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Abstract

Forecasts of engine exhaust emissions that may be practicably achievable for future commercial aircraft operating at high altitude cruise conditions are compared to cruise emissions for present day aircraft. These results summarize jet aircraft emissions studies reported in the Climatic Impact Assessment Program (CIAP) Monograph 2 "Propulsion Effluents in the Stratosphere." The forecasts are based on: (1) knowledge of emission characteristics of combustors and augmentors; (2) combustion research in emission reduction technology; and (3) trends in projected engine designs for advanced subsonic or supersonic commercial aircraft. Recent progress that has been made in the evolution of emissions reduction technology will be discussed.

Summary

Forecasts of engine exhaust emissions that may be practicably achievable for future commercial aircraft operating at high altitude cruise conditions are compared to cruise emissions for present day aircraft. These results summarize jet aircraft emissions studies reported in the Climatic Impact Assessment Program (CIAP) Monograph 2 "Propulsion Effluents in the Stratosphere." The forecasts are based on: (1) knowledge of emission characteristics of combustors and augmentors; (2) combustion research in emissions reduction technology; and (3) trends in projected engine designs for advanced subsonic or supersonic commercial aircraft. Most of the research related to cruise emissions is concerned with reducing the quantity of nitrogen oxides emitted into the stratosphere. Current subsonic and supersonic commercial aircraft produce as much as 20 grams of NO_2 per kilogram of fuel burned during cruise. Experimental combustors that have been designed to minimize emissions have achieved levels as low as 6-8 gNO_2/kg fuel at simulated cruise, while laboratory burners have reached levels less than 1 gNO_2/kg fuel. A substantial research and development effort will be required to demonstrate the practicality of incorporating these low emission combustor concepts into actual engine hardware and to determine the level to which emissions may be reduced without compromising engine performance and [illegible]ility.

Introduction

This paper summarizes studies to forecast future jet aircraft exhaust emissions that were performed in support of the Climatic Impact Assessment Program (CIAP). Cruise emission predictions for future subsonic and supersonic commercial jet aircraft are compared to measured or estimated emission levels for present-day aircraft. The Department of Transportation organized the CIAP effort in order to determine the potential climatic effects of perturbations of the upper atmosphere caused by the propulsion effluents of a world-wide high-altitude aircraft fleet projected to the year 1990 and beyond (ref. 1). The overall findings of the CIAP study reported in ref. 1 are based on the analyses of data compiled in six monographs, which are to be published in mid-1975. These six monographs are entitled: (1) The Natural Stratosphere of 1974, (2) Propulsion Effluents in the Stratosphere, (3) The Stratosphere Perturbed by Propulsion Effluents, (4) The Natural and Radiatively Perturbed Troposphere, (5) Impacts of Climatic Change on the Biosphere, and (6) Economic and Social Measures of Biologic and Climatic Change.

Most of the cruise emission data for present-day jet aircraft that are presented herein were extracted from Chapter 4 of Monograph 2 (ref. 2) entitled "Emission Characteristics of Representative Current Engines." The cruise emission predictions for future jet aircraft were obtained from Chapter 5 of Monograph 2 (ref. 2) entitled "Forecast of Jet Engine Exhaust Emissions of High Altitude Commercial Aircraft Projected to 1990" (also described in ref. 3 and 4).

Most of the discussion presented in this paper will pertain to the problem of reducing NO_x since it is believed to be the most significant pollutant formed during high altitude cruise. The subject matter will be divided into the following six sections: (1) Cruise Emissions for Present-Day Commercial Jet Aircraft, (2) NO_x Formation Considerations, (3) Effect of Operating Conditions on NO_x Emissions, (4) NO_x Reduction Research, (5) Design Trends for Future Commercial Jet Aircraft Engines, and (6) Forecasts of Future Cruise NO_x Emissions.

Cruise Emissions For Present-Day Commercial Jet Aircraft

The constituents present in the jet engine exhaust include oxides of nitrogen (NO_x), carbon monoxide, total hydrocarbons (unburned plus partially oxidized hydrocarbons), soot (carbon), SO_x (SO_2 plus SO_3), trace elements, carbon dioxide, and water. During cruise, the combustion efficiency of core engine combustors is very nearly 100 percent; therefore carbon monoxide (CO) and total hydrocarbon (THC) emissions are very small. Typical cruise emission indices (grams of pollutant per kilogram of fuel burned) for CO and THC are 4 and 0.1, respectively. Future supersonic commercial aircraft that use augmentors during cruise would have somewhat higher CO and THC emissions. The CO and THC emission indices for a future supersonic aircraft with augmentation during cruise might be as high as 30 and 10, respectively. Aside from the possible need to reduce CO and THC emissions from augmentors, the cruise CO and THC emissions are not considered to be a significant problem with the exception that techniques for reducing NO_x may result in increasing carbon monoxide emissions. Thus a tradeoff exists between the desired emissions levels for NO_x and CO (ref. 5). The quantity of soot (carbon) emitted during cruise is estimated to be about 0.1 gC/kg fuel for current engines and about 0.02 gC/kg fuel for future engine designs.

Of all the constituents formed during high altitude cruise, only NO_x (NO plus NO_2) and SO_x (SO_2 plus SO_3) are considered to pose a serious threat to the global environment (ref. 1 and 6). Nitrogen oxides are of concern because of the ozone depletion problem, and SO_x is of concern because of sulfate aerosol formation which may reduce solar radiation. The emission index for SO_x, which is directly related to the amount of sulfur in the fuel, is currently about 1 gSO_2/kg fuel. Lower SO_x emissions may be accomplished by increasing the degree of hydrodesulfurization at the refinery.

Cruise NO_x emission indices from current subsonic and supersonic aircraft engines are presented in Table I. Available engine operating data are also included in this Table. Most of these data were obtained from Chapter 4, Monograph 2 (ref. 2). The data for the JT8D engine were obtained from (ref. 7), and the data for the CF6-50 engine were obtained from (ref. 8).

In general, the NO_x emission index increases with increasing combustor inlet temperature and pressure as a result of higher compressor pressure ratios and/or higher flight speeds, and approach a maximum value of about 18-20 g NO_2/kg fuel for the latest production engines for both subsonic and supersonic aircraft. The NO_x emission index is conventionally expressed as grams of NO_2 per kilogram of fuel burned even though most of the NO_x in the exhaust is in the form of nitric oxide (NO).

NO_x Formation Considerations

At full power conditions, combustors operate with high inlet temperatures, high inlet pressures, and high fuel-air ratios - all of which contribute to the formation of NO_x. The NO_x formation rate increases with increasing flame temperature, and flame temperature increases proportionately with increases in combustor inlet temperature. Higher combustor inlet temperatures result from higher engine compressor pressure ratios or from higher aircraft flight speeds, particularly during supersonic cruise. Nonuniform fuel distribution in the primary zone also causes locally high flame temperatures.

The effect of flame temperature on the formation of NO_x is illustrated in figure 1. These results were calculated for a combustor burning premixed fuel and air at an inlet temperature of about 800 K, a pressure of 5.5 atm, and a residence time of 2 milliseconds. The formation of NO_x increases exponentially with increasing flame temperature.

Conventional combustors have average flame temperatures of the order of 2300 to 2500 K in the primary zone since they are designed to operate near an equivalence ratio of unity where near maximum flame temperatures occur. The equivalence ratio is the ratio of the average local fuel-air ratio to the stoichiometric fuel-air ratio, which is that required for complete combustion of the fuel. Because a conventional combustor operates with a nonhomogeneous diffusion flame, the effect of average primary-zone flame temperature on NO_x formation is not as strong as that shown in figure 1. Although some reductions in NO_x could be achieved if flame temperature could be lowered by burning leaner fuel-air mixtures, a more effective approach is to reduce locally high flame temperature by improving fuel atomization and mixing. The greatest reductions in NO_x, however, can be obtained by using lean premixed, prevaporized fuel/air mixtures. The homogeneous fuel-air mixtures which result from premixing and prevaporizing are characterized by the strong effect of flame temperature on NO_x displayed in figure 1.

Another cause of high NO_x formation levels is excessive residence time of combustion gases in the primary zone. The formation of NO_x tends to be somewhat linear with residence time over a limited time span for a primary zone equivalence ratio near unity. This effect tends to be less significant as the equivalence ratio is reduced. The residence time in a combustion chamber is typically of the order of about 2 to 4 milliseconds. However, the equilibrium value of NO_x is not approached until after several seconds and is much higher than the quantity of NO_x which is actually formed within a typical combustion chamber. Residence time may be reduced by either increasing velocities in the primary zone or by providing more rapid quenching of the combustion products.

Effect of Operating Conditions on NO_x Emissions

Combustor Operating Conditions

The combustor operating variables that influence the formation of NO_x include combustor inlet temperature, combustor inlet pressure, combustor reference velocity, combustor temperature rise, inlet fuel temperature, and inlet air humidity. The variation of flame temperature with combustor inlet temperature is very close to being linear. The NO_x emission index was shown to increase exponentially with flame temperature in figure 1; therefore, as expected the NO_x emission index also increases exponentially with combustor inlet temperature. Different investigators (ref. 2, Chapter 4 and ref. 9) have correlated the NO_x

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emission index with $e^{T_3/a}$ where T_3 is the combustor inlet temperature and a is an empirically determined constant. These different investigators have used values of the constant "a" from 169 to 288 K to correlate their experimental data. The broad spread in this value may be attributed to differences in combustor geometry and specifically to differences in the primary zone equivalence ratio and the degree of homogenity of the fuel-air mixture in the primary zone.

In general, most investigators have determined that the NO_x emission index varies directly with the square root of pressure. The NO_x emission index tends to be inversely proportional to the combustor reference velocity since reference velocity is inversely proportional to primary zone residence time. In conventional combustors, the NO_x emission index increases directly with the temperature rise across the combustor (over-all equivalence ratio). The effect of fuel temperature and inlet air humidity are discussed in ref. 10 and 9, respectively. Reference 10 observed that the NO_x emission index increases at a rate of 6 percent per 100 K increase in fuel temperature. The NO_x emission index was shown to increase with decreasing inlet air humidity at a constant exponential rate of e^{19H} (where H is humidity, gH_2O/g dry air) in (ref. 9). The humidity of the atmosphere at cruise altitudes is essentially zero.

Engine/Aircraft Operating Conditions

The engine/aircraft operating conditions that affect the NO_x emission index are compressor pressure ratio, turbine inlet temperature, flight Mach number, and cruise altitude. These variables influence the NO_x emission index through their effect on combustor operating conditions. The combustor inlet temperature during cruise is a function of the combined total temperature rise across the inlet diffuser and the compressor. For supersonic cruise, the total temperature rise across the diffuser due to the ram pressure rise becomes quite significant. Thus, the NO_x emission index increases with increases in compressor pressure ratio and flight Mach number. The combustor inlet total pressure increases with increasing compressor pressure ratio, increasing Mach number, and decreasing altitude.

NO_x Reduction Research

As discussed previously, the NO_x emission index may be reduced by reducing the flame temperature and residence time in the primary zone. Over the last several years, a great deal of research has been conducted by various government agencies and engine manufacturers to evolve techniques for reducing the formation of NO_x in gas turbine combustors. No attempt will be made herein to survey the literature on this subject. Instead, several recent fundamental and applied research programs will be summarized that are indicative of the status of technology for reducing NO_x emissions during cruise.

Fundamental Fuel-Lean Combustion Experiments

Conventional combustors are designed to burn a near stoichiometric mixture of fuel and air at full power operating conditions. The reduction of NO_x by lowering the primary zone flame temperature may be approached by burning leaner fuel-air mixtures. Lean burning is most effective when local high temperature zones are eliminated by the use of a homogeneous fuel-air mixture. This can be obtained by premixing a prevaporized fuel upstream of the combustor.

Experiments have been conducted at NASA Lewis Research Center to determine the minimum level to which NO_x could be reduced in an idealized fuel-lean premixing-prevaporizing burner. Testing has been performed in the laboratory flame-tube apparatus shown schematically in figure 2. Gaseous propane or atomized Jet-A is injected upstream of a perforated-plate flame holder with sufficient distance to provide a completely prevaporized/premixed fuel-air mixture to the primary zone (flame zone) test section. Exhaust gas samples can be extracted at varying distances downstream of the flame holder to insure that combustion is completed at the sample measurement position. Some of the results obtained to date are presented in figure 3 where the emission index of NO_x is plotted as a function of equivalence ratio. These data which were obtained at an inlet temperature of 800 K, a pressure of 5.5 atm., and a residence time of 2 milliseconds are compared with a theoretical plot calculated from a well-stirred reactor model. Extremely low values of NO_x(<1 g/kg) were obtained at the very lean equivalence ratios (<0.5). The good agreement with the well-stirred reactor model predictions indicates that good premixing was obtained. All data shown were taken with combustion efficiencies greater than 99%; however, the lowest values were obtained at the edge of the combustion flammability limits and any slight perturbation in flow caused combustion blowout. Because of this stability sensitivity, these results are considered to be near the fundamental lower limit of NO_x emissions for the type of experimental hardware used in this investigation. It is important to note that the operating conditions for this experiment were very carefully controlled and do not necessarily duplicate conditions in an actual engine except for the levels of inlet pressure and temperature which simulate a typical supersonic cruise condition.

By moving the gas sampling probe axially (fig. 2), it was possible to determine the effect of residence time on NO_x emissions. The results plotted in figure 4 show that at 0.[illegible] equivalence ratio, a reduction in residence time from 3 msec to 2 msec gives a 43% decrease in NO_x. At 0.4 equivalence ratio, however, the same reduction in residence time gives only a very small drop in NO_x. Thus, residence time becomes less important to NO_x formation as equivalence ratio is decreased to very lean values. This is due to lower rates of NO_x formation at lean conditions.

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In considering residence time reduction for NO_x control it is important to determine the minimum residence time required for good combustion efficiency. Bands of constant combustion efficiency are shown in figure 4. The shaded area represents combustion efficiency of 99 to 99.7%. The cross-hatched portion represents combustion efficiencies of less than 99%. Data which fell in the unshaded portion of the graph have combustion efficiency greater than 99.7%. The results of these experiments show that for good combustion efficiency, less NO_x was produced with very lean equivalence ratios and long residence times than at somewhat higher equivalence ratios and short times. More details of this experiment are given in (ref. 11). A similar experiment with similar results is being conducted under a NASA contract with General Applied Science Laboratories (ref. 12).

Another evaluation of the premix technique is being conducted under NASA contract to the Solar Division of International Harvestor using "quasi-combustor" type tubular test hardware, figure 5. The concepts shown in figure 5 represent two different approaches to achieve very lean combustion using premixed fuel-air. The "Jet-Induced Circulation Combustor" concept uses jets of premixed fuel-air to create a large recirculation of hot gases into the flame zone which aids in maintaining combustion stability at very low equivalence ratios. The "Vortex Air Blast Combustor" concept uses a rotating flow field to create a similar effect. These combustors differ from the flame tube apparatus (fig. 2) in that no attempt has been made to completely vaporize the fuel upstream of the combustor. Even though the fuel entering these combustors is not completely prevaporized or premixed, preliminary results have been encouraging, and preliminary NO_x emission data for the "Vortex Air Blast Combustor" concept have approached the low levels obtained in the flame-tube apparatus (fig. 2) at simulated supersonic cruise conditions.

The minimum NO_x level of premixed gas phase combustion is limited by the lean flammability limit (minimum flame temperature). Even lower NO_x emissions might be obtained if burning with lower flame temperatures could be achieved by means of catalytic combustion.

The potential application of catalytic reactors to the design of a low emission aircraft gas turbine combustor is discussed in Chapter 3, Monograph 2 (ref. 2). Preliminary results from the evaluation of a catalytic reactor in a laboratory burner using JP-1 fuel (ref. 13) indicated that near 100 percent combustion efficiency could be attained with negligible NO_x formation over a limited range of operating conditions. At an inlet temperature of 650 K, pressure of 7 atm, reference velocity of 13.7 m/sec, and fuel-air ratio of 0.0212 (exit temperature of about 1370 K), a NO_x emission index of less than 0.1 gNO_2/kg was observed (less than 2 ppm, which is about the level of the measurement error of the gas analysis system). At this operating condition, the emission indices for CO and total hydrocarbons were about 1.5 and 0.3 g/kg, respectively. Combustion efficiency decreased markedly as either fuel-air ratio was lowered below a value of about 0.02 or inlet temperature was reduced below a value of about 650 K. At an inlet temperature, above 650 K, exit temperatures up to 1600 K were achieved with good efficiency. Temperatures above 1600 K were avoided to prevent damage to the catalytic reactor. Reactor pressure drop was about 1% of the static inlet pressure at 13.7 m/s reference velocity and 1600 K exit temperature.

Although these initial experimental results are quite encouraging, extensive research is required to establish the feasibility of developing a catalytic combustor for an aircraft gas turbine engine. Methods for obtaining complete combustion over a wider range of operating conditions must be explored. This might be achieved by either using a combination of catalyst with different operating characteristics or by evolving a hybrid two stage combustor consisting of a catalytic reactor and a more conventional flame stabilizer. Catalysts must be developed that are insensitive to poisoning or deactivation in the environment of the gas turbine combustor. Substrates and methods for bonding catalyst on these substrates must be developed that will insure reliable mechanical integrity against thermal and vibrational stresses. Methods to prevent spalling of either catalyst or ceramic substrates must be evolved to avoid deterioration of the combustor or foreign object damage to the turbine. Fuel preparation (premixing-prevaporization) designs must be evolved that provide uniform fuel-air mixtures to the catalytic reactor that avoid preignition or flame propagation (flashback) problems. Catalyst and substrate materials and structures must be developed that demonstrate both good performance and durability at higher operating temperatures. All of these areas must be investigated in greater detail before an honest judgment can be made regarding the practicality of developing a catalytic combustor for an aircraft gas turbine engine.

Applied Low Pollutant Combustor Research

The fundamental low-NO_x combustion concepts described in the previous section have not reached the state of development where they have been tested in properly scaled combustor hardware nor have they been evaluated for performance and durability over the entire range of required operating conditions. As a matter of fact, practical combustor designs incorporating these concepts will require either more than one stage of combustion or variable geometry for control of airflow and fuel flow in order to permit satisfactory performance at both low and full-power conditions. This section will briefly describe test programs being conducted in a more advanced state of real combustor hardware.

Multizone combustors. A large part of the effort on the evaluation of low pollutant emission combustors conducted in-house by NASA has been with the swirl-can-mod'ar combustor shown in figure 6. Figure 6(a) is a photograph of a full-annular array of 120 swirl can modules arranged in three radial rows. A cross-sectional view of this combustor is shown in figure 6(b) and the components of the swirl can module are illustrated in figure 6(c). Each module is composed of a carburetor cup, swirler, and flame stabilizer. Fuel is injected into the carburetor cup where it premixes with air flowing through the cup and then passes through a swirler into the wake created by the flame stabilizer which acts as a quasi-bluff body in the air flowing around the module. The swirling fuel-air mixture provides for a small stable flame zone in the stabilizer wake. The combination of a small flame zone and premixed fuel-air provides for low residence times and some degree of gas temperature control in the flame zone.

The quantitative NO_x reductions achievable with the swirl-can combustor are shown in figure 7. NO_x emission indices for a swirl-can combustor are compared to a more conventional single annular combustor and a double annular combustor at varying inlet air temperatures. These combustors were tested at 6 atm pressure and an exit temperature of 1500 K. Compared to a conventional combustor, two-fold reductions in NO_x are achievable with the swirl-can. The double annular combustor data also presented is from an advanced experimental design which contains 64 fuel nozzles arranged on two annuli. This is slightly greater than twice the number of fuel nozzles contained in a conventional large annular combustor. Superior fuel and air management resulting from this arrangement produces decreased levels of NO_x.

Experimental clean combustor program. The goal of this NASA Lewis contract program is to develop and demonstrate technology to decrease pollutant emissions from modern aircraft turbine engines. This technology is mainly applicable to high bypass ratio turbofans for advanced wide-body subsonic jet aircraft. However, the combustor technology evolved in this program is also applicable to engines for supersonic aircraft. NASA Lewis has awarded contracts for this program to General Electric and Pratt & Whitney. Each contract effort is being conducted in three separate phases. The first phase involved the evaluation of various candidate low-pollutant combustor concepts. The second phase consists of refining the more promising concepts evolved during the first phase, and the third phase consists of an actual demonstration of the more promising low pollutant combustors in a state-of-the-art engine. The Phase I effort included evaluation tests at simulated supersonic cruise operating conditions.

Phase I of the Experimental Clean Combustor Program has been completed. The combustor configurations tested in Phase I were mainly judged by their idle and takeoff emissions. Several of the combustor configurations either achieved or closely approached the idle emissions (CO and total hydrocarbons) goals. Significant reductions in NO_x were also achieved; however, all fell short of the NO_x emission goal at takeoff. The more promising combustors achieved a NO_x emission index at simulated takeoff of about 15 gNO_2/kg fuel compared to a value of about 13 gNO_2/kg fuel that is required to meet EPA emission standards. These EPA emission standards which are described in (ref. 14) are applicable only to low altitude flight operations (below 915 meters). Current production values for these engines during takeoff are about 36 gNO_2/kg fuel. The best NO_x emission indices observed during Phase I at either simulated subsonic or supersonic cruise were of the order of 6-8 gNO_2/kg fuel.

The primary objectives of the Phase II effort will be to improve the overall performance and durability of the more promising combustor configurations without sacrificing the improved emission characteristics demonstrated in Phase I and to assess engine compatibility of these combustors. Specific attention will be directed to improving combustor exit temperature distribution, reducing pollutants further at all engine operating conditions including intermediate power settings and improving altitude relight characteristics. Each contractor is currently conducting Phase II testing and each is evaluating two combustor designs.

The two advanced technology CF6 engine combustor configurations being evaluated in Phase II are shown along with the standard CF6-50 combustor in figure 8. Both designs utilize the concept of fuel scheduling for reducing idle pollutant emissions. The pilot stages of both the radial/axial staged and the double annular are optimized for high efficiency (low CO & THC emissions) at engine idle fuel-air ratios. The main stages are optimized for lean combustion (low NO_x) at full-power fuel-air ratios. Various combinations of fuel scheduling can be used for off-design operation such as approach and climb out power settings. The radial/axial staged configuration utilizes a premixed fue' air approach in the main stage whereas the d[illegible] annular configuration uses an air-blast type [illegible] to obtain lean combustion in the main stage.

The two advanced technology JT9D engine combustor configurations being evaluated in Phase II are shown along with the standard JT9D combustor in figure 9. As with the CF6 configurations both designs use fuel scheduling as the principal approach to controlling idle pollutant emissions. Optimization of the individual stages at idle and full power conditions is used for overall emission control. The hybrid configuration utilizes a parallel (radial) fuel staging approach with a premix technique in the pilot stage and a variation of the swirl can concept in the main stage. This configuration is an attempt to mate the lowest CO & THC emission design (premix pilot stage) and the lowest NO_x emission design (swirl-can-module stage) that was tested in Phase I. The vorbix configuration utilizes a series-type (axial) fuel staging approach with standard type pressure atomizing fuel nozzles in the pilot and main stages. The main stage has high intensity swirlers immediately with the swirl-can-modular combustor shown in figure 6. Figure 6(a) is a photograph of a full-annular array of 120 swirl can modules arranged in three radial rows. A cross-sectional view of this combustor is shown in figure 6(b) and the components of the swirl can module are illustrated in figure 6(c). Each module is composed of a carburetor cup, swirler, and flame stabilizer. Fuel is injected into the carburetor cup where it premixes with air flowing through the cup end then passes through a swirler into the wake created by the flame stabilizer which acts as a quasi-bluff body in the air flowing around the module. The swirling fuel-air mixture provides for a small stable flame zone in the stabilizer wake. The combination of a small flame zone and premixed fuel-air provides for low residence times and some degree of gas temperature control in the flame zone.

The quantitative NO_x reductions achievable with the swirl-can combustor are shown in figure 7. NO_x emission indices for a swirl-can combustor are compared to a more conventional single annular combustor and a double annular combustor at varying inlet air temperatures. These combustors were tested at 6 atm pressure and an exit temperature of 1500 K. Compared to a conventional combustor, two-fold reductions in NO_x are achievable with the swirl-can. The double annular combustor data also presented is from an advanced experimental design which contains 64 fuel nozzles arranged on two annuli. This is slightly greater than twice the number of fuel nozzles contained in a conventional large annular combustor. Superior fuel and air management resulting from this arrangement produces decreased levels of NO_x.

Experimental clean combustor program. The goal of this NASA Lewis contract program is to develop and demonstrate technology to decrease pollutant emissions from modern aircraft turbine engines. This technology is mainly applicable to high bypass ratio turbofans for advanced wide-body subsonic jet aircraft. However, the combustor technology evolved in this program is also applicable to engines for supersonic aircraft. NASA Lewis has awarded contracts for this program to General Electric and Pratt & Whitney. Each contract effort is being conducted in three separate phases. The first phase involved the evaluation of various candidate low-pollutant combustor concepts. The second phase consists of refining the more promising concepts evolved during the first phase, and the third phase consists of an actual demonstration of the more promising low pollutant combustors in a state-of-the-art engine. The Phase I effort included evaluation tests at simulated supersonic cruise operating conditions.

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downstream of the fuel injection point to promote very intense, rapid mixing of the fuel and air in the flame zone. The combination of the intense mixing and hot gases exiting from the pilot stage allow lean operation in the main stage and also reduce residence time due to quick quenching of the hot gases. A more detailed description of this program is presented in (ref. 15 and 16).

Design Trends for Future Commercial Jet Aircraft Engines

Jet aircraft emission forecasts were based on engine design projections described in CIAP Monograph 2, Chapter 5 (ref. 2) and (ref. 4). It is predicted that future commercial subsonic jet aircraft will be equipped primarily with advanced high-bypass turbofan engines and that either a duct-burning turbofan or a nonaugmented (dry) turbojet could be candidates for a future advanced supersonic transport.

Fuels

Conventional JP or hydrocarbon type fuels will probably be the only fuel used by commercial jet aircraft until far beyond 1990. Alternate sources of jet fuel such as shale oil and coal syncrudes may become available sometime after 1985. These "synthetic" crudes generally contain more nitrogen, oxygen, and sulfur, and less hydrogen than crude petroleum. However, the undesirable compounds of nitrogen, oxygen, and sulfur may be removed and the percent hydrogen increased by means of various hydrotreating and hydrocracking processes. Higher organic nitrogen concentrations than are currently present in jet fuel must be avoided because 50 to 90 percent of this fuel bound nitrogen may be converted to nitric oxide during combustion (ref. 17). In principle, jet fuels could be produced from shale oil or coal syncrudes that simulate, in all important respects, those presently derived from petroleum. If so, the cruise emission characteristics of jet fuel derived from shale oil or coal syncrudes would not be expected to differ greatly from fuel derived from petroleum. Emission forecasts for substitute fuels such as liquified hydrogen or liquified natural gas (LNG) have also been included in Monograph 2, Chapter 5 (ref. 2), but it is unlikely that these fuels would be used until far beyond the late 1990's; therefore, the discussion in this report is limited to the JP-fueled aircraft.

Future Subsonic Aircraft Engines

Production or growth versions of aircraft such as the Boeing 747, McDonnell Douglas DC-10, and Lockheed 1011 will probably be in service until at least 1990. Engines for these aircraft (CF-6, JT9D, and RB211) manufactured after 1978 will require modifications in order to meet EPA emission standards (ref. 14). Advanced high-bypass turbofan engines utilizing low emission combustor technology could be incorporated into these aircraft between 1980 and 1985 if they are available. An Advanced Technology Transport (ATT) utilizing an advanced high-bypass turbofan engine could be operational in the early 1990's.

Projected values for the overall compressor pressure ratio for advanced high-bypass turbofan engines range from about 25 to 40. Compared to the latest production engines for subsonic commercial jet aircraft (Table I), these advanced engines would have combustor inlet temperatures and pressures, and exit temperatures ranging from current to higher values. Combustors for these advanced engines could be required, during cruise, to operate with inlet temperatures as high as about 800 K, with inlet pressures as high as about 15 atm., and with exit temperatures as high as 1600 - 1700 K.

Future Supersonic Aircraft Engines

The Concorde and Tupolev TU-144 or growth versions of these aircraft will probably continue to be in service during the 1980 to 1990 time period; however, advanced supersonic transports of greater size and range would not be expected to enter service before 1990. The engine selection for an advanced supersonic transport will be influenced significantly by noise constraints. Either a duct-burning turbofan or a nonaugmented (dry) turbojet could be considered as a candidate for this application. An advanced supersonic transport would be expected to cruise within a Mach number range of 2.2 to 2.7.

Duct-burning turbofan or dry turbojet engines with projected overall pressure ratios (SLTO) ranging from about 10 to 25 are predicted for future commercial supersonic aircraft. Compared to the operating conditions for the Concorde's Olympus 593 engines (Table I), these advanced engines would have combustor inlet temperatures and pressures, and exit temperatures ranging from current to higher values. Combustors for these advanced engines could be required, during cruise, to operate with inlet temperatures as high as 900 - 1000 K, with inlet pressures as high as 10 - 15 atm., and with exit temperatures as high as 1600 - 1800 K.

Forecasts of Future Cruise NO_x Emissions

Recommendations for future cruise NO_x reductions are presented in references 1 and 6 based on the results of the various CIAP studies. Reductions in the cruise NO_x emission index for current engines of anywhere from six to sixty-fold are recommended. The actual reductions required would be dependent on the future size of the aircraft fleet, cruise altitudes and the amount of cruise time in the stratosphere. Supersonic cruise would be entirely within the stratosphere; however, subsonic cruise in the stratosphere would occur only for a portion of the flight envelope. Therefore, NO_x reductions necessary for future subsonic aircraft are very dependent on the percent of their flight envelope that occurs within the stratosphere.

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Projected Low-Emission Combustor Technology

The projected combustor technology that might be utilized in the advanced propulsion systems described in the previous section are based on a projection of the emission reduction technology discussed in reference 2 (Chapter 5). The evolution of low emission combustor technology available by the 1980 to 1985 time period will be motivated by the need to meet the 1979 EPA emission standards (ref. 14). These emission standards presently pertain only to subsonic aircraft; however, additional standards for supersonic aircraft have also been proposed. These standards are currently only applicable to aircraft operations below 915 meters (landing-takeoff cycle). Many of the concepts being investigated to reduce NO_x for the proposed EPA landing-takeoff cycle would also be effective in reducing NO_x during cruise.

Research programs such as the NASA "Experimental Clean Combustor Program" described previously are applying low emission technology to combustor redesign. The representative engine manufacturers are also engaged in independent research efforts aimed at the development of low emission combustors that would comply with the proposed EPA standards. The type of low-pollutant combustor hardware being evolved and evaluated in research efforts such as the NASA "Experimental Clean Combustor Program" are probably representative of the level of technology that could be available within the next decade. More optimistic predictions of the level of low-pollutant combustor technology that might be available in the future are predicated on the conversion of fundamental concepts such as fuel-lean premixing-prevaporizing burners into practical combustor designs.

Cruise NO_x Emission Index Forecast

The NO_x emission indices listed in Table I for current commercial jet aircraft would be characteristic of existing production engines manufactured prior to 1979 that would continue to be in service during the 1980 to 1985 time period. These engines would not be required to meet the proposed 1979 EPA emission limits since the regulation would only apply to engines either manufactured or certified after 1978. The range of cruise NO_x emission index values of 18-20 gNO_2/kg fuel listed in Table I for the latest subsonic and supersonic commercial aircraft represents a pessimistic projection for future engines. The pessimistic forecasts might result if water injection were to be used partially or totally for the reduction of NO_x during takeoff, in order to meet EPA low altitude emission standards, which would not result in a comparable reduction in NO_x during cruise.

The more probable range of values for the cruise NO_x emission index that might be achievable in advanced engines within the next decade were based on the low-pollutant combustor technology being evolved in efforts such as the NASA "Experimental Clean Combustor Program." Values for the NO_x emission index of 3-8 gNO_2/kg fuel were predicted for future subsonic aircraft using advanced high-bypass turbofan engines, and values of 3-14 g/NO_2/kg fuel were predicted for future supersonic aircraft using advanced duct-burning turbofan or dry turbojet engines. The spread in these predictions is due to the range of possible combustor operating conditions for advanced engines, and the uncertainty as to the degree to which these combustors designs will be able to incorporate fuel-lean premixing-prevaporizing burner concepts.

Optimistic predictions based on the eventual development of a combustor burning premixed-prevaporized fuel near the lean flammability limit indicate that cruise NO_x emission indices of one or less may be attainable in engines for future subsonic and supersonic commercial jet aircraft. These predicted values represent a goal to be approached in practical combustor design. Although NO_x emission indices of one or less have been achieved in laboratory-type burners, a considerable effort will be required to convert this fundamental research into practical combustor technology.

Concluding Remarks

It is premature to arrive at a judgment as to whether or not future commercial aircraft engines will be able to attain cruise NO_x emission indices that are as much as 60 times lower than values for current aircraft engines. Chemical kinetics calculations and fundamental laboratory burner tests conclude that these lower NO_x emission indices are theoretically possible. However, a great deal of ingenuity on the part of combustor design engineers will be required to convert fundamental concepts such as the premixed-prevaporized fuel-lean burner into practical combustor hardware. Research and development programs such as the "NASA Experimental Clean Combustor Program" are attempting to establish a technology base for the design of low emission combustors. A substantial amount of development time and testing will be required to translate experimental technology into production technology that fulfills the safety, reliability, and economic requirements of a commercial aircraft.

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TABLE I. - CRUISE NO_X EMISSIONS FROM CURRENT COMMERCIAL JET AIRCRAFT

AIRCRAFT	ENGINE	CRUISE ALTITUDE, KM	CRUISE MACH NUMBER	COMBUSTOR INLET TEMPERATURE,	COMBUSTOR INLET PRESSURE, ATM	NO_X EMMISSION INDEX, g NO_2/kg
SUBSONIC						
BOEING 707	P&W JT3D	10.7	0.85	~570	~4	6
BOEING 727	P&W JT8D	10.7	0.80	610	5.7	8
BOEING 747	P&W JT9D-70	10.7	0.84	710	10	19
McDONNELL DOUGLAS DC-10	G.E. CF-6-50	10.7	0.85	730	11.4	16.5
LOCKHEED 1011	ROLLS ROYCE RB 211	10.7	0.85	720	10.4	20
SUPERSONIC						
CONCORDE	OLYMPUS 593	17.7	2.0	820	6.5	18
TUPOLEV 144	KUZNETOV NK-144	----	----	---	----	18

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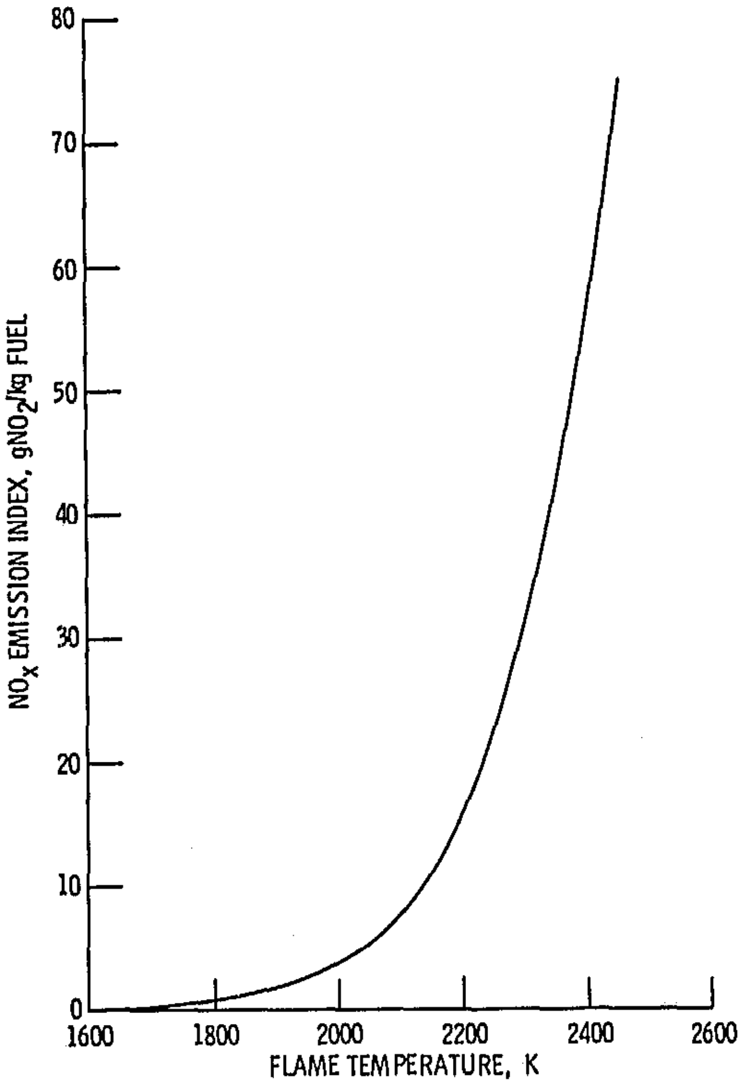

Figure 1. - Effect of flame temperature on NO_x emission index for an ideal premixing-prevaporizing combustor; combustor inlet temperature, 800 K; pressure, 5.5 atm.; and residence time, 2 milliseconds.

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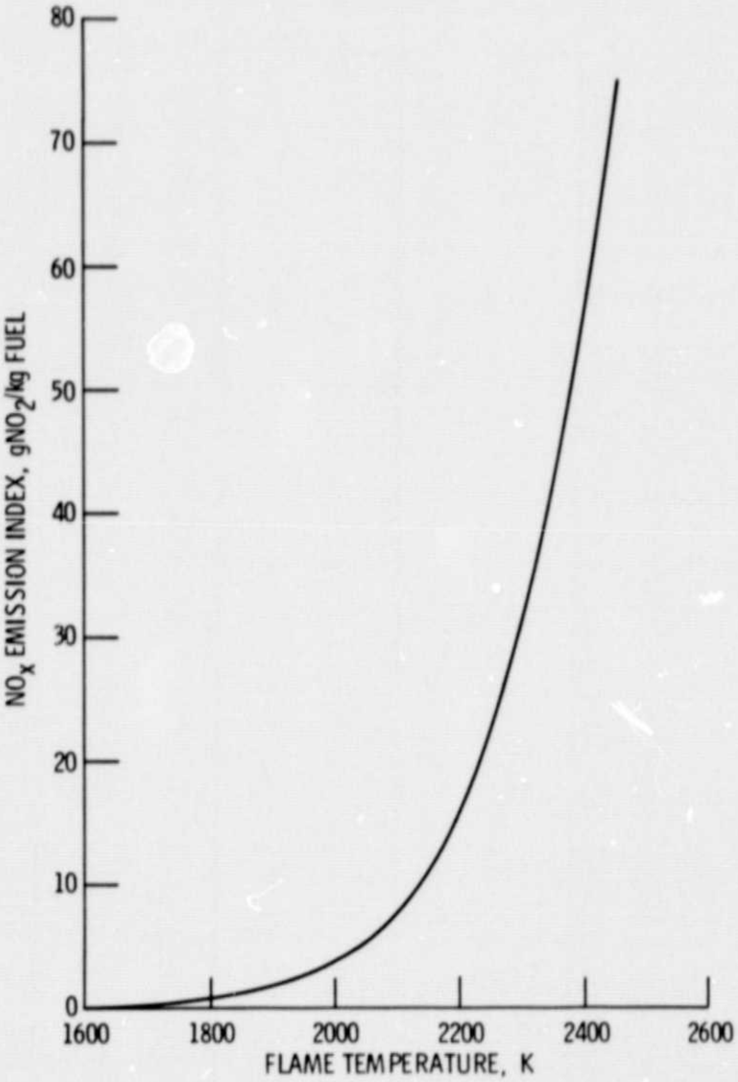

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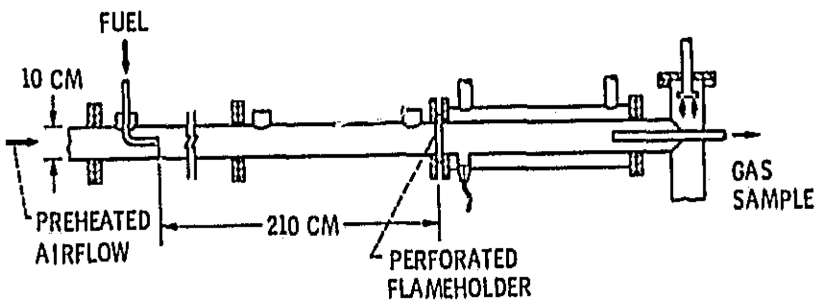


Figure 2. - Premixed primary zone test section.

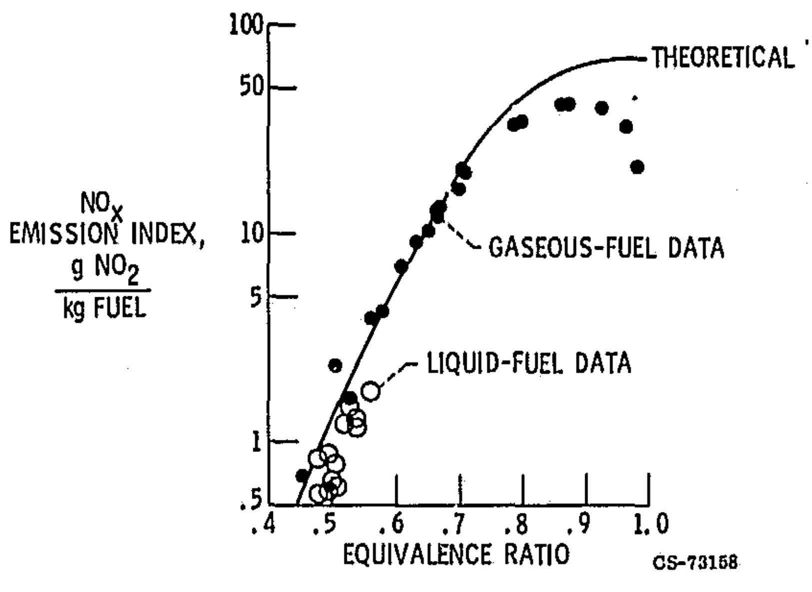
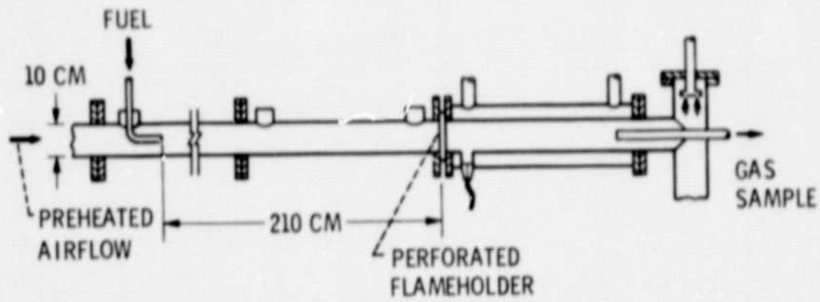


Figure 3. - Variation of NO_x emission index with equivalence ratio in a premixing-prevaporizing burner; inlet temperature, 800 K; pressure, 5.5 atm.; and residence time, 2 milliseconds.



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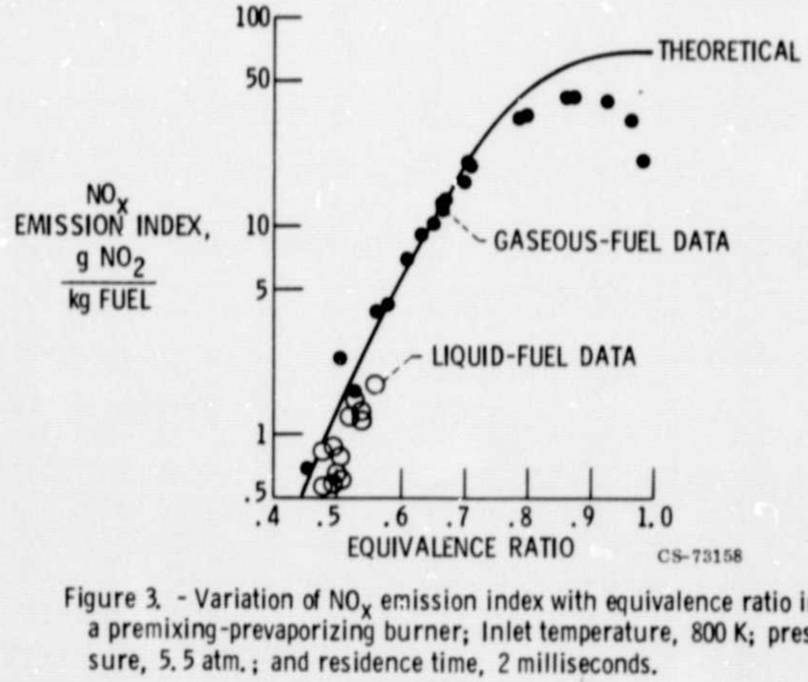

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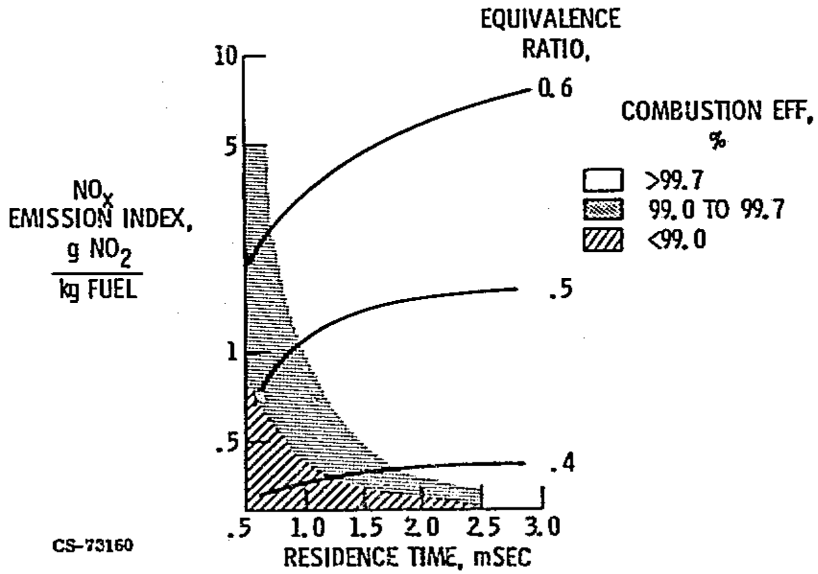
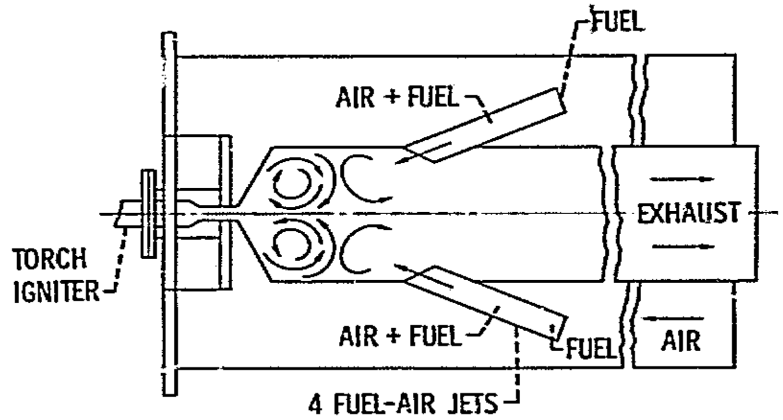
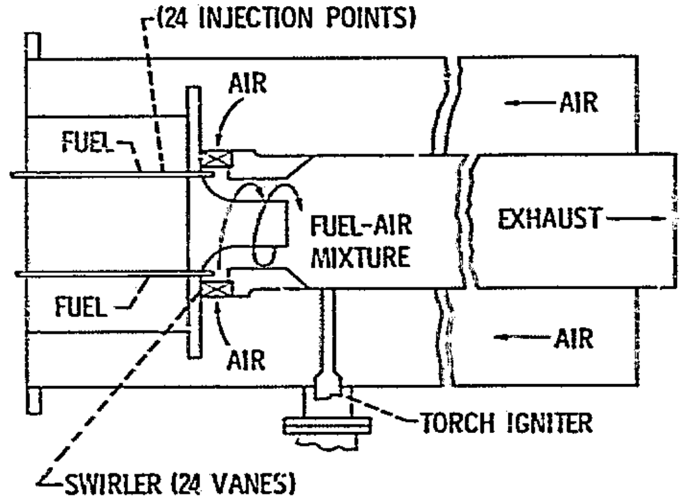


Figure 4. - Effect of residence time on NO_x emission index in premixing prevaporizing burner; inlet temperature, 800 K; pressure, 5.5 atm.

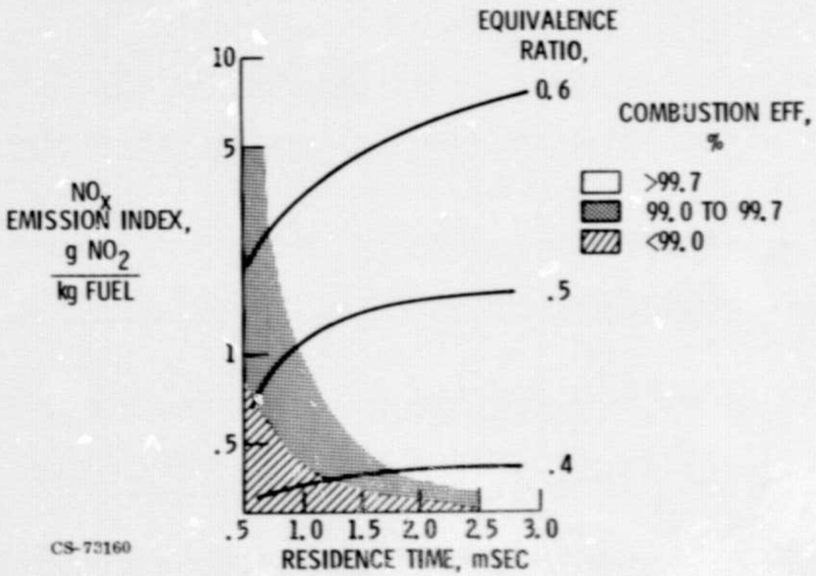


(a) JET-INDUCED CIRCULATION COMBUSTOR CONCEPT.



(b) VORTEX AIRBLAST COMBUSTOR CONCEPT.

Figure 5. - Ultra-low NO_x combustor concepts.



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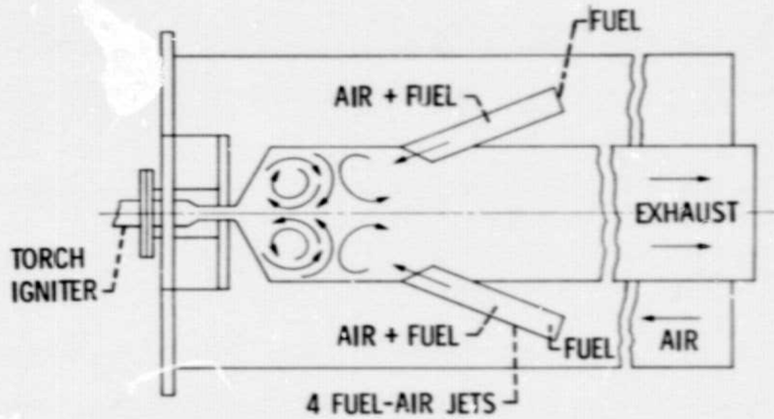
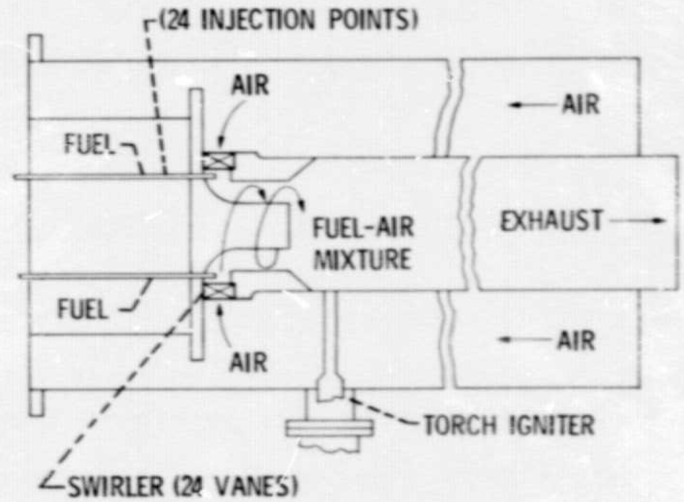
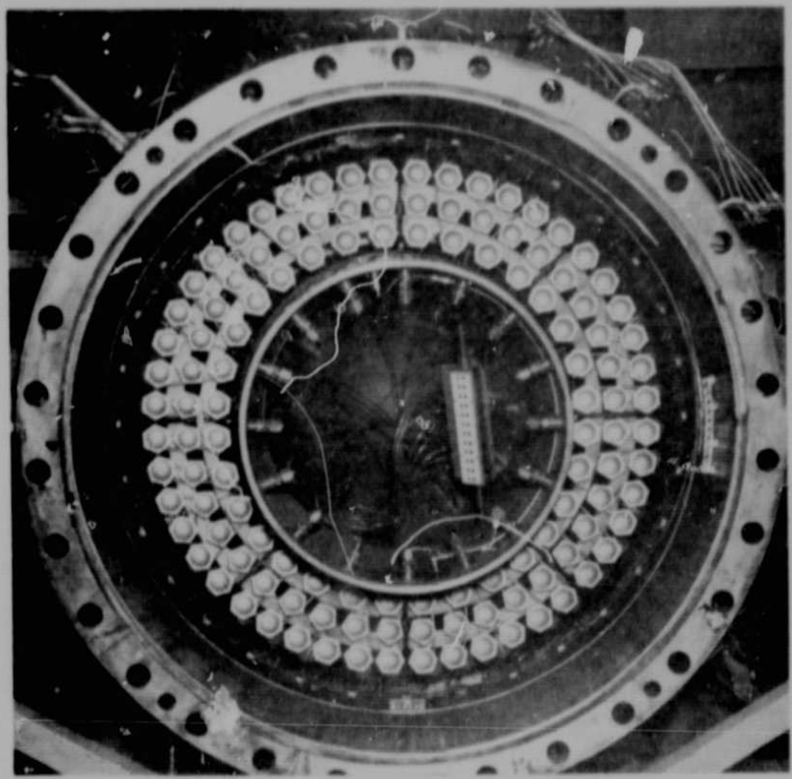


(a) JET-INDUCED CIRCULATION COMBUSTOR CONCEPT.

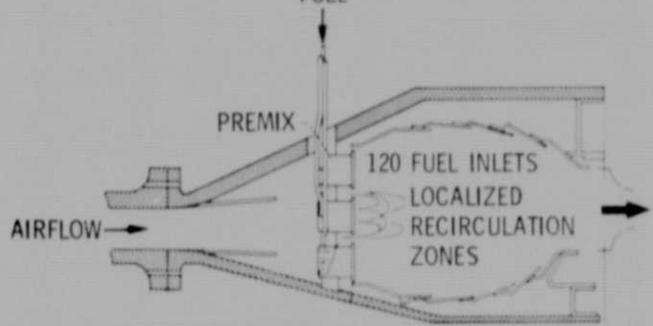


(b) VORTEX AIRBLAST COMBUSTOR CONCEPT.

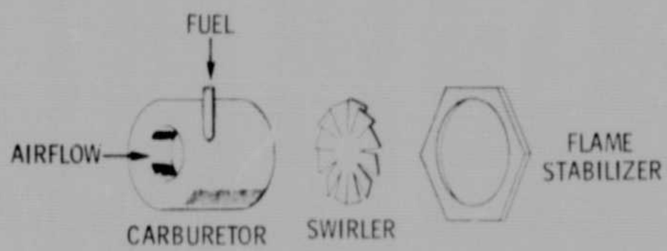
Figure 5. - Ultra-low NO_x combustor concepts.



(a) PHOTO OF FULL ANNULAR COMBUSTOR.



(b) CROSS-SECTIONAL VIEW OF FULL ANNULAR COMBUSTOR.



(c) MODULE COMPONENTS.

Figure 6. - NASA Experimental Swirl-Can-Modular Combustor.

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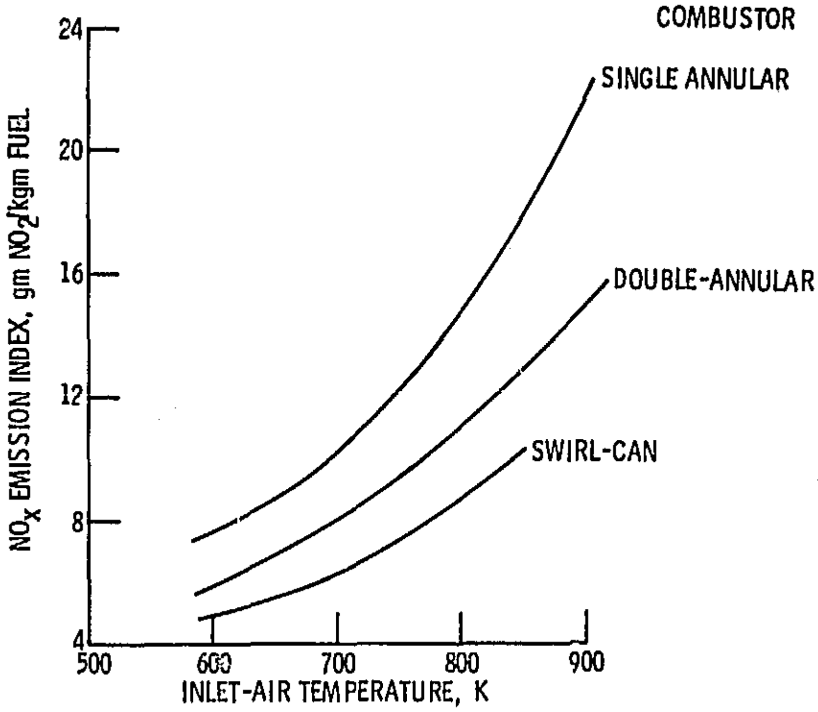
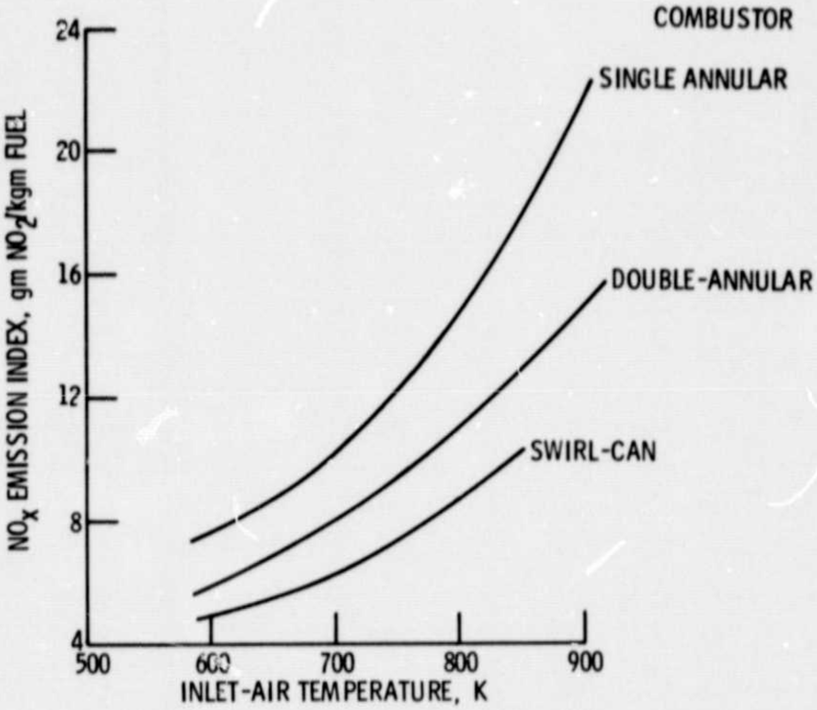


Figure 7. - Variation of NO_x emission index with combustor inlet temperature for single and multi-zone combustors. Combustor inlet pressure, 6 atm; exit temperature, 1500 K.

E-8390



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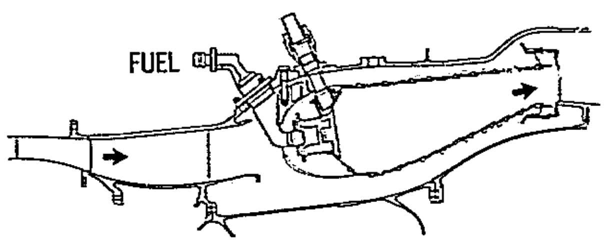
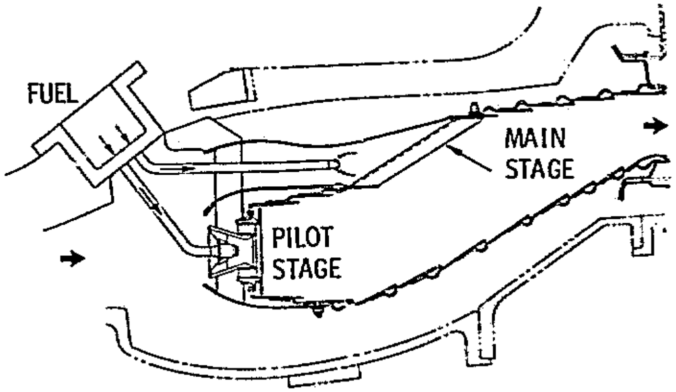
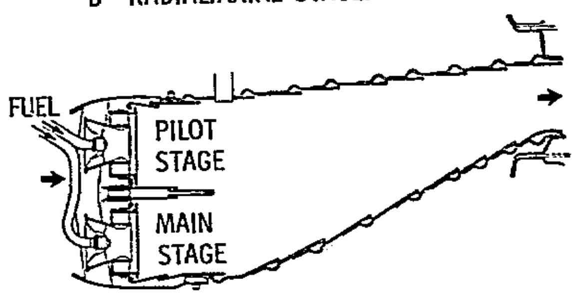


A - CF6-50 ENGINE COMBUSTOR

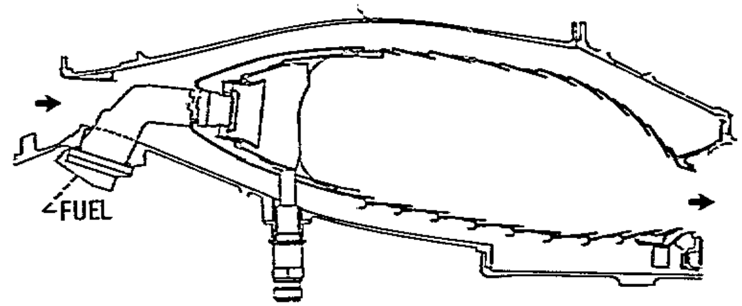


B - RADIAL/AXIAL STAGED COMBUSTOR

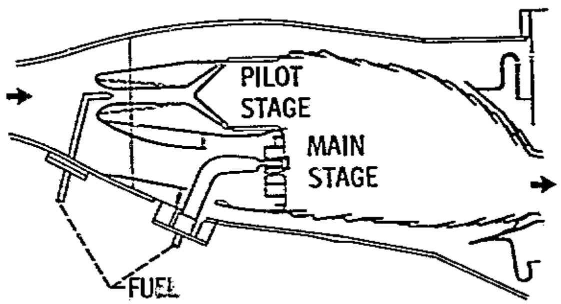


C - DOUBLE ANNULAR COMBUSTOR

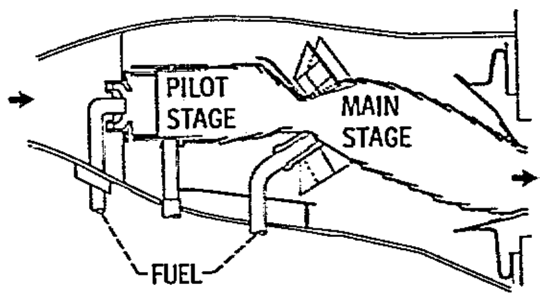
Figure 8. - Experimental clean combustor program, phase 2 - CF6-50 engine.



A - JT9D ENGINE COMBUSTOR

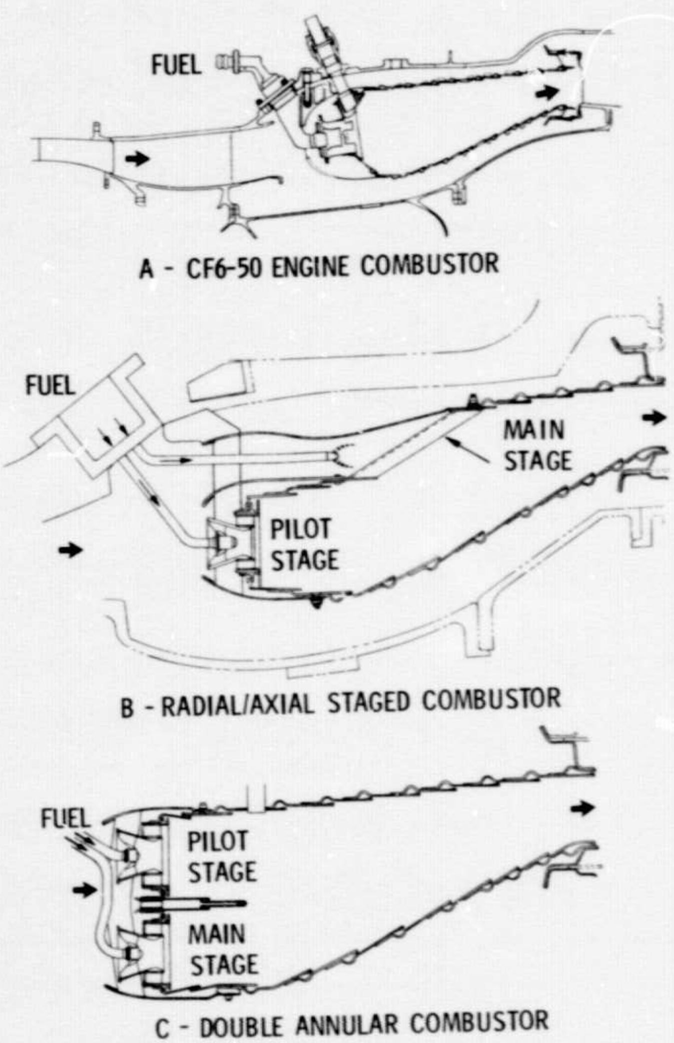


B - HYBRID COMBUSTOR



C - VORBIX COMBUSTOR

Figure 9. - Experimental clean combustor program, phase 2 JT9D engine.



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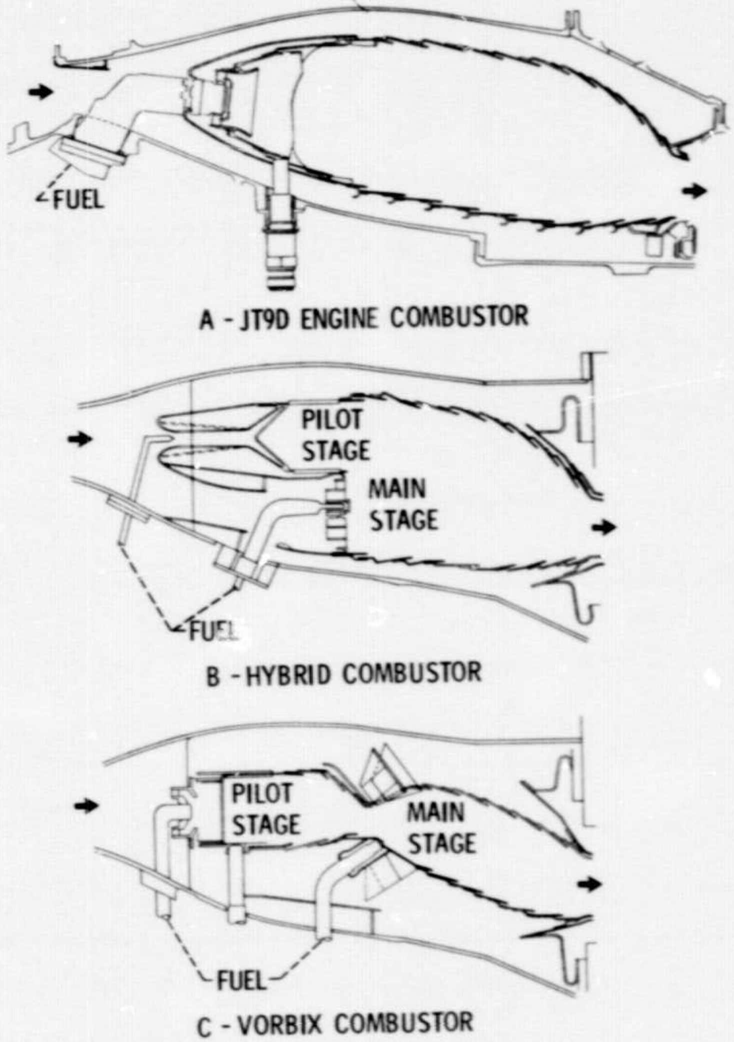

Figure 9. - Experimental clean combustor program, phase 2 JT9D engine.