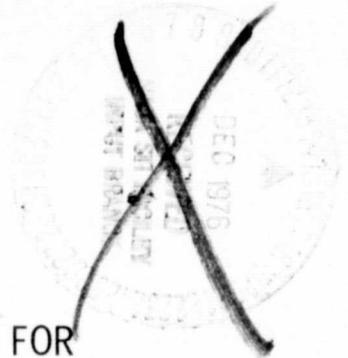


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EMISSIONS AND PERFORMANCE OF CATALYSTS FOR
GAS TURBINE CATALYTIC COMBUSTORS



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TECHNICAL PAPER to be presented at the
Twenty-second Annual International Gas Turbine Conference
sponsored by the American Society of Mechanical Engineers
Philadelphia, Pennsylvania, March 27-31, 1977

ABSTRACT

Three noble-metal monolithic catalysts were tested in a 12-centimeter diameter combustion test rig to obtain emissions and performance data at conditions simulating the operation of a catalytic combustor for an automotive gas turbine engine. Tests with one of the catalysts at 800 K inlet mixture temperature, 3×10^5 Pa (3 atm) pressure, and a reference velocity (catalyst bed inlet velocity) of 10 m/sec demonstrated greater than 99 percent combustion efficiency for reaction temperatures higher than 1300 K. With a reference velocity of 25 m/sec the reaction temperature required to achieve the same combustion efficiency increased to 1380 K. The exit temperature pattern factors for all three catalysts were below 0.1 when adiabatic reaction temperatures were higher than 1400 K. The highest pressure drop was 4.5 percent at 25 m/sec reference velocity. Nitrogen oxides emissions were less than 0.1 g NO_2 /kg fuel for all test conditions.

E-8975

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SUMMARY

Three noble-metal monolithic catalysts were tested in a 12-centimeter diameter combustion test rig to obtain emissions and performance data at conditions which simulated the operation of a catalytic combustor for automotive gas turbine engines. Propane fuel was premixed with indirectly preheated air to provide a homogeneous fuel-air mixture at the catalyst bed inlet. Tests were conducted at an inlet mixture temperature of 800 K, a pressure of 3×10^5 Pa (3 atm), and a range of reference velocities (catalyst inlet velocities) of 10 to 25 m/sec. The adiabatic reaction temperature was varied from 1100 to 1500 K by changing the fuel-air ratio.

Emissions of carbon monoxide and unburned hydrocarbons decreased with increasing reaction temperature and increased with increasing reference velocity. At a reference velocity of 10 m/sec, the three catalysts produced carbon monoxide emissions of 18.4 g CO/kg fuel and an unburned hydrocarbons emission index of 2.22 g HC/kg fuel at adiabatic reaction temperatures of about 1310, 1360, and 1320 K, respectively. These steady-state emissions correspond with the most stringent proposed federal emissions standards, assuming a vehicle fuel economy of 15 miles per gallon, and they result in a combustion efficiency greater than 99 percent. When the refer-

ence velocity was increased from 10 to 25 m/sec, the adiabatic reaction temperature for the first two catalysts had to be raised by about 70 K to meet the same emissions standards and achieve the same combustion efficiency. The third catalyst was inefficient at 25 m/sec for temperatures as high as 1420 K so data was not recorded for velocities higher than 20 m/sec. Nitrogen oxides emissions were less than 0.1 g NO₂/kg fuel for all conditions tested.

The exit temperature pattern factors for the three catalysts were near or below 0.1 for reaction temperatures of 1350 to 1400 K and a reference velocity of 20 m/sec. The highest pressure drop of the three catalysts was 4.5 percent at 25 m/sec reference velocity and 1400 K reaction temperature.

Long-term durability was not part of this study; however, no loss of catalyst performance was observed after 2½ to 3½ hours testing with any of the catalysts.

INTRODUCTION

Three commercially-produced noble-metal catalysts were tested to evaluate their emissions and performance as part of a catalyst selection program for an automotive gas turbine catalytic combustor.

Catalysis permits fuel oxidation to take place at temperatures well below the lean flammability limit of the fuel used. For this reason, the use of catalysts in gas turbine combustors to replace part of the thermal reaction zone makes it possible to maintain stable combustion with peak temperatures that are about 1000 K lower than is conventional practice (ref. 1). Combustion at such reduced temperatures can

be expected to produce several orders of magnitude less thermally-fixed nitrogen oxides emissions than result from conventional combustion techniques (ref. 2).

In order to avoid locally hot regions which could damage the catalyst bed, it will be necessary to premix the fuel with inlet air to form a mixture which is nearly all vapor and has a nearly uniform fuel-air ratio profile at the catalytic reactor inlet face. Because of this necessary fuel preparation, a catalytic combustor might be considered to be a premixed combustor which uses a catalytic, instead of a thermal, reaction zone to permit stable combustion at lower reaction temperatures. The reacting of uniform fuel-air mixtures with little or no dilution downstream of the reactor could result in nearly uniform combustor exit temperature profiles. The elimination of temperature peaks permits higher average exit temperatures without damage to the turbine blades and thereby reduces the specific fuel consumption (ref. 3).

To explore the potential emissions and performance benefits, a number of catalytic combustor evaluations have been made. Many of the published results of tests obtained at actual combustor operating conditions used a proprietary Engelhard catalytic reactor (refs. 4, 5, and 6). Reactor diameters varied for these tests from 12 centimeters (ref. 5) to 18 centimeters (ref. 4); inlet temperatures from 600 to 800 K were tested with pressures of up to 10.5×10^5 Pa (10.5 atm), reference velocities (catalyst inlet velocities) from 11 to 40 m/sec

and reaction temperatures as high as 1600 K. The study of reference 4 used Jet A fuel, reference 5, propane, and reference 6, both coal gas and No. 2 distillate oil. Combustion efficiencies were near 100 percent for reaction temperatures above about 1400 K with reference velocities on the order of 15 m/sec. Tests made at higher velocities required higher reaction temperatures to maintain complete combustion. Emissions of nitrogen oxides were less than 0.1 g NO₂/kg fuel for all test conditions of references 4 and 5, but concentrations as high as 12 ppm were reported in reference 6. Both references 5 and 6 found the exit temperature profile to be nearly uniform. Somewhat smaller test sections (8.9 centimeters in diameter) were tested by Wampler, Clark, and Gaines (ref. 7) using propane fuel and platinum catalysts. Complete combustion was recorded at a reference velocity of 4 m/sec, an inlet temperature of 720 K and an exit temperature of 1144 K. The NO_x emission index was 0.042 g NO₂/kg fuel.

Comparisons of catalysts obtained from several manufacturers have been reported in references 8 and 9. The study of reference 8 was for an aircraft gas turbine engine operating at an idle condition using a thermal pre-burner and a catalytic reactor downstream. This hybrid arrangement has been shown to meet the 1983 EPA aircraft emissions standards for class T2 engines at the idle condition.

In reference 9, experiments were described in which several 12-centimeter diameter catalysts made by W. R. Grace and by Oxy-Catalyst were tested at 800 K inlet temperature, 3×10^5 Pa (3 atm) pressure and reference velocities of 10 to 25 m/sec. At 10 m/sec

reference velocity, complete combustion was observed at temperatures as low as 1400 K with the W. R. Grace Davex 512A/512B catalyst; however, some loss of activity was observed after about 3 hours testing with all of the catalysts tested.

A demonstration of long-term catalyst durability has been reported in reference 10. An Engelhard catalyst was tested for 1000 hours at 14 m/sec reference velocity and 1600 K reaction temperature with No. 2 distillate oil. Steady-state emissions at the end of that period were still below the most stringent proposed Federal exhaust emissions standards for automobiles.

Lewis Research Center is conducting studies intended to lead to the demonstration of a catalytic combustor in an automotive gas turbine engine which meets the most stringent automotive exhaust emissions standards with a combustor pressure drop of less than 3 percent. This program is jointly sponsored by NASA and ERDA and includes both the development of fuel-air preparation systems (ref. 11) and commercial catalyst evaluation (refs. 2 and 9). The study reported here is part of the continuing evaluation of catalysts.

Automotive gas turbines operate on a regenerative cycle with combustor inlet temperatures of about 1000 K and reference velocities of around 25 m/sec at all power settings from idle to full power; combustor inlet pressures vary from 1.5×10^5 Pa (1.5 atm) at idle to 4×10^5 Pa (4 atm) at full power, and turbine inlet temperatures range from 1100 K at idle to about 1300 K at full power. In this study, evaluation of catalysts was performed with the 12-centimeter diameter

test section of reference 9 at conditions generally representative of the automotive regenerative cycle although the inlet propane-air mixture temperature was only 800 K due to nonvitiated preheater temperature limitations. A value of 3×10^5 Pa (3 atm) was chosen as a representative inlet pressure with ranges of reference velocities of 10 to 25 m/sec and reaction temperatures (combustor exit temperatures) of 1100 to 1500 K. Thus, the conditions for any particular power setting were not duplicated, but the results should be applicable to the full range of power settings.

Tests were made with three catalysts, one each from Engelhard Industries, W. R. Grace and Company, and Oxy-Catalyst Incorporated. The Engelhard catalyst was selected for this study because of its promising performance in furnace tests of catalyst activity (ref. 2). The Grace catalyst had twice the noble-metal loading and used a larger-celled substrate than the Grace Davex 512A/512B which showed outstanding performance in the tests of reference 9. The Oxy-Catalyst catalyst was identical to that tested in reference 9 except that a substrate with 0.16 centimeter, instead of 0.32 centimeter, diameter cells was used. Each of the catalyst test reactors consisted of four identical 12-centimeter diameter and 2.5-centimeter long catalyst elements in tandem.

APPARATUS AND PROCEDURE

Details of the experimental rig are given in figure 1. Figure 1(a) is a schematic overview of the combustion test duct. The air supply was indirectly preheated to temperatures as high as 850 K. The duct

was 10.25 centimeters in diameter with flanges to permit interchanging various test sections. Downstream of the test section was a water quench to cool combustion products before they were exhausted through a back-pressure valve to the atmosphere.

The experiments described in this report used commercial-grade propane with the properties given in Table I. The fuel was introduced through a tube located 150 centimeters upstream of the test section to allow time for thorough mixing of the propane and air. Propane was injected into the air stream in an upstream direction through a 0.5-centimeter diameter hole on the duct centerline. Measurements of the fuel-air ratio profile which resulted from this configuration were made using the apparatus and technique of reference 11. A maximum variation of ± 10 percent from the mean fuel-air ratio was observed and the minimum value occurred near the duct centerline.

Both air and fuel flowrates were measured with ASME standard orifices. Inlet and exit pressures were measured at wall static taps 9 centimeters upstream of the test section and 12 centimeters downstream of the exit instrumentation section, respectively. Because static and total pressures differed by less than 0.2 percent in these experiments, the static pressures measured can be considered to be equivalent to the total pressures.

Details of the catalyst test section are shown in figure 1(b). This test section was 12.1 centimeters in diameter. Provision was made for eight temperature-measuring stations spaced 2.9 centimeters apart axially along the test section. At each measuring plane there were eight

thermocouples, positioned in an array as shown in figure 1(b), measuring at the center of equal areas. Between each pair of thermocouple arrays one catalyst element, 12 centimeters in diameter and 2.5 centimeters long, could be placed. Thus, the rig provided the capability for testing a seven-element reactor, although only four identical elements were tested at one time in the studies reported here, and measurements of both the temperature history along the length of the reactor and temperature profiles at each cross section could be made. The first array of thermocouples was used to measure the inlet mixture temperature. Chromel-Alumel thermocouples were used in this array. The next two arrays were not used. The fourth array of thermocouples was also Chromel-Alumel, while Pt/Pt-13 percent Rh thermocouples were used in arrays five through eight. The four catalyst elements tested were placed between arrays 4 and 5, 5 and 6, 6 and 7, 7 and 8, as shown in figure 1(b).

A water-cooled instrumentation section containing an additional thermocouple array and a gas sampling probe was located downstream of the catalyst test section. Details are given in figure 1(b). The thermocouple array consisted of 12 Pt/Pt-13 percent Rh thermocouples in a plane 14 centimeters downstream of the last test-section array. The gas-sampling probe, located 1.3 centimeters downstream of the thermocouple array, was a fixed-position water-cooled probe with five sampling orifices located in the centers of equal cross sectional areas. The orifices were manifolded together to provide an average sample for the cross section.

An 18-meter length of 0.95-centimeter diameter stainless steel tubing connected the gas sample probe with the exhaust-gas analyzers. To prevent condensation of unburned hydrocarbons, the sample line tubing was electrically heated to maintain a gas temperature between 410 and 450 K. Gas analysis equipment included a Beckman Model 402 flame ionization detector for measuring unburned hydrocarbon concentration, Beckman Model 315B nondispersive infrared analyzers for carbon monoxide and carbon dioxide, and a Thermo-Electron Model 10A chemiluminescent analyzer for nitric oxide and total NO_x concentration. Water vapor was removed from the sample with a Hankinson Series E refrigeration-type dryer before analyzing for CO , CO_2 , or NO_x ; however, the actual wet-basis concentration was determined by correcting for the water vapor resulting from combustion. Inlet air humidity was found in previous studies to be essentially zero (ref. 5) and was not measured in this study.

Figure 1(c) is a view of the catalyst test section from the inlet. It shows the positions of the thermocouple arrays 1 and 4. A catalyst element can be seen just below the fourth-array thermocouple.

Three different catalysts were tested: An Engelhard EVD 1412, a Grace Davex 524A(D), and an Oxy-Catalyst 1.8. Figure 2 shows one element of each of the three different catalysts and Table II gives the available specifications of each catalyst. The EVD 1412 used a substrate with a sine-wave cell, the 524A(D) a rectangular cell, and the 1.8 a round cell. All three had similar cell densities. The EVD 1412 was a palladium catalyst, while the 524A(D) and 1.8 were mixtures of platinum and palladium.

All tests were performed with an inlet fuel-air mixture temperature of 800 K and a pressure of 3×10^5 Pa (3 atm). The EVD 1412 and 524A(D) were tested with reference velocities of 10, 15, 20, and 25 m/sec, and the 1.8 was tested at 10, 15, and 20 m/sec. At these conditions all the catalysts were sufficiently active that reaction occurred for all fuel-air ratios tested without any additional heating of the catalyst bed. Exit temperatures were varied from 1100 to 1500 K.

RESULTS AND DISCUSSION

The experimental emissions and pattern factor results are reported as a function of the equivalence ratio and the corresponding adiabatic reaction temperature in figures 3 to 6. The equivalence ratio was determined by making a carbon balance from the exhaust gas analysis; the adiabatic reaction temperature was computed from this equivalence ratio and the measured reactor inlet conditions using the computer program of reference 12. A comparison of the carbon-balance equivalence ratio with that established from fuel and airflow measurements gives an indication of how closely the gas sample represents the average composition at the sampling station and also provides a check of fuel and airflow measurements. For the data reported here, the ratio of the carbon-balance equivalence ratio to the flows equivalence ratio was a minimum of 0.9 and a maximum of 1.22; however, for most of the data it had a value between 1.0 and 1.20.

Emissions

The emissions results of figures 3 and 4 and the combustion efficiencies given in figure 5 were computed from measurements taken

about 15 centimeters downstream of the catalyst bed. In many tests, a temperature rise between the bed exit thermocouples (thermocouple array 8 in fig. 1(b)) and the downstream thermocouple array was observed. This increase in temperature was an indication of continuing thermal reactions downstream of the catalyst when oxidation in the catalyst was incomplete; it occurred only when measured catalyst bed exit temperatures were higher than 1100 K. Thermal reaction was seen in tests with the EVD 1412 for velocities greater than or equal to 15 m/sec, with the 524A(D) for velocities greater than or equal to 20 m/sec, and with the 1.8 for all reference velocities tested. Thus, for the EVD 1412 and 524A(D) with low velocities, the oxidation reactions tended to take place only within the catalyst bed, while higher velocities left unreacted species available for thermal reaction downstream. As the reaction temperature was raised at the higher velocity conditions, complete reaction again took place within the catalyst bed; for example, no downstream thermal reaction was apparent for adiabatic reaction temperatures greater than about 1350 K at 20 m/sec or 1400 K at 25 m/sec in the 524A(D) tests. When reactions were not completed within the catalyst bed the temperature rise across the catalyst bed was, in a few cases, as little as 75 percent, and usually greater than 85 percent, of the temperature rise from the bed inlet to the thermocouples at the gas sampling probe station.

Downstream thermal reactions have also been observed in other catalyst studies (refs. 6 and 9) in which these reactions were shown to contribute significantly to the overall combustion efficiency of the re-

actor. In addition to the downstream thermal reactions, there is another important thermal-reaction phenomenon which can take place within the catalyst bed passages. Wampler, Clark, and Gaines (ref. 7) noted that their combustion efficiencies were higher than should have resulted from purely catalytic combustion with mass-transfer-limited reaction rates. Their explanation was that thermal reactions were induced within the catalyst substrate passages by the catalytic reactions occurring at the passage walls. The importance of catalytically-supported thermal combustion was also discussed in some detail in references 13 and 14.

The measured carbon monoxide emissions are presented in figure 3. Results of the tests with the EVD 1412 catalyst are given in figure 3(a), with the 524A(D) catalyst, figure 3(b), and with the 1.8 catalyst, figure 3(c).

Typically, CO emissions are low at low reaction temperatures because unreacted fuel passes through the catalyst. As the reaction temperature (equivalence ratio) is increased, the CO emissions increase to a maximum value, then begin to decrease as the CO formed begins to oxidize to CO_2 . This trend of increasing, then decreasing, CO concentration as reaction temperature increased can be seen in both figures 3(a) and (b) in the 20-m/sec data. Although this same effect of reaction temperature on CO concentration was also observed for the other conditions of figures 3(a) to (c), the data at these conditions was only recorded and plotted for reaction temperatures greater than that at which the maximum CO occurred.

For the EVD 1412 (fig. 3(a)) and 524A(D) (fig. 3(b)) catalysts, data was obtained at 10, 15, 20, and 25 m/sec reference velocities. The 20-m/sec condition was tested first in each case, followed by 15, 20, and 25 m/sec. Then, to check the validity of the data and to see if any loss of activity might have occurred during the $2\frac{1}{2}$ to $3\frac{1}{2}$ hours testing of each catalyst, the 20-m/sec condition was retested. The repeat data are shown as solid points on the figures. Figures 3(a) and (b) show that the repeated CO data fell along the same curve as the original data.

When the 1.8 catalyst was tested, the data were obtained in the same sequence: 20, 15, and 10 m/sec. However, when the 25 m/sec condition was established there was no evidence that the CO had begun to decrease for equivalence ratios as high as 0.28 (1420 K adiabatic reaction temperature). To avoid testing at excessive temperatures, the tests at this condition were then abandoned and the 20 and 10 m/sec data repeated. This repeat data is shown in figure 3(c) with solid symbols. In each case, the repeated tests produced CO which was slightly lower than the original data.

For all three catalysts an increase in the reaction temperature or a decrease in the reference velocity caused the CO to decrease once the maximum value had been attained.

To provide some means of comparison based on realistic emissions standards, an emission index reference was determined from the proposed Federal automobile exhaust emission standard of 3.4 g CO/mile. Assuming a vehicle fuel economy of 15 miles/gallon and a fuel density of 2.77 kg/gallon, this standard translates into an emission index of

18.4 g CO/kg fuel. This reference is indicated in figures 3(a), (b), and (c). It should be noted that the emissions measured in this study resulted from steady-state tests, while the standard is based on operation over a cycle which includes transients and start-up; therefore, the determination of what conditions are required to achieve the reference emission index is meaningful primarily in comparing the performance of different catalysts. The choice of a fuel economy figure to calculate an emission index from the vehicle emissions standard is somewhat arbitrary, and while 15 miles/gallon is low compared with the potential of advanced-technology automotive gas turbine engines, it is representative of present technology. A higher value of fuel economy would raise the value of the reference emission index and, therefore, make the standard easier to meet.

From figure 3 the adiabatic reaction temperature can be determined at which the reference emission index was obtained; these temperatures are tabulated in Table III(a) for the three catalysts and four reference velocities. The EVD 1412 reached the reference value at lower temperatures than the other catalysts, but the temperature required to achieve the reference emission index for the three catalysts differed by a maximum of only 40 K for velocities up to 20 m/sec.

The unburned hydrocarbon emissions, shown in figures 4(a), (b), and (c), decreased with increasing adiabatic reaction temperatures at constant reference velocity while an increase in reference velocity produced an increase in emissions.

When tests were repeated at the 20 m/sec velocity, the data agreed

with the original experimental curve for both the EVD 1412 (fig. 4(a)) and 524A(D) (fig. 4(b)). The second tests of the 1.8 (fig. 4(c)) at both 10 and 20 m/sec resulted in slightly lower emissions than were originally measured. It is possible that surface contaminants may have been present initially and were burned off during testing.

The reference emission index for unburned hydrocarbons was based on the proposed automotive standard of 0.41 g HC/mile, a fuel economy of 15 miles/gallon, and a fuel density of 2.77 kg/gal to produce 2.22 g HC/kg fuel. This value is shown in figures 4(a), (b), and (c), and the temperatures at which the reference level was reached is given in Table III(b). There was not a great difference among the three catalysts with regard to this temperature, although the EVD 1412 catalyst achieved the reference emission index at the lowest temperature. The temperatures were little different from those required to meet the CO reference.

The temperatures shown in Table III are above 1300 K for all test conditions; therefore, to operate the catalytic combustor with low emissions in the automotive gas turbine engine downstream dilution will be required to achieve the turbine inlet temperatures of 1100 K (at idle) to 1300 K (at full power). Future automotive gas turbine engines may operate with higher turbine inlet temperatures, and it may be possible for those applications to operate a catalytic combustor with little or no downstream dilution.

For the conditions tested nitrogen oxides emissions for all three catalysts were below 0.06 g NO₂/kg fuel. The reference emission in-

dex for NO_x using the proposed 0.4 g NO/mile standard is 2.17 g NO_2/kg fuel. These figures demonstrate the ultra-low NO_x potential which the catalytic combustor has when burning nitrogen-free fuels.

Combustion Efficiency

An emission index of 46 g CO/kg fuel contributes 1 percent to combustion inefficiency as does an emission index of 10 g HC/kg fuel; thus, the emissions reported in figures 3 and 4 can be used to compute a combustion efficiency. The results of this calculation are shown in figure 5. Repeated data for the EVD 1412 (fig. 5(a)) and 524A(D) (fig. 5(b)) at 20 m/sec and for the 1.8 (fig. 5(c)) at 20 and 10 m/sec are also shown. As was observed with reference to the CO and unburned hydrocarbons data, the derived combustion efficiency shows good repeatability for both the EVD 1412 and 524A(D). The combustion efficiency of the 1.8 increased slightly compared with the original data.

The EVD 1412 generally achieved the best combustion efficiency for a given reaction temperature of the three catalysts tested, although the performance differences between it and the 524A(D) were not large. At 10 m/sec reference velocity, a reaction temperature of 1300 K produced 99 percent combustion efficiency. When a reference velocity of 25 m/sec was tested the temperature had to be raised to 1380 K to achieve the same efficiency.

The catalysts tested in the study of reference 9 were compared on the basis of the adiabatic reaction temperature required to achieve 90 percent combustion efficiency. That efficiency was obtained at the

lowest temperature with the Grace Davex 512A/512B catalyst. At 800 K inlet temperature, 3×10^5 Pa (3 atm) and 10 m/sec reference velocity, 90 percent combustion efficiency was recorded with this catalyst at 1210 K; at 25 m/sec the required temperature for this efficiency increased to 1350 K. For comparison, the present tests showed that 90 percent combustion efficiency at 10 m/sec was achieved at 1200 K with the EVD 1412, at 1210 K with the 524A(D), and 1260 K with the 1.8. With a reference velocity of 25 m/sec, the EVD 1412 gave 90 percent efficiency at 1320 K and the 524A(D), at 1310 K. The 1.8 was not tested above 20 m/sec. Unlike the present tests, the tests of reference 9 showed a loss of activity for all catalysts tested, including the Grace Davex 512A/512B, after about 3 hours' testing over a range of conditions.

No Engelhard catalyst was tested in the study of reference 9, but both the Grace Davex 512A/512B catalyst and the Oxy-Catalyst 1 catalyst tested for that study can be compared with the Grace and Oxy-Catalyst specimens evaluated in this report. The Grace Davex 512A/512B catalyst had half the noble metal loading and a higher substrate cell density (45 cells/cm^2 compared with 31 cells/cm^2) than the Davex 524A(D) of this study. In addition, the 524A(D) wash-coat was stabilized to help it maintain surface area at higher temperatures. The net effect of these differences was that the 524A(D) produced somewhat higher efficiencies at the higher velocities and had better durability - at least for the short period of time both catalysts were tested. The Oxy-Catalyst 1 catalyst of reference 9 used a substrate with 0.32 centimeter diameter round cells (10 cells/cm^2)

while the present Oxy-Catalyst 1.8 had 0.16 cm diameter round cells (34 cells/cm²). Although the same total amount of catalyst was used for both tests, the higher surface area of the present test catalyst produced 90 percent combustion efficiency at lower adiabatic reaction temperatures. At 10 m/sec, the temperatures required to achieve 90 percent efficiency were 1260 K for the small-celled Oxy-Catalyst of the present tests and 1360 K for the large-celled Oxy-Catalyst catalyst of reference 9. At 20 m/sec the temperatures were 1400 and 1470 K, respectively.

The exit temperatures measured 14 centimeters downstream of the catalyst bed were typically 50 to 100 K lower than the computed adiabatic reaction temperatures when complete combustion was indicated by the exhaust gas analysis. This difference can be accounted for by considering radiation losses from the thermocouples and cooling losses from the flowing gas stream to the water-cooled instrumentation section walls.

Pattern Factor

The exit temperature pattern factor is defined as

$$\bar{\delta} = \frac{T_m - T_a}{T_a - T_i}$$

where

T_m maximum temperature measured in the combustor exit plane

T_a average measured combustor exit temperature

T_i average measured combustor inlet temperature

In this study, the temperature was measured both at the exit plane of

the catalyst and at the gas-sampling station 14 centimeters downstream. The exit temperature pattern factor based on the downstream temperature measurements is presented in figures 6(a), (b), and (c) for the EVD 1412, 524A(D), and 1.8, respectively. Because of the importance of the thermal reaction zone to the performance of a catalytic combustor (ref. 9), the use of the downstream temperatures rather than the catalyst exit temperature to compute pattern factor should give a more realistic picture of what might be expected from a catalytic combustor.

A homogeneous fuel-air mixture reacted in a uniformly-coated catalyst with no heat loss should produce a pattern factor of zero. In the experiments reported here, the local fuel-air ratio actually deviated from the mean value by about ± 10 percent (see Apparatus and Procedure); thus, if there were no mixing downstream of the reactor, the lowest pattern factor which could be expected would be 0.1. Mixing of combustion products downstream of the catalyst bed could be expected to reduce this value.

Nonuniformities in catalyst substrate geometry and catalyst coating result in varying combustion efficiencies throughout the bed. As the fuel-air ratio (reaction temperature) is increased, the local combustion efficiencies throughout the bed also increase to produce a more uniform exit temperature profile; thus, in the result of figure 6, the pattern factors for all three catalysts exhibit the same trend: decreasing as reaction temperature is increased to values less than 0.1. For both the EVD 1412 (fig. 6(a)) and 1.8 (fig. 6(c)) tests, the pattern factor also increased with reference velocity. For the 524A(D) (fig. 6(b)) the

pattern factor was independent of velocity within the scatter of the data. The pattern factors for all three catalysts was less than 0.1 for adiabatic reaction temperatures greater than 1400 K.

If the catalyst exit temperature had been used instead of the downstream temperatures to compute the pattern factor the values would have been higher than those in figure 6 by about a factor of 2 at the highest reaction temperatures. This difference is the result of two effects: first, the thermal reaction zone permits greater mixing of the effluent from the catalyst bed, and, second, the thermal zone permits continued reaction in parts of the flow which may not yet have reacted completely. Within the catalyst bed, temperatures measured near the outer diameter were typically on the order of 100 K lower than those measured near the centerline. This difference is the result of heat losses from the periphery of the catalyst bed.

The pattern factors were computed from measurements of 12 thermocouples (see fig. 1(b)), which gives a measuring density of 1 thermocouple per 9.5 cm^2 of exit plane area. Jones (ref. 15) showed that a measuring density of 1 temperature sample for every 5.88 cm^2 was adequate to give the pattern factor within ± 10 percent; therefore, the uncertainty in the present measurements is probably somewhat greater than that. Jones also noted that low values of pattern factor (such as those observed in this study) are more susceptible to errors in sampling than are high values.

Pressure Drop

The measured combustor pressure drop is reported as a function of reference velocity for adiabatic reaction temperatures of 1300 and 1400 K in figure 7. The Grace Davex 524A(D) produced the highest pressure drop of the three catalysts tested - 4.5 percent at 25 m/sec and 1400 K. The Oxy-Catalyst 1.8 produced only 2 percent loss at 20 m/sec and 1400 K. For comparison, the Grace catalysts tested for reference 9, which had smaller cells than that tested in this study, produced 6 percent pressure drop at 25 m/sec. The Oxy-Catalyst catalysts tested for reference 9, which had larger cells than the sample tested here produced only 1 percent pressure drop at 20 m/sec.

The exponent n in the dependency

$$\frac{\Delta p}{p} \propto v^n$$

was about 1.5 for all three of the catalysts tested. This exponent is the result of a combination of transition and turbulent flow through the substrate cell passages; for example, at 10 m/sec, the exit Reynolds number varied from 9000 for the Engelhard to 14 000 for the Oxy-Catalyst.

The catalytic combustor goal of less than 3 percent pressure drop requires that the catalyst bed be limited to about 2 percent pressure drop to allow for the loss through the fuel-air mixing process and through the diffuser. This goal was met by the catalysts tested here for reference velocities of 15 to 20 m/sec. Because these ve-

locities are lower than typical automotive gas turbine combustor values, it is possible that the diameter of a catalytic combustor may have to be on the order of 25 percent larger than that of current automotive gas turbine combustors.

CONCLUDING REMARKS

Catalysts from three manufacturers were tested as part of an evaluation of catalysts for automotive gas turbine engine catalytic combustors. The temperature required to achieve 90 percent combustion efficiency with two of the catalysts was lower than had been achieved in previous tests (ref. 9).

The data presented were obtained with propane fuel because it is relatively easy to vaporize and premix it with air. Propane also has a much higher autoignition temperature than most liquid fuels. However, because propane is more difficult to oxidize than the traditional gas turbine fuels, such as Jet A or Diesel, the results presented probably tend to show poorer performance than might be achieved with some other fuels.

The effects of changes in substrate geometry and catalyst loading can be seen by comparing the present results with those obtained in previous tests. The Oxy-Catalyst catalyst used in the study of reference 9 had a substrate with 10 cells/cm^2 ; with that catalyst, an adiabatic reaction temperature of 1470 K was found to be necessary to produce 90 percent combustion efficiency at a reference velocity of 20 m/sec. For the present Oxy-Catalyst tests a substrate with 34 cells/cm^2 was used and a temperature of 1400 K gave 90 percent

efficiency; at the same time, however, the pressure drop increased from 1 to 2 percent at 20 m/sec. The cell density of the Grace catalyst was reduced from 45 cells/cm² for the reference 9 tests to 31 cells/cm² for this study; this change resulted in a decrease in pressure drop at 25 m/sec from 6 to 4.5 percent. In addition to the change in passage number density the catalyst loading was increased, and this change permitted 90 percent efficiency to be achieved at lower reaction temperatures even though the number of substrate passages was decreased.

All three of the catalysts tested may have potential for still further improvement in pressure drop and combustion efficiency, and the results of this study do not show any manufacturer to have a clearly superior catalyst technology. It may be possible to increase catalyst loading, make changes in substrate passage size and shape, and either increase or decrease catalyst bed length. Changes in bed length and passage geometry entail trade-offs between pressure drop and combustion efficiency, and the final selection will involve some compromise between these two performance characteristics. Before the catalytic reactor can be designed a study of the required length and volume of the downstream thermal reaction zone will be required, and the effect of various catalyst substrate materials on response time is needed. Catalyst activation temperatures have to be determined; final reactor design may include a combination of several different catalysts on different substrates with a low-activation-energy catalyst followed by high-efficiency catalysts. Catalyst durability has to be demonstrated (ref. 10).

In addition to the catalytic reactor, a practical catalytic combustor will require a fuel/air preparation system (ref. 11) and some means to heat the catalyst to its activation energy for cold start conditions. Variable combustor geometry may also be required to permit the combustor to operate over a narrow range of conditions while the engine operates over a wider range.

It should be evident, then, that a great deal of basic design information has yet to be obtained and a number of developmental areas have to be explored before a practical catalytic combustor can be demonstrated.

REFERENCES

1. Blazowski, W. S., and Walsh, D. E., "Catalytic Combustion: An Important Consideration for Future Applications," Combustion Science and Technology, Vol. 10, No. 5/6, 1975, pp. 233-244.
2. Anderson, D. N., "Preliminary Results from Screening Tests of Commercial Catalysts with Potential Use in Gas Turbine Combustors. Part I: Furnace Studies of Catalyst Activity," NASA TM X-73410, 1976.
3. Rosfjord, T. J., "Catalytic Combustors for Gas Turbine Engines," AIAA Paper No. 76-46, Jan. 1976.
4. Blazowski, W. S., and Bresowar, G. E., "Preliminary Study of the Catalytic Combustor Concept as Applied to Aircraft Gas Turbines," AFAPL-TR-74-32, Air Force Aero Propulsion Lab., Wright-Patterson AFB, Oh., May 1974.

5. Anderson, D. N., Tacina, R. R., and Mroz, T. S., "Performance of a Catalytic Reactor at Simulated Gas Turbine Combustor Operating Conditions," NASA TM X-71747, 1975.
6. DeCorso, S. M., et al., "Catalysts for Gas Turbine Combustors - Experimental Test Results," ASME Paper No. 76-GT-4, Mar. 1976.
7. Wampler, F. B., Clark, D. W., and Gaines, F. A., "Catalytic Combustion of C_3H_8 on P_T Coated Monolith," Fall Meeting of the Combustion Institute, Western States Section, California State University at Northridge, Calif., Paper No. 74-36, Oct. 1974.
8. Siminski, V. J., "Development of a Catalytic Combustor for an Aircraft Gas Turbine Engine," presented at the Catalytic Combustion Workshop of the Environmental Protection Agency, Raleigh, North Carolina, May 1976.
9. Anderson, D. N., "Preliminary Results from Screening Tests of Commercial Catalysts with Potential Use in Gas Turbine Combustors. Part II: Combustion Test Rig Evaluation," NASA TM X-73412, 1976.
10. Carrubba, R. V., "Catalysts and Catalytic Substrates Material for Gas Turbine Engine Combustor," presented at the Catalytic Combustion Workshop of the Environmental Protection Agency, Raleigh, North Carolina, May 1976.
11. Tacina, R., "Experimental Evaluation of Two Premixing-Prevaporizing Fuel Injection Concepts for a Gas Turbine Catalytic Combustor," NASA TM X-73422, 1976.
12. Gordon, S., and McBride, B. J., "Computer Program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance, Incident and Reflected Shocks, and Chapman-Jouguet Detonations," NASA SP-273, 1971.

13. Pfefferle, W. C., et. al., "Catathermal Combustion: A New Process for Low-Emissions Fuel Conversion," ASME Paper No. 75-WA/Fu-1, Nov. -Dec. 1975.
14. Carrubba, R. V., et. al., "Catalytically-Supported Thermal Combustion for Emission Control," presented at the Electric Power Research Institute NO_x Control Technology Seminar, San Francisco, California, Feb. 1976.
15. Jones, R. E., "Effect of Exit Temperature Sampling Density on Measured Combustor Performance," NASA TN D-6352, 1971.

TABLE I. - PROPERTIES OF COMMERCIAL GRADE
PROPANE USED IN THIS STUDY

Analysis: Propane (C_3H_8)	90.800 percent by volume
Methane (CH_4)	.128
C_2 -hydrocarbons	.035
C_4 - and C_5 -hydrocarbons	2.708
Carbon dioxide (CO_2)	2.792
Nitrogen (N_2)	2.642
Oxygen (O_2)	.005

Lower heating value: 44 100 J/g

TABLE II. - CATALYST SPECIFICATIONS

Catalyst manufacturer	Catalyst designation	Catalyst composition	Catalyst loading	Substrate manufacture	Substrate designation	Substrate composition	Cell density, cells/cm ²	Cell shape
Engelhard Industries W. R. Grace and Co. Oxy-Catalyst, Inc.	EVD 1412	Pd	Proprietary	Corning	-----	Cordierite	35	Sine-wave
	Davex 524A(D)	Pd/Pt:1/1	6.5 kg/m ³	W. R. Grace	Poramic 200	Cordierite	31	Rectangular
	1.8	Pd/Pt:2/1	1.8 kg/m ³	General Refractories	1.6 mm R	Mullite	34	Round

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TABLE III. - ADIABATIC REACTION TEMPERATURE AT
WHICH REFERENCE EMISSIONS ARE ACHIEVED

[Inlet mixture temperature, 800 K; inlet pressure,
 3×10^5 Pa (3 atm).]

(a) Carbon monoxide

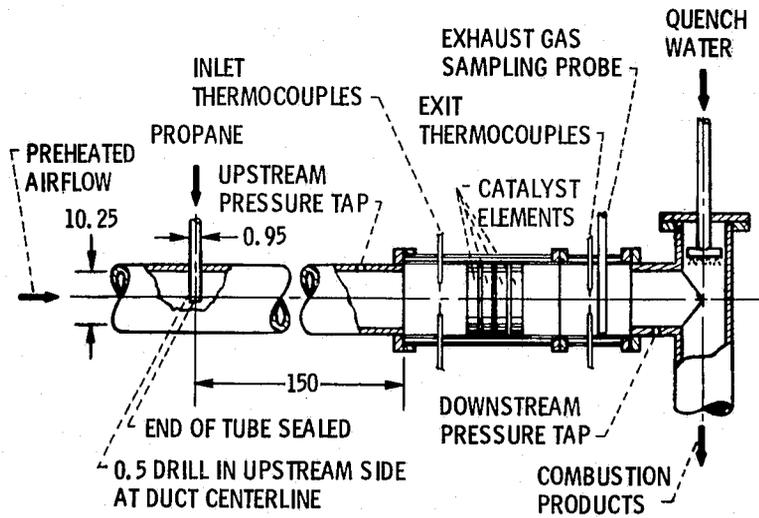
3.4 g/mile at 15 miles/gallon fuel economy gives
an emission index reference of 18.4 g CO/kg fuel
This emission index is achieved at the following
steady-state reaction temperatures (K):

	Reference velocity, m/sec			
	10	15	20	25
Engelhard EVD 1412.	1322	1337	1388	1394
Grace Davex 524A(D)	1352	1374	1404	1414
Oxy-Catalyst 1.8	1320	1360	1428	----

(b) Unburned hydrocarbons

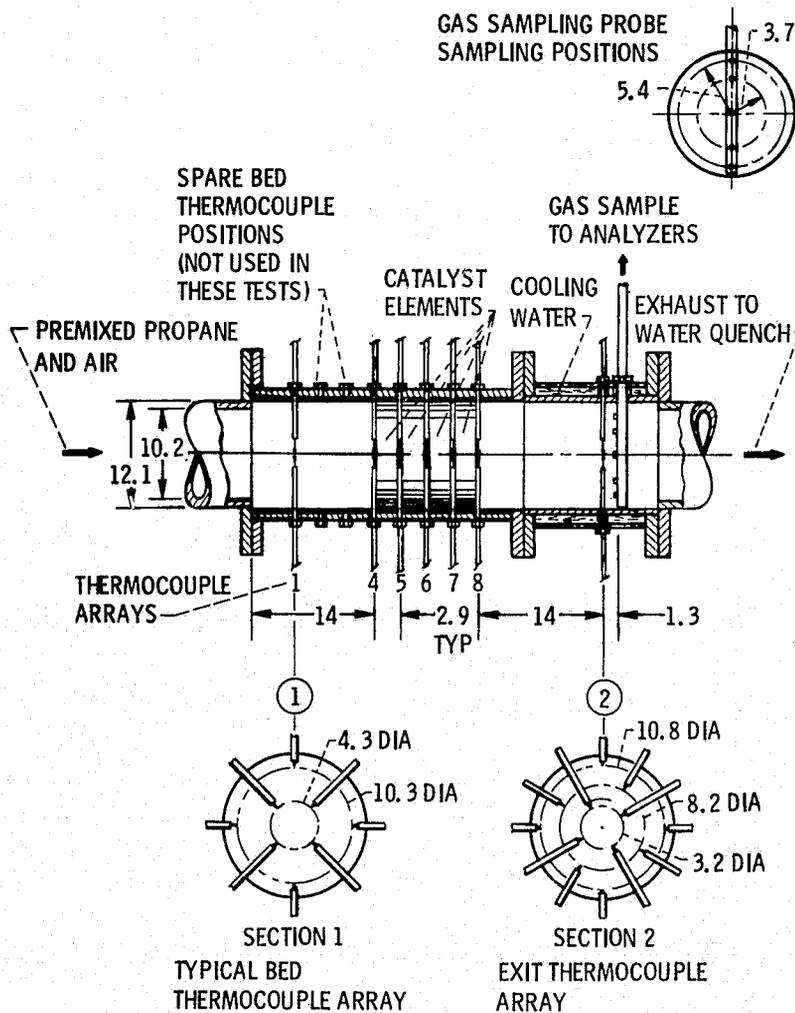
0.41 g/mile at 15 miles/gallon fuel economy gives
an emission index reference of 2.22 g HC/kg fuel.
This emission index is achieved at the following
~~steady-state~~ steady-state reaction temperatures (K):

	Reference velocity, m/sec			
	10	15	20	25
Engelhard EVD 1412	1305	1334	1366	1378
Grace Davex 524A(D)	1366	1396	1428	1432
Oxy-Catalyst 1.8	1320	1370	1452	----



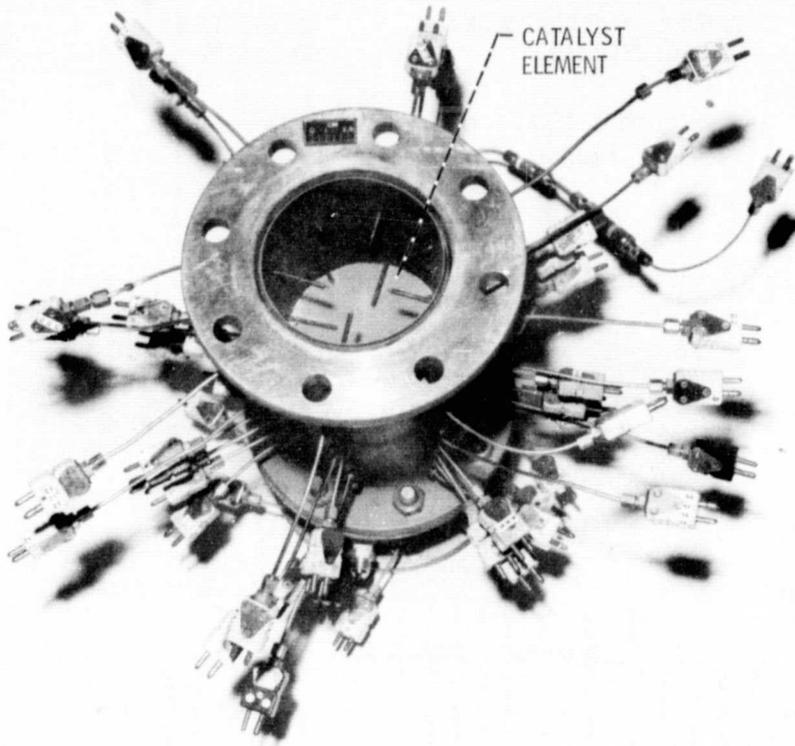
(a) SCHEMATIC OF TEST DUCT. (DIMENSIONS ARE IN CM.)

Figure 1. - Experimental rig.



(b) SCHEMATIC OF TEST SECTION.

Figure 1. - Continued.



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(C) INLET VIEW OF TEST SECTION.

Figure 1. - Concluded.

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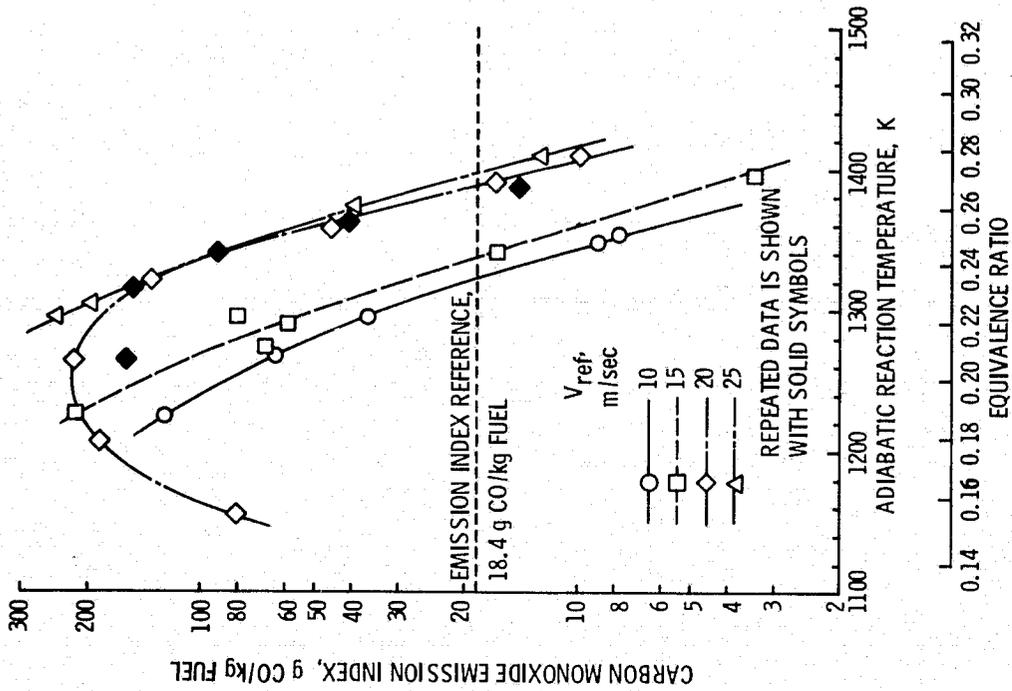
C-76-3179

ENGELHARD EVD 1412

W. R. GRACE DAVEX 524A (D)

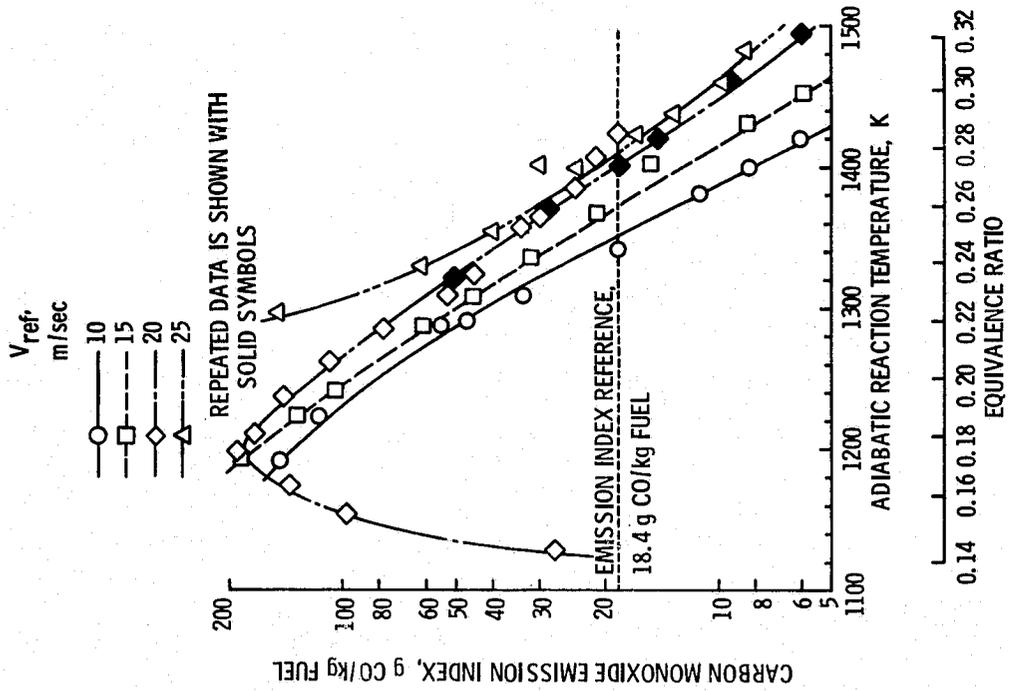
OXY-CATALYST 1.8

Figure 2. - Catalyst test elements.



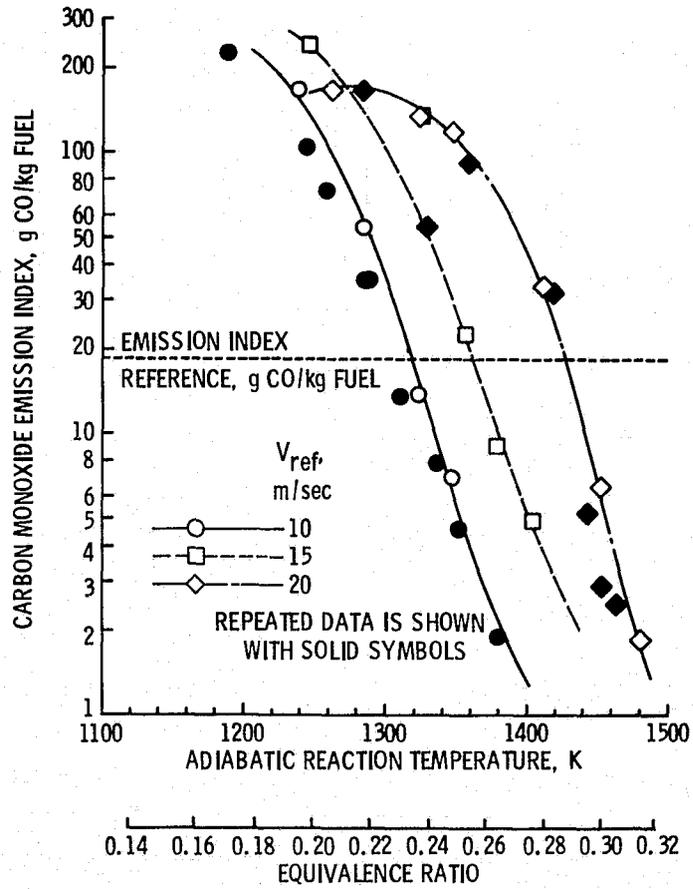
(a) ENGELHARD EVD 1412.

Figure 3. - Carbon monoxide emissions. Inlet mixture temperature, 800 K; inlet pressure, 3×10^5 Pa (3 atm).



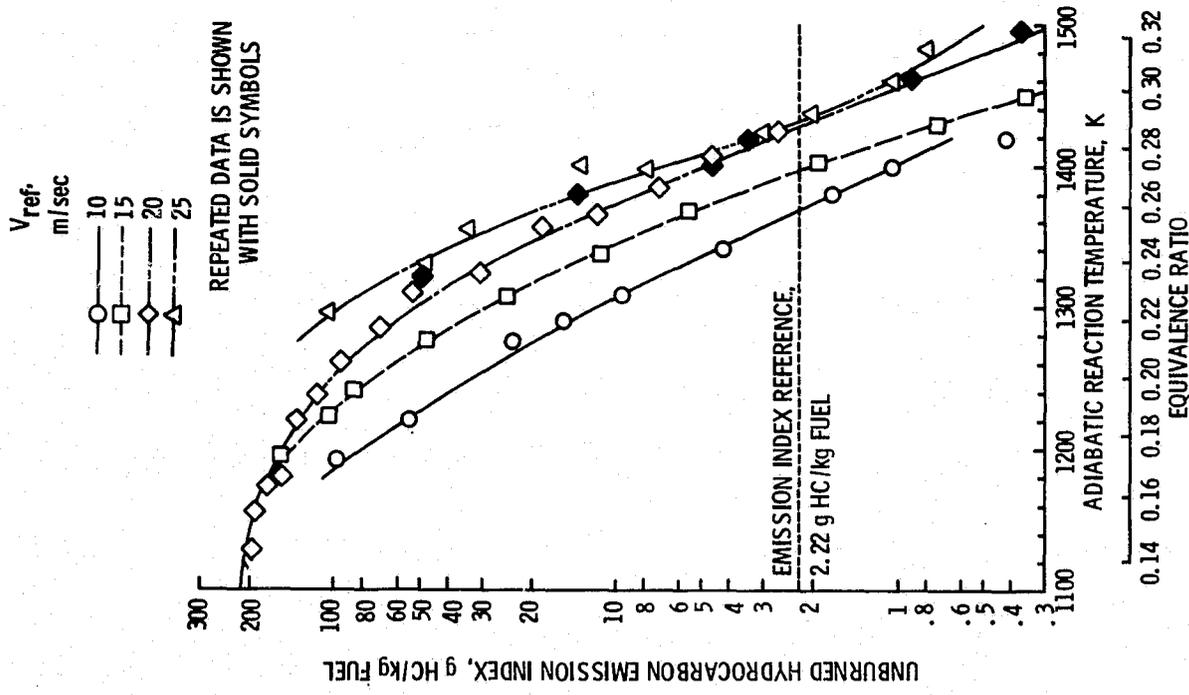
(b) W. R. GRACE DAVEX 524A (D).

Figure 3. - Continued.



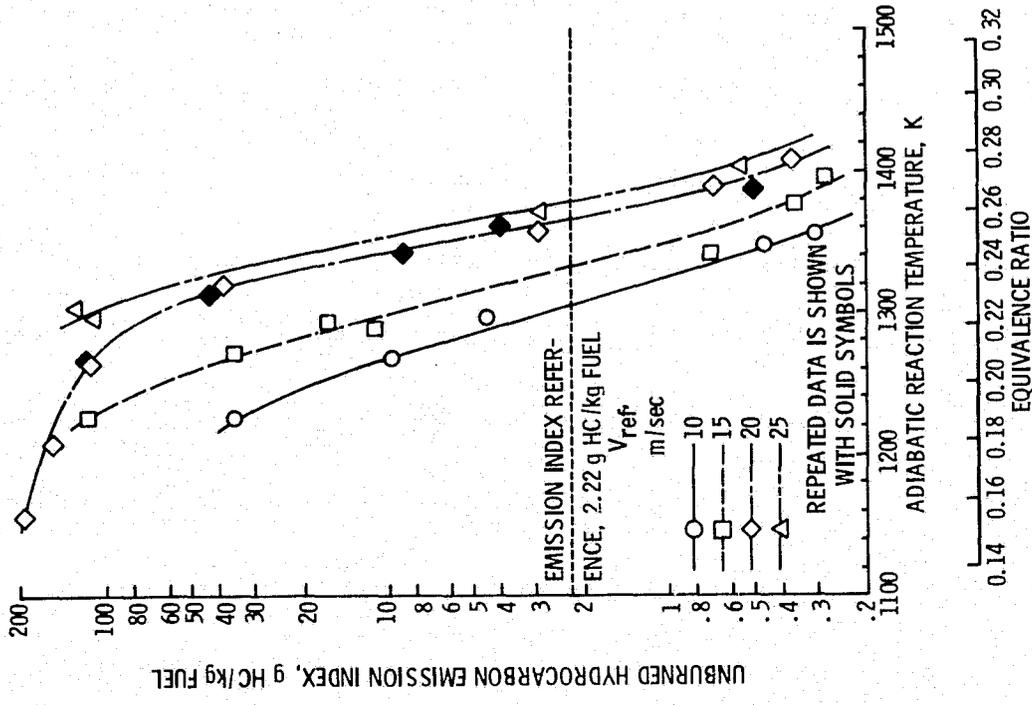
(c) OXY-CATALYST 1.8.

Figure 3. - Concluded.



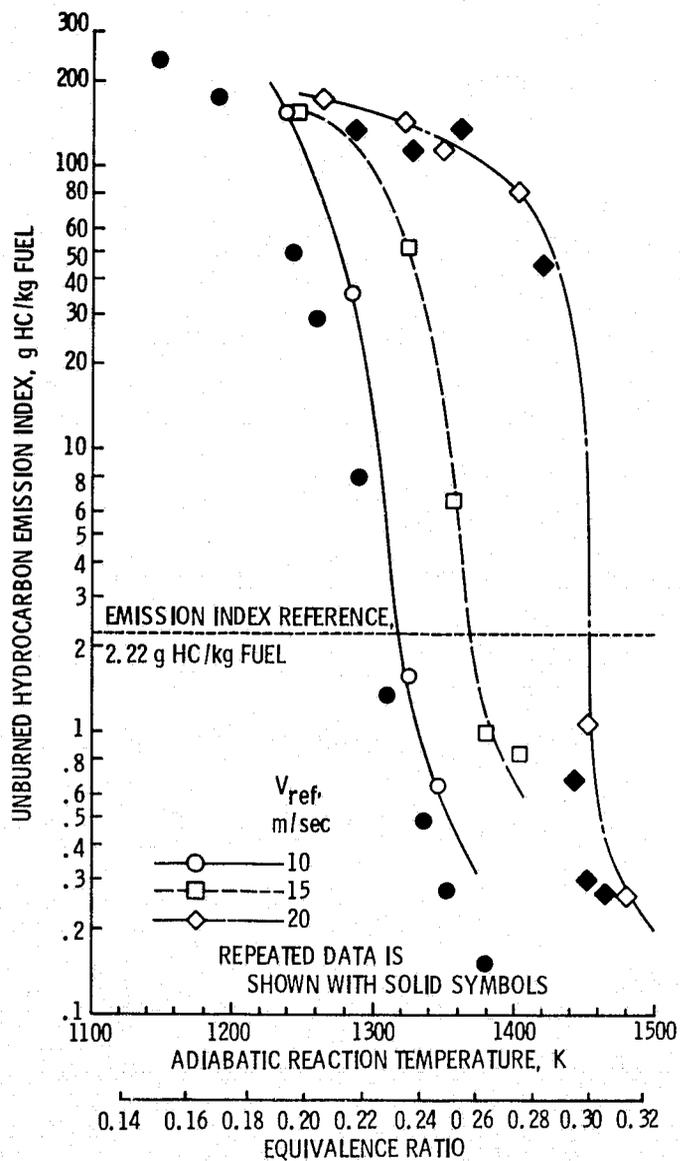
(b) W. R. GRACE DAVEX 524A (D).

Figure 4 - Continued.



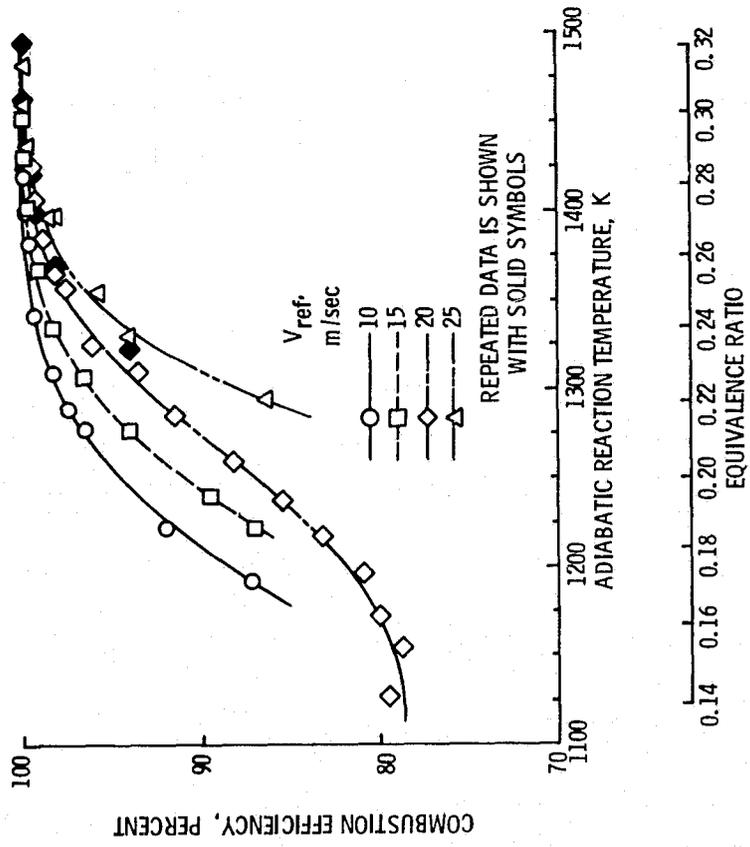
(a) ENGELHARD EVD 1412.

Figure 4. - Unburned hydrocarbons emissions. Inlet mixture temperature, 800 K; inlet pressure, 3×10^5 Pa (3 atm).

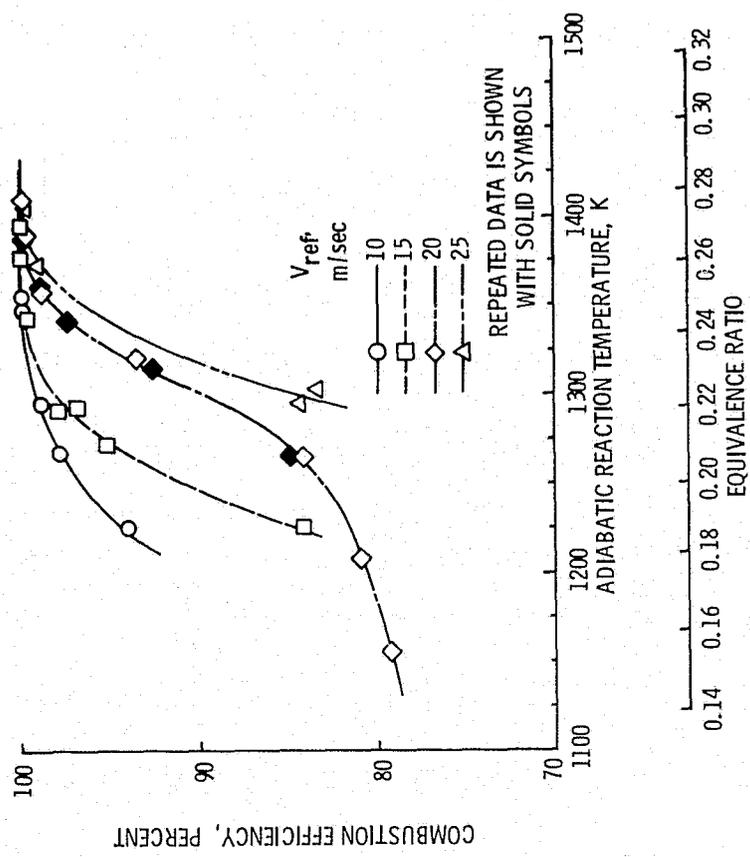


(c) OXY-CATALYST 1.8.

Figure 4. - Concluded.



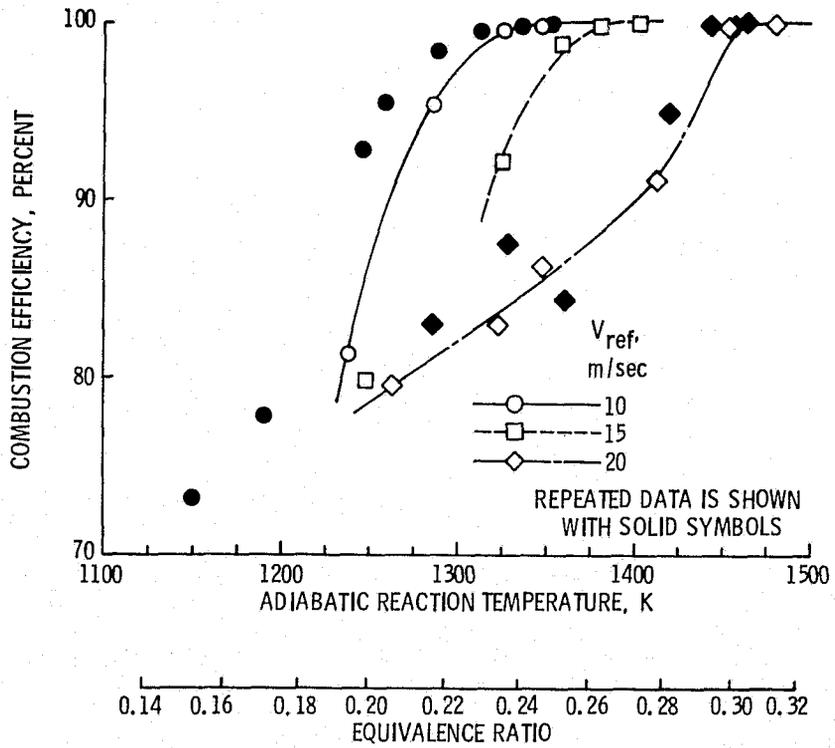
(a) ENGELHARD EVD 1412.



(b) W. R. GRACE DAVEX 524A (D).

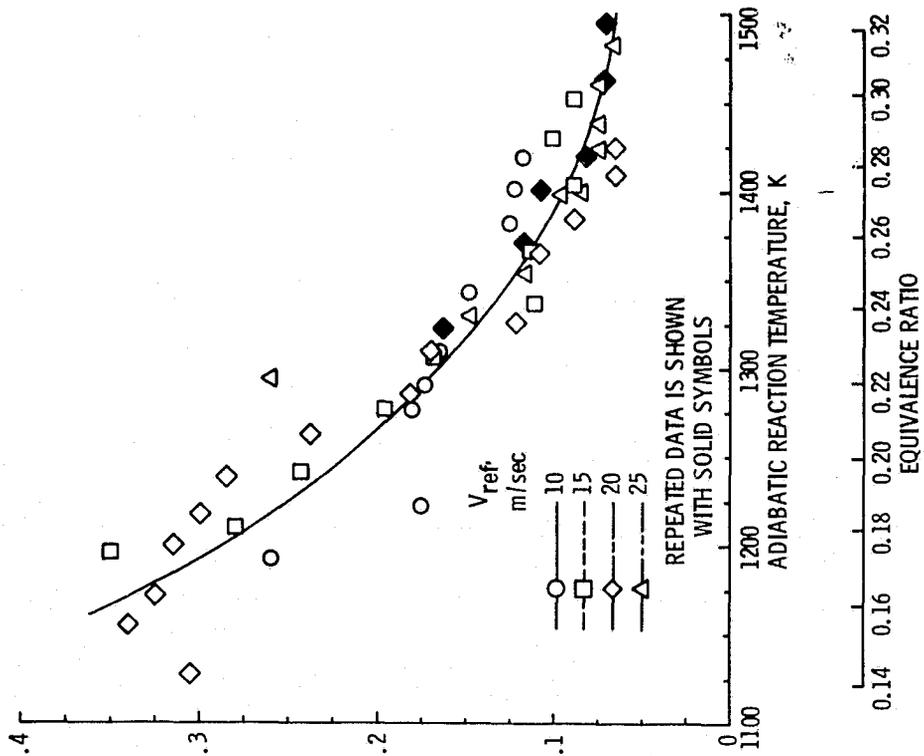
Figure 5. - Combustion efficiency. Inlet mixture temperature, 800 K; inlet pressure, 3×10^5 Pa (3 atm).

Figure 5. - Continued.



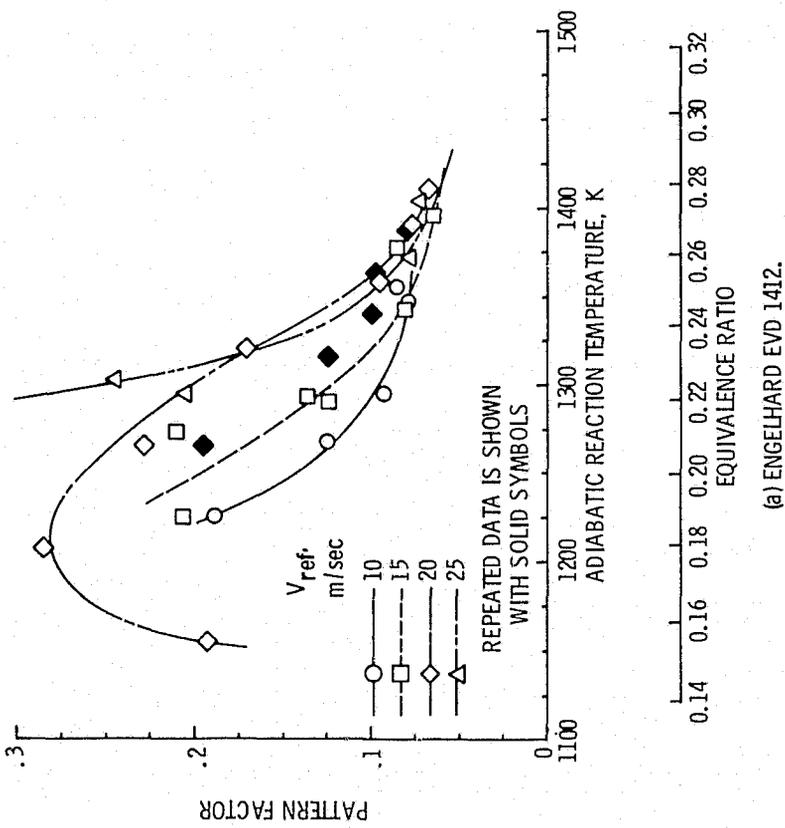
(c) OXY-CATALYST 1.8.

Figure 5. - Concluded.



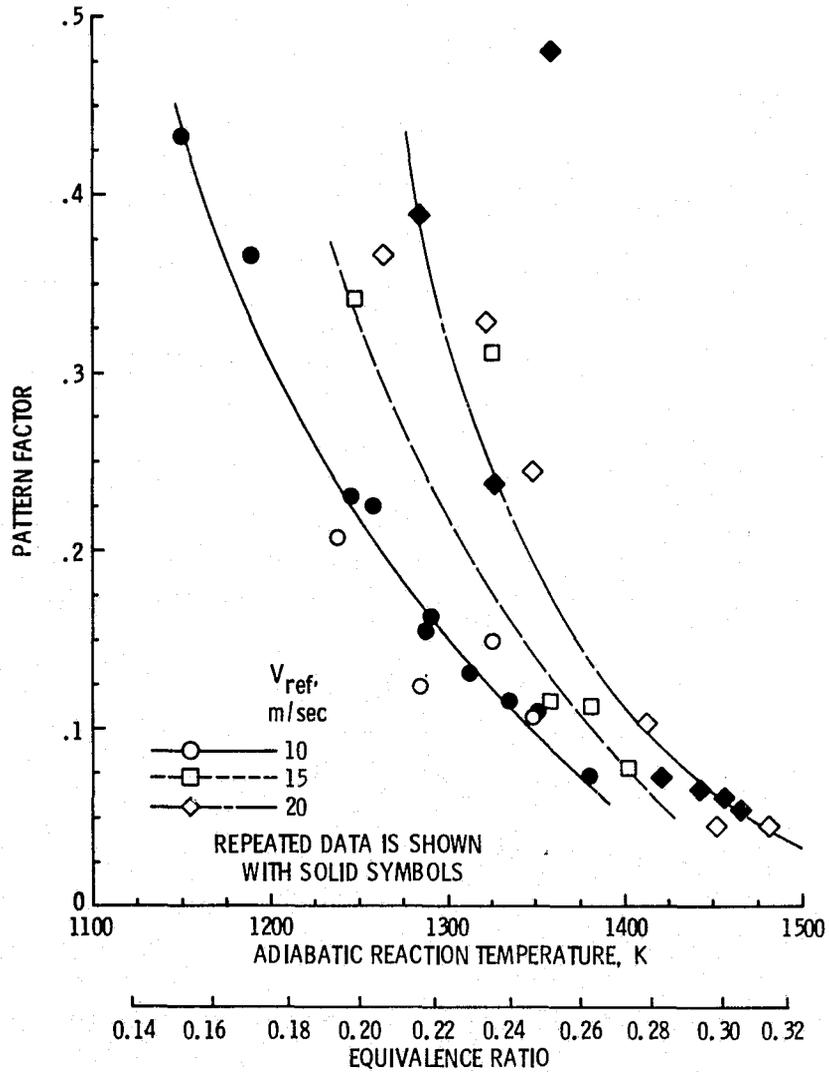
(b) W. R. GRACE DAVEX 524A (D).

Figure 6. - Continued.



(a) ENGELHARD EVD 1412.

Figure 6. - Exit temperature pattern factor. Inlet mixture temperature, 800 K; inlet pressure, 3×10^5 Pa (3 atm).



(c) OXY-CATALYST 1.8.

Figure 6. - Concluded.

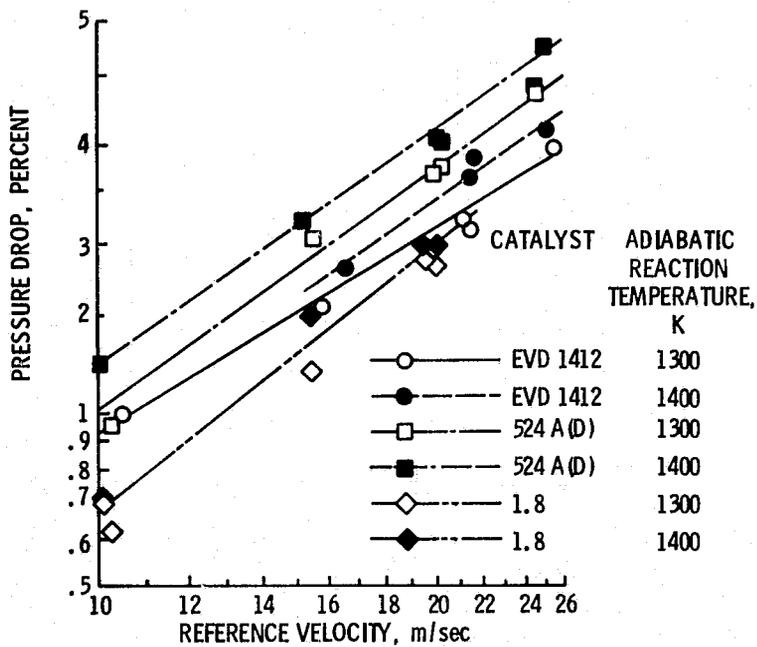


Figure 7. - Reactor pressure drop. Inlet mixture temperature, 800 K; inlet pressure, 3×10^5 Pa (3 atm).