NASA TECHNICAL MEMORANDUM

NASA TM X-71794

NASA TM X-71794

(NASA-TM-X-71794) SWIRL-CAN COMBUSTOR PERFORMANCE TO NEAR-STOICHIOMETRIC FUEL-AIR RATIO (NASA) 27 p HC $4.00 CSCL 21E

N76-14123

Unclas

G3/07 06785

SWIRL-CAN COMBUSTOR PERFORMANCE TO NEAR-STOICHIOMETRIC FUEL-AIR RATIO

by Larry A. Diehl and James A. Biaglow
Lewis Research Center
Cleveland, Ohio 44135

TECHNICAL PAPER to be presented at Twenty-first Annual International Gas Turbine Conference sponsored by the American Society of Mechanical Engineers
New Orleans, Louisiana, March 21-25, 1976

SWIRL-CAN COMBUSTOR PERFORMANCE TO NEAR-STOICHIOMETRIC FUEL-AIR RATIO

by Larry A. Diehl* and James A. Biaglow*

ABSTRACT

Emissions and performance characteristics were determined for two full-annulus swirl-can modular combustors operated to near-stoichiometric fuel air ratios. The purposes of the tests were to obtain stoichiometric data at inlet-air temperatures up to 894 K and to determine the effect of module number by investigating 120 and 72 module swirl-can combustors. The maximum average exit temperature obtained with the 120-module swirl-can combustor was 2465 K with a combustion efficiency of 95 percent at an inlet-air temperature of 894 K. The 72-module swirl-can combustor reached a maximum average exit temperature of 2306 K with a combustion efficiency of 92 percent at an inlet-air temperature of 894 K. At a constant inlet air temperature, maximum oxides of nitrogen emission index values occurred at a fuel-air ratio of 0.037 for the 72-module design and 0.044 for the 120-module design. The combustor average exit temperature and combustion efficiency were calculated from emissions measurements. The measured emissions included carbon monoxide, unburned hydrocarbons, oxides of nitrogen, and smoke.

E-8471

INTRODUCTION

An experimental test program was conducted to determine the emissions and performance characteristics of two full-annulus swirl-can combustors operated to near-stoichiometric fuel-air ratios. Measured emissions included oxides of nitrogen, carbon monoxide, unburned hydrocarbons and smoke.

---

*Aerospace engineer; NASA-Lewis Research Center, Cleveland, Ohio

The swirl-can combustor has received considerable attention as . combustor design suitable for reducing oxides of nitrogen emissions. However, the primary application for swirl-can combustor technology has always been for engines requiring very high turbine inlet-air temperatures. Certain design features of the combustor which make it suitable for both applications include:

1. An array consisting of a large number of fuel injection/flame holder modules which distribute combustion uniformily across the annulus.

2. Quick mixing of burning gases and diluent air occurs because the swirl-can combustor passes nearly all of the airflow through the primary combustion zone, and large interfacial mixing areas exist between combustion gases and airflow around the swirl-cans.

3. Short combustor lengths and small recirculation zones are realized for burning and mixing which tend to limit oxides of nitrogen formation. The short combustor lengths also reduce the required amount of liner cooling air. For high temperature-rise applications small liner flows are advantageous in minimizing the tendency towards a peaked radial temperature profile at the combustor exit.

Swirl-can combustors have been investigated for several years at NASA Lewis Research Center. Initial tests of a swirl-can combustor to near-stoichiometric fuel-air ratios are reported in reference 1. More recent studies (refs. 2 and 3) have included pollutant emissions measurements at stoichiometric conditions. However, near-stoichiometric operation in these previous studies was limited to inlet-air temperatures of 589 K only. Three-row and two-row swirl-can combustor configurations were also tested during the Phase I portion of the NASA Experimental Clean Combustor Program (refs. 4 and 5). Results of these tests and a two-row design investigated in reference 6 showed no significant difference in performance or emissions between the two types of combustors. However, testing was conducted only to exit temperatures of 1500 K.

This study expands the investigation of swirl-can combustors operating to near-stoichiometric fuel-air ratio to include higher inlet-air temperatures up to 894 K. In addition, by utilizing three and two-row combustor designs consisting of 120 and 72 swirl-can modules respectively, the effects of module number and different hydraulic radius on combustor performance at exit temperatures greater than 1500 K would also be evaluated. The specific test conditions included combustor inlet-air temperatures of 589, 756, 839 and 894 K; reference velocities from 24 to 37 meters per second; inlet total pressure of 6 atmospheres, and fuel-air ratios from 0.020 to 0.065. All tests were conducted using ASTM Jet-A fuel.

APPARATUS AND PROCEDURE

Test Facility

Testing was conducted in a connected-duct component test facility at the Lewis Research Center. A detailed description of the facility and instrumentation are contained in reference 9.

Combustor Designs

The test combustors shown in figure 1 are annular designs 0.514 meters long from the diffuser inlet to the combustor exit plane and 1.067 meters in outer diameter. The three-row combustor consists of an array of 120 modules positioned in three circumferential rows. The two-row combustor consists of 72 modules with an equal number in each row. The only airflow introduced downstream of the array was liner cooling air which accounted for 9 to 12 percent of the total airflow. A photograph of a typical three-row design is shown in figure 2. The three-row concept differed from that of references 1 to 3 in module design and liner cooling airflow. The module design used in the two-row is basically the same as the module design of references 7 and 8.

Typical combustor modules are shown in figure 3. Each module consists of a carburetor, a cone swirler, and a flame stabilizer. The two combustors differed in method and location of fuel entry, swirler design, and flame stabilizer geometry. For the three-row design fuel was injected so that it impacted the apex of the axial flow cone swirler (fig. 3(a)), while in the two-row design the fuel was injected downstream of the swirler so that it impacted the upstream face of the circular disc which was mounted from the swirler face (fig. 3(b)). The three-row flame stabilizer was a flat-plate design, while the two-row design provided outer swirl which was counter-rotational compared to the inner fuel swirler. Detailed design features of each combustor are listed in table I. A sector view of the array of each combustor is shown in figure 4.

Test Conditions

All tests were conducted using ASTM Jet-A fuel. The combustor fuel-air ratio was varied over a range from 0.020 to 0.065. For combustor exit average temperatures below 1700 K, combustor exit total pressures and temperatures were measured in the exit plane at 3° circumferential increments by three equally spaced five-point rotatable probes. At higher exit temperatures these rakes were removed and three 5-point fixed-position total-pressure rakes were installed. The combustor total airflow was 50 kg/sec for the three-row design and 32 kg/sec for the two-row design. The airflow for the two-row design was scaled so that critical combustor parameters such as reference velocity and pressure drop, both of which are listed in table II, were comparable. The combustor inlet pressure was 6 atmospheres.

Exhaust Gas Pollutant Sampling

Concentration measurements of nitric oxide, total oxides of nitrogen, carbon monoxide, unburned hydrocarbons, oxygen and carbon dioxide were obtained with an on-line sampling system. The samples were drawn at the combustor exit plane by means of three equally spaced (circumferentially) 5-point radial-averaged water-cooled rotating probes. The three probes were manifolded to a single sampling line and provided a 39 point survey of the exit. A total survey of the combustor exit required approximately seven minutes.

Gas Sample System

The sampling line was steam heated to 420 K. Sample line pressure was maintained at 6.9 newtons per square centimeters in order to supply sufficient pressure to operate the instruments. Sufficient sample is vented at the instruments to provide a line residence time of about 2 seconds.

The exhaust gas analysis system is a packaged unit consisting of five commercially available instruments along with associated peripheral equipment necessary for sample conditioning and instrument calibration. In addition to visual readout, electrical inputs are provided to an IBM 360/67 computer for on-line analysis and evaluation of data.

The hydrocarbon content of the exhaust gas in determined by a Beckman Instruments Model 402 Hydrocarbon Analyzer. This instrument is of the flame ionization detector type. The oxygen analyzer is a Beckman Instruments Model 778 and is a polarographic type.

The concentration of the oxides of nitrogen is determined by a Thermo Electron Corporation Model 10A Chemiluminescent Analyzer. The instrument includes a thermal reactor to reduce NO_2 to NO and was operated at 973 K. Both carbon monoxide (CO) and carbon dioxide (CO_2) analyzers are of the nondispersive infrared (NDIR) type (Beckman Instruments Model 315B).

Smoke Number Measurement

The smoke sampling procedure as recommended in reference 10 was followed as closely as possible. The samples were drawn at the combustor exit plane from one circumferential location and at three radial locations at the combustor exit through a water-cooled stainless steel probe. The sample was transported to the filtering material (Whatman no. 4 filter paper) through approximately 4.5 meters of stainless steel line. The sample rate through the filter was 2.36×10^{-4} cubic meters per second. The filter was placed on a black background tile to measure comparative reflectance using a Welch Densichron and reflective unit (3832 A). A Welch Gray Scale (cat. no. 3827 T) was used as a calibration reference.

Gas Sample Procedure

All analyzers were checked for zero and span prior to each test run and rechecked between data points. Solenoid switching within the console allows rapid selection of zero, span or sample modes. Therefore, it was possible to perform frequent checks to ensure calibration accuracy without disrupting testing.

Carbon monoxide and carbon dioxide emissions were corrected for water vapor removed. The correction included both inlet-air humidity which was nominally 0.003 kilograms of water per kilogram of air and water vapor from combustion.

In order to check the sample validity, a fuel-air ratio based of the measured carbon concentrations was compared to metered fuel and airflow measurements. The carbon-based fuel-air ratios were within 95 to 110 percent of the metered values. For most test runs the carbon-based values were higher than the metered. This is to be expected as the probe sampling system does not completely cover the exit radial height and, thus, excludes the liner cooling air. The fuel-air ratio obtained from the fuel and airflow measurements was used in the computation of all emission indices and is the fuel-air ratio given on all data plots.

The combustor equilibrium temperature rise was computed using the equilibrium program described in reference 11. A modified version of this program was also used to compute a temperature rise which corresponded with exit emission measurements. For this purpose, the actual combustion process was assumed to be a constant-enthalpy, constant-pressure problem. A tagged portion of the carbon in the system was allowed to react only to carbon monoxide, the remainder to react normally. By increasing the tagged portion of the carbon it was possible to force the equilibrium program to consider a "frozen-equilibrium" composition whose carbon monoxide content is greater than would be predicted by equilibrium considerations alone. An iteration was performed until the total carbon monoxide in the system agreed with the experimental measurement. The temperature computed for this composition was assumed to be the combustor exit temperature. Combustion efficiency was then computed as the ratio of this computed temperature rise to the equilibrium temperature rise.

The work of references 1 to 3 relied on a choked nozzle as the primary means to determine exit temperature and combustion efficiency. While combustion efficiency could also be inferred from the emissions measurements of the previous studies the results were somewhat restricted as samples were obtained at a single circumferential location. Because the emissions results presented for this study were obtained with a rotating sampling system, combustion exit temperature and combustion efficiency calculated from the measured emissions can be considered to be representative of average exit conditions. This approach eliminated the need for the choked nozzle and its associated operational difficulties.

RESULTS AND DISCUSSION

For Jet-A fuel the stoichiometric fuel-air ratio is 0.067. The maximum test fuel-air ratio for the three-row combustion was 0.064. This is because the fuel-air ratio was deliberately maintained slightly below the stoichiometric value in an attempt to minimize burning with the liner cooling air. The maximum test fuel-air ratio for the two-row combustor was 0.055. This is because at higher fuel-air ratios combustion efficiency was less than 90 percent or maximum liner temperatures exceeded 1200 K both of which had been chosen as arbitrary limits.

Unburned Hydrocarbons

The emission index for unburned hydrocarbons obtained with the three-row design is shown in figure 5. With the exception of the 589 K inlet-air temperature hydrocarbon levels were low even at the highest fuel-air ratios. In all cases emission indices were 10 grams per kilogram of fuel or less. Minimum emissions occurred at fuel-air ratios of approximately 0.038. Emissions from the two-row combustor, which was operated only at the three highest inlet-air temperatures, were nearly identical to those of the three-row design and did not exceed 0.40 grams per kilogram of fuel over the range of fuel-air ratios tested.

Carbon Monoxide

Carbon monoxide emissions are shown in figure 6. The overall levels shown here are extremely high compared to combustors operating at conventional exit temperatures. At the highest fuel-air ratios the emission index levels were from 450 to 550 grams per kilogram of fuel depending on the combustor inlet-air temperature. The emission levels for the two-row design (fig. 6(b)), were significantly higher than for the three-row combustor.

Shown for comparison in figure 6 are the levels of carbon monoxide, predicted for a theoretical equilibrium composition of the exhaust gas, which were computed using the method of reference 11. These values establish the practical lower limit for carbon monoxide emissions at the combustor exit and are not indicative of inefficient operation. Levels of carbon monoxide greater than the equilibrium level indicate inefficient operation. At a given fuel-air ratio an increase in combustor inlet-air temperature produces an increase in the exhaust gas temperature and a consequent increase in the level of equilibrium carbon monoxide. The actual combustor CO emissions decrease with increasing inlet-air temperature indicating an increase in combustion efficiency.

Oxides of Nitrogen Emissions

Measured values of emission index for oxides of nitrogen (NO_x) are shown in figure 7. The most striking feature of the curves is that at a constant inlet-air temperature the maximum NO_x emission index occurs at an intermediate fuel-air ratio. It is possible to explain this phenomena on a qualitative basis. As the fuel-air ratio is increased, oxides of nitrogen increase until stoichiometric conditions are obtained in the wake of the modules. At this point the concentration of oxygen not used in the combustion process is very small and it becomes more difficult for the rate of NO_x formation to increase. As the fuel-air ratio is further increased competition from carbon monoxide for the available oxygen increases and the rate of formation of NO_x begins to decrease.

The amount of available oxygen for NO_x formation explains why the peak in the oxides of nitrogen curves of figure 7 occurred at a fuel-air ratio of

0.038 for the two-row design and at 0.045 for the three-row design. As noted in table I, the module fuel swirler of the three-row design has a greater open area and lower fuel flow than the two-row. Thus the depletion of oxygen in the swirler wake (a function of the local fuel-air ratio) would tend to occur at higher overall fuel-air ratios for the three-row as compared to the t. -row design.

Combustion Efficiency and Average Exhaust Temperature

As already noted, the combustion efficiency was determined by taking the ratio of the temperature rise evaluated from emissions measurements to the equilibrium temperature rise. The results are shown in figure 8. Combustion efficiency for the two models at inlet-air temperatures of 894 K was greater than 99 percent for fuel-air ratios up to 0.034. For higher fuel-air ratios, particulary above 0.040, where carbon monoxide increases rapidly, efficiency falls off and is dependent on inlet-air temperature. The effect of inlet-air temperature is more pronounced for the three row combustor. As an example, for the three-row design at 0.064 fuel-air ratio combustion efficiency increased from 91 to 95 percent as inlet-air temperature was increased from 589 to 894 K.

The combustion efficiency is shown as a function of the calculated average exit temperature in figure 9. In order to make differences in performance between the two combustors more readily apparent, the data at 894 K for the three-row design are repeated as a dashed line in figure 9(b). At high exit temperatures (2200 K or above) the combustion efficiency of the three-row design was approximately 5 percent greater than that of the two-row design. The reason for this difference will be discussed in a later section.

At an inlet air temperature of 894 K, the three-row combustor achieved the highest sustained average exit temperature recorded in the test program with a temperature of 2465 K and an efficiency of 95.2 percent. Maximum average exit temperature for the two-row combustor was 2306 K with a 92.0 percent efficiency at 894 K inlet-air temperature.

Smoke Emissions

The smoke number data obtained during the test program are shown in figure 10. At conventional exit temperatures smoke numbers were low. For large engines which would use combustors of this size, a maximum smoke number of 25 would meet the Environmental Protection Agency standards (ref. 12). With increasing fuel-air ratio, locally fuel-rich regions are formed and smoke production increases dramatically. Noted on the curves are the fuel-air ratios at which a smoke number of 25 is achieved. As expected, increasing inlet-air temperature tends to increase the fuel-air ratio at which smoke becomes objectionable. Only at the highest inlet-air temperature did smoke number remain below 25 for the three-row combustor. Smoke data for the two-row combustor were obtained only at the 894 K inlet-air temperature. For comparable inlet-air temperatures smoke emissions for the two-row combustor were significantly higher than for the three-row combustor. This result is compatable with the previous discussion of fuel swirler open area which affects the formation of rich fuel regions in the module wakes.

Combustor Durability

During the course of the test program the three-row combustor accumulated approximately 16 hours of test time at combustor average exit temperatures above 1700 K. The two-row design accumulated 8 hours of test time. Durability of the combustor liners and of the swirl-can modules were of particular concern during the tests. Liner temperatures were monitored for signs of excess metal temperature. For the three-row design at an inlet-air temperature of 894 K and an exit temperature of 2465 K the maximum recorded liner temperature was 1144 K. Typical two-row maximum liner temperature was 1220 K. Examination of the combustors after the tests showed no burning of the module swirlers or flame stabilizers, although some of the blockage tabs used in the two-row design were damaged.

Comparison of Combustors

With the exception of the fuel-air ratio at which maximum NO_x was observed, the oxides of nitrogen emissions were similar. As noted earlier, the more-open fuel swirler and slightly lower fuel flow per module for the three-row design permitted higher fuel-air ratios before overly rich mixtures were formed in the module wakes. This effect resulted in peak NO_x values for the three-row combustor occurring at a higher fuel-air ratio. The leaner mixture in the module wake, at a given fuel-air ratio, also resulted in better smoke performance for the three-row combustor.

The major differences in combustor performance for the two models was combustion efficiency at higher fuel-air ratios. This difference was mainly due to large variances in carbon monoxide as shown in figure 6 and not to unburned hydrocarbons which, as previously stated, were the same for both combustors. The comparability of unburned hydrocarbon levels indicate that differences in the method and location of fuel injection did not effect the resultant fuel preparation. The loss in combustion efficiency of the two-row design compared to the three-row is mainly attributed to the combustors surface-to-volume ratio (table I) and the outer liner design. The two-row outer liner was not contoured outward to as great an extent as the three-row design. This contour, coupled with the higher surface-to-volume ratio resulted in greater quenching of the CO-oxidation reactions in the liner cooling air thus producing the lower combustion efficiency at the high fuel-air ratios.

Concluding Remarks

The range of operating conditions and emission measurements reported herein are more complete than those of previous studies. These results indicate that the problems involved in operating a combustor at stoichiometric exit temperatures are solvable.

Of greatest significance in the testing of the two combustors was the way NO_x and CO formation was affected at the higher fuel-air ratios by the swirler open area and combustor surface-to-volume ratio, which affects the quenching of CO. This result seems evident in spite of the large number of design differences between the two combustors. However, more recent studies have indicated that the CO oxidation in these combustors is mixing limited. It is therefore possible that the differences in CO levels between the two combustors is in part due to flameholder design and the resultant mixing.

The emission levels of NO_x and, especially, of CO are very high at near stoichiometric exit temperatures. An engine operating at such levels would not satisfy the Environmental Protection Agency 1979 Standards. Techniques to limit NO_x, such as lean burning, could not be applied when overall stoichiometric operation is desired. Engine tailpipe CO emissions could be somewhat less than the tested combustor levels depending on the extent of recombination in the turbine expansion process. However, it appears that the applications for very high temperature rise combustors will be limited.

SUMMARY OF RESULTS

Emissions and performance characteristics were determined for two full-annulus swirl-can combustors operated to near stoichiometric fuel-air ratio. Measured emissions included; oxides of nitrogen, carbon monoxide, unburned hydrocarbons, and smoke. Test conditions included; combustor inlet-air temperatures of 589, 756, 839 and 894 K; reference velocities ranging from 24 to 37 meters per second; an inlet pressure of 6 atmospheres; and fuel-air ratios varying from 0.020 to 0.065. The following results were obtained:

(1) Combustor average exit temperature and combustor efficiency were calculated from combustor emissions as determined from a total-traverse at the combustor exit. For fuel-air ratios greater than 0.040, combustion efficiency decreased with increasing fuel-air ratio in a near-linear manner. Increasing combustor inlet-air temperature tended to improve combustion efficiency at a given fuel-air ratio. For the three-row combustor at a fuel-air ratio of 0.064 and a combustion inlet-air temperature of 589 K, a combustion effiency of 91 percent was obtained which corresponds to an exit temperature of 2250 K. When combustion inlet-air temperature was increased to 894 K, a combustion efficiency of 95 percent was obtained which corresponds to an exit temperature of 2465 K.

(2) At a constant inlet-air temperature, maximum oxides of nitrogen emission index values occurred at a fuel-air ratio of 0.037 for the two-row design and 0.044 for the three-row design.

(3) For fuel-air ratios greater the 0.040, carbon monoxide emissions increased rapidly and at the highest fuel-air ratios the emission index levels were from 450 to 550 grams per kilogram of fuel depending on the combustor inlet-air temperature. The CO emission levels for the two-row design were significantly higher than for the three-row combustor; thus, the three-row operated at higher combustion efficiency.

(4) Unburned hydrocarbon emissions were below 1.4 grams per kilogram

of fuel even at the highest fuel-air ratios at inlet-air temperatures of 756 and higher.

(5) For conventional operating conditions, smoke emissions were negligible for both models. At higher equivalence ratios, an SAE smoke number of 25 was exceeded for three of the inlet-air temperatures but remained below 25 at an inlet-air temperature of 894 K for the three-row combustor.

REFERENCES

1. Niedzwiecki, R. W., Juhasz, A. J., and Anderson, D. N., "Performance of a Swirl-Can Primary Combustor to Outlet Temperatures of 3600° F (2256 K)," NASA TM X-52902, Sept. 1970.
2. Niedzwiecki, R. W., and Jones, R. E., "Pollution Measurements of a Swirl-Can Combustor," Paper 72-1201, presented at AIAA/SAE Joint Specialist Conf., Nov.-Dec. 1972.
3. Niedzwiecki, R. W., and Jones, R. E., "Parametric Test Results of a Swirl-Can Combustor." Presented at American Institute of Chemical Engineers 75th National Meeting, Detroit, Mich., June 4-6, 1973.
4. Roberts, R., Peduzzi, A., and Vitti, G. E., "Experimental Clean Combustor Program. Phase I - Final Report," NASA CR-134736, 1975.
5. Bahr, D. W., and Gleason, C. C., "Experimental Clean Combustor Program. Phase I - Final Report," General Electric Co. Rept. GE74AEG380, Evendale, Ohio, June 1975; also NASA CR-134737, 1975.
6. Biaglow, J. A., and Trout, A. M., "Performance and Pollution Measurements of Two-Row Swirl-Can Combustor Having 72 Modules," NASA TM X-3170, Jan. 1975.

7. Mularz, E. J., Wear, J. D., and Verbulecz, P. W., "Pollution Emissions From Single Swirl-Can Combustor Modules at Parametric Test Conditions," NASA TM X-3167, Jan. 1975.

8. Mularz, E. J., Wear, J. D., and Verbulecz, P. W., "Exhaust Pollutant Emissions From Swirl-Can Combustor Module Arrays at Parametric Test Conditions," NASA TM X-3237, June 1975.

9. Adam, P. W., and Norris, J. W., "Advanced Jet Engine Combustor Test Facility," NASA TN D-6030, Nov. 1970.

10. "Aircraft Gas Turbine Engine Exhaust Smoke Measurement," Aerospace Recommended Practice 1179, SAE, 1970.

11. 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.

12. "Control of Air Pollution From Aircraft and Aircraft Engines. Environmental Protection Agency," Federal Register, Vol. 38, 1973, pp. 19088-19103.

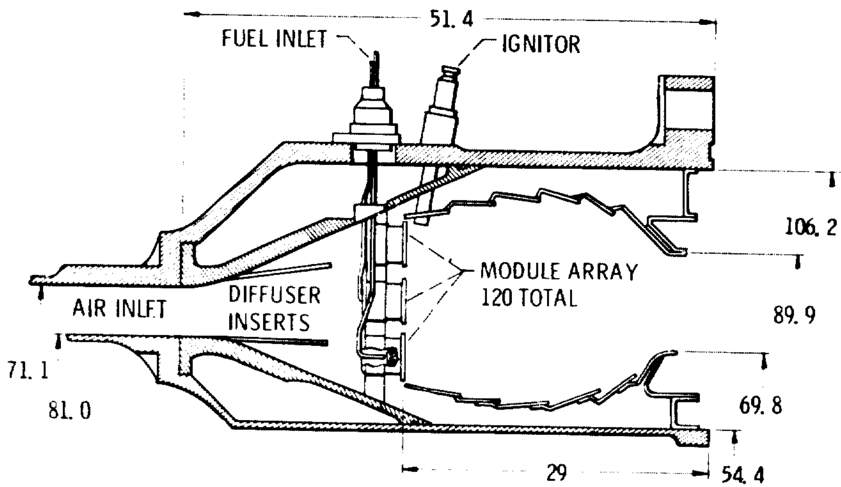
TABLE I. - SELECTED COMBUSTOR DESIGN VARIABLES

Variable	Three-row design	Two-row design
Fuel swirler effective open area, cm^3	3.45	2.71
Blockage at flameholder array, percent	67	75
Surface to volume ratio, m^{-1}	1.08	1.37
Heat release rate* joule/hr/m^3/atm	5.41×10^{11}	4.54×10^{11}
Fuel flow/module* k_g/sec	0.0208	0.0227
Liner cooling flow,* percent of total airflow	11	11

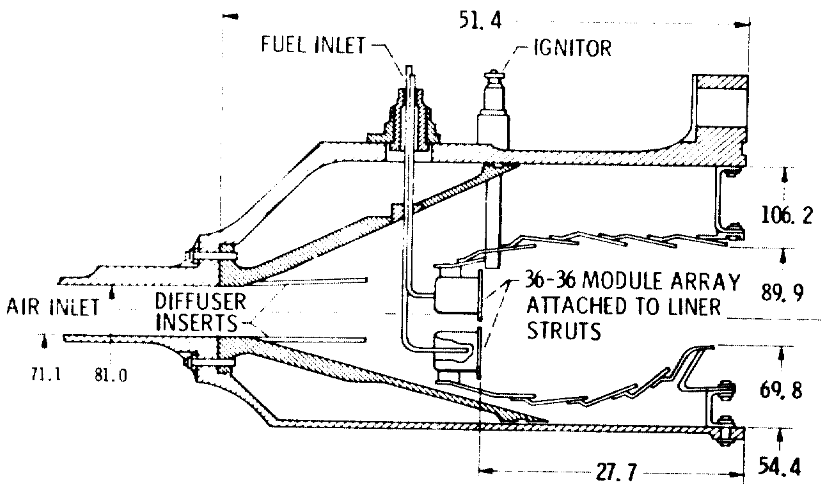
*At 0.050 fuel-air ratio.

TABLE II. - NOMINAL COMBUSTOR TEST CONDITIONS

Nominal combustor inlet-air temperature, K	Reference velocity m/sec		Combustor isothermal pressure loss percent of total inlet	
	Three row	Two row	Three row	Two row
589	25	22	4.7	5.2
756	32	29	6.2	6.2
839	35	31	6.8	6.4
894	37	34	7.5	7.9



(a) THREE-ROW SWIRL-CAN COMBUSTOR.



(b) TWO-ROW 72 MODULE SWIRL-CAN COMBUSTOR.

Figure 1. - Full-annular high-temperature combustors. (Dimensions are in cm.)

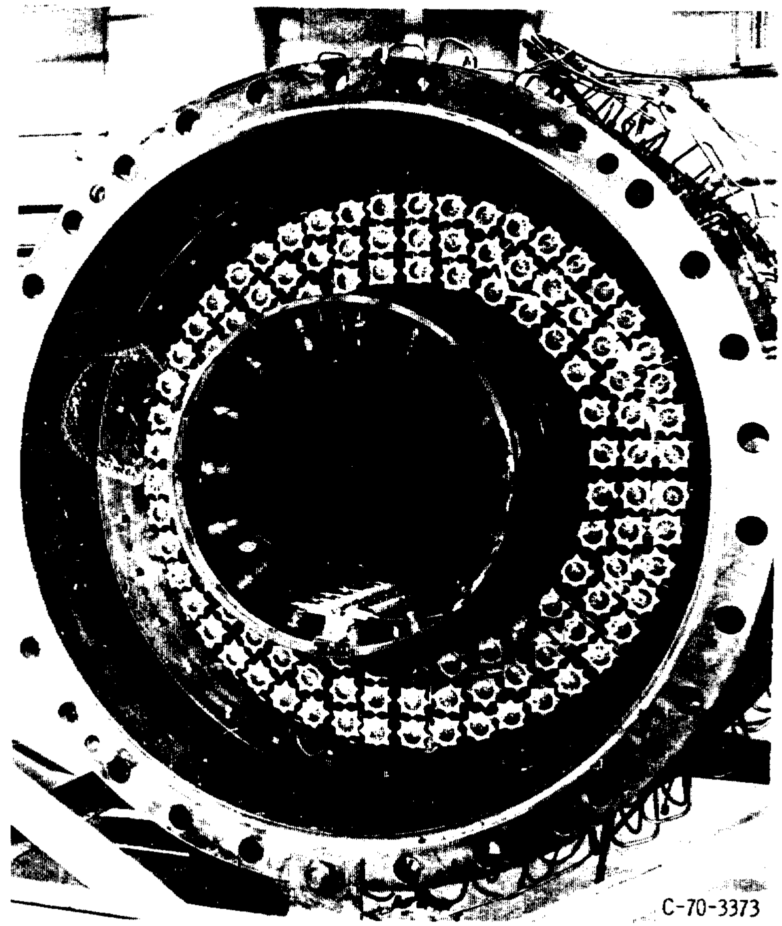
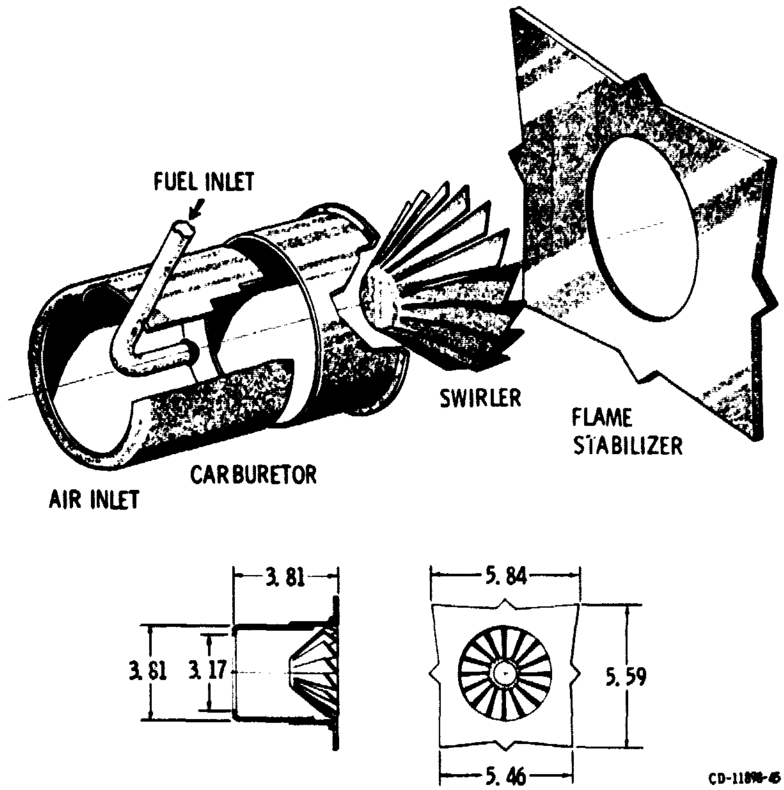
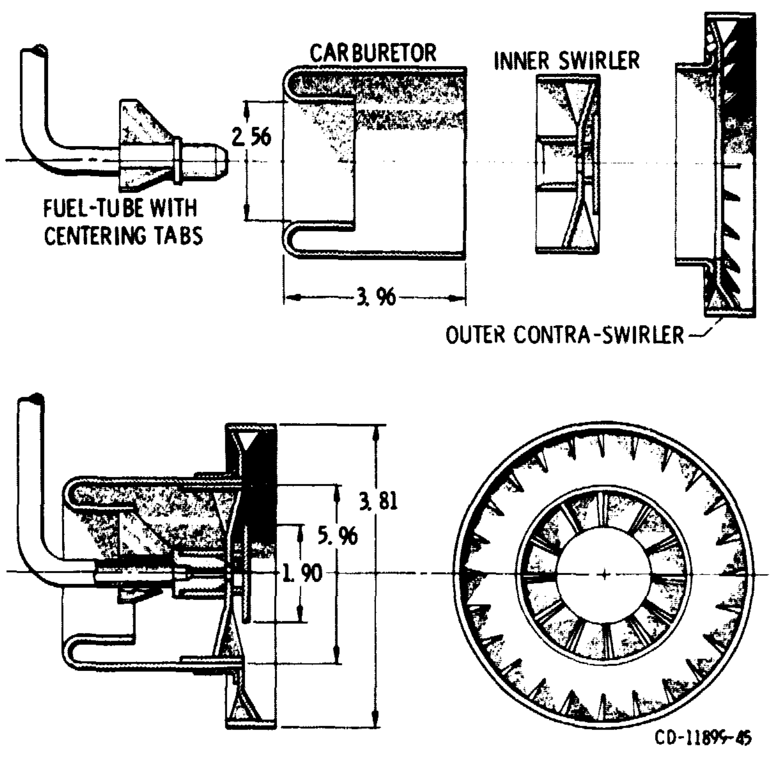


Figure 2. - Typical annular swirl-can combustor.

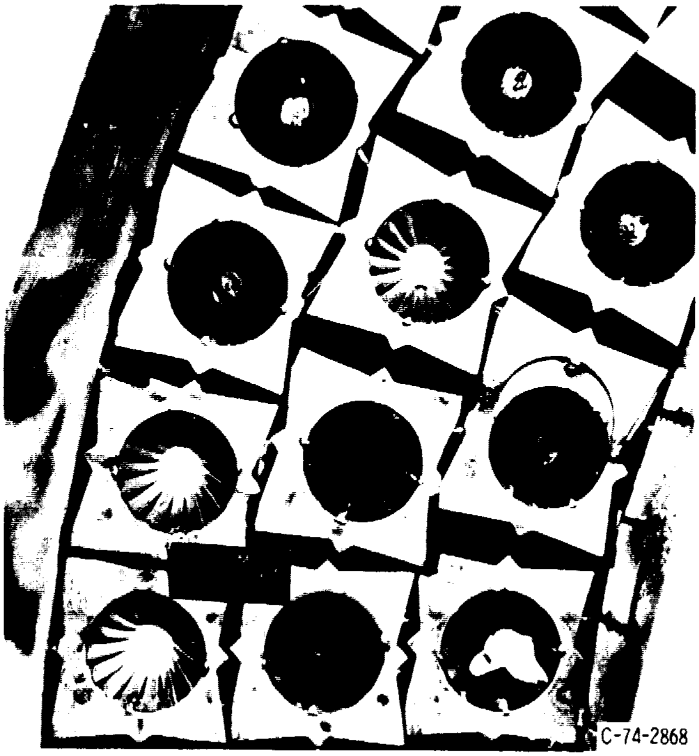


(a) MODULE FOR THREE-ROW COMBUSTOR.



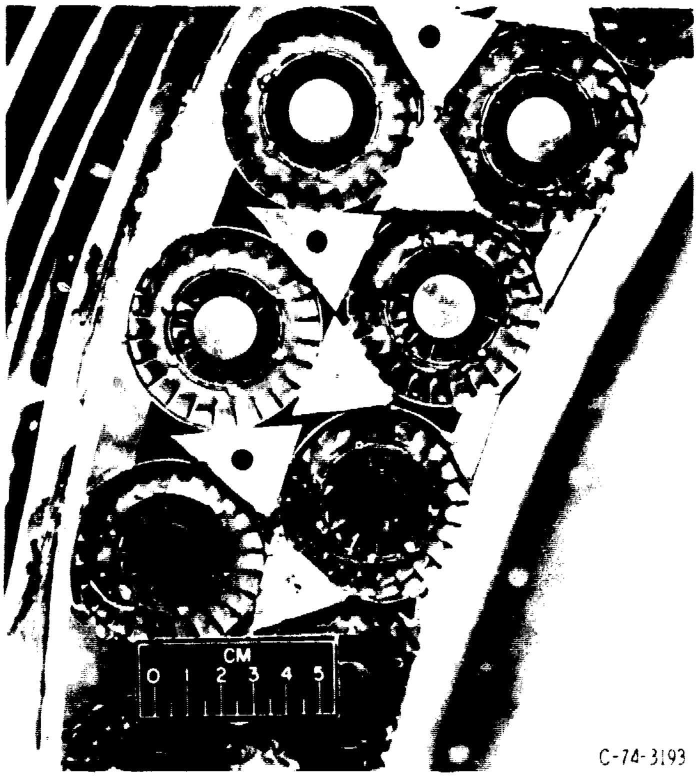
(b) MODULE FOR TWO-ROW COMBUSTOR.

Figure 3. - Swirl-can module details. (Dimensions are in cm.)



C-74-2868

(a) THREE-ROW COMBUSTOR.



C-74-3193

(b) TWO-ROW COMBUSTOR.

Figure 4. - Sector view of combustor module array.

ORIGINAL PAGE IS
OF POOR QUALITY

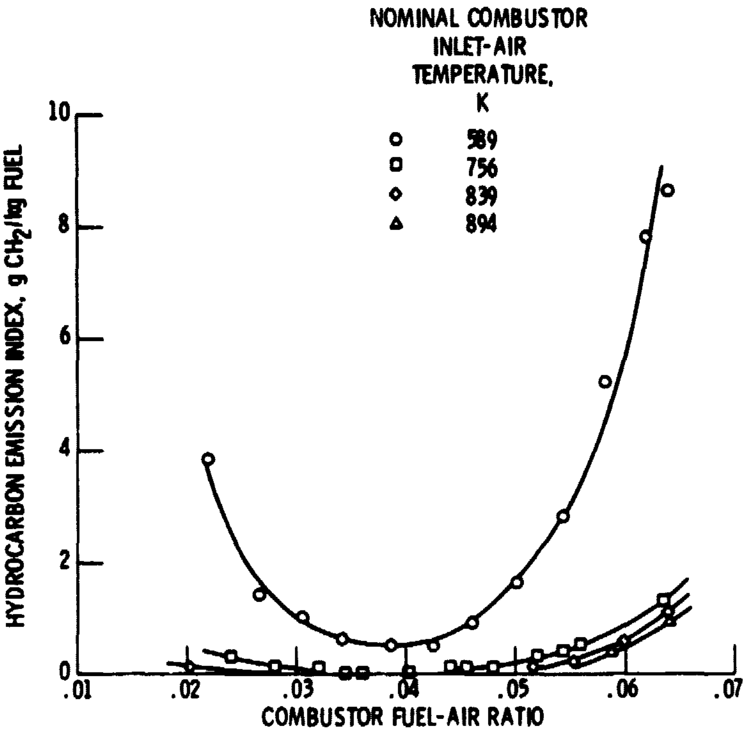


Figure 5. - Unburned hydrocarbon emission index for three-row combustor. Inlet pressure 6 atmospheres.

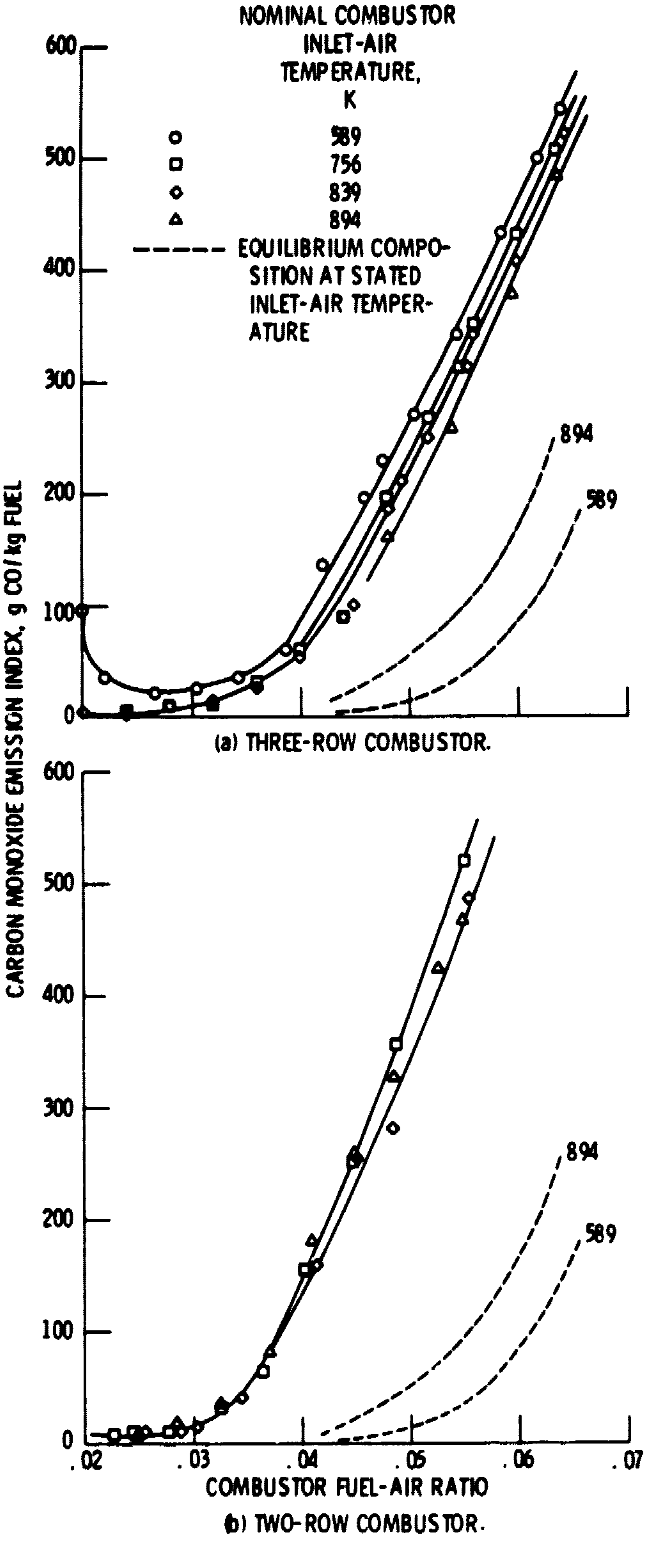


Figure 6. - Carbon monoxide emission index. Inlet pressure 6 atmospheres.

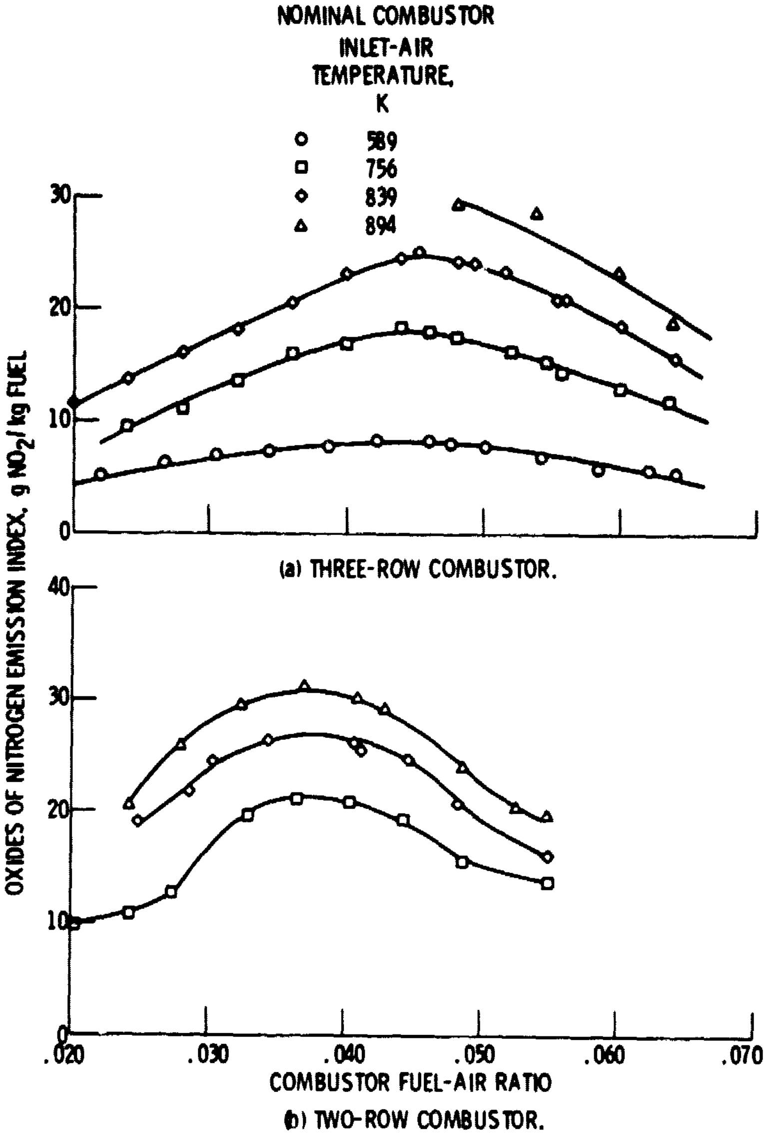


Figure 7. - Oxides of nitrogen emission index. Inlet pressure 6 atmospheres.

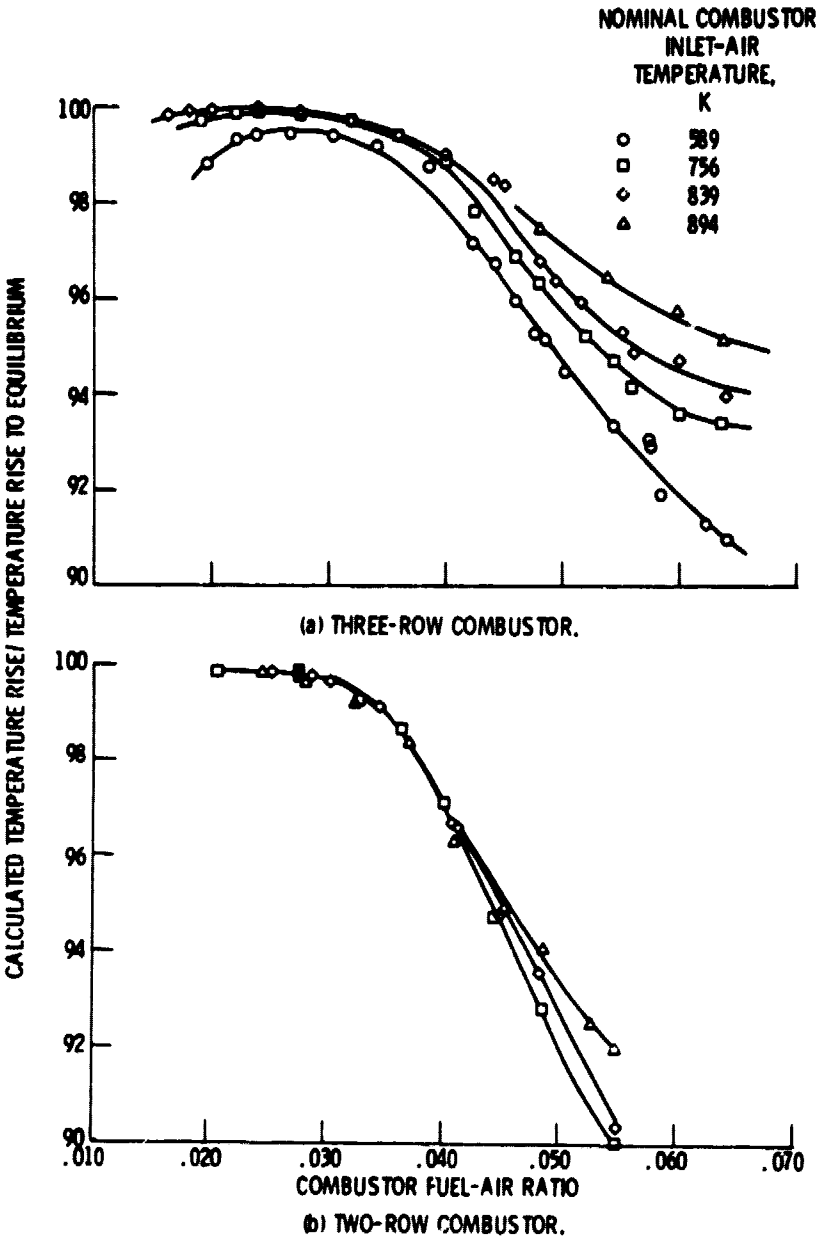


Figure 8. - Combustion efficiency as a function of combustor fuel-air ratio. Inlet pressure 6 atmospheres.

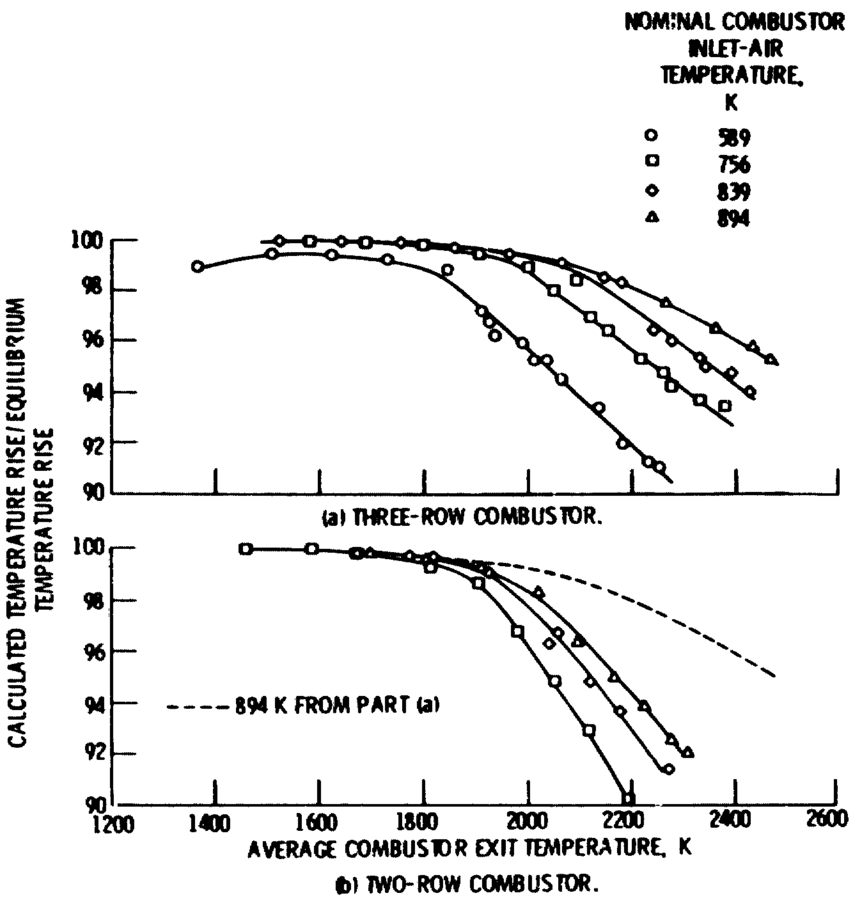


Figure 9. - Combustion efficiency as a function of combustor exit temperature. Inlet pressure 6 atmospheres.

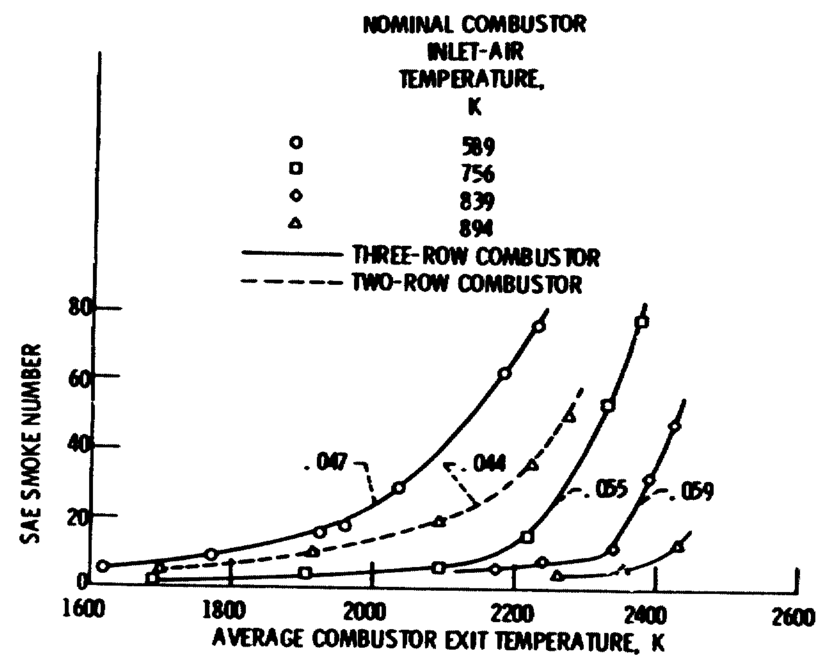


Figure 10. - Combustor smoke characteristics. Inlet pressure 6 atmospheres. Numbers on curves denote fuel-air ratio for smoke number of 25.