General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

PERFORMANCE AND EMISSIONS OF A CATALYTIC REACTOR WITH PROPANE, DIESEL, AND JET A FUELS

David N. Anderson
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

1. Report No. NASA TM-73786	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle PERFORMANCE AND EMISSIONS OF A CATALYTIC REACTOR WITH PROPANE, DIESEL, AND JET A FUELS		5. Report Date September 1977
		6. Performing Organization Code
7. Author(s) David N. Anderson		8. Performing Organization Report No. E-9349
		10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address Energy Research and Development Administration Division of Transportation Energy Conversion Washington, D.C. 20545		14. Sponsoring Agency Code Report No. CONS/1011-20

15. Supplementary Notes

Prepared under Interagency Agreement EC-77-A-31-1011.

16. Abstract

As part of the ERDA-funded Gas Turbine Highway Vehicle Systems project, tests were made to determine the performance and emissions of a catalytic reactor operated with propane, No. 2 diesel, and Jet A fuels. A 12-cm diameter and 16-cm long catalytic reactor using a proprietary noble metal catalyst was operated at an inlet temperature of 800 K, a pressure of 3×10^5 Pa and reference velocities of 10 to 15 m/s. No significant differences between the performance of the three fuels were observed when 98.5-percent purity propane was used. The combustion efficiency for 99.8-percent purity propane tested later was significantly lower, however. The diesel fuel contained 135 ppm of bound nitrogen and consequently produced the highest NO_x emissions of the three fuels. As much as 85 percent of the bound nitrogen was converted to NO_x. Steady-state emissions goals based on half the most stringent proposed automotive standards were met when the reactor was operated at an adiabatic combustion temperature higher than 1350 K with all fuels except the 99.8-percent purity propane. With that fuel, a minimum temperature of 1480 K was required.

17. Key Words (Suggested by Author(s)) Emissions Combustors Catalysts Fuels	18. Distribution Statement Unclassified - unlimited STAR Category 44 ERDA Category UC-93
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price*

* For sale by the National Technical Information Service, Springfield, Virginia 22161

PERFORMANCE AND EMISSIONS OF A CATALYTIC REACTOR

WITH PROPANE, DIESEL, AND JET A FUELS*

by David N. Anderson

Lewis Research Center

SUMMARY

Tests were conducted to determine if catalyst evaluations using propane fuel gave data which could be applied to catalytic combustors burning diesel or Jet A fuels. The work was part of an ERDA-supported Gas Turbine Highway Vehicle Systems project. The catalytic reactor was 12 cm in diameter, 16 cm long, and consisted of two proprietary monolithic metal substrates arranged in series. A platinum catalyst was used in the first monolith and palladium in the second. Tests were performed at an inlet temperature of 800 K, a pressure of 3×10^5 Pa, and a reference velocity range of 10 to 15 m/s. The fuel-air ratio was varied to obtain adiabatic combustion temperatures from 1260 to 1500 K.

The combustion efficiency with 98.5-percent purity propane fuel was the same as that obtained with either No. 2 diesel or Jet A fuels. However, later tests with 99.8-percent purity propane produced significantly lower combustion efficiency.

At an adiabatic combustion temperature of 1400 K, the reactor pressure drop increased from 1.7 percent at 12 m/s to 3.5 percent at 25 m/s. The pressure drop across the fuel injector and mixing passage for the liquid fuels added about 0.5 percent to that of the reactor at 12 m/s and 1.6 percent at 25 m/s.

Steady-state emissions goals were based on half the most stringent proposed automotive emissions standards of 0.248 g NO_2/km, 2.1 g CO/km, and 0.254 g HC/km. The CO emission index goal of 13.6 g CO/kg fuel was achieved when the adiabatic combustion temperature was higher than about 1350 K at a reference velocity of 12 m/s for the

E-9349

98.5-percent purity propane, No. 2 diesel, and Jet A. A minimum temperature of 1470 K was required to achieve the goal with 99.8-percent propane. The unburned hydrocarbons goal of 1.64 g HC/kg fuel was met when the reactor was operated at 12 m/s with adiabatic combustion temperatures above about 1310 K for the 98.5-percent propane, No. 2 diesel, and Jet A, or above 1480 K with the 99.8-percent propane. NO_x emissions were well below the goal of 1.6 g NO_2/kg fuel for all three fuels at all test conditions, but NO_x emissions from combustion of No. 2 diesel fuel were higher by at least a factor of 50 compared with the other fuels because of a significant level of bound nitrogen in the diesel. As much as 85 percent of the diesel fuel nitrogen was converted to NO_x.

INTRODUCTION

Catalytic combustion provides a means to efficiently react very lean fuel-air mixtures, thereby producing low emissions of NO_x, CO, and unburned hydrocarbons. Lewis Research Center is evaluating catalytic combustion as part of an ERDA-funded program studying improvements for the automotive gas turbine engine.

One improved gas turbine engine cycle defined in reference 1 has a constant turbine inlet temperature of 1310 K at all engine speeds, a combustor inlet temperature which decreases from 1210 K at idle to 970 K at full speed, and a pressure which ranges from 1.4×10^5 Pa at idle to 4.5×10^5 Pa at full speed. Previous reports of catalyst tests in this program (refs. 2 and 3) showed that at steady-state with an inlet temperature of 800 K and a pressure of 3×10^5 Pa, emissions goals of 1.6 g NO_2/kg fuel, 13.6 g CO/kg fuel, and 1.64 g HC/kg fuel could be met with reactors made from commercial catalysts. These goals were based on achieving emissions of half the most stringent proposed automotive standards. For a catalytic combustor diameter comparable to that of current automotive gas turbine combustors the reactor pressure drop would only be about 2 percent of the upstream total pressure.

The tests of references 2 and 3 were made with gaseous propane fuel to simulate a prevaporized liquid fuel and to permit simpler fuel-air premixing techniques than would be required for liquid fuels. While the results were encouraging, propane would not be commonly used in gas turbine engines; therefore, experiments were conducted to determine how well catalyst performance with propane fuel represents that with No. 2 diesel and Jet A fuels. Gasoline was not included because of test cell safety restrictions.

Performance measurements of No. 2 diesel and Jet A fuels in a conventional diffusion-flame combustion test rig (refs. 4 and 5) have shown that No. 2 diesel is more difficult to burn because of its higher aromatic content. Another study (ref. 6) reported higher combustion efficiencies for propane than for Jet A in an annular combustor. This difference may have been due to improved fuel-air mixing when propane was used, rather than to differences in fuel properties, however.

In the presence of a catalyst, fuels may not have the same relative performance as in gas-phase combustion. Studies of catalytic reaction of different fuels have produced limited data. Two studies (refs. 7 and 8) reported that good efficiency resulted whether propane, No. 2 diesel, or JP-4 fuel was used; however, only one test condition was cited, and it is possible that at other conditions there would be differences in the three fuels' performances relative to each other.

The ignition temperature measurements of reference 9 suggest that No. 2 diesel fuel should have a higher combustion efficiency than propane in a catalytic reactor. When both fuels were used to perform parametric tests with an aged catalyst (ref. 10), the No. 2 diesel did, in fact, produce significantly higher combustion efficiencies than propane.

The study reported here used the same 12-cm diameter, 16-cm long catalytic reactor designated J4 in reference 3. Tests were performed with propane, No. 2 diesel, and Jet A fuels at an inlet fuel-air mixture temperature of 800 K, a pressure of 3×10^5 Pa, and reference velocities (catalyst inlet velocities) of 10-15 m/s. The fuel-air ratio was varied to give a range of adiabatic combustion temperatures from 1260 to 1500 K.

EXPERIMENTAL DETAILS

Properties of the fuels used are given in table I. Initial tests were performed with propane fuel using the first batch of commercial-purity propane shown in table I(a). Some of these results were reported in reference 3. After the reactor had been operated for a total of about 20 hours, further tests were made using Jet A fuel (table I(b)), No. 2 diesel fuel (table I(b)), and a second batch of propane (table I(a)), in that sequence

The two lots of propane differed in the concentrations of minor constituents. The first contained 98.5 percent propane by volume, 0.5 percent heptane, and 0.3 percent hydrogen. Batch 2 was 99.8 percent pure propane with 0.15 percent ethane, no hydrogen, and negligible heptane. The diesel fuel had nearly twice the aromatic content as the Jet A and almost fifty times as much bound nitrogen.

The tests were performed in the 12-cm diameter combustion rig illustrated in figure 1. The propane fuel was heated to 350 K to insure complete vaporization and was introduced into the airstream 150 cm upstream of the catalytic reactor. Details of the propane injector are shown in figure 1.

A multiple conical tube injector developed by Tacina (ref. 11) was used to introduce the No. 2 diesel and Jet A fuels into the airstream. The injector was made with 21 conical tube sections as shown in figure 2. Fuel was injected at the upstream, small diameter end of each tube through 21 0.5-mm inside diameter fuel tubes. Each fuel tube was 25.4 cm long; this uniformity insured that equal quantities of fuel were injected at each of the 21 locations for good dispersion of fuel across the test section inlet duct. Introduction of the fuel into the small end of each conical tube produces better atomization because the air velocity is higher at this location than in the main airstream. This injector was removed during tests with propane fuel.

Measurements of the fuel-air ratio profile across the duct at the inlet plane of the catalytic reactor showed a variation of less than ±10 percent from the mean value for both the Jet A (ref. 11) and propane

fuels. Vaporization of the Jet A was complete at 800 K. The diesel fuel distribution and vaporization were not measured but are expected to be the same as that of the Jet A.

Temperature measurements were obtained at the four stations shown in figure 1. The inlet mixture temperature was obtained at Station 1, the mid-bed temperature at Station 2, the reactor exit temperature at Station 3, and the downstream temperature at Station 4. At the first three stations, an array of eight thermocouples permitted measurement of both radial and circumferential temperature variations. At Station 4 twelve thermocouples were used. The Station 1 thermocouples were Chromel-Alumel, and those in Stations 2-4 were Pt vs Pt-13% Rh.

The exhaust gas was sampled just downstream of Station 4. The water-cooled sampling probe had 5 ports which were 1.5 mm in diameter and located at the positions shown in figure 1. The ports obtained a sample from each of 5 equal cross-sectional area segments of the exhaust duct and fed a manifold to provide an average sample. An 18-m length of 0.5-cm diameter stainless steel tubing connected the probe with the gas analyzers. This sampling line was electrically heated to maintain the sample between 410 and 450 K. Concentration of CO and CO_2 were measured with Beckman Model 315B nondispersive infrared analyzers, unburned hydrocarbons with a Beckman Model 402 flame ionization detector, and nitrogen oxides (NO and NO_2) with a Thermo Electron Model 10A chemiluminescent analyzer. Water vapor was removed with a Hankinson Series E refrigeration-type dryer before the sample was analyzed for CO, CO_2, or NO_x, and corrections were made to obtain the actual, wet-basis concentrations.

The catalytic reactor consisted of two elements which were each 12 cm in diameter and 7.6 cm long. They are described further in table II and pictured in figure 3. The study of reference 3 showed that this reactor had performance characteristics similar to those of a number of other reactors using commercial catalysts. The batch 1 (98.5-percent purity) propane was used for that study.

To reduce heat loss, the reactor housing was constructed with a double wall incorporating an annular air gap. In addition, the outside of the housing was insulated. The downstream section, which contained the Station 4 instrumentation (fig. 1), was water cooled.

MEASUREMENTS AND COMPUTATIONS

All tests were conducted at an inlet fuel-air mixture temperature of 800 K and a pressure of 3×10^5 Pa. Exhaust emissions were measured with reference velocities of 10-15 m/s while pressure drop data were obtained with velocities of 12-25 m/s.

The emissions were measured as concentrations in ppm by volume and converted to emission indexes using the expression

$$\text{E.I.}_x = C_x \times 10^{-3} \; \frac{1+f}{f} \; \frac{M_x}{M_p}$$

where

E.I._x emission index of specie x, gx/kg fuel

C_x concentration of specie x, ppm V

f fuel-air weight ratio, (kg/s) fuel/(kg/s) air

M_x molecular weight of specie x, gx/mole x

M_p molecular weight of combustion products, g products/mole products

The combustion efficiency was computed from the difference between the measured and the equilibrium levels of CO and unburned hydrocarbons using the expression

$$\text{EFF} = 100 - 0.1 \left(\text{E.I.}_{CH} - \text{E.I.}_{CH,EQ} \right)$$

$$-0.1 \frac{HV_{CO}}{HV_{FUEL}} \left(\text{E.I.}_{CO} - \text{E.I.}_{CO,EQ} \right)$$

where

EFF   combustion efficiency, percent

E.I._{x} emission index, gx/kg fuel

HV_{x} heating value of x, J/kg

Equilibrium concentrations $(\text{E.I.}_{x,EQ})$ were obtained from the computer program of reference 12.

The fuel-air ratio was determined both by metering the fuel and air flow rates and by making a carbon-balance from the measured concentrations of CO, CO_2 and unburned hydrocarbons. The carbon-balance fuel-air ratio was between 96 and 100 percent of the measured value for the propane and Jet A fuels and 86 to 89 percent for the No. 2 diesel. The carbon-balance fuel-air ratio was considered more reliable and was used to calculate the adiabatic combustion temperature with the equilibrium program of reference 12. The combustion efficiency and emissions data will be presented as a function of this adiabatic combustion temperature to permit a direct comparison of the results for all three fuels. Due to heat losses from the test rig, the calculated adiabatic combustion temperatures were about 100 K higher than the measured temperatures at Station 4.

RESULTS AND DISCUSSION

Combustion Efficiency

The combustion efficiency for each of the test fuels is given in figure 4 as a function of the adiabatic combustion temperature. The data

were obtained at reference velocities of 10 and 15 m/s for the 98 5-percent propane tests and at 12 m/s for the 99 8-percent propane, No 2 diesel, and Jet A tests. The combustion efficiency with Jet A at 12 m/s was lower than the 98 5-percent propane efficiency at 10 m/s but higher than the 98 5-percent propane at 15 m/s. Thus, these two fuels gave comparable efficiencies. The No. 2 diesel fuel produced slightly lower efficiencies than the Jet A, and the 99 8-percent propane fuel gave significantly lower combustion efficiencies.

The combustion efficiency increased steeply with adiabatic combustion temperature. At a temperature of 1330 K the combustion efficiency was 99.5 percent with Jet A fuel and 98 5 percent with No. 2 diesel. The 98.5-percent propane gave efficiencies of 99.8 percent at a reference velocity of 10 m/s and 97 5 percent at 15 m/s. The 99.8-percent propane operated with efficiencies above 90 percent only when the adiabatic combustion temperature was greater than 1450 K.

As part of the series of tests with each fuel, initial conditions with that fuel were repeated to determine if loss of catalyst activity had occurred. Although repeatability was good throughout the study, the earliest tests with the 98 5-percent propane could not be conducted again at the completion of the study because that propane was no longer available. Repetition of these tests would have indicated if a slow decline in catalyst activity had occurred. Thus, it is not clear whether the difference in performance between the two batches of propane was due to differences in the two fuels or to a loss of catalyst activity to which only the propane, but not the No. 2 diesel or Jet A, was sensitive.

Pressure Drop

The pressure drop as a percent of the total upstream pressure is presented in figure 5 for reference velocities of 12 to 25 m/s. All of the data were obtained at an adiabatic combustion temperature of 1400 K. Tests with propane from batch 2 produced poor combustion efficiencies at that temperature, and, consequently, lower pressure drop. These

data are not included in the figure. Two sets of results are shown for No. 2 diesel and Jet A fuels in figure 5. The upper curve is the pressure drop recorded between two taps, one of which was located upstream of the conical-tube fuel injector and the other downstream of the catalytic reactor. The lower curve is the pressure drop for the reactor alone. Thus, the upper curve is representative of the pressure drop which might be experienced in a practical catalytic combustor since it includes the loss across the fuel injector and mixing passage as well as that across the reactor.

The combined pressure loss of the reactor, mixing passage, and fuel injector increased from 1.6 percent at 10 m/s reference velocity to over 5 percent at 25 m/s. At 12 m/s the loss was 2 percent with about 1.6 percent due to the reactor alone. These losses correspond with 64 and 51 dynamic heads respectively. Thus, the total pressure drop through a catalytic combustor can be kept low providing the application permits moderate to low reference velocities.

Emissions

Automotive emissions standards are expressed in terms of the total weight of pollutants formed per unit distance of a specified driving cycle which includes starting and transients as well as steady-state operation. Emissions data were obtained only at steady-state conditions in this study. Emission index goals were based on half the proposed automotive standards of 2.1 g CO/km, 0.254 g HC/km and 0.248 g NO_x/km. If an average fuel consumption of 9.35 km/1000 cm^3 (22 mi/gal) is assumed, the average cycle emission index values become 13.6 g CO/kg fuel, 1.64 g HC/kg fuel, and 1.60 g NO_x/kg fuel. These are the goals for this study.

The carbon monoxide emissions are shown in figure 6 as a function of the adiabatic combustion temperature. As with the combustion efficiency, the CO emissions for Jet A at a reference velocity of 12 m/s were generally between the values for the 98.5-percent propane at 10

and at 15 m/s. No. 2 diesel fuel gave slightly higher CO emissions than the Jet A, and the 99.8-percent propane gave considerably higher CO emission levels.

The CO emission index goal of 13.6 g CO/kg fuel is noted on the figure. The goal was achieved with combustion temperatures above 1320 K for 98.5-percent propane at 10 m/s, 1340 K for Jet A at 12 m/s, and 1360 K for No. 2 diesel at 12 m/s and 98 5-percent propane at 15 m/s. Temperatures in excess of 1470 K were required to meet the goal with 99.8-percent propane at 12 m/s.

Figure 7 gives the unburned hydrocarbons emission index as a function of the adiabatic combustion temperature. The emissions for 98.5-percent propane at 10 m/s reference velocity and Jet A at 12 m/s were similar with a minimum combustion temperature of 1290 K required to achieve the unburned hydrocarbon emission index goal Again diesel emissions at 12 m/s were somewhat higher; a combustion temperature above 1330 K was required to achieve the goal With the 98.5-percent propane tested at 15 m/s, the emissions goal was attained at 1340 K. A combustion temperature higher than 1480 K was required to meet the hydrocarbon emissions goal when the 99.8-percent propane was used.

NO_x emissions which result from the oxidation of nitrogen in the air (thermal NO_x) are extremely low at the combustion temperatures of this study (ref. 2), while the conversion of fuel nitrogen can lead to significant quantities of NO_x. The No. 2 diesel fuel used for the present study contained 135 ppm of bound nitrogen (see table I(b)), while the Jet A contained insignificant quantities and the propane had immeasurable nitrogen. As a result, NO_x emissions with the Jet A and propane fuels were less than 0.05 g NO_2/kg fuel, which corresponds with concentrations near the lower measurable limit for the analyzer. These emissions will not be reported because of uncertain accuracy. The use of No. 2 diesel fuel resulted in much higher emissions as shown in figure 8. The data scatter is from 0.28 g NO_2/kg fuel to 0.38 g NO_2/kg fuel, but the bulk of the data are between 0.3 and 0.35 g NO_2/kg fuel. These emissions are well below the goal of 1.6 g NO_2/kg fuel at all combustion temperatures.

The results of figure 8 can also be expressed as a percentage of the fuel nitrogen which is oxidized to NO_x, and this conversion is shown in figure 9 for operation with No. 2 diesel fuel. Conversions between 70 and 75 percent were computed for most of the data, although the results ranged from 64 to 85 percent These values compare with 80 percent conversion reported in another catalyst study (ref. 13) Even if 100 percent conversion of fuel nitrogen to NO_x were to occur, the NO_x goal of 1.6 g NO_2/kg fuel would not be exceeded with fuels containing as much as 487 ppm bound nitrogen in the absence of thermal NO_x

CONCLUDING REMARKS

The catalytic reactor used in this study gave nearly the same combustion efficiency and emissions of carbon monoxide and unburned hydrocarbons whether operated with No. 2 diesel or Jet A fuels. Similar performance was also obtained from initial tests with 98.5-percent pure propane, but later operation with 99.8-percent pure propane resulted in significantly lower combustion efficiency and higher carbon monoxide and unburned hydrocarbons emissions. It was not possible to determine if this difference in performance was due to the small differences in the propane used or to a loss in catalyst activity to which only propane, but not the No. 2 diesel or Jet A, was sensitive.

Only the No. 2 diesel fuel contained significant concentrations of fuel-bound nitrogen; consequently, this fuel produced NO_x emissions which were about 50 times higher than those from the propane or Jet A combustion. At the conditions of catalytic combustion, oxidation of nitrogen in the air produces negligible NO_x, and all of the NO_x observed can be attributed to conversion of fuel-bound N. Up to 85 percent of the diesel fuel N was oxidized to NO_x. Even with such high conversions of fuel N, catalytic combustion can produce low NO_x emissions because of negligible production of thermal NO_x.

Additional tests are required to determine if the use of different catalysts results in a change in the relative performance of different

fuels and if this relative performance is sensitive to catalyst aging or changes in test conditions. The results of this study indicate that propane fuel may not always give performance representative of that obtained with other fuels.

REFERENCES

1. Klann, John L., and Tew, Roy C., Jr., "Analysis of Regenerated Single-Shaft Ceramic Gas Turbine Engines and Resulting Fuel Economy in a Compact Car," NASA TM X-3531 (1977).

2. Anderson, D. N., Tacine, R. T., and Mroz, T. S., NASA TM X-73589 (1977).

3. Anderson, D. N., Effect of Catalytic Reactor Length and Cell Density on Performance, paper presented at the 2nd Workshop on Catalytic Combustion, Raleigh, North Carolina (1977).

4. Ingebo, R. D., and Norgren, C. T., NASA TM X-71803 (1975).

5. Ingebo, R. D., and Norgren, C. T., NASA TM X-3255 (1975).

6. Wear, J. D., and Jones, R. E., NASA TN D-7135 (1973).

7. Pfefferle, W. C., et al., ASME Winter Annual Meeting, Paper 75-WA/Fu-1, Houston (1975).

8. De Corso, S. M., et al., ASME Gas Turbine Conference and Products Show, Paper 76-GT-4, New Orleans (1976)

9. Carrubba, R. V., et al., Catalytically - Supported Thermal Combustion for Emission Control, paper presented at the EPRI NO_x Control Technology Seminar, San Francisco, Calif. (1976).

10. Heck, R. M., Energy Research and Development Administration Report No. CONS/9416-1 (1977). also NASA CR-135132.

11. Tacina, R. T. , Experimental Evaluation of Fuel Preparation Systems for an Automotive Gas Turbine Catalytic Combustor, paper presented at the Second Workshop on Catalytic Combustion, Raleign, North Carolina (1977).

12. Gordon, S. and McBride, B. J. , NASA SP-273 (1971).

13. Carrubba, R. V. , Engelhard Catathernal Combustion Program, paper presented at the EPA Workshop on Catalytic Combustion, Raleign, North Carolina (1976).

TABLE I - TEST FUELS PROPERTIES

(a) Propane (Commercial purity)

	Batch 1	Batch 2
Analysis in percent by volume:		
Propane (C_3H_8)	98 5088	9C 8288
Methane (CH_4)	0 0000	0 0060
Ethane (C - hydrocarbons)	0 0000	0 1498
Heptane (C_4 and C_5-hydrocarbons)	0 5138	0 0052
Hydrogen (H_2)	0 2989	0 0000
Argon	0 0212	0 0000
Carbon dioxide	0 3300	0 0065
Oxygen	0 0000	0 0037
Lower heating value, J/g	44100	44100

(b) No 2 Diesel and Jet A

	No 2 Diesel	Jet A
Initial boiling point, K	394	451
Final boiling point, K	574	535
Distillation point (10%), K	478	468
Specific gravity at 290 K	0.847	0 812
Viscosity at 295 K, 10^{-6} m^2/sec	3.64	2.08
Hydrogen-Carbon atom ratio	1 8	1 9
Aromatics, percent	27.55	16.12
Nitrogen content, ppm by weight	135	2.8
Lower heating value, J/g	42980	43260

TABLE II. – DESCRIPTION OF CATALYST ELEMENTS

Element number	1	2
Element designation	JM1	JM2
Position in reactor	Upstream	Downstream
Manufacturer	Johnson Matthey, Ltd.	Johnson Matthey, Ltd.
Catalyst	Pt	Pd
Loading, kg/m^3	5.3	5.3
Substrate	Metal foil, corrugated and wound into a cylinder	Metal foil, corrugated and wound into a cylinder
Cell density, $cells/cm^2$	62	62
Element diameter, cm	12	12
Element length, cm	7.6	7.6
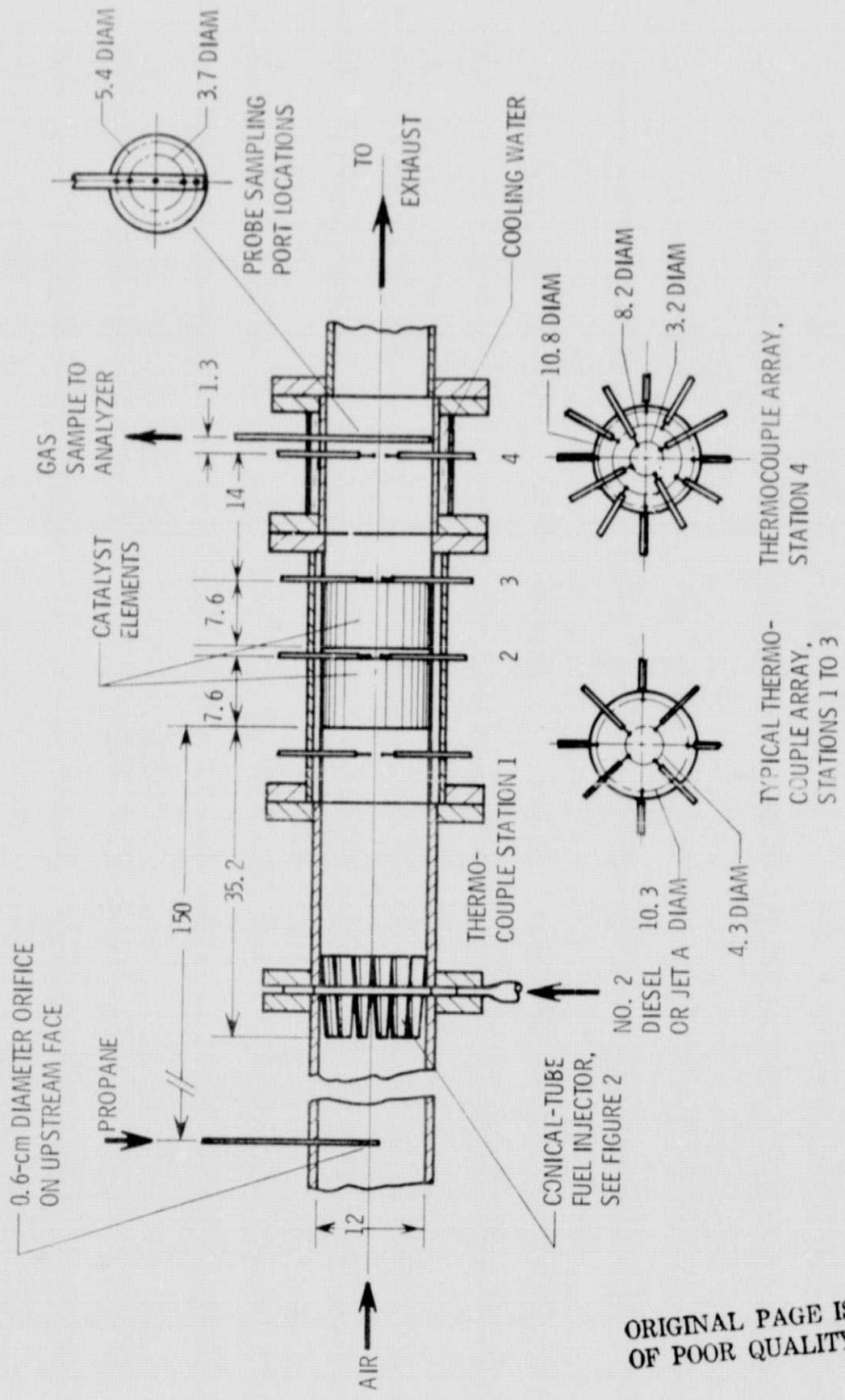
Figure 1. - Rig cross-section. (Dimensions in cm.)

0.6-cm DIAMETER ORIFICE
ON UPSTREAM FACE

PROPANE

12

AIR

150

35.2

7.6

7.6

7.6

14

1.3

THERMO-
COUPLE STATION 1

CONICAL-TUBE
FUEL INJECTOR,
SEE FIGURE 2

NO. 2
DIESEL
OR JET A

10.3
DIAM

4.3 DIAM

TYPICAL THERMO-
COUPLE ARRAY,
STATIONS 1 TO 3

CATALYST
ELEMENTS

GAS
SAMPLE TO
ANALYZER

PROBE SAMPLING
PORT LOCATIONS

5.4 DIAM

3.7 DIAM

TO
EXHAUST

COOLING WATER

2   3   4

10.8 DIAM

8.2 DIAM

3.2 DIAM

THERMOCOUPLE ARRAY,
STATION 4

FUEL
TUBE

AIR →

0 CM 2.5

0 CM 2.5

↑
FUEL

↑
FUEL

(a) UPSTREAM VIEW.

(b) SIDE VIEW.

Figure 2. - Multiple conical tube injector for Jet-A and diesel fuels.
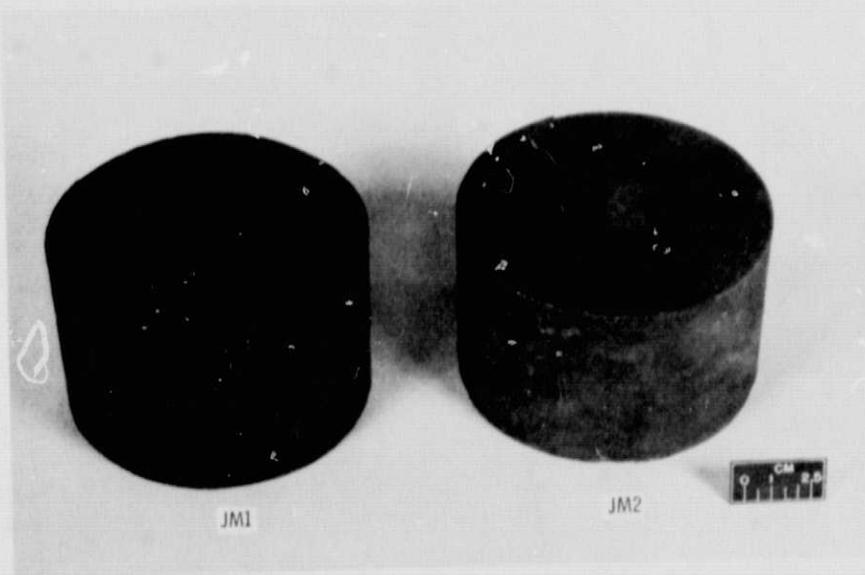
(a) OVERALL VIEW.

Figure 3. - Catalyst elements.
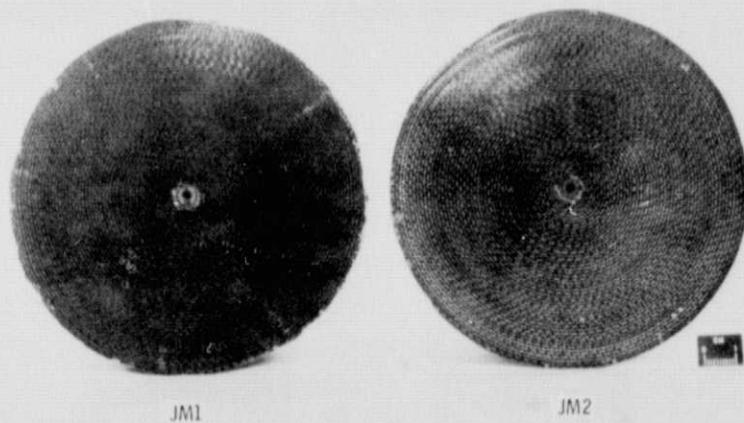
(b) INLET VIEW.

Figure 3. - Concluded.
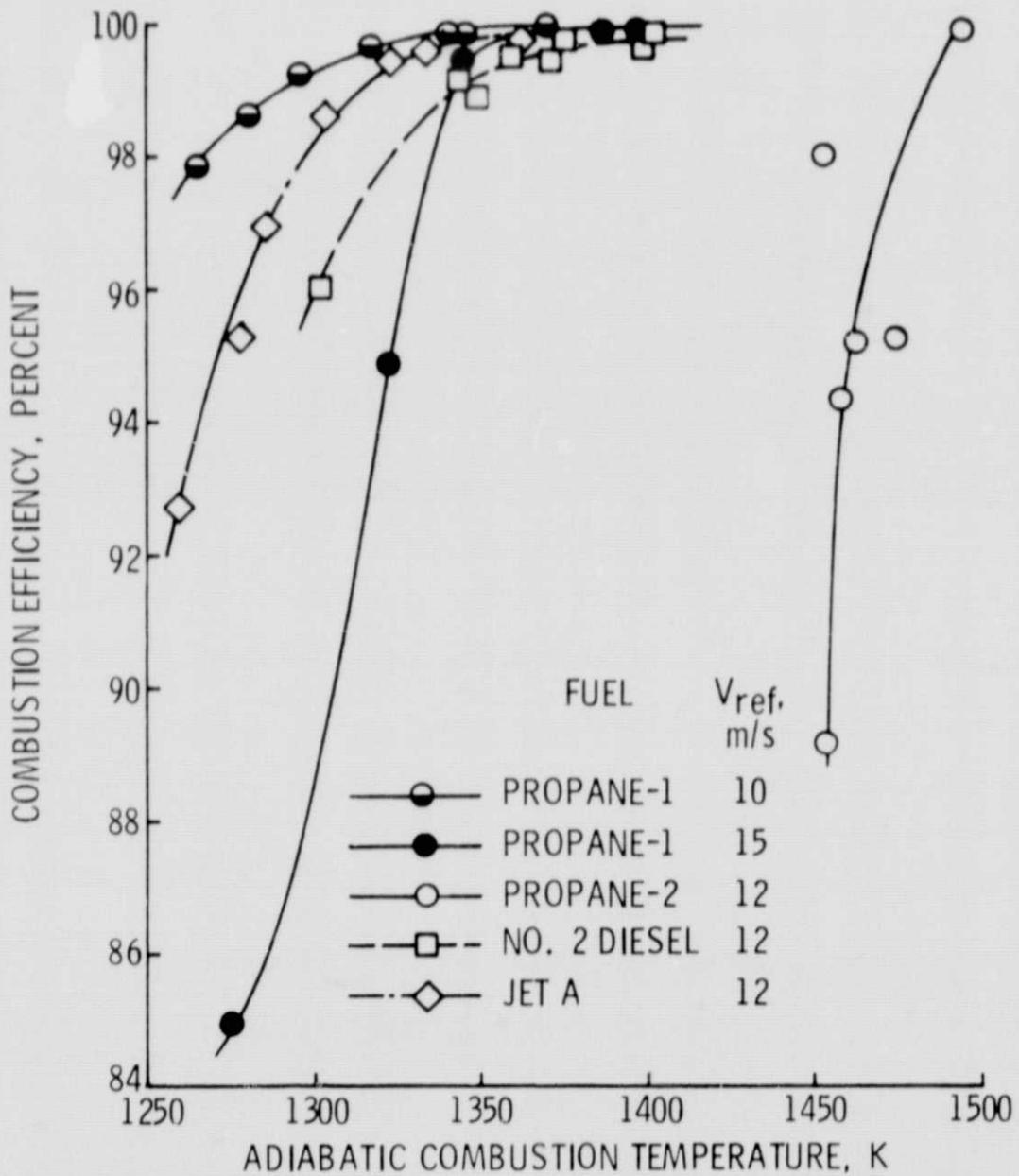
Figure 4. – Combustion efficiency. Inlet mixture temperature, 800 K; inlet pressure, 3×10^5 Pa.
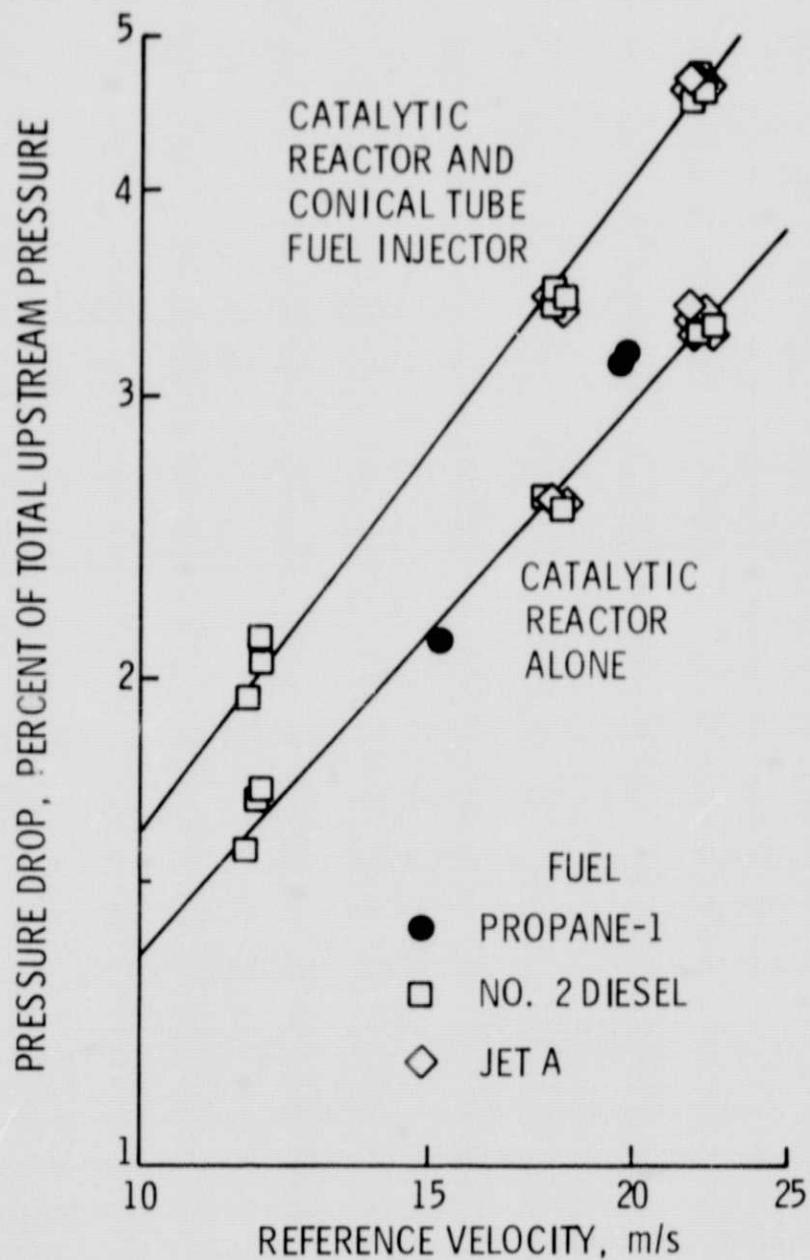
Figure 5. - Pressure drop. Inlet mixture temperature, 800 K; inlet pressure, 3×10^5 Pa; adiabatic combustion temperature, 1400 K.
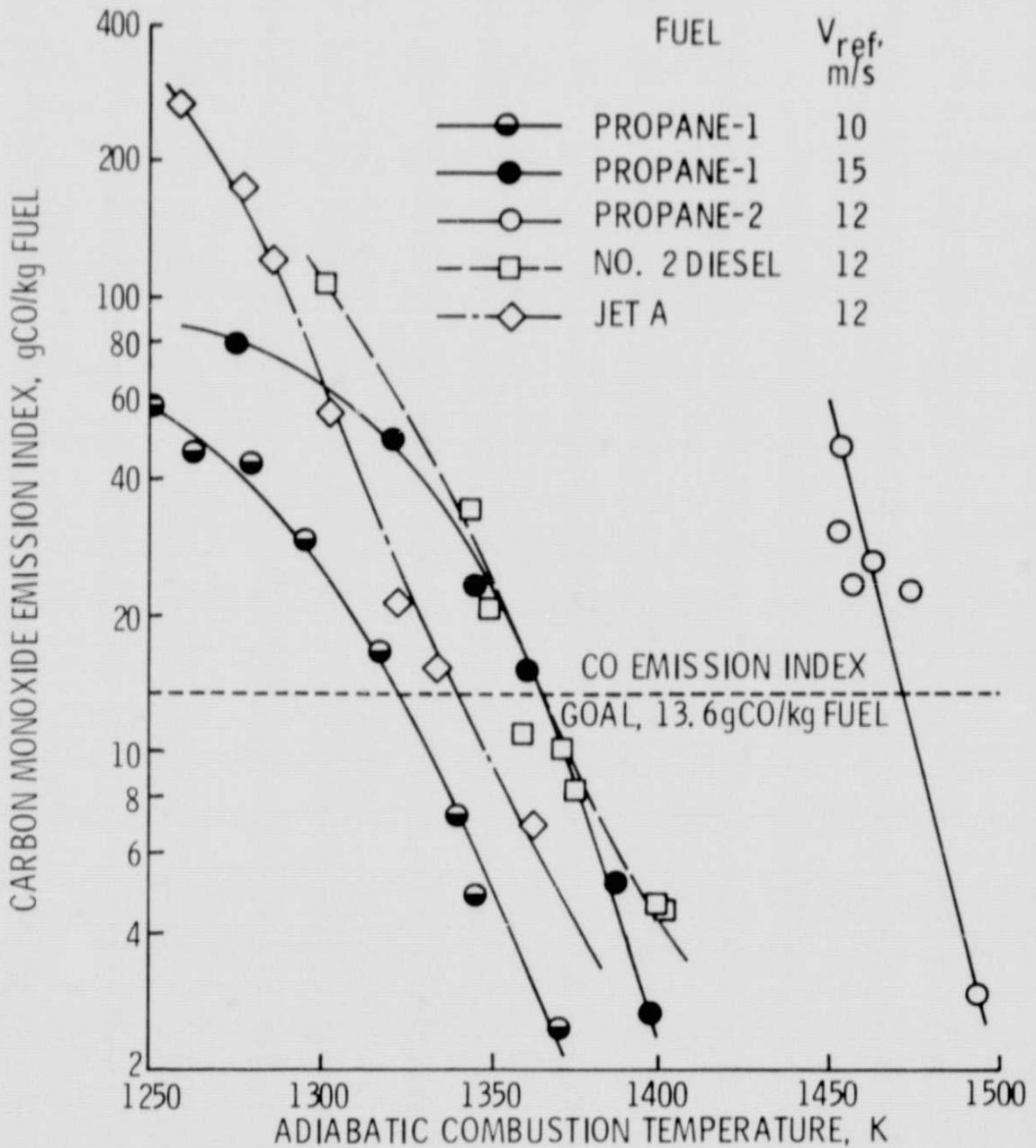
Figure 6. - Carbon monoxide emissions. Inlet mixture temperature, 800 K; inlet pressure, 3×10^5 Pa.
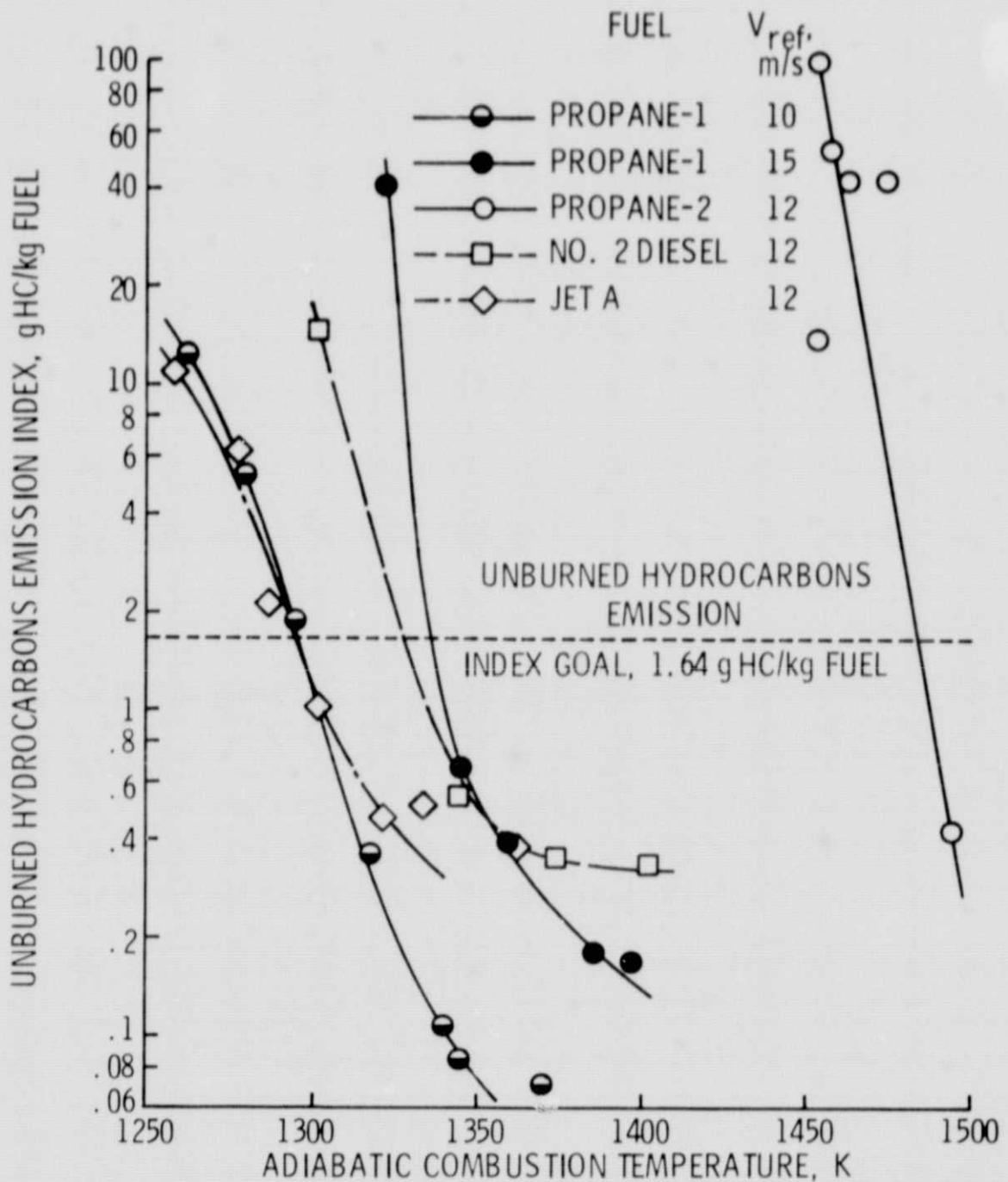
Figure 7. - Unburned hydrocarbons emissions. Inlet mixture temperature, 800 K; inlet pressure, 3×10^5 Pa.
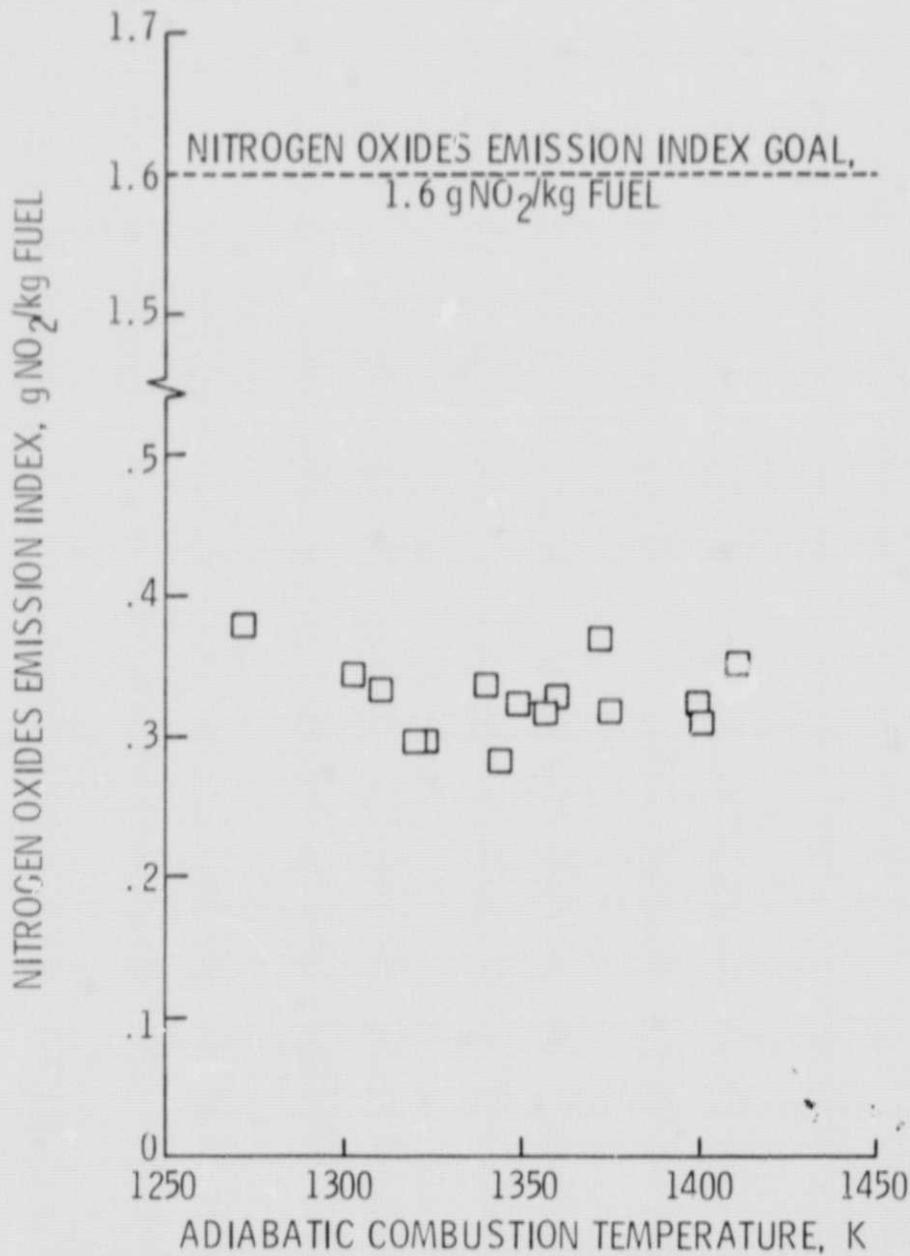
Figure 8. - Nitrogen oxides emissions with
No. 2 diesel fuel. Inlet mixture temper-
ature, 800 K; inlet pressure, 3×10^5 Pa;
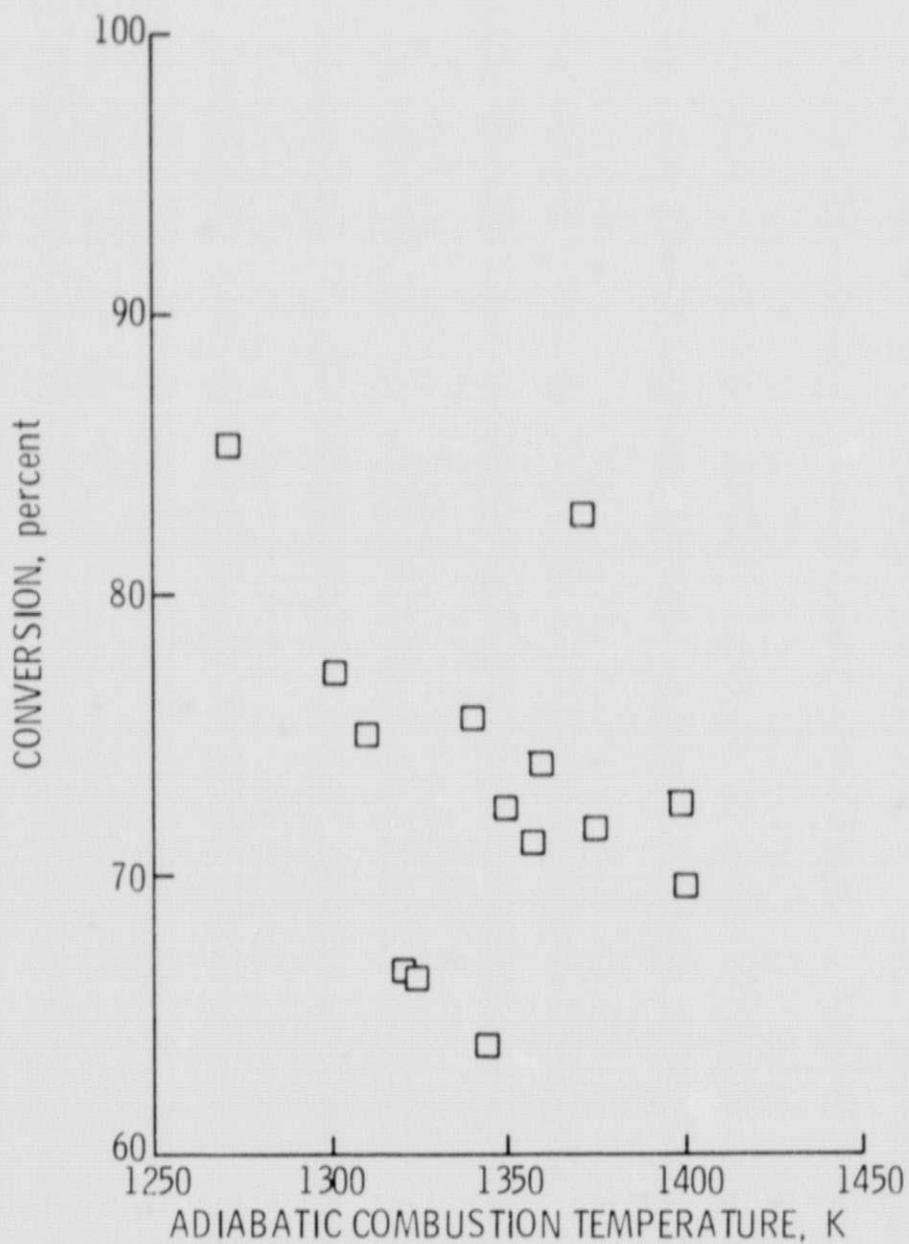reference velocity, 12 m/s.

Figure 9. - Conversion of fuel N to NO_x with No. 2 diesel fuel. Inlet mixture temperature, 800 K; inlet pressure, 3×10^5 Pa; reference velocity, 12 m/s.