N73-19824

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DESIGN AND EVALUATION OF COMBUSTORS FOR REDUCING AIRCRAFT ENGINE POLLUTION

by Robert E. Jones and Jack Grobman
Lewis Research Center
Cleveland, Ohio 44135

TECHNICAL PAPER proposed for presentation at
Forty-first Meeting of AGARD/Propulsion and Energetics Panel
London, England, April 9-13, 1973

ABSTRACT

This report summarizes some of the NASA Lewis Research Center's recent efforts in reducing exhaust emissions from turbine engines. Various techniques employed and the results of testing are briefly described and referenced for detail. The experimental approaches taken to reduce oxides of nitrogen emissions include the use of: multizone combustors incorporating reduced dwell time, fuel-air premixing, air atomization, fuel prevaporization and gaseous fuel. Since emissions of unburned hydrocarbons and carbon monoxide are caused by poor combustion efficiency at engine idle, the studies of fuel staging in multizone combustors and air assist fuel nozzles have indicated that large reductions in these emissions can be achieved. Also, the effect of inlet-air humidity on oxides of nitrogen was studied as well as the very effective technique of direct water injection. The emission characteristics of natural gas and propane fuels were measured and compared with those of ASTM-A1 kerosene fuel.

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Robert E. Jones and Jack Grobman
Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio 44135

E-7334

SUMMARY

This report summarizes some of the NASA Lewis Research Center's recent efforts in reducing exhaust emissions from turbine engines. Various techniques employed and the results of testing are briefly described and referenced for detail. The effort arises from the increasing concern for the measurement and control of emissions from gas turbine engines. The greater part of this research is focused on reducing the oxides of nitrogen formed during takeoff and cruise in both advanced CTOL, high pressure ratio engines and advanced supersonic aircraft engines. The experimental approaches taken to reduce oxides of nitrogen emissions include the use of: multizone combustors incorporating reduced dwell time, fuel-air premixing, air atomization, fuel prevaporization, water injection and gaseous fuels. In the experiments conducted to date, some of these techniques have been more successful than others in reducing oxides of nitrogen emissions. In all cases, considerably more research will be required to develop combustors employing one or more of these experimental techniques without sacrificing over-all combustor performance. Tests are being conducted on full-annular combustors at pressures up to 6 atmospheres and on combustor segments at pressures up to 30 atmospheres.

Emissions of unburned hydrocarbons and carbon monoxide are caused by poor combustion efficiency at conditions such as engine idle. The use of fuel staging in multizone combustors and air assist fuel nozzles have indicated that large reductions in hydrocarbon and carbon monoxide emissions can be achieved. Studies are also being conducted on the use of diffuser bleed and variable combustor geometry to try to optimize the combustor airflow distribution over the wide range of operating conditions.

The effect of inlet-air humidity on the generation of oxides of nitrogen was studied as well as the very effective technique of direct water injection. The emission characteristics of natural gas and propane fuels were measured and are compared to those of ASTM-A1 kerosene fuel.

INTRODUCTION

This report describes some of the present efforts of the NASA Lewis Research Center in reducing the pollutant levels of gas turbine engine combustors with the primary emphasis on reducing oxides of nitrogen at takeoff and cruise conditions. Concern over air pollution has drawn the attention of combustion engineers to the quantities of exhaust emissions produced by gas turbine engines. Two general areas of concern have been established; urban pollution in the vicinity of airports and pollution in the stratosphere (refs. 1 and 2). The principal urban pollutants are emissions of unburned hydrocarbons and carbon monoxide during engine idle and taxi, and oxides of nitrogen and smoke during take-off. Oxides of nitrogen are presently considered to be the most critical emission product during high altitude cruise (ref. 3).

Redesigning the gas turbine combustor to accomplish a significant reduction in oxides of nitrogen will be a difficult task, since oxides of nitrogen are formed during any combustion process involving air. The amount formed is controlled by the chemical reaction rate and is a function of the flame temperature, residence time of combustion gases at the highest temperatures, the concentrations of oxygen and nitrogen present, and to a lesser extent the combustor pressure. Trends in combustor operating conditions indicate a steady rise in combustor inlet air temperature due to increases in engine pressure ratios and increasingly higher flight speeds (ref. 4). These effects increase the flame temperature with subsequent increases in the production of oxides of nitrogen.

The combustion work reported in this paper is pursuing several varied techniques for reducing the formation of gaseous pollutants. To reduce concentrations of oxides of nitrogen, combustors are being tested that have reduced reaction zone dwell time. Also, studies are also being conducted on ways to reduce the reaction zone temperature. Idle emissions are being reduced by improving combustion efficiency at off-design operating conditions. Combustor smoke is being minimized by careful control of the reaction zone equivalence ratios and by rapid mixing in the reaction zone.

These techniques for gaseous pollutant control are being evaluated on several full-annular combustors as well as in high pressure combustor segment tests. Techniques under study include the use of many small recirculation zones to reduce reaction zone dwell time, the use of premixing; air atomization and prevaporization of fuel; fuel staging and simulated variable combustor geometry; the use of direct water injection; and tests with a variety of fuels including natural gas and propane.

TEST PROCEDURES

Combustor testing is conducted in a variety of connected-duct test facilities at the Lewis Research Center. All inlet-air temperatures are obtained without vitiating the inlet air flow. Several test facilities have vitiating heaters to raise the inlet temperature still higher. However, they are never used during tests where the measurement of combustor pollutant levels is required. For full-annualr combustors, tests can be conducted at exact conditions simulating high altitude, high Mach number flight. Each test facility is equipped with on-line gas analysis instruments for pollutant measurements. The exhaust constituents, CO_2 and CO, are measured using nondispersive infrared (NDIR) instruments, oxides of nitrogen, NO and NO_2 are measured using chemiluminescence instruments equipped with a thermal converter to reduce NO_2 to NO prior to measurement. Unburned hydrocarbons are measured using a flame-ionization detector maintained at a temperature of 450 K. Unburned hydrocarbons from kerosene fuels are assumed to have the composition CH_2.

Gas sampling techniques vary from test to test. Most samples are taken from one or more internally manifolded fixed rakes. Some gas samples are taken with traversing probes on both segment and annular combustor tests. The samples are transported to the gas analysis instruments through heated stainless-steel tubes. Sample transit time through the transfer tube is minimized by venting a large amount of the sample flow at the instruments and by maintaining the pressure in the transfer tube at approximately 2 atmospheres. The sampling procedures and techniques used, follow the guidelines specified in SAE ARP 1256 (ref. 5). Smoke measurements are also made by sampling at the combustor exhaust plane. The smoke number is determined by collecting the particulates on filter paper and obtaining a reflectance reading of the stain. This technique has been standardized in SAE ARP 1179 (ref. 6).

The representativeness of the gas sample is checked by comparing the computed gas-sample fuel-air ratio to the fuel-air ratio calculated from flow rate measurements. Only data obtained where these fuel air ratios agree to within ±15 percent is accepted.

EMISSION REDUCTION RESULTS AND DISCUSSION

Multizone Combustors

Combustor descriptions. - Full annular combustor testing at NASA-Lewis has emphasized two combustor concepts for decreasing burning zone length. These are the swirl-can combustor and the double annular combustor. The swirl-can combustor is shown in Fig. 1 and 2. The combustor is of annular design, 0.514 m long and 1.067 m in diameter. The combustor consists of 120 individual swirl-can modules which distribute combustion uniformly across the annulus. The modules are arranged in three concentric rows with fuel flow independently controlled to each row. There are 48 modules in the outer row, 40 in the center and 32 in the inner row.

The combustor module design is shown in Fig. 3. Each module premixes fuel with air in the carburetor, swirls the mixutre, stabilizes combustion in its wake, and provides interfacial mixing areas between the bypass air through the array and the hot gases in the wake of the module. More detailed information on swirl-can combustors can be found in Refs. 7 to 9.

The other full-annulus combustor being investigated with a shortened burning zone is referred to as a double-annular, ram induction combustor. A cross-sectional sketch of this combustor is shown in Fig. 4. Constructing the combustion zone as a double-annulus permits the reduction of overall combustor length while maintaining an adequate ratio of length to annulus height in each combustion zone. This feature allows a considerable reduction in length to be made over a single annulus with the same overall height.

Individual control of the inner and outer annulus fuel systems of the double annular combustion zone provides a useful method for adjusting the outlet radial temperature profile.

The ram-induction combustor differs from the more conventional combustors in that the compressor discharge air is allowed to penetrate into the combustion and mixing zones without diffusing to as high a static pressure. The kinetic energy of the inlet air is thereby used to promote rapid mixing of air and fuel in the primary zone, and of diluent air and burned gases in the mixing zone. The airflow is efficiently turned into the combustor by two rows of vaned turning scoops that penetrate into the combustor. A more detailed discussion of the ram-induction concept is provided in Refs. 10 through 14.

Oxides of nitrogen emissions. - The emissions of oxides of nitrogen ($NO + NO_2 = NO_x$) for the multizone combustors are shown in Fig. 5. Also shown on this figure are data from a single-annular combustor, Refs. 15 and 16. The NO_x emission index, grams of NO_2 produced per kilogram of fuel burned, is shown as a function of the combustor exit average temperature. The test conditions; pressure, inlet-air temperature and reference velocity were the same for all three combustors. The numbers in parentheses are the number of fuel injection sources of each combustor. Increasing the number of fuel injection sources and spreading the combustion more uniformly throughout the combustor appears to be a very effective way of reducing the emission of NO_x. The techniques of premixing fuel and air and rapid quenching of the combustion reaction, both incorporated into the swirl-can approach, are also considered to be a principle factor for producing the lower NO_x emissions of these combustors. Figure 6 compares the NO_x emission level for the three combustor types with increasing inlet-air temperature and a constant exit temperature of 1500 K. The trend with increasing inlet-air temperature is an exponential increase in NO_x emission index. The use of multizone combustors or combustors that spread combustion as much as possible is a very effective way to reduce NO_x emissions. At an inlet-air temperature of 755 K the swirl can combustor produces only 60 percent as much NO_x as the more conventional single-annular combustor. Figure 7 shows the emissions of NO_x for the swirl-can combustor for inlet-air temperatures up to 840 K and fuel air ratios up to 0.0695. For the ASTM-A1 fuel used in these tests, the stoichiometric fuel-air ratio is 0.0676. This swirl-can combustor was designed for near stoichiometric operation and as such is larger than would be required for operation at more usual turbine inlet temperatures. The figure shows a strong dependence of NO_x emissions on both inlet-air temperature and on fuel-air ratio. However as the fuel-air ratio is increased the formation of NO_x eventually reaches a constant level and as stoichiometric fuel air ratios are approached the measured concentrations of NO_x were noticed to decline. Though this effect is only clearly demonstrated at an inlet-air temperature of 590 K, there is no reason to believe that similar effects would not be observed at the higher inlet-air temperatures. A more complete discussion of all the emission characteristics of swirl-can combustors can be found in Refs. 7 and 8.

The effects of combustor residence time on NO_x emissions is shown in Fig. 8 for the two multizone combustors. Increasing the combustor reference velocity (decreasing the residence time) causes a corresponding decrease in the NO_x emission level. The effect is virtually linear with residence time as is indicated by the dashed line with a slope of minus one.

Smoke number. - The smoke emissions of the swirl-can combustor are shown in Fig. 9. These data were obtained during a test to stoichiometric operating conditions at a pressure level of 6 atmospheres, (ref. 9). No smoke was detected when the combustor exit temperature was below 1950 K. The smoke increases rapidly as the overall stoichiometric fuel-air ratio is approached. For comparison, the smoke number of the double-annulus combustor at an exit average temperature of 1500 K and the same operating conditions as on Fig. 9 is approximately 14. This illustrates the point that fuel-air premixing as occurs in swirl-cans is a very effective way of reducing combustor smoke.

Air Atomization

High pressure combustor tests were made to determine pollutant emissions and performance characteristics obtained with low fuel pressure drop air-atomizing fuel nozzles designed to utilize the air-stream momentum in atomizing ASTM A-1 fuel (ref. 17). Similar tests were made with pressure-atomizing fuel nozzles for comparison. With the present trend in development toward advanced turbojet engines with high compressor-pressure ratios, the problem of developing low pollutant combustors has become more difficult at the resulting high levels of inlet-air pressure and temperature.

One of the main advantages of air atomizing fuel nozzles is their flexibility in design in producing fuel sprays which spread out fairly uniformly across the airstream. With improved atomization and mixing obtained from air atomizing fuel nozzles, it would be expected that nitric oxide concentrations could be reduced (ref. 18). Besides being relatively simple in design and fabrication, air atomizing fuel nozzles are less susceptible to fuel fouling at high inlet-air temperatures as compared with the pressure atomizing type.

Air atomizing nozzles were tested under ambient flow conditions in a full scale Lucite model of an experimental combustor to determine spray patterns produced with water injection. Photographs taken at several water air ratios and reference veloçities showed that a splash cone type of air atomizing nozzle gave a better distribution of liquid and a finer spray of water droplets than that obtained with a radial jet type of air atomizer. As expected from water spray tests, radial jet nozzles gave high smoke numbers in preliminary combustor tests. Thus, the splash cone air atomizing nozzle, shown in Fig. 10, was selected for the high pressure combustor tests.

The fuel nozzle assembly shown in the figure consists of a diffuser snout in which a portion of the air from the compressor is captured and flows through the air swirler and around the splash cone nozzle. The air swirler produces a rotating airflow which assists in evenly distributing the fuel droplets and stabilizing the subsequent flame. Low pressure fuel is injected from the combination fuel supply and splash cone support through four 0.16 cm diameter orifices onto the curved face of the nozzle. Fuel splashes over the nozzle lip and is atomized by the swirling airstream. At the point where the airstream first contacts the fuel, the diffuser passage converges to accelerate the flow of the resultant fuel-air mixture which is then suddenly expanded into the combustor by the diverging portion of the diffuser. The nozzle assembly can be used either singly or in combination to provide the required distribution for can combustors, can-annular combustors, or annular combustors.

A high pressure combustor segment 0.456 m (18 in.) long with a maximum cross section of 0.153 by 0.305 m (6 by 12 in.) was tested with the splash-cone air atomizing and conventional simplex pressure atomizing fuel nozzles (ref. 17) at inlet-air pressures of 4 to 20 atmospheres, inlet air temperatures as high as 590 K, reference velocities of 12.4 to 26.1 m/sec (41 to 86 ft/sec), and fuel air ratios of 0.008 to 0.020. Pollutant emissions obtained with the splash cone air atomizing nozzle configuration are compared with results obtained with pressure atomizing fuel nozzles. Most of the results to be described herein were obtained at an inlet total temperature of 590 K, a reference velocity of 21.4 m/sec, and a fuel-air ratio of 0.015.

The variation of the nitrogen oxide emission index with pressure is shown in Fig. 11. Emission index generally increased with increasing inlet air pressure. However, there was a considerable drop in emission index with the splash cone nozzle when inlet air pressure was increased from 10 to 20 atmospheres. This was attributed to improved atomization of the fuel when airstream momentum was increased. In this case, momentum was increased by increasing the airstream density. Thus, at an inlet air pressure of 20 atmospheres, it was found that the nitrogen oxide emission index was considerably lower with the splash cone air atomizing nozzle than with the pressure atomizing nozzle. These tests were conducted with a fixed air entry hole geometry. It is conceivable that further reductions in oxides of nitrogen might be attained by adjustments in liner airflow distribution.

Increasing inlet air pressure from 4 to 10 atmospheres increased exhaust smoke numbers for all of the fuel nozzles that were tested. However, smoke number decreased slightly with the splash cone nozzle when inlet air pressure was increased from 10 to 20 atmospheres. As previously mentioned, nitric oxide emission index decreased in a similar manner which was attributed to improved fuel atomization when airstream momentum was increased. Thus, with the air atomizing splash cone nozzle, an improvement in fuel atomization at high inlet air pressure tended to counteract the general tendency of smoke number to increase with increasing inlet air pressure. However, at 20 atmospheres inlet air pressures, the splash cone nozzle had a smoke number of about 35, somewhat higher than one of the pressure atomizing nozzles tested but lower than that of another. It should be noted that the inlet air temperature of 590 K was somewhat below the design "takeoff" condition of 20 atmospheres and 755 K (1360° R). Thus, smoke numbers are somewhat higher than might be expected at the design takeoff condition since increasing inlet temperatures tend to reduce smoke number.

Increasing either inlet-air pressure or temperature decreased carbon monoxide and unburned hydrocarbon emission indexes with both the splash cone and pressure atomizing nozzles. The comparison between the splash cone and the pressure atomizing nozzle indicated that both carbon monoxide and unburned hydrocarbons were lower with splash cone nozzles at an inlet air temperature of 589 K (1060° R) over a range of pressure of 4 to 20 atmospheres although the combustion efficiencies for both fuel nozzles were near 100 percent. Initial results for the air atomizing splash cone fuel nozzle are promising but a great deal more research is required to attain further reductions in oxides of nitrogen and smoke, and to evaluate combustor durability and altitude relight capabilities.

Fuel Prevaporization

A study was conducted to determine the effect of prevaporization on the exhaust emissions from an experimental combustor (ref. 19). Two methods for reducing oxides of nitrogen are to reduce the reaction zone temperature (flame temperature) and to reduce the reaction zone dwell time. The reaction zone temperature may be reduced by operating with a more homogeneous fuel air mixture that is either fuel rich or fuel lean. The fuel air mixture could be made more homogeneous either by increasing mixing intensity, by premixing the fuel and air before they enter the reaction zone, or by prevaporizing the fuel before it enters the reaction zone. A more homogeneous fuel air mixture should also minimize emission products caused by incomplete combustion. Eliminating the process of fuel droplet evaporation within the reaction zone could enable a reduction in reaction zone dwell time.

Operating a combustor with prevaporized kerosene fuel would require a heat exchanger to convert the liquid fuel to vapor prior to injection into the reaction zone. Due to limitations that might be imposed by the heat exchanger, the combustor may operate with only partially vaporized fuel over a part of the flight conditions. One of the objectives of the tests described herein was to determine emission levels with varying degrees of vaporization. Vaporized propane was used to simulate vaporized kerosene. Propane was chosen to eliminate the complexities of operating a liquid fuel boiler and because its burning characteristics are similar to kerosene. Two different dual fuel nozzles were used to inject varying proportions of liquid ASTM A-1 fuel and gaeous propane into the test combustor as shown in Fig. 12. The experimental combustor that was used is similar to that described in the previous section. At a given fuel-air ratio, the summation of the mass flowrates for liquid ASTM A-1 and gaseous propane was held constant as the proportion of gaseous propane was varied from 0 to 100 percent. Fuel injector No. 1 consists of a simplex nozzle located in the center of the assembly for injecting liquid kerosene and a series of eight evenly spaced holes concentric with the simplex orifice for injecting gaseous propane. Fuel injector No. 2 is a commercial duplex nozzle in which the center orifice was used for injecting liquid kerosene and the annular orifice was used for injecting gaseous propane. The tests described herein were conducted over a range of inlet pressure and temperature of 4 to 20 atmospheres and 475 to 700 K, respectively, a fuel-air ratio of 0.014 and a reference velocity of 21.3 m/sec.

Figure 13 shows the variation in the emission index for oxides of nitrogen with inlet temperature for varying proportions of gaseous propane. The results obtained using fuel injector No. 1 indicate that as the inlet temperature is increased from 478 to 700 K, the emission index for oxides of nitrogen increases from 6 to 22 for 0 percent vapor. The effect of vapor fuel on the NO_x emission index is negligible up to an inlet temperature of about 590 K. The reduction in NO_x that occurred as the proportion of vapor fuel was increased became more significant as inlet temperature was increased further. At 700 K, a considerable improvement was obtained, amounting to a 24 percent decrease in NO_x, as the proportion of vapor was increased from 0 to 100 percent. The results obtained with fuel injector No. 2 were similar with the exception that the general level for the NO_x emissions was lower.

Figure 14 shows the variation in smoke number with inlet total pressure for varying proportions of gaseous fuel. As inlet pressure was increased from 4 to 20 atmospheres, the smoke number for fuel injector No. 1 increased from 12 to 27 with 0 percent vapor. At a pressure of 20 atmospheres, increasing the proportion of vapor from 0 to 100 percent, decreased the smoke number by 60 percent. Fuel injector No. 2 produced a marked increase in smoke number as pressure was increased.

Fuel injector No. 1 displayed a higher level for the NO_x emission index but a lower level of smoke number than injector No. 2. The observed differences are attributed to differences in degree of fuel air mixing between the two configurations. It appears that fuel injector No. 2 had less mixing causing it to operate at locally fuel rich conditions thus producing more smoke but lesser amounts of NO_x. No attempt was made to alter reaction zone airflow distribution in these tests. The results indicate, however, that further reduction in NO_x might be obtained by improvements in fuel air mixing (premixing) or by adjusting the amount of primary zone airflow.

The combustor operated at combustion efficiencies near 100 percent for all test conditions described herein. Nevertheless, the emission index for carbon monoxide decreased significantly as the proportion of vapor increased from 0 to 100 percent as shown in Fig. 15. The corresponding emission indices for total hydrocarbons were negligible for all test conditions.

Idle Emissions

Emission of unburned hydrocarbons and carbon monoxide are often prevalent during engine idle and taxi. These emissions are of primary concern in the vicinity of airports. The cause of these emissions is poor combustion efficiency at the combustor operating conditions typical of ground idle. Typically these conditions are low combustor pressure, 2 to 4 atmospheres; low inlet-air temperature 365 to 480 K, and low fuel-air ratios of 0.0075 to 0.01. Measured engine combustion efficiencies vary from 88 to 96 percent. Two approaches are being tried in an attempt to improve idle combustion efficiency. These are the use of fuel staging in multizone combustors and use of an air-assisted fuel nozzle.

Fuel staging. - Fuel staging as applied to multizone combustors means that only one of the several possible zones receives fuel during idle. When the overall fuel-air ratio is maintained at that value required for idle the burning zone has a significantly higher than average fuel-air ratio. With pressure atomizing fuel nozzles this means a higher pressure drop during idle which in turn gives finer atomization and better combustion efficiency. With swirl-can modules the fuel flow to the active row is high enough so that a well developed spray is formed. At very low fuel flow rates per module the fuel has been observed to dribble rather than be sprayed from the swirl cans. The results of the fuel staging tests are shown in table I and reported in detail in Refs. 8 and 20. The double annulus combustor emissions are compared with combustion in both annuli and staged to inner annulus. Similar data are shown for the swirl-can combustor.

It is apparent that large reductions in emission levels can be obtained by this simple technique. The levels of pollutant reduction demonstrated still may not be sufficient and further improvements may be required.

Air assist fuel nozzles. - Improving fuel atomization by using an air assist fuel nozzle can significantly reduce unburned hydrocarbon and carbon monoxide emissions at idle operating conditions by improving combustion efficiency. This might be done as shown in Fig. 16. Here a conventional dual orifice fuel nozzle is modified so that during idle, high pressure air is injected through the secondary orifice. Only small amounts of air are needed. For higher power settings the air would be shut off and secondary fuel would be injected in the conventional manner.

Figure 17 illustrates the reductions in hydrocarbons and carbon monoxide that were obtained by using air assist fuel injection in a dual orifice nozzle, in a single J-57 engine combustor can at simulated engine idle conditions. Increases in atomizer air pressure (delta p) represent increases in the air through one orifice of the fuel nozzle. Fuel is supplied through the other orifice. The addition of air through the nozzle improved fuel atomization with the main effect being a dramatic improvement in combustion efficiency. Attendant reductions of approximately 80 percent in hydrocarbons and 30 percent in carbon monoxide emission index levels were realized. More details on this technique, including a description of the nozzle configuration, are given in Ref. 21.

Control of Combustor Airflow Distribution

Another technique which may have substantial potential for reducing emissions is the control of the combustor airflow distribution as a way of controlling the primary zone equivalence ratio. Two approaches are being taken: the use of short diffusers incorporating bleed for airflow profile control; and the use of variable combustor geometry.

Diffuser tests. - Short diffusers incorporating bleed on both walls are being tested in a full annulus test facility described in Ref. 22. This test facility has the capability to test many different diffuser geometries. Tests have been conducted on an asymmetric wall diffusers (ref. 23), dump diffusers and a wide variety of short length diffusers incorporating bleed on both diffuser walls. We find that large changes in the diffuser exit flow profile can be caused by the application of small quantities of bleed flow. Additionally, bleed can cause the diffuser to flow more efficiently and diffuser total pressure losses can be significantly reduced.

An application of diffuser bleed is illustrated in Fig. 18. As shown in Fig. 18(a) the combustor inlet velocity profile without bleed has the majority of the airflow bypassing the primary zone. This condition should be optimum for low pollutant emissions at idle and enhanced altitude relight capability. At takeoff and cruise conditions, Fig. 18(b), the combustor inlet velocity profile is straightened by applying outer wall bleed for optimum operation.

Variable geometry. - Variable combustor geometry could be a very effective way of controlling the combustor primary zone equivalence ratio. At conditions such as engine idle variable geometry could be used to optimize the primary zone equivalence ratio to minimize the emissions of hydrocarbons and carbon monoxide. Similarly at altitude relight conditions the primary zone fuel air ratio could be optimized for reignition. At take-off or cruise the combustor geometry would again be changed and now optimized to minimize smoke and oxidies of nitrogen. At present the only variable geometry configurations being studied are for improved altitude relight and improved idle emission control. This work is being done on a modified version of the double-annulus combustor.

Water Injection Tests

Direct injection of water into the primary zone of a combustor is another very effective way to minimize the emissions of oxides of nitrogen. However, practical aircraft considerations limit the use of water injection only for takeoff. Water injection lowers the flame temperature and serves as a diluent in the air stream. Both effects reduce the maximum combustion temperature and thereby reduce the emissions of NO_x. Figure 19 compares data for three different combustors all using slightly different techniques for direct water injection. The ratio of NO_x emission indices with and without water injection is shown as a function of the water-air ratio. Water injection in the single annular combustor was by spraying water into the combustor snout upstream of each fuel nozzle. Water injection in the segment combustor was from the secondary ports of the nozzles used for comparison of propane fuel injection (nozzle No. 1, fig. 12). Water injected in this manner mixes much more intimately with the fuel and is significantly more effective in reducing NO_x emissions. These effects however do influence the levels of other pollutants as combustion efficiency may be lowered by water injection. Some increase in CO levels during water injection have been observed but are not considered to be significant in view of the low values without water injection.

Inlet air humidity. - Variations in inlet-air humidity have been shown to reduce the level of oxides of nitrogen emissions. Tests were conducted using the single annular combustor described previously. Water was sprayed into the inlet-air far enough upstream of the combustor so that it would be completely vaporized before reaching the combustor. The results of these tests are shown in Fig. 20. Data were obtained over a wide range of inlet-air temperatures and humidities. The trends with increasing humidity are the same; an exponential decrease in the NO_x emission index with increasing humidity.

Alternate Fuels

The single annular combustor of Ref. 15 has been tested with natural gas fuel. Reference 25 gives details of the work done to determine an optimum method of injecting natural gas fuel. Natural gas does not display stable combustion over as wide a range of operating conditions as conventional kerosene fuels used in aircraft turbine engines in spite of its higher heating value. The narrow combustible limits and high chemical stability account for the poor performance of natural gas fuel at off design engine operating conditions, Refs. 26 and 27.

Natural gas does have an advantage over keorsene fuels in its well documented tendency to produce lower emissions of NO_x (ref. 28). Figure 21 compares the emissions of NO_x for ASTM-A1 fuel and natural gas fuel over a range of inlet-air temperatures. Exit temperature was constant at approximately 1500 K, combustion efficiency was approximately 100 percent and test pressure was 6 atmospheres. In general, the use of natural gas resulted in approximately a fifty percent reduction in NO_x emissions. In an attempt to further reduce the emissions of NO_x, direct water injection was tried. As expected, the combustor performance was severely degraded. At an inlet-air temperature of 590 K, the combustor blew out at a water-air ratio of 0.025. Direct water injection was marked by noisy, unstable combustion and reduced combusion efficiency. Gas analysis data show that about 90 percent of the combustion inefficiency is due directly to unburned fuel. Where combustion could be maintained, the use of direct water injection did decrease the emissions of NO_x.

CONCLUDING REMARKS

Research on most of the combustor concepts mentioned will be continuing in an effort to better understand ways of minimizing the pollutants from combustors. The goals that have been established for future gas turbine engines will require that there be new technology in combustor design. Several trends and approaches are well understood but with the exception of exhaust smoke have yet to be demonstrated on flight engines. In addition to the aircraft engine emissions research being conducted "in-house" by NASA/Lewis, a contracted effort designated as the "Experimental Clean Combustor Program" has recently been initiated. The goal of the "Experimental Clean Combustor Program" is to make a substantial reduction in all pollutant levels of advanced CTOL engines. The primary emphasis of these contracts will be to demonstrate a 75 percent reduction in NO_x emissions. However there will also be attempts to significantly reduce the emissions at idle. Demonstration of the best combustor concepts will evenutally include ground static tests in a large high pressure ratio engine.

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TABLE I. - EFFECT OF FUEL STAGING

Idle Operation

P_3 = 4 atm
T_3 = 480 K
f = 0.008

Type of combustor	Annulus	Effi-ciency	H/C	CO
Swirl Can	All	< 50	> 200	~80
	Inner	~100	15	40
Double Annular	Both	92	98	132
	Inner	~100	15	78

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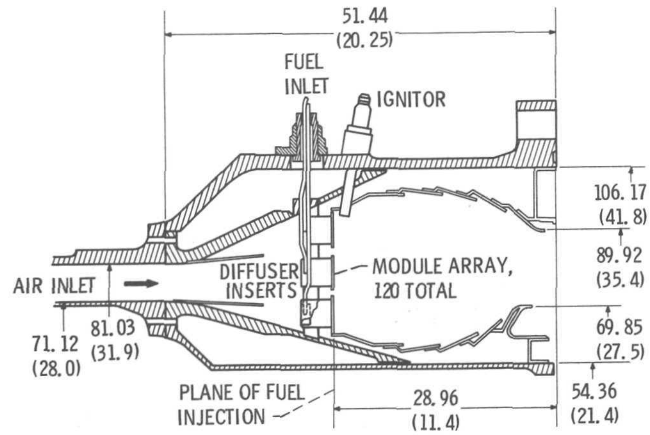

Figure 1. - Full annular model of high-temperature combustor. (Dimensions in centimeters (in.).)

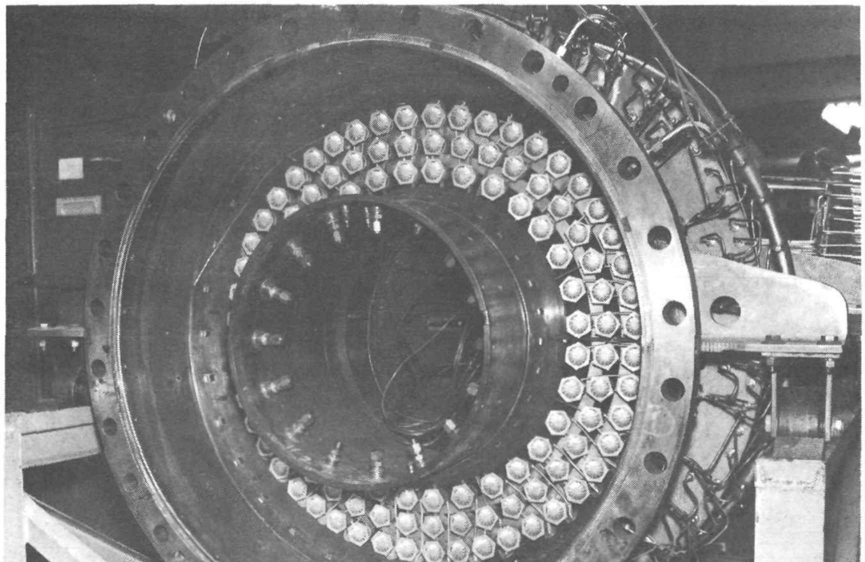

Figure 2. - Annular swirl-can-modular combustor.

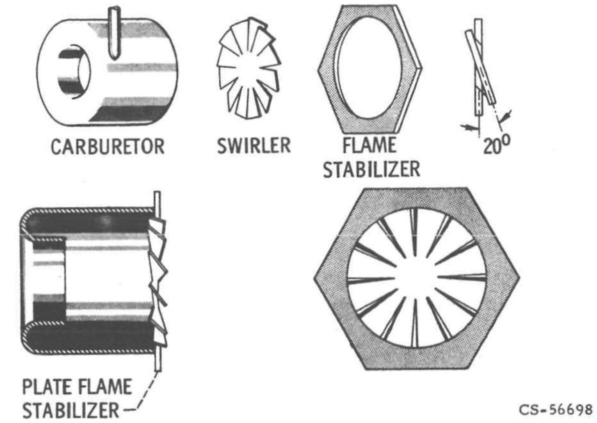

Figure 3. - Combustor module details.

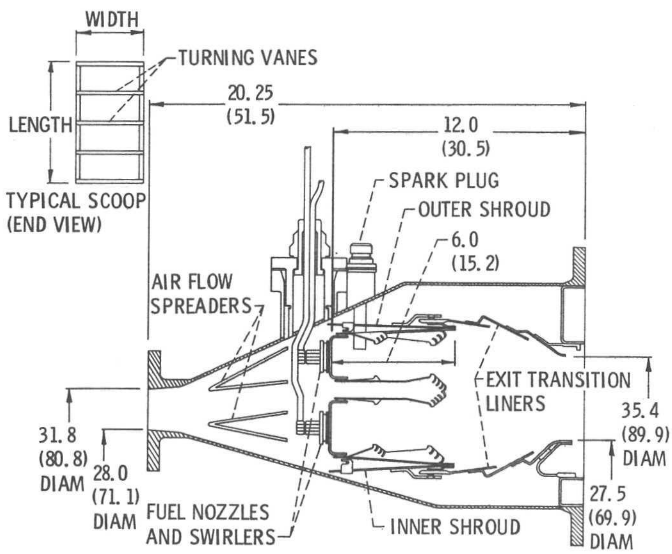

Figure 4. - Cross-section of double-annular ram induction combustor. Dimensions are in inches (cm).

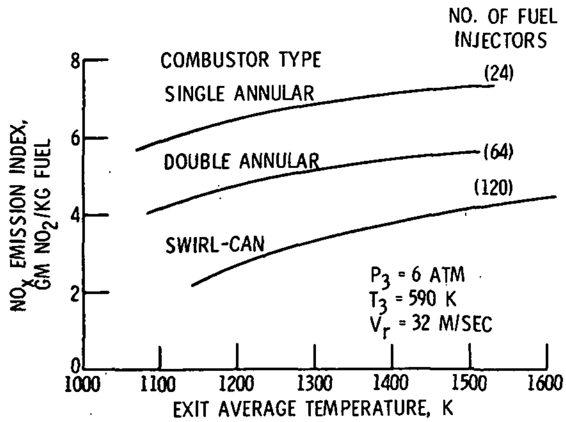

Figure 5. - Comparison of NO_x emissions of single zone and multizone combustors.

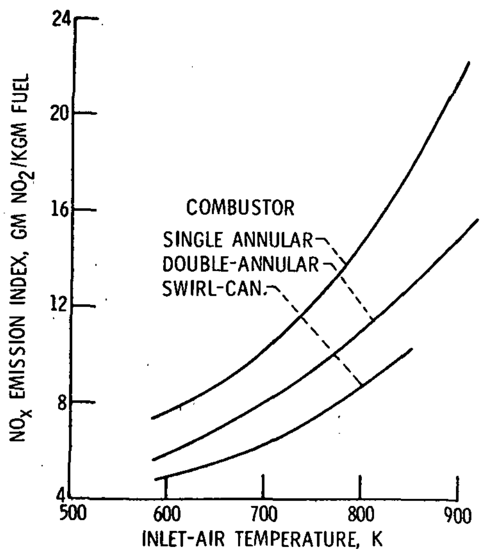

Figure 6. - Variation of NO_x emission index with increasing inlet-air temperature for single and multizone combustors at a pressure of 6 atmospheres and an exit average temperature of 1500 K.

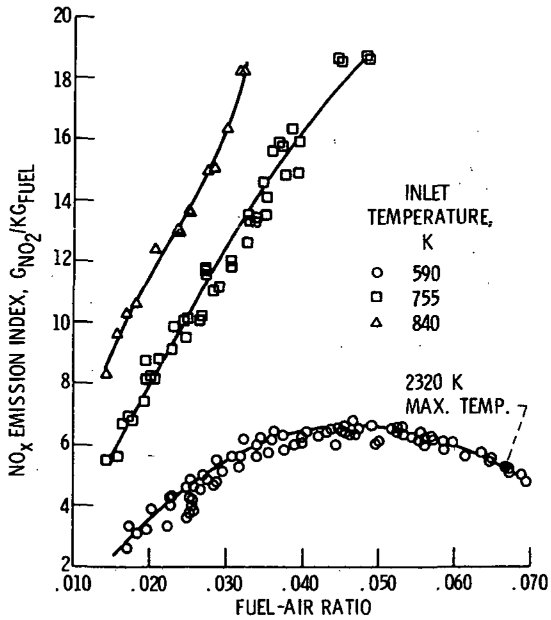

Figure 7. - Effects of combustor inlet temperature and fuel-air ratio on oxides of nitrogen formation in a swirl-can combustor. Combustor inlet pressure, 5 to 6 atmospheres: airflow, 38.5 to 50 kg/sec.

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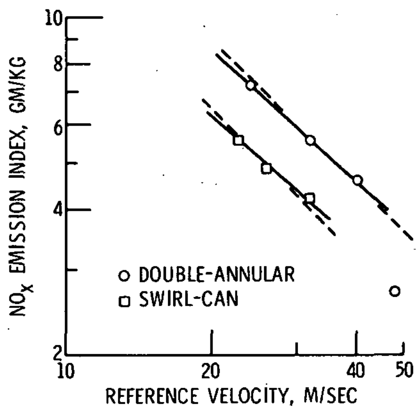

Figure 8. - Effect of reference velocity on NO_x emissions of multizone combustors. Inlet-air temperature, 590 K; inlet pressure, 6 atmospheres.

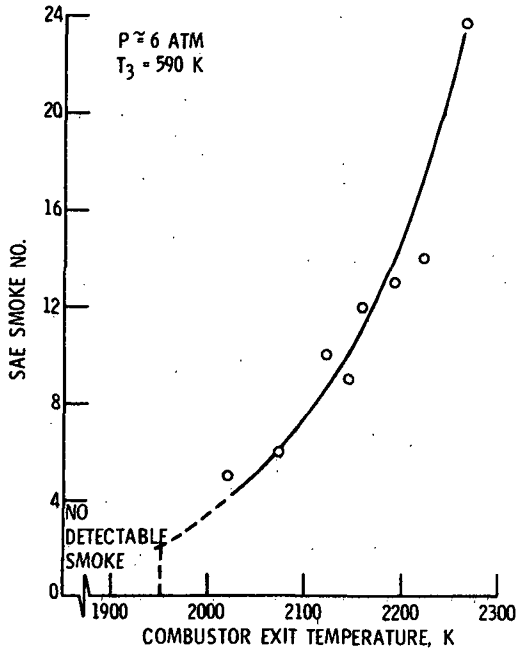

Figure 9. - Variation of smoke number with exit temperature for the swirl-can combustor.

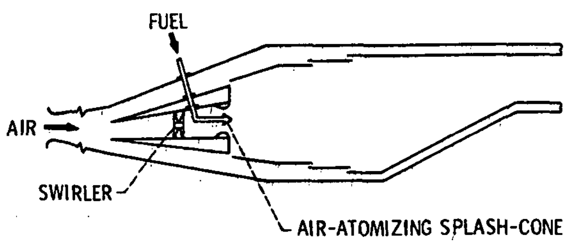

Figure 10. - Sketch of high pressure combustor using air atomizing splash cone fuel injectors.

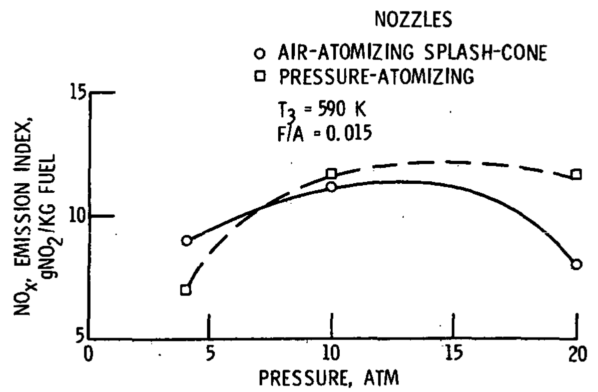

Figure 11. - Effect of combustor pressure on NO_X emissions for air atomizing and pressure atomizing fuel injectors.

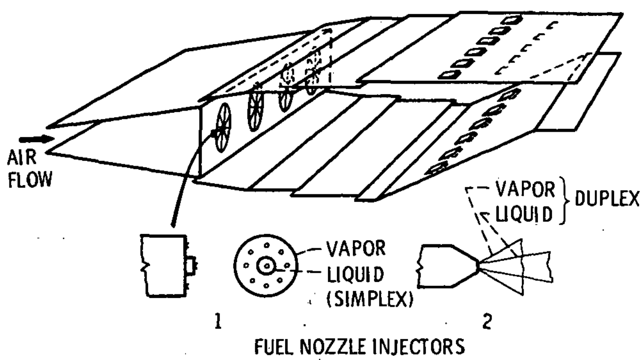

Figure 12. - Sketch of test combustor with dual fuel injection system for liquid ASTM A-1 and gaseous propane.

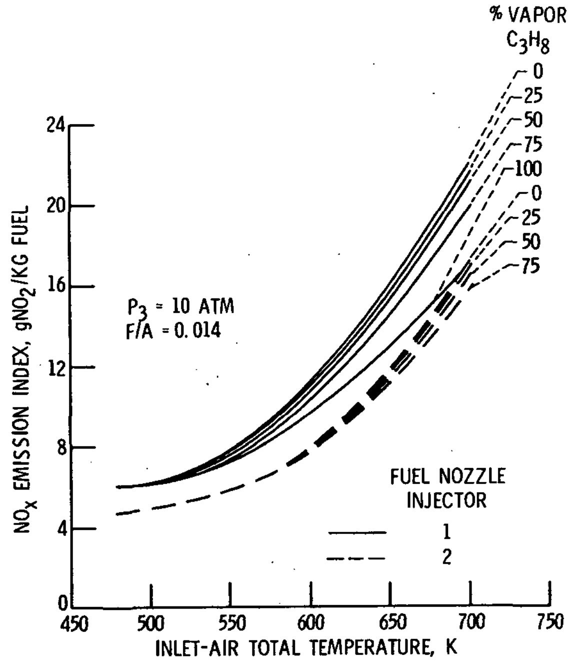

Figure 13. - Variation in NO_x emission index with inlet total temperature for various percentages of gaseous propane.

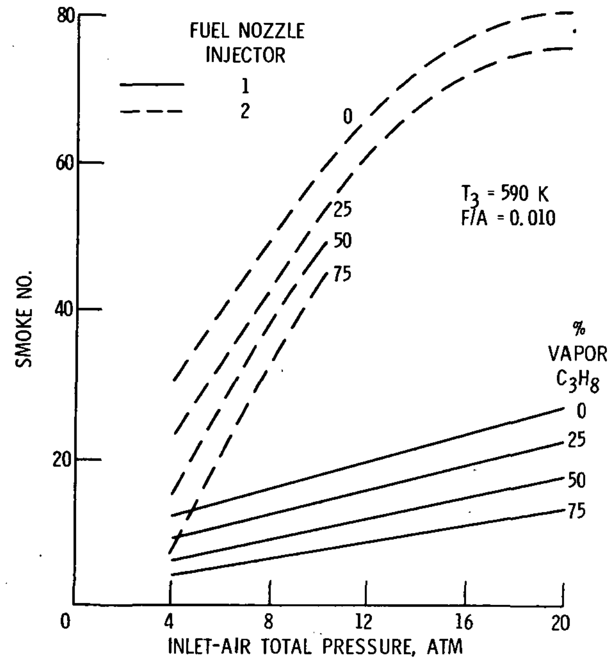

Figure 14. - Variation in smoke number with inlet total temperature for various percentages of gaseous propane.

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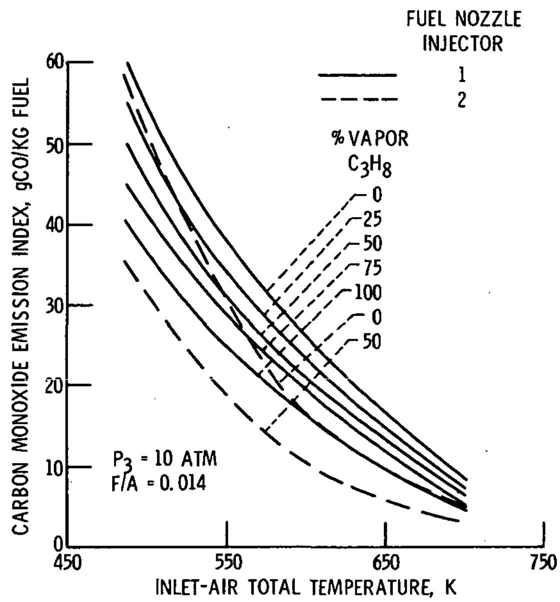

Figure 15. - Variation in carbon monoxide emission index with inlet total temperature for various percentages of gaseous propane.

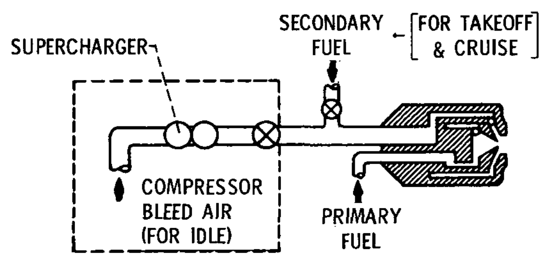

Figure 16. - Sketch of air-assist fuel injection system.

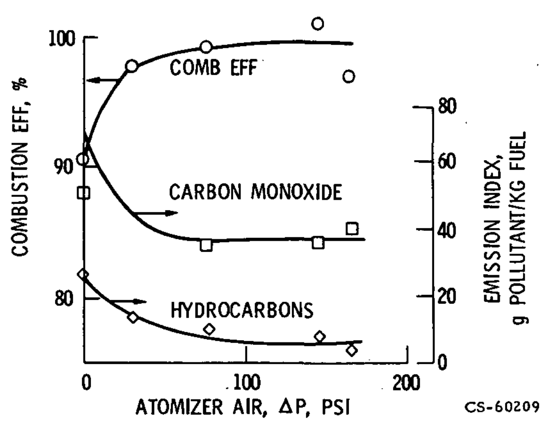

Figure 17. - Variations in combustion efficiency and emission indices for carbon monoxide and total hydrocarbons with the atomizer pressure drop of an air-assist fuel nozzle at simulated idle conditions.

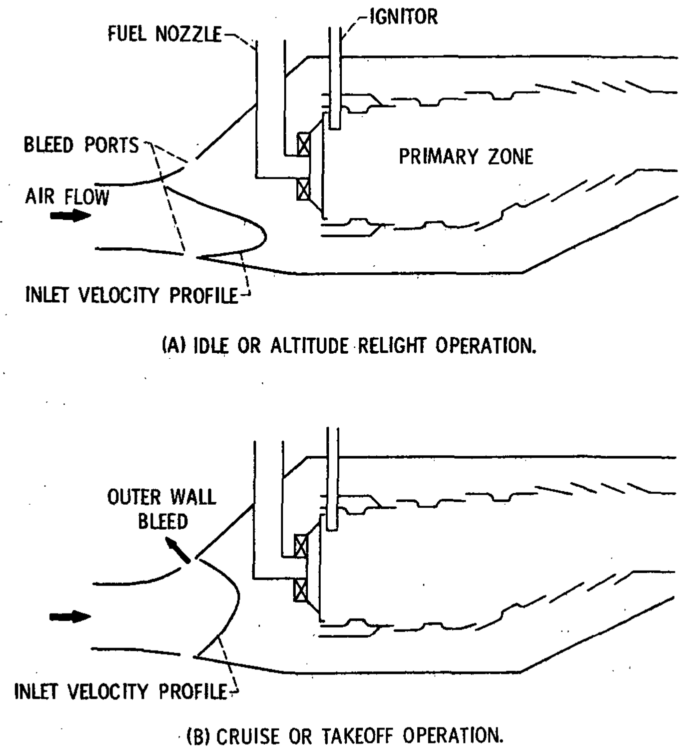

Figure 18. - Application of diffuser bleed in conventional annular combustor.

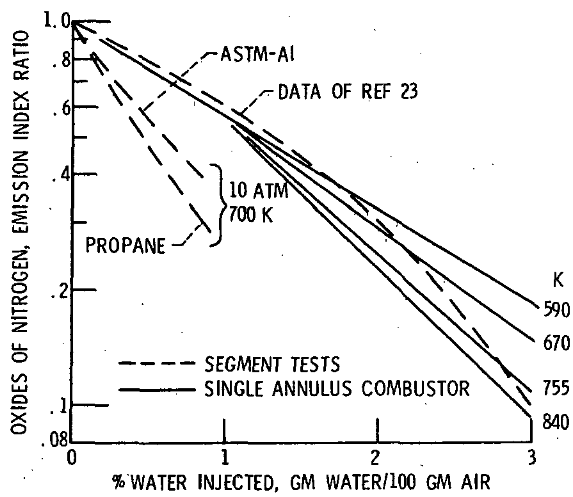

Figure 19. - Effect of water injection on emissions of oxides of nitrogen.

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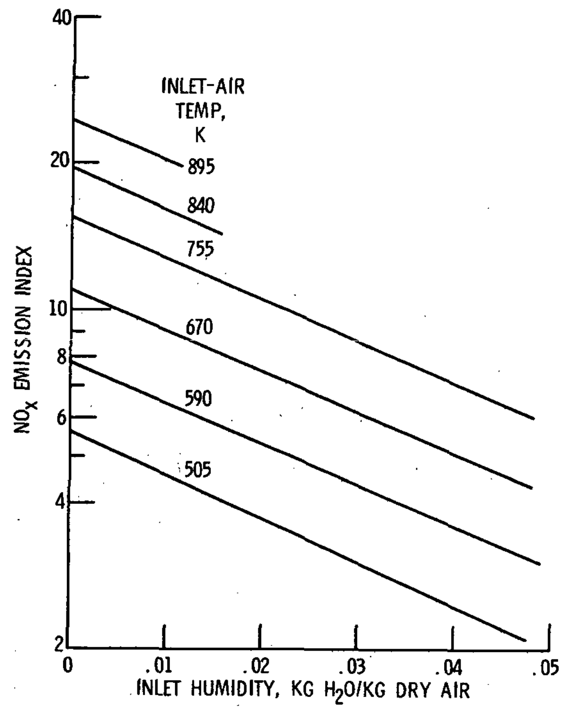

Figure 20. - Effect of inlet air humidity on NO_x emisions. Combustor pressure, 6 atmospheres; exit temperature, 1500 K.

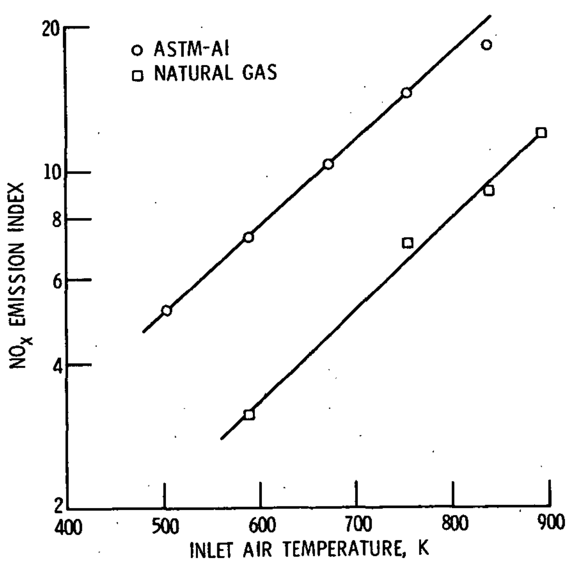

Figure 21. - Comparison of NO_x emissions of ASTM-1 and natural gas fuels. Combustor pressure, 6 atmospheres; exit temperature, 1500 K.