https://ntrs.nasa.gov/search.jsp?R=19760016181 2020-03-22T16:01:00+00:00Z

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.

Produced by the NASA Center for Aerospace Information (CASI)

NASA TECHNICAL MEMORANDUM

NASA TM X-73412

NASA TM X-73412

(NASA-TM-X-73412) PRELIMINARY RESULTS FROM SCREENING TESTS OF COMMERCIAL CATALYSTS WITH POTENTIAL USE IN GAS TURBINE COMBUSTORS. PART 2: COMBUSTION TEST RIG EVALUATION (NASA) 26 p HC $4.00 CSCL 21E G3/07

N76-23269

Unclas 28143

PRELIMINARY RESULTS FROM SCREENING TESTS OF COMMERCIAL CATALYSTS WITH POTENTIAL USE IN GAS TURBINE COMBUSTORS PART II. COMBUSTION TEST RIG EVALUATION

by David N. Anderson
Lewis Research Center
Cleveland, Ohio 44135

TECHNICAL PAPER to be presented at
the Workshop on Catalytic Combustion sponsored
by the U.S. Environmental Protection Agency
Raleigh, North Carolina, May 23-26, 1976

JUN 1976
RECEIVED
NASA STI FACILITY
INPUT BRANCH

ABSTRACT

Several commercial monolithic catalysts manufactured by W. R. Grace and Company and by Oxy-Catalyst, Inc. were tested in a combustion test rig to determine their suitability for use in a gas-turbine combustor primary zone. The catalyst test bed consisted of two to four elements of 12-centimeter diameter by 2.5-centimeter long monolith. Results are presented of the measured combustion efficiency and catalyst bed temperature history for an inlet propane-air mixture temperature of 800 K, a pressure of 3×10^5 newtons per square meter, inlet velocities of 10 to 25 meters per second and equivalence ratios of 0.1 to 0.3. The best catalysts tested gave combustion efficiencies of virtually 100 percent for reaction temperatures ranging from 1325 K at 10 meters per second to 1400 K at 25 meters per second. This performance was only possible with fresh catalysts. The catalysts tested were not specifically developed for use at these conditions and showed some loss in activity after about 3 hours' testing.

E-8774

PRELIMINARY RESULTS FROM SCREENING TESTS OF COMMERCIAL CATALYSTS WITH POTENTIAL USE IN GAS TURBINE COMBUSTORS

PART II. COMBUSTION TEST RIG EVALUATION

by David N. Anderson

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

SUMMARY

Several W. R. Grace and Oxy-Catalyst catalysts were tested in a 12-centimeter diameter combustion test rig with premixed propane and air to determine their suitability for use in a gas turbine combustor primary zone.

The most effective catalysts were platinum-palladium catalysts on substrates with small, square cells (cell density, 45 cells per sq. cm). With a reactor made up of four 12-centimeter diameter by 2.5 centimeter long elements of this catalyst, an adiabatic reaction temperature of 1350 K was sufficient to produce 90 percent combustion efficiency at a reference velocity of 25 meters per second, an inlet mixture temperature of 800 K, and a pressure of 3×10^5 newtons per square meter. A reaction temperature about 150 K higher was required to achieve the same combustion efficiency with a reactor made up of four elements using a substrate having much larger round cells and a cell density of 10 cells per square centimeter. However, the small-cell substrate gave 6 percent pressure drop at these conditions, which was about four times the pressure loss of the large-cell reactor.

Temperatures measured along the length as well as downstream of the reactor showed that significant thermal reactions took place downstream of the last catalyst element when the final catalyst temperature was greater than 1100 K. Interior reactor temperatures were sometimes higher than the adiabatic reaction temperature.

A diffusion limit to the temperature rise was observed in both types of substrate; however, it occurred later in the small-cell reactor. The large-cell substrate showed evidence of catalytically supported thermal reactions in the last two elements.

Nitrogen oxides emissions were below 0.5 parts per million for reaction temperatures as high as 1600 K while combustion efficiencies of the small-cell reactor reached essentially 100 percent for reference velocities between 10 and 20 meters per second and reaction temperatures near 1400 K.

E-8744

These catalysts were not specifically developed for the test conditions and showed a loss of catalytic activity over a period of about 3 hours' testing. Previously reported tests showed that an Engelhard reactor, which had been developed for these conditions, required comparable or higher temperatures for the same performance but lasted nearly 20 hours before degraded activity was observed.

INTRODUCTION

This report describes tests conducted on selected catalysts in a 12-centimeter diameter combustion test rig to determine their suitability for use in the primary zone of a gas turbine combustor.

A number of feasibility tests of catalytic combustion have been reported (refs. 1 to 4) in response to the need for low-emission combustors for gas turbine engines. Although these tests demonstrated good combustion efficiency and extremely low nitrogen oxides emissions at gas turbine operating conditions, the acceptable operating range was also shown to be very narrow. Combustor exit temperatures above 1400 K were necessary to insure good performance, while temperatures above 1600 K were avoided to prevent damage to the catalyst. In addition to the need to extend this operating range for greater combustor flexibility, there was also an interest to determine what commercial catalysts might provide catalytic combustion capability.

Preliminary furnace testing of catalysts (ref. 5) showed that, of the commercial samples tested, Engelhard, W. R. Grace, and Oxy-Catalyst monoliths demonstrated the greatest activity at low temperatures. For this reason, they were selected for further testing in a 12-centimeter diameter combustion test duct. Results of the tests of the Grace and Oxy-Catalyst catalysts are reported here for an inlet propane-air mixture temperature of 800 K, a pressure of 3×10^5 newtons per square meter, and a range of reference velocities from 10 to 25 meters per second. The reference velocity is the velocity determined from the mass flow rate, reactor inlet temperature and pressure, and maximum cross sectional area of the reactor. In this experiment the reactor cross-sectional area used in determining reference velocity was 114.9 square centimeters.

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 back-pressure valve was used to control the test-section pressure.

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 220 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. Both air and fuel flow rates 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 no more than four elements were tested at one time in the studies reported here. Measurements of both temperature profiles and temperature history 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, and 7 and 8, as shown in figure 1(b). For most tests, all four elements were the same, although some tests were made with combinations of different catalyst elements; in one set of tests, only two elements were used.

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. It was in a plane 14 centimeters downstream of the last test-section array. The gas-sampling probe was located 1.3 centimeters downstream of the thermocouple array. It 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. 3) 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. An element of Grace Davex 512B catalyst can be seen just under the fourth array thermocouples.

The catalysts tested were all manufactured by either W. R. Grace and Company, or Oxy-Catalyst, Incorporated. Each catalyst is described in Table II. Note that all of the W. R. Grace catalysts are on a Grace Poramic 290 cordierite substrate, while the Oxy-Catalyst catalysts used a General Refractories Versagrid 3.2 millimeter mullite substrate. The table shows that the Poramic has more than four times the cell density of the Versagrid. The difference in the size and shape of the cells in these two substrates can be seen in figure 2. The elements shown are identical to the elements used in these tests except that the illustrated specimens were not coated with catalyst. Each element was 12 centimeters in diameter and 2.5 centimeters long.

RESULTS AND DISCUSSION

Temperature History

The temperatures measured along the length of each set of catalyst elements is shown in figure 3. The temperatures reported are the averages of the eight thermocouples in each array. Although the inlet mixture temperature was 800 K for all tests, the temperatures recorded at the inlet face of the first catalyst element were always somewhat higher than this as a result of radiation from the hot catalyst elements.

Figure 3(a) gives data taken with four elements of Grace Davex 512B catalyst. Temperatures measured with a set of Grace Davex 512A had characteristics identical to those of the 512B. For reference, the temperatures which would be achieved after complete, adiabatic combustion at the equivalence ratios tested are shown next to each measured temperature history. Although heat loss from the walls can be expected in this experiment, the adiabatic reaction temperature provides a guide of how completely the reactions have proceeded.

The reaction temperatures were computed with an equilibrium computer program (ref. 6) using an equivalence ratio determined by the exhaust-gas analysis. Fuel-flow measurements were subject to transducer drift and were felt to be less reliable than gas analysis measurements; however, equivalence ratios determined from fuel and airflow measurements were generally lower than those from exhaust-gas analysis by less than 20 percent. The equivalence ratios and adiabatic reaction temperatures quoted throughout this report were determined from the exhaust-gas analysis.

The results in figure 3(a) are given for two nominal equivalence ratios. At the 0.19 equivalence ratio, temperatures were nearly identical for both 10 and 15 meters per second reference velocity. However, at 15 meters per second the adiabatic reaction temperature was higher than at 10 meters per second as a result of a slightly higher equivalence ratio.

When the nominal equivalence ratio was increased to 0.26, the results showed the expected effect of reference velocity, with higher catalyst temperatures resulting from lower velocities. Final combustion temperatures measured 14 centimeters downstream of the last catalyst element were near the adiabatic reaction temperatures in each case.

For all conditions, the largest part of the catalyst temperature rise occurred about equally across the first two elements. Additional elements contributed much less. Although the dwell time in the third element was decreased as a result of the higher temperature compared with elements 1 and 2, it was only on the order of 10 to 15 percent less than the dwell time through the second element and therefore does not fully explain the reduced conversion. Apparently, diffusion of fuel and oxygen molecules to the surface could not take place rapidly enough within the third and fourth elements to provide the surface concentration of reactants required to match the high rates of reaction typical of the first two elements.

The indicated drop in temperature across the last element was probably a result of thermocouple radiation errors rather than a cooling effect. The catalyst exit-plane thermocouples radiated to the cooled instrumentation section walls; therefore, they read lower values than those between elements 3 and 4 which radiated to, or received radiation from, the hot substrate surface.

Downstream of the last element the temperatures continued to increase as a result of thermal reactions. This effect was observed whenever the catalyst exit temperature was about 1100 K or greater. Although this temperature is below the reaction temperature at which a propane flame blows out, intermediate species such as hydrogen and carbon monoxide may exist in large concentrations and such species oxidize readily at 1100 K. Free radical concentration may also be high and help to sustain thermal combustion.

The Grace Davex 516 catalyst is a base metal oxide. The results given in figure 3(b) show somewhat less activity across the second element compared with the first. Temperatures recorded for an equivalence ratio of 0.18 showed a lack of thermal activity. This result was typical of all the tests when final catalyst temperatures were less than 1100 K.

Grace Davex 517 (fig. 3(c)) is a palladium catalyst and the temperature history had characteristics similar to those of the Davex 512A and 512B catalysts. The temperatures recorded after elements two and three at 10 meters per second with an equivalence ratio of 0.28 were higher than the adiabatic reaction temperature. The temperatures were measured in the gas stream but were subjected to radiation from the catalyst substrate. Due to the fact that reactions take place primarily at the surface, the substrate is at a higher temperature than the gas stream. Because the substrate can reach temperatures higher than the adiabatic reaction temperature (ref 7), the thermocouple readings can also be higher than equilibrium.

The Oxy-Catalyst test elements, as noted in the APPARATUS AND PROCEDURE section, had a much larger cell than did the Grace elements. The effect of this large cell can be seen in figures 3(d) and (e). Diffusion limited the temperature rise across the second element in the same way it did across the third Grace elements.

However, the temperature rise across the third, and often the fourth, Oxy-Catalyst element was higher than that across the second. This result may be due to the catalytically supported thermal oxidation described in references 8 and 9. Appreciable thermal reaction was again observed downstream of the catalyst when the temperature after the last element was higher than about 1100 K, and, as was noted earlier for the Grace catalysts, temperatures higher than the adiabatic reaction temperature were recorded between catalyst elements. An example of this latter phenomenon is the 10 meters per second, 0.31 equivalence ratio condition in figure 3(d).

The only difference between the two catalysts supplied by Oxy-Catalyst was that the wash coat applied to the substrate was stabilized for catalyst 5, but was not for catalyst 4. The data demonstrated essentially the same characteristics for both catalysts, although the temperatures throughout catalyst 5 were somewhat lower than those of catalyst 4 when operated at the same test conditions.

To see if the large temperature rises across elements 3 and 4 which were observed with the Oxy-Catalyst catalysts would also occur when these large-cell elements were preceded by the small-cell Grace elements, two elements of Davex 512B followed by two of Oxy-Catalyst 4 were tested. The large third and fourth element temperature rise was not observed, as seen in figure 3(f). One explanation might be that because of the large temperature rise across the first two Grace elements, the Oxy-Catalyst elements were not exposed to as high a concentration of unoxidized species

as when they were preceded by other Oxy-Catalyst elements.

The Grace Davex 519 rare-earth-oxide catalyst was found to require a high temperature for appreciable activity in the furnace screening tests of reference 5. To determine what contribution such a catalyst might make in the high-temperature portion of a catalytic reactor, tests were made with two elements of Grace Davex 512B followed by two of Davex 519. Figure 3(g) shows that the rare-earth oxide had virtually no effect on the temperature rise. Some cooling may in fact have occurred over the first of the rare-earth-oxide elements.

Because of the significance of thermal reaction and the apparently small contribution of the last two elements of various Grace Davex catalysts, a final series of tests was made using only two elements of Grace Davex 512B. They were placed in the usual positions of the first two elements of the four-element reactors. The results of these tests showed (fig. 3(h)) that two elements provided sufficient oxidation to initiate thermal reaction, providing the equivalence ratio was high enough. In the case of the 10-meters-per-second condition, nearly complete combustion was achieved 5.5 centimeters downstream of the second element, but cooling through the water-cooled exit instrumentation section reduced the final temperature by 35 K from the maximum value measured. Although this cooling effect would have been present in all the tests made, it was often masked by the temperature rise which resulted from continuing reactions.

Temperature Uniformity

The use of eight thermocouples at each measuring plane along the catalyst test section provided information on variations in temperature at each cross section. Typical results are shown in figure 4. Temperatures in each of the four quadrants are given, and values measured near the wall are distinguished from interior temperatures. The exact position of the thermocouples in each plane is shown in figure 1(b). Temperatures measured nearest the wall and nearest the duct centerline with the downstream 12-thermocouple rake (see fig. 1(b)) are also included in figure 4.

Figures 4(a) and (b) show results typical of measurements made with four elements of the Grace Davex catalysts. Figure 4(a) reports tests with a nominal equivalence ratio of 0.19, which gave a combustion efficiency of 90 percent. The temperatures show that wall-cooling effects were significant, with wall temperatures averaging about 200 K less than interior temperatures at the catalyst exit plane (11.4 cm downstream of the leading thermocouple). This result suggests that performance would have been much better if the wall had been insulated.

Temperature variations measured near the center of the bed at the exit plane were on the order of 10 percent of the temperature rise from the bed inlet to exit. This result suggests uniformity in both fuel-air mixture and catalyst properties.

Downstream temperatures (25.5 cm from the leading thermocouple) showed evidence of mixing: some interior temperatures were lower than wall values.

Figure 4(b) gives the results for the same catalyst but at a higher equivalence ratio and, therefore, combustion efficiency. Again, a wide spread in temperatures existed due to cooling effects at the duct wall. Interior temperatures at the catalyst exit plane now varied by less than 4 percent of the bed temperature rise.

Typical results of the measurements using four Oxy-Catalyst elements are presented in figure 4(c). The characteristics were similar to those found with Grace Davex catalysts; i.e., cold walls and hot interiors. Between the third and the fourth catalyst element (8.5-cm measuring station) interior temperatures were as much as 90 K higher than the adiabatic reaction temperature with a quadrant-to-quadrant variation of about 12 percent of the reaction temperature rise. The coldest wall temperature was nearly 400 K less than the highest interior temperature. The resulting thermal stress cracked the mullite substrate in the third and fourth elements.

Exhaust Emissions

Emissions of unburned hydrocarbons, carbon monoxide (CO) and total nitrogen oxides, NO_X ($NO + NO_2$) were measured. NO_X emissions were about 0.5 parts per million or less for all the catalysts tested even at the highest reaction temperatures (1600 K).

The emissions of unburned hydrocarbons and CO are related to the combustion efficiency. For the reaction temperatures included in this study, both total unburned hydrocarbons and CO will be essentially zero if reactions have proceeded completely to equilibrium. Therefore, any measured emissions of these species indicates that potential exists for further reaction. One percent combustion inefficiency can result from emissions of either 10 grams HC per kilogram fuel burned or 50 grams CO per kilogram fuel, or, usually, some combination of both pollutants. For the test results presented here the ratio of the CO emission index (g CO/kg fuel) to that of unburned hydrocarbons was generally about 5 when combustion efficiency was greater than 99.5 percent. When efficiency was on the order of 80 percent or less, unreacted fuel passed through the catalyst and CO emissions were consequently less than those of the unburned hydrocarbons.

Combustion Efficiency

The probe with which the exhaust gases were sampled to determine combustion efficiency was located 14.1 centimeters downstream of the last catalyst element; therefore, the reported efficiencies are those which

resulted after thermal oxidation had taken place. Efficiencies based on thermocouple measurements at the same measuring plane were about the same as the exhaust-gas-analysis values.

Figure 5 presents the combustion efficiency results for each of the catalysts tested. The abscissa is the temperature which would be achieved for complete combustion of the fuel with adiabatic conditions.

For each of the catalysts tested the efficiency increased from 80 to 95 percent over a relatively small increment of adiabatic exit temperature. Combustion efficiency increased as the adiabatic reaction temperature (that is, equivalence ratio) increased, or as the reference velocity decreased. In a few cases (for example, Davex 516, fig. 5(c), and Oxy-Catalyst 5, fig. 5(f)) the expected velocity effect was reversed, and a decrease in velocity resulted in a decrease in combustion efficiency. This effect was the result of a loss of catalytic activity, and in each case the higher velocity condition was the first tested. Figure 5(f) shows how later tests at 20 meters per second gave poorer performance than the original test points at that condition. A systematic study of the loss of activity with these catalysts was not made; however, some loss of activity was observed for all the catalysts tested after about 3 hours' testing.

Temperature Required to Achieve 90 Percent Combustion Efficiency

For comparative purposes it is helpful to select an arbitrary combustion efficiency, say 90 percent, and determine the adiabatic reaction temperature from figure 5 which is required to give this efficiency. This temperature could be considered a minimum operating temperature for good performance.

The temperature at which 90 percent combustion efficiency occurs is plotted in figure 6 as a function of reference velocity for each of the catalysts tested. Also shown in figure 6, for comparison, is the curve which resulted from earlier tests of a reactor with Engelhard DXA 111 catalyst reported in reference 3. The measuring station for those tests was 27 centimeters downstream from the inlet face of the catalyst, compared with 25.5 centimeters for the tests reported here.

The Grace Davex 512A and 512B catalysts produced a 90 percent combustion efficiency at the lowest temperature of any of the catalysts tested. The two gave nearly identical performance.

Higher temperatures were required for good performance with the Davex 516 catalyst than with either the 512A or 512B. This result was predicted by the furnace tests of reference 5. Contrary to those test results, however, the Davex 517 required higher temperatures than the 512A, 512B, or 516 catalysts.

Both of the Oxy-Catalyst units required high temperatures relative to the Grace catalysts. However, the results were not significantly different from those obtained with the previously tested Engelhard reactor (ref. 3). The large cell structure of the Oxy-Catalyst elements was seen in the discussion of figure 3 to be responsible for a diffusion limit to the reaction rate.

The hybrid reactor using both Grace Davex 512B and Oxy-Catalyst 4 elements gave a performance approximately midway between the curves for those two catalysts by themselves. The 512B/519 hybrid was slightly better than the 512B/Oxy-Catalyst 4.

Finally, the use of only two elements of Davex 512B gave poorer performance than the use of 4 elements of 512B. Although the temperature history data of figure 3 indicated little additional reaction following the second catalyst element, this result of figure 6 shows that the final two elements did have a significant contribution in continuing the reactions. The use of the relatively inactive Grace Davex 519 or of the large-cell Oxy-Catalyst 4 for the final two elements also gave better performance than was obtained by relying on thermal reaction alone. However, the improved performance with four catalyst elements also has to be evaluated with respect to pressure-drop considerations.

Although all of the catalysts of this program performed well relative to the Engelhard DXA 111 catalysts tested earlier, the catalysts in this program showed some loss of activity after only about 3 hours of testing, while the Engelhard catalyst had about 20 hours of operation before any loss of activity was observed (ref. 3). A complete evaluation of the active lifetimes of the various catalysts was outside the scope of this study, but will be a necessary part of any final catalyst evaluation.

Pressure Drop

The pressure drop measured across the catalyst elements is shown in figure 7 as a function of the reference velocity. As can be expected, the small cell size of the Grace substrate results in relatively high pressure drop compared with the large-cell substrate used for the Oxy-Catalyst elements. However, even at 25 meters per second, the Grace pressure drop is only about 6 percent. The Oxy-Catalyst elements produced only about one-fourth the pressure drop of the Grace elements, while the pressure drop of the Engelhard reactor tested in reference 3 fell between that of the Grace and Oxy-Catalyst reactors. The use of two elements of Grace catalyst alone gave only slightly less pressure drop than when two elements of Oxy-Catalyst were added to two of Grace.

CONCLUDING REMARKS

The data presented in this report were part of a preliminary evaluation of commercial catalysts to determine which might be suitable for catalytic combustion of hydrocarbon fuels in a gas turbine engine. None of the catalysts tested were specifically developed for this application; therefore, the ability of all the catalysts tested to perform well over a small range of adiabatic reaction temperatures suggests that the catalytic combustor concept has a great deal of potential.

Two substrate compositions were included in these tests. The mullite (on which the Oxy-Catalyst catalyst was coated) has a higher use-temperature than the cordierite (Grace) but was found to be more susceptible to thermal shock and cracking. Catalytic combustion will probably require other substrate materials; silicon carbide, for example, has a higher use temperature than mullite and is more resistant to thermal cracking. Because the need for high-temperature capability has not existed for automotive exhaust catalysts, development of high-temperature substrates has not been necessary. As a result, production capabilities and cost considerations currently favor the use of mullite or cordierite rather than silicon carbide or other high-temperature monolith. The possibility of super-equilibrium temperatures in the substrate will need to be considered in establishing the required use-temperature.

Although superior performance was demonstrated with a substrate having a small square cell structure, possible effects of cell shape were not studied and the best cell size was not determined. An optimum design for a catalytic reactor may require that several elements be used having different cell shape and size to avoid diffusion limitations and to take advantage of catalytically supported thermal reactions. Cells will have to be as large as possible, consistent with good performance, to keep pressure drop low.

Other areas of importance to reactor development which require investigation include the determination of the balance between catalytic and thermal reaction which gives optimum performance, and the establishment of activity lifetimes for various candidate catalysts. Continued catalyst development should provide both improved catalyst durability and a greater range of good combustion efficiency. Further evaluations will be made as these improved catalysts become available.

REFERENCES

1. Blazowski, William S.; and Bresower, Gerald E.: Preliminary Study of the Catalytic Combustor Concept as Applied to Aircraft Gas Turbines. AFAPL-TR-74-32, Air Force Aero Propulsion Lab. (AD-781762), 1974.

2. Wampler, F. B.; Clark, D. W.; and Gaines, F. A.: Catalytic Combustion of C_3H_8 on Pt Coated Monolith. Paper No. 74-36, Western States Section of the Combustion Institute, 1974.

3. Anderson, David N.; Tacina, Robert R.; and Mroz, Thaddeus S.: Performance of a Catalytic Reactor at Simulated Gas Turbine Combustor Operating Conditions. NASA TM X-71747, 1975.

4. DeCorso, S. M.; et al.: Catalysts for Gas Turbine Combustors-Experimental Test Results. ASME Paper 76-GT-4, Mar. 1976.

5. Anderson, David 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.

6. Gordon, Sanford; and McBride, Bonnie J.: Computer Program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance, Incident and Reflected Shocks, and Chapman-Jouguet Detonations. NASA SP-273, 1971.

7. Hegedus, L. Louis: Temperature Excursions in Catalytic Monoliths. Am. Inst. Chem. Engrs. J., vol. 21, no. 5, Sept. 1975, pp. 849-853.

8. Pfefferle, W. C.; et al.: Catathermal Combustion: A New Process for Low-Emissions Fuel Conversion. ASME Paper 75-WA/Fu-1, Nov.-Dec. 1975.

9. Carrubba, R. V.; Chang, M.; Pfefferle, W. C.; and Polinski, L. M.: Catalytically-Supported Thermal Combustion for Emission Control. Paper presented at the Electric Power Research Institute NO_x Control Technology Seminar, San Francisco, California, Feb. 6, 1976.

TABLE I. - PROPERTIES OF COMMERCIAL GRADE

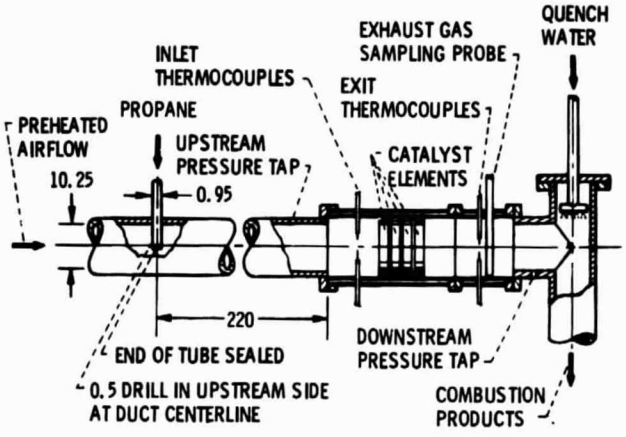
PROPANE USED IN THIS STUDY

Analysis:	Propane (C_3H_8)	90.800 percent by volume
	Methane (CH_4)	0.128
	C_2-hydrocarbons	0.035
	C_4- and C_5-hydrocarbons	2.708
	Carbon dioxide (CO_2)	2.792
	Nitrogen (N_2)	2.642
	Oxygen (O_2)	0.005

Lower heating value: 44,100 J/g

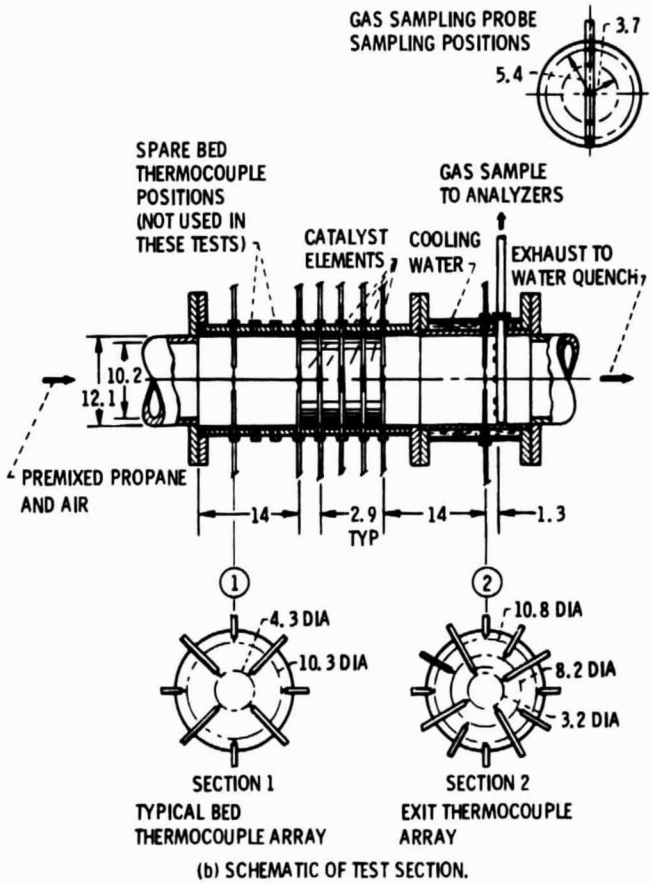
TABLE II. - TEST CATALYSTS

Manufacturer	Designation	Catalyst	Loading	Wash coat	Substrate mfg.	Substrate comp.	Cell density ($cells/cm^2$)	Cell shape
W. R. Grace & Co.	Davex 512A	Pt	NA	NA	W. R. Grace & Co. Poramic 290	Cordierite	45	Square
	512B	Pt	NA	↓	↓	↓	↓	↓
	516	CoO	NA					
	517	Pd	0.44 %					
	519	CeO_2	NA					
Oxy-Catalyst	4	Pd/Pt: 2/1	2 g/1	Unstabilized	General Refractories Versagrid	Mullite	10	Round
	5	Pd/Pt: 2/1	1.8 g/1	Stabilized		Mullite	10	Round



(a) SCHEMATIC OF TEST DUCT. (DIMENSIONS ARE IN CM.)
Figure 1. - Experimental rig.

E-8744



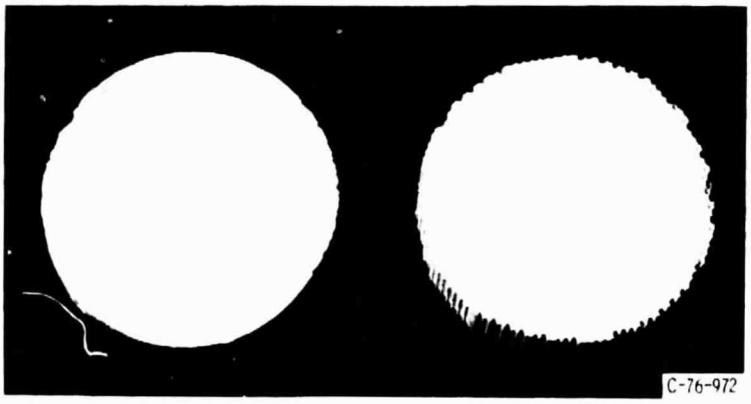
(b) SCHEMATIC OF TEST SECTION.
Figure 1. - Continued.

ORIGINAL PAGE IS
OF POOR QUALITY

C-76-458

(C) INLET VIEW OF TEST SECTION.

Figure 1. - Test rig.



C-76-972

W. R. Grace
PORAMIC 290
CORDIERITE

GENERAL REFRACTORIES
VERSAGRID 3.2 MM ROUND
CELL MULLITE

Figure 2. - Substrate configurations.

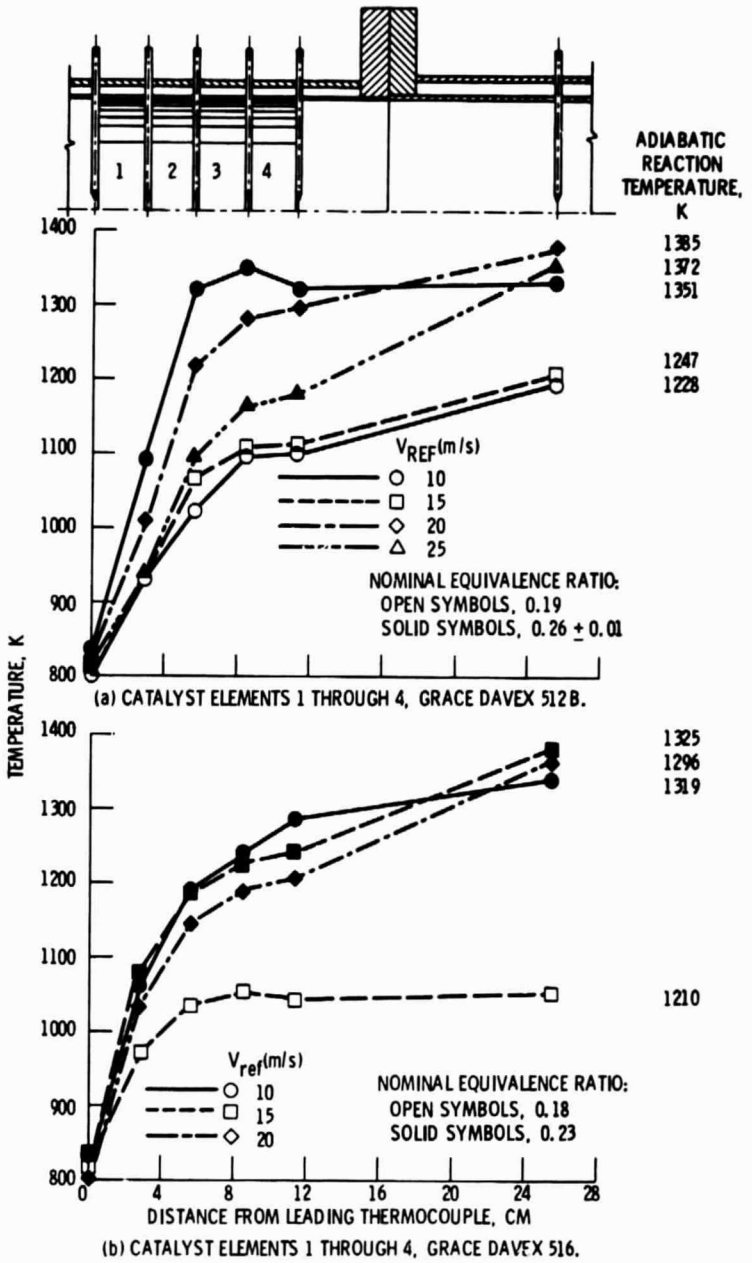
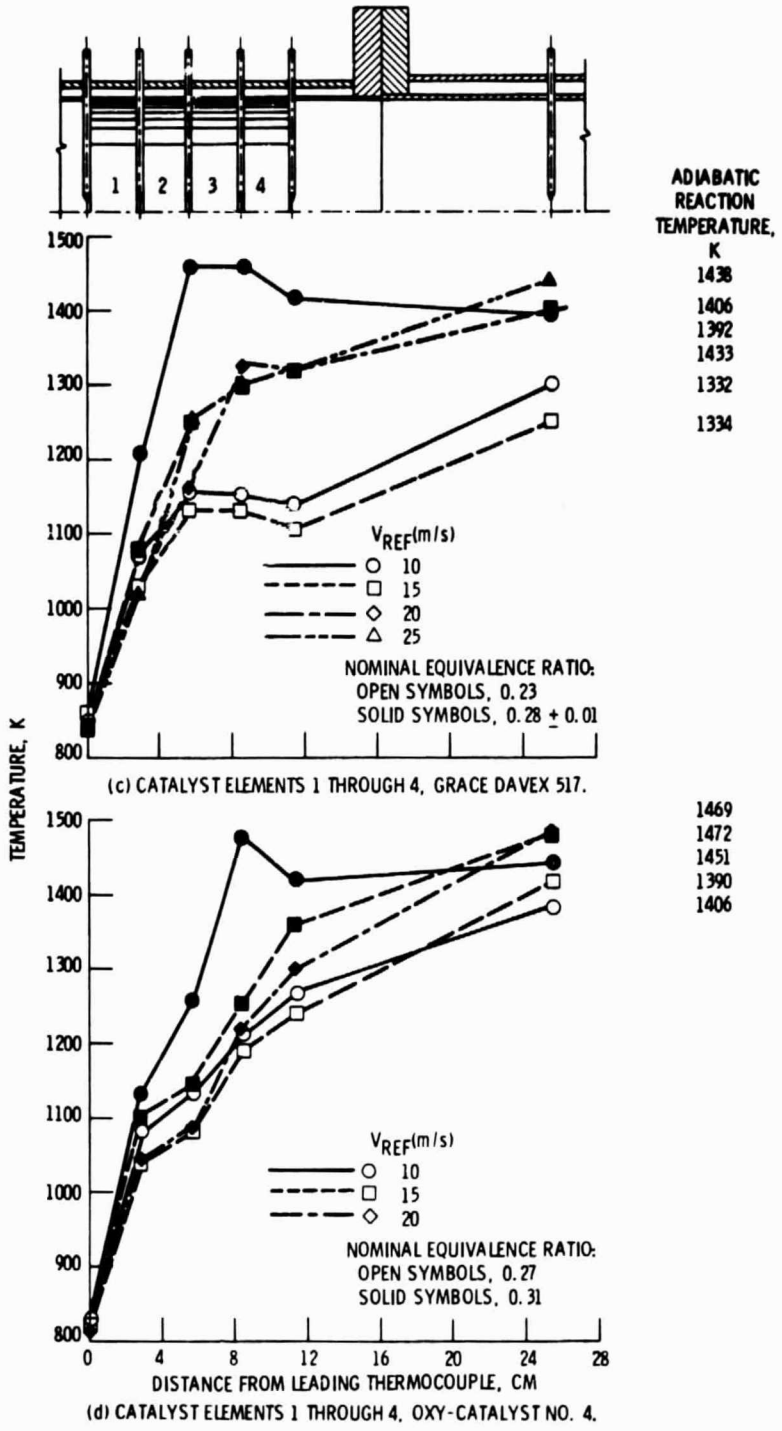


Figure 3. - Temperature history, inlet mixture temperature, 800 K; inlet pressure, 3×10^5 newtons per square meter.

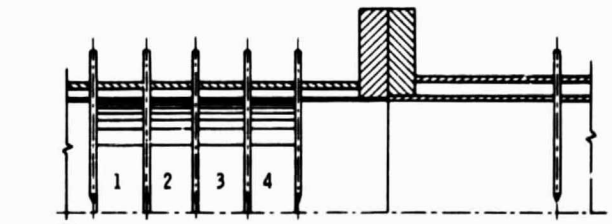
ORIGINAL PAGE IS
OF POOR QUALITY



(c) CATALYST ELEMENTS 1 THROUGH 4, GRACE DAVEX 517.

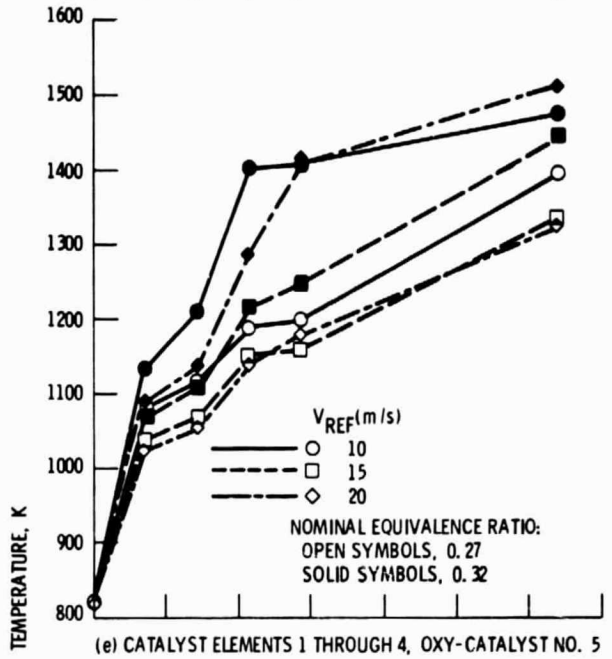
(d) CATALYST ELEMENTS 1 THROUGH 4, OXY-CATALYST NO. 4.

Figure 3. - Continued.



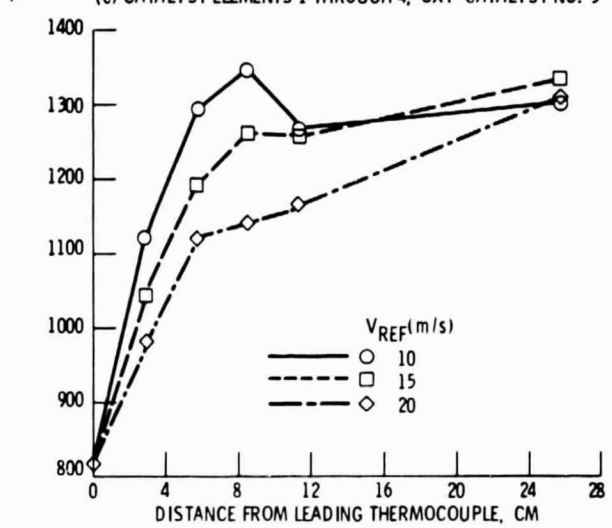
ADIABATIC REACTION TEMPERATURE, K

1484
1483
1483
1406
1399
1400



(e) CATALYST ELEMENTS 1 THROUGH 4, OXY-CATALYST NO. 5

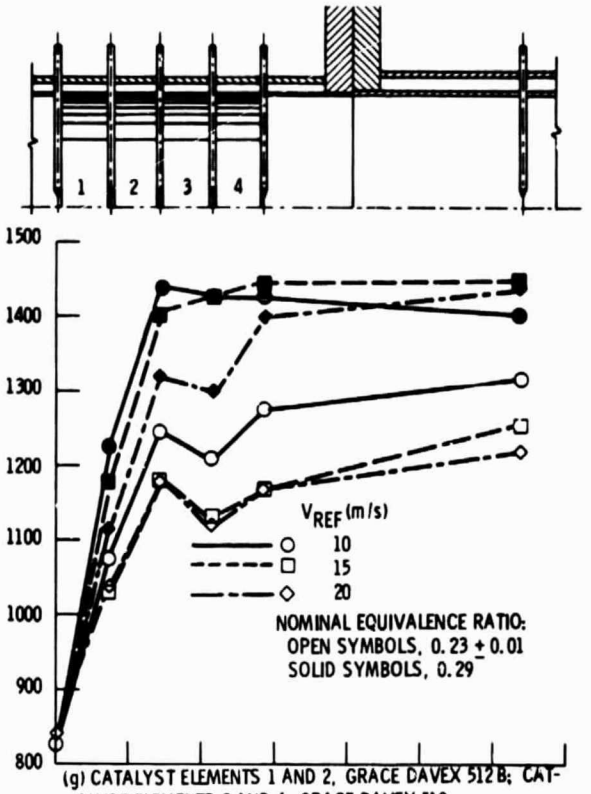
1374
1359
1366



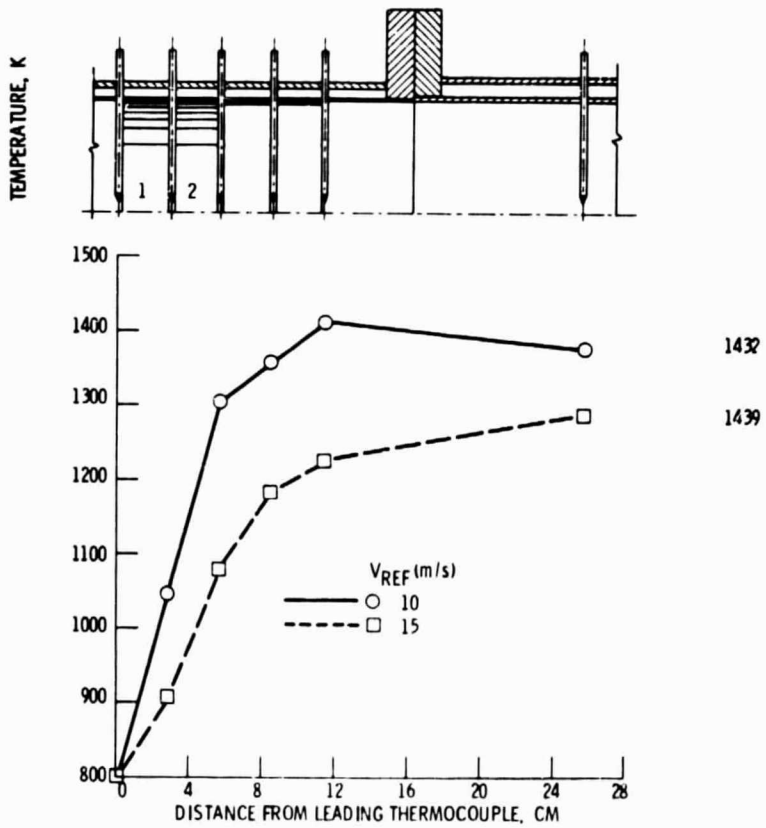
(f) CATALYST ELEMENTS 1 AND 2, GRACE DAVEX 512B; CATALYST ELEMENTS 3 AND 4, OXY-CATALYST NO. 4; NOMINAL EQUIVALENCE RATIO, 0.25.

Figure 3. - Continued.

ORIGINAL PAGE IS
OF POOR QUALITY



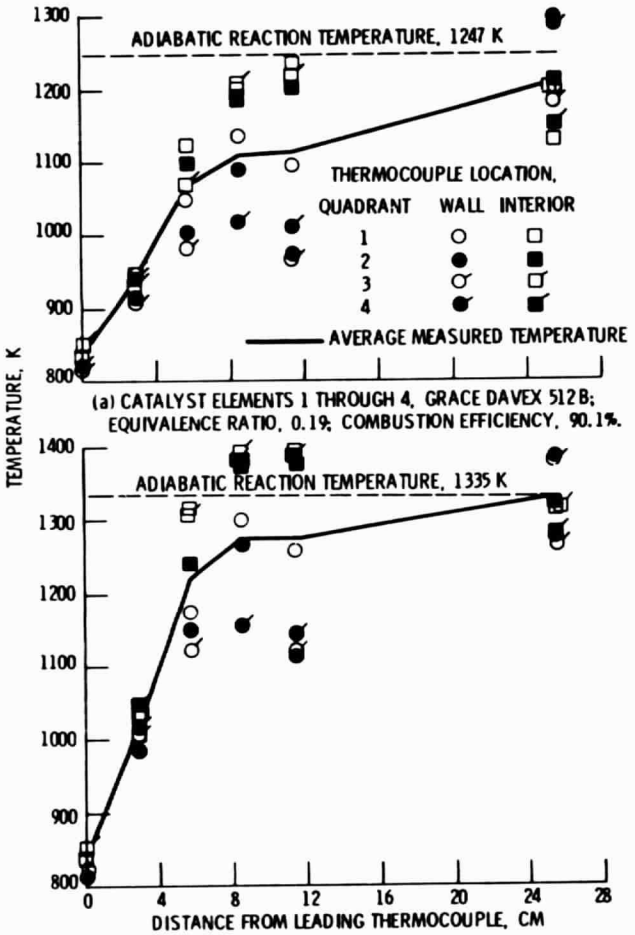
(g) CATALYST ELEMENTS 1 AND 2, GRACE DAVEX 512B; CATALYST ELEMENTS 3 AND 4, GRACE DAVEX 519.



(h) CATALYST ELEMENTS 1 AND 2, GRACE DAVEX 512B; NOMINAL EQUIVALENCE RATIO, 0.30.

Figure 3. - Concluded.

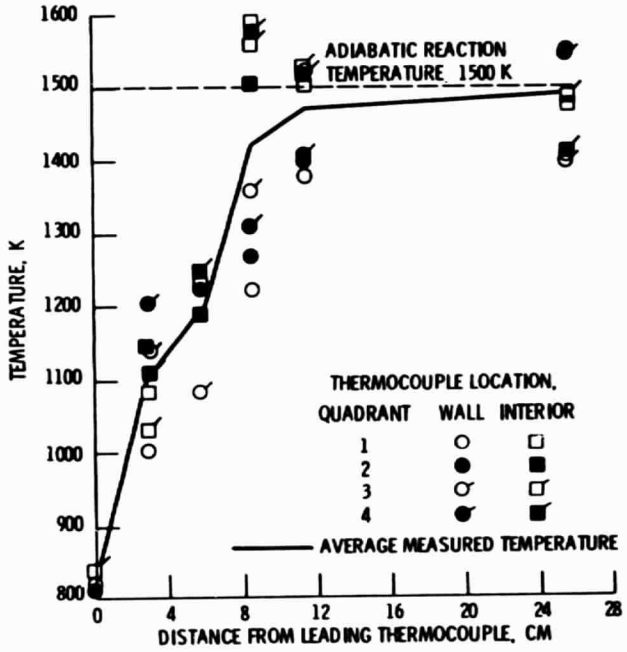
ORIGINAL PAGE IS
OF POOR QUALITY



(a) CATALYST ELEMENTS 1 THROUGH 4, GRACE DAVEX 512 B; EQUIVALENCE RATIO, 0.19; COMBUSTION EFFICIENCY, 90.1%.

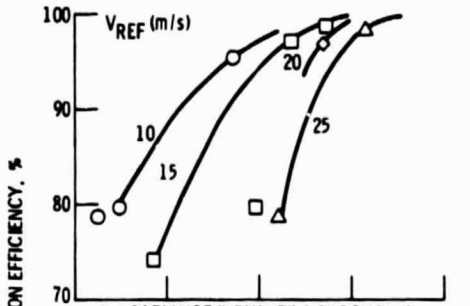
(b) CATALYST ELEMENTS 1 THROUGH 4, GRACE DAVEX 512 B; EQUIVALENCE RATIO, 0.24; COMBUSTION EFFICIENCY, 99.2%.

Figure 4. - Uniformity of measured temperature; inlet mixture temperature, 800 K; inlet pressure, 3×10^5 newtons per square meter; reference velocity, 15 meters per second.

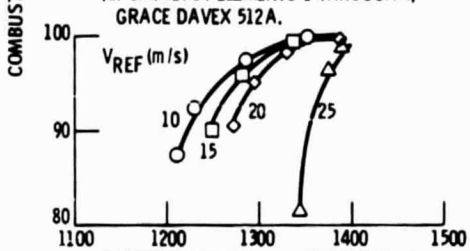


(c) CATALYST ELEMENTS 1 THROUGH 4, OXY-CATALYST NO. 4; EQUIVALENCE RATIO, 0.32; COMBUSTION EFFICIENCY, 99.7%.

Figure 4. - Concluded.

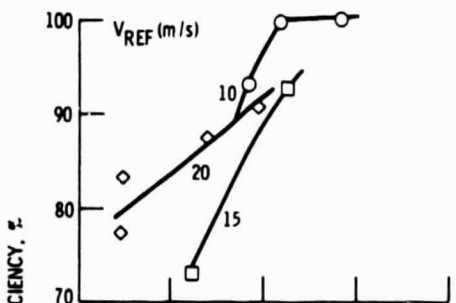


(a) CATALYST ELEMENTS 1 THROUGH 4, GRACE DAVEX 512A.

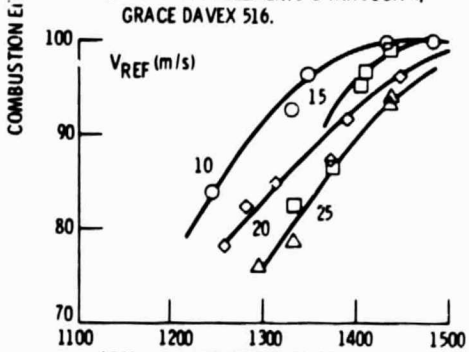


(b) CATALYST ELEMENTS 1 THROUGH 4, GRACE DAVEX 517B.

Figure 5. - Combustion efficiency; inlet mixture temperature, 800 K; inlet pressure, 3×10^5 newtons per square meter; measuring station, 25.5 cm downstream of catalyst inlet face.

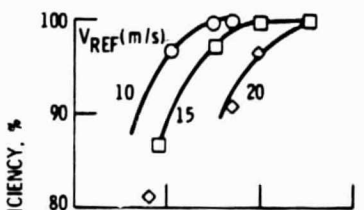


(c) CATALYST ELEMENTS 1 THROUGH 4, GRACE DAVEX 516.

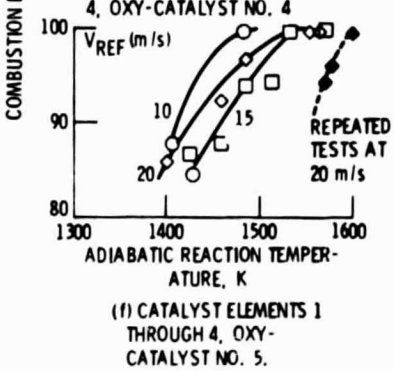


(d) CATALYST ELEMENTS 1 THROUGH 4, GRACE DAVEX 517.

Figure 5. - Continued.

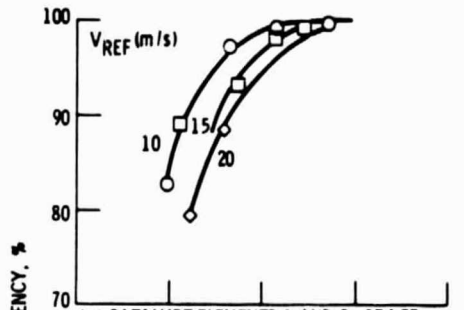


(e) CATALYST ELEMENTS 1 THROUGH 4, OXY-CATALYST NO. 4

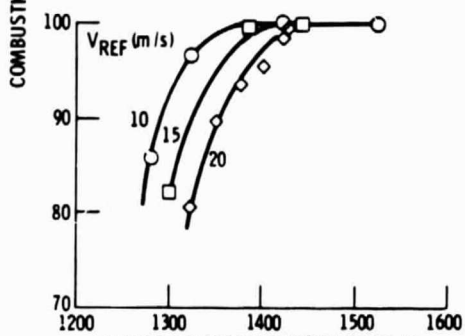


(f) CATALYST ELEMENTS 1 THROUGH 4, OXY-CATALYST NO. 5.

Figure 5. - Continued.

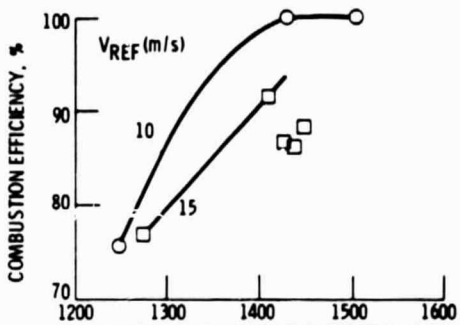


(g) CATALYST ELEMENTS 1 AND 2, GRACE DAVEX 512B; CATALYST ELEMENTS 3 AND 4, OXY-CATALYST NO. 4.



(h) CATALYST ELEMENTS 1 AND 2, GRACE DAVEX 512B; CATALYST ELEMENTS 3 AND 4, GRACE DAVEX 519.

Figure 5. - Continued.



(i) CATALYST ELEMENTS 1 AND 2, GRACE DAVEX 512B.

Figure 5. - Concluded.

ORIGINAL PAGE IS
OF POOR QUALITY

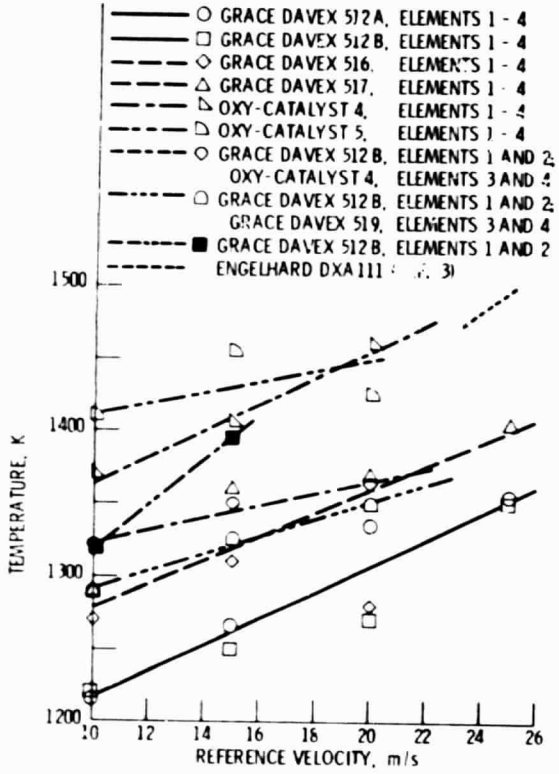


Figure 6. - Adiabatic reaction temperature required for 90 % efficiency; inlet mixture temperature, 8[illegible] K; inlet pressure, 3×10^5 newtons per square meter; measuring station, 25.5 cm downstream of catalyst inlet face.

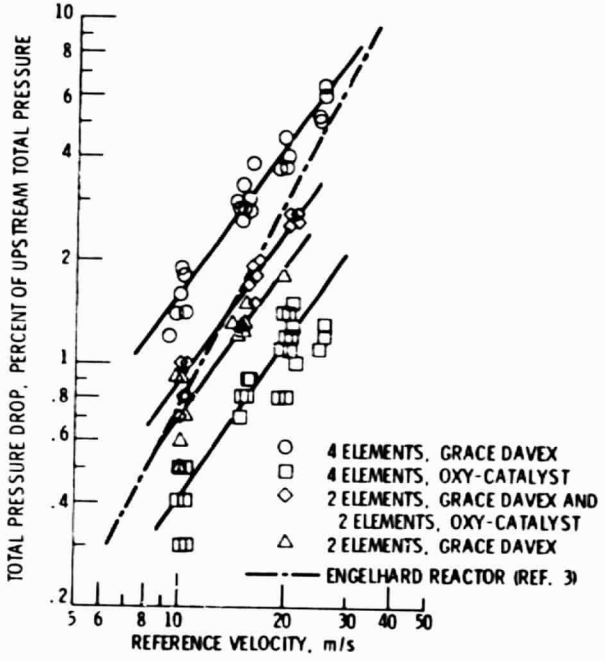


Figure 7. - Test section pressure drop; inlet mixture temperature, 800 K; inlet pressure, 3×10^5 newtons per square meter; range of equivalence ratio, 0.1 to 0.37.

NASA-Lewis