in Table 3-3. H_2S has a wider flammable range, a lower adiabatic flame temperature, and a lower minimum ignition temperature than does propane.

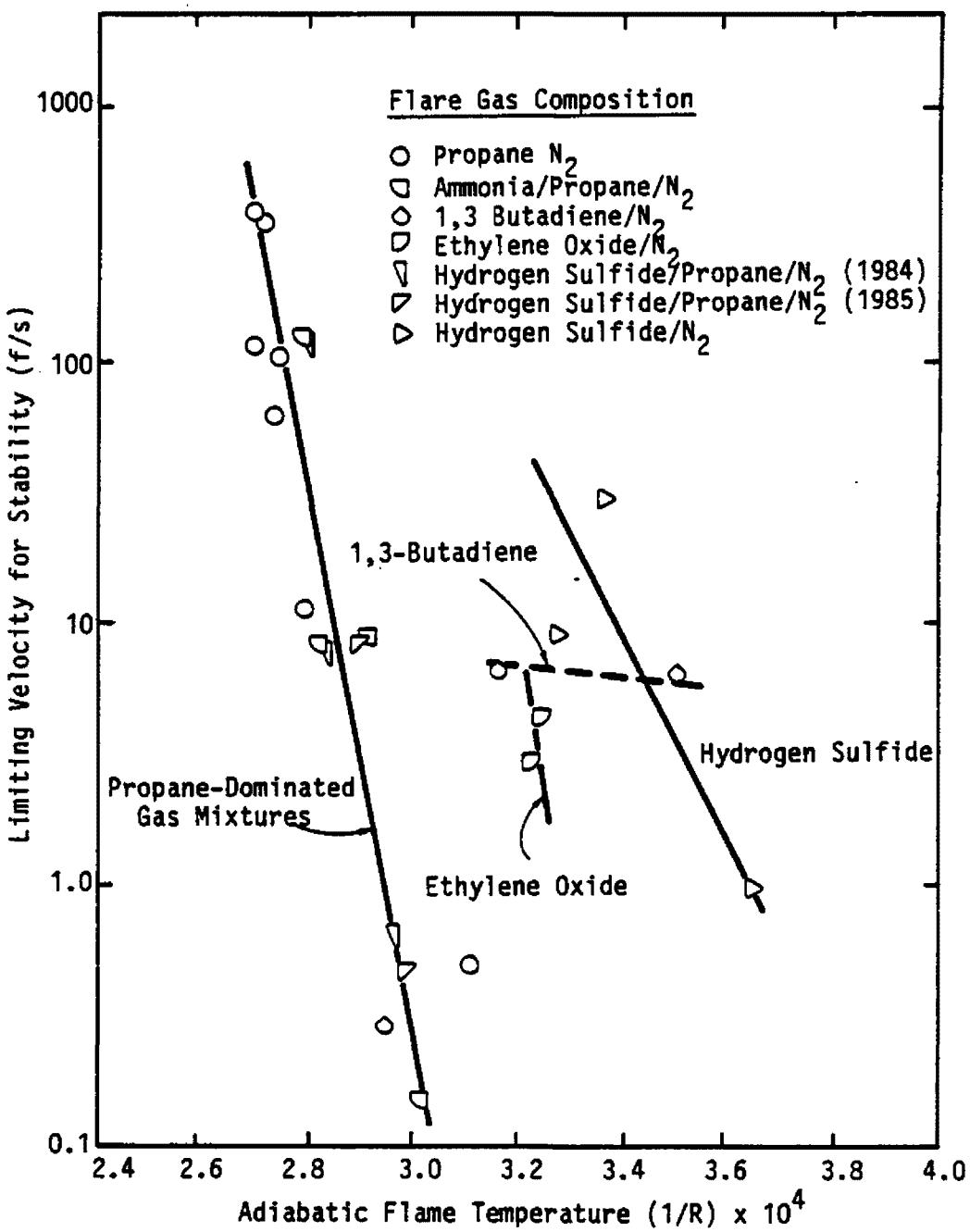


Figure 3-4. Calculated adiabatic flame temperature versus limiting stable gas exit velocity from an unassisted 3-inch open pipe flare.

TABLE 3-3. PHYSICAL PROPERTIES[1] OF H_2S AND PROPANE AT 60°F, 1 ATMOSPHERE

Property	H_2S	Propane
Molecular Weight	34.076	44.097
Gas Density, (scf/lb)	11.4	8.77
Lower Heating Value (Btu/scf)	588	2350
(Btu/lb)	6700	20600
Flammability Limits in Air (%)		
Lower	4.3	2.1
Upper	45.5	10.1
Adiabatic Flame Temperature for Stoichiometic Combustion With Air (R)		
Calculated[2]	3338	3838
Literature	NA[3]	4055
Ignition Temperature (F)	558	871-898
Flame Velocity (f/s)	NA[3]	0.95-1.3

1. Data From: Balzhiser, R. E., M. R. Samuels, and J. D. Eliasson, Chemical Engineering Thermodynamics, 1972
   CRC Handbook of Tables for Applied Engineering Science, 2nd Ed., 1976
   CRC Handbook of Chemistry and Physics, 53rd Ed., 1972-73
   Howard, H. F. and G. W. Jones, "Limits of Flammability of Gases and Vapors", USBM Bulletin 503, 1952
   GPSA Engineering Data Book, 1972
   Gas Engineers Handbook, 1st Ed., 1965
   North American Combustion Handbook, 1st Ed., 1952

2. Calculated by integration of heat capacity data

3. Not Available

These differences indicate differences in other factors in Equation 3-1 which could influence kinetic rates for reactions in H_2S and propane flames.

The relationship between flame stability and flare combustion efficiency (see Appendix D for efficiency definitions) has been developed in previous studies. Figure 3-5 relates propane combustion efficiency for the H_2S/propane/N_2 gas mixtures to the ratio of actual gas heating value and the minimum heating value required to produce a stable flame at that velocity. This correlation is within the range previously developed for a variety of gas mixtures and flare head types and designs. Combustion efficiency is high, exceeding 98 percent, for stability conditions greater than about 1.2. When stability conditions decrease below 1.2, combustion efficiency can rapidly decrease below 98 percent.

A similar correlation for H_2S destruction efficiency is seen in Figure 3-6. All data points except one fall within or above the previously determined destruction efficiency region for ammonia, 1,3-butadiene, ethylene oxide, and propane. High destruction efficiency, greater than 99 percent, is attained for stability conditions greater than about 1.2. Destruction efficiency rapidly drops below 98 percent when the stability criteria decreases below 1.2. The presence of the single low efficiency point outside the shaded area is from a test that may have been influenced by ambient conditions or an upset or discontinuity in flow control or sample procedures. Since these tests were predominantly conducted very near the limit of flame stability, any slight change radically affected flare performance and efficiency.

Destruction efficiency of H_2S is compared to destruction efficiency of propane in Figure 3-7. For the H_2S/propane/N_2 mixtures and operating conditions of these tests, H_2S destruction efficiency was consistently higher than propane combustion efficiency. This indicates that H_2S flames may be more stable and react more quickly than propane flames. Figure 3-2 shows that H_2S flames are more stable than propane flames.

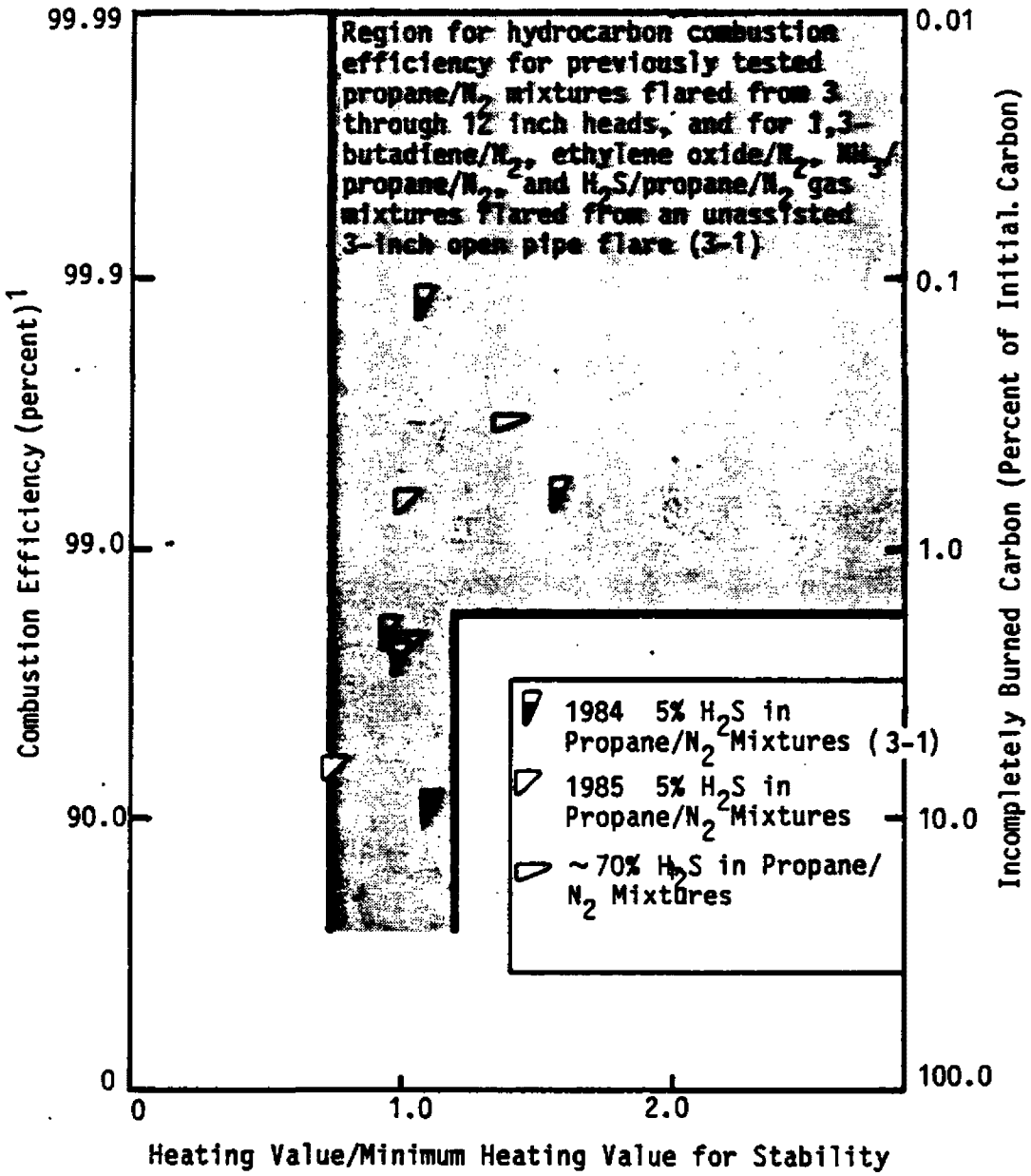


Figure 3-5. Propane combustion efficiency of H_2S/propane/N_2 gas mixtures flared from an unassisted 3-inch open pipe flare.

1. Scale is log (100 - Combustion Efficiency)

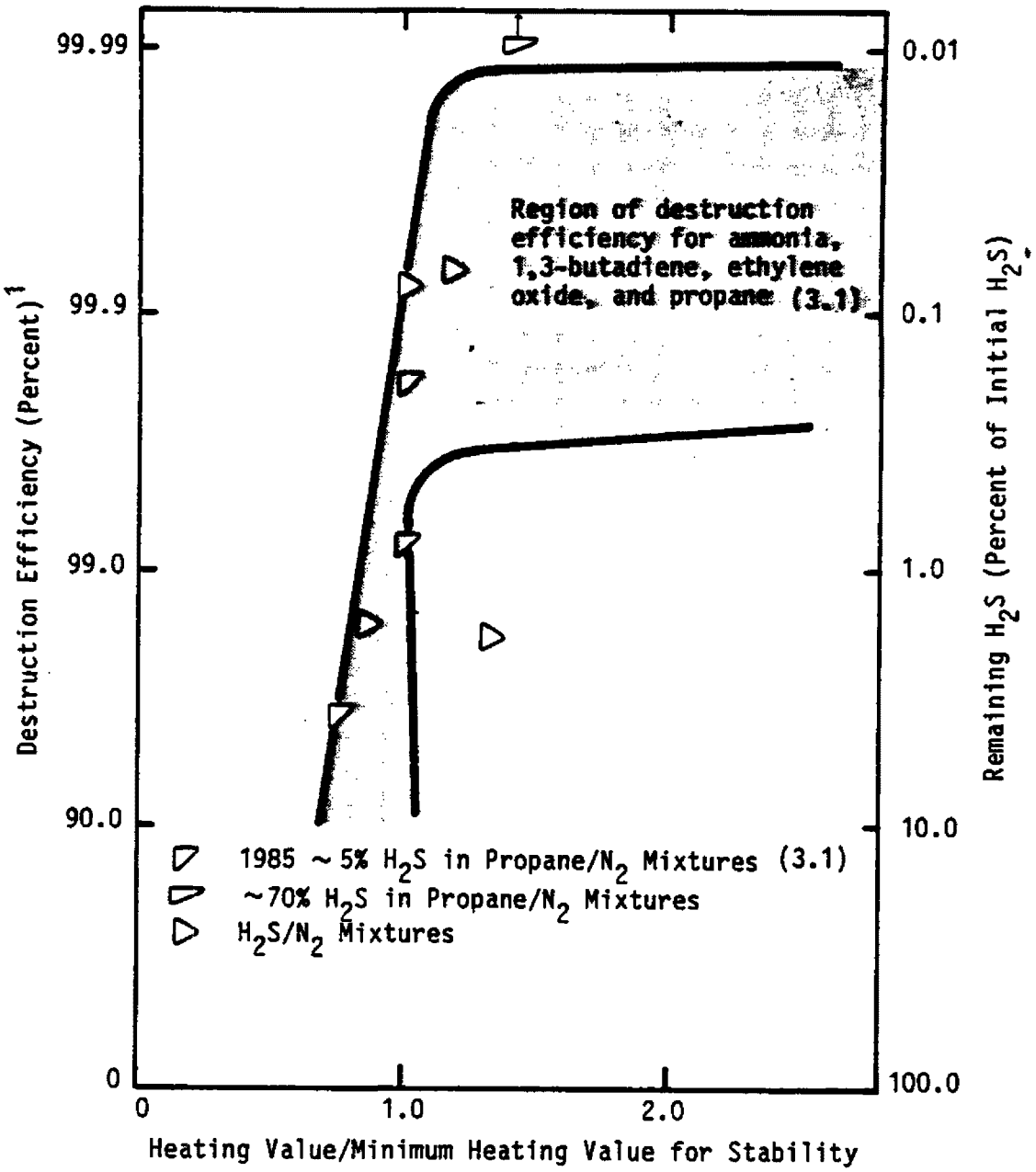


Figure 3-6. Destruction efficiency of H_2S gas mixtures flared from an unassisted 3-inch open pipe flare.

1. Scale is log (100-Destruction Efficiency)

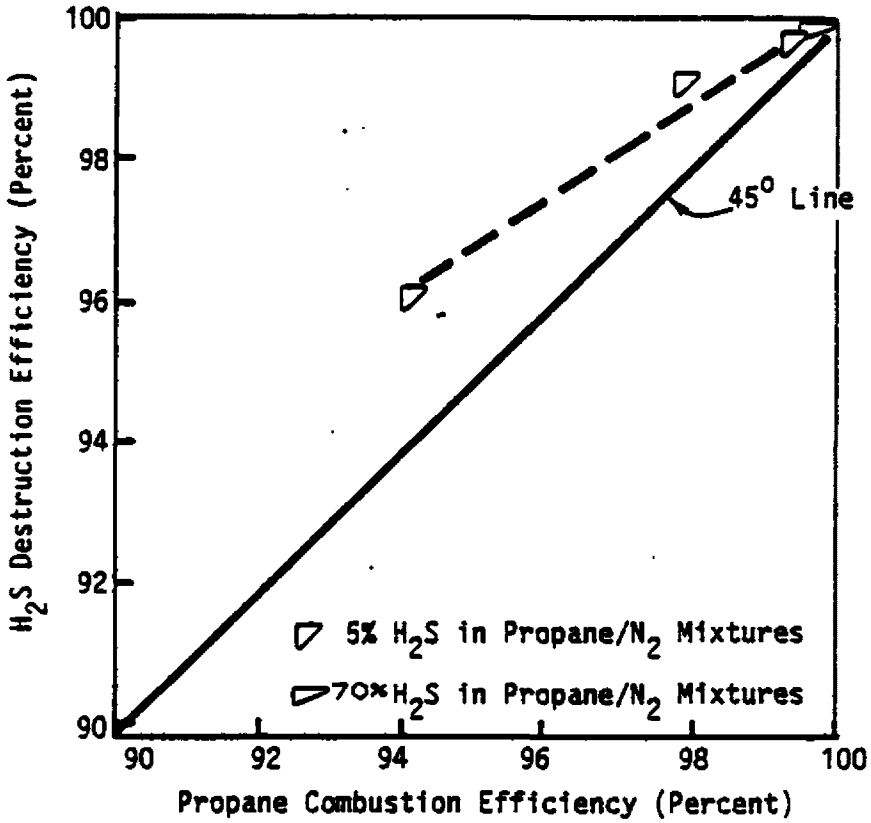


Figure 3-7. Correlation between H_2S destruction efficiency and propane combustion efficiency for H_2S/propane/N_2 mixtures flared from an unassisted 3-inch open pipe flare.

3.4 References

1. Pohl, J. H. and N. R. Soelberg, "Evaluation of the Efficiency of Industrial Flares: Flare Head Design and Gas Composition," EPA Report No. 600/2-85-106, NTIS No. PB86-100559/AS, 1985.

2. Noble, R. K., M. R. Keller, and R. E. Schwartz, "An Experimental Analysis of Flame Stability of Open Air Diffusion Flames", AFRC International Symposium on Alternative Fuels and Hazardous Wastes, Tulsa, OK, 1984.

4.0 PILOT ASSISTED TEST RESULTS

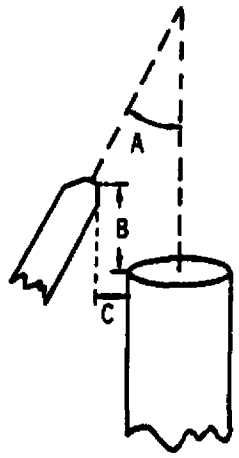
Very little testing of pilot assisted flares has previously been conducted at EER or reported in the literature. Most previous work at EER has been on unassisted flares, in order to simplify the test programs and to evaluate operating parameters independent of pilot assist. Industrially, however, continuous gas pilots are commonly used to ensure safe, continuous and emergency flaring.

Upon recommendation of the flare Technical Advisory Committee, more extensive pilot assisted testing has been conducted at EER. For these tests, the flare gas was a mixture of propane blended with nitrogen to vary the gas heating value. Utility-supplied natural gas was used for the pilot gas. Open pipes of 3 and 6-inch diameter were used as the flare heads. Single, double, and triple pilots were tested. The single pilot was a John Zink Co. 2-inch gas pilot equipped with a flame front generator. The double and triple pilots were manufactured by EER and are similar to the Zink pilot. Orientation of the pilots to the flare as suggested by the Advisory Panel is shown in Figure 4-1.

Operating parameters evaluated were the number of pilots and the pilot gas flowrate. Tests were conducted on the 3-inch and 6-inch flares with a single pilot and a nominal pilot gas flowrate of 2 scfm. Using the 6-inch flare, tests were also conducted with the single pilot at pilot gas flowrates ranging from 1-5 scfm. Tests were also conducted on the 6-inch flare with single, double, and triple pilots, maintaining the total pilot gas rate at 2 scfm.

The flare gas exit velocity range for all these tests was limited to the range between 8-150 f/s for the 3-inch head and 5-50 f/s for the 6-inch head. Lower velocities were not used because of the high pilot gas rate relative to propane flowrate in the flare gas. Higher velocities were limited by the maximum nitrogen flowrate capacity of the Flare Test Facility.

A. Single pilot



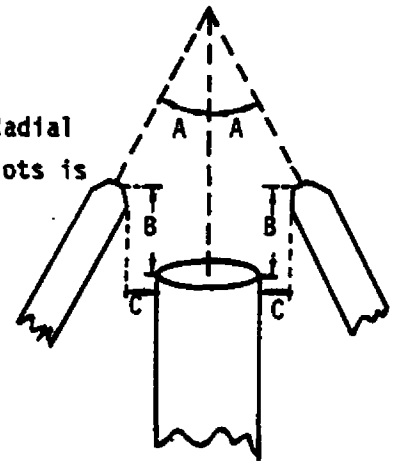
Dimensions:

A. 30 degrees

B. 2.5 inches

C. 1 inch

B. Double pilot . Radial angle between pilots is 180 degrees.



C. Triple pilot. Radial angle between pilots is 120 degrees.

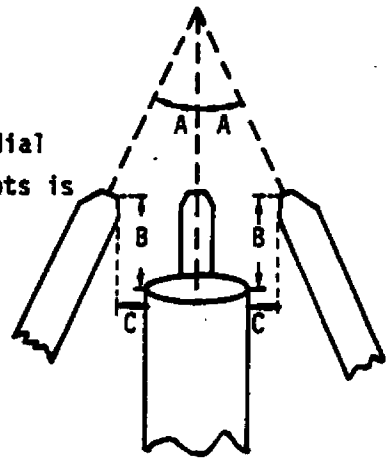


Figure 4-1. Schematics of single, double, and triple pilots.

4.1 Flame Stability

For all combinations of pilot assist, flame stability limit curves were determined. The flame stability limit is defined in Appendix C as the condition where a decrease in flare gas heating value or an increase in flare gas exit velocity results in flame blow-out. The previously used flame stability limit determination procedure was to incrementally decrease the flare gas heating value at constant gas exit velocity until flame destabilization and blowout occurs. This definition and procedure could not be applied in the pilot assisted tests because the presence of a pilot prevented flame blowout, even at very low flare gas heating values. Consequently, the definition and determination of the flame stability limit were more subjective. The gas heating value required for 98 percent combustion efficiency at a given flare gas velocity was observed to be the operating condition where the last faint flickers of orange color completely disappeare and the flame envelope becomes completely transparent, except for blue-orange cones near the pilot and flare tips. This limit is determined by gradually decreasing the flare gas heating value, maintaining constant gas exit velocity and pilot gas flowrate and observing the flame, as orange and yellow color in the flame decreases and eventually disappears. This definition applies to specific pilot assisted tests of this study burning propane/nitrogen mixtures.

Flame stability for the 3-inch pilot assisted head is shown in Figure 4-2. Curves defining stable, stability limit, and unstable flames are shown. The gas heating value includes the added heating value contribution of the pilot gas. Some scatter in the data points is due to the subjectivity of the visual measurements and to slight fluctuations in the ambient conditions, such as lighting and wind variations. For a given gas exit velocity, the stability curves occur at significantly lower gas heating values than the region of stability limit curves for unassisted 3 through 12-inch flares. Clearly, this pilot-assisted open pipe flare can be operated stably at much lower total heating values (pilot gas included) than the same flare without pilot assist. Again, it should be noted that these data are for very simple open pipe flares. In commercial practice a variety of aerodynamic

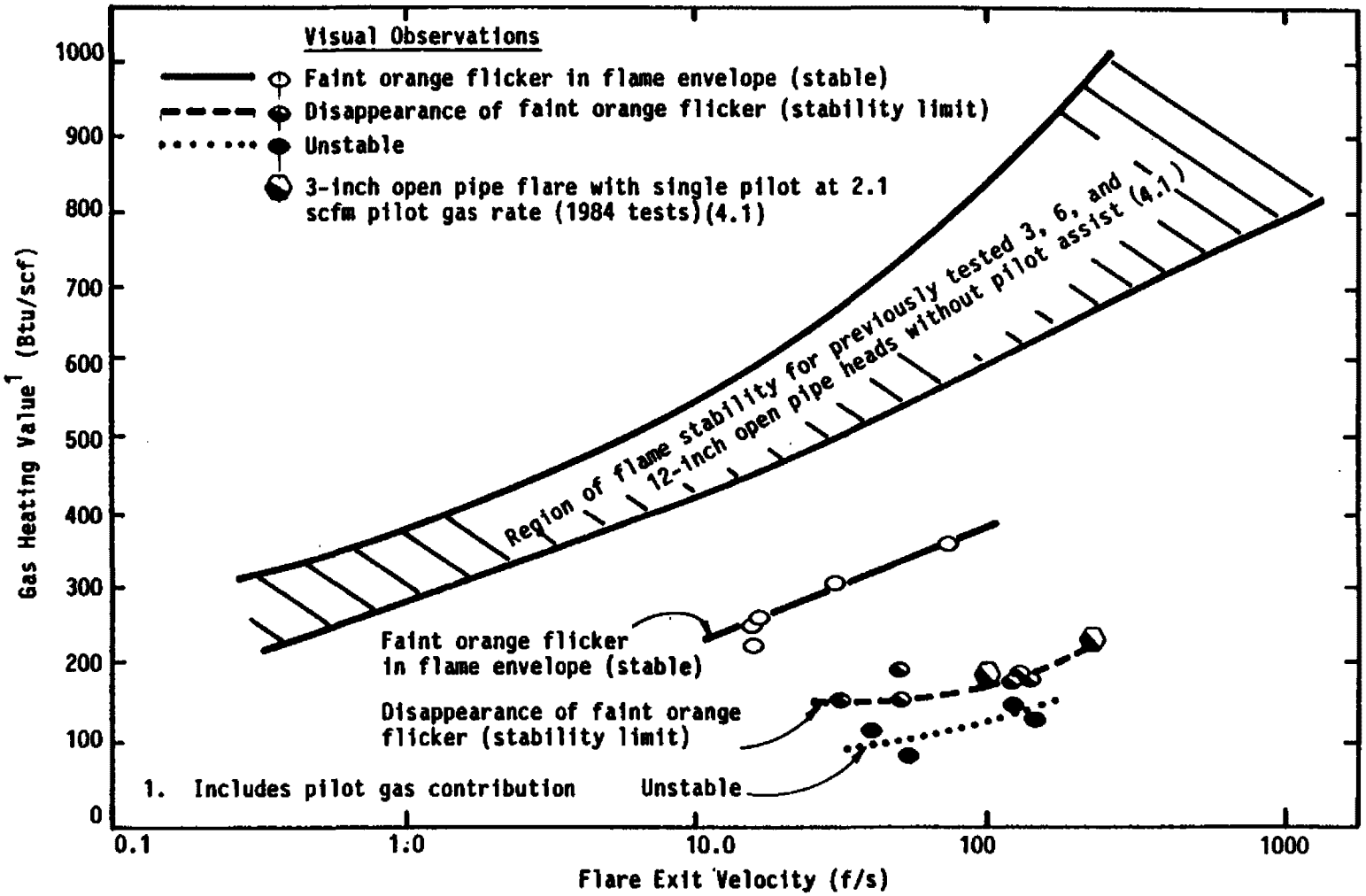


Figure 4-2. Flame stability curve for 3-inch pipe flare with a single pilot at a pilot gas flowrate of 2.1 - 2.2 scfm natural gas.

stabilization devices are commonly used. Flares with such features may exhibit differences between piloted and non-piloted performance which are smaller than for the simple system studied here.

Flame stability curves for the 6-inch flare with a single pilot at low, medium, and high pilot gas rates are shown in Figure 4-3 through 4-5. For each pilot gas flowrate series, the curves of total gas heating value (including pilot) vs flare gas exit velocity for the stability limit, as defined by the disappearance of orange coloring in the flame envelope, are shown. These stability limit curves depend only slightly on velocity in the range tested. For low and medium pilot gas flowrate, the limiting total gas heating value is about 150 Btu/scf for flare gas exit velocities between 5.6-45 f/s. For comparison, Figure 4-4 shows that this limiting heating value is the same as that for the 3-inch pilot assisted flare with a medium pilot gas rate, at a flare gas exit velocity of 35 f/s. The limiting heating value for the tests with high pilot gas rate is also constant, but slightly lower at about 120 Btu/scf. Tests conducted below this level were in the unstable regime.

Flame stability curves for the 6-inch flare with multiple pilots are shown in Figure 4-6. The stability limit for the double and triple pilot tests is flat at a constant heating value of about 130 Btu/scf, for gas exit velocities between 10-30 f/s. This is slightly lower than for the single pilot assisted tests at equal or lower pilot gas rates, but slightly higher than for the single pilot tests at higher pilot gas rates. At gas exit velocities above 40 f/s, the stability limit for the multiple pilot tests gradually increases as it does for the 3-inch pilot assisted flare tests.

Use of pilot assist greatly enhanced flame stability during these tests. For 3 and 6-inch unassisted open pipe flares, operated with propane-nitrogen gas exit velocity of 40 f/s, the minimum gas heating value required to maintain a flame is about 540 Btu/scf. If a 2 scfm natural gas pilot used, the total heating value (including pilot contribution) required for a stable flame can be reduced to 150 Btu/scf. At this condition, the flame envelope becomes transparent and by definition, the stability limit is reached. For

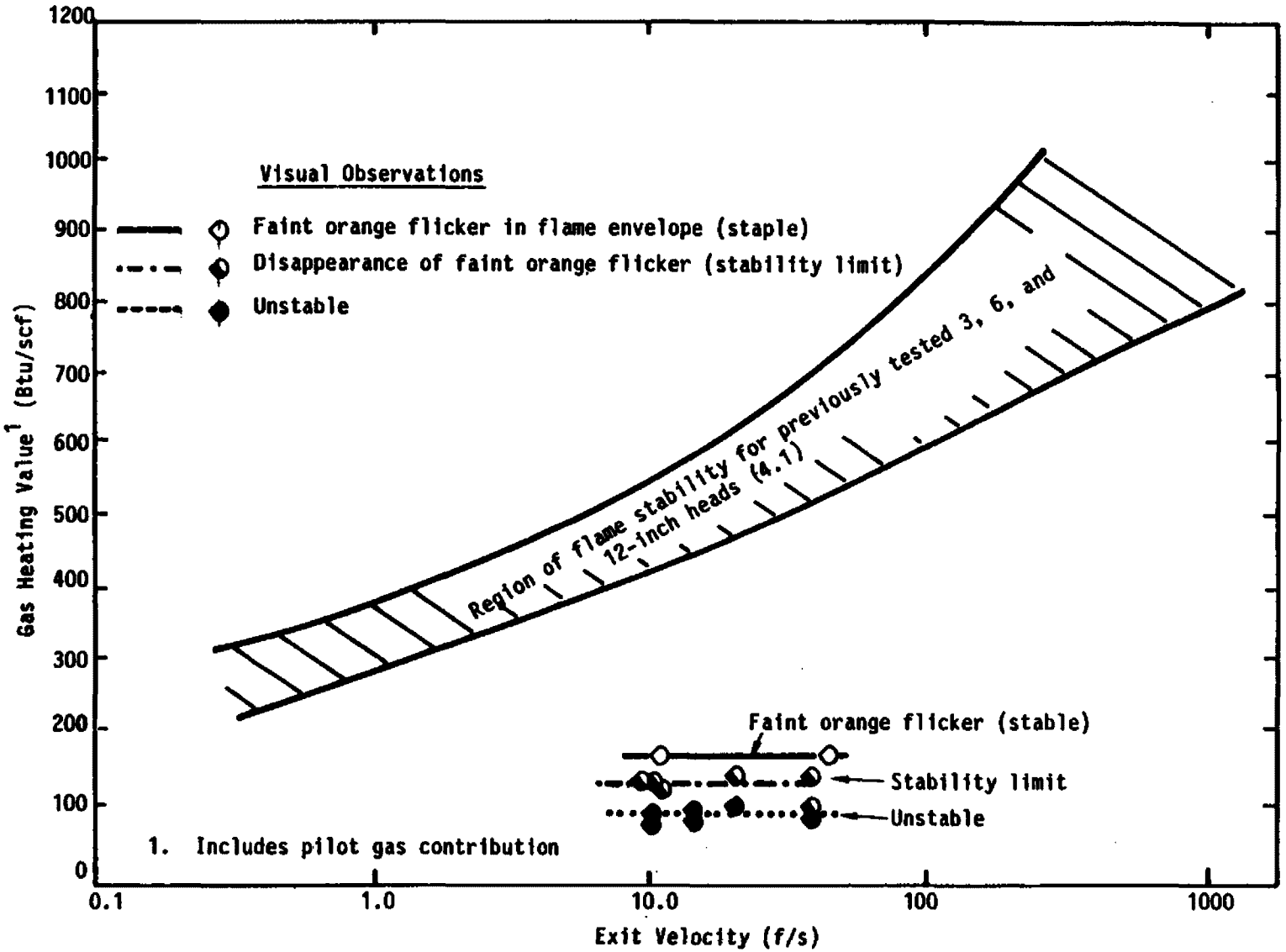


Figure 4-3. Flame stability curves for 6-inch open pipe flare with a single pilot at a pilot gas flowrate of 1.0 - 1.1 scfm natural gas.

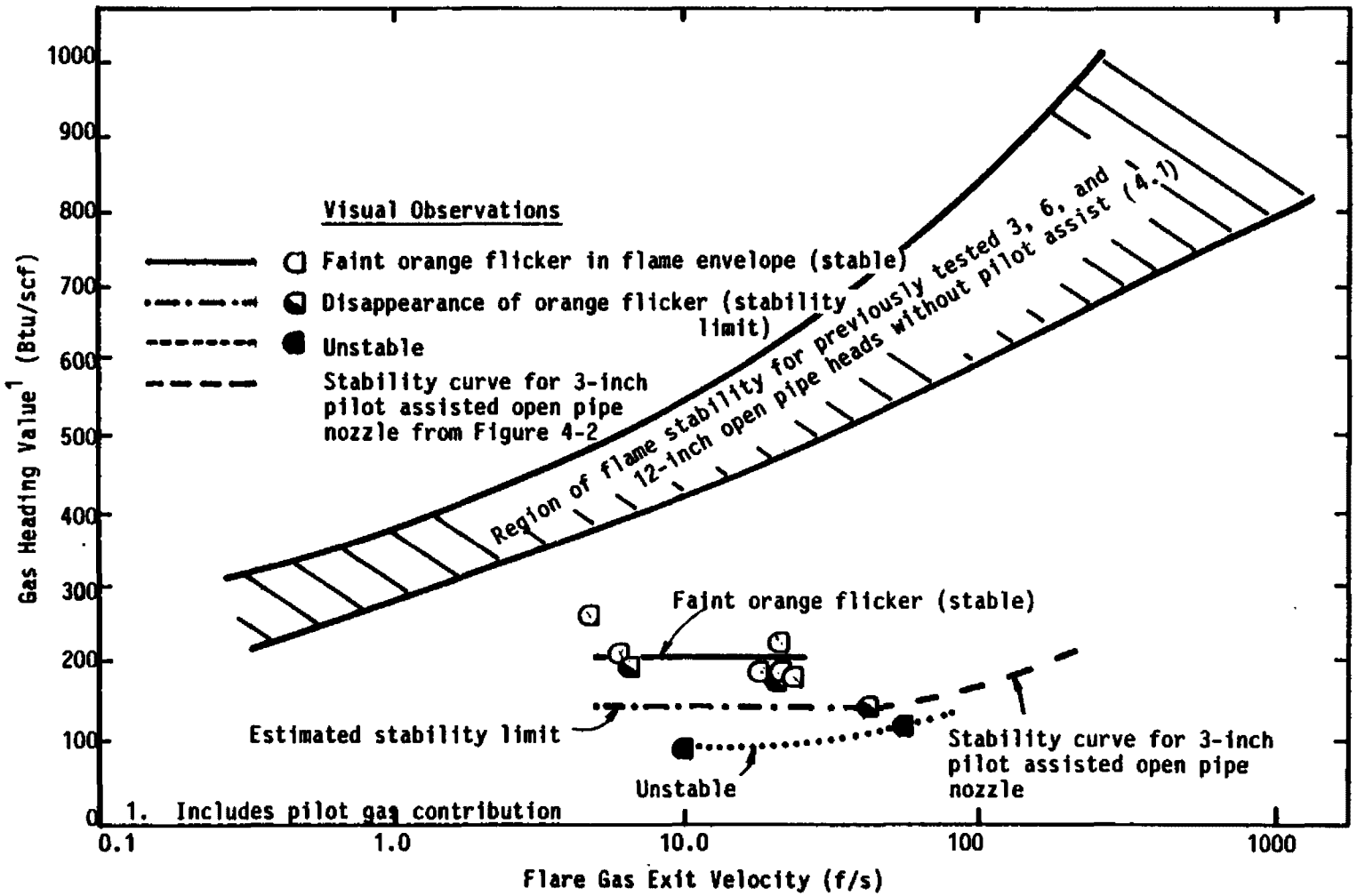


Figure 4-4. Flame stability curves for 6-inch open pipe flare with a single pilot at a pilot gas flowrate of 2.1 - 2.4 scfm natural gas.

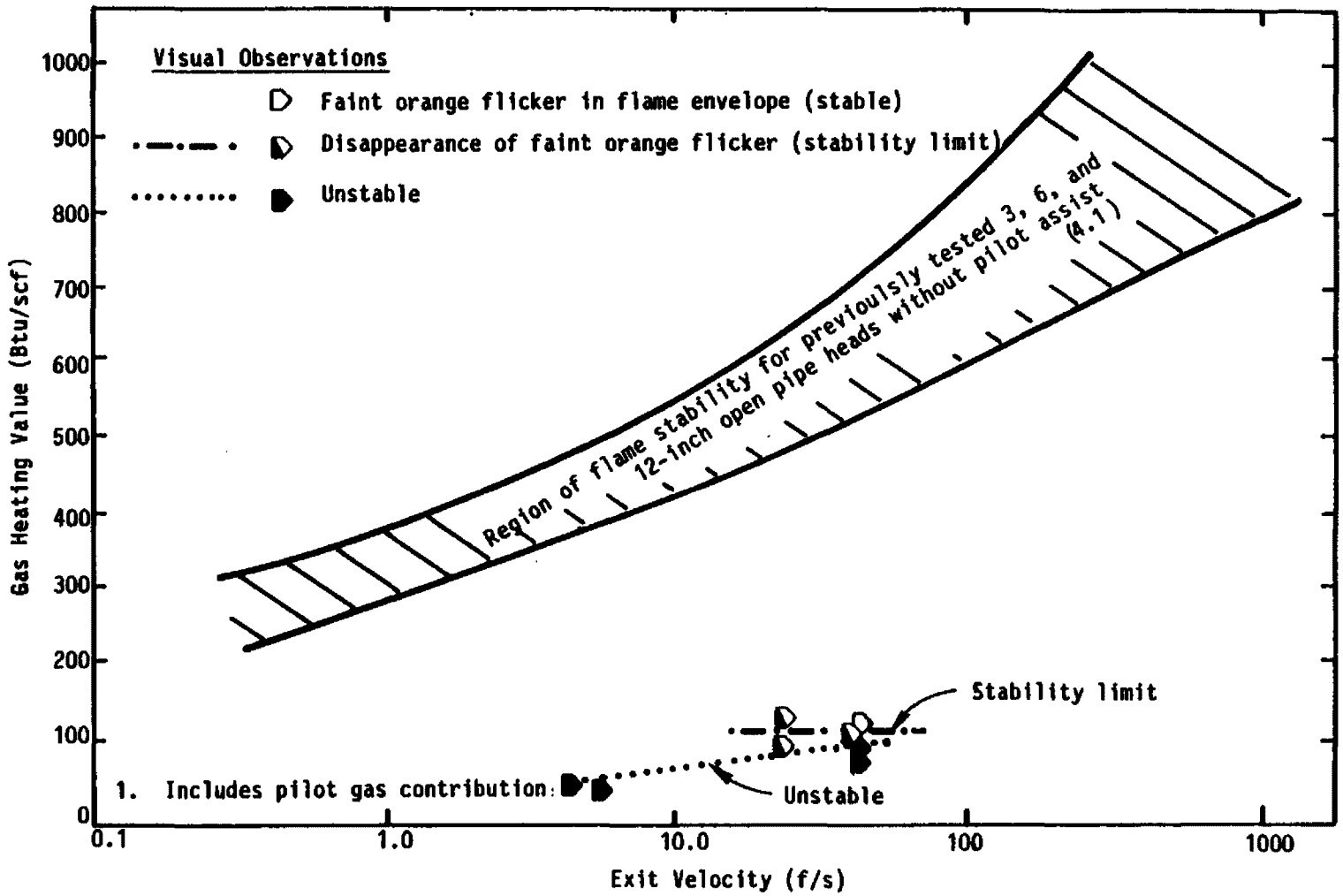


Figure 4-5. Flame stability curves for 6-inch open pipe flare with a single pilot at a pilot gas flowrate of 3.9 - 5.4 scfm natural gas.

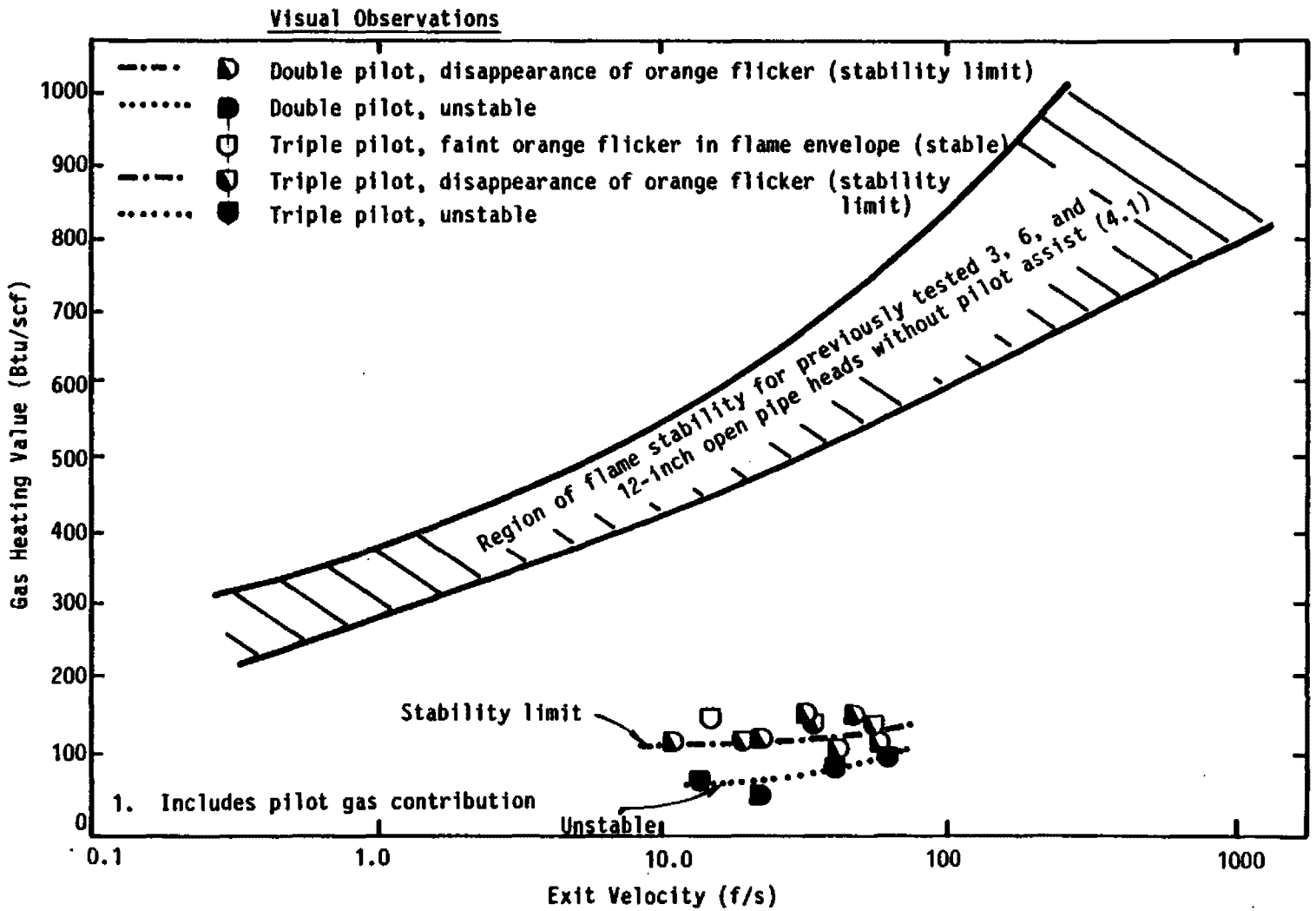


Figure 4-6. Flame stability curve for 6-inch open pipe flare with multiple pilots at a total pilot gas flowrate of 2.0 - 2.3 scfm natural gas.

the 6-inch flare, the same heating value reduction can be attained with the pilot at only 1 scfm. Added pilot assist, however, only marginally increases flame stability. Increasing the pilot gas rate to 5 scfm only reduces the limiting heating value to 120 Btu/scf for the 6-inch flare. Increasing the number of pilots to two or three while keeping the total pilot gas rate constant at 2 scfm decreases the limiting heating value to 130 Btu/scf.

Another indicator of improved flame stability with pilot assist is the calculated adiabatic flame temperature of the gas mixtures flared at or near the stability limit. In Figure 4-7, the maximum stable exit velocity is compared to the adiabatic flame temperature for pilot assisted and non assisted flares tested at EER. The pilot assisted flares could stably burn propane/N_2 gas mixtures with much lower adiabatic flame temperatures than non assisted flares could burn H_2S/N_2, ethylene oxide/N_2, and especially propane/N_2 gas mixtures. The scatter in the data for the pilot assisted tests is apparently due to the increased difficulty in determining the flame stability limit due to fluctuations in ambient conditions and because the flame cannot be extinguished with pilot assist.

4.1.1 Scaling Flame Stability

The quantitative flame stability results discussed above are applicable to flares of similar size and geometry (open-pipe, no aerodynamic or other stabilization devices). There is however a question with regard to the extent that these data are scalable to flares of a larger size. In an earlier study, Pohl and Soelberg (4.1) have reported aerodynamic and flame stability similarities for flare heads sized from 2-1/2 to 12 inches in diameter. Extrapolation of the pilot-assisted results for the 3 and 6-inch heads, with one to three pilots at a pilot gas flowrate range between 1-5 scfm, may be used to predict flame stability for pilot-assisted open pipe flares up to 12 inches in diameter. A conservative prediction would be further limited by (1) using the minimum pilot gas to flare gas volumetric flowrate ratio of these tests (0.002) as the minimum allowable ratio for operation, (2) using three pilots on a 12-inch flare (even though little dependence of stability on number of pilots was observed on the 6-inch head)

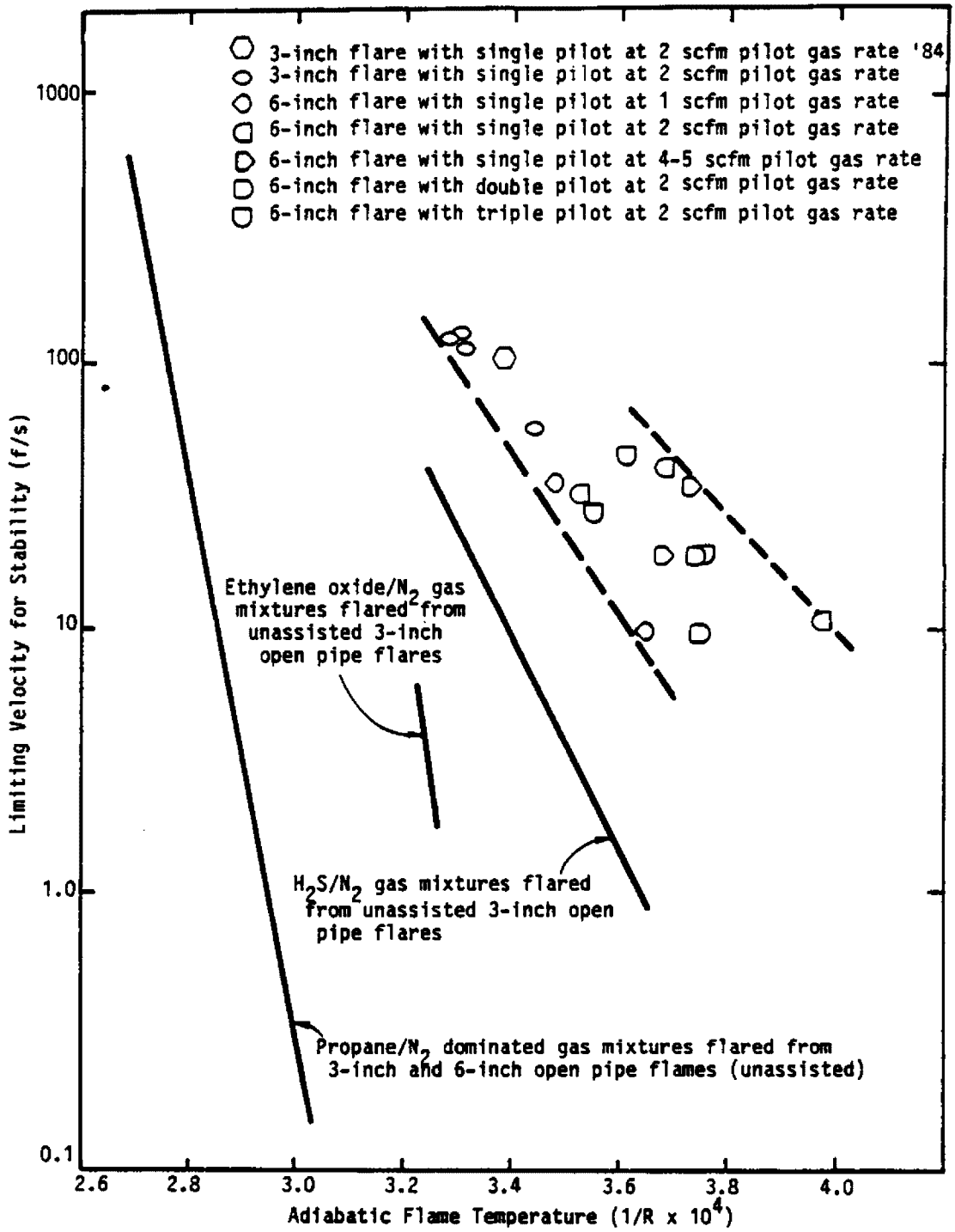


Figure 4-7. Calculated adiabatic flame temperature vs. limiting stable gas exit velocity for propane/N_2 gas mixtures flared using pilot-assisted 3-inch and 6-inch open pipe flares.

for improved mixing, and (3) limiting the maximum exit velocities to ranges tested.

With these limitations, a conservative prediction of minimum heating value is 150 Btu/scf for a stable flame on a 12-inch open pipe flare with three natural gas pilots. The maximum flare gas exit velocity for stability would be about 35 f/s. For velocities above 35 f/s, results from the 3-inch pilot-assisted head tests show increasing heating value limits with increasing velocity, up to a minimum heating value of 240 Btu/scf at 200 f/s. Maintaining the minimum experimental pilot gas/flare gas ratio of 0.002, the minimum total pilot gas rate would be about 20 scfm when the flare gas exit velocity is 200 f/s.

Predictions such as these, although conservative, are based on extrapolations of the pilot scale data. Verification of these predictions by further, larger scale pilot-assisted stability testing is however required before these predictions can be considered valid. Only qualitative results of the test data reported herein can be applied to flares that have aerodynamic or other stability enhancing devices.

4.2 Combustion Efficiency

Previous EER studies have shown that flare combustion efficiency can be related to flame stability. This correlation also holds for the pilot assisted flares with the flame stability limits defined as above, as shown in Figure 4-8. Measured combustion efficiencies for the pilot assisted flares are within approximately the same region of efficiency vs stability ratio already developed for unassisted 3, 6, and 12-inch flares.

Combustion efficiency is greater than 98 percent for stability ratio conditions greater than about 1.2. Combustion efficiency rapidly decreases when the ratio of (heating value)/(minimum heating value required for stability) decreases below about 1.2. The major difference between the pilot assisted and unassisted flares efficiency results is that measurements for the assisted flares were made at very low gas heating values, ranging from

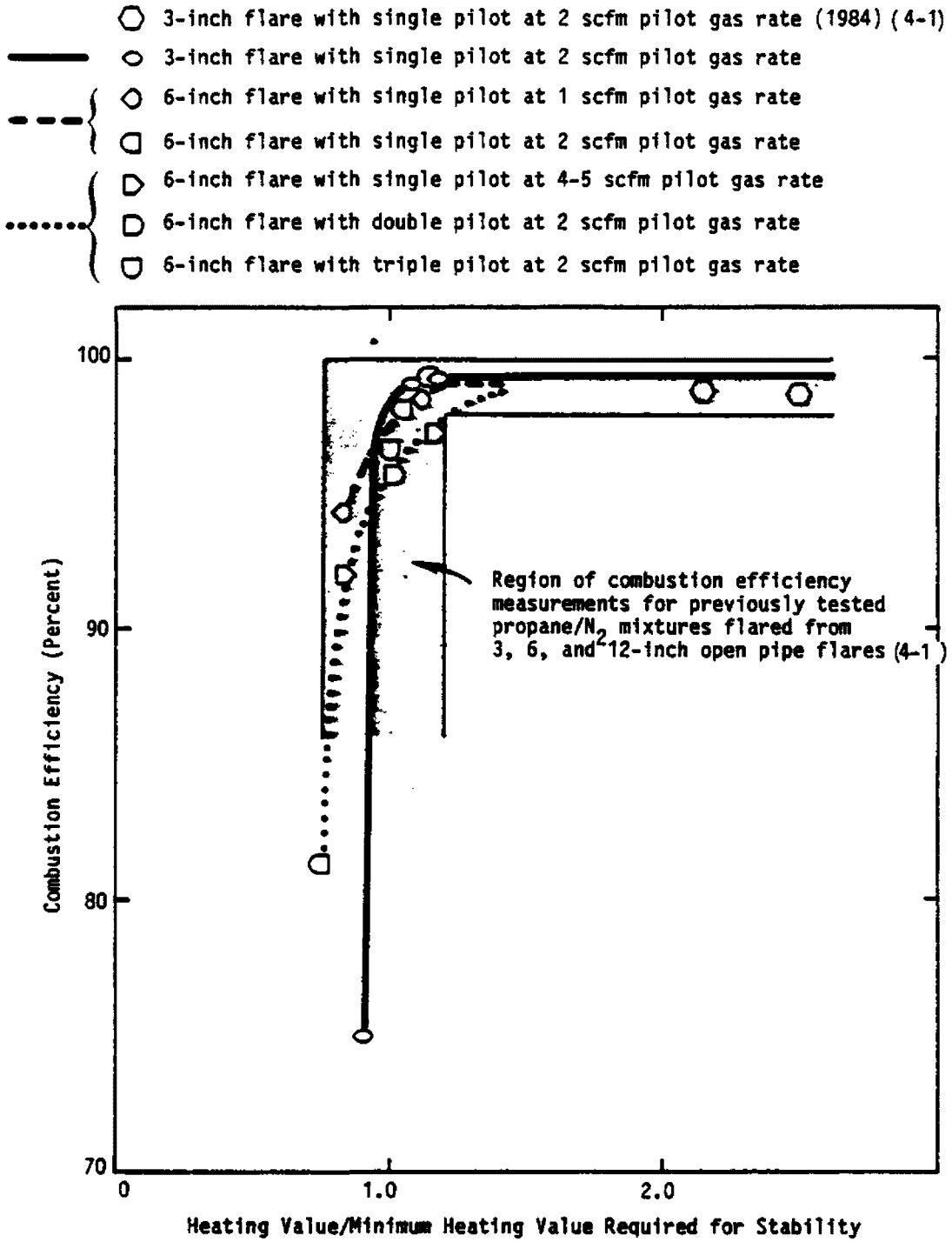


Figure 4-8. Combustion efficiency of pilot-assisted flares.

100-211 Btu/scf while measurements for the unassisted flares made at higher gas heating values of 273-2350 Btu/scf. The stability limits for the pilot assisted flares are much lower than the stability limits at the same gas exit velocities compared to the unassisted flares. However, high combustion efficiency is maintained for the pilot assisted flares until the gas heating value, including the pilot contribution, decreases to within 1.2 times the stability limit heating value.

There are some subtle differences between combustion efficiency performance of the pilot assisted heads. Combustion efficiency greater than 98 percent for the 3-inch pilot assisted flare is maintained even down to a stability ratio of 1.0, demonstrating higher combustion efficiency between 1.0 and 1.2 stability ratio than for the 6-inch pilot assisted head. This could be due to the fact that, for the 3-inch head, the differences between the pilot (and pilot gas flow) are less than for the 6-inch head. Therefore, the impact of the pilot flame is greater on the flame from the 3-inch head than on the flame from the 6-inch head. Also, tests for the 3-inch head were conducted at slightly higher gas heating values than for the 6-inch head, because the stability limit curve for the 3-inch head was not as low as the curves for the 6-inch head.

Below a stability ratio of 1.0, however, the decrease in combustion efficiency for the 6-inch head at the high pilot gas rate and for the double and triple pilot is less rapid than for the 6-inch head with the single pilot at medium and low pilot gas rates, and the 3-inch pilot assisted head. This is because, even at conditions near and below the stability limit, high relative pilot gas rates or multiple pilots can improve otherwise very low combustion efficiency.

4.3 References

4.1 Pohl, J. H. and N. R. Soelberg, "Evaluation of the Efficiency of Industrial Flares: Flare Head Design and Gas Composition," EPA Report No. 600/2-85-106, NTIS No. PB86-100559/AS, 1985.

APPENDIX A

EPA FLARE TEST FACILITY AND PROCEDURES

A.1 Flare Test Facility

The EPA Flare Test Facility (FTF), shown in Figure A-1, was designed and built by EER at their El Toro Test Site for the U.S. Environmental Protection Agency, under EPA Contract No. 68-02-3661. The facility was completed in 1982. The facility is reviewed briefly below, and is described in more detail by Joseph, et al. (A.1) and Pohl, et al. (A.2).

For wind protection, the FTF is located in a box canyon surrounded by 70-foot cliffs. The facility includes gas delivery systems, a flare head mount enclosed in a framework structure supporting (1) screens for additional wind protection, and (2) plume sample probes, and a building containing delivery system controls and analytical instruments. The facility is designed for relief gas flows ranging from 10 to over 40,000 scfh. The maximum flow depends on gas composition.

Gases are delivered to the flare and auxiliary equipment through parallel manifolds shown in Figure A-2. Propane, natural gas, and nitrogen manifolds each have three orifice meters and one small rotameter, each with its own control valve. These manifolds were designed to accurately measure and control a wide range of flowrates. One additional manifold of two parallel orifice meters (not shown) is used to measure the flow of one additional flare gas. The propane, natural gas, and nitrogen manifolds and flow lines are constructed of carbon steel. The flow line and manifold system for the additional flare gas is constructed of stainless steel, for compatability with corrosive gases such as ammonia and hydrogen sulfide.

There are also similar supply systems for steam, sulfur dioxide (tracer) and air. Steam is used (1) for steam-assisted flare tests, (2) in steam heat exchangers for vaporizing sulfur dioxide and flare test gases, and (3) for

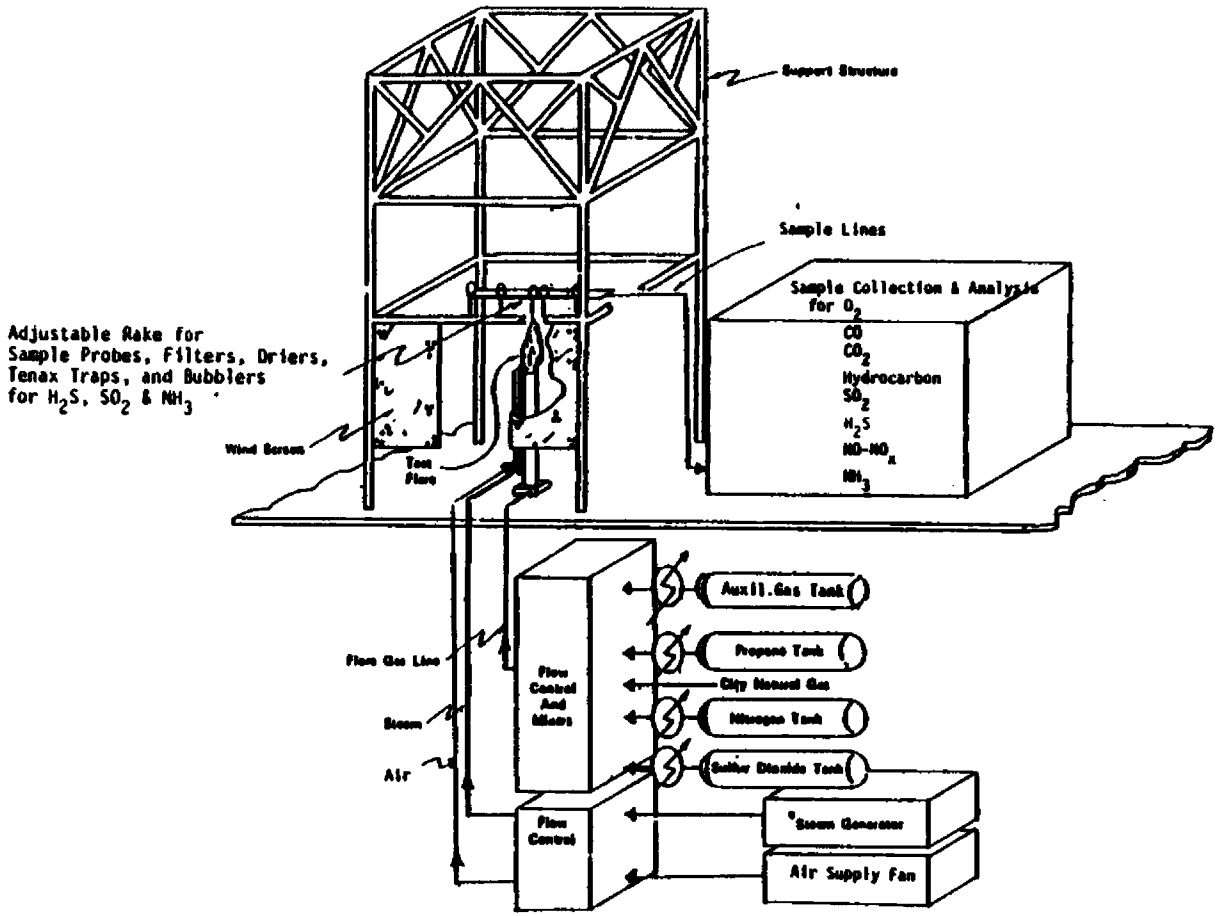


Figure A-1. EPA Flare Test Facility (FTF) at EER.

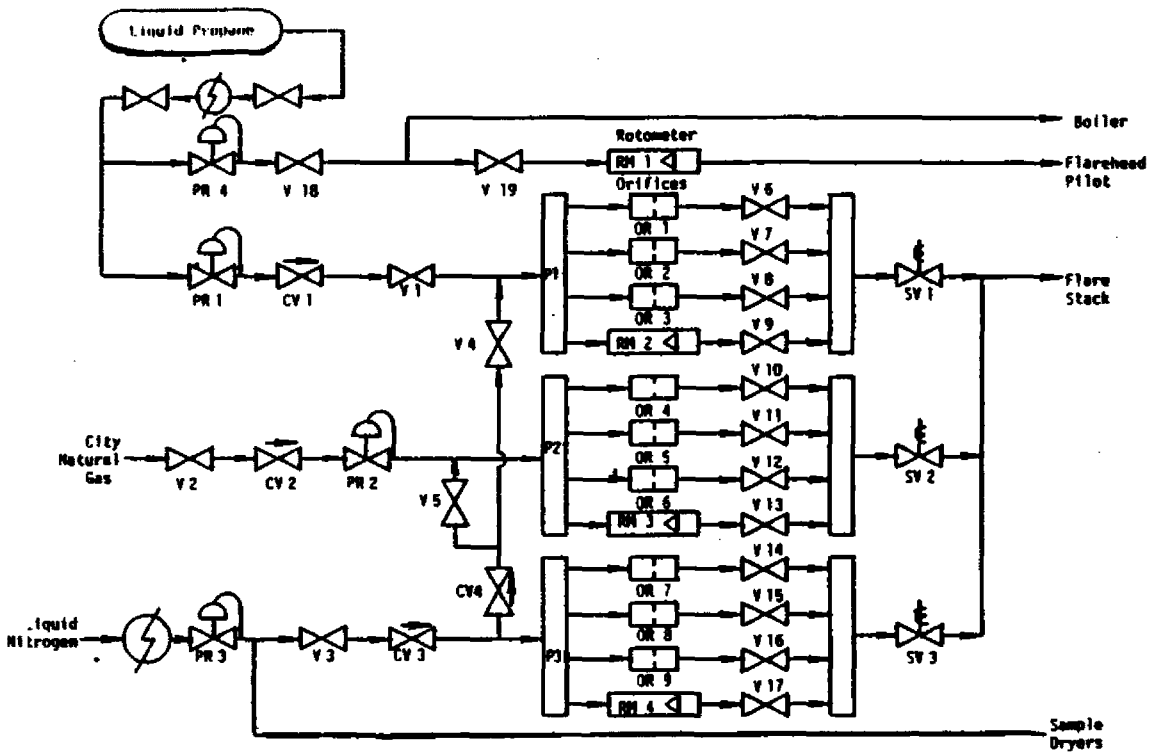


Figure A-2. Fuel flow control and metering system schematic.

sample probe heating. Sulfur dioxide is used as a tracer for flare test mass balances. Air is used during air-assisted flare tests.

Flare and tracer gases (except natural gas) are supplied from cylinders or tanks. Propane is stored as a liquid in a 2,100 gallon tank. At low flowrates, natural vaporization is sufficient to supply propane gas for flaring; at higher flowrates, propane-fired vaporizers are used to increase the propane flowrate up to 15,000 scfh. Natural gas is supplied by the local utility at a maximum flowrate of 7,000 scfh. Nitrogen is delivered from either a liquid nitrogen tank or liquid nitrogen cylinders to banks of finned-tube atmospheric vaporizers capable of providing a maximum nitrogen flowrate exceeding 24,000 scfh. Other liquified flare gases such as hydrogen sulfide are delivered from cylinders and vaporized in a steam heat exchanger. This system can deliver over 4,000 scfh of gas, depending upon the compound.

Steam is produced using a 15 hp gas-fired boiler. The boiler can supply up to 400 lbs/hr of 100 psig saturated steam. Sulfur dioxide, used as an inert tracer, is fed from liquid SO_2 cylinders and vaporized through a steam-heated vaporizer at a flowrate of up to 7 scfh. Air is supplied by a forced-draft fan at a maximum flowrate of 60,000 scfh, at a static pressure of 17.6 inches H_2O.

The sample collection and analysis system is shown in Figure A-3. Plume samples are collected using five stainless-steel, steam-heated probes mounted on a movable rake. Samples are collected concurrently from five different radial locations in the plume. Pumps draw the soot- and moisture-laden samples into the probes, where filters collect the soot for subsequent weight measurement. Membrane tube bundles in Permapure dryers are used to selectively remove water vapor from the sample stream. The dried gas samples are collected in Tedlar bags for analysis of O_2, CO, CO_2, total hydrocarbons, H_2S, SO_2, and NO/NO_x content. Other species such as SO_2, H_2S or NH_3 are concentrated into aqueous solutions in absorption bubblers.

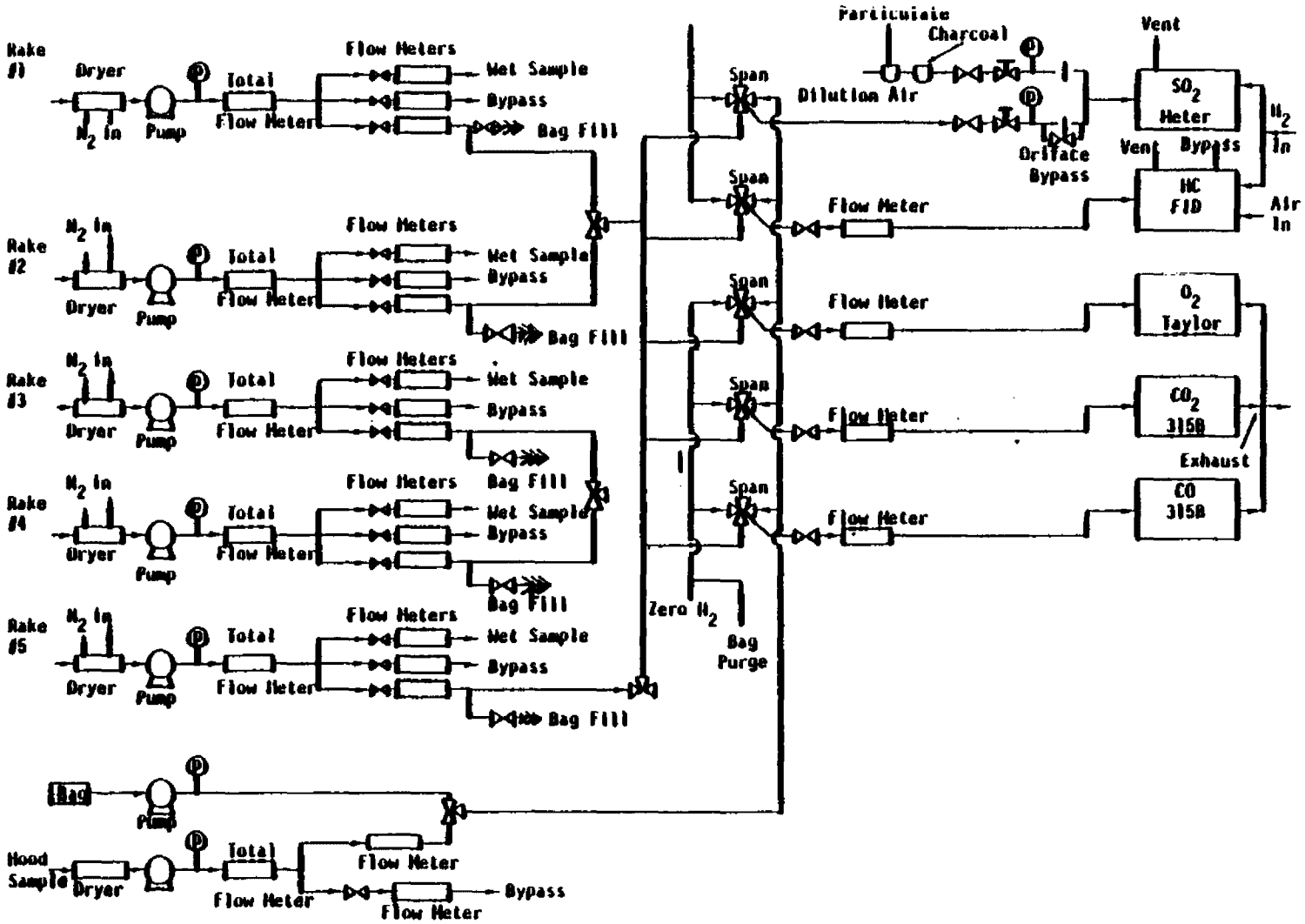


Figure A-3. Flare Test Facility sample system.

A.2 FTF Procedures

The Flare Test Facility (FTF) test procedure includes measuring background conditions, igniting the flame, establishing test conditions, sampling, and analysis. Tests are not conducted in rainy weather or when the wind speed is greater than 5 mph. Most testing is done in the morning, when the weather is calm. A typical test requires about 4 hours, although the actual sample period is only 20 minutes.

Before each test, the ambient air is sampled and analyzed for background levels of O_2, CO, CO_2, hydrocarbons, SO_2, NO/NO_x, soot, and for H_2S or NH_3, if applicable. The flame is then ignited using a hand-held spark igniter or a Zink flame front propagating igniter, and the test conditions are set by adjusting the gas flowrates. Most of the tests were conducted near the stability limit of the flame. The flame stability limit is determined by adjusting the flowrates until the flame becomes unstable and is eventually extinguished.

After test conditions are set, plume samples are collected for 20 minutes in order to time-average perturbations and collect sufficient amounts of sample for analysis. Samples are collected from five different radial locations, at a height above the flame experimentally determined to be beyond the flame envelope. If the probes are too high, air dilution of the samples reduces combustion product measurement accuracy. If the probes are located too low, inside the flame envelope, incompletely burned samples may be collected, which would result in artificially low combustion efficiency measurements.

While the plume is being sampled, the flame structure and other characteristics such as color are recorded visually and photographically. After sample collection and flame observations are complete, the flame is shut down. Sample analysis is then conducted to measure levels of O_2, CO, CO_2, HC, NO/NO_x, soot, and other species in the plume samples.

A.3 References

A.1 Joseph, D., J. Lee, C. McKinnon, R. Payne, and J. Pohl, "evaluation of the Efficiency of Industrial Flares: Background-Experimental Design-Facility", EPA Report No. 600/2-83-070, NTIS No. PB83-263723, August 1983.

A.2 Pohl, J. H., R. Payne, and J. Lee, "Evaluation of the Efficiency of Industrial Flares: Test Results", EPA Report No. 600/2-84-095, NTIS No. PB84-199371, May 1984.

APPENDIX B

FLARE SCREENING FACILITY AND TEST PROCEDURES

B.1 Flare Screening Facility

The laboratory-scale Flare Screening Facility (FSF) is used to inexpensively, quickly, and easily identify potential difficulties in flaring a wide variety of compounds. Advantages of the FSF over the Flare Test Facility are its small size, low operating cost for gases and materials, the ability to obtain complete, undiluted samples of flare combustion products, the ability to close mass balances, and the increased safety for flaring toxic gases. This facility is reviewed briefly below, and is described in more detail by Pohl and Soelberg (B.1).

Figure B-1 shows the FSF schematic. The facility was adapted to burn either liquid or gaseous compounds supplied from pressure cylinders and metered through calibrated rotameters. Combustion air is injected to the reactor co-axially with the fuel stream, through a flow straightening screen. By maintaining a very low air velocity relative to the fuel velocity, effects of the co-current air stream on the fuel stream are minimized. Test results verify that the flame behavior is similar to that of a jet in a quiescent atmosphere.

The flame is completely enclosed in a water-cooled reactor shell, with sample probes located at the reactor outlet. The shell isolates the flame from the environment and prevents air dilution of the flare products. This allows complete mass balance closure over the system. A single sample probe is located at the reactor shell outlet to enable sampling of a well-mixed plume sample.

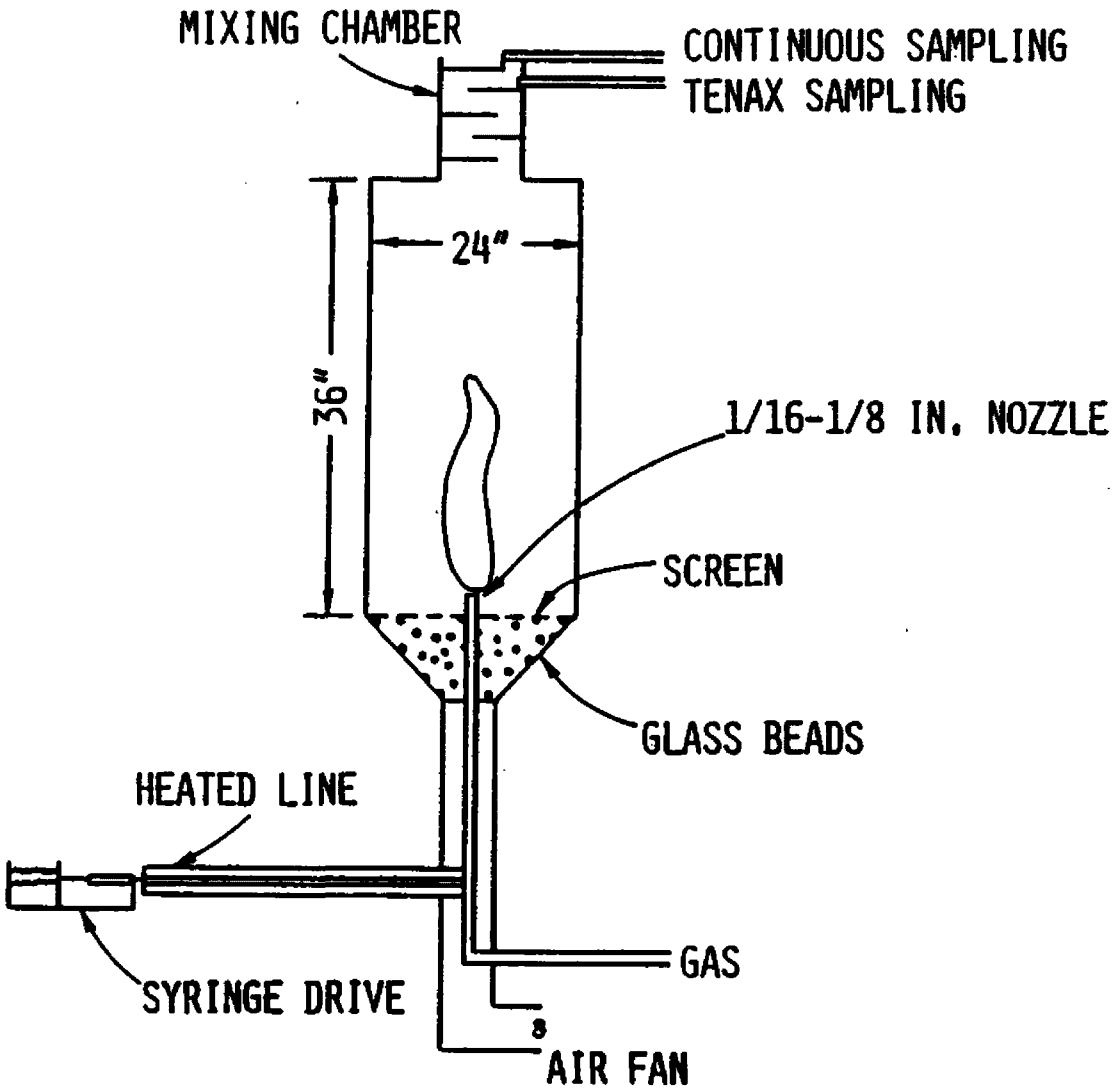


Figure B-1. Flare Screening Facility (FSF).

B.2 FSF Test Procedures

The FSF test procedures are simpler than the FTF test procedures. Since the facility is enclosed, it is not subject to environmental conditions such as wind or rain. The system is smaller and hence, more easily monitored. Probe positioning is unnecessary, since the sample probes are located permanently at the reactor outlet.

For each test, all the instruments are zeroed and calibrated. The flame is ignited by hand, and flow conditions are set. There is some time lapse, depending on the gas flowrates, for flare steady state to be achieved after gas flowrate or mixture changes because of gas residence time in the flowlines. After steady state is reached, sample collection is initiated and visual and photographic flame observations are recorded. Plume samples collected in Tedlar bags are analyzed for O_2, CO, CO_2, total hydrocarbons, H_2S, SO_2, NO/NO_x content, and other species using the instruments shown in Figure A-3. Plume samples are also bubbled through gas scrubber bottles for concentration and subsequent analysis of such species as H_2S, SO_2, and NH_3.

B.3 Reference

B.1 Pohl, J. H. and N. R. Soelberg, "Evaluation of the Efficiency of Industrial Flares: Flare Head Design and Gas Composition", EPA Report No. EPA-600/2-85-106, NTIS No. PB86-100559/AS, September 1985.

APPENDIX C

FLARE FLAME STABILITY LIMIT

C.1 Stability Limits

Previous work (C.1 through C.4) has related flare combustion and destruction efficiency to flame stability. A stable flame exhibits high efficiency. However, as flame conditions approach the stability limit, efficiency can rapidly decrease.

The flame stability limit is defined as the operating condition where an increase in flare gas exit velocity or a decrease in flare gas heating value results in flame blowout. Theoretically, this occurs when the gas velocity is not reduced to the flame velocity before the gas becomes diluted (by air entrainment and mixing) below its lower flammability limit or when the flame speed is less than the imposed velocity.

A characteristic exit velocity vs heating value curve, maintaining all other conditions constant, can be generated for each flare head and gas mixture combination. This curve is generated by determining the minimum gas heating value attainable before flame blowout, for a range of different gas exit velocities. At exit velocity and heating value combinations above this curve, a flame will be present; at conditions below the curve, there will be no flame.

C.2 References

C.1 Pohl, J. H., R. Payne, and J. Lee, "Evaluation of the Efficiency of Industrial Flares: Test Results", EPA Report No. 600/2-84-095, NTIS No. PB84-199371, May 1984.

C.2 Pohl, J. H., J. Lee, R. Payne and B. Tichenor, "The Combustion Efficiency of Flares", 77th Annual Meeting and Exhibition of the Air Pollution Control Association, San Francisco, CA, June 1984.

C.3 Pohl, J. H. and N. R. Soelberg, "Evaulation of the Efficiency of Industrial Flares: Flare Head Design and Gas Composition"; EPA Report No. EPA-600/2-85-106, NTIS No. PB86-100559/AS, September 1985.

C.4 Pohl, J. H., N. R. Soelberg and E. Poncelet, "The Structure of Large Buoyant Flames", American Flame Research Committee Fall Meeting, Livermore, CA, 16-18 October 1985.

APPENDIX D

DATA ANALYSIS

D.1 FTF Data Analysis

Data reduction and analysis must be conducted on the flare test results to determine flare combustion efficiency. Results of FTF tests must be corrected for background levels of sampled species and air dilution of the plume. Also, numerical integration must be conducted using the local probe measurements and velocities calculated from jet theory. The development and details of the Flare Test Facility data analysis procedures are already reported (D.1, D.2) so only a summary is provided here.

Data reduction is conducted on the FTF plume sample results to determine local air dilution of the combustion products, local combustion and destruction efficiencies, and integrated overall average combustion and destruction efficiencies. The local dilution factor is:

$$DF = \frac{Y_m - Y_{af}}{Y_b - Y_m} \qquad \text{D-1}$$

where DF = dilution factor = volume of air in the local sample divided by the volume of stoichiometric combustion products.

Y = local concentration of O_2, CO_2, or SO_2 (tracer)

m = measured in plume

af = air-diluent-free, stoichiometric basis

b = background

Combustion efficiency is defined as the degree to which all fuel materials have been completely oxidized. The local combustion efficiency is based upon local probe measurements of plume constituents, whereas the

integrated average combustion efficiency is calculated by integrating the local plume fluxes to obtain average compositions of plume species. Since local plume measurements are diluted by ambient air, they must be corrected for the background levels of plume species in the ambient air. These corrections are made using equation D-2:

$$Y_{h,c} = Y_{h,m} - \left(\frac{DF}{DF+1}\right) Y_{h,c} \qquad \text{D-2}$$

where h = plume species
c = corrected

Local combustion efficiency (CE) can then be calculated using equation D-3:

$$CE = 1 - \frac{\Sigma_i \, \nu_i \, Y_{i,c}}{\Sigma_j \, \nu_j \, Y_{j,c}} \qquad \text{D-3}$$

where ν = stoichiometric coefficient
i = incompletely burned species
j = completely and incompletely burned species

Local destruction efficiency is similar to local combustion efficiency, but is a measure of the degree of destruction of the particular fuel material. It is equal to the combustion efficiency for that species only when there are no incompletely burned intermediates, such as CO or soot for hydrocarbon species. Local destruction efficiency (DE) for a fuel species is calculated using equation D-4:

$$DE = 1 - \frac{Y_{k,c}}{\Sigma_l \mu_l \; Y_{l,c}} \qquad \text{D-4}$$

where k = fuel species

l = completely and incompletely burned species from the fuel species.

Integrated average combustion and destruction efficiencies are computed by first combining the local corrected plume composition with the local plume velocity to obtain a local corrected mass flux for each plume constituent. The local corrected plume species concentrations are found using equation D-2, and the local plume velocity is calculated from jet theory using equations D-5 and D-6:

$$V_{r,x} = V_{max} \exp\left[-5 \frac{R_r}{X}^{2}\right] \qquad \text{D-5}$$

$$V_{max} = V_o \left[0.16 \left(\frac{X}{d}\right) - 1.5\right] \qquad \text{D-6}$$

where V = velocity

R = radial distance from plume centerline

X = probe axial distance above flare head

r = radial position

max = maximum

o = flare head outlet

Numerical integration of the local fluxes is used to calculate average combustion and destruction efficiencies using equations D-7, D-8, and D-9:

$$CE = 1 - \frac{\Sigma_r \Sigma_i \nu_i Y_{i,c} V_r A_r}{\Sigma_r \Sigma_j \nu_j Y_{j,c} V_r A_r} \qquad \text{D-7}$$

$$DE = 1 - \frac{\Sigma_r Y_{k,c} V_r A_r}{\Sigma_r \Sigma_l \nu_l Y_{l,c} V_r A_r} \qquad \text{D-8}$$

$$A_r = \pi(R_{r+1} - R_r) \qquad \text{D-9}$$

where A_r = radial area sampled by probe r (Figure D-1).

D.2 FSF Data Analysis

Data analysis for the Flare Screening Facility (FSF) test results is much simpler than for the Flare Test Facility (FTF) test results. The FSF flare flame is completely enclosed within a steel reactor shell. The inlet fuel and combustion air flowrates are metered, so the plume flowrates of excess air and air-free combustion products can be directly calculated based upon the combustion stoichiometry of the gas:

$$\dot{V}_{e.a.} = (SR-1)\ \dot{V}_{r.a.} \qquad \text{D-10}$$

where $\dot{V}$ = volumetric flowrate, scfh
e.a. = excess air
S.R. = stoichiometric ratio
r.a. = required air for 100% combustion

$$\dot{V}_p = \dot{V}_g \Sigma_i \nu_i P_i \qquad \text{D-11}$$

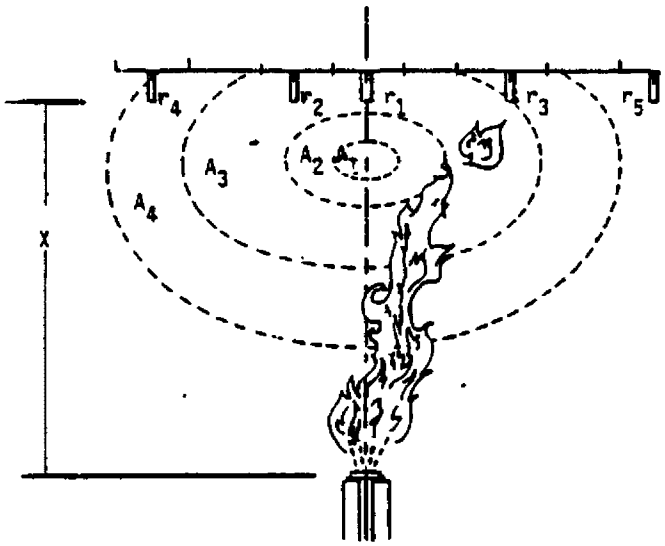


Figure D-1. Schematic of integration geometry.

where p = stoichiometric products of combustion with air (air-free basis, 0 percent O_2)

g = inlet gas

ν = stoichiometric coefficient

i = combustion product species "i"

$$\dot{V}_t = \dot{V}_{e.a.} + \dot{V}_p \qquad \text{D-12}$$

where t = total plume

This approach assumes 100 percent combustion, in order to determine the excess air, combustion product, and total plume flowrates. The same assumption was used in data reduction of the pilot-scale tests. Where combustion is only slightly less than 100 percent, flowrate errors due to this assumption are small. Even where combustion is significantly less than 100 percent, the error in total plume flowrate is small, because a majority of the plume gas is nitrogen, unaffected by combustion efficiency (discounting $N_2 \rightarrow NO_x$ reactions and combustion of nitrogen-containing fuel species, D.2).

The plume is sampled at the reactor exit, where the plume is well mixed. This eliminates the need for collection of multiple local plume samples across the plume radius, assumptions of local velocities at radial locations in the plume, and the integration of local species fluxes to calculate total plume species flowrates, because species concentrations in the plume sample are representative of average plume concentrations. Species flowrates in the plume are calculated using the measured concentrations and the plume flowrate found from equation D-13:

$$\dot{V}_i = \dot{V}_t \, Y_i \qquad \text{D-13}$$

where Y = mole fraction

In cases of high combustion efficiency, the plume concentration levels of incompletely combusted species such as CO and hydrocarbons are near background levels. The plume species flowrates must then be corrected by subtracting the background contribution:

$$\dot{V}_{i,c} = \dot{V}_i - \dot{V}_a Y_{i,b} \qquad \text{D-14}$$

where c = corrected
b = background

Combustion and destruction efficiencies are calculated using equations D-15 and D-16.

$$CE = 1 - \frac{\Sigma_i \nu_i \dot{V}_{i,c}}{\Sigma_j \nu_j \dot{V}_{i,c}} \qquad \text{D-15}$$

where i = incompletely burned species
j = incompletely and completely burned species

$$DE = 1 - \frac{\dot{V}_{k,c}}{\Sigma_l \nu_l \dot{V}_{l,c}} \qquad \text{D-16}$$

where k = fuel species
l = incompletely and completely burned species that came from the fuel species

D.3 References

D.1 Pohl, J. H., R. Payne, and J. Lee, "Evaluation of the Efficiency of Industrial Flares: Test Results", EPA Report No. 600/2-84-095, NTIS No. PB84-199371, May 1984.

D.2 Pohl, J. H. and N. R. Soelberg, "Evaluation of the Efficiency of Industrial Flares: Flare Head Design and Gas Composition", EPA Report No. EPA-600/2-85-106, NTIS No. PB86-100559/AS, September 1985.

APPENDIX E

QUALITY ASSURANCE

E.1 Flowrate Measurement

The flare gases used at both the Flare Test Facility and the Flare Screening Facility were prepared by mixing the pure components. Accurate measurement and flow control of the pure gases was required to prepare the desired flare gas composition and operate the flare at the desired gas exit velocity. Accurate flowrate measurement and control over a very wide range was achieved by using banks of calibrated parallel-flow square-edged orifice plates at the Flare Test Facility. For the smaller-scale Flare Screening Facility, banks of parallel-flow rotameters were used for accurate flowrate measurements.

Each of the orifice plates used at the Fare Test Facility was calibrated using the working gas for that orifice and a standard pre-calibrated laminar flowmeter, dry gas meter, or wet test meter to obtain the flow coefficient for that particular orifice and gas. This orifice coefficient was used in equation E-1 for flowrate measurement:

$$\dot{V} = K \left(\frac{P \Delta P}{MW\ T} \right)^{1/2} \qquad \text{E-1}$$

where $\dot{V}$ = flowrate, scfm

K = orifice coefficient

P = static orifice pressure, psia

ΔP = orifice differential pressure, feet H_2O column

MW = gas molecular weight

T = orifice temperature, R.

The standard deviation of K for 13 different orifices used in this test program was less than 5.4 percent, and less than 3.0 percent for the majority.

A similar procedure was used to calibrate the rotameters used for flowrate measurement in the Flare Screening Facility. Each rotameter was calibrated using the working gas and pre-calibrated dry gas meters, wet test meters, or water displacement columns. Variations in pressure and temperature between the calibrated and actual operating values were corrected for using equation E-2:

$$\dot{V}_2 = \dot{V}_1 \left(\frac{P_2 \; T_1}{P_1 \; T_2} \right)^{1/2} \qquad \text{E-2}$$

where subscript 1 is for conditions during the calibration, and subscript 2 is for operating conditions.

E.2 Sample Analysis

Accurate sample analysis is critical for determining reliable combustion and destruction efficiency results. Table E-1 shows the analytical methods, instruments, and accuracies used in this test program. The listed accuracies are for the concentration ranges most typically encountered at the Flare Test Facility. Accuracy for a specific method may change if concentration levels for the sampled species are outside the ranges listed in Table E-1.

Many of the analytical methods of Table E-1 were developed in previous EER flare studies (E.1, E.2), but methods for H_2S and SO_2 measurement were evaluated in this study. Results of these evaluations are reported in Section 3 of this report. Only the most reliable of these methods were used for H_2S and SO_2 measurements in the typical ranges observed at the Flare test Facility shown in Table E-1.

TABLE E-1. FLARE FACILITY ANALYTICAL METHODS

SPECIES	INSTRUMENT	PRINCIPLE	RANGE	ACCURACY	MEASURED CONCENTRATIONS
O_2	Taylor 570A	Paramagnetism	0-100%	±0.2% of Measured	18-21%
CO	Beckman 315A	NDIR	0-2%	±0.1 ppm	3-500 ppm
CO_2	Beckman 315B	NDIR	0-20%	±0.02% of Measured	0.05-2%
Total Hydrocarbons	Beckman 400	FID	0-5000 ppm	±0.5 ppm	3-1300 ppm
H_2S	Draeger Tubes	Color-Indicating Chemical Reaction	0.5-2000 ppm	±20% of Measured	0-1000 ppm
	Colorimeter	Methylene blue Reaction	0.5-20 ppm	±50% of Measured	
SO_2	Draeger Tubes	Color-Indicating Chemical Reaction	0.5-5000 ppm	±20% of Measured	0-1000 ppm
	Barium Perchlorate Titration	Barium Perchlorate Reaction	1-2000 ppm	±15% of Measured	
NH_3	Ion-Specific Electrode	Ionic Potential	0.1-10 ppm	±15% of Measured	0.1-0.6 ppm
NO/NO_x	Teco 14B-E	Chemiluminescence	0.05-10 ppm	±5% of Measured	0.02-10 ppm
Particulate	Filter	Timed Collection	$0-10^{-6}$ lb/cf	±10% of Measured	$10^{-8}-10^{-6}$ lb/cf

E.3 References

E.1 Joseph, D., J. Lee, C. McKinnon, R. Payne, and J. Pohl, "Evaluation of the Efficiency of Industrial Flares: Background-Experimental Design-Facility", EPA Report No. 600/2-83-070, NTIS No. PB83-263723, August 1983.

E.2 Pohl, J. H., R. Payne, and J. Lee, "Evaluation of the Efficiency of Industrial Flares: Test Results", EPA Report No. 600/2-84-095, NTIS No. PB84-199371, May 1984.

APPENDIX F

CONVERSION FACTORS

To Convert From English		To Metric		Multiply By
Btu	British Thermal Unit	kJ	Kilojoule	1.055
cfm	Cubic Feet per Minute	m^3/h	Cubic Meters per Hour	1.700
in	Inch	m	Meter	0.0254
in H_2O	Inches Water Column	Pa	Pascal	249
psi	Pounds per Square Inch	Pa	Pascal	6893
ft	Foot	m	Meter	0.3048
cf	Cubic Foot	m^3	Cubic Meter	0.02832
lb	Pound	kg	Kilogram	0.4536
mph	Miles per Hour	km/h	Kilometers per Hour	1.609

Degrees Rankine (R) is converted to degrees Celsius (C) via the following formula:

$$C = 5/9 (R - 492)$$

Degrees Fahrenheit (F) is converted to degrees Celsius (C) via:

$$C = 5/9 (F - 32)$$

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16. ABSTRACT The report is the fourth in a series on a research program which will result in quantification of emissions from, and efficiencies of, industrial flares. The report gives test data on the combustion efficiency and destruction efficiency of (1) gas mixtures containing H2S, and (2) flare flames with pilot flame stabilization. (NOTE: Previous reports were limited to tests burning propane/N2 mixtures on pipe flares without pilot flare stabilization, and discussed the influence of the flared gas and flare head design on destruction and combustion efficiency without stabilization by pilot flares.) The latest tests, conducted on 3- and 6-in. open pipe flares without aerodynamic flame stabilization devices, led to conclusions including: (1) gas mixtures of H2S/N2 can be stably flared at much lower volumetric gas heating values than can propane/N2 mixtures; (2) destruction and combustion efficiencies greater than 98% are obtained for gas mixtures of H2S/N2 and H2S/propane/N2 when the gas heating value is at least 1.2 times the level required to produce a stable flame; (3) for mixtures containing both H2S and propane, H2S destruction efficiency was consistently higher than propane combustion efficiency; and (4) combustion efficiencies greater than 98% for pilot assisted flares are achieved when the heating value is greater than 1.2 times that required to stabilize the flame.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Flames	Stationary Sources	21B
Hydrogen Sulfide	Industrial Flares	07B
Nitrogen	Flame Stabilization	
Propane		07C

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