FLARE EFFICIENCY STUDY

by

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ABSTRACT

A full-scale experimental study was performed to determine the efficiencies of flare burners as devices for the disposal of hydrocarbon emissions from refinery and petrochemical processes. The primary objectives of the study were to determine the combustion efficiency and hydrocarbon destruction efficiency for both air- and steam-assisted flares under a wide range of operating conditions. Test results indicate that flaring is generally an efficient hydrocarbon disposal method for the conditions as evaluated. The study provides a data base for defining the air quality impact of flaring operations.

The test methodology utilized during the study employed a specially constructed 27-foot sample probe suspended by a crane over the flare flame. The sample extracted by the probe was analyzed by continuous emission monitors to determine concentrations of carbon dioxide (CO_2), carbon monoxide (CO), total hydrocarbons (THC), sulfur dioxide (SO_2), oxides of nitrogen (NO_x), and oxygen (O_2). In addition, the probe tip temperature, ambient air temperature, and wind speed and direction were measured. Integrated samples of the relief gas were collected for hydrocarbon species analysis by gas chromatograph. Particulate matter samples were also collected during the smoking flare tests.

The rigorous test program included flare testing under thirty-four different operating conditions during a three-week period in June 1982. Test variables included Btu content of the relief gas (propylene diluted with nitrogen), relief gas flow rates, steam flow rates, and air flow rates. When flares were operated under conditions representative of good industrial operating practices, the combustion efficiencies at the sampling probe were determined to be greater than 98 percent. Combustion efficiencies were observed to decline under conditions of excessive steam (steam quenching) and high exit velocities of low Btu gases.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

AGL	-- Above ground level
Btu	-- British thermal unit
Btu/hr	-- British thermal unit per hour
Btu/min	-- British thermal unit per minute
Btu/SCF	-- British thermal unit per standard cubic foot
FEP	-- fluro elastic polymer
ft/min	-- feet per minute
HP	-- horsepower
ID	-- inside diameter
in^2	-- square inch
lbs/hr	-- pounds per hour
l/g	-- liters per gram
mg/l	-- milligrams per liter
OD	-- outside diameter
PPM	-- parts per million by volume
psia	-- pounds per square inch absolute
psig	-- pounds per square inch gauge pressure
SCFM	-- standard cubic feet per minute @ 14.7 psia and 70°F

SYMBOLS

CO	-- carbon monoxide
CO_2	-- carbon dioxide
N_2	-- nitrogen
NO_x	-- nitrogen oxides
O_2	-- oxygen
SF_6	-- sulfur hexafluoride
SO_2	-- sulfur dioxide
THC	-- total hydrocarbon

SECTION 1

INTRODUCTION

This document is a report on an experimental study to determine the efficiencies of flare burners as devices for the control of continuous hydrocarbon emissions. The primary objectives of this study were to determine the combustion efficiency and hydrocarbon destruction efficiency for both air- and steam-assisted flares over a wide range of operating conditions that might be encountered in continuous low flow industrial applications. The study excluded abnormal flaring conditions which might represent large hydrocarbon releases during process upsets, start-ups and shutdowns.

Both government and industry environmental officials are concerned with the effects of flaring hydrocarbons on the air quality. However, since flares do not lend themselves to conventional emission testing techniques, few attempts have been made to characterize flare emissions. Flare emission measurement problems include: the effects of high temperatures and radiant heat on test equipment, the meandering and irregular nature of flare flames due to external winds and intrinsic turbulence, the undefined dilution of flare emission plume with ambient air, and the lack of suitable sampling locations due to flare and/or flame heights, especially during process upsets when safety problems would predominate.

Previous flare efficiency studies did not encompass the range of variables encountered in the industrial setting. Limited test conditions of flare types, relief gas types, Btu content, relief gas flow rate, and steam-to-relief gas ratios were explored. This study was intended to add to the available literature on the subject by testing the flaring of an olefin (propylene) in both air- and steam-assisted flares with test variables of relief gas flow rate, relief gas Btu content, and steam-to-relief gas ratio.

Separate elements of this flare efficiency study were sponsored by the U.S. Environmental Protection Agency (EPA) and the Chemical Manufacturers Association (CMA). Other project participants included John Zink Company who provided flares, test facility and flare operation, and Optimetrics, Inc. who operated the EPA's Remote Optical Sensing of Emissions (ROSE) system. Engineering-Science, Inc. (ES) operated the extractive flare sampling and analysis systems and prepared this report.

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SECTION 2

CONCLUSIONS

TECHNICAL SUMMARY

Figure 1 is an overview of the equipment used to operate and test the flares. The test methodology utlized during the study employed a specially constructed 27-foot sample probe suspended by a crane over the flare flame. The sample extracted by the probe was analyzed by continuous emission monitors to determine concentrations of carbon dioxide (CO_2), carbon monoxide (CO), total hydrocarbons (THC), sulfur dioxide (SO_2), oxides of nitrogen (NO_x) and oxygen (O_2). In addition, the probe tip temperature, ambient air temperature and wind speed and direction were measured. Integrated samples of the flare plume were collected for hydrocarbon species analysis by gas chromatograph. Particulate matter samples were collected during the smoking flare tests. Sulfur use was attempted as a tracer material in an effort to determine the dilution of the relief gas between the flare burner and the sampling probe location. However, the implementation of this unproven sulfur balance method for determining dilution ratios was unsuccessful.

The term "combustion efficiency" was used during this study as the primary measure of the flares' performance. Conceptually, this term defines the percentage of flare emissions that are completely oxidized to CO_2. Mathematically the combustion efficiency is defined as:

$$\% \text{ CE} = \frac{CO_2}{CO_2 + CO + THC + Soot} \times 100$$

Where:

CO_2 = parts per million by volume of carbon dioxide

CO = parts per million by volume of carbon monoxide

THC = parts per million by volume of total hydrocarbon as methane

Soot = parts per million by volume of soot as carbon[*].

Table 1 summarizes the results of the flare efficiency tests. The rigorous test program included flare testing under thirty-four different operating conditions during a three-week period in June 1982. Test variables included Btu content of the relief gas (propylene diluted with nitrogen), relief gas flow rates, steam flow rates and air flow rates. Five of the thirty-four tests were divided into thirteen subtests for purposes of data analysis because the flare operation did not represent steady-state conditions. The Btu content of the relief gas was varied from 2,183 to 192 Btu/SCF for the steam-assisted flare, and from 2,183 to 83 Btu/SCF for the air-assisted flare. The relief gas flow

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[*] In most cases, the "soot" term was zero.
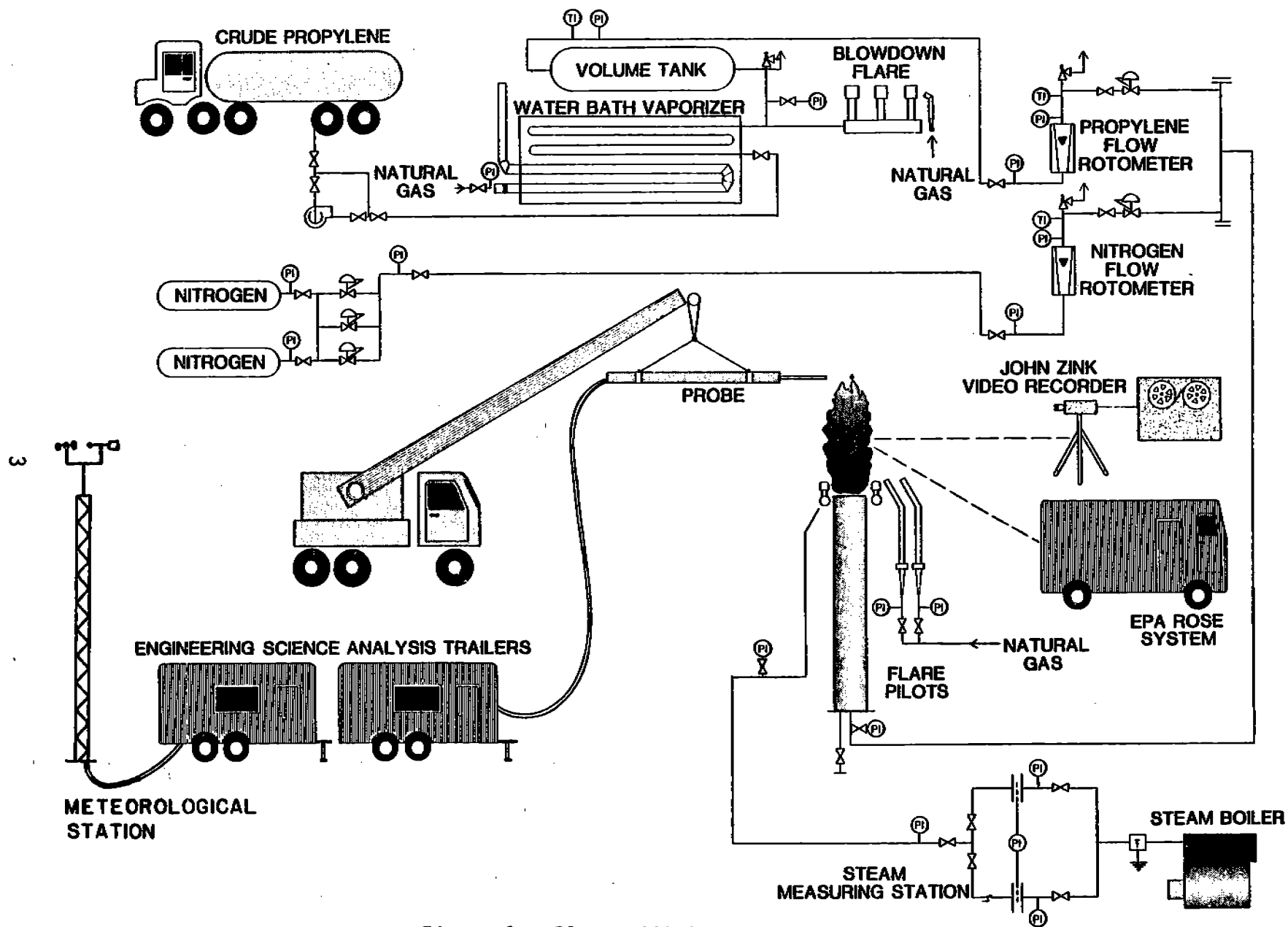
Figure 1. Flare efficiency test systems.

TABLE 1. FLARE EFFICIENCY TEST RESULTS

Test Number	Relief Gas		Steam-to-Relief Gas Ratio (Lb/Lb)	Combustion Efficiency (%)	Comments
	Flow (SCFM)	Heating Value (Btu/SCF)			
STEAM-ASSISTED FLARE TESTS					
1	473	2183	0.688	99.96	
2	464	2183	0.508	99.82	
3	456	2183	0.448	99.82	Incipient smoking flare
4	283	2183	0	99.80*	Smoking flare
8	157	2183	0	98.81*	Smoking flare
7	154	2183	0.757	99.84	Incipient smoking flare
5	149	2183	1.56	99.94	
67	148	2183	0.725	--	Sampling probe in flare flame
17	24.5	2183	0.926	99.84	
50	24.4	2183	3.07	99.45	
56	24.5	2183	3.45	99.70	
61	25.0	2183	5.67	82.18	Steam-quenched flame
55	24.7	2183	6.86	68.95	Steam-quenched flare
57	703	294	0.150	99.90	
11a	660	305	0	99.79	
11b	599	342	0	99.86	
11c	556	364	0	99.82	
59a	591	192	0	97.95	
59b	496	232	0	99.33	
60	334	298	0	98.92	
51	325	309	0.168	98.66	
16a	320	339	0	99.73	No smoke
16b	252	408	0	99.75	No smoke
16c	194	519	0	99.74	Incipient smoking flare
16d	159	634	0	99.78	Smoking flare
54	0.356	209	0	99.90	
23	0.494	267	0	100.01	
52	0.556	268	77.5	98.82	
53	0.356	209	123	99.40	
AIR-ASSISTED FLARE TESTS			Air Flow, Hi, Low, Off		
26	481.6	2183	Hi	99.97	
65	159	2183	Off	99.57*	Smoking flare; no air assistance
28	157	2183	Hi	99.94	
31	22.7	2183	Low	99.17	
66	639	158	Off	61.94	Detached flame observed
29a	510	168	Low	54.13	Detached flame; no air assistance
29b	392	146	Low	64.03	Detached flame; with air assistance
64	249	282	Low	99.74	
62	217	153	Low	94.18	Flame slightly detached
63	121	289	Low	99.37	
33	0.714	83	Low	98.24	
32a	0.556	294	Low	98.94	
32b	0.537	228	Low	98.82	

* Not accounting for carbon present as soot (see Table 10).

rates ranged from 703 SCFM to 0.35 SCFM (purge flow rate) for the steam-assisted flare, and from 639 SCFM to 0.54 SCFM (purge flow rate) for the air-assisted flare.

CONCLUSIONS AND OBSERVATIONS

- When flares are operated under conditions which are representative of industrial practices, the combustion efficiencies in the flare plume are greater than 98%.

- Steam- and air-assisted flares are generally an efficient means of hydrocarbon disposal over the range of operating conditions evaluated.

- Varying flow rates of relief gas have no effect on steam-assisted flare combustion efficiencies below an exit velocity of 62.5 ft/sec. (42·61 miles/h).

- Varying Btu content of relief gases have no observed effect on steam-assisted flare combustion efficiencies for relief gases above 300 Btu/SCF. A slight decline in combustion efficiency was noted for relief gases below 300 Btu/SCF.

- Flaring low Btu content gases at high exit velocities may result in lower combustion efficiencies for air-assisted flares.

- Smoking flares achieve high gaseous hydrocarbon destruction efficiencies.

- In many cases, where high combustion efficiencies were observed, the carbon monoxide and hydrocarbon concentrations observed in the flare plume were approximately equal to those found in ambient air.

- Concentrations of NO_x emissions in the flare plume were observed to range from 0.5 to 8.16 ppm.

- The combustion efficiency data were insensitive to sampling probe height within the normal operating heights of the probe.

- Further development of a technique to use sulfur or another material as a tracer material to determine the flare dilution ratios is required.

- Steam-assisted flares burning relief gases with less than 450 Btu/SCF lower heating value did not smoke, even with zero steam assistance.

- The meandering of the flame's position relative to the sampling probe with varying wind conditions affected the continuous measurements but had no apparent effect on the combustion efficiency values.

- Higher concentrations of THC and CO were not observed during the purge rate flare tests.

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SECTION 3

TESTING METHODOLOGY

EXPERIMENT DESIGN AND FLARE OPERATION

The flare tests were designed to determine the combustion efficiency and hydrocarbon destruction efficiency of flares under a variety of operating conditions. The tests were devised to investigate routine industrial flaring operations. Conditions representative of emergency flaring operations were not investigated. The primary flare operating variables were:

- Flow rate of relief gas;
- Heating value of relief gases; and
- Steam-to-relief gas ratio (steam flare only).

The preliminary test plan called for twenty-seven tests, with each test having a different combination of flare operating variables. The operating variables were defined as follows:

Relief Gas Flow

High — 25 foot flame length.

Intermediate — 1/6 of high flow.

Low — 1/20 of high flow.

The maximum practical flame length that could be tested was approximately 25 feet due to height limitations of the crane boom holding the sampling probe. This was the limiting factor for setting the maximum relief gas flow rate.

Heating Value

High — Heating value of the undiluted relief gas (zero nitrogen flow) (2,200 Btu/ft^3).

Intermediate — Twice the low heating value condition (300-600 Btu/ft^3).

Low — Lowest heating value that will maintain combustion (high nitrogen flow) (less than 200 Btu/ft^3).

Steam Flow

High — Steam-to-relief gas mass ratio of 1.0.

Intermediate — Steam-to-relief gas mass ratio of 0.5.

Low — Steam flow at incipient smoking.

Zero

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The preliminary test plan called for determination of the vertical profile of the plume by sampling at least four different heights above the flame. As discussed on page 34, this was not done due to the insensitivity of combustion efficiency to probe height. Following the vertical profile measurements, the flare's efficiency was to be determined at the vertical point where the combustion reactions are complete but prior to further dilution with ambient air.

A technical pretest meeting was held on May 6, 1982 at the John Zink Company flare demonstration facility in Tulsa, Oklahoma to allow the project participants to finalize the test plans. During this meeting, six (6) smoking flare test designs were adopted in addition to the 27 tests previously mentioned, for a total of 33 planned tests. Other items discussed during this meeting included: the division of responsibilities, lines of communication, quality assurance procedures, safety considerations, schedules and testing sequence.

During the early stages of the test program, the participants learned more about the characteristics of flares, and it became apparent that several of the planned tests were not practical and/or did not represent the intended flare operating conditions. Therefore, sixteen of the thirty-three planned tests (numbered 1 through 33) were cancelled and a substitute group of tests (numbered 50 through 67) were formulated in the field and executed in their place. The most common reason for abandoning tests was that many of the planned incipient smoking tests and smoking steam-assisted flare tests would not smoke, even with zero steam flow.

During each test the flows of the flare feed gases were monitored and maintained as close as practical to the target levels. For several tests it was not possible, due to physical constraints, to maintain all the flow rates at constant level. This was particularly true for those tests that called for high nitrogen flow. As the pressure in the N_2 cylinder banks declined during a test, the nitrogen flow would tend to decrease, resulting in higher relief gas heating values.

Sulfur was selected as a tracer material to allow estimation of the dilution of the relief gas from the flare burner tip to the sampling probe. Sulfur was chosen primarily because of the availability of monitoring instrumentation to measure part-per-billion levels of sulfur using flame photometry. Helium was considered as a tracer material. However, this material is difficult to quantify at levels less than several tens of parts per million and thus, would require large quantities of gas. Additionally, helium cannot be detected on a continuous basis as can SO_2. Sulfurhexafluoride (SF_6) was also considered as a tracer material. However, SF_6 is not stable at the elevated temperatures found in a flare flame.

The sulfur in the relief gas originated from three primary sources: 1) naturally occurring reduced sulfur in the crude propylene, 2) sulfur added to the propylene in the form of butyl mercaptan (approximately 1 gallon butyl mercaptan/6,800 gallons crude propylene), and 3) sulfur dioxide gas added to the relief gas stream. All three sources and forms of sulfur are presumably oxidized to SO_2 as the relief gas is burned. The flare emissions were then analyzed for total sulfur as SO_2 using flame photometry.

Crude propylene was selected for the relief gas because it is relativly difficult to burn smokelessly, as compared to paraffins. The availability of propylene and safety considerations also influenced its selection as the relief gas. Lower Btu content relief gases were obtained by diluting the crude propylene with inert nitrogen. Flow rates for both the propylene and the nitrogen were controlled by appropriately sized metering valves and rotameters. Steam flow to the steam-assisted flares was controlled by a metering valve and monitored by an orifice meter. Sulfur dioxide was added to the relief gas during some of the tests to increase the levels of tracer material. The flow of SO_2 was monitored and regulated by a rotameter and metering valve assembly. Figure 2 is a schematic of the flow controls and plumbing used to operate the test flares. Figure 3 presents photographs of the flow control manifold assembly and the nitrogen cylinder manifold arrangement.

SAMPLING AND ANALYSIS

An extractive sampling system was used to collect the flare emission samples and transport these samples to two mobile analytical laboratories. Figure 4 is a diagram of the sampling and analysis system. The extractive sampling system consisted of a specially designed 27-foot sampling probe which was suspended over the flare flame by support cables and a hydraulic crane. This probe consisted of a 5-foot unheated section of 1" stainless steel pipe coupled with a 22-foot heated section of 5/8" stainless steel tubing. The heated section was insulated and housed in a 3" pipe which provided support for the entire probe assembly. Guy wires were attached to both ends of the 3" pipe support to position and secure the probe from ground level. Figure 5 contains photographs of the flare emission sampling probe.

Gaseous flare emission samples entered the sampling system via the probe tip, passed through the particulate filter, through the heated probe section and then were carried to ground level by a 3/8" heated FEP teflon tube sample line. The sampling system temperature was maintained above 100 C to prevent the condensation of water vapor. The flare emission sample was divided into three possible paths. A fraction of the heated sample was passed through an EPA Reference Method 4 sampling train to determine the moisture content of the sample. A second fraction was directed through a moisture removal cold trap and thence, into a sampling manifold in one of the mobile laboratories. Sample gas in this manifold was analyzed by continuous monitors for O_2, CO, CO_2, NO_x and THC on a dry-sample basis. A third fraction of the sample was directed into a heated sampling manifold in the other mobile laboratory. Sample gas in this manifold was analyzed for SO_2 and hydrocarbon species on a wet basis.

TYPES OF FLARE BURNERS TESTED

The steam-assisted flare used for the test series was a John Zink Standard STF-S-8 flare tip with two constant ignition pilots. Overall length was 12'-3 1/2" with the upper 7'-3" constructed of stainless steel and the lower 5'-1/2" made from carbon steel. The maximum capacity of the tip is rated by John Zink Company at approximately 53,300 lbs/hr for crude propylene at 0.8 Mach exit velocity. However, the STF-S-8 would not burn this volume of gas and remain totally smokeless. The capacity of steam flow through the flare steam manifold
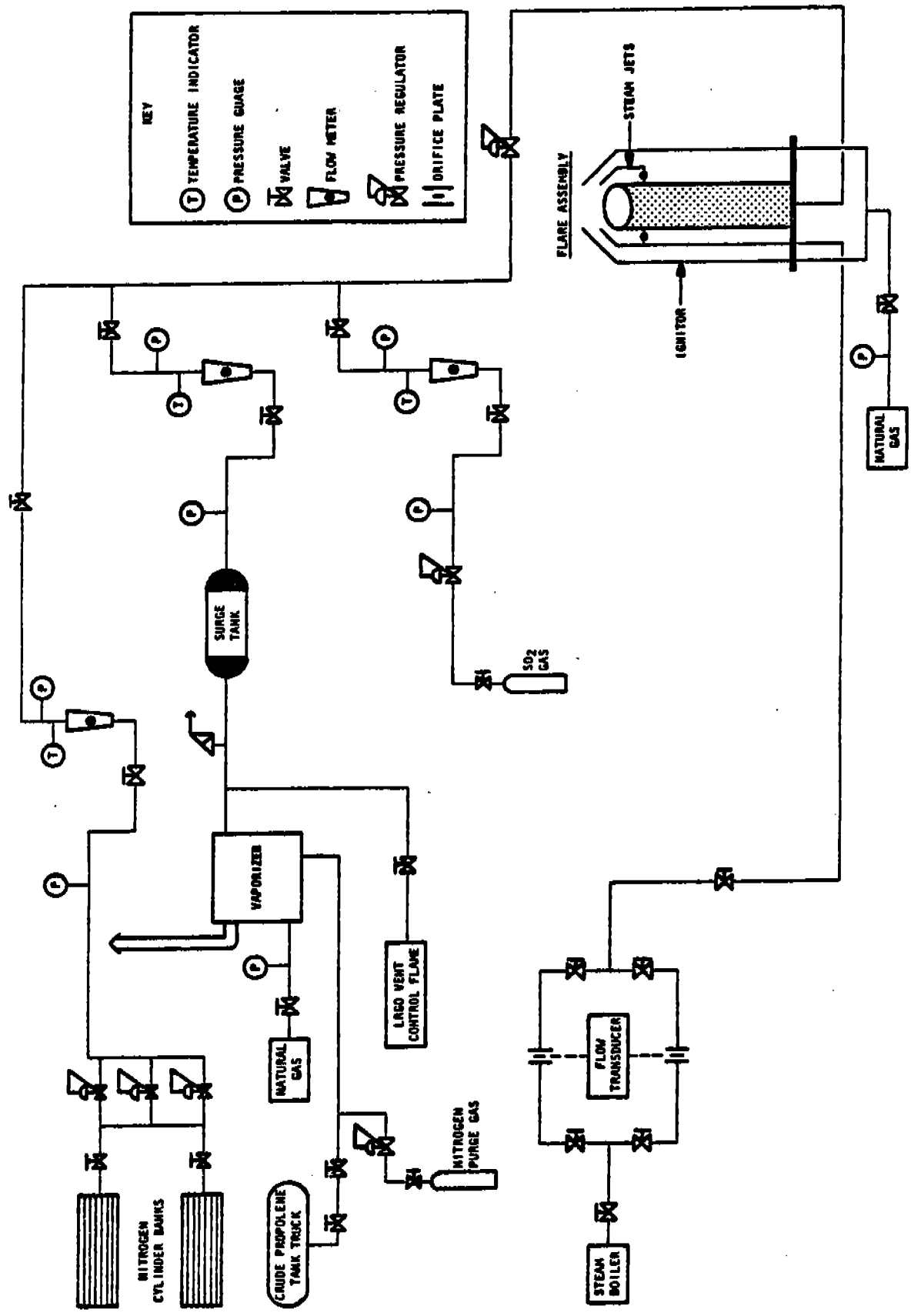
Figure 2. Flare flow control system.

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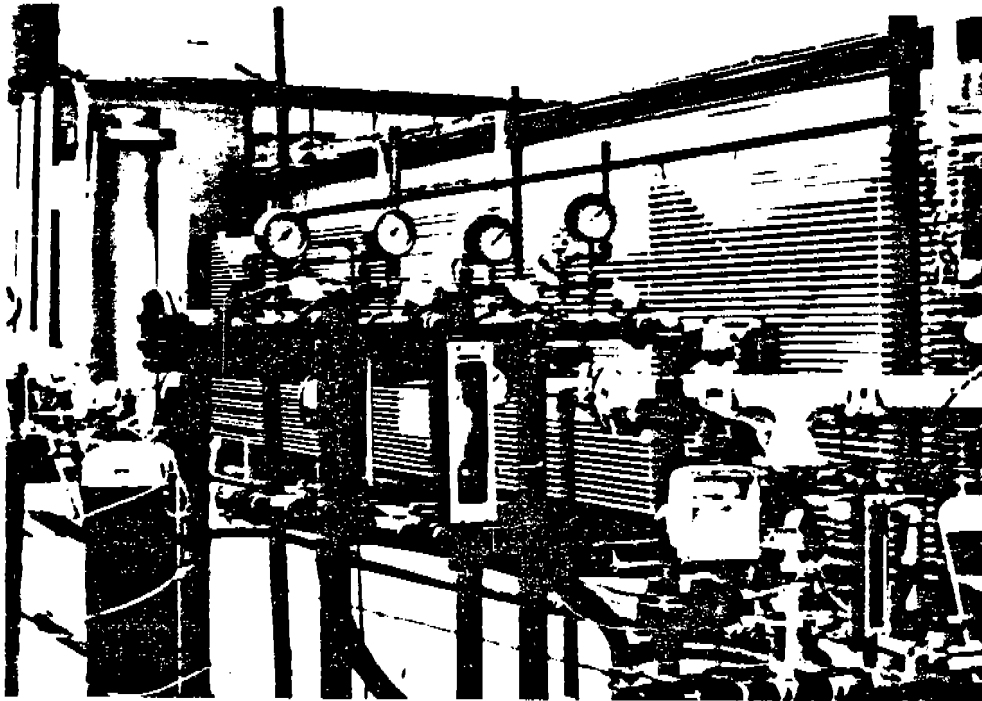
Flow Control Manifold
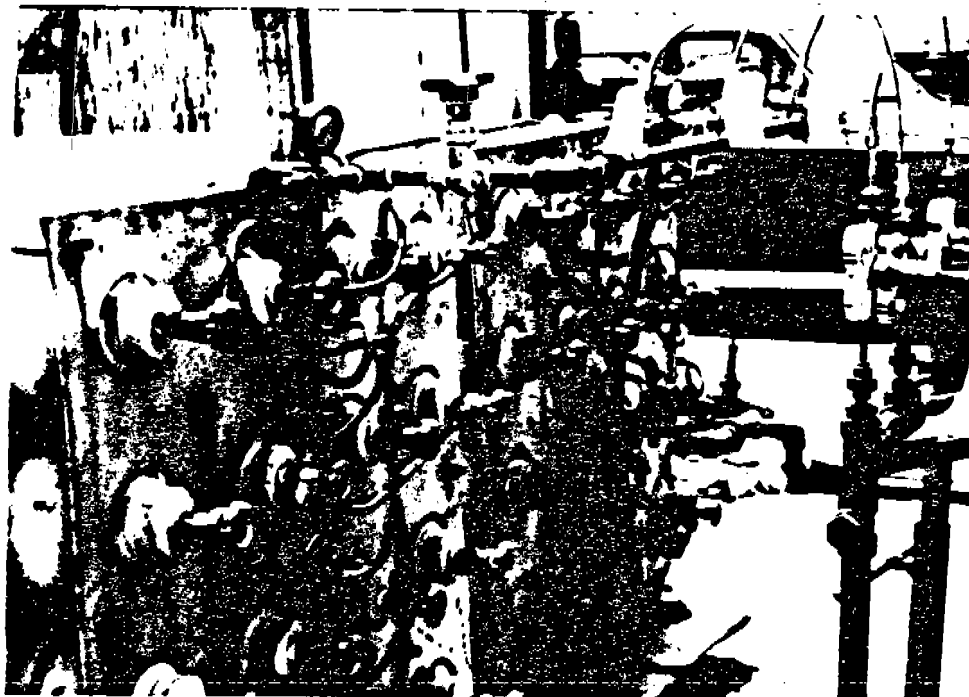
Nitrogen Cylinder Manifold

Figure 3.   Flow control and nitrogen cylinder manifolds.

CRANE SUPPORT

PARTICULATE FILTER

THERMOCOUPLE

HEATED PROBE SECTION

UNHEATED PROBE SECTION

HEAT TRACE SAMPLE LINE

METEOROLOGICAL TOWER

MOISTURE DETERMINATION APPARATUS

EXHAUST

MOBILE LAB #1

MOBILE LAB #2

HEATED MANIFOLD

SAMPLE PUMP

COLD TRAP

SAMPLE PUMP

EXHAUST

EXHAUST

CO_2 ANALYZER

THC ANALYZER

CO_2 ANALYZER

CO ANALYZER

NO_x ANALYZER

TEMPERATURE MONITOR

INTEGRATED BAG SAMPLE PORT

HYDROCARBON SPECIE ANALZER

SO_2 TRACER ANALYZER

DATA LOGGER

TAPE DRIVE

Figure 4. Flare sampling and analysis system.
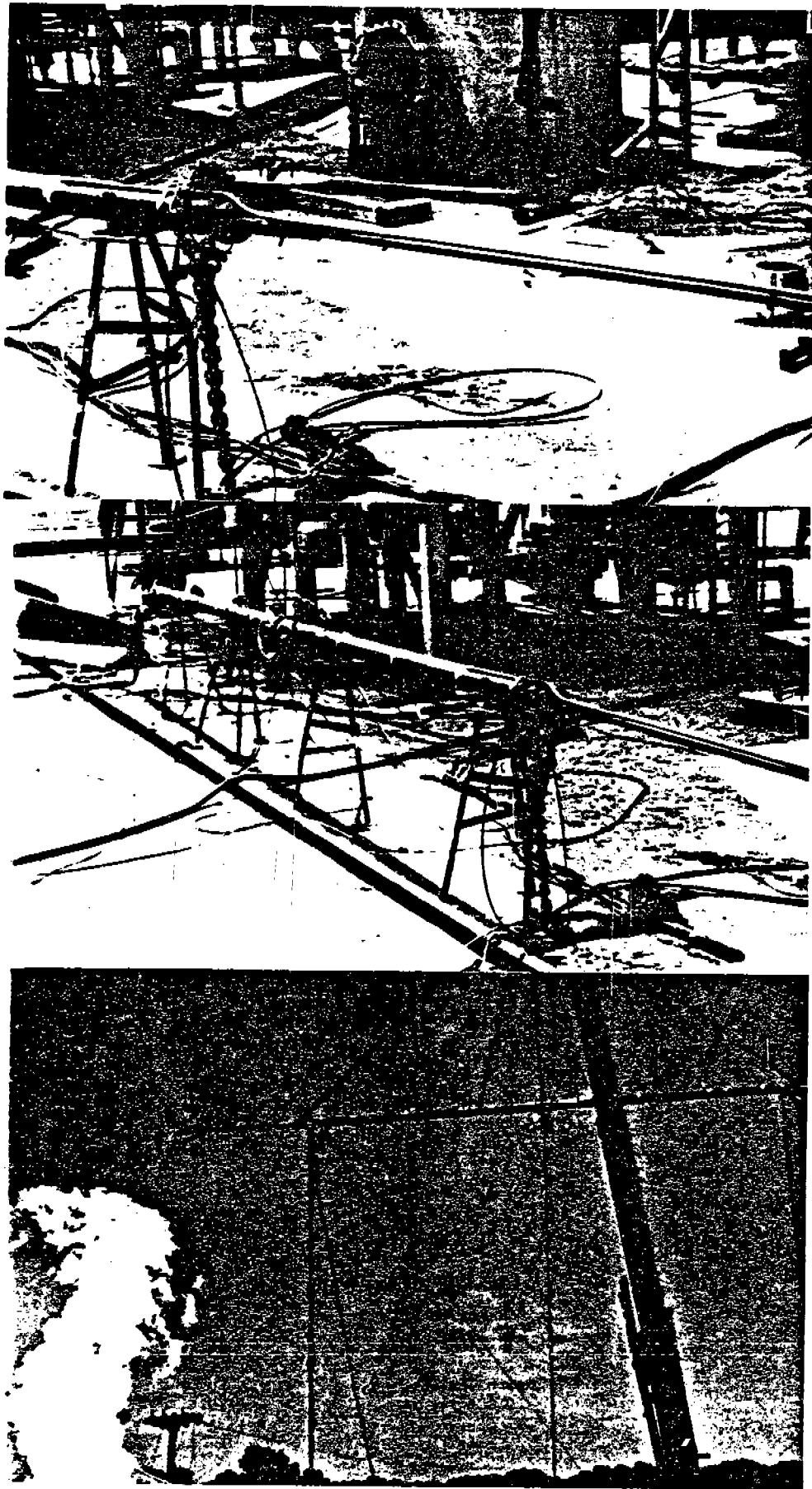
Figure 5. Flare emission sampling probe.

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is 10,080 lbs/hr based on steam conditions of 100 psig and 338°F. The recommended steam flow for this flare is approximately 0.4 pounds of steam per pound of crude propylene. The steam jet total flow area is 1.92 in² and the unobstructed flow area at the exit of the 8 5/8" ID steam-assisted flare tip is 27.0 in².

The air-assisted flare was the John Zink STF-LH-457-5 flare with two constant ignition pilots. The overall length of this flare was 13'-2". The upper portion of this flare's air plenum and burner are constructed of stainless steel and the lower portion is of carbon steel. The maximum capacity of the air-assisted flare is approximately 23,500 lbs/hr of crude propylene, which can be burned smokelessly through use of an air blower. The blower used for this test series was 7 1/2 HP vane axial fan located in the base of the 18 1/4" ID air riser. The relief gas is delivered to the tip by an 4" OD internal riser with the air supplied around the outside through the air riser and plenum. The relief gas is discharged via a specially designed "spider" on the end of the internal riser. The total area of the relief gas holes in the spider burner was 5.30 in² for the tests on high Btu content relief gas and 11.24 in² for the tests on low Btu content gases. The air flow and air flow velocity are proprietary information and are not included in this report.

Typical field installations of air-assisted flares utlize two-speed forced draft fans. The blower normally runs at low speed with automatic advancement to high speed upon an increased relief gas flow signal. The blower is also automatically returned to low speed when the increased relief gas condition subsides. Some deadband is normally provided to avoid excessive speed cycling of the blower with oscillating flows. Normal low speed operation handles approximately one-third of the maximum smokeless duty. The air-assisted flare used in these tests employed an adjustable air inlet vane assembly instead of a two-speed fan. Adjustment of the vane assembly allowed duplication of the high and low speed air flow rates without the two-speed fan.

Two different "spider" burner tips were employed during the air-assisted flare tests. The LH burner tip, designated at "A", was used for tests 26, 65, 28 and 31 for high Btu content gases, and the burner tip designated as "B" was used for the low Btu content gas tests 66, 29, 64, 62, 63, 33 and 32.

John Zink Standard STF-6-2 pilots were used for both flare tips. At 15 psig, the pilots were designed to burn 300 SCFH of natural gas. The natural gas burned in the pilots had a lower heating value of 921 Btu/SCF. Two pilots were used on both the air- and steam-assisted flares, resulting in 552,600 Btu/hr being supplied to the flare by the pilots.

FLARE TEST PROCEDURES

All key personnel involved in the execution of the flare tests were in communication with one another via a hard wire intercom system. This communications system included the following: JZ test coordinator, ES instrument operator, CMA test observer, EPA ROSE operator, steam flow operator, rotameter operator, vaporizer operator, crane operator, propylene truck/nitrogen bank operator and video camera operator. All conversations between these persons during tests were recorded on the video tape and on a portable tape

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recorder. In addition, the two ES mobile laboratories were in communication via a separate intercom system.

Flaring was not begun until all key personnel were at their stations and verified that they were prepared to initiate a formal test. Then the test coordinator would call for flare ignition and the gas flows to the flare would be adjusted to the previously agreed nominal values. Once the flows were stabilized the probe would be brought into position by manipulating the hydraulic crane and guy wires.

The probe positioning objective was to place the probe tip as close as possible to the flare flame without the probe being in the flame. The intent was to sample the flame emission plume as close as possible to the combustion zone to minimize the of dilution of the plume by ambient air. The probe tip was kept out of the flame so as not to bias the data with gases that were still undergoing combustion reactions.

Probe positioning was directed by the JZ test coordinator. The test coordinator's visual probe positioning was aided by observers located in different quadrants surrounding the flare and the CMA observer who was situated on an elevated platform. Additionally, the ES instrument operator monitored the probe tip temperature, CO, CO_2, and THC.

When the project participants agreed that the probe was positioned as well as was feasible, the test coordinator announced the initiation of the test and data collection ensued. The probe position was adjusted as required during the test to compensate for changes in wind conditions causing movement of the flame and the plume away from the probe tip. These adjustments were both vertical and lateral. The primary criteria for determining the need to adjust the probe position was a decline in probe tip temperature. Short-term declines in temperature (i.e. less than one minute) were common as the flare flame and plume moved with intermittent changes in the wind. However, extended temperature declines (i.e., greater than two minutes) were regarded as a significant shift of the wind and signaled the need to adjust the probe position.

Data collecton continued for each test for a target period of 20 minutes. The actual test duration was dependent on a number of factors which influenced decision of when to terminate the tests. These factors included:

1. The effects of the flare's radiant heat on buildings, personnel and test equipment in the area;

2. The representativeness of the data from the standpoint of being able to maintain good probe positioning during the majority of the test; and

3. The consumption rates of propylene and nitrogen.

BACKGROUND MEASUREMENTS

Ambient air concentrations of the compounds of interest were measured in the test area before and after each test or series of tests. These background

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measurements were collected for a minimum period of five minutes. The background measurements collected before the tests were typically initiated fifteen to thirty minutes before the anticipated start of the next test. Background measurements collected after the tests were initiated as soon as all the instruments indicated a complete return to baseline concentrations (typically five to ten minutes after test completion). On occasions when several tests were executed in a relatively short time period (less than four hours), the same pair of before and after background measurements were applied to more than one test. On other occasions a set of background measurements collected after a test would also suffice as the background data set collected before the next test.

CONTINUOUS EMISSION ANALYZERS

Flare emission measurements of carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), oxides of nitrogen (NO_x), total hydrocarbons (THC) and sulfur dioxide (SO_2) were measured by continuous analyzers that responded to real time changes in concentrations. These analyzers obtained their samples from the sample manifolds in the two mobile laboratories. Table 2 is a summary of the instrumentation used during the tests. The operating principles of these instruments are well known and are not discussed in detail in this report.

The instruments were operated according to the manufacturers' recommendations, utilizing the primary measurement ranges listed in Table 2. The only exceptions to this were the operation of the THC and SO_2 analyzers. During some tests it was necessary to change the operating range of the THC analyzer to higher scales due to elevated levels of these compounds. The Meloy SA 285 SO_2 analyzer was modified to incorporate a 1:5 sample dilution system. This was necessary in order to minimize the effect of variable O_2 content in the flare emissions on the instrument response.

All instruments were housed in air conditioned mobile laboratories to minimize the effects of temperature on instrument response. However, given the high radiant heat effects of some of the flare tests, it was not always possible to maintain a constant temperature within the mobile labs. This factor had the greatest effect on the NO_x and SO_2 analyzers which employed photomultiplier tubes in their detection systems. The effect of rising ambient temperature was noted as a slight shift in the instrument baseline.

HYDROCARBON SPECIES ANALYSIS

Flare emission samples were collected during each test for gas chromatographic analysis for hydrocarbon species. These samples were of two forms: instantaneous samples and time integrated samples. The instantaneous samples were periodically withdrawn directly from the sample manifold during each test and injected into the chromatograph via a gas sample loop. The time integrated samples were transferred from the manifold into a six liter Tedlar® bag over a period of five to ten minutes. Subsequently, the integrated samples were analyzed by gas chromatograph. The analysis techniques for the integrated and instantaneous samples were the same. Only the sampling differed. Table 3 outlines the operating conditions of gas chromatograph.

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TABLE 2. FLARE EMISSION ANALYZERS AND INSTRUMENTATION

Make and Model	Parameter	Primary Operating Range	Operating Principle
Thermo Electron Model 10	NO_x	0-25 ppm	Chemiluminescence
Horiba PIR 2000	CO	0-1,000 ppm	Infrared absorption
Horiba PIR 2000	CO_2	0-5%	Infrared absorption
Teledyne 320 AX	O_2	0-25%	Electro catalysis
Scott 116	Total hydrocarbon	0-100 ppm	Flame ionization
Carle 211 Gas Chromatograph	Hydrocarbon Species	N/A	Flame ionization
Meloy SA 285 (ES Modified)	Tracer (SO_2)	0-5 ppm	Flame photometry
Climatronics Electronic Weather Station	Wind Speed Wind Direction Ambient Temperature	0-50 mph 0-540 40-120°F	Photo chopper Precision potentiometer Thermistor
Omega Thermocouple Assembly	Probe Temperature	-300° to 2300°F	Chromel-Alumel exposed bead thermocouple

TABLE 3. GAS CHROMATOGRAPH OPERATING CONDITIONS

Gas Chromatograph:	Carle 211
Column:	4.9 foot x 1/8 in. stainless steel
Packing:	n-octane/porasil C, 100/120 mesh
Oven Temperature:	35 °C
Sample Loop Temperature:	35 °C
Carrier Gas:	Nitrogen
Carrier Flow:	35 cc/min.
Sample Loop Size:	1 cc
Sample Valve:	Carle 6 port, selonoid activation
Detector Type:	Flame ionization detector
Calibration Basis:	Methane equivalents (parts per million)
Lower Detection Limit:	0.05 ppm as CH_4
Valving Scheme:	Direct injection, no backflush

Elution Times:	Minutes
Methane	1.27
Ethane/Ethylene	1.62
Propane	2.44
Propylene	2.91
Butane	4.68

TEMPERATURE MEASUREMENTS

The temperature at the sampling probe tip was continuously monitored during the tests with a chromel-alumel thermocouple in conjunction with a digital thermometer. The thermocouple selected was an exposed bead type so as to minimize the response time. An open end stainless steel shield protected the thermocouple from the flame's radiant heat and still allowed free circulation of the flare emission around the thermocouple. Thermocouples were also installed in the heat trace line, the heated manifold and the heated probe assembly to allow monitoring of these tempertures during the tests.

PARTICULATE ANALYSES

The probe assembly included an in-line particulate filter housed inside the heated section of the probe about six feet from the probe tip. This in-line particulate filter assembly served two purposes: 1) collection of particulate samples from smoking flares for subsequent analysis, and 2) maintaining the cleanliness of the sampling system. The preweighed filter elements used were of the thimble configuration and constructed of 0.3 micrometer glass fiber.

The filters were changed before and after each of the smoking flare tests. Following the tests the filters were reweighed to determine the mass of particulate collected. This information, combined with the measured flow rate of sample through the probe assembly, allowed the calculation of the gross particulate concentration of the flare emission at the sampling location. It should be noted however, that these particulate samples were not collected isokinetically and thus, represent only gross estimates of the particulate concentration. The flare particulate emissions were not isokinetically sampled because it was not practical to directly measure the plume velocity. Due to small particle sizes, the lack of isokinetic sampling conditions is probably insignificant.

MOISTURE DETERMINATIONS

The moisture content of the sampled flare emissions were determined by the procedures set forth in EPA's Reference Method 4 (40 CFR 60 Appendix A). A gas sample was extracted from the heated sample line and passed through a series of four impingers immersed in an ice bath. The impingers removed the water from the sample stream by condensation and by adsorption on silica gel. The weight gain of the impingers was measured to determine the moisture content of the sample. The only deviation from the published method required by this appication was a reduction in the size of the sample passed through the impingers. Due to the short duration of the test, it was not possible to sample the full 21 SCF volume recommended in the published method. This deviation only slightly affects the accuracy of the moisture determinations.

The purpose of collecting moisture samples was to provide data to allow conversion of concentrations measured on a wet basis to a dry basis and vice versa. This was believed to be important since the instrumental analyses were conducted on both a wet and dry basis. However, the moisture determinations revealed low levels of moisture content by weight (3.8% (volume basis) average

for steam-assisted flare tests and 3.0% average for air-assisted flare tests). Therefore, moisture corrections were not applied to the data because of their low levels and questionable accuracy. It is not believed that moisture corrections would enhance the value of the data.

The results of the moisture determinations may be found in Section 4 of this report.

METEOROLOGICAL MEASUREMENTS

The ambient wind speed, wind direction and temperature was monitored at the flare test facility concurrently with the collection of flare emission data. The meteorological sensors were situated as close as was practical to the test flares at an elevation approximately the same as the flare tip (12 feet, 8 inches AGL).

Due to the numerous air flow obstructions in the test area the wind data are not expected to correspond with the prevailing Tulsa area winds. Rather, the wind data were intended to represent the wind encountered by the subject flare flames.

Testing of the flares was found to be infeasible when wind velocities exceeded 5 miles per hour. Elevated wind velocities prevented sustained and consistent positioning of the probe in the flare plume.

AUDIO AND VIDEO RECORDINGS

Audio and video recordings were made during the flare tests. Video recordings were made to document the flame behavior and the probe position relative to the flame. The video camera was positioned to have an unobstructed view of the flame by placing it on a platform approximately 20 feet above ground level. The distance from the flare to the camera was approximately 50 feet.

Audio recordings were made of the verbal observations of the participants during the tests. The audio recordings were made on the same magnetic tape used for the video recordings. The intercom system served as the source of all audio recordings.

The audio and video recordings were made primarily as means of documentation of the tests and to allow possible future more detailed analyses of the data with respect to flame behavior. These recordings were not generally used in the data analysis contained in this report. The one exception to this is the use of the recordings to identify the point at which smoking began during Test 11 relative to the increasing Btu content of the relief gas.

SECTION 4

DATA COLLECTION AND CALCULATIONS

CONTINUOUS ANALYZERS' DATA ACQUISITION

The outputs of the continuous monitoring instruments used for this study were analog signals that were proportional to the magnitude of the parameter being monitored. These output signals were recorded on both a strip chart recorder and on a data logging system. The strip chart records provided a permanent, continuous record of the analyzer output and a graphical display that aided in the data interpretation. The electronic data logger system provided a convenient means to record and process a large quantity of data. Although the data logger served as the primary means of data acquisition, the strip chart records provided a back-up data acquisition system and documentation for the data logger.

The data logger employed for this project was a Monitor Labs Model 9300. This instrument was coupled with a 9-track magnetic tape recorder (Kennedy Model 9800) and a ten-digit manual data entry system. The functions of the data logger were as follows:

- Scan each instrument output (approximately every 12 seconds);

- Convert the analyzer's analog output to a digital value;

- Scale the digital value to a useful unit of measure (ppm, mph, etc.);

- Record the scaled instantaneous value on the 9-track magnetic tape.

- Average the instantaneous values to one-minute averages;

- Print the one-minute averages on paper tape for on-site review; and

- Label each set of data with the time and the appropriate manually entered status data.

The original test plan called for the data logger to scan each channel once every six seconds. However, this was not possible given the number of input channels to the data logger (10), the required functions, and the speed of the instrument. Each input channel was scanned for instantaneous data approximately once every twelve seconds.

The data logger's internal clock was set as closely as possible to Central Daylight Savings Time (CDST). This clock was used as the standard time for all data acquisition relating to the flare tests.

The printed paper tape output of the data logger provided means to review the data being recorded on-site by the data logger. This data was compared with the strip chart data to ensure integrity in the entire data acquisition system. Likewise, the paper tape output was used to indicate the combined instrument and data logger responses to the routine zero and span calibration gas inputs. An example paper tape output may be found in this report's Appendix.

A 10-digit manual data entry system allowed the labeling of each set of data as it was collected. This system was used to record the following:

Record Digits	Parameter
0, 1	Test number designation
2, 3, 4, 5	Sampling probe height (feet and inches)
6, 7, 8	Spare
9	Status of data 0 = Calibration data 1 = Acceptable test data 2 = Change in test conditions 3 = Questionable data 4 = Ambient background data 5 = Trial test burn 6 = Probe positioned in fire 7, 8 = Spare 9 = Disregard data

HYDROCARBON SPECIES DATA

The gas chromatography data for hydrocarbon species was recorded by a Hewlett-Packard Model 3390 Integrator. This device accepted the analog signal from the gas chromatograph and plotted the peaks which correspond to the hydrocarbon species. The integrator also determined the retention time for each peak and the peak areas which are proportional to the hydrocarbon concentration. This data was recorded by a printer/plotter on a paper tape. The peak area values recorded on this tape were subsequently reduced to units of parts per million by volume of methane equivalents.

DOCUMENTATION

The performance of these tests was documented by the following:

- Logbooks maintained by CMA project participants. These records contain a test chronology, records of field observations, records of flow rates of gases feeding the flare and preliminary field data records copied from the data logger paper tape. These logbooks are stored at CMA's headquarters in Washington, D.C.

- Logbooks maintained by ES test personnel. These records contain a chronology of all events associated with the flare tests that are related to the analysis of flare plume gases. This recorded data includes records of calibrations, zero and span checks, sampling probe heights, test observations, moisture determination data, particulate mass loading data, difficulties encountered and solutions offered. These logbooks are stored at the ES Austin, Texas office.

- Strip chart records. This includes continuous recordings of CO, CO_2, NO_x, THC, SO_2, O_2, probe temperature, wind speed, wind direction, ambient temperature and the gas chromatograph integrator. These records are maintained at the ES Austin, Texas office.

- Video and audio recordings. These magnetic tapes include the audio recordings of the participants' comments and observations made during each test through the intercom system. The video tapes also include a visual record of the flare flame during the tests. Copies of these tapes are stored at the JZ Tulsa, OK facility; the EPA, IERL Office, Research Triangle Park, North Carolina; and the CMA headquarters in Washington, D.C.

- Data tapes. These paper tapes and magnetic computer tape contain all the validated data logged by the data logger during the tests. The paper tapes are stored at the ES Austin, Texas office. Copies of magnetic tape are stored at CMA headquarters, Washington, D.C., and at the ES Austin, Texas office.

CALCULATIONS

The following calculation formulas and constants were employed to reduce the data presented in this report.

Combustion Efficiency

$$\% \ CE = \frac{CO_2}{CO + CO_2 + THC} \cdot 100$$

Where: CO, CO_2 and THC are flare plume concentrations (corrected for background) of these parameters in parts per million by volume. (The THC term is expressed in terms of methane equivalents corrected for background.) Note that soot corrections were made only for Tests 4, 8, and 65 (see pages 43-46).

Gaseous Flows

$$F_t = \frac{\dfrac{\% \ MR}{100} \cdot MF}{\sqrt{\dfrac{MW}{29} \cdot \dfrac{14.7}{P+14.7} \cdot \dfrac{T+460}{530}}}$$ Standard Rotameters (SCFM)

$$F_t = \frac{MR}{\sqrt{\dfrac{MW}{29} \cdot \dfrac{14.7}{P+14.7} \cdot \dfrac{T+460}{530}}}$$ Direct Reading Rotameters (SCFH)

Where: F_t = gas flow at time t
% MR = percent of full-scale meter reading for standard flow
MR = meter reading for direct reading rotameters
MF = flowmeter calibration factor (SCFM)

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MW = molecular weight of gas in flow meter
 P = flowmeter back pressure (PSIG)
 T = temperature of gas (°F)
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Flow Meter Calibration Factors

Meter Designation	Flow Meter Calibration Factor (SCFM)
699 MT	745.4
391 MT	409.5
R13M-25-3	128.8
R10M-25-3	26.04
R8M-26-2	2.13

Gas Constants

Gas	Density (lbs/ft^3)	Lower Heating Value (Btu/ft^3)	Molecular Weight
Crude Propylene	0.1106	2183	42.4
Nitrogen	0.1700	0	28
Sulfur Dioxide	0.0730	0	64

Steam Orifice Flows

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3" orifice maximum flow = 2,250 lbs/hr
1-1/2" orifice maximum flow = 600 lbs/hr
1/2" orifice maximum flow = 200 lbs/hr
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$$F_t = F_{Max}\sqrt{\frac{\text{\% Chart} - 20}{80} \cdot \frac{P_g}{P_o}}$$

Where: F_t = steam flow at time t (lbs/hr)

F_{Max} = maximum steam flow through orifice (lbs/hr)

% Chart = response of recorder coupled with flow transducer

20 = zero offset of recorder

80 = full-scale recorder response

P_g = steam pressure, (psia)

P_o = base pressure, (psia)

Average Flows

$$F_A = \frac{F_{t_1} + F_{t_2} + F_{t_3} + \ldots F_{t_z}}{z}$$

Where: F_A = average flow rate for each test

z = number of flow rate readings during each test

F_{t_z} = flow reading numbered 1...z at time t

SECTION 5

REVIEW OF FLARE TEST RESULTS

The test reviews contained in this section are grouped by the experimental variables of flow rate and Btu content of the relief gas. The test reviews consist of a narrative description of the test conditions and the results by test group. The measured combustion efficiency of the flare is the term which is used in these discussions to evaluate the flare performance.

Statistical data summaries are presented on a test-by-test basis in the appendix to this report (Appendix B). The data presented in these summaries were calculated from the instantaneous data values (collected at approximately 12-second intervals) which have been corrected by subtracting background concentrations. No adjustment was made for moisture. These summaries include average values, standard deviations, number of observations and combustion efficiency calculations for each test. The combustion efficiencies for each test were calculated by two methods: (1) the "average combustion efficiency" values listed in the summaries are the average values of all of the instantaneous combustion efficiency calculations performed on the instantaneous data values; (2) the "overall combustion efficiency" term was calcuclated from the average concentration values of CO, CO_2 and THC for the entire test. The differences between these two calculation methods are not regarded as significant. The "overall combustion efficiency" term is used in this report for comparison between tests.

The chronological order in which the tests were performed minimized piping and equipment changes in the field, and this order is substantially different from the groupings listed here. The test numbering system is not sequential since many tests were added or deleted from the planned sequence. Tests numbered 1 through 33 represent tests which were completed in accordance with the planned test series. Tests numbered 50 through 67 represent test conditions which were planned and implemented in the field in place of the deleted tests.

The results for tests numbered 11, 16, 59, 29 and 32 have been divided into subtests (designated 11(a), 11(b), etc.). These test data were divided into subtests for data analysis because the flare operating conditions significantly changed during the tests. The division into subtests allowed the data to more closely represent steady-state flare operation. All other tests were judged to represent steady-state flare operation. The criteria for steady-state flare operation were that all individual flow readings must be within +10% of the average flow.

STEAM-ASSISTED FLARE TESTS

Twenty-three tests were completed on the John Zink Company (STF-S-8) steam-assisted flare. The flare operating conditions and the results of these tests are summarized in Table 4.

TABLE 4.   STEAM-ASSISTED FLARE SUMMARY

Test Conditions		Test Number	RELIEF GAS*							Steam Flow (lbs/hr)	Steam-to-Relief Gas Ratio (lb/lb)	Combustion Efficiency Percent
			Flow (SCFM)	Exit Velocity (ft/min)	Lower Heating Value (Btu/SCF)	Propylene Flow (lbs/hr)	(SCFM)	Nitrogen Flow (lbs/hr)	(SCFM)			
High Btu Content	Decreasing Flow Rate	1	473	2,523	2,183	3,138	473	0	0	2,159	0.688	99.96
		2	464	2,475	2,183	3,078	464	-	-	1,564	0.508	99.82
		3	456	2,432	2,183	3,027	465	-	-	1,355	0.448	99.82
		4	283	1,509	2,183	1,875	283	-	-	-	-	98.80**
		8	157	837	2,183	1,044	157	-	-	..	-	98.81**
		7	154	821	2,183	1,019	154	-	-	722	0.757	99.84
		5	149	795	2,183	991	149	-	-	1,543	1.56	99.94
		67	148	789	2,183	980	148	-	-	711	0.725	See pg. 28.
	Low Flow Rate — Excessive Steam Flow Rates	17	24.5	131	2,183	162	24.5	-	-	150	0.926	99.84
		50	24.4	130	2,183	162	24.4	-	-	498	3.07	99.45
		56	24.5	131	2,183	163	24.5	-	-	562	3.45	99.70
		61	25.0	133	2,183	166	25.0	-	— not y	941	5.67	82.18
		65	24.7	132	2,183	164	24.7	-	3 N2	1,125	6.86	68.95
Low Btu Content	Decreasing Flow Rate	57	703	3,749	294	629	94.8	2,663	608 23.6	497	0.150	99.90
		11(a)	660	3,520	305	612	92.2	2,489	568 24.6	-	-	99.93
		11(b)	599	3,195	342	623	93.9	2,210	505 28.2	-	-	99.86
		11(c)	556	2,965	364	616	92.8	2,028	463 30.4	-	-	99.82
		59(a)	591	3,152	192	345	52	2,361	539 14.6	-	-	98.11
		59(b)	496	2,645	232	350	52.7	1,942	443 18	-	-	99.32
		60	334	1,781	(298) 209	212	32	1,325	302 16	-	-	98.92
		51	325	1,733	309	305	46	1,222	279 25	256	0.168	98.66
		16(a)	320	1,707	339	329	49.6	1,182	270 27.8	-	-	99.74
		16(b)	252	1,344	408	313	47.2	897	205 34.9	-	-	99.75
		16(c)	194	1,035	519	307	46.2	650	148 47.2	-	-	99.74
		16(d)	159	848	634	307	46.3	496	113 62	-	-	99.78
	Purge Flow Rate*** — Excessive Steam Flow Rates	54	0.356	1.90	209	0.226	0.0341	1.41	0.322	-	-	99.90
		23	0.494	2.63	267	0.451	0.0680	2.13	0.487	-	-	100.01
		52	0.556	2.96	268	0.452	0.0682	2.14	0.488	201	77.5	98.82
		53	0.356	1.90	209	0.226	0.0341	1.41	0.322	201	123	99.40

* All values at standard conditions of $70^\circ F$ and 29.92 in Hg.

** Not accounting for carbon present as soot (see Table 10).

*** For purge flows the pilot contributed greater than 95% of the total combustible gas to the flare.

High Btu Content Relief Gases

This test group addresses the steam flare's combustion efficiency while burning high Btu content relief gases at variable flow rates and various steam-to-relief gas ratios. Tests numbered 1, 2 and 3 examined the burning of the crude propylene at the normal (high) rate of approximately 3,100 lbs/hr with steam-to-relief gas ratios ranging from 0.688 to 0.448. Test 3 was run at the steam flow which yielded incipient smoking of the flare. No significant change in the combustion efficiency values was noted between these three high flow rate tests. What little hydrocarbons were present were predominately methane. Likewise, the average corrected CO concentrations for these tests were low, ranging from 3.8 to 13.8 ppm.

The CO_2 values reported during the first minute of test 3 are lower than those which were prevalent during the remainder of the test. The combustion efficiency data does not appear to be influenced by this unexplained anomoly.

The background data file applied to test 3 has a negative average value for CO (-0.4 ppm). This was caused by the physical limitations of the CO analyzer. This instrument was operated on the lowest available range (0-1000 ppm). At this range, the practical limit for accurately adjusting the analyzer's zero response was +3.0 ppm. Therefore, it is not surprising that slightly negative background CO values could be recorded during conditions of low ambient CO concentrations.

The average corrected total hydrocarbon value reported for test 1 is -0.7 ppm. This negative value results from the measured ambient background THC concentration being higher than the THC concentration measured above the flare flame.

Tests numbered 4 and 8 were performed with crude propylene relief gas flows of 1,875 and 1,044 lbs/hr without any steam assistance to the flare. These conditions purposely resulted in a heavily smoking flare condition. The relief gas flow rates for test number 4 were reduced from those used in tests 1, 2 and 3 in order to keep the flame length within the probe height constraints.

The combustion efficiencies for these two tests are reported as 98.80% and 98.81%. It should be noted that these combustion efficiency calculations do not account for the carbon lost as soot; only carbon present as gaseous species are considered (CO, CO_2, and THC). Higher levels of CO were observed during these tests (61 to 75 ppm corrected) in comparison to tests 1, 2 and 3. However elevated levels of unburned gaseous hydrocarbons were not detected. The hydrocarbon species data shows the predominant species present to be methane and acetylene.

Particulate samples of the soot were collected during these two tests. This data is addressed later in this section.

Tests numbered 7 and 5 were designed to represent flaring of a high Btu content gas at an intermediate flow rate. The steam-to-relief gas ratio was 1.56 for test 5 and represented the high steam flow case, while the ratio of 0.757 for test 7 yielded incipient smoking. Both of these tests at intermediate

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flow rates yielded similar combustion efficiency results to the high flow rate tests (1, 2 and 3). The observed combustion efficiencies were 99.94% and 99.84% for tests 5 and 7 respectively. Methane accounted for the major fraction of the total hydrocarbons present in the flare emissions. The corrected CO levels for both tests were fairly low at 4.1 ppm for test 5 and 7.9 ppm for test 7.

During test 67 the sampling probe was deliberately placed in the flare flame. This is in contrast to the other tests which sought to sample in the flare plume above the flame. The purpose of this short test was to demonstrate the upscale instrument responses to the partially combusted gases in the flame. Concentrations of CO and THC were observed to rise sharply and offscale as the probe was placed in the flame. THC concentrations were observed to be greater than 100 ppm and CO concentrations were observed to be greater than 2,280 ppm. The data collected during this test does not represent the combustion efficiency of the flare since the sample was collected within the flame. The average values for THC and CO reported in the statistical summary are disregarded since these numbers excluded the overrange observations.

Low Flow Rate, High Btu Relief Gases

Tests numbered 17, 50, 56, 61 and 55 examined the effects of increasing steam flows on the flaring of a high Btu content relief gas at a low flow rate (approximately 164 lbs/hr). Test 17 yielded results similar to the high and intermediate flow rate tests. The overall combustion efficiency was calculated to be 99.84% and the corrected average concentrations of THC and CO were low at -0.5 and 6.1 ppm, respectively. (The negative THC value resulted from the measured concentration being lower than the background concentration.) It was determined during this test that a steam-to-relief gas ratio of 0.926 was required for smokeless operation at the designated flow rate.

Tests 50, 56, 61 and 55 were performed at increasing steam flow rates. The steam-to-relief gas ratios used for these tests are regarded as being higher than those that would represent good engineering practice. Steam-to-relief gas ratios for tests 50 and 56 were 3.07 and 3.45 and yielded combustion efficiencies of 99.45% and 99.70%. By contrast the steam-to-relief gas ratios for tests 61 and 55 were 5.67 and 6.86 and resulted in lower observed combustion efficiencies of 82.18% and 68.95%. This data suggests that steam-to-relief gas ratios above 3.5 may cause inefficient combustion.

The total hydrocarbon and CO concentrations for tests 50 and 56 were fairly low in keeping with the high observed combustion efficiencies. However, the hydrocarbon specie data for these two tests show that a larger fraction of the total hydrocarbon was present as unburned propylene (approximately 1/4 of the total hydrocarbon for test 56 and 1/2 of the total hydrocarbon for test 50) in comparison to the previously discussed tests. In tests 61 and 55, with the lower observed combustion efficiencies, the CO and THC concentrations were elevated and propylene represented approximately 3/4 fraction of the total hydrocarbon.

Test 61 was a repeat of Test 55. This repeat test was performed because of uncertainties regarding probe placement during test 55. The flaring of the high heating value relief gas at a low flow with a very high steam rate yielded a low luminosity flame that prevented accurate visual placement of the probe.

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Additionally, test 55 was conducted during variable wind conditions. Test 61 was performed at night to aid visual probe positioning and to take advantage of stable wind conditions. The only significant difference between test 61 and test 55 was that the steam-to-relief gas ratio for test 61 was somewhat lower (5.7 versus 6.9). This ratio is still regarded as being very high and not representative of typical industrial operating practices. The effect of steam quenching on the flare combustion efficiency is evidenced in the test data.

Low Btu Content Relief Gases

The flaring of low Btu content relief gases was simulated by diluting the high Btu crude propylene with inert nitrogen. Thus, by changing the relative flow rates of nitrogen and crude propylene to the flare, the heating value of the relief gas could be varied. For this series of tests, the Btu content of the relief gases ranged from 634 Btu/SCF to 192 Btu/SCF, and the relief gas flow rates ranged from 3,292 lbs/hr to 803 lbs/hr.

The original test plan called for the series of tests involving low Btu content relief gases to include variations in the steam flow to achieve incipient smoking and smoking conditions. However, for most of these tests smoking was not observed, even with zero steam flow. Only when the lower heating value rose above 450 Btu/SCF during test 16 was smoking observed.

Tests numbered 11, 59 and 16 in this series were divided into subtests because the flare operation was not steady-state during these tests. Due to physical limitations in the nitrogen flow control system, the flow of nitrogen decreased with respect to time causing a corresponding increase in the lower heating value of the relief gas. The division into subtests allowed the data to more closely represent steady-state flare operation.

Test 57 represented the highest flow rate of a low Btu content gas that was tested. The flare was supplied with 3292 lbs/hr of relief gas with a lower heating value of 294 Btu/SCF and a steam-to-relief gas ratio of 0.150 steam/lb relief gas. Test 51, by comparison, represented flaring of a similar heating value gas (309 Btu/SCF) with a similar steam-to-relief gas ratio (0.168), but at a lower flow rate of 1,527 lbs/hr. Tests 57 and 51 achieved combustion efficiencies of 99.90% and 98.66%, respectively. Corrected hydrocarbon concentrations of 2.0 ppm and 11.5 ppm and CO concentrations of 5.0 ppm and 34.1 ppm were obtained for tests 57 and 51, respectively. The slightly lower combustion efficiency of test 51 is also observed in the hydrocarbon species data. The observed hydrocarbons in test 57 were approximately 20% non-methane species, while the hydrocarbons in test 51 were comprised of 58% non-methane species.

The flames for tests 57 and 51 were of low luminosity and visual positioning of the probe was difficult. These two tests were the only low Btu flare tests where steam was supplied to the flare. The background file as applied to test 51 (and tests 23 and 52) lists probe tip temperatures that are higher than ambient levels. This is believed to be caused by the probe acting as a heat reservoir from the test event that immediately preceded. This anomaly does not effect the combustion efficiency data.

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Tests 11, 59, 60 and 16 examined the flaring of relief gases with heating values of 192 Btu/SCF to 634 Btu/SCF at flow rates ranging from 3,101 lbs/hr to 803 lbs/hr with zero steam flow to the flare. The variations in observed combustion efficiencies for this set of tests was fairly narrow, ranging from 99.93% to 98.11%.

Test 59 demonstrated the flaring of a low Btu content gas at a high flow rate with no steam. The nitrogen flow decreased during this test from 2,453 lbs/hr to 1,726 lbs/hr due to declining pressure in the nitrogen cylinders. This resulted in an increase in the Btu content of the relief gas from 182 Btu/SCF to 257 Btu/SCF from the beginning to the end of the test. This corresponds to a slightly lower combustion efficiency for test 59(a) than for test 59(b).

Tests 59(a) and 59(b) had the lowest Btu content relief gases of the group. Likewise, these tests exhibited slightly lower combustion efficiencies. This observation is confirmed in the hydrocarbon species data which shows test 59 to have elevated total hydrocarbon concentrations (as compared with tests 11, 60 and 16), and non-methane hydrocarbons representing 92% of the total. These results indicate that some unburned hydrocarbons were sampled during this test.

Test 11 was to demonstrate the flaring of low heating value gas at a flow rate of approximately 3,100 lbs/hr. No steam was supplied to the flare. The flow rate of nitrogen to the flare declined somewhat during the test, thus, causing a corresponding increase in the heating value of the flare gas. Therefore, this test has been divided into three subtests [11(a), 11(b) and 11(c)] for purposes of data analysis. The data does not indicate any change in the flare combustion efficiency with the change in nitrogen flow.

Test 16 was designed to be a smoking flare test utilizing an intermediate flare gas flow with a low heating value gas. No steam was supplied to the flare. As was the case with Test 11, the nitrogen flow declined during the test and hence, the test was divided into subtests for data analysis [tests 16(a), 16(b), 16(c), 16(d)].

During the initial period of the test, when the heat content of the flare gas was the lowest, the flare did not emit smoke. However, as the nitrogen flow declined and the heat content of the flare gas increased, the flare began to smoke. The smoking began approximately nine and one-half minutes from the start of the test [during subtest 16(b)] when the heating value of the flare gas reached approximately 450 Btu/SCF. The smoking increased with increasing Btu content of the relief gas. The onset of smoking and the change in heating value did not have any obvious effects on the gaseous combustion efficiency data (if carbon lost as smoke is excluded from the combustion efficiency calculations).

Test 60 was similar to Test 16(a) except the Btu content was slightly lower at 298 Btu/SCF instead of 339 Btu/SCF. The flow rates for the two tests were similar with exit velocities of 1781 and 1707 ft/min. The observed combustion efficiency for test 60 was 98.92% as compared with 99.74 for test 16(a). As was the case for test 59, this slightly lower combustion efficiency is believed to be a result of the lower Btu content of the relief gas.

Purge Rate Relief Gas Flows

Tests 54, 23, 52 and 53 examined purge gas flare operations. Purge flows are sometimes used in flare operations to prevent oxygen encroachment into the flare system during the time that no relief gas is provided the flare. It should be noted for these tests that the flow of natural gas from the flare pilots was significantly greater than the flow of the purge gases. The two pilots burned a total of 10 SCFM (9210 Btu/min) of natural gas as compared with purge flows of 0.56 to 0.36 SCFM (149 to 74 Btu/min). Thus, the overall combustion efficiency measurements for these tests were primarily a measure of the flare pilots. During these tests only an occasional flicker of flame could be observed at the flare header.

Tests 54 and 23 were performed without the addition of steam to the flare. These tests yielded high observed overall combustion efficiencies of 99.90% and 100.01%. The calculated combustion efficiency greater than 100% for test 23 resulted from the observed hydrocarbon level above the flare being slightly lower than the measured ambient background hydrocarbon concentrations. The corrected total hydrocarbon concentration for tests 54 and 23 were 0.0 and -5.0 ppm.

Tests 52 and 53 were similar to tests 54 and 23 except 210 lbs/hr steam was supplied for the former. The calculated combustion efficiencies for tests 52 and 53 were 98.82% and 99.40%. This slight decline in the combustion efficiency is believed to be due to steam quenching of the combustion process. Corrected total hydrocarbon values observed for tests 52 and 53 are 15.2 and 10.9 ppm. Correspondingly, the CO concentrations for tests 54 and 23 were lower than for tests 52 and 53 (6.8 and 4.5 ppm versus 16.0 and 23.9 ppm). Likewise, non-methane species represented a larger percentage of the total hydrocarbon for tests 52 and 53 than for tests 54 and 23.

The probe tip temperatures during the first three and one-half minutes of test 53 were not recorded by the data logger. This temperature data was recovered from the strip chart record. The low, steady wind speeds that prevailed during test 54 allowed the collection of twenty minutes of relatively consistent data. However, during the latter part of the test the wind speed was observed to increase with a corresponding decrease in probe tip temperature, CO_2 concentration, and SO_2 concentration.

AIR-ASSISTED FLARE TESTS

Eleven tests were completed on the John Zink Company STF-LH-457-5 air-assisted flare. The flare operating conditions and results are summarized in Table 5.

High Btu Content Relief Gases

Four tests numbered 26, 65, 28 and 31 were conducted on undiluted crude propylene burned in the air-assisted flare. The flow of relief gas for these tests ranged from 3,196 lbs/hr to 150.8 lbs/hr. All these tests achieved observed combustion efficiencies greater than 99.0%.

TABLE 5. AIR-ASSISTED FLARE SUMMARY

Test Conditions		Test Number	RELIEF GAS*							Air Flow	Combustion Efficiency (%)
			Flow (SCFM)	Velocity (ft/min)	Heating Value (Btu/SCF)	Propylene Flow (lbs/hr)	Propylene Flow (SCFM)	Nitrogen Flow (lbs/hr)	Nitrogen Flow (SCFM)		
High Btu Content	Decreasing Flow Rate	26	481.6	13087	2183	3196	481.6	-	-	High	99.97
		65	159	4320	2183	1056	159	-	-	Off	99.57 **
		28	157	4266	2183	1043	157	-	-	High	99.94
		31	22.7	617	2183	151.8	22.7	-	-	Low	99.17
Low Btu Content	Decreasing Flow Rate	66	639	8192	158	308	46.4	2598	593	Off	61.94
		29(a)	510	6538	168	261.9	39.3	2062	471	Low	55.14
		29(b)	392	5025	146	173	26.2	1602	366	Low	65.65
		64	249	3192	282	214	32.2	949	217	Low	99.74
		62	217	2782	153	101	15.3	884	202	Low	94.18
		63	121	1551	289	106	16	464	105	Low	99.37
	Purge Flow Rate	33	0.714	9.1	83	0.181	0.0272	3.01	0.687	Low	98.24
		32(a)	0.556	7.1	294	0.498	0.0750	2.10	0.481	Low	98.91
		32(b)	0.537	6.9	228	0.374	0.0563	2.10	0.481	Low	98.86

* All values at standard conditions of 70°F and 29.92 in Hg.

** Not accounting for carbon present as soot (see Table 10).

The hydrocarbon species data for the higher flow rate tests 26, 65 and 28 show the bulk of the total hydrocarbon present as methane. Test 31 integrated hydrocarbon species data shows only 14% of the total hydrocarbon present as methane. Correspondingly test 31 has the lowest flow rate and combustion efficiency of the group. The data collected during test 28 exhibits more variation than usual due to the unstable wind conditions that were present.

One of the ambient background files that is applied to this data (file 32) shows slightly higher concentrations of CO and CO_2 and lower concentrations of THC during the first minute of data than are prevalent during the majority of the background period. The probable explanation for this is that the probe temporarily was in the plume of another combustion source in the area. This abberation does not significantly effect the test results.

Test 65 represents the combustion of a high Btu content hydrocarbon at an intermediate flow rate and no air assistance. This test essentially represents a repeat of test 28 without the air blower switched on. During the test, the flame was observed to smoke.

Low Btu Content Relief Gases

Five tests were performed on low Btu content relief gases with the air-assisted flare. The relief gas flows for these tests ranged from 2,906 to 570 lbs/hr and the lower heating values varied from 146 to 289 Btu/SCF.

Tests 66, 29 and 62 of this group yielded the lowest combustion efficiencies observed for the air-assisted flare tests. Correspondingly, these tests involved the lowest Btu content relief gases (146 to 158 Btu/SCF) that were tested on the air-assisted flare. The flare flames for these tests were of low luminosity and were observed to be detached from the flare tip. This detached flame condition is not regarded as good engineering practice. Predictably, the major portions of the unburned hydrocarbons present in the flare plume were in the form of propane and propylene. Likewise, elevated CO concentrations were observed during tests 66, 29 and 62.

In contrast to the above low efficiency tests, the air-assisted flaring of 282 and 289 Btu/SCF relief gases during tests 64 and 63 proved to be much more efficient. These higher Btu content relief gases were flared at lower flow rates (1,163 and 590 lbs/hr) than the previously discussed tests and yielded good combustion efficiencies of 99.74% and 99.37%. Methane comprised 61% of the total hydrocarbon for test 64 and only 29% of the total hydrocarbon for the less efficient test 63.

The CO_2 data from test 63 shows a three minute period in the middle of the test with CO_2 concentrations observed near ambient levels. This is believed to have been caused by the flare plume shifting away from the sampling probe due to a wind shift. This is evidenced by shifts in wind speed and direction and a decline in probe tip temperature that corresponds to the decline in CO_2 concentrations. This shift in CO_2 concentrations caused a corresponding decline in the combustion efficiency data. Therefore, the average combustion efficiency data presented for this test is regarded as conservative.

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The first thirteen minutes of data collected during test 29 was designated as test 66. The difference between these two tests was that the air-assisted flare's axial fan was turned off for test 66 and turned on for test 29. Both the propylene and the nitrogen flows were observed to decrease during test 29, thus resulting in unsteady flare operation. Therefore, the test was divided into two subtests [29(a) 29(b)] in an effort to make the data within each subtest more closely approximate steady-state flare operation.

Purge Rate Relief Gas Flows

Tests 33 and 32 evaluated the performance of the air-assisted flare in burning purge rate flows of low Btu content gases. As was the case for the steam flare purge gas tests, the overall efficiency of the purge gas combustion is masked by the flare pilots.

The purge flows for tests 33 and 32 are ranged from 0.714 SCFM to 0.537 SCFM as compared with the 10 SCFM flow of natural gas from the pilots. The lower heating values of the purge gases for these tests ranged from 83 Btu/SCF to 294 Btu/SCF. The observed combustion efficiencies for these tests were 98.24% for test 33 and 98.87% for test 32. These values are slightly lower than those observed for the steam-assisted flare purge gas tests. However, the majority of hydrocarbon measured in the flare plume was found to be methane, thus, suggesting that incomplete combustion of the natural gas from the flare pilots may have caused the lower combustion efficiencies.

The flow of crude propylene to the flare did not remain constant throughout test 32. Hence, the test data was divided into two subtests [32(a) and 32(b)] appropriate for data analysis.

SENSITIVITY OF COMBUSTION EFFICIENCY TO PROBE HEIGHT

During the course of the test series the position of the flare sampling probe was frequently adjusted to keep the probe tip as near as possible to the middle of the flare plume and as close to the flame as possible without being in the flame. These changes were necessary to compensate for changes in the wind that occurred during the tests and resulted in changes in the flare flame pattern and location. Not infrequently, the probe was situated at several different locations and heights during a test.

The vertical position of the probe did not have a definable effect on the combustion efficiency data. Figures 6 and 7 are graphs of combustion efficiency versus probe height that demonstrate the insensitivity of the vertical probe position to the combustion efficiency measured at the probe tip.

EFFECT OF STEAM-TO-RELIEF GAS RATIO
ON COMBUSTION EFFICIENCY

Steam injection is a technique commonly used in flare operations to enhance the combustion process. The steam-assisted flare tests performed in this project included a wide range of steam flows and steam-to-relief gas ratios.

34
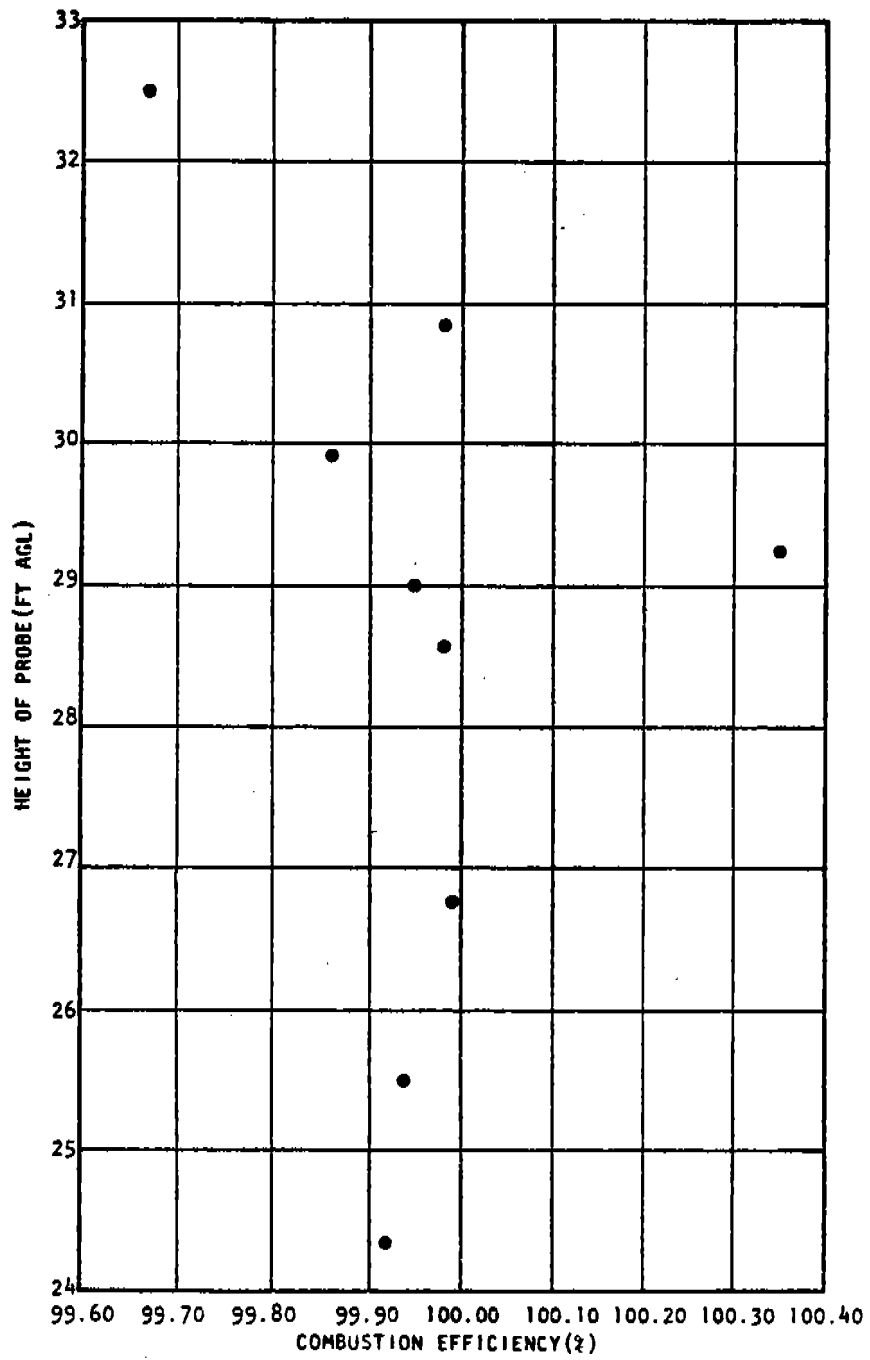
Figure 6. Sensitivity of combustion efficiency to probe height.
Test 28
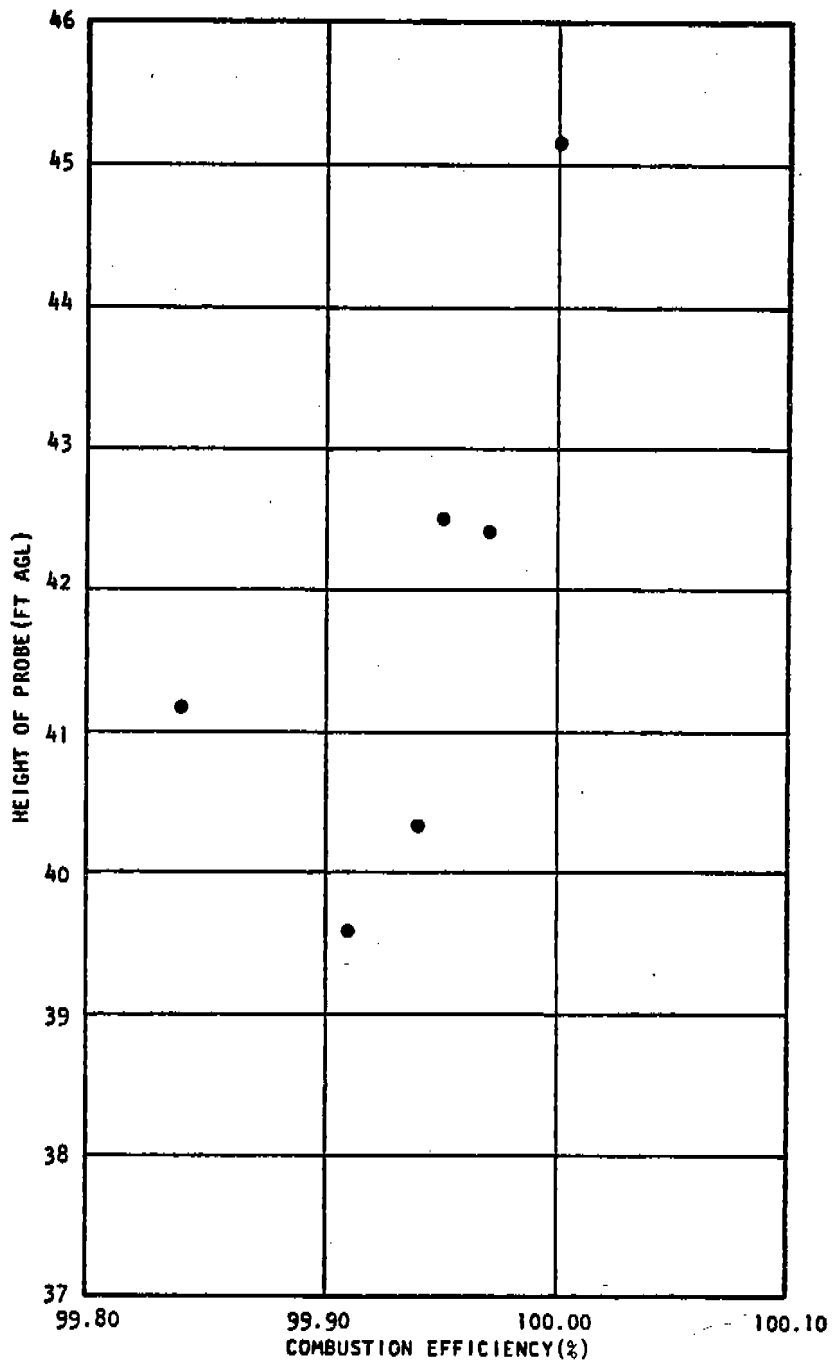
Figure 7.   Sensitivity of combustion efficiency to probe height.
Test 57

Figure 8 is a graph of the effect of steam-to-relief gas ratios on the measured combustion efficiencies of high Btu content relief gases. This plot shows general tendencies for combustion efficiencies to decline at higher or lower than normal steam flows. This data suggests that steam-to-relief gas ratios ranging from 0.4 to 1.5 yield the best combustion efficiencies. The smoking flare tests at zero steam flow were observed to have slightly lower combustion efficiencies than the other comparable tests at normal steam flows. Presumably this is due to the lack of steam-induced turbulence and reaction in the combustion process. It should be noted that these combustion efficiency values do not account for carbon lost as smoke.

The steam flows during the low flow rate tests were at too low a velocity to promote good combustion. Likewise, because of the low relief gas flows the steam to hydrocarbon ratios were greater than for the higher flow rate tests. In the case of tests 61 and 55, the excessive steam-to-relief gas ratios are believed to have caused steam quenching of the flame.

FLARE NO_x EMISSIONS

Emissions of NO_x from both steam- and air-assisted flare plumes were measured during this test program. The NO_x concentrations observed during these tests were fairly low in comparison to other types of combustion sources. However, the NO_x concentrations were subject to undefined dilutions of ambient air and steam not normally encountered in other sources. Corrected NO_x concentrations ranged from 0.50 to 8.16 ppm.

The NO_x mass emission rates were estimated from the NO_x and CO_2 data suggested by EPA:

$$E_{NO_x} = \frac{\text{Moles } NO_x}{\text{Moles } CO_2} \cdot \frac{46 \text{ lbs/mole } NO_x}{44 \text{ lbs/mole } CO_2} \cdot \frac{132 \text{ lbs } CO_2 \text{ produced}}{42 \text{ lbs propylene burned}}$$

$$\cdot \; 47.2 \; \frac{\text{lbs propylene burned}}{10^6 \text{ Btu}}$$

$$E_{NO_x} = \frac{\text{PPM } NO_x \text{ Measured}}{\text{PPM } CO_2 \text{ Measured}} \cdot 155.0 = \text{lb } NO_x/10^6 \text{ Btu}$$

Where:

$$\frac{\text{Moles } NO_x}{\text{Mole } CO_2} = \frac{\text{PPM } NO_x \text{ Measured}}{\text{PPM } CO_2 \text{ Measured}}$$

Assumptions:

1. 100 % combustion of propylene (fuel assumed to be 100% propylene);
2. Equal dilution of NO_x and CO_2 between flare plume and sampling probe;
3. Neglect Btu content of flare pilots (612,600 Btu/hr, gross);[*]
4. 47.2 lbs/10^6 Btu higher heating value for propylene.

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[*] For purge tests, this assumption is invalid.

37
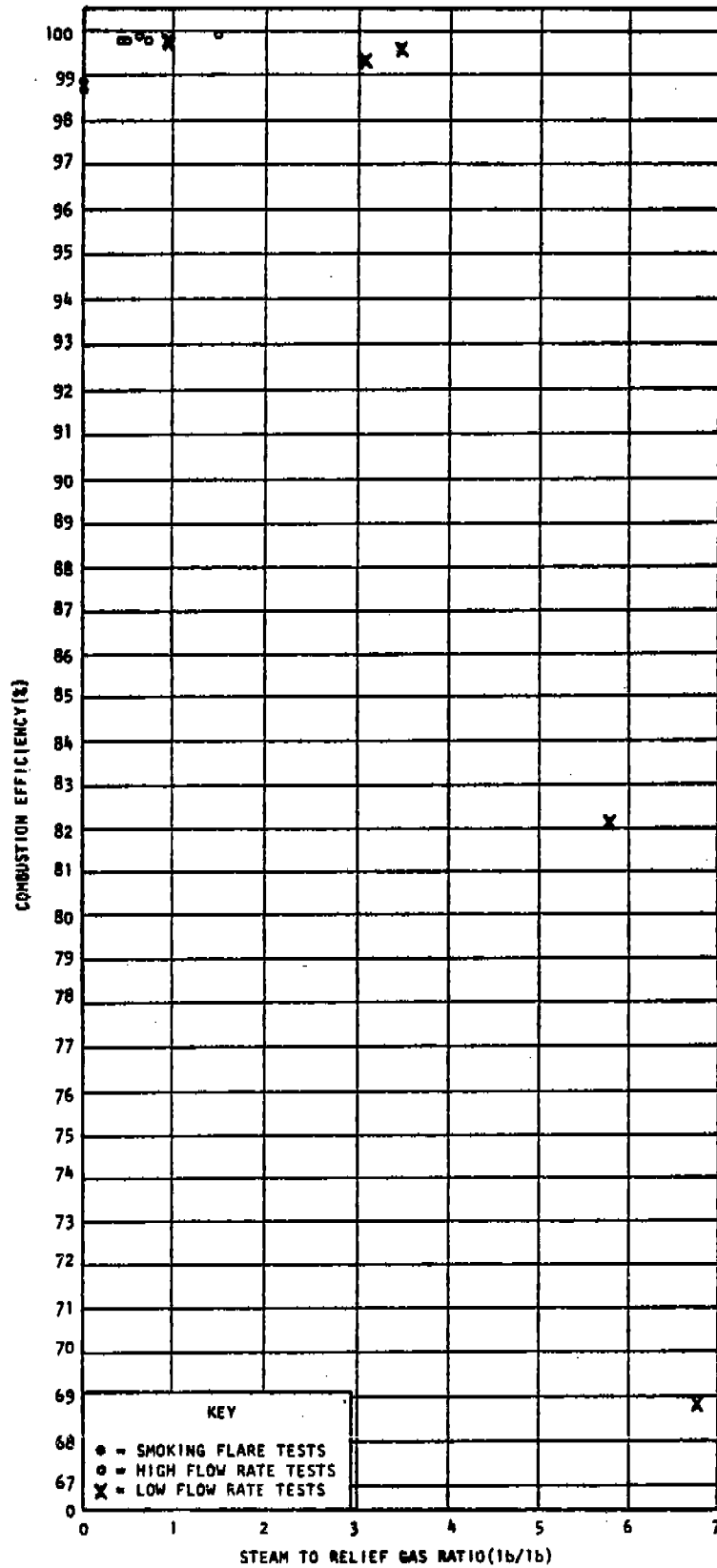
Figure 8. Effect of steam-to-relief gas ratios on flare combustion efficiency.
(High Btu content relief gases)

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Table 6 summarizes the NO_x results of these calculations. This treatment of the NO_x data yields NO_x emission rates ranging from 0.018 to 0.208 lbs/10^6 Btu. Examining this data shows no clear patterns of high or low emissions between test groups. One possible exception to this is the high Btu content air-assisted flare tests which yielded the highest calculated NO_x emission rates.

HYDROCARBON ANALYSES

Hydrocarbon analyses were performed both by continuous total hydrocarbon monitor and by gas chromatograph for hydrocarbon species. The samples for the gas chromatograph were taken from the heated sample manifold (wet basis) and either directly injected into the instrument (an instantaneous sample) or collected in a Tedlar® bag over a period of time (integrated bag sample), and subsequently, analyzed by the same gas chromatograph. The continuous hydrocarbon analyzer withdrew its sample from an unheated sample manifold (dry basis) and measured total hydrocarbon (THC) directly. Both the chromatograph and the continuous hydrocarbon analyzer utilized flame ionization detectors. Thus, three sets of hydrocarbon data are available for each test.

Tables 7 and 8 present a summary of the hydrocarbon data collected during the steam- and air-assisted flare tests. All three sets of hydrocarbon data show good agreement between their total hydrocarbon values for those tests with lower THC concentrations (high combustion efficiency tests). In addition, the instantaneous and bag sample values show good agreement (considering the different sampling techniques) throughout the range of values. However, some discrepancies are noted between the continuous THC values and the gas chromatograph THC analyses at the higher concentrations encountered during the lower combustion efficiency tests. These discrepancies at higher THC concentrations are believed due primarily to the absorption of unburned propylene in the cold trap associated with the dry basis sampling system utilized by the continuous THC analyzer. It is believed that the propylene was subject to loss by virtue of its solubility in the water in the cold trap. This may have been the situation despite the precaution of using a minimum-contact design cold trap condenser.

The sample concentrating effect of the cold trap is believed to be negligible due to the low moisture content of the gaseous samples. Variations between the response characteristics of the gas chromatograph's and the continuous THC analyzer's detectors are not thought to be significant. Both instruments were calibrated in terms of parts per million by volume of methane equivalents.

The continuous total hydrocarbon analyzer's data is believed to be the most useful for evaluating the higher combustion efficiency tests where methane was the major fraction of the total hydrocarbon. However, in the case of the lower combustion efficiency tests where water soluble propylene could have been lost in the continuous analyzer's sampling system, the integrated bag samples provide the most representative total hydrocarbon data. Likewise, since the reported combustion efficiency values were based on the continuous total hydrocarbon data, these values may be biased high for the lower combustion efficiency tests due to the potential loss of propylene in the sampling system.

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TABLE 6. FLARE NOₓ RESULTS

		Test No.	NO_x* Concentration (PPMᵥ)	CO_2* Concentration (PPMᵥ)	NO_x Mass Emission (lbs/10⁶ BTU)
Steam-Assisted Flare	High Btu Content	1	3.09	7,052	0.068
		2	2.16	4,719	0.071
		3	1.54	2,496	0.095
		4	1.96	6,616	0.046
		8	1.45	5,400	0.042
		7	1.62	5,224	0.048
		5	2.09	7,052	0.046
		67	3.77	N/A	N/A
		17	1.00	3,499	0.044
		50	0.50	4,220	0.0187
		56	0.58	3,120	0.029
		61	1.32	6,273	0.033
		55	0.38	2,012	0.029
	Low Btu Content	57	2.68	6,945	0.060
		11	3.69	5,269	0.108
		59	1.41	5,413	0.040
		60	0.99	3,685	0.042
		51	0.57	3,347	0.026
		16	1.87	4,059	0.071
		54	5.00	7,115	0.109
		23	5.90	8,465	0.108
		52	0.68	2,622	0.040
		53	2.83	5,741	0.076
Air-Assisted Flare	High Btu Content	26	5.34	6,270	0.132
		65	2.40	4,878	0.076
		28	8.16	6,076	0.208
		31	4.02	4,568	0.136
	Low Btu Content	66	0.97	2,432	0.062
		29	1.06	2,179	0.075
		64	1.24	3,282	0.058
		62	0.60	3,076	0.030
		63	1.57	4,184	0.058
		33	0.74	1,857	0.061
		32	1.75	3,702	0.073

* Corrected for background.

TABLE 7. HYDROCARBON ANALYSIS SUMMARY
STEAM-ASSISTED FLARE TESTS

Test No.	Continuous THC Analyzer Avg. Conc.*	Instantaneous Samples, Average Values*							Bag Samples, Average Values*						
		C_1	C_2/C_2^*	C_2^*	C_3	C_3^*	C_4	THC	C_1	C_2/C_2^*	C_2^*	C_3	C_3^*	C_4	THC
1	3.7	2.2	-	-	-	-	-	2.2**	3.0	-	-	-	-	-	3.0**
2	6.5	3.0	-	-	-	-	-	3.0**	2.8	-	-	-	-	-	2.8**
(3)	4.3	2.5	-	2.04	.23	2.33	-	2.5**	3.5	-	-	-	-	-	3.5**
(4)	10.5	4.73	0.68	2.51	0.25	2.66	-	10.8	6.19	0.76	2.95	0.34	0.77	-	11.0
(8)	9.5	5.70	0.63	3.00	0.15	1.82	-	11.3	5.87	0.63	1.46	0.18	0.34	-	8.5
(7)	9.9	1.79<	0.20	0.30	0.12	0.35	-	2.8	2.92	-	0.22	0.23	0.56	-	3.9
5	4.9	2.4	-	-	-	-	-	2.4**	3.08	-	0.32	0.30	0.29	0.03	4.0
17	4.7	2.59	0.25	-	0.09	-	-	2.9	3.12	0.59	0.35	0.15	0.06	-	4.3
50	12.0	3.59	1.08	0.49	1.34	5.65	-	12.1	4.31	1.90	0.95	2.21	7.65	-	12.6
56	8.2	4.06	0.12	0.10	0.19	1.52	-	6.0	4.91	1.46	1.06	0.88	2.22	-	10.5
(61)	964	45.6	143	69.2	635	2,675	-	3,568	24.2	67.4	33.5	282	1,182	1.08	1603
(65)	742	14.07	3.35	0.20	268	1,075	-	1,361	16.5	36.6	21.0	259	1,061	-	1402
57	7.8	6.72	0.37	0.03	0.29	0.50	-	7.9	7.54	0.53	0.16	0.36	0.82	-	9.4
11	6.6	4.29	0.24	0.52	0.31	0.71	-	6.1	5.70	1.33	0.35	0.32	0.79	0.02	8.5
(59)	36.1	4.00	2.96	1.05	3.30	9.63	-	20.9	4.31	5.17	1.72	13.0	31.4	-	55.6
60	14.3	3.75	1.28	0.55	1.47	−6.22	-	13.3	4.45	3.05	1.31	2.63	14.2	0.08	25.6
51	22.8	5.82	0.56	0.53	0.50	1.78	-	9.2	8.19	3.73	3.83	1.38	5.92	-	23.1
(16)	6.4	6.06	0.49	0.18	0.64	2.16	-	9.5	6.55	0.48	0.25	0.55	1.15	-	9.0
(54)	6.5	3.15	0.64	-	1.76	2.42	-	8.0	3.46	0.64	0.33	0.86	1.57	0.02	6.9
23	6.3	3.47	0.03	-	0.06	-	-	3.6	3.95	0.05	-	0.09	0.11	-	4.2
(82)	24.6	7.66	1.74	0.03	5.21	21.24	-	35.9	6.65	2.49	4.23	6.70	27.8	-	47.9
(55)	15.6	3.39	0.90	0.31	2.04	6.10	-	12.7	3.97	1.53	0.55	3.22	13.6	-	22.9

Left margin: High Btu Content · Low Btu Content

* All values are ppm by volume methane equivalents; uncorrected for background THC.

** The gas chromatograph electrometer attenuation was set to a less sensitive scale for these analyses.

KEY: Methane, C_1 Propane, C_3 Butane, C_4
Ethane, C_2 Propylene, C_3^* Total Hydrocarbon, THC
Ethylene, C_2^* Acetylene, C_2^*

Page number (left margin): 41

Handwritten annotations (top):
Continued $\bar{X} + \sigma$ for steam assisted
and air assisted THC test results in Sep. '82

for n=23, $\bar{X}_{C_1}$ = 4.65 ppm (1.79 to 13.0)
n=14, $\bar{X}_{C_2/C_2^*}$ 1.67 (0.07 to 14.7)
n=18, $\bar{X}_{C_2^*}$ = 0.96 (0.03 to 5.64)
n=19, $\bar{X}_{C_3}$ = 2.53
n=18, $\bar{X}_{C_3^*}$ 12.8

Bottom handwritten:
$\bar{X}$ = 3.15 $\bar{X}$ = 0.84 $\bar{X}$ = 3.02 $\bar{X}$ = 7.68
$\bar{X}$ = 1.67

n=11, avg ratio of C_2^* to THC = 8.4%, max = 26.5%
σ = 8.3% min = 0.4%

n=11, avg ratio of C_3^* to THC = 25.3, max = 46.8%
σ = 19.1 min = 6%

n=16, C_1 to THC = 67.2% max = 100%
σ = 26% min = 19%

n=12, C_3 to THC = 6.09%
σ = 4.02%

TABLE 8. HYDROCARBON ANALYSIS SUMMARY
AIR-ASSISTED FLARE TESTS

	Test No.	Continuous THC Analyzer Avg. Conc.*	Instantaneous Samples, Average Values*							Bag Samples, Average Values*						
			C_1	$C_2/C_2^=$	$C_2^\equiv$	C_3	$C_3^=$	C_4	THC	C_1	$C_2/C_2^=$	$C_2^\equiv$	C_3	$C_3^=$	C_4	THC
High Btu Content	26	11.3	3.36	0.86	0.15	0.67	2.02	-	7.06	3.18	-	-	0.22	0.78	--	4.18
	65	4.8	4.63	0.07	0.18	0.07	0.06	-	5.0	4.50	0.11	0.32	0.16	0.18	-	5.3
	28	6.0	4.15	0.19	0.03	0.18	0.54	-	5.1	3.43	0.09	0.05	0.22	0.77	-	4.6
	31	15.7	4.85	4.93	1.20	3.62	29.0	-	43.6	4.12	3.20	2.19	3.82	15.36	-	28.8
Low Btu Content	66/29	1,238	25.5	69.1	27.4	513	1,992	-	2,627	31.4	47.4	21.1	474	1,965	0.20	2,539
	64	8.7	7.59	0.54	0.06	0.36	0.82	-	9.37	7.35	1.14	0.68	0.85	1.97	-	12.0
	62	109	13.1	14.7	5.64	32.8	249	0.08	315	16.6	16.5	6.16	33.7	139	0.09	214
	63	15.3	5.97	1.57	0.78	1.67	6.45	0.03	16.5	6.18	1.83	0.63	2.60	10.4	-	21.6
	33	32.1	25.1	2.71	0.10	1.44	3.38	10.2	42.9	27.6	12.7	0.10	1.83	5.19	0.11	47.5
	32	34.1	15.6	1.71	0.28	0.93	2.19	-	20.7	29.7	3.96	0.65	1.67	4.31	0.13	40.4

*All values are ppm by volume of methane equivalents, uncorrected for ambient background THC.

KEY: Methane, C_1
Ethane, C_2
Ethylene, $C_2^=$
Propane, C_3
Propylene, $C_3^=$
Acetylene, $C_2^\equiv$
Butane, C_4
Total Hydrocarbon, THC

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from n=7 g ratio of C_1 to THC = 50.5% max = 92.6%
σ = 32.8 min = 4.2%

n=7 $C_2^=$ to THC = 2.3 max = 3.6%
σ = 1.4 min = 0.6%

n=7 $C_3^=$ to THC = 33% max = 79
σ = 28% min = 1.2%

Figure 9 is an example of a gas chromatograph analysis of the flare emissions.

PARTICULATE MATERIAL ANALYSES

Samples of the particulate material emitted from the flare flame were collected during the flare test series. An in-line fiberglass filter collected these samples for determination of particulate mass loading and subsequent analysis for polynuclear aromatic compounds (PNA's) by gas chromatography/mass spectroscopy. The PNA data is reported in Appendix D.

Table 9 is a summary of the mass particulate concentration data collected during the test series. The data show distinct differences between particulate loadings of nonsmoking and smoking flare tests.

The combustion efficiency calculations used in this report as a measure of the flares' performance did not account for the carbon lost as particulate material in the smoke. Only terms for CO, CO_2 and THC concentrations are used in these combustion efficiency calculations. Therefore, the gaseous combustion efficiency values reported for the smoking flare tests would be expected to be higher than the real combustion efficiency.

The following equation was used to include the carbon lost as particulate material for smoking flare tests 4, 8 and 65.

$$CE\% = \frac{CO_2}{CO_2 + CO + THC + C_p} \times 100$$

Where:

CO_2 = carbon dioxide concentration (PPM_v)

CO = carbon monoxide concentration (PPM_v)

THC = total hydrocarbon concentration (PPM_v as methane)

C_p = particulate concentration (PPM_v assuming smoke particulate as gaseous elemental carbon and ideal gas, 2.03 1/g).

Table 10 outlines the results of calculating the combustion efficiency using this particulate corrected method.

DILUTION RATIO AND DESTRUCTION EFFICIENCY DETERMINATIONS

The attempt to use sulfur as a tracer material for the flare tests yielded disappointing results. The tracer technique was employed in lieu of measuring the volumetric flow rate of the flare plume. Volumetric flow rate determinations in an open combustion system such as a flare are not feasible. The intent was to complete a sulfur balance between the flare burner and the sampling probe in order to calculate the effective dilution of the flare gas due to combustion, steam, forced air and ambient air. By knowing the dilution ratio, estimates of flare destruction efficiency and emission rates can be calculated. Unfortu-

43

```
                                                      1.29 METHANE
               1.62 ETHANE
         1.91  ACETYLENE
                  2.44   PROPANE
                                                      2.89  PROPYLENE

        3.52

STOP
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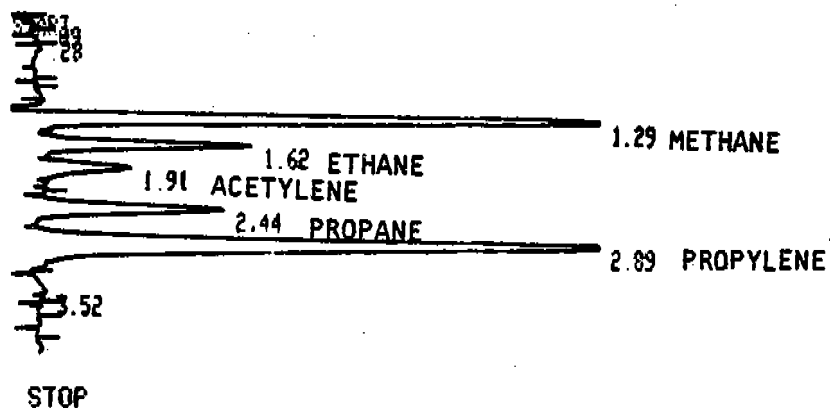
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RUN #  194                    JUN/21/82  14:11:08
ID   26128.00

ESTD
   RT        AREA  TYPE  CAL.      AMOUNT
  0.09        291  PB              0.000
  0.28        198  PB              0.000
  1.29      92868  PV    1.        3.501
  1.62      46859  VV              0.000
  1.91      23201  VV              0.000
  2.44      20129  VP              0.000
  2.89      87374  PB              0.000
  3.52       1044  PV              0.000


TOTAL AREA=      271960
MUL FACTOR= 1.0000E+00
```

Figure 9. Example gas chromatogram hydrocarbon analysis.
(Test 50)

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TABLE 9. PARTICULATE ANALYSIS

Test No.	Filter No.	Wt. gain, (grams)	Sample Time[1] (minutes)	Sample Rate (ℓ/min)	Concentration (μg/ℓ)
2, 3, 1, 5, 7	A-1	0.0063	---	18.51	---
7, 17, 50, 51 23, 52, 53, 54	F-1	0.0071	---	18.51	---
4 (Smoking)	F-2	0.0810	16	18.51	274
8 (Smoking)	F-3	0.0819	25	18.51	177
55, 56, 11, 57 16, 59, 60, 61 28, 31, 26, 29 33, 32, 62, 63 64, (80, 81, 82 83, 84)[2]	F-4	0.0179	---	18.51	---
65 (Smoking)	F-5	0.0183	25	18.51	40

[1] Includes time for probe positioning while probe was in the plume but before formal initiation of the test.

[2] Separate tests conducted for John Zink Company not reported herein.

TABLE 10.   SMOKING FLARE COMBUSTION EFFICIENCIES

Test	Particulate Concentration		Combustion Efficiency (percent)	
	(μg/l)	(μl/l)	Particulate Corrected	Reported
4	274	557	91.21	99.80
8	177	360	92.72	98.81
65	40	81	97.95	99.57

nately, considerable difficulty was encountered in quantifying and maintaining constant levels of sulfur in the relief gas.

The primary source of flare gas for this series of tests was a tank truck of 6,800 gallons of crude propylene to which approximately 4 liters of butyl mercaptan were added. This addition of mercaptan should have yielded a sulfur concentration of approximately 89 ppm (by weight) in addition to the naturally occurring sulfur in propylene (estimated at 2 - 10 ppm). An extremely wide range of results were obtained from these analyses. Thus, there is considerable doubt as to the actual concentration of sulfur in the propylene. Additionally, this data cast doubt on whether or not the concentration of sulfur was stable or if a fraction of the sulfur could have combined with the steel tank, iron pipe or other materials which were in contact with the propylene.

The sulfur content of the nitrogen used for dilution of the propylene and the sulfur content of the steam condensate were found to be very low and did not represent a significant contribution to the overall sulfur balance.

The levels of SO_2 measured during the initial tests were lower than expected, and in some cases, challenged the practical detection limit of the analyzer. After completion of ten of the thirty-four tests, provisions were made to add SO_2 gas into the relief gas stream in order to elevate the sulfur levels in the flare emission into a midrange level. This modification was plagued with mechanical failures that prevented the addition of SO_2 to many of the subsequent tests and was not accomplished at a uniform rate.

The sulfur balance data yielded results that were much higher than would reasonably be expected to occur. In addition, the ratio of SO_2 to CO_2 concentrations in the flare emissions were not constant as was expected, either between tests or within tests. The SO_2 and CO_2 ratio should be constant given that both these gases are subject to the same dilution effects and assuming a constant level of sulfur in the relief gas and no effect due to background concentrations.

Because of the doubts surrounding the sulfur balance dilution ratios, an alternate means of calculating dilution ratios was formulated using the CO_2 data. This technique assumes stoichiometric combustion and is frequently used in evaluating emissions from other combustion sources. However, the CO_2 dilution technique was not well received because: (1) it did not provide a measure of dilution independent of the combustion measurement, and (2) the flare plume did not maintain steady-state conditions relative to the sampling probe.

By making simplifying assumptions, destruction efficiency calculations can be made and are provided in Appendix C. With regard to flare efficiencies, it should be noted that in a smokeless flare, the total hydrocarbon destruction efficiency will always be greater than the combustion efficiency. This is because, by definition, the percentage of hydrocarbon that is converted to CO_2 (combustion efficiency) is equal to or less than the percentage of relief gas that is converted to CO and CO_2 (destruction efficiency).

MOISTURE DETERMINATIONS

The moisture content of the flare emissions was gravimetrically determined using an ice-bath condenser type of moisture trap. Table 11 lists the results of these moisture analyses. The moisture data were lower than expected with an average of 3.0% moisture measured for the air-assisted flares and 3.8% moisture measured in the steam-assisted flare samples. A description of the methodology used for moisture determinations may be found page 18 of this report.

OTHER FLARE TEST ANALYSES

A composite sample of the steam condensate was collected and analyzed for sulfur and hydrocarbon content. The results of these analyses are as follows:

Sulfate	less than 1 mg/l
Sulfide	0.03 mg/l
Hydrocarbon	0.13 mg/l

The crude propylene that was used during the test series as the basis for flare fuel was analyzed by both the propylene vendor and by ES. The results of these analyses are as follows:

Analyst	Propylene	Propane	Ethane/Ethylene
Vendor	80.2	19.8	---
ES	79.4	18.5	1.9%

For the purposes of this test series, the differences between these two analyses is not significant.

The nitrogen used to dilute the crude propylene to a lower heating value gas was analyzed for hydrocarbon content. The nitrogen was found to contain 0.33 ppm by volume of hydrocarbon methane equivalents.

TABLE 11. FLARE EFFICIENCY TEST
MOISTURE CONTENT OF SAMPLES
(EPA METHOD 4)

Test Number	Moisture (Volume %)
2	<1
3	N/A
1	7.1
5	<1
7	3.6
17	2.8
50	2.9
51	3.0
23	3.5
52	5.5
53	7.1
54	4.6
4	3.1
8	3.0
55	4.6
56	3.7
11	1.9
57	2.9
16	4.8
59	N/A
60	N/A
61	N/A
28	2.1
31	3.2
26	3.4
66	3.3
29	3.3
33	2.9
32	2.9
62	2.9
64	2.9
63	2.9
65	3.8

SECTION 6

QUALITY ASSURANCE AND QUALITY CONTROL ACTIVITIES

MULTIPOINT CALIBRATIONS

Before the collection of data was initiated, the continuous analyzers were checked for proper operation. A key element of the operational checks was the multipoint calibrations. These multipoint calibrations consisted of challenging the analyzers with a zero gas and several upscale concentrations of the gaseous compounds of interest. Calibrations were conducted at the concentrations anticipated to be in the flare emission plume. The purpose of these multipoint calibrations was to demonstrate instrument response linearity both within instrument ranges and between instrument ranges. Table 12 lists the analyzer ranges and gas concentration ranges used for these checks. The criteria for calibration curve acceptability was no more than 5% deviation from the input value within a range and no more than a 10% deviation from the reference standard between ranges.

The source of the calibration gases was aluminum compressed gas cylinders certified by their manufacturers to be accurate within + 2% of their listed concentrations. The gas standards for NO_x and CO were traceable to the National Bureau of Standards' standard reference materials. The compressed gas standard for SO_2 calibrations was contained in a Teflon® lined aluminum cylinder and was certified on-site against a graviametrially calibrated SO_2 permeation device.

In addition, the efficiency of the NO_2 to NO converter in the NO_x analyzer was checked using the procedure recommended in EPA Reference Method 20 (40 CFR 60 Appendix A). The converter efficiency was found to be greater than 99% efficiency in the conversion of NO_2 to NO.

The response of the probe tip thermocouple was verified at ambient temperature against the calibrated meteorological station thermistor and was checked for $0°C$ response in an ice water bath.

ZERO AND SPAN CHECKS

Before and after each test or series of tests, all the continuous analyzers were challenged with zero gas and a single upscale concentration of the compound of interest. The purpose of these calibration checks was two-fold. First the collection of the zero/span data provided a data base to allow estimation of the analyzer's precision of measurement. Secondly, the gas standards used for the zero and span checks provided points of reference for instrument calibration adjustment between tests. Thus, the zero/span checks provided a mechanism to both monitor and maintain the precision of the data.

Table 13 is a summary of the zero span check data.

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TABLE 12.   MULTIPOINT CALIBRATION CHECKS

Analyzer	Instrument Ranges Checked	Calibration Gas Levels [1]
CO	0-5,000 ppm 0-3,000 ppm 0-1,000 ppm[2]	3,490 ppm 1,003 ppm 252 ppm[3]
CO_2	0-5%[2] 0-10% 0-15%	5.01%[3] 10.0%
THC[4]	0- 100 ppm[2] 0-1000 ppm 0- 500 ppm	50 ppm[3] 159 ppm 500 ppm
NO_x	0-25 ppm[2] 0-100 ppm 0-250 ppm 9-1000 ppm	3.7 ppm 17 ppm[3] 92 ppm
O_2	0-25%[2]	21.0%[3] 12.1% 2.0%
SO_2	0-1 ppm range (Instrument modified with 1:5 dilution system to yield an effective 0-5 ppm range)	.934 ppm[3] .404 ppm .103 ppm

[1] All instruments' zero responses were verified with zero nitrogen.
[2] Primary operating range used during tests.
[3] Concentrations used for routine span checks and calibration adjustments.
[4] THC analyzer calibrated on methane.

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TABLE 13. ZERO/SPAN CHECK SUMMARY

Parameter	No. of Checks	Average Deviation of Instrument Response to Span Value	Standard Deviation	Upper 95% Probability Limit	Lower 95% Probability Limit
CO	29	-0.91%	±1.88%	+2.77%	-4.59%
CO_2	30	-1.16%	±3.09%	+4.90%	-7.16%
THC	31	-0.13%	±2.65%	+5.06%	-5.32%
NO_x	29	+2.94%	±4.37	+11.51%	-5.63%
O_2	29	-0.07%	±1.32%	+2.52%	-2.66%
SO_2	34	-3.25%	±4.98%	+6.51%	-13.01%
HC Species	33	-0.80%	±2.20%	+5.11%	-3.51%

During the initial tests, zero/span checks were conducted between each test. As the project progressed, confidence in the reliability of the instruments increased and the frequency of these calibration checks was reduced by allowing two or three tests to be completed between zero/span checks. As a minimum, zero/span checks were conducted at the beginning and end of each test day.

INSTRUMENT RESPONSE TIMES AND
THROUGH-PROBE CALIBRATION CHECKS

The response time for each instrument was adjusted to allow comparision of individual data values. The goal was to ensure that all the instruments were analyzing a fraction of the same sample at the same time. The synchronization of the instrument responses permitted data calculations to be performed on the instantaneous data as well as on the one-minute and test averages. For example, the combustion efficiency calculations, which included data from three separate instruments, could be performed on each set of instantaneous data because the three analyzers were simultaneously sampling the same flare emission gas.

The instrument synchronization was accomplished by adjusting the sample tubing length and volume between the sample manifold and the instrument and adjusting the sample flow rate to the analyzer. In this manner, the transit time of the sample between the manifold and the instrument could be adjusted. These adjustments were made in reference to the instruments' initial upscale response time.

The upscale and downscale response times of the instruments were checked by introducing calibration gases through the probe and timing the subsequent response of the instrument. Table 14 summarizes the results of these response time checks.

An adaptor fitting was attached to the probe tip to allow the introduction of the calibration gases. This 1/4" tube to 1" pipe adapter fitting presented a flow restriction on the entire sampling system that was not present during the normal sampling. Thus, the response times reported in Table 14 may be somewhat slower than the actual response times encountered during the sampling.

The introduction of calibration gases through the probe tip also served to verify the integrity of the sampling system. There were no significant differences observed in instrument responses to calibration gases introduced directly into the analyzers as compared to calibration gases which were passed through the probe. This evidence suggests that the sampling assembly did not alter the composition of the flare emissions during the sampling.

Leak checks of the sampling system were performed on several occasions during the test series. The procedure followed was to introduce zero nitrogen in the probe tip and monitor the oxygen content of the sampling system. If leaks were present in the sample system, they would be evidenced by elevated oxygen levels in the sampling system. Table 15 presents the results of these leak checks. This leak check data is believed to be conservative since the installation of the required adapter fitting on the probe tip during these

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TABLE 14. INSTRUMENT RESPONSE TIMES

	(Up Scale (Seconds)		Down Scale (Seconds)	
	Initial	90% Response	Initial	90% Response
CO	32	115	30	115
CO_2	30	123	25	120
THC	35	147	34	125
NO_x	32	77	25	69
O_2	30	123	25	120
SO_2	29	90	32	80

TABLE 15.   SAMPLING SYSTEM LEAK CHECKS

Date	Input	O_2 Analyzer Response	Percent [1] Leakage
6/17/82	N_2	0.80%	3.8%
6/17/82	N_2	0.25%	1.2%
6/18/82	N_2	0.31%	1.5%
6/19/82	N_2	0.24%	1.1%
7/ 1/82	N_2	0.30%	1.4%

[1] Assuming 20.95% oxygen in ambient air.

checks caused an increase in the vacuum present in the sampling system as compared to during normal flare emission sampling.

The zero response of the other continuous analyzers to zero nitrogen passed through the sampling system was also verified during the leak checks.

BACKGROUND MEASUREMENTS

Ambient air component concentrations of CO, CO_2, THC, NO_x, O_2 and SO_2 were collected immediately before and after each of the tests or series of tests. The collection of this background data documented the influence of local ambient air concentrations on the flare emission measurements. The background concentrations of these compounds of interest could have had a significant effect on the data given the dilution effects of ambient air in both steam- and air-assisted flare emissions. This is especially true in this situation since other combustion sources were present and operating in the test area. A complete listing of the background concentration measurements is contained in the data volume (Volume II) of this reort.

The background data was applied to the flare emission data by subtraction. The average background values were subtracted from each raw flare emission concentration values to determine the corresponding corrected value. This subtraction removed any data bias between tests that was caused by variable ambient concentrations. Additionally, the subtraction of the average of the background concentrations before and after each test helped to compensate the data for instrument calibration drift that may have occurred between these periods. It is recognized that to properly account for background concentrations, a dilution factor correction is required. As discussed previously, dilution factors were not obtained in this study. Calculations indicate that an error of less than 0.1% in combustion efficiency (for CE's greater than 98%) is caused by the background correction method employed herein. As shown below, this error is less than the sampling and analysis error. Therefore, the background correction described above is suitable for this study.

COMBUSTION EFFICIENCY ERROR ANALYSIS

It is assumed that accuracy of the combustion efficiency calculations is dependent on two primary sources of error: (1) the accuracy of the listed concentrations of the calibration gases, and (2) the accuracy of the instruments' measurements of the gaseous samples (instrument drift, interference, repeatability, etc.). Other systemic errors due to sampling, data acquisition, etc. are assumed to be negligible.

Table 16 lists estimates of the magnitude of these two primary types of error for each of the continuous analyzers. The instrument error data in this table was calculated from the instrument responses to the routine span calibration checks. The calibration gas error data are nominal values supplied by the vendors of the calibration gases.

Although these two types of errors are independent of each other, it is assumed for this worst-case error analysis that they reinforce and are additive. Likewise, it should be noted that the measurement errors of variables in the

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TABLE 16. ERROR ESTIMATES

Parameter	Instrument Precision Standard Deviation of Span	Instrument Error	Calibration Gas Accuracy Error	Total Worst Case Accuracy Error
CO	1.88%	±4.7 ppm	±5.0 ppm	±9.7 ppm
CO_2	3.09%	±1545 ppm	±1000 ppm	±2545 ppm
HC	2.65%	±1.3 ppm	±1.0 ppm	±2.3 ppm
NO_x	4.37%	±0.7 ppm	±0.3 ppm	±1.0 ppm
O_2	1.32%	±0.27%	±0.42%	±0.69%
SO_2	4.98%	±0.046 ppm	±0.019 ppm	0.065 ppm

combustion efficiency calculations are independent of one another. However, for this worst-case analysis it is assumed that the errors in the measurements of CO, CO_2 and THC concentrations reinforce.

For this worst-case analysis two sets of concentration values for CO, CO_2 and THC were selected: (1) for the high combustion efficiency case, and (2) for the low combustion efficiency case. The total worst-case accuracy error values were applied to these two sets of concentration values to determine the effects on the combustion efficiency calculations.

	High Efficiency Test	Low Efficiency Test
CO Observation (ppm)	8	1000
CO_2 Observation (ppm)	7000	5000
THC Observation (ppm)	4	90
% CE Best Estimate	99.83	82.10
% CE Highest Estimate	100	87.49
% CE Lowest Estimate	99.46	69.02

This exercise shows that the high combustion efficiency test data are less sensitive to accuracy errors than are the low combustion efficiency test data. This analysis also provides worst-case estimates of the magnitudes of the combustion efficiency accuracy errors. It should be noted that the real accuracy errors (which were not directly measured) are expected to be less than those listed above since the sources of error are independent and do not necessarily reinforce.

Another mechanism for examining the quality of the combustion efficiency determinations is to examine the variance of repetitive determinations based on consecutive measurements of CO, CO_2 and THC within each test. The data listing and analysis program used to compile the data from these tests incorporated routines to calculate the combustion efficiency from each set of data collected every twelve seconds. The variance (and standard deviation) of the average combustion efficiency value was determined from this data set as an indicator of the precision of the data. The standard deviations of the consecutive measurements of combustion efficiency ranged from + 0.1% to +11.1%. As in the worst-case error analysis, the largest variances occurred with the low combustion efficiency tests and the smallest variances were obseved with the high combustion efficiency tests.

APPENDIX A

GRAPHICAL REVIEW OF SELECTED TESTS

Five of the thirty-four flare efficiency tests completed during this project were selected for more detailed data analysis via graphical aids. The selected tests are as follows:

Test	Flare Type	Flare Gas Flow (SCFM)	Heating Value (Btu/SCF)	Steam-to-Flare Gas Ratio (lb/lb)	Combustion Efficiency Percent
3	Steam-assisted	456	2183	0.45	99.8
55	Steam-assisted	24.7	2183	6.9	68.9
57	Steam-assisted	703	294	0.15	99.9
28	Air-assisted	157	2183	--	99.4
33	Air-assisted	0.714	83	--	98.2

These tests were selected because they represented a fairly wide range of flow rates, heating values and combustion efficiencies. Figures A-1 and A-2 are photographs of the flare taken during these tests.

Three types of graphical test data plots were compiled from the digitized instantaneous data collected on magnetic tape via a data logger. A detailed listing of these data may be found in a separate data volume to this report (Volume II). The plots chosen for this exercise are as follows:

SO_2 and Probe Temperature versus Time;

THC and CO versus Time; and

CO and Combustion Efficiency versus time.

Figures A-3 through A-17 are the graphical plots of this data.

The plots of SO_2 and probe temperature show a positive correlation between these two parameters. The temperature values are observed to lead the SO_2 values by about 0.3 minutes. This time lead indicates the difference in response times between the thermocouple/digital thermometer assembly and the sampling system/SO_2 analyzer. The positive correlation between these two parameters is due to both parameters being indicators of probe position relative to the flame.

The graphical presentations of THC and CO_2 versus time show variable amounts of positive correlation between these two species. Theoretically,

given a flare burning with constant combustion efficiency, the ratio of THC to CO_2 should be constant regardless of flame postion relative to the probe. This is shown to be the case in the plot for Test 55 and to a lesser extent Test 57. Tests 3, 28 and 33 show little or no correlation between concentrations of THC and CO_2.

The graphs of combustion efficiency and CO versus time show an inverse relationship between CO and concentrations on the combustion efficiency. This demonstrates the importance of the CO term in the combustion efficiency calculations and the usefulness of CO measurements as a primary indicator of relative combustion efficiency.

These plots of the test data also serve to graphically show the typical range and variation of concentrations and temperature observed during the flare tests.

Test 33
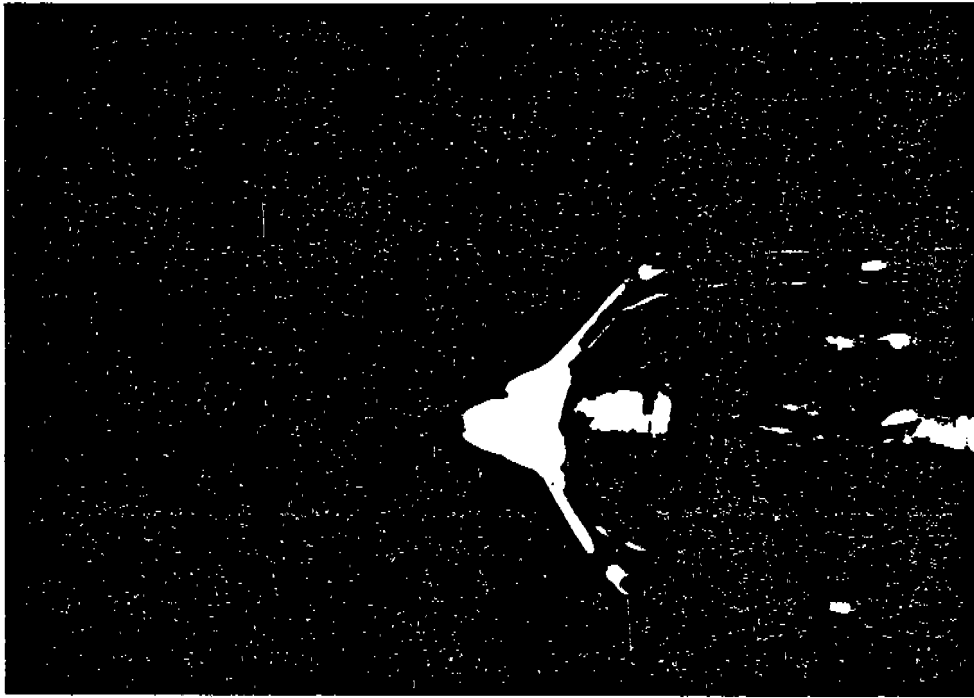
Test 3

Figure A-1. Photographs of flare taken during tests.

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Test 57   Test 28

Figure A-2.   Photographs of flare taken during tests.
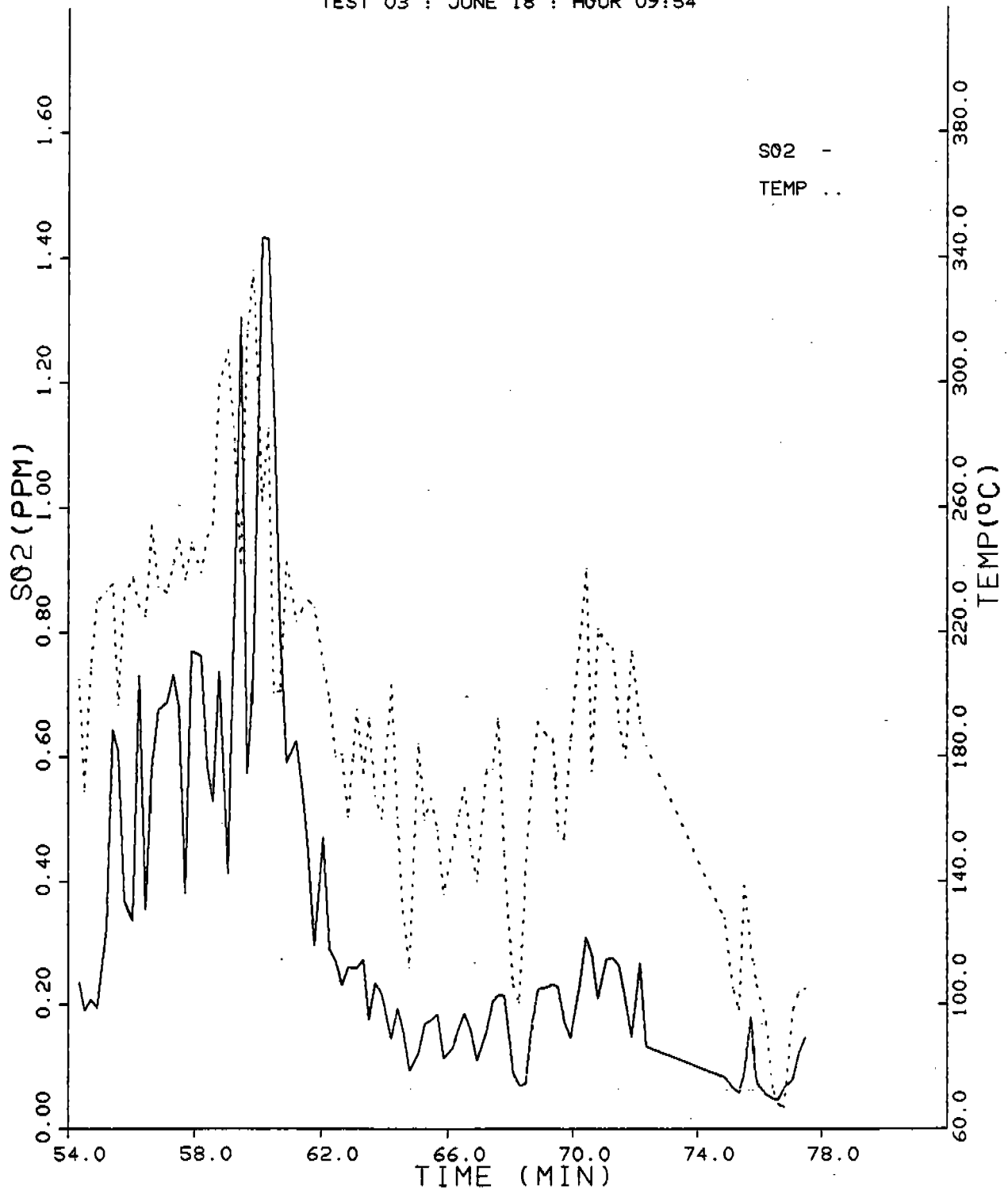
Figure A-3. SO2 and temperature vs. time.

TEST 03 : JUNE 18 : HOUR 09:54
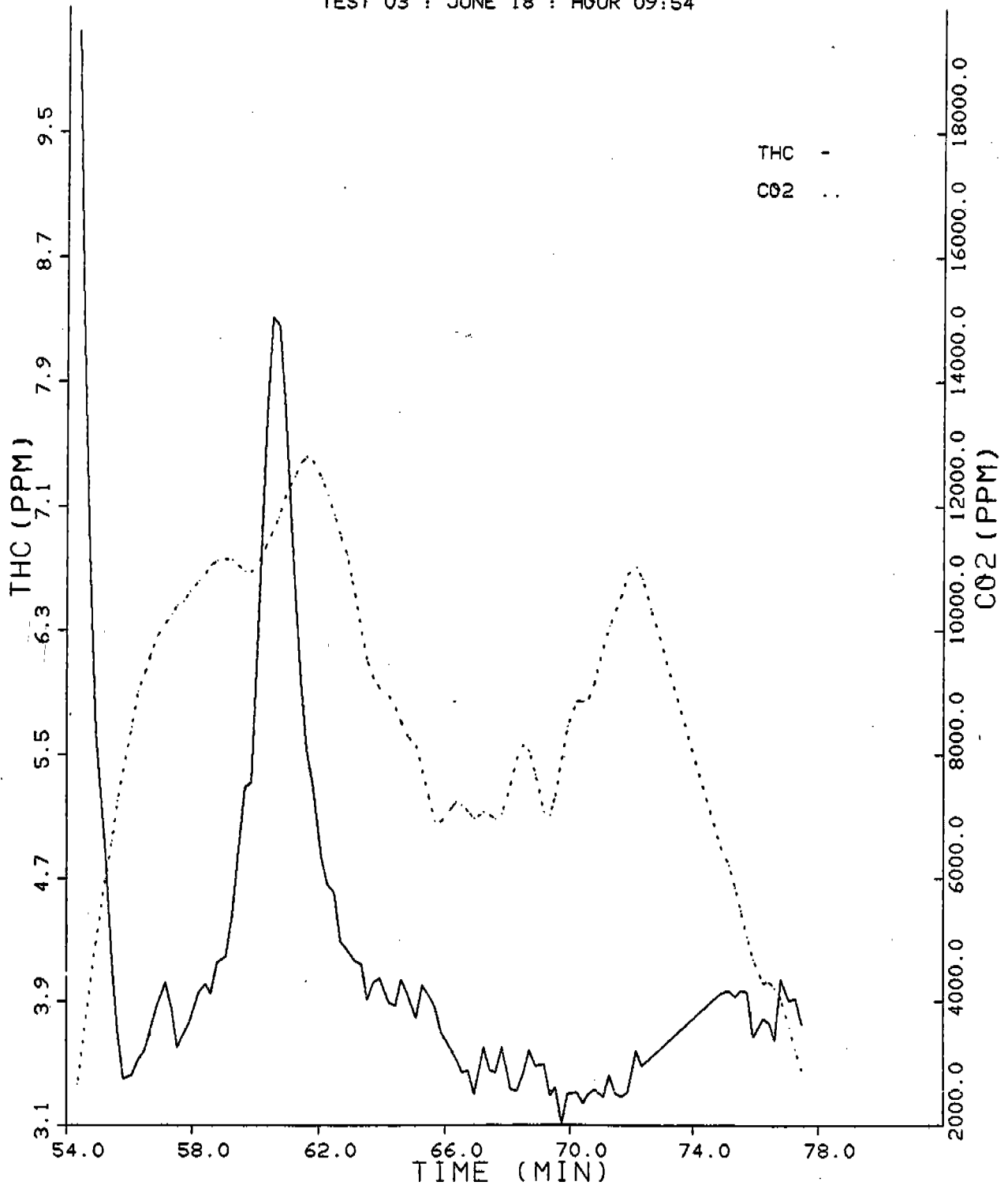
Figure A-4.   THC and CO2 vs. time.

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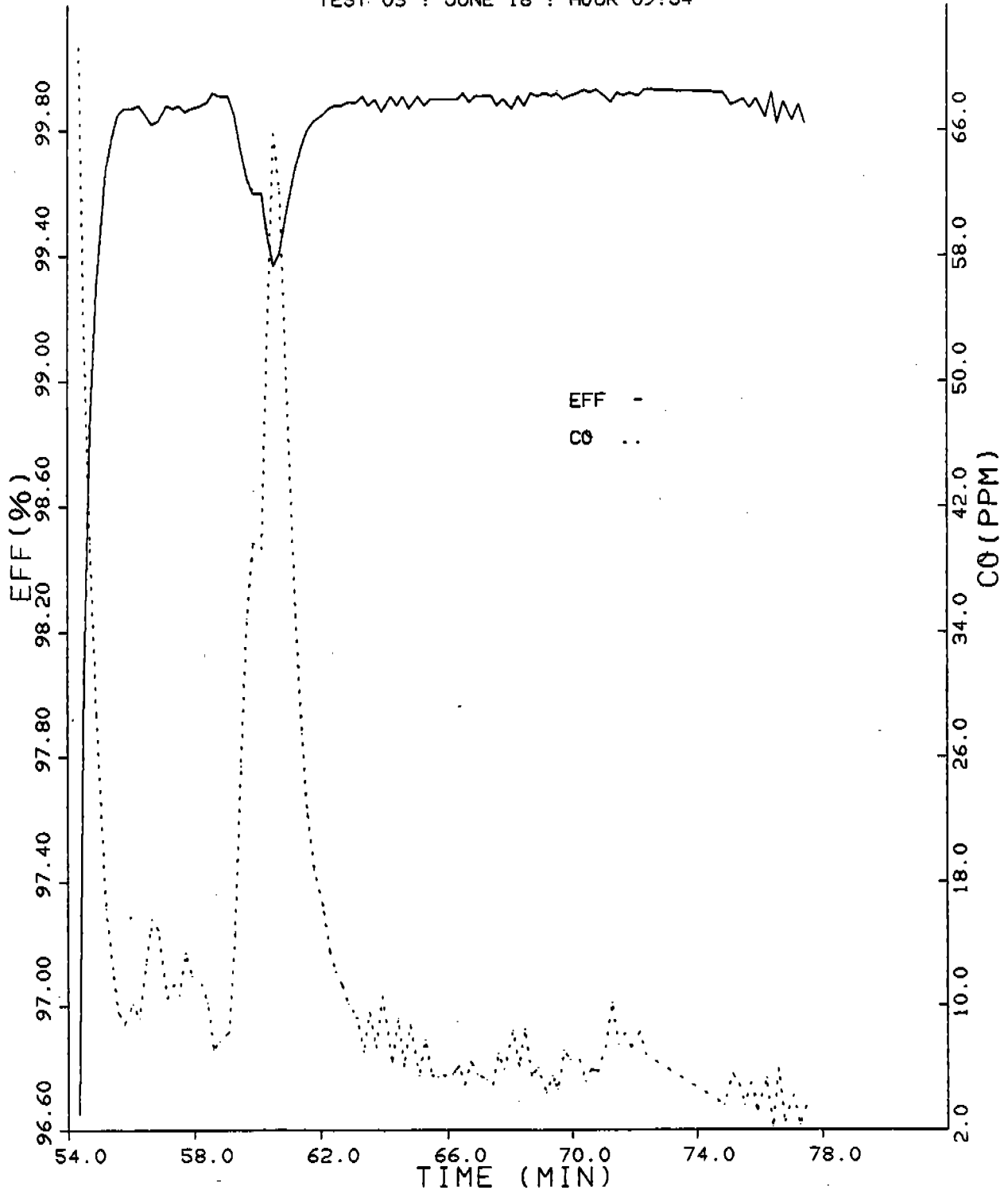
Figure A-5. Efficiency and CO vs. time.

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TEST 55 : JUNE 23 : HOUR 14:03
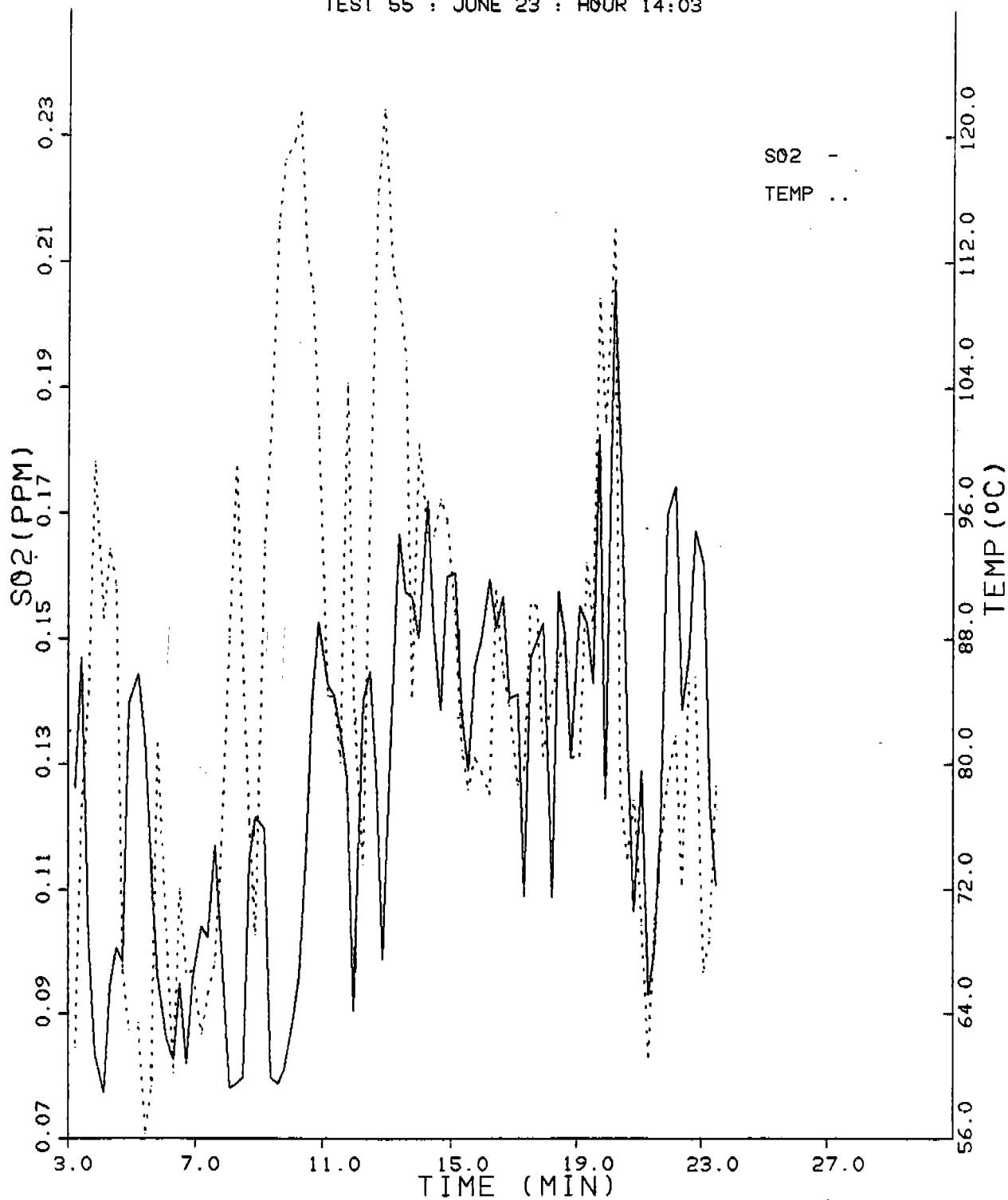
Figure A-6.   SO$_2$ and temperature vs. time.

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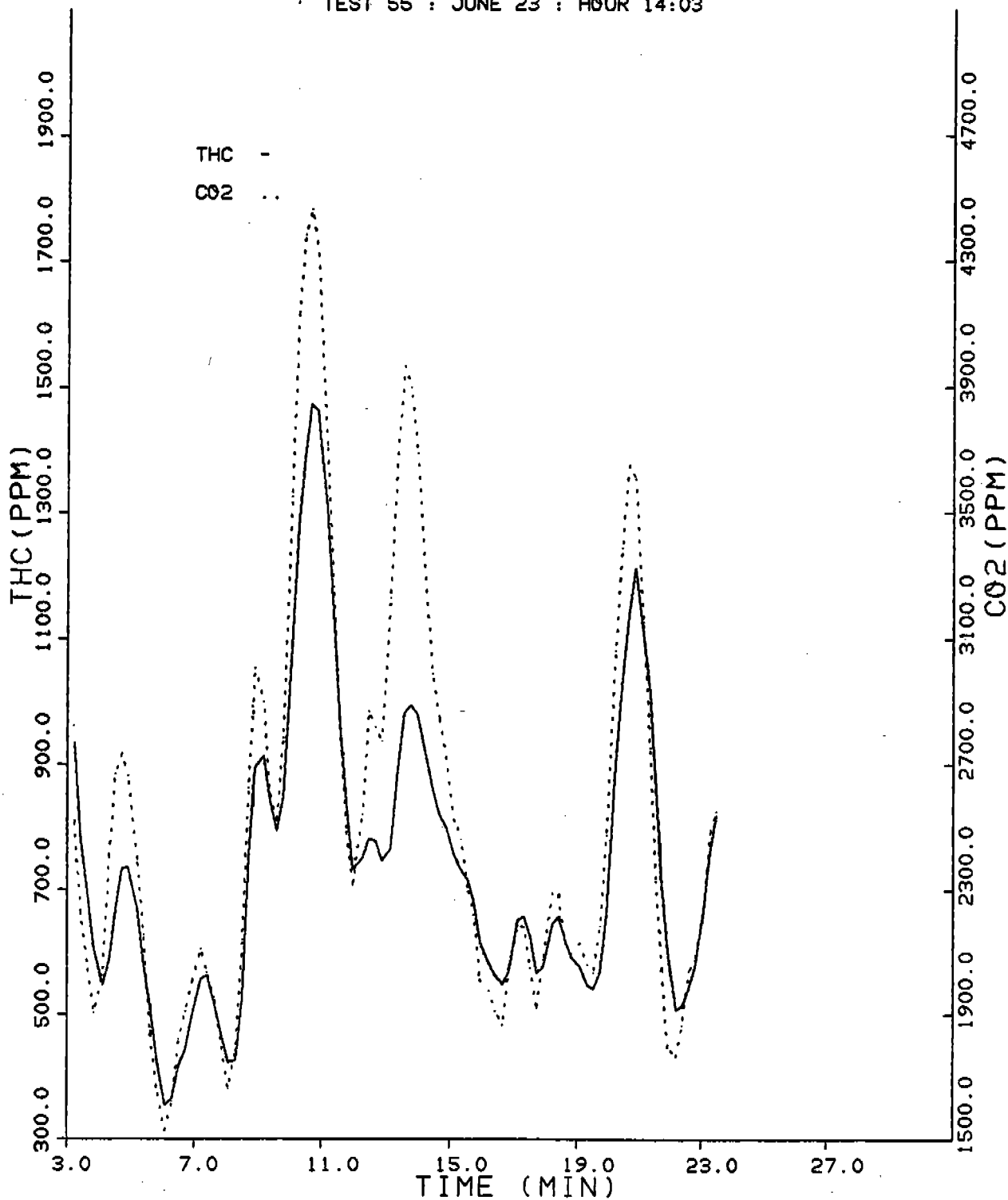
Figure A-7.   THC and CO_2 vs. time.

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TEST 55 : JUNE 23 : HOUR 14:03
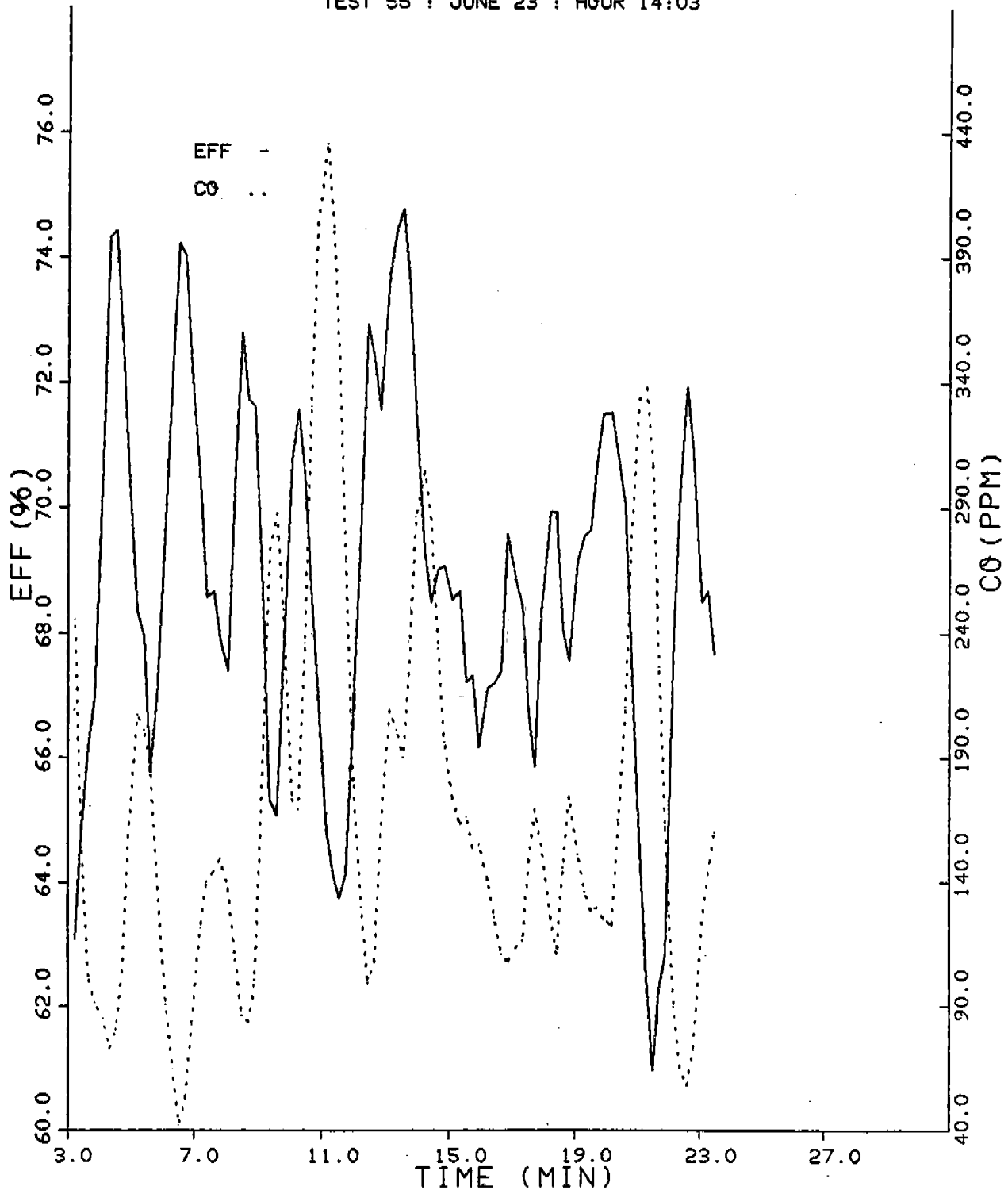
Figure A-8. Efficiency and CO vs. time.

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Figure A-9.   SO2 and temperature vs. time.

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Figure A-10. THC and CO2 vs. time.

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TEST 57 : JUNE 24 : HOUR 09:13
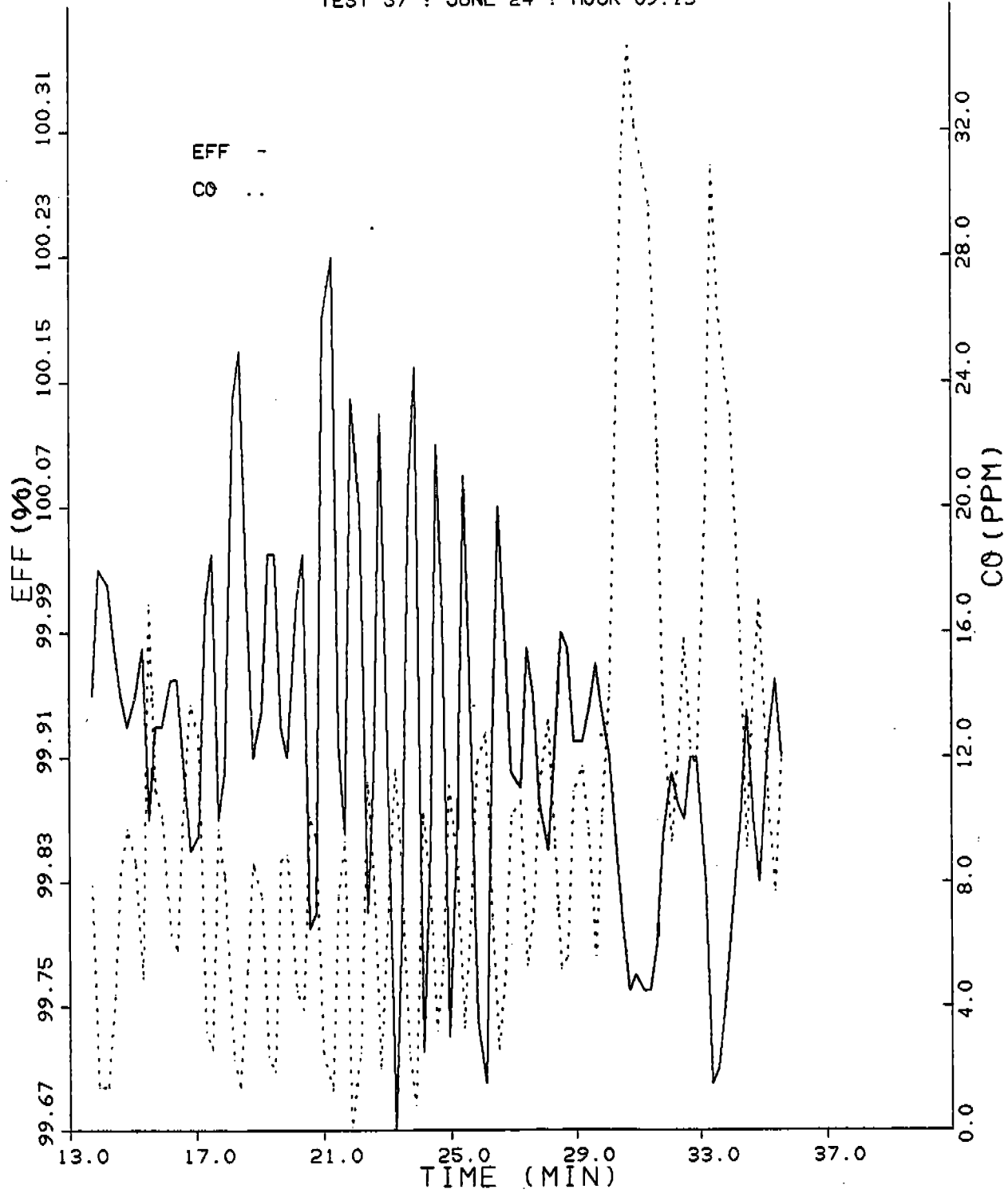
Figure A-11. Efficiency and CO vs. time.

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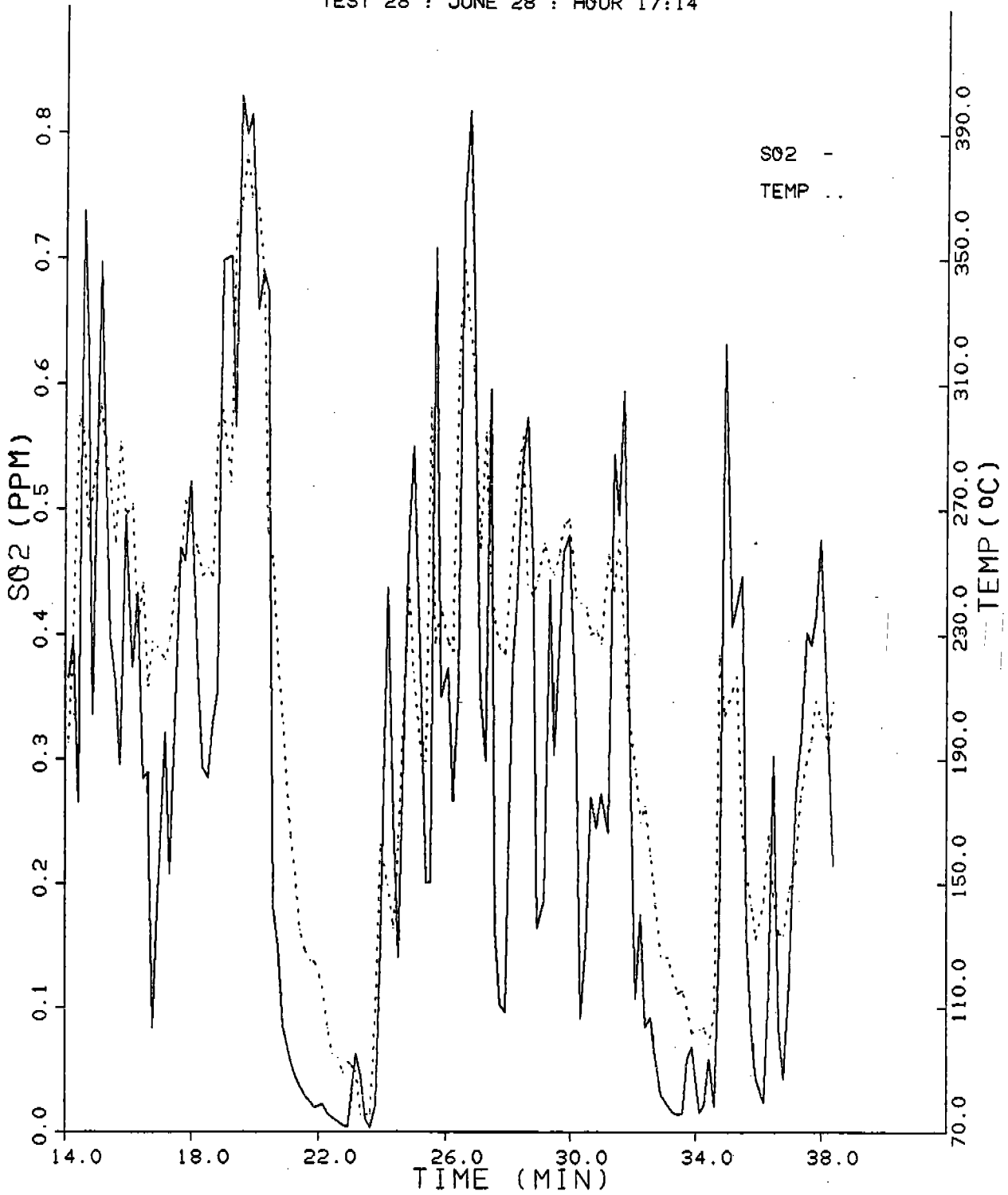
Figure A-12.   SO2 and temperature vs. time.

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TEST 28 : JUNE 28 : HOUR 17:14
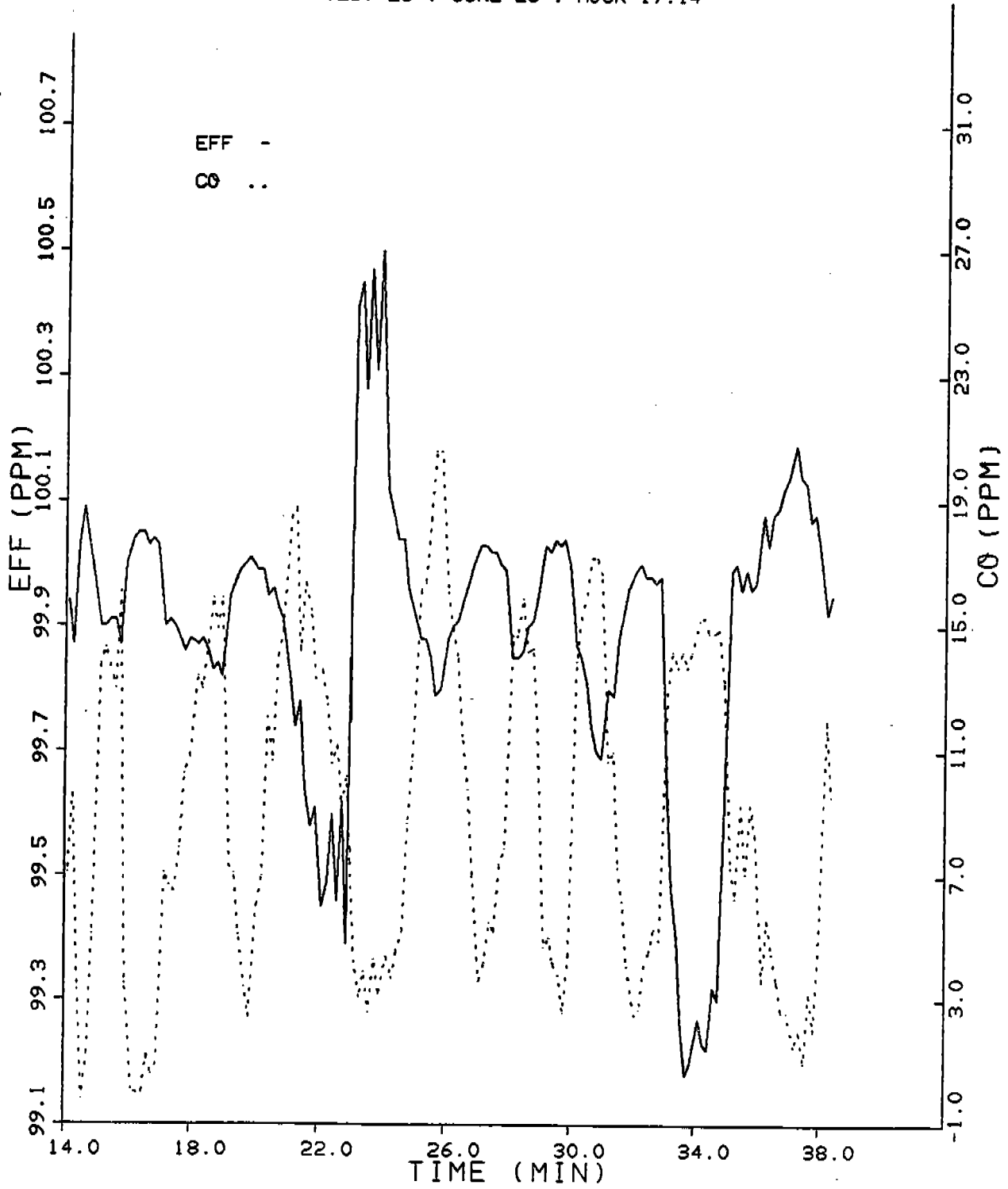
Figure A-13. Efficiency and CO vs. time.

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TEST 28 : JUNE 28 : HOUR 17:14
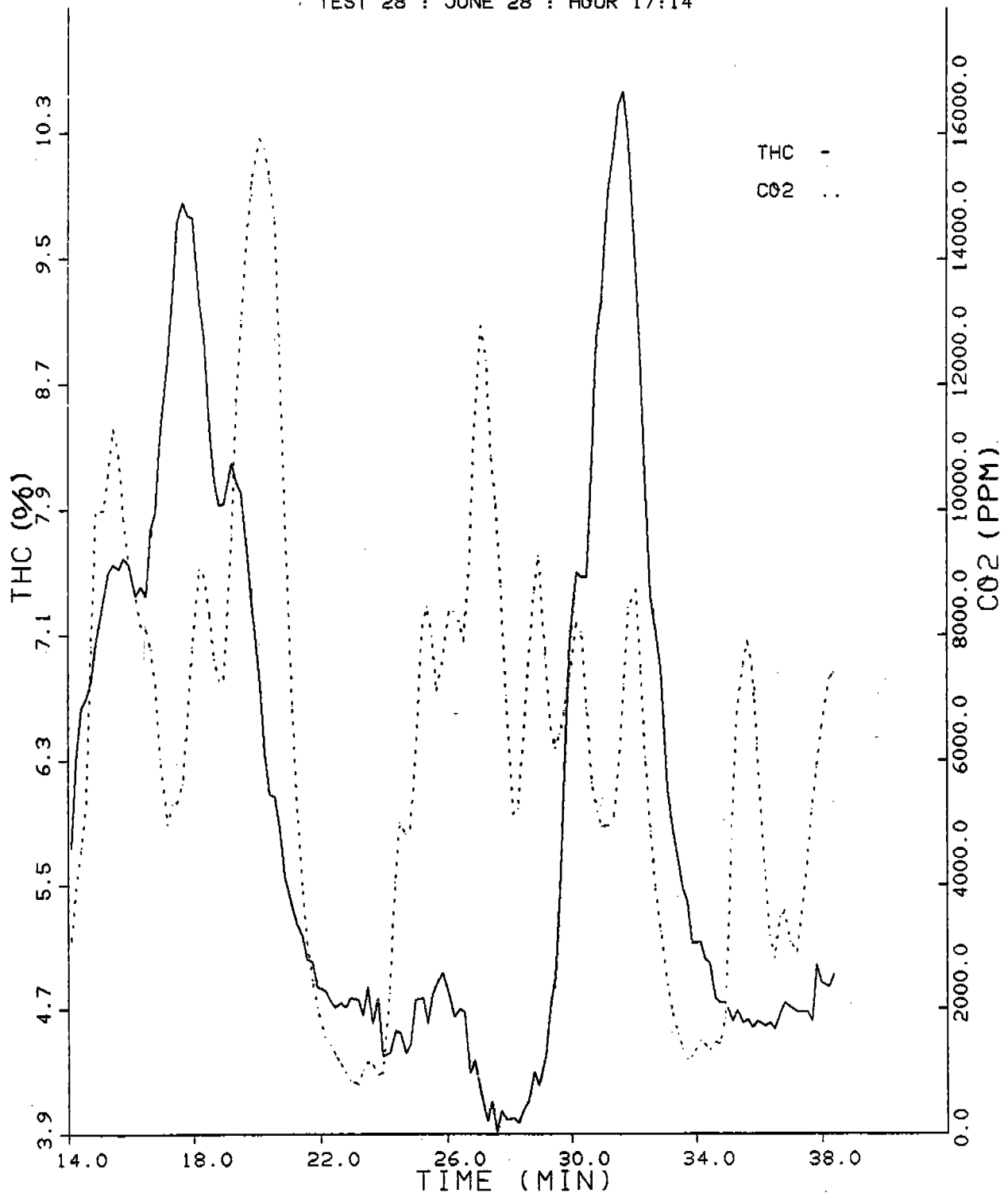
Figure A-14. THC and CO2 vs. time.

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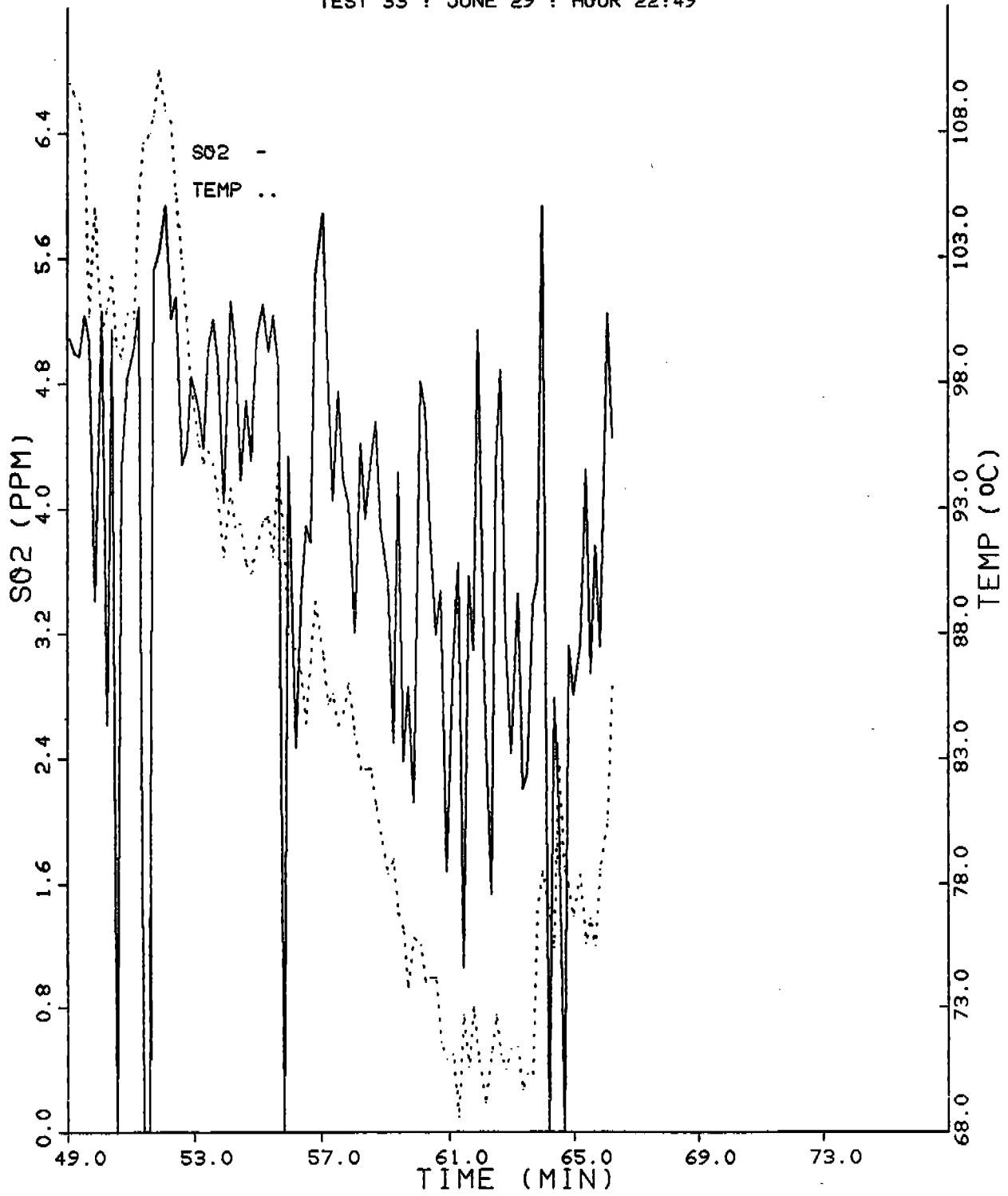
Figure A-15. SO₂ and temperature vs. time.
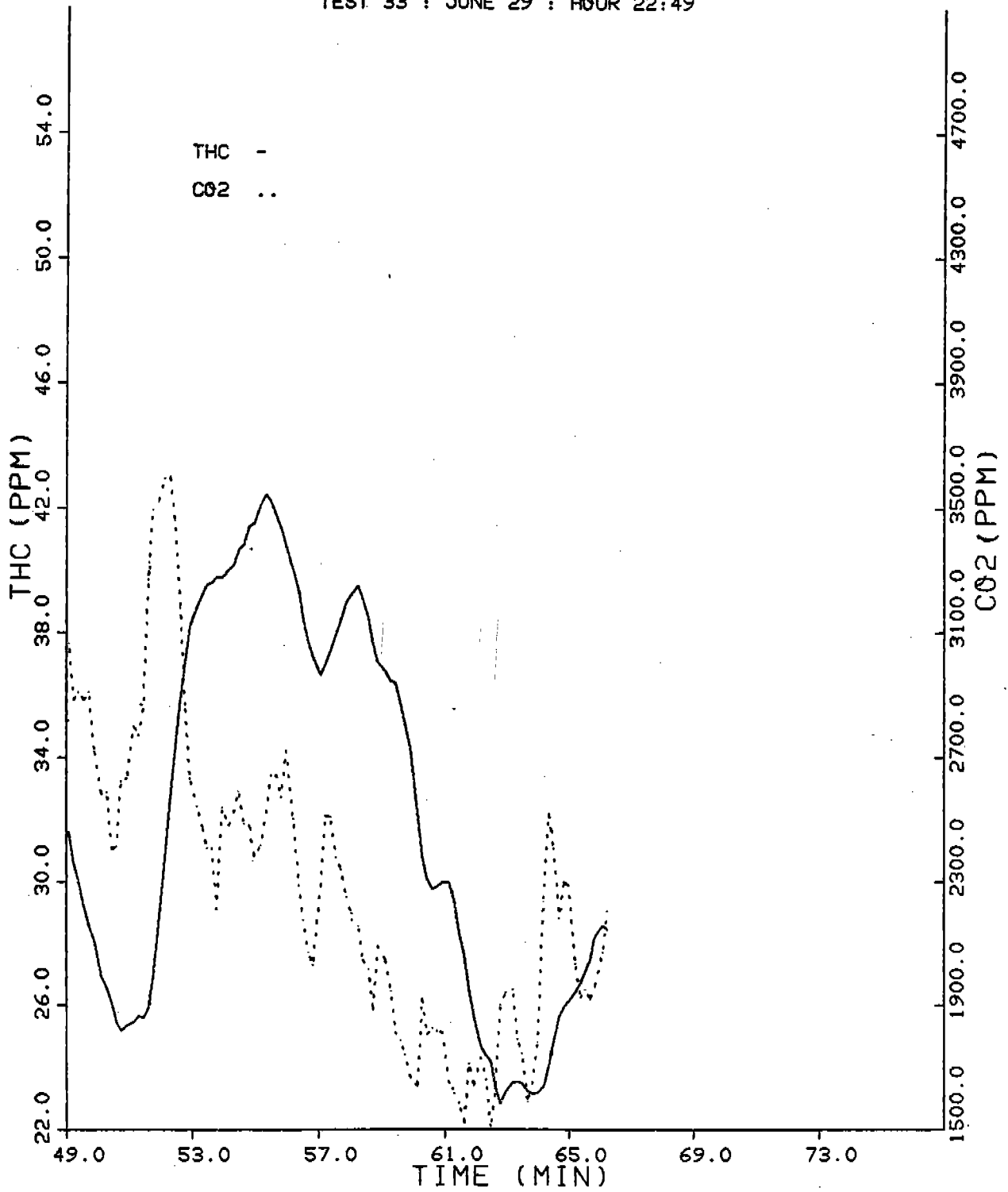
Figure A-16.   THC and CO_2 vs. time.

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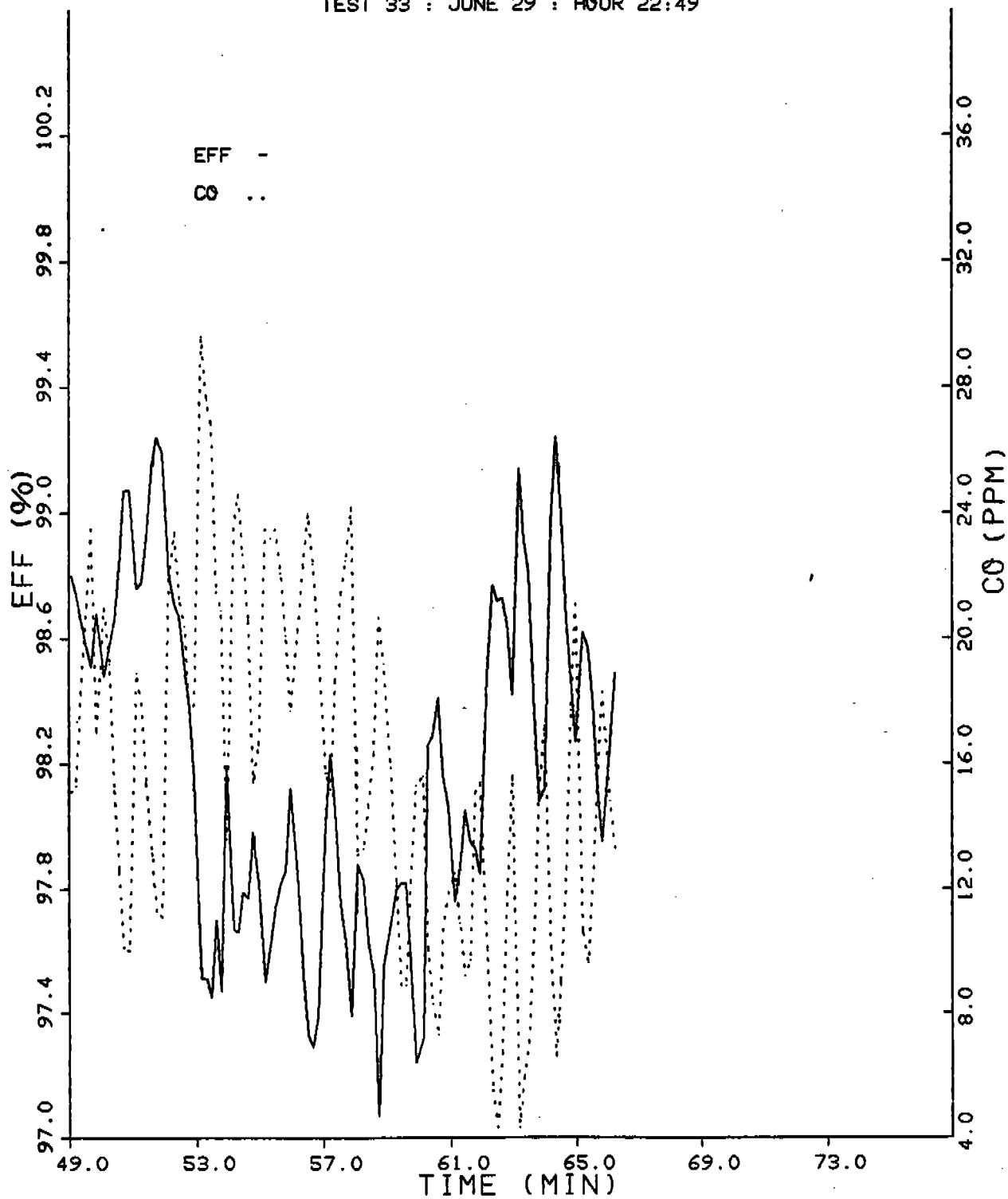
Figure A-17. Efficiency and CO vs. time.

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	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE*	175.3	0.053	3.09	19.46	3.8	7052.	-0.7	3.5	267.	30.1	99.9
STANDARD DEVIATION	73.8	0.047	2.12	0.62	1.4	3498.	0.2	1.2	24.	0.6	0.1
NUMBER OF OBSERVATIONS	117	117	117	117	117	117	117	117	117	117	117
AVERAGE BACKGROUND	28.2	0.073	0.45	20.43	4.7	373.	4.4	2.9	285.	28.0	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 4	18/13:17:29	18/13:32:10
BACKGROUND 5	18/14:14:22	18/14:22:07

OVERALL COMBUSTION EFFICIENCY = 99.96%

* All concentrations here and throughout Appendix B have been corrected via subtraction. Thus, the actual measured value (i.e., uncorrected) is the "average" plus the "average background" (last row).

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TEST 2
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	158.7	0.197	2.16	19.73	8.5	4719.	0.2	2.8	199.	33.6	99.8
STANDARD DEVIATION	45.6	0.152	1.31	0.42	12.9	1684.	1.3	0.9	33.	0.6	0.2
NUMBER OF OBSERVATIONS	84	84	84	84	84	84	84	84	84	84	84
AVERAGE BACKGROUND	38.2	-0.008	1.41	20.26	6.3	388.	5.2	2.7	198.	31.5	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 1	17/16:52:27	17/16:55:38
BACKGROUND 2	17/17:25:51	17/17:30:47

OVERALL COMBUSTION EFFICIENCY = 99.82%

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	189.4	0.336	3.46	19.48	13.8	8159.	1.2	3.0	221.	30.5	99.8
STANDARD DEVIATION	56.1	0.296	1.64	0.49	14.5	2567.	1.3	0.9	27.	0.4	0.4
NUMBER OF OBSERVATIONS	98	98	98	98	98	98	98	98	98	98	98
AVERAGE BACKGROUND	29.6	0.005	0.33	20.58	-0.4	394.	3.1	3.2	218.	27.2	

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BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 3	18/10:26:06	18/10:29:29

OVERALL COMBUSTION EFFICIENCY = 99.82%

TEST 4
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMF(C)	COMBUSTION EFFICIENCY
AVERAGE	153.4	0.153	1.96	20.05	75.3	6616.	5.3	1.4	184.	32.8	98.8
STANDARD DEVIATION	38.6	0.080	0.96	0.52	35.5	3004.	2.9	0.2	8.	0.2	0.2
NUMBER OF OBSERVATIONS	57	57	57	57	57	57	57	57	57	57	57
AVERAGE BACKGROUND	24.9	0.003	0.11	21.09	3.1	497.	5.2	0.8	186.	26.3	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 18	22/21:21:17	22/21:27:29
BACKGROUND 19	22/22:48:09	22/22:54:34

OVERALL COMBUSTION EFFICIENCY = 98.80%

TEST 8
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	127.0	0.065	1.45	20.30	61.1	5400.	3.7	0.9	185.	32.2	98.9
STANDARD DEVIATION	33.2	0.040	0.96	0.52	36.1	3094.	3.9	0.3	11.	0.9	0.3
NUMBER OF OBSERVATIONS	84	84	84	84	84	84	84	84	84	84	84
AVERAGE BACKGROUND	31.4	0.008	0.12	21.12	3.8	495.	5.8	0.6	153.	26.6	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 19	22/22:48:09	22/22:54:34
BACKGROUND 20	22/23:27:41	22/23:32:10

OVERALL COMBUSTION EFFICIENCY = 98.81%

	PRORE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	138.4	0.044	1.62	20.13	7.9	5224.	0.3	3.1	262.	26.7	99.8
STANDARD DEVIATION	39.7	0.026	0.96	0.41	3.4	2254.	1.0	0.9	24.	0.5	0.1
NUMBER OF OBSERVATIONS	103	103	103	103	103	103	103	103	103	103	103
AVERAGE BACKGROUND	24.0	0.002	0.06	20.87	0.1	396.	9.6	2.4	280.	24.5	

BACKGROUND AMBIENT MEASUREMENTS

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BACKGROUND FILE	TIME REGIN	TIME END
BACKGROUND 8	21/10:55:50	21/11:04:28
BACKGROUND 9	21/11:55:06	21/12:01:30

OVERALL COMBUSTION EFFICIENCY = 99.84%

TEST 5
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	172.8	0.070	2.09	19.42	4.1	6115.	-0.1	2.9	294.	30.8	99.9
STANDARD DEVIATION	54.6	0.060	1.25	0.49	1.6	2908.	0.2	1.0	59.	0.6	0.1
NUMBER OF OBSERVATIONS	165	165	165	165	165	165	165	165	165	165	165
AVERAGE BACKGROUND	32.8	0.022	1.00	20.28	3.4	368.	5.0	2.7	289.	29.9	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 6	18/16:23:48	18/16:39:05
BACKGROUND 7	18/17:45:33	18/17:49:39

OVERALL COMBUSTION EFFICIENCY = 99.94%

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	470.9	0.018	3.77	20.19	N/A	3758.	N/A	6.6	77.	25.8	N/A
STANDARD DEVIATION	160.0	0.001	4.32	0.69	N/A	2241.	N/A	2.0	13.	0.3	N/A
NUMBER OF OBSERVATIONS	21	21	21	21	N/A	21	N/A	21	21	21	N/A
AVERAGE BACKGROUND	22.2	-0.002	0.18	20.92	5.4	362.	3.3	3.1	131.	22.1	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 51	19/10:13:18	19/10:32:57

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TEST 17
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PFM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	124.8	0.023	1.00	20.38	6.1	3493.	-0.5	1.8	255.	26.9	99.8
STANDARD DEVIATION	35.1	0.011	0.84	0.40	3.9	2274.	0.6	0.9	77.	0.4	0.2
NUMBER OF OBSERVATIONS	135	135	135	135	135	135	135	135	135	135	135
AVERAGE HACKGROUND	29.4	0.005	-0.05	20.86	0.2	434.	5.2	1.8	276.	26.3	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 9	21/11:55:06	21/12:01:30
BACKGROUND 10	21/13:26:34	21/13:38:50

OVERALL COMBUSTION EFFICIENCY = 99.84%

TEST 50
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	131.5	0.031	0.50	20.19	16.7	4220.	6.6	2.2	269.	27.7	99.4
STANDARD DEVIATION	43.9	0.013	0.30	0.38	11.0	2179.	5.9	0.8	91.	3.5	0.3
NUMBER OF OBSERVATIONS	103	103	103	103	103	103	103	103	103	103	103
AVERAGE BACKGROUND	33.2	0.009	0.12	20.91	0.1	415.	5.4	2.0	229.	28.0	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 10	21/13:26:34	21/13:38:55
BACKGROUND 11	21/14:19:40	21/14:29:33

OVERALL COMBUSTION EFFICIENCY = 99.45%

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	120.4	0.252	0.58	20.67	7.9	3120.	1.6	2.4	148.	31.8	99.7
STANDARD DEVIATION	40.4	0.221	0.43	0.44	6.3	2190.	1.6	1.0	40.	0.4	0.3
NUMBER OF OBSERVATIONS	134	134	134	134	134	134	134	134	134	134	134
AVERAGE BACKGROUND	32.9	0.016	0.78	21.23	0.2	515.	6.6	2.3	177.	30.8	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 21	23/13:09:36	23/13:19:44
BACKGROUND 22	23/15:18:53	23/15:26:12

OVERALL COMBUSTION EFFICIENCY = 99.70%

TEST 61
STATISTICAL SUMMARY χ

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	166.8	0.039	1.32	19.47	398.4	6273.	961.7	1.7	68.	21.1	81.6
STANDARD DEVIATION	32.6	0.012	0.47	0.34	117.0	1823.	251.4	0.6	12.	0.1	3.8
NUMBER OF OBSERVATIONS	58	58	58	58	58	58	58	58	58	58	58
AVERAGE BACKGROUND	21.2	0.003	0.11	20.46	-0.6	397.	3.5	0.4	70.	21.2	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 30	24/22:18:40	24/22:30:09
BACKGROUND 31	25/00:08:59	25/00:17:09

OVERALL COMBUSTION EFFICIENCY = 82.18%

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TEST 55
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	HS (HPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	85.6	0.112	0.38	20.83	171.0	2012.	735.5	2.2	187.	30.9	68.9
STANDARD DEVIATION	16.0	0.030	0.32	0.21	83.9	686.	242.1	0.8	39.	0.4	3.1
NUMBER OF OBSERVATIONS	93	93	93	93	93	93	93	93	93	93	93
AVERAGE BACKGROUND	32.9	0.016	0.78	21.23	0.2	515.	6.6	2.3	177.	30.8	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 21	23/13:09:36	23/13:19:44
BACKGROUND 22	23/15:18:53	23/15:26:12

OVERALL COMBUSTION EFFICIENCY = 68.95%

TEST 57
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	199.7	0.113	2.68	19.80	5.0	6945.	2.0	1.5	168.	23.7	99.9
STANDARD DEVIATION	72.5	0.067	2.05	0.89	7.6	4163.	2.3	0.5	25.	0.3	0.1
NUMBER OF OBSERVATIONS	100	100	100	100	100	100	100	100	100	100	100
AVERAGE BACKGROUND	23.3	-0.004	0.19	21.11	5.3	424.	5.8	1.0	156.	22.7	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 25	24/08:40:29	24/08:54:22
BACKGROUND 26	24/09:44:11	24/09:50:57

OVERALL COMBUSTION EFFICIENCY = 99.90%

TEST 11
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	159.7	0.163	3.69	20.03	7.1	5269.	1.6	1.2	135.	23.3	99.8
STANDARD DEVIATION	31.6	0.057	1.18	0.33	5.2	3156.	1.9	0.4	24.	0.3	0.2
NUMBER OF OBSERVATIONS	63	63	63	63	63	63	63	63	63	63	63
AVERAGE BACKGROUND	21.4	-0.003	0.22	21.34	3.6	512.	5.0	1.1	88.	21.0	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 23	24/07:07:06	24/07:14:22
BACKGROUND 24	24/07:55:07	24/08:04:46

OVERALL COMBUSTION EFFICIENCY = 99.83%

	PROHE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	139.8	0.135	3.31	20.10	4.7	6677.	0.2	1.2	130.	23.2	99.9
STANDARD DEVIATION	30.4	0.042	1.02	0.35	4.2	1446.	1.4	0.4	24.	0.3	0.1
NUMBER OF OBSERVATIONS	33	33	33	33	33	33	33	33	33	33	33
AVERAGE BACKGROUND	21.4	-0.003	0.22	21.34	3.6	512.	5.0	1.1	88.	21.0	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 23	24/07:07:06	24/07:14:22
BACKGROUND 24	24/07:55:07	24/08:04:46

OVERALL COMBUSTION EFFICIENCY = 99.93%

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	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	181.5	0.198	4.17	19.92	8.6	8158.	3.0	1.1	149.	23.4	99.9
STANDARD DEVIATION	7.7	0.028	0.74	0.21	4.9	608.	0.9	0.3	16.	0.1	0.1
NUMBER OF OBSERVATIONS	18	18	18	18	18	18	18	18	18	18	18
AVERAGE BACKGROUND	21.4	-0.003	0.22	21.34	3.6	512.	5.0	1.1	88.	21.0	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 23	24/07:07:06	24/07:14:22
BACKGROUND 24	24/07:55:07	24/08:04:46

OVERALL COMBUSTION EFFICIENCY = 99.85%

TEST 11C
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	181.4	0.189	4.00	19.98	11.6	8210.	3.3	1.4	125.	23.5	99.8
STANDARD DEVIATION	19.2	0.081	1.73	0.38	4.6	1108.	1.5	0.4	25.	0.1	0.1
NUMBER OF OBSERVATIONS	12	12	12	12	12	12	12	12	12	12	12
AVERAGE BACKGROUND	21.4	-0.003	0.22	21.34	3.6	512.	5.0	1.1	88.	21.0	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 23	24/07:07:06	24/07:14:22
BACKGROUND 24	24/07:55:07	24/08:04:46

OVERALL COMBUSTION EFFICIENCY = 99.82%

TEST 59
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	139.3	0.060	1.41	19.53	49.9	5413.	33.3	0.9	94.	22.2	98.4
STANDARD DEVIATION	26.3	0.024	0.50	0.39	26.4	1481.	24.7	0.6	67.	0.1	1.0
NUMBER OF OBSERVATIONS	57	57	57	57	57	57	57	57	57	57	57
AVERAGE BACKGROUND	20.4	0.002	0.18	20.61	0.0	421.	2.9	0.5	93.	21.8	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 29	24/21:16:12	24/21:31:11
BACKGROUND 30	24/22:18:40	24/22:30:09

OVERALL COMBUSTION EFFICIENCY = 98.49%

TEST 594
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	142.4	0.052	1.30	19.44	62.1	5575.	45.3 .	1.0	72.	22.1	97.9
STANDARD DEVIATION	29.9	0.025	0.53	0.40	23.8	1659.	21.7	0.6	46.	0.1	0.9
NUMBER OF OBSERVATIONS	38	38	38	38	38	38	38	38	38	38	38
AVERAGE BACKGROUND	20.4	0.002	0.18	20.61	0.0	421.	2.9	0.5	93.	21.8	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 29	24/21:16:12	24/21:31:11
BACKGROUND 30	24/22:19:40	24/22:30:03

OVERALL COMBUSTION EFFICIENCY = 98.11%

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TEST 599
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	133.1	0.076	1.62	19.71	25.4	5090.	9.4	0.7	140.	22.3	99.3
STANDARD DEVIATION	15.9	0.014	0.35	0.30	7.9	1002.	3.1	0.6	79.	0.0	0.1
NUMBER OF OBSERVATIONS	19	19	19	19	19	19	19	19	19	19	19
AVERAGE BACKGROUND	20.4	0.002	0.18	20.61	0.0	421.	2.9	0.5	93.	21.8	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 29	24/21:16:12	24/21:31:11
BACKGROUND 30	24/22:18:40	24/22:30:03

OVERALL COMBUSTION EFFICIENCY = 99.32%

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	02 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	99.7	0.052	0.99	19.70	28.3	3685.	11.8	1.3	65.	21.7	98.8
STANDARD DEVIATION	20.7	0.014	0.47	0.33	9.5	1290.	2.9	0.4	12.	0.0	0.4
NUMBER OF OBSERVATIONS	97	97	97	97	97	97	97	97	97	97	97
AVERAGE BACKGROUND	21.2	0.003	0.11	20.46	-0.6	397.	3.5	0.4	70.	21.2	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 30	24/22:18:40	24/22:30:09
BACKGROUND 31	25/00:08:53	25/00:17:09

OVERALL COMBUSTION EFFICIENCY = 98.92%

TEST 51
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	119.6	0.039	0.57	19.85	34.1	3347.	11.5	2.3	193.	30.1	98.5
STANDARD DEVIATION	45.4	0.017	0.66	0.60	32.3	2564.	12.1	0.8	27.	0.2	0.9
NUMBER OF OBSERVATIONS	78	78	78	78	78	78	78	78	78	78	78
AVERAGE BACKGROUND	35.1	-0.003	0.42	20.45	0.6	410.	11.3	2.3	186.	29.6	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 13	21/18:30:47	21/18:37:39

OVERALL COMBUSTION EFFICIENCY = 98.66%

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	129.5	0.121	1.87	20.43	7.7	4059.	2.4	1.7	149.	22.7	99.7
STANDARD DEVIATION	20.7	0.056	1.02	0.38	3.5	1501.	1.5	0.6	22.	0.2	0.1
NUMBER OF OBSERVATIONS	103	103	103	103	103	103	108	103	103	103	103
AVERAGE BACKGROUND	24.7	-0.002	0.26	21.17	0.6	394.	6.0	0.8	188.	22.3	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 27	24/11:26:05	24/11:35:44

OVERALL COMBUSTION EFFICIENCY = 99.75%

TEST 16A
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	113.0	0.082	1.39	20.55	6.1	3236.	2.3	1.8	136.	22.8	99.7
STANDARD DEVIATION	22.4	0.033	1.02	0.44	3.5	1657.	1.8	0.8	13.	0.1	0.1
NUMBER OF OBSERVATIONS	34	34	34	34	34	34	34	34	34	34	34
AVERAGE BACKGROUND	24.7	-0.002	0.26	21.17	0.4	394.	6.0	0.8	188.	22.3	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 27	24/11:26:05	24/11:35:44

OVERALL COMBUSTION EFFICIENCY = 99.74%

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	148.6	0.168	2.42	20.20	9.6	5291.	3.5	1.4	151.	22.9	99.8
STANDARD DEVIATION	11.7	0.050	0.98	0.36	3.7	1183.	0.7	0.5	24.	0.1	0.1
NUMBER OF OBSERVATIONS	28	28	28	28	28	28	28	28	28	28	28
AVERAGE BACKGROUND	24.7	-0.002	0.26	21.17	0.4	394.	6.0	0.8	188.	22.3	

PACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 27	24/11:26:05	24/11:35:44

OVERALL COMBUSTION EFFICIENCY = 99.75%

	PRORE TEPP(C)	SO2 (PPM)	NOY (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	125.0	0.107	1.57	20.59	7.3	3419.	1.4	1.9	164.	22.4	99.7
STANDARD DEVIATION	8.7	0.052	0.77	0.24	2.8	896.	0.8	0.4	14.	8.1	0.1
NUMBER OF OBSERVATIONS	22	22	22	22	22	22	22	22	22	22	22
AVERAGE BACKGROUND	24.7	-0.002	0.26	21.17	0.4	394.	6.0	0.8	188.	22.3	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
PACKGROUND 27	24/11:26:05	24/11:35:44

OVERALL COMBUSTION EFFICIENCY = 99.74%

TEST 160
STATISTICAL SUMMARY   X

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	136.3	0.138	2.28	20.36	7.9	4458.	2.0	1.9	155.	22.4	99.8
STANDARD DEVIATION	7.4	0.045	0.81	0.24	2.5	627.	1.3	0.6	26.	0.1	0.1
NUMBER OF OBSERVATIONS	19	19	19	19	19	19	19	19	19	19	19
AVERAGE BACKGROUND	24.7	-0.002	0.26	21.17	0.4	394.	6.0	0.8	188.	22.3	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 27	24/11:26:05	24/11:35:44

OVERALL COMBUSTION EFFICIENCY = 99.78%

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	197.1	0.559	5.00	19.15	6.8	7115.	0.0	1.5	225.	31.6	99.9
STANDARD DEVIATION	48.1	0.478	2.29	0.51	3.8	2757.	0.8	0.6	31.	0.4	0.1
NUMBER OF OBSERVATIONS	92	92	92	92	92	92	92	92	92	92	92
AVERAGE BACKGROUND	34.4	0.085	0.22	20.35	0.8	354.	6.5	1.4	211.	31.4	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 16	22/16:52:39	22/17:09:36
BACKGROUND 17	22/17:41:43	22/17:46:35

OVERALL COMBUSTION EFFICIENCY = 99.90%

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	233.1	0.018	5.90	18.72	4.5	8465.	-5.0	1.5	160.	28.4	100.2
STANDARD DEVIATION	111.5	0.017	5.31	1.31	4.5	6646.	0.9	0.5	21.	0.1	0.5
NUMBER OF OBSERVATIONS	103	103	103	103	103	103	103	103	103	103	103
AVERAGE BACKGROUND	35.1	-0.003	0.42	20.45	0.6	410.	11.3	2.3	186.	29.6	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 13	21/18:30:47	21/18:37:3²

OVERALL COMBUSTION EFFICIENCY = 100.01%

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TEST 52
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	118.2	0.801	0.68	19.92	16.1	2622.	15.2	0.9	165.	28.0	98.7
STANDARD DEVIATION	14.3	0.003	0.31	0.17	5.0	851.	4.8	0.3	20.	0.2	0.4
NUMBER OF OBSERVATIONS	80	80	80	80	80	80	80	80	80	80	80
AVERAGE BACKGROUND	39.9	-0.004	0.02	20.46	-0.5	380.	9.4	1.5	179.	28.5	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 13	21/18:30:47	21/18:37:39
BACKGROUND 14	21/20:15:10	21/20:20:44

OVERALL COMBUSTION EFFICIENCY = 98.82%

TEST 53
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	160.6	0.729	2.83	19.22	23.9	5741.	10.9	2.0	235.	30.4	99.3
STANDARD DEVIATION	47.1	0.264	1.89	0.68	12.4	3489.	6.4	0.8	33.	0.3	0.4
NUMBER OF OBSERVATIONS	112	112	112	112	112	112	112	112	112	112	112
AVERAGE BACKGROUND	30.5	0.050	0.14	20.50	0.3	375.	5.7	2.2	225.	30.6	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 15	22/13:13:56	22/13:18:48
BACKGROUND 16	22/16:52:39	22/17:09:36

OVERALL COMBUSTION EFFICIENCY = 99.40%

TEST 26
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	VS (MPH)	VD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	194.0	0.356	5.34	13.62	5.5	6270.	-3.9	3.1	250.	37.7	100.0
STANDARD DEVIATION	42.5	0.220	2.93	0.44	2.1	2646.	0.9	1.0	29.	0.5	0.1
NUMBER OF OBSERVATIONS	124	124	124	124	124	124	124	124	124	124	124
AVERAGE BACKGROUND	32.8	0.013	0.80	20.63	0.2	375.	7.4	2.4	244.	33.5	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 35	29/13:34:20	29/14:01:22
BACKGROUND 36	29/14:44:11	29/14:58:17

OVERALL COMBUSTION EFFICIENCY = 99.97%

TEST 65
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	111.3	0.062	2.40	20.33	20.3	4878.	0.6	2.1	172.	31.0	99.5
STANDARD DEVIATION	26.6	0.024	1.82	0.35	5.1	2168.	1.4	0.5	12.	0.2	0.3
NUMBER OF OBSERVATIONS	83	83	83	83	83	83	83	83	83	83	83
AVERAGE BACKGROUND	26.4	0.001	0.15	21.14	4.1	399.	4.2	1.8	179.	26.9	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 47	30/23:31:27	30/23:36:34
BACKGROUND 49	1/00:10:30	1/00:14:28

OVERALL COMBUSTION EFFICIENCY = 99.57

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	212.1	0.329	8.16	19.66	3.2	6078.	0.7	3.5	290.	31.6	99.9
STANDARD DEVIATION	71.9	0.224	5.92	0.62	5.4	3562.	1.8	1.5	87.	0.7	0.3
NUMBER OF OBSERVATIONS	143	143	143	143	143	143	143	143	143	143	143
AVERAGE BACKGROUND	30.7	0.009	0.73	20.51	5.9	250.	5.3	1.0	324.	30.2	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 32	28/16:23:13	28/16:38:57
BACKGROUND 33	28/17:57:13	28/18:04:50

OVERALL COMBUSTION EFFICIENCY = 99.94%

TEST 31
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	159.3	1.226	4.02	19.83	27.9	4568.	10.1	2.8	315.	31.1	99.1
STANDARD DEVIATION	37.6	0.751	2.34	0.56	12.1	2258.	3.7	1.1	43.	0.3	0.4
NUMBER OF OBSERVATIONS	121	121	121	121	121	121	121	121	121	121	121
AVERAGE BACKGROUND	30.4	0.022	0.59	20.53	0.5	327.	5.6	3.0	317.	30.2	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 33	28/17:57:13	28/18:04:50
BACKGROUND 34	28/18:56:54	28/19:05:46

OVERALL COMBUSTION EFFICIENCY = 99.17%

TEST 66
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	102.2	0.935	0.97	20.05	229.4	2432.	1265.0	0.6	144.	29.7	60.6
STANDARD DEVIATION	25.5	0.395	0.53	0.39	114.2	1177.	510.7	0.2	23.	0.1	11.1
NUMBER OF OBSERVATIONS	69	69	69	69	69	69	69	69	69	69	69
AVERAGE BACKGROUND	28.9	0.026	0.00	21.01	2.4	337.	12.7	1.1	173.	29.1	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 3A	29/20:52:49	29/20:56:53
BACKGROUND 39	29/21:46:27	29/21:55:10

OVERALL COMBUSTION EFFICIENCY = 61.94%

TEST 29
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	86.3	1.365	1.06	20.23	180.9	2179.	1177.6	0.6	190.	29.3	60.0
STANDARD DEVIATION	14.3	0.502	0.40	0.23	46.3	789.	296.4	0.3	19.	0.2	10.5
NUMBER OF OBSERVATIONS	57	57	57	57	57	57	57	57	57	57	57
AVERAGE BACKGROUND	28.9	0.026	0.00	21.01	2.4	337.	12.7	1.1	178.	29.1	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 38	29/20:52:49	29/20:56:53
BACKGROUND 39	29/21:46:20	29/21:55:10

OVERALL COMBUSTION EFFICIENCY = 61.60%

TEST 29A
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	75.1	1.236	1.09	20.34	146.6	1529.	1097.1	0.6	191.	29.5	54.1
STANDARD DEVIATION	8.1	0.509	0.40	0.22	28.6	476.	243.0	0.3	21.	0.1	10.8
NUMBER OF OBSERVATIONS	28	28	28	28	28	28	28	28	28	28	24
AVERAGE BACKGROUND	28.9	0.026	0.00	21.01	2.4	337.	12.7	1.1	178.	29.1	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 38	29/20:52:48	29/20:56:53
BACKGROUND 39	29/21:46:20	29/21:55:10

OVERALL COMBUSTION EFFICIENCY = 55.14%

TEST 29A
STATISTICAL SUMMARY Y

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	97.2	1.489	1.04	20.12	213.9	2808.	1255.4	0.7	189.	29.2	65.6
STANDARD DEVIATION	9.9	0.470	0.41	0.18	34.6	440.	325.6	0.3	15.	0.1	7.7
NUMBER OF OBSERVATIONS	29	29	29	29	29	29	29	29	29	29	29
AVERAGE BACKGROUND	28.9	0.026	0.00	21.01	2.4	337.	12.7	1.1	178.	29.1	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 38	29/20:52:48	29/20:56:53
BACKGROUND 39	29/21:46:20	29/21:55:10

OVERALL COMBUSTION EFFICIENCY = 65.6%

TEST 64
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	105.0	0.051	1.24	20.42	8.6	3282.	-0.1	0.9	185.	25.3	99.7
STANDARD DEVIATION	10.1	0.014	0.47	0.20	3.7	896.	1.9	0.3	23.	0.1	0.2
NUMBER OF OBSERVATIONS	67	67	67	67	67	67	67	67	67	67	67
AVERAGE BACKGROUND	29.0	0.032	0.03	21.11	-1.7	428.	8.8	0.7	184.	25.1	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 40	30/00:13:08	30/00:15:14
BACKGROUND 41	30/02:01:53	30/02:08:14

OVERALL COMBUSTION EFFICIENCY = 99.74%

TEST 62
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	108.3	0.841	0.60	20.39	90.2	3076.	99.8	0.9	175.	25.2	93.8
STANDARD DEVIATION	22.1	0.667	0.36	0.39	32.0	1206.	30.6	0.2	15.	0.1	1.6
NUMBER OF OBSERVATIONS	113	113	113	113	113	113	113	113	113	113	113
AVERAGE BACKGROUND	29.0	0.032	0.03	21.11	-1.7	428.	8.8	0.7	184.	25.1	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 40	30/00:10:08	30/00:15:14
BACKGROUND 41	38/02:01:53	30/02:08:14

OVERALL COMBUSTION EFFICIENCY = 94.18%

TEST 63
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	123.4	0.057	1.57	20.13	19.9	4184.	6.5	1.4	97.	24.8	99.1
STANDARD DEVIATION	30.4	0.037	1.06	0.48	9.8	2204.	6.7	0.7	44.	0.6	1.2
NUMBER OF OBSERVATIONS	106	106	106	106	106	106	106	106	106	106	105
AVERAGE BACKGROUND	29.0	0.032	0.03	21.11	-1.7	428.	8.8	0.7	184.	25.1	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 40	30/00:10:08	30/00:15:14
BACKGROUND 41	30/02:01:53	30/02:08:14

OVERALL COMBUSTION EFFICIENCY = 99.37%

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	86.6	3.793	0.74	20.66	15.8	1857.	17.5	1.0	181.	26.9	98.2
STANDARD DEVIATION	12.5	1.440	0.29	0.11	5.6	500.	6.4	0.2	11.	0.2	0.5
NUMBER OF OBSERVATIONS	102	102	102	102	102	102	102	102	102	102	102
AVERAGE BACKGROUND	27.5	0.044	-0.03	21.23	0.1	436.	14.6	1.0	175.	26.9	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 39	29/21:46:20	29/21:55:10
BACKGROUND 40	30/00:10:08	30/00:15:14

OVERALL COMBUSTION EFFICIENCY = 98.24%

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	120.9	3.281	1.75	20.49	22.7	3702.	19.5	0.8	189.	26.3	98.9
STANDARD DEVIATION	36.7	1.098	1.09	0.36	11.0	1732.	11.8	0.2	12.	0.1	0.3
NUMBER OF OBSERVATIONS	121	121	121	121	121	121	121	121	121	121	121
AVERAGE BACKGROUND	27.5	0.844	-0.03	21.23	0.1	436.	14.6	1.0	175.	26.9	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 39	29/21:46:20	29/21:55:10
BACKGROUND 40	30/00:10:08	30/00:15:14

OVERALL COMBUSTION EFFICIENCY = 98.87%

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	80.3	2.204	0.63	20.90	12.2	1761.	7.3	0.9	199.	26.3	98.9
STANDARD DEVIATION	9.7	0.827	0.25	0.11	6.3	520.	5.4	0.2	7.	0.1	0.4
NUMBER OF OBSERVATIONS	44	44	44	44	44	44	44	44	44	44	44
AVERAGE BACKGROUND	27.5	0.044	-0.03	21.23	0.1	436.	14.6	1.0	175.	26.9	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 39	29/21:46:20	29/21:55:10
BACKGROUND 40	30/00:10:08	30/00:15:14

OVERALL COMBUSTION EFFICIENCY = 98.91%

TEST 329
STATISTICAL SUMMARY

	PROBE TEMP(C)	SO2 (PPM)	NOX (PPM)	O2 (PCT)	CO (PPM)	CO2 (PPM)	THC (PPM)	WS (MPH)	WD (DEG)	AMBIENT TEMP(C)	COMBUSTION EFFICIENCY
AVERAGE	144.1	3.896	2.39	20.27	28.8	4811.	26.5	0.7	184.	26.3	98.9
STANDARD DEVIATION	23.9	0.680	0.63	0.22	8.2	1077.	8.3	0.2	11.	0.1	0.2
NUMBER OF OBSERVATIONS	77	77	77	77	77	77	77	77	77	77	77
AVERAGE BACKGROUND	27.5	0.044	-0.03	21.23	0.1	436.	14.6	1.0	175.	26.9	

BACKGROUND AMBIENT MEASUREMENTS

BACKGROUND FILE	TIME BEGIN	TIME END
BACKGROUND 39	29/21:46:20	29/21:55:10
BACKGROUND 40	30/00:10:08	30/00:15:14

OVERALL COMBUSTION EFFICIENCY = 98.86%

APPENDIX C

CALCULATION OF DESTRUCTION EFFICIENCY (DE)

While dilution factors are required for an accurate determination of destruction efficiency (DE), estimates of DE can be made for total hydrocarbons (THC) and for individual hydrocarbon species. Assuming:

(a) All carbon resulting from combustion is accounted for in the measurements,

(b) Dilution is neglected, and

(c) The relief gas is 80% propylene and 20% propane.

One can calculate DE's as follows:

$$DE_{THC} = \frac{CO_2 + CO + Soot}{CO_2 + CO + Soot + THC} \times 100$$

$$DE_{Propylene} = \frac{0.8(CO_2 + CO + Soot + THC) - C_{Propylene}}{0.8(CO_2 + CO + Soot + THC)} \times 100$$

$$DE_{Propane} = \frac{0.2(CO_2 + CO + Soot + THC) - C_{Propane}}{0.2(CO_2 + CO + Soot + THC)} \times 100$$

where:
DE_{THC} = Total Hydrocarbon DE (%)
$DE_{Propylene}$ = Propylene DE (%)
$DE_{Propane}$ = Propane DE (%)
$C_{Propylene}$ = Measured Propylene Concentration (ppmv)
$C_{Propane}$ = Measured Propane Concentration (ppmv)
and all other variables as previously defined.

Tables C-1 and C-2 provide calculated values for DE_{THC}, $DE_{Propylene}$, $DE_{Propane}$ for each of the tests. Note that a Combustion Efficiency (CE) value is also provided, and in some cases, it differs from CE values reported in previous tables. This is due to the method of calculating CE:

(a) THC, $C_{Propylene}$, and $C_{Propane}$ values from the integrated bag samples (Tables 7 and 8) were used instead of the continuous THC data used in previous calculations. As noted in the report, there are differences between the continuous and integrated bag THC results.

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TABLE C-1. DESTRUCTION EFFICIENCY ESTIMATES
STEAM-ASSISTED FLARE TESTS

Test Number	CE (%)	DE_{THC} (%)	$DE_{Propylene}$ (%)	$DE_{Propane}$ (%)
High Btu Tests				
1	99.85	99.96	-	-
2	99.66	99.95	-	-
3	99.80	99.96	-	-
4	91.67	99.86	99.99	99.98
8	93.15	99.87	99.99	99.99
7	99.79	99.93	99.99	99.98
5	99.82	99.94	99.99	99.98
17	99.73	99.89	100.00	99.98
50	99.37	99.73	99.80	99.76
56	99.49	99.71	99.92	99.88
61	76.92	81.51	82.96	83.74
55	61.63	65.81	67.65	68.42
Low Btu Tests				
57	99.73	99.87	99.99	99.98
11	99.67	99.85	99.98	99.97
59	98.22	99.06	99.34	98.91
60	98.71	99.38	99.59	99.68
51	98.48	99.39	99.81	99.82
16	99.61	99.80	99.97	99.94
54	99.81	99.91	99.97	99.91
23	99.84	99.93	100.00	99.99
52	97.93	98.44	98.87	98.91
53	99.24	99.63	99.72	99.74

TABLE C-2. DESTRUCTION EFFICIENCY ESTIMATES AIR-ASSISTED FLARE TESTS

Test Number	CE (%)	DE_THC (%)	DE_Propylene (%)	DE_Propane (%)
High Btu Tests				
26	99.85	99.94	99.99	99.98
65	97.95	99.90	100.00	99.99
28	99.78	99.93	99.98	99.98
31	98.84	99.42	99.61	99.61
Low Btu Tests				
66	49.98	54.17	55.66	57.22
29	48.03	51.53	53.11	54.76
64	99.49	99.68	99.93	99.89
62	92.05	94.38	95.44	95.57
63	99.14	99.54	99.72	99.72
33	97.31	97.98	99.72	99.61
32	98.50	99.04	99.87	99.80

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(b) Since the integrated bag sample hydrocarbon data were used and no background data were available for propane and propylene, the measured values for hydrocarbons in the flare plume were not "corrected" by subtracting background concentrations. Thus, the CE and DE values in the following tables were calculated from a consistent set of data.

(c) Did not segment tests 11, 16, 29, and 32 due to lack of hydrocarbon species data.

SOOT COMPOSITION
ES ENGINEERING-SCIENCE

February 1, 1983

Dr. Bruce Tichenor
Industrial Processes Branch (MD-63)
U.S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711

Dear Dr. Tichenor:

In response to your letter dated December 9, 1982, and our subsequent telephone conversation, I am providing a summary of the procedures used for the PNA analyses of soot collected during the flare efficiency test.

The sample probe assembly included an in-line particulate filter housed inside the heated section of the probe about six feet from the probe tip. This in-line particulate filter assembly served two purposes: 1) collection of particulate samples from smoking flares for subsequent analysis, and 2) maintaining the cleanliness of the sampling system. The preweighed filter elements used were of the thimble configuration and constructed of 0.3 micrometer glass fiber.

The filters were changed before and after each of the smoking flare tests. Following the tests the filters were reweighed to determine the mass of particulate collected. This information, combined with the measured flow rate of sample through the probe assembly, allowed the calculation of the gross particulate concentration of the flare emission at the sampling location. It should be noted however, that these particulate samples were not collected isokinetically and thus, represent only gross estimates of the particulate concentration. The flare particulate emissions were not isokinetically sampled because it was not practical to directly measure the plume velocity.

Table 1 is a summary of the mass particulate concentration data collected during the test series. Although these samples were not collected isokinetically, the data shows distinct differences between particulate loadings of nonsmoking, lightly smoking (Test 65) and heavily smoking (Test 4) flare tests.

Samples were prepared for PNA analysis by Soxhlet extraction of the air filters as received with 200 mL of methylene chloride for 24 (+2) hours. The condenser water was chilled to 1 - 4°C and no solvent loss (bp 40°C) was noted. The samples were transferred to bottles and the glassware washed with additional methylene chloride which was added to sample. Samples were dried for several days over anhydrous sodium sulfate which had been kiln-fired at 450°C to remove organic compounds. Sample extract volumes were carefully reduced to 1 mL using Kuderna-Danish flasks and three-ball Snyder columns.

Sample extracts were analyzed by GC/MS using a 60 meter J & W fused-silica DB-1 bonded SE-30 capillary column, using d_{12}-Chrysene as an internal standard. Individual compound response factors were obtained by running a standard mix prepared from EPA standard solution concentrates, and spiked with d_{12}-chrysene. Quantitation was based on integrated peak areas and was performed by the GC/MS data system.

As a further quality assurance measure, a solvent blank was run, spiked with d_{12}-chrysene, and was found to be free of interfering peaks. No recovery efficiency data can be given, since there was only one of each sample. Ideally, one should consider collecting at least one replicate sample which could be spiked (directly onto the soot) with a known addition of a surrogate PNA. By this means, an indication of the efficiency of recovery of PNA's from the soot matrix could be obtained. Tables 2 and 3 summarize the results of the PNA analyses.

As I indicated in our telephone conversation, I am unable to calculate these results in terms of mass emission rates (e.g., $mg/10^6$ Btu, mg/hr, etc.) because of the lack of isokinetic sampling and a measure of the dilution between the reaction zone and the sampling probe.

If you have any questions, please call me at 512/444-5830.

Sincerely,

Marc McDaniel

Attch.

/kg

Table 1. Flare Efficiency Study Particulate Analysis.

Test No.	Filter No.	Wt. gain, (grams)	Sample Time [1] (minutes)	Sample Rate (ℓ/min)	Concentration ($\mu g/\ell$)
2, 3, 1, 5, 7	A-1	0.0063	---	18.51	---
7, 17, 50, 51 23, 52, 53, 54	F-1	0.0071	---	18.51	---
4 (Heavily Smoking)	F-2	0.0810	16	18.51	274
8 (Smoking)	F-3	0.0819	25	18.51	177
55, 56, 11, 57 16, 59, 60, 61 28, 31, 26, 29 33, 32, 62, 63 64, 80, 81, 82 83, 84	F-4	0.0179	---	18.51	---
65 (lightly Smoking)	F-5	0.0183	25	18.51	40

[1] Includes time for probe positioning while probe was in the plume but before formal initiation of the test.

Table 2. Total Polynuclear Aromatic Hydrocarbons in Filter Samples, in Micrograms[1].

E.S. Sample #	F_1	F_2	F_3	F_4	F_5
napthalene	(0.05)[2]	1.9	1.8	–[3]	–
acenapthylene	–	3.3	6.2	–	–
acenapthene	–	–	0.25	–	–
fluorene	–	(0.02)	0.61	–	–
phenanthrene	0.35	4.7	11.	(0.02)	(0.06)
anthracene	–	0.24	1.5	0.32	–
pyrene	0.77	6.0	17.	0.25	0.38
fluoranthene	0.96	8.3	21.	0.93	0.63
benzanthracene	0.13	0.18	4.7	1.0	0.21
chrysene	0.12	0.28	5.6	1.2	0.17
benzo(a)pyrene	–	1.2	4.4	2.6	–
1,2;5,6 dibenzanthracene	–	–	–	–	–
1,12 benzoperylene	–	–	–	1.2	–

1 – Also equal to concentration in final 1 mL extract, in µg/mL (ppm).

2 – The calculated amount is given in parenthesis if it is below twice the stated detection limit in the extract (0.05ppm). Note that some compounds were detected at concentrations below the stated detection limit.

3 – a dash indicates that the compound was not present above the stated detection limit.

Table 3. Analytical Results for Polynuclear Aromatics in Filter Samples.

E.S. Sample #	F_1	F_2	F_3	F_4	F_5
SumX Sample #	1767	1768	1769	1770	1771
Sample weight,g	0.0071	0.0810	0.0819	0.0179	0.0183
Compound	PNA concentrations, µg/g soot (ppm)				
napthalene	< 14	23	22	nd [2]	nd
acenapthylene	nd	41	76	nd	nd
acenapthene	nd	nd	3.1	nd	nd
fluorene	nd	<1	7.4	nd	nd
phenanthrene	49	58	130	<5	<5
anthracene	nd	3.0	18	18	nd
pyrene	110	74	210	14	21
fluoranthene	140	100	260	52	34
benzanthracene	18	2.2	57	56	11
chrysene	17	3.5	68	67	9.3
benzo(a)pyrene	nd	15	54	145	nd
1,2;5,6 dibenzanthracene	nd	nd	nd	nd	nd
1,12-benzoperylene	nd	nd	nd	67	nd
Detection Limit[1]	7	0.6	0.6	3.	3.

1 - Dependent on sample size. Corresponds to 0.05ppm in 1 mL extract. Con-
centrations of substances found but less than twice the detection limit
are reported as less than (<) twice the detection limit.

2 - nd = none detected at or above the stated detection limit.

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15. SUPPLEMENTARY NOTES IERL-RTP project officer is Bruce A. Tichenor, Mail Drop 63, 919/541-2547.

16. ABSTRACT The report gives results of a full-scale experimental study to determine the efficiencies of flare burners for disposing of hydrocarbon (HC) emissions from refinery and petrochemical processes. With primary objectives of determining the combustion efficiency and HC destruction efficiency for both air- and steam-assisted flares under a wide range of operating conditions, it provides a data base for defining the air quality impact of flaring. Test results indicate that flaring is generally an efficient HC disposal method for the conditions evaluated. Test methodology involved a special 27-ft sample probe suspended by a crane over the flare flame. The sample extracted by the probe was analyzed by continuous emission monitors to determine concentrations of CO_2, CO, total HC, SO_2, NOx, and O_2. In addition, the probe tip temperature, ambient air temperature, and wind speed and direction were measured. Integrated samples of the relief gas were collected for HC species analysis by gas chromatograph. Particulate matter samples were collected during the smoking flare tests. When flares were operated under conditions representing good industrial operating practice, combustion efficiencies at the sampling probe were greater than 98 percent. Combustion efficiencies declined under conditions of excessive steam (steam quenching) and high exit velocities of low-Btu content gases.

17.	KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
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